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Texas Integrated Flooding Framework

FINAL REPORT

Texas Integrated Flooding Framework

TEXAS WATER DEVELOPMENT BOARD

USGS science for a changing world

US Army Corps of Engineers.

The Meadows Center for Water and the Environment
Texas State University

MEADOWS REPORT 26-001

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Texas Integrated Flooding Framework

FINAL REPORT | 2021-2026

Texas Integrated Flooding Framework

Produced in Partnership

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Cover Photo: Flooding caused by Hurricane Harvey in Southeast Texas © Staff Sgt. Daniel J. Martinez, Air National Guard

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This collaborative science endeavor was shaped by four distinct Technical Advisory Teams and carries the voices of more than 500 expert contributors, flood planning practitioners, and stakeholders engaged throughout the project.

Funding for this work was provided by the Texas General Land Office through the Community Development Block Grant Disaster Recovery Program and managed by the Texas Water Development Board.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. The mention of any organization, service, or product in this report and materials is for informational purposes only and does not imply endorsement or sponsorship by TIFF or its partner agencies.

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A highway immersed in floodwaters from Hurricane Harvey ©Luke Sharrett, Bloomberg

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Foreword From the TIFF Project Manager

The Texas Integrated Flooding Framework (TIFF) planning project was initiated in response to a growing and urgent challenge in Texas: compound flooding, which occurs when drivers such as heavy rainfall, storm surge, and riverine flooding interact to amplify flood impacts. As Texas continues to experience more frequent and intense flood events, TIFF has enhanced our understanding of these complex phenomena to improve the state's preparedness and resilience, which is essential for protecting communities, infrastructure, and ecosystems across the state.

The project's impacts are far-reaching. A cornerstone of the TIFF initiative was its collaborative nature. The project brought together key state and federal partners, including the Texas Water Development Board, the U.S. Geological Survey, the U.S. Army Corps of Engineers, The Meadows Center for Water and the Environment at Texas State University, and the Texas General Land Office. This interagency collaboration ensured that the project leveraged a wide range of expertise, data, and resources. To further strengthen the technical foundation of the project, TIFF brought more than 100 additional subject matter experts from across disciplines to the task. These Technical Advisory Teams provided critical input on data needs, modeling approaches, visualization tools, communication strategies, and planning frameworks. They not only guided the planning phase but also represent a lasting asset for the state—an expert network that can continue to support future flood resilience efforts.

Although TIFF was conceived in the aftermath of Hurricane Harvey with an initial focus on Harvey-impacted areas, **TIFF also specifically serves the culturally and hydrologically unique Lower Rio Grande Valley (LRGV).** To tailor research, tools, and recommendations to the distinct challenges of Starr, Hidalgo, Willacy, and Cameron counties, TIFF collaborated with local and regional stakeholders to add LRGV experts to Technical Advisory Teams, conduct a regional data inventory and gap analysis, integrate region-specific datasets into the new TIFF Coastal Data Surfer, evaluate coastal flood modeling challenges, update the regional model inventory, and develop targeted communication products for the region.

Building directly on the first three years of foundational work, TIFF centered on targeted studies, technology investments, and embedding TIFF outputs into flood risk planning and decision-making processes.

Cross-sector collaboration enabled TIFF to take a comprehensive approach to flood planning, addressing key areas such as:

- Data Needs and Management – identifying gaps in existing datasets and establishing protocols for data integration and accessibility
- Technologies and Modeling – evaluating current modeling capabilities and exploring innovative technologies to simulate complex flood scenarios and flood hazard analysis
- Visualization and Communication – developing guidelines and strategies to effectively communicate flood risks to stakeholders and the public
- Planning and Coordination – creating suggestions for coordinated planning across agencies and jurisdictions

TIFF produced actionable guidelines and recommendations. These were aimed at informing future flood-related projects, similar to the Texas General Land Office's Combined River Basin Flood Studies, and at enhancing the state's overall flood resilience. The recommendations cover improvements in data infrastructure, modeling techniques, visualization platforms, planning tools, and communication strategies to ensure that Texas is better equipped to anticipate and respond to compound flood events.

The future vision of TIFF shifts from planning to implementation and creating tangible products and models that can be deployed in real-world scenarios.

Ultimately, TIFF is a foundation for the future of flood science in Texas. TIFF will continue to evolve as a dynamic framework for increasing flood resilience in Texas, fostering collaboration among state and federal agencies, academic institutions, local governments, private sector partners, and the members of Technical Advisory Teams. This ongoing involvement will ensure that TIFF remains grounded in the latest science and best practices, while also fostering innovation and cross-sector collaboration.

By leveraging the insights and recommendations detailed in this report, TIFF aims to transform how Texas prepares for and mitigates compound flooding, ultimately leading to safer, more resilient communities.

Amin Kiaghadi, Ph.D., P.E.
TWDB Coastal Science Manager and TIFF Project Manager (2021-2025)

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History and Acknowledgments

When Hurricane Harvey made landfall in 2017, the scale of devastation was overwhelming for Texas. The storm destroyed properties, homes, and lives. As communities struggled to recover, state and federal agencies recognized a critical issue: **Texas lacked the tools and strategies needed to respond to a storm of Harvey's magnitude and prepare for future flood events of similar scale.** Out of these discussions, a clear purpose emerged: Empower Texas decision-makers with the information they need.

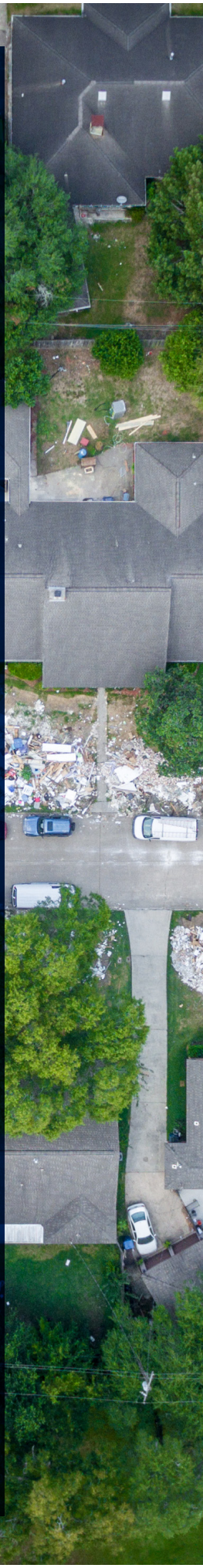
The idea for TIFF was born when colleagues from the Texas Water Development Board (TWDB), the United States Geological Survey (USGS), and the United States Army Corps of Engineers (USACE) began exploring how to better coordinate their work in the wake of Hurricane Harvey to help Texas better understand and manage compound flood risk along the coast. Those early discussions gained momentum when the Texas General Land Office (GLO) recognized that this effort aligned closely with broader state recovery and mitigation goals and TIFF began to take shape with GLO's support through Community Development Block Grant Disaster Recovery (CDBG-DR) funding.

The partnership officially launched in 2020, with TWDB designated as the lead agency and USGS and USACE serving as core technical partners. Two representatives from each agency were identified to serve as the Steering Committee for TIFF. The Meadows Center for Water and the Environment at Texas State University (Meadows Center) was selected to join the Leadership Team to guide project implementation, maximize engagement with external experts, and convey the resulting process outcomes to GLO and the public. Each entity brought its own expertise and perspective to the table, united by a shared vision to develop the tools and knowledge needed to understand and plan for compound flooding along the Texas coast:

- USACE provided specialized modeling expertise in coastal, freshwater, and marine systems. Their work emphasizes hydrologic, hydraulic, and coastal engineering, with a focus on the following areas: numerical modeling, flood risk management planning, and modeling data management and dissemination.
- USGS added decades of experience in operating large-scale coastal monitoring and environmental research projects, supporting the project with its capacity for specialized monitoring and data collection in coastal, freshwater, and marine systems.
- TWDB ensured that the needs and voices of Texas communities remained at the forefront. They also contributed expertise in geospatial modeling, regional flood planning, machine learning, hurricane storm surge simulation, rainfall-induced flooding, and the water-energy nexus.
- Meadows Center brought its unique blend of technical, science communication, and stakeholder engagement expertise to translate the objectives and goals into an accountable action plan and a structure to guide and support decision-making.

This Leadership Team is only one component of the TIFF partnership. More than 100 leading experts accepted nominations to volunteer their expertise via four Technical Advisory Teams (TATs) which guided the development of TIFF's four core components. Additionally, each component was supported by external Study Providers working behind the scenes to conduct literature reviews and the research necessary to meet the TIFF Objectives. These Study Providers included:

- Andrew Kennedy of the University of Notre Dame, Department of Civil and Environmental Engineering and Earth Sciences
- Ben Hodges of the University of Texas (UT)–Austin, Maseeh Department of Civil, Architectural, and Environmental Engineering
- Clint Dawson of the UT–Austin, Department of Aerospace Engineering & Engineering Mechanics
- David Johnson and Aaron Dewar of Purdue University, School of Industrial Engineering
- Elizabeth Le of UT-Austin, School of Information



Aerial photograph of Texas coast following landfall of Hurricane Ike in Galveston (2008) © NOAA

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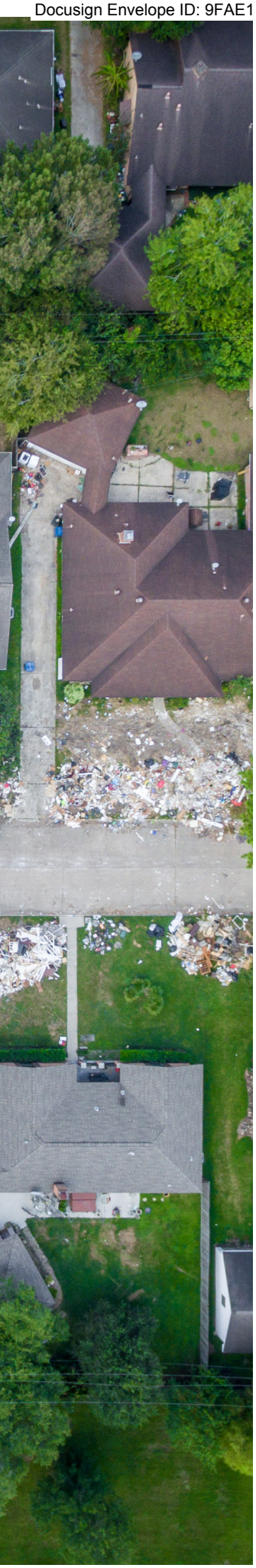

- Felipe Quintero Duque, Marcela Rojas Oliveros, and Nicolás Velásquez Giron of the University of Iowa, Iowa Institute of Hydraulic Research
- Gabriele Villarini and Renato Amorim of Princeton University, Department of Civil and Environmental Engineering and the High Meadows Environmental Institute
- Jianhong-Jennifer Ren, Tusha Sinha, and Hua Li of Texas A&M University (TAMU)–Kingsville, Department of Environmental Engineering
- Keri Stephens, Jovana Andelkovic, Tara Tasuj, and Samanta Varela of UT–Austin, Department of Communication Studies, Moody College of Communication
- Saugata Datta of UT–Austin Department of Earth and Planetary Sciences
- Meredith Carr, Chris Massey, Norberto Nadal, Fatima Bukhari, Ahmad Tavakoly, Chris Massey, Gaurav Savant, Gregory S. Karlovits, Avital Breverman, William Campbell, Roham Bakhtyar, Tate McAlpin, William Evans, Diana Stevens, Tacy Jensen, Caroline McCabe, Heath Sand, and Kristine Gollinger of USACE
- Sam Wallace, Glenn Harwell, and Jonathan Thomas of USGS
- Sina Khani, Mark Loveland, and Erik Valseth of UT–Austin, Computational Hydraulics Group at the Oden Institute for Computational Engineering & Sciences
- Suzanne A. Pierce of UT–Austin, Texas Advanced Computing Center (TACC)

The additional leadership of the following individuals and stakeholder entities were pivotal in turning a shared idea into a working, forward-looking framework. Their voices helped connect the technical work to long-term planning efforts across the Texas coast:

- Caimee Schoenbaechler, Former Steering Committee member, Manager of Coastal Science, TWDB
- Carla G. Guthrie, Director, Surface Water Division, TWDB
- Coraggio Maglio, Former Steering Committee member, Galveston District Hydraulics and Hydrology Branch Chief, USACE
- GLO River Basin Flood Study Groups
- Luci Cook-Hildreth, Former TIFF Project Coordinator, TWDB
- Meagan Willis, Project Manager, USACE-Galveston District
- Patrick Kerr, Former Galveston District Hydraulics and Hydrology Branch Chief, USACE
- Rikki Weaver, Flood Framework Coordinator, TWDB
- Samuel H. Rendon, Former Steering Committee member and Hydrologist, USGS–Gulf Coast Program Office
- Saul Nuccitelli, Former Steering Committee member and Director of Flood Science and Community Assistance, TWDB
- Skyler Levrier, Project Manager, GLO
- Texas A&M AgriLife's Community Health and Resource Management Program (CHARM)
- Texas Disaster Information System (TDIS)
- TWDB's Regional Flood Planning Groups (RFPGs)
- Tyler Payne, Former Senior Project Manager, GLO

Like the systems it seeks to model, TIFF is dynamic and continues to be shaped by the unique inputs of diverse experts and local stakeholders. We share this acknowledgment with all of the scientists, public servants, planners, communicators, emergency responders, and communities across Texas working to address the complexities of coastal flooding and build a more resilient future for the Texas coast.

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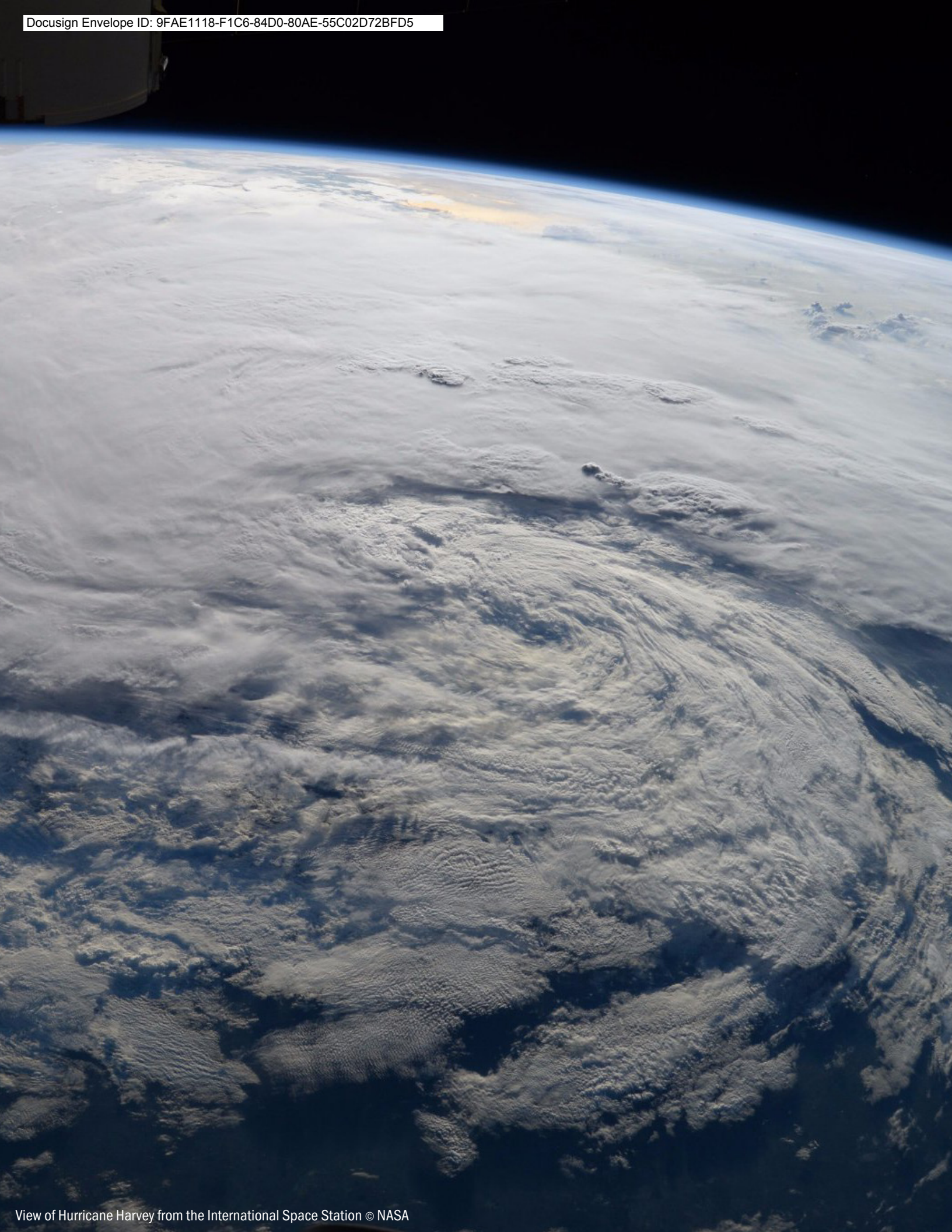

View of Hurricane Harvey from the International Space Station © NASA

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Contents

Foreword From the TIFF Project Manager **5**

Executive Summary **23**

Summarized Component Achievements and Progress 24

TIFF Component 1: Data and Monitoring Gap Analysis 24

TIFF Component 2: Data Management and Visualization 25

TIFF Component 3: Integrated Flood Modeling Framework 25

TIFF Component 4: Planning and Outreach 26

TIFF Structure and Development **27**

Project Identity 27

Purpose and Need 27

Mission and Vision 27

Geographic Scope 27

The Scar of Hurricane Harvey 27

The Unique Hydrology of the Lower Rio Grande Valley 28

Project Structure 29

The TIFF Leadership Team 29

Technical Advisory Teams 33

TIFF Literature Review and Research Partners (Study Providers) 36

The Larger TIFF Community 37

Introduction to Compound Flooding **38**

Flooding Sources 39

Flooding Behaviors 40

1 Component 1: Data and Monitoring Gap Analysis **43**

1.1 What is Data and Monitoring Gap Analysis? 43

1.2 Why Data and Monitoring Gap Analysis Matters to Texas 43

1.3 The Guiding Objectives of TIFF Component 1 43

1.4 Approach to Objectives 44

1.5 Implementation of Objectives 53

Objective 1: Establish a Data and Monitoring TAT 53

Objective 2: Assist TDIS in determining the appropriate data structure for creating a tool to inventory, display, and evaluate the availability of all data applicable to flood-related analyses used for planning and mitigating coastal floods 54

Objective 3: Provide TDIS with associated data linkages for critical coastal flood analysis use cases 57

Objective 4: Evaluate and provide feedback to GLO on 1) the initial data inventory provided by the RBFS Study Providers and the TWDB RFPGs, and 2) the associated data availability tool provided by TDIS 58

Objective 5: Perform a gap analysis for use cases with the feedback of the TATs to identify data needed to improve observations for coastal flood analysis 59

Objectives 6 and 7: Develop and recommend a plan to periodically update the data inventory and perform data gap analyses 61

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Objective 8: Evaluate and provide updates on new monitoring technologies 62

Objective 9: Make recommendations pertinent to future data and monitoring for coastal flood analysis to GLO 63

The Component 1 Recommendations 66

C1.2A: Enhance the Coastal Data Surfer for displaying, inventorying, and evaluating data to support flood planning, modeling, mapping, and mitigation along the Texas coast 67

C1.5A: Expand measurement networks to include under-sampled locations, prioritizing areas by flood frequency and severity 68

C1.5B: Establish a Nearshore Wave Data Collection Network along the Texas coast to address critical data gaps and enhance the understanding of extreme wave events, improve daily flood forecasting, and strengthen coastal risk assessment 69

C1.5C: Develop and maintain a centralized Subsidence Monitoring Dashboard to serve as a comprehensive, user-friendly platform to consolidate, analyze, and utilize subsidence data 70

C1.5D: Compile, collect, process, and integrate high-resolution land cover data to enhance flood models for the entire Texas coast and provide guidelines for implementation into Texas coastal flood modeling systems 71

C1.5E: Collect bathymetric data for priority areas along the Texas coast to address critical data gaps, strengthen coastal flood modeling efforts, and improve flood forecasting 71

C1.5F: Integrate historical datasets from the Texas Coastal Ocean Observation Network (TCOON) in the National Oceanic and Atmospheric Administration's operational database 72

C1.8A: Operate testing sites that evaluate water monitoring devices to ensure their reliability, operational effectiveness, and compliance with regulatory standards 73

C1.8B: Assess extent of High-Frequency radar accuracy for wave measurements 75

2 Component 2: Data Management and Visualization 77

2.1 What is Data Management and Visualization? 77

2.2 Why Data Management and Visualization Matters to Texas 77

2.3 The Guiding Objectives of TIFF Component 2 77

2.4 Approach to Objectives 78

2.5 Implementation of Objectives 81

Objective 1: Establish a Data Management and Visualization TAT 81

Objective 2: Assist TDIS with designing and testing the conceptual framework for managing, visualizing, and disseminating large volumes of coastal flood-related datasets, including data visualization system(s) 82

Objective 3: Conduct an inventory of coastal flood-related user interfaces 86

Objective 4: Recommend guidelines for coastal flood UIs, including the level of end-user access, analysis capability, visualizations, and datasets 89

Objective 5: Assist TDIS with computational hardware/software requirements for flood-related analysis and visualization 131

Objective 6: Make recommendations for future data management and visualization needs 137

The Component 2 Recommendations 138

C2.3A: Improve online tools to maximize user comprehension by studying user gaze patterns and other user responses to different flood risk visualizations and interactive tools 139

C2.3B: Improve emergency planning and response by better understanding the decision-making of Texas residents facing evacuation during a flood 139

C2.3C: Identify more understandable ways of communicating flood risk to the public than current "frequency-based terminology" (e.g., "100-year Flood") 140

C2.3D: Create Flood Risk Planning Flashcards to support Texas flood planners and decision-makers 141

C2.3E: Require Texas agencies to collect three standardized shapefiles for all state-funded flood-related projects to improve state flood coordination 142

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

C2.4A: State and local agencies should implement ***The TIFF Communication Guidelines*** to enhance consistency, clarity, and accessibility of flood information 143

C2.4B: Create and validate flood safety messages that better reach target users in the Lower Rio Grande Valley 143

C2.4C: State and local agencies should consider adopting the TIFF Target Group Pilot Test methodology to enhance the consistency of designing and evaluating meaningful flood communication tools 144

C2.4D: Develop new State of Texas tool to share lessons of Texas' flood history to help residents better predict future flood risks based on historical patterns 145

C2.4E: Develop a Texas-specific AI Flood Risk Tool to help target users find flood information 146

3 Component 3: Integrated Flood Modeling Framework 149

3.1 What is an Integrated Flood Modeling Framework? 149

Understanding Flood Modeling 149

3.2 Why An Integrated Flooding Framework Matters To Texas 156

The Challenge of Compound Flooding in Flood Protection Design 158

3.3 The Guiding Objectives of TIFF Component 3 159

3.4 Implementation of Objectives 162

Objective 1: Establish an Integrated Flood Modeling TAT 162

Objective 2: Evaluate and provide feedback on initial inventory of existing and proposed meteorologic, hydrologic, hydraulic, estuarine, and surge models by the Study Providers to support inland and coastal flood hazard identification 163

Objectives 3 and 4: Perform literature reviews to identify potential meteorological, hydrologic, hydraulic, and hydrodynamic models for evaluating and mitigating flood risk for Texas and probabilistic methods for flood hazard estimation 169

Objective 5: Develop recommendations for conceptual model-coupling workflow(s) for assessment of compound flooding hazard in the coastal Texas region 185

The Component 3 Recommendations 216

C3.2B: Develop one- and two-dimensional hydraulic and hydrologic models for the main stem of the Rio Grande, extending from Peñitas, TX to the Gulf 217

C3.3A: Evaluate the Analysis of Record for Calibration across Texas for potential flood hazard analysis uses 218

C3.3B: Advance hydraulic modeling simulations with HEC-RAS distributed-memory parallelization 219

C3.3C: Advance artificial intelligence/machine learning techniques for flood modeling 219

C3.3D: Integrate urban stormwater and flood hazard hydrodynamics model applications 220

C3.3E: Quantify the impacts of erosion on storm surge 221

C3.3F: Quantify wind-driven inland flows to enhance flooding models 222

C3.3G: Enhance wave models and data to improve accuracy in populated areas 222

C3.3H: Automate topography and bathymetry data processing 223

C3.3I: Quantify sensitivities of existing models to wind forcing, bathymetry, bottom friction, and turbulence, with an initial emphasis on bathymetry 224

C3.3J: Develop guidelines for nature-based features to reduce flood risk 224

C3.3K: Use physics-based numerical modeling to evaluate the coastal flood risk reduction performance of nature-based solutions applied in Lower Rio Grande Valley watersheds 225

C3.3L: Develop a machine learning model that leverages artificial intelligence to evaluate the flood risk reduction performance of nature-based solutions applied in Lower Rio Grande Valley watersheds 226

C3.3M: Study the viability of using managed aquifer recharge as a flood risk reduction strategy in the Lower Rio Grande Valley 228

C3.3N: Conduct sediment transport and channel capacity analyses on the Rio Grande and Arroyo Colorado to quantify geomorphic changes and vegetation growth that may impair flood conveyance 228

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

C3.4A: Advance the use of the Joint Probability Method in compound hazard assessment 229

C3.4B: Develop a Tropical Cyclone Rainfall Generator 230

C3.4C: Conduct retrospective modeling of historic landfalling hurricanes using high-resolution weather models 230

C3.4D: Develop rapid predictions of flooding hazards 231

C3.4E: Collect ground-truth data to develop a machine learning model that leverages artificial intelligence and remote sensing to detect and map high-risk flood zones across the Lower Rio Grande Valley 231

C3.4F: Leverage historical and real-time monitoring data to develop a machine learning model that evaluates how coastal storm surges influence flood dynamics in the Lower Rio Grande Valley 233

C3.5A: Develop the Texas Coastal Flood Framework (TxCFF) for compound flood assessment to support flood recovery and emergency response efforts along the Texas coast 234

4 Component 4: Flood Planning and Outreach 241

4.1 What is Flood Planning and Outreach? 241

4.2 Why Flood Planning and Outreach Matters to Texas 241

4.3 The Guiding Objectives of TIFF Component 4 241

4.4 Approach to Objectives 242

4.5 Implementation of Objectives 245

Objective 1: Establish a Planning and Outreach TAT 245

Objective 2: Coordinate with the RFPGs and stakeholders to identify flood planning and mitigation scenarios consistent with regional flood planning efforts, beginning by establishing a working relationship with RFPGs or their Coastal Liaisons to identify TIFF end-users 246

Objective 3: Develop and implement a comprehensive outreach plan to engage the RFPGs and other stakeholders regarding flood planning and mitigation efforts, reassessing user needs annually regarding flood planning and mitigation efforts and requirements, and providing the results by updating the comprehensive outreach plan and preparing an annual progress report 247

Objective 4: Evaluate and provide feedback on the initial inventory of planning datasets provided by the GLO Regional Flood Study Groups 249

Objective 5: Perform a literature review on planning tools and develop a list of data modeling needs for planning tools 251

Objective 6: Support the development of flood communications and educational materials 254

Objective 7: Investigate the opportunities to balance local cost-effective flood risk management analysis with regional flood risk considerations 255

Objective 8: Make recommendations pertinent to flood planning and outreach/communication to GLO 261

The Component 4 Recommendations 262

C4.5A: Develop a flood tool for hazard and loss assessments to improve state flood planning and prediction 263

C4.5B: Teach stakeholders how to use flood risk maps for preparedness to enhance community flood resilience 263

C4.6A: Establish online learning center within the Texas Disaster Information System to improve sharing of flood education resources 265

C4.6B: Expand K-12 flood education to help students better understand and respond to flooding 266

C4.6C: Better understand stakeholder social norms related to flood decision-making 266

C4.6D: Use a branding campaign to enhance online engagement with key flood information on TexasFlood.org 267

C4.6E: Address flooding caused by illegal dumping in the Lower Rio Grande Valley by simplifying drainage education and applying behavioral intervention strategies 268

C4.7A: Establish a Texas Flood Coordination Office (TFCO) to optimize local, state, and federal project impacts 269

C4.7B: Appoint a State Flood Communication Officer to facilitate interorganizational coordination in flood research 271

C4.7C: Formalize cooperative local and regional flood planning in the Lower Rio Grande Valley 271

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

C4.7D: Enhance regional Flood Early Warning Systems in the Lower Rio Grande Valley by centralizing existing flood monitoring and forecasting efforts 273

C4.7E: Develop Safe Pass, a Transportation Flood Resilience Initiative in the Lower Rio Grande Valley 274

5 TIFF Facilitation 277

The Meadows Center for Water and the Environment 278

The TIFF Project Charter 278

Facilitation Deliverables 280

Facilitation Strategies 281

Establishing a "TIFF" Identity and Branding for Enhanced Coherence and Consistency 281

Accessible Communication of Complex Information 281

Neutrality, Transparency, and Responsiveness to Advisor Input 282

Designing and Delivering Effective Meetings 282

Engagement Tools for Participation and Feedback 282

Facilitation Activities 283

The TIFF Recommendations Process 287

TIFF Recommendations for the Footprint of Hurricane Harvey 287

TIFF Recommendations for Lower Rio Grande Valley 288

Interagency Collaboration Lessons Learned 289

Challenges That Shaped These Lessons 289

6 Texas Integrated Flooding Framework Recommendations Handouts 292

Actionable Recommendation summaries that can be printed as handouts to guide decision-making

7 References 406

Appendices are available as separate downloads on the Texas Integrated Flooding Framework's reports webpage.

Appendix A: Data and Monitoring Gap Analysis

Appendix B: Data Management and Visualization

Appendix C: Integrated Flood Modeling Framework

Appendix D: Flood Planning and Outreach

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Satellite view of Galveston and Pelican Island from space ©NASA

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

List of Figures

Figure A-1. Compound flooding conditions – multiple and overlapping interactions between flooding types within the design conditions of all infrastructure. 38

Figure 1-1. Diagram showing the 11 TIFF coastal data classes developed to organize metadata and enable effective filtering of datasets for specific needs. 45

Figure 1-2. A preview of the Coastal Data Surfer landing webpage. 47

Figure 1-3. A simplified schematic highlighting the web interface's two options for interacting with the data inventory: by a guided questionnaire or through a manual filter of the underlying data inventory database. 48

Figure 1-4. A dynamic result count updates based on prior answers and this selection, helping users understand how their criteria refine the dataset and supporting better discovery and relevance for both technical and non-technical users. 49

Figure 1-5. Screenshot displaying the interactive map interface where users can explore data layers by thematic category. Users can click on any of the following categories to view and load relevant map layers: Atmospheric, Natural Environment, Built Environment, Ecological, Imagery, Literature Sources, Models, Natural Hazards, Mitigation Support, and Demographics. 50

Figure 1-6. Screenshot displaying a visual mask applied around the state of Texas, reducing visual clutter from neighboring states. 50

Figure 1-7. Screenshot highlighting map layers that have a *'?'* icon. 51

Figure 1-8. Screenshot showing an alert that appears when a user attempts to load layers with high data density without zooming in. 51

Figure 1-9. Schematic of the purpose-driven inventory structure. 55

Figure 1-10. Example of hydrologic modeling using the HEC-HMS within the purpose-driven structure. 56

Figure 1-11. A decision tree linking the necessary data for hydrologic analysis using the USACE HEC-HMS. Linkages include FEMA's Hazard Mitigation Grant Program (HMGP), SWAT, and PRMS. 58

Figure 2-1. Participatory Design Pyramid (prepared by Study Providers Keri K. Stephens, Suzanne A. Pierce, Jovana Andelkovic, Samanta Varela, Ruoxiao Su, and Emaly Aguilar, 2024; and modified after Newbold, 2018). 80

Figure 2-2. Conceptual diagram of a human-in-the-loop process supporting the use of AI applications to accelerate exploration and discovery tasks for systematic and diagnostic literature searches (Pierce, SA 2024). 90

Figure 2-3. Defining groups involved in the design of flood communication products. These concepts vary according to agency; some people are recipients of information, while others have the capacity to impact decisions. Readers should consider these nuances in meaning. 96

Figure 2-4. The Stakeholder Decision Map summarizes the identified stakeholder groups, their technical user levels, current and future communication paths, and the types of decisions they need to make regarding coastal flooding. 97

Figure 2-5. *Property Owners* and stakeholders supporting their flood-related decisions. 101

Figure 2-6. Hispanic Texans are the largest demographic group in Texas as of 2022. 103

Figure 2-7. The TIFF Guidelines for Coastal Flood Information Design and Communication (*The TIFF Communication Guidelines*). 106

Figure 2-8. Sample flood risk conditions for test properties. 112

Figure 2-9. A map of the Lower Rio Grande Valley, including Cameron, Hidalgo, Starr, and Willacy Counties. 116

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Figure 2-10. Step-by-step TGP Test workflow using artificial intelligence. 126

Figure 3-1. Conceptual cascade of flood risk (flood inundation triggers a flood response from the system; the integration of that flood response across probabilities, or return intervals, is the flood hazard; hazards with resiliency and consequences provide quantification of risk). 149

Figure 3-2. Modeled water surface elevation (feet) in the Houston area without river inflow (left), and with synthetic extreme river inflows (right), using winds and oceanic storm surge from Hurricane Ike. Results are from the coastal flood model (ADCIRC). 151

Figure 3-3. Conceptual diagram of model and data couplings within a TxCFF. 161

Figure 3-4. Area covered by the USACE Georeferenced Coastal Model. 168

Figure 3-5. Overview of the literature review of state-of-practice of modeling and probabilistic analysis for flood hazard characterization for coastal Texas. 170

Figure 3-6. Examples of compound flood models found in the literature. Process-based modeling systems include all flood processes (hydrology, hydraulics, ocean, and waves), while reduced-physics models are simplified and may not represent all components. Couplings between process-based models, reduced-physics models, and data-driven models are possible, but are neglected for simplicity in presentation. 181

Figure 3-7. Decision support tree for the application of Nature-Based Solutions (NBS) in the LRGV. 185

Figure 3-8. Rio Grande drainage basin showing gage locations. 190

Figure 3-9. Rio Grande isoline envelope curves with relative probability and design events. 191

Figure 3-10. Examples of conceptual workflows for a TxCFF (adapted from Liu et al, 2025). SWL and CWL represent surge and compound water elevation, respectively. 193

Figure 3-11. The Houston/Galveston priority testbed region. 200

Figure 3-12. The Freeport priority testbed region. 202

Figure 3-13. The Rio Grande/Lower Laguna Madre priority testbed region. 204

Figure 3-14. The Beaumont/Port Arthur priority testbed region. 206

Figure 3-15. The Corpus Christi priority testbed region. 206

Figure 3-16. The Matagorda Bay priority testbed region. 206

Figure 3-17. The Brownsville/South Padre Island priority testbed region. 206

Figure 3-18. Map showing the storm tracks for Hurricanes Allen, Bret, and Dolly in relation to the ADCIRC model domain and the location of the Port Isabel NOAA tides and currents gage location. 209

Figure 3-19. Map showing two-dimensional color contours of mesh element resolution (units in feet), for the extended and updated unstructured ADCIRC mesh used in the LRGV study. The black lines indicate the boundary of the original CTXCS Study mesh. 210

Figure 3-20. Study area and 2D mesh visualized in RAS Mapper. 211

Figure 3-21. AdH model domain and elevations. 211

Figure 3-22. Map of the LRGV area with several locations marked and labeled for use in comparing modeling results. 212

Figure 3-23. Hurricane Allen modeled vs observed water surface elevation (ft.) Port Isabel, Texas. 213

Figure 3-24. Tasks/steps to build the TxCFF. 235

Figure 4-1. The TIFF Star shows the five major elements of trust for building a reliable brand among the selected target users. 248

Figure 5-1. Timeline illustrating key project milestones. 284

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

List of Tables

Table 1-1. Component 1 Objectives for Data and Monitoring Gap Analysis and associated Recommendations. 66
Table 2-1. Generated inventory matrix for conducting an inventory analysis on the existing coastal UIs. 88
Table 2-2. The types of Texas public target users where flood insurance is a key decision..... 98
Table 2-3. Public target users more at-risk to floods due to needs for specific types of information. 98
Table 2-4. Public target users more at-risk due to infrastructure concerns..... 99
Table 2-5. Public target users responsible for others (caretakers). 99
Table 2-6. Percent and number of Spanish speakers in Texas coastal counties as of 2022. 104
Table 2-7. Demographics for the Texas survey to test *The TIFF Communication Guidelines*..... 113
Table 2-8. Questions asked during interviews. 117
Table 2-9. Workshop station and survey design summary..... 119
Table 2-10. Statistical workshop findings overview..... 121
Table 2-11. Communication pitfalls identified during the TIFF workshops, CLE, and analyses of past flood response efforts with potential strategies to address identified pitfalls. 124
Table 2-12. LRGV Flood Information Collection categories and communication readiness..... 125
Table 2-13. Design prompts for testable hypotheses, experimental tasks, and observable metrics. 127
Table 2-14. TGP Test designs to assess scientific uncertainty for flood risk visualization and communication with *Property Owners* and *Property Renters*. 128
Table 2-15. Evaluation metrics, measurement methods, frequency of measurement, and target outcomes across evaluation metric categories for assessing the effectiveness of communication and visualization tools. 129
Table 2-16. Examples of computational and data resources for CHS-TX..... 132
Table 2-17. Component 2 Objectives for Data Management and Visualization and associated Recommendations..... 138
Table 3-1. Numerical model types of compound flood inundation modeling systems..... 154
Table 3-2. Current and potential use cases for types of inundation modeling. 155
Table 3-3. Inventory matrix metadata fields and their descriptions..... 165
Table 3-4. TIFF Model inventory count by software..... 167
Table 3-5. A comparison of the process complexity represented in the considered hydrologic models..... 174
Table 3-6. A description of the hydrologic processes represented by the models..... 175
Table 3-7. A comparison of the process complexity represented in the considered hydraulic models. 176
Table 3-8. A description of the hydraulic processes represented by the considered models..... 177
Table 3-9. A SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis for storm surge models..... 178
Table 3-10. Compound flood hazard framework levels..... 188
Table 3-11. Design events for the LRGV..... 191
Table 3-12. Model skill and performance evaluation matrix..... 198
Table 3-13. Component 3 Objectives for an Integrated Flood Modeling Framework and associated Recommendations. . 216
Table 4-1. Planning model inventory example: HEC's Flood Damage Reduction Analysis..... 250
Table 4-2. Component 4 Objectives for Flood Planning and Outreach and associated Recommendations..... 262

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Acronyms

ACRONYM	DEFINITION
ADCIRC	ADvanced CIRCulation Model
AdH	Adaptive Hydraulics
AEP	Annual Exceedance Probability
AI	Artificial Intelligence
AIC	Aikake Information Criteria
AOI	Areas of Interest
AORC	Analysis of Record for Calibration
API	Application Programming Interface
AWS	Amazon Webservice
BCA	Benefit-Cost Analysis
BLE	Base Level Engineering
BEG	Bureau of Economic Geology
CBI	Conrad Blucher Institute
CDBG-DR	Community Development Block Grant Disaster Recovery Program
CDS	Coastal Data Surfer
CFD	Computational Fluid Dynamics
CFM	Certified Floodplain Manager
CHARM	Community Health And Resource Management
CHART	Coastal Hazards Analysis and Risk Toolkit
CHG	Computational Hydraulics Group
CHL	Coastal and Hydraulics Lab
CHS	United States Army Corps of Engineers Coastal Hazards System
CHS-CF	Coastal Hazards System-Compound Framework
CHS-LA	Coastal Hazards System–Louisiana
CHS-PCHA	Coastal Hazards System–Probabilistic Coastal Hazard Analysis Framework
CHS-TX	Coastal Hazards System–Texas
COOP	Cooperative Observer Network
CO-OPS	NOAA's Center for Operational Oceanographic Products and Services
CPU	Central Processing Unit
CSRM	Coastal Storm Risk Management
CSTORM	Coastal Storm Modeling and Production Systems
CSTORM-MS	Coastal Storm Modeling System
CTXCS	Coastal Texas Comprehensive Study
CWL	Combined Water Level
DDF	Depth Damage Curve
Delft3D	3D modeling suite to investigate hydrodynamics, sediment transport and morphology and water quality for fluvial, estuarine and coastal environments
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
EQ	Environmental Quality
ERDC	Engineer Research and Development Center
FAIR	Findable, Accessible, Interoperable, and Reusable

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

ACRONYM	DEFINITION
FEMA	Federal Emergency Management Agency
FFE	First Floor Elevation
FI-DD	Flood Inundation Data-Driven Model
FI-H	Flood Inundation Hybrid Model
FI-I, FI-II, FI-III, FI-IV	Flood Inundation Models 1-4
FIRM	Flood Insurance Rate Map
FRM	Flood Risk Management
FVCOM	Finite Volume Community Ocean Model
G2CRM	Generation 2 Coastal Risk Model
GCM	Global Climate Model
GCOOS	Gulf of Mexico Coastal Ocean Observing System
GenAI	Generative AI
GIS	Geographic Information System
GLO	Texas General Land Office
GPM	Gaussian Process Metamodeling
GPU	Graphics Processing Unit
GSSHA	Gridded Surface / Subsurface Hydrologic Analysis Model
GUI	Graphical User Interface
H&H	Hydrologic and Hydraulic
HAI	Human-Centered Artificial Intelligence
HCFCD	Harris County Flood Control District
HDF5	Hierarchical Data Format version 5
HEC-FDA	Hydrologic Engineering Center's Flood Damage Reduction Analysis Model
HEC-HMS	USACE Hydrologic Engineering Center Hydrologic Modeling System
HEC-RAS	USACE Hydrologic Engineering Center River Analysis System
HEC-SSP	Hydrologic Engineering Center's Statistical Software Package
HF	High Frequency
HL	Hazard Level
HMGP	Hazard Mitigation Grant Program
HPC	High Performance Computing
HUD	U.S. Department of Housing and Urban Development
HURDAT2	Hurricane Database 2
IBWC	International Boundary and Water Commission
IDRT	Institute for a Disaster Resilient Texas
IIHR	Iowa Institute of Hydraulic Research
InFRM	Interagency Flood Risk Management
InSAR	Interferometric Synthetic Aperture Radar
IWR	Institute for Water Resources
JCBP-TX	Joint Coastal Bivariate Probability Study–Texas
JPM	Joint Probability Model
JPM-AMP	Joint Probability Model with Augmented by Metamodel Prediction
JPM-OS	Joint Probability Model with Optimal Sampling
JSON	JavaScript Object Notation
LEP	Limited English Proficiency

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ACRONYM	DEFINITION
LiDAR	Light detection and ranging
LISFLOOD	Large-scale Inundation Simulation model
LRGFCP	Lower Rio Grande Flood Control Project
LRGV	Lower Rio Grande Valley
M3FR	Measuring, Mapping, and Managing Flood Risk in Texas Modeling Catalog
MIKE SHE, MIKE 21 HD, MIKE 11 HD, MIKE+ Rivers	Models developed by DHI for hydrology and hydraulics
ML	Machine Learning
MODFLOW	Modular Finite-Difference Flow Model
MOM	Maximum of the Maximum
MPI	Message Passing Interface
NBS	Nature-Based Solutions
NDBC	National Data Buoy Center
NED	Net Economic Development
NetCDF	Network Common Data Form
NFHL	National Flood Hazard Layer
NFIP	National Flood Insurance Program
NNBF	Natural and Nature-Based Feature
NOAA	National Oceanic and Atmospheric Administration
NOPP	National Oceanographic Partnership Program
NSI2	National Structure Inventory 2
NWIS	National Water Information System
NWM	National Water Model
NWS	National Weather Service
OSE	Other Social Effects
OSP	Open Science Platforms
P&G	U.S. Water Resource Council's 1983 Principles and Guidelines for Water and Related Land Implementation Studies
PE	Professional Engineer
POM	Princeton Ocean Model
PRIMo	Parallel Raster Inundation Model
PRISM	Parameter-Elevation Relationships on Independent Slopes Model
PRMS	Precipitation Runoff Modeling System
QA/QC	Quality Control / Quality Assurance
RATES	Research, Applied Technology, Education and Service
RBFS	Combined River Basin Flood Studies
RED	Regional Economic Development
RFPG	Regional Flood Planning Group
SC	Steering Committee
SCHISM	Semi-implicit Cross-scale Hydroscience Integrated System Model
SECOORA	Southeast Coastal Ocean Observing Regional Association
SFHA	Special Flood Hazard Area
SFINCS	Super Fast INundation of CoastS

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

ACRONYM	DEFINITION
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
SLR	Sea Level Rise
SMART	Specific, Measurable, Attainable, Relevant, and Time-based
STWAVE	Steady-State Spectral Wave Model
SWAN	Simulating Waves Near Shore
SWAT	Soil and Water Assessment Tool
SWL	Still Water Level
SWMM	Storm Water Management Model
TABS	Texas Automated Buoy System
TACC	Texas Advanced Computing Center
TAD	Tidal Analysis Datum
TAMU	Texas A&M University
TAT	Technical Advisory Team
TCEQ	Texas Commission on Environmental Quality
TCOON	Texas Coastal Ocean Observation Network
TCRM	Tropical Cyclone Rainfall Model
TCRMP	Texas Coastal Resiliency Master Plan
TDEM	Texas Division of Emergency Management
TDIS	Texas Disaster Information System
TEA	Texas Education Agency
TEKS	Texas Essential Knowledge and Skills
TFCO	Texas Flood Coordination Office
TFMA	Texas Floodplain Management Association
TGP Test	Target Group Pilot Test
TIFF	Texas Integrated Flooding Framework
TRITON	Two-dimensional Runoff Inundation Toolkit for Operational Needs
TWDB	Texas Water Development Board
TxCFF	Texas Coastal Flood Framework
TxDOT	Texas Department of Transportation
TxGIO	Texas Geographic Information Office
TxRR	Texas Rainfall Runoff Model
UFS	Unified Forecast System
UI	User Interface
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
UT	University of Texas
UX	User Experience
VIC	Variable Infiltration Capacity
WASH123D	Watershed Systems of 1D, 2D, and 3D Models
WRF	Weather Research Forecast
WSE	Water Surface Elevation
WWOD	WaterWorks OnDemand

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A rainbow appears behind a flooded neighborhood in Jamaica Beach, Texas © Brandon Bell

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Executive Summary

Compound flooding occurs when multiple drivers such as storm surge, heavy rainfall, and riverine flooding overlap simultaneously or in sequential combination, and communities are faced with evaluating multiple flooding sources and hazards all at the same time. The challenge of analyzing and modeling compound floods is that the effects cannot be treated separately and simply added together because each flooding type has interactions with the others, which affect the transport and behavior of flood waters.

Hurricane Harvey was a compound flood event and left a historic mark on Texas as one of the costliest and most devastating natural disasters to impact the state. In its wake, with the realization that our existing state tools and data were not sufficient to predict or prepare for events of this complexity, TIFF partners envisioned an interagency and interdisciplinary pursuit of four guiding questions: What is the state of knowledge and the needed next steps for 1) flood data monitoring and gap analysis, 2) flood data management and visualization, 3) integrated flood modeling, and 4) flood planning and outreach.

With **five years and four million dollars**, the group set out to identify top experts in flood science fields, conduct a data gap analysis, carry out original research, elicit expert feedback and peer-review, and ultimately, identify recommendations aimed at building a roadmap for efficient coastal flood resilience in Texas. This aggressive yet intentionally collaborative process ensured that the best available expertise shaped every outcome of this comprehensive flood risk reduction planning project.

TIFF was funded by the GLO Community Development and Revitalization Department to improve the modeling, data collection, data management, visualization, planning, and outreach efforts in counties affected by Hurricane Harvey. As additional funding became available, TIFF expanded its work to include targeted research in the LRGV where unique conditions required additional region-specific consideration and positioned the region as a case study and testbed for refining selected TIFF approaches across the Texas coast. TWDB served as the lead agency coordinating a partnership with USGS and USACE. The Meadows Center served as the process facilitators.

The planning project's ultimate goal was to deliver actionable, science-based recommendations and guidelines to help Texas meet its pressing flood challenges. By focusing on the four guiding questions (TIFF Components), **TIFF seeks to provide practical solutions to all levels of decision-makers grappling with the known and potential impacts of coastal flooding in Texas.**

TIFF produced 54 detailed recommendations (as well as a multitude of research findings, guidelines, and best practices presented in this report and its appendices). Four overarching proposals emerged as central to advancing Texas flood resilience, underscoring the value of expert-driven review:

1. The creation of a coordinated, accessible online platform to centralize coastal flood-related data for planning and mitigation (The Coastal Data Surfer (CDS))
2. The identification of best practices to improve how agencies design visualizations and communication tools for diverse audiences (*The TIFF Guidelines for Coastal Flood Information Design and Communication* (*The TIFF Communication Guidelines*))
3. The proposal for a flexible software framework that couples flood models with analysis tools and workflows for integrated flood risk assessment (The Texas Coastal Flooding Framework (TxCFF))
4. The establishment of a coordinating office to centralize flood efforts, enhance collaboration, and optimize state and federal project impacts (The Texas Flood Coordination Office (TFCO))

The 54 TIFF Recommendations **capture the specific investments needed to advance flood monitoring, modeling, communication, and planning in Texas.** Each recommendation is designed to articulate what is needed, implementation actions, and where feasible, approximate costs. Collectively, the recommendations are designed to provide funders and policymakers with a clear roadmap for strength-

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ening the state's flood resilience, ensuring that communities, infrastructure, and ecosystems along the Texas coast are better protected for the future. The project also sought to provide guidelines and recommendations specific to the LRGV region. For example, one essential proposal recommends formal investments into multi-jurisdictional/multi-sector agreements and projects, as appropriate, to focus flood planning activities on shared areas of interest in the LRGV.

Summarized Component Achievements and Progress

TIFF is a collaborative initiative designed to gather the best available flood science information to produce actionable, science-based recommendations for enhancing Texas coastal flood resilience. The Leadership Team, TATs, Study Providers, and other key stakeholders contributed their expertise to guide and review the evolving work over the course of the project.

Each component followed a structured approach to meet its Objectives, beginning with a literature review and/or inventory analysis to establish a foundation of knowledge guiding research design. This was followed by a gap analysis to identify missing or incomplete data, original research and tool development, and feedback from select Technical Advisors that shaped the recommendations for improved flood analysis, communication, outreach, and modeling.

TIFF Component 1: Data and Monitoring Gap Analysis

Component 1 focused on crossing institutional barriers to catalog, understand, vet, and share the available data and identify additional data necessary for a comprehensive modeling framework to inform the decisions that will shape Texas.

The literature review/inventory analysis covered available flood-related datasets, existing data-model linkages, and critical monitoring technologies and data frameworks needed to support coastal flood analysis in Texas. It considered best practices for building data inventories and creating interactive platforms for data sharing, with an emphasis on the need to improve the accessibility of flood data for decision-makers at all levels. With support from TDIS, TIFF designed a data structure capable of supporting a wide range of coastal, hydrologic, atmospheric, and inland datasets essential for flood-risk analysis in the Texas coastal region. The process improved statewide data accessibility and strengthened the foundation upon which the CDS could perform reliable inventory and gap-assessment functions for the Texas coast. The LRGV served as an ideal testbed region for building CDS capabilities.

Gap analysis efforts focused on specific "use cases" to identify data needed to improve coastal flood observations, and revealed shortcomings in metadata standards, data compatibility, and coverage of specialized data such as bathymetry, subsidence, and nearshore wave data. Existing monitoring databases have inconsistent data and categorization, existing sensor networks are insufficient to capture meaningful data, and existing data collection efforts are often duplicated. In the LRGV, areas with data scarcity or poor quality are typically highly localized drainage networks, areas with limited bathymetric coverage, and coastal inlets subject to frequent geomorphic change.

Key findings of the Component's work emphasize the need for specialized data such as nearshore wave measurements, updated bathymetry, and robust subsidence monitoring to enhance our understanding of compound flooding along the Texas coast. The resulting TIFF Recommendations include expanding sensor networks, deploying and assessing new sensor and radar technologies, and integrating high-quality data into Texas coastal flood modeling systems. The CDS is envisioned as the key mechanism for keeping the data inventory and gap analysis active and up-to-date via end-user searches, interactive mapping, real-time updates, and improved data access and visualization.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

TIFF Component 2: Data Management and Visualization

Component 2 sought to understand and address the data management and visualization needs of technical and non-technical user groups in Texas by developing tailored strategies for information tools and communication approaches designed to motivate behavior change.

TIFF performed a comprehensive review of the efforts conducted by major agencies responsible for flood data and communication to assemble a coastal flood user interface (UI) inventory and identify opportunities to improve coastal flood-related visualization tools. An additional literature review assessed the essential components and strategic considerations for designing a conceptual framework for managing, visualizing, and disseminating coastal flood-related datasets. The literature review identified communication best practices and effective flood risk data visualization strategies.

The gap analysis revealed shortcomings in existing communication and visualization tools, particularly in usability, accessibility, and contextual relevance for vulnerable populations.

Notable gaps include the need for statewide standardized guidelines for designing flood communication and visualization resources for user groups; the need for best practices for menu-driven dashboards and information interfaces that transparently convey model uncertainty; and clear approaches to integrate model data and outputs into flood planning. In the LRGV, existing communication and visualization tools generally lack bilingual messaging, incorporated cultural norms and values, and messaging around critical regional flood-related concerns, including drainage infrastructure challenges and illegal dumping practices.

Findings revealed the need for early and ongoing user engagement when designing communication and visualization tools, planning for evaluation and integrating measures of success from the beginning of the design process, and adapting communications over time to ensure alignment with user needs and perspectives. The resulting TIFF Recommendations call for statewide adoption of standardized communication guidelines, clearer terminology for flood probabilities (especially in bilingual formats), and behavioral studies with target user groups to optimize interface designs and emergency planning.

TIFF Component 3: Integrated Flood Modeling Framework

Component 3 tackled the technical challenges of developing an integrated modeling framework to support inland and coastal flood hazard identification.

The initial inventory collected information on existing statewide flood-related modeling and data-driven studies and projects (with a focus on coastal flooding and including some local projects). The purpose of this TIFF Statewide Inventory of Flood-Related Modeling and Data-Driven Studies/Projects was to avoid duplicating efforts and to facilitate collaboration and communication among stakeholders. The inventory (of 140 statewide and 16 local projects at the time of this report) is intended to serve as a living document for interested stakeholders and contains basic project information, project details, funding sources, and contact information for the various projects with regional importance across the state (**Appendix C-12**). Additions to the inventory can be made on the TIFF website.

A systematic literature review was conducted with expert teams across hydrology, hydraulics, meteorology, coastal engineering, and probabilistic hazard analysis to analyze the state-of-the-art in flood modeling tools and methods relevant to Texas (coastal, inland, and riverine). The review considered probabilistic analysis approaches along with a variety of models (meteorologic, hydrologic, hydraulic, coastal and estuarine surge, wave, and compound flooding models), identifying strengths, limitations, and application contexts for each modeling type. TIFF conducted an additional literature review exploring the potential of nature-based solutions (NBS) as an effective flood mitigation strategy, with a focus on exploring the feasibility of integrating NBS for flood mitigation into the LRGV's flood management planning.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

The gap analysis highlighted fragmentation caused by limited sharing of coastal flood model metadata and the absence of standardized workflows for coupling diverse models, which currently rely on custom and labor-intensive solutions. The analysis also identified other key gaps, including incomplete geographic model coverage, poor metadata quality, and challenges in quantifying and communicating model uncertainties.

The findings highlight the need for a robust, integrated framework to link disparate models, facilitate data transfer, and support modular workflows for compound flood risk assessment across the Texas coast. (See TIFF Recommendation for The Texas Coastal Flooding Framework or TxCFF.) TIFF used the LRGV as a testbed location to explore the options and technical challenges associated with implementing the integrated framework. These efforts included 1) exploring remote sensing data and machine learning techniques as scalable, low-data alternatives to traditional hydraulic modeling; 2) developing an interim, screening-level bivariate analysis workflow to support compound flood analysis capabilities within hydrologic and hydraulic (H&H) modeling workflows; and 3) evaluating different model coupling frameworks for hydrodynamic numerical models in the region for use in compound coastal flood modeling.

Additional resulting TIFF Recommendations include prioritizing open-source community model coupling frameworks, standardizing and automating data/model sharing, developing model and study databases, and improving wave and erosion modeling.

TIFF Component 4: Planning and Outreach

Component 4 worked to bridge the gap between technical modeling and community priorities, ensuring that flood mitigation strategies are informed by the people and places they are designed to protect. In addition, the component considered the influence of compound flooding on planning efforts and comprehensive flood risk management that reconciles local interventions with regional solutions.

The targeted literature review and inventory analysis examined planning tools and models from federal, state, and local agencies, with a focus on how these tools support decision-making for compound flooding and risk reduction. The inventory cataloged tools based on their applications, data requirements, and limitations and identified key gaps such as outdated databases, inconsistent data standards and reporting formats for planning studies, and missed opportunities to unify ongoing flood risk reduction initiatives.

Gap analysis efforts were shaped by extensive stakeholder engagement, including dialogue with the Coastal Liaisons of the RFPGs, and revealed significant complexities when trying to reconcile project-specific interventions with regional-scale solutions: **1)There is a lack of access to accurate and understandable information about compound floods; 2) There is a need to expand flood risk management (FRM) policy development and evaluations beyond local boundaries, and 3) There is a need to expand characterization of specific and/or multiple sources of flood hazard and associated risk.** For the LRGV testbed, data gaps include comprehensive H&H modeling, regional flood risk assessment to determine key flood pathways and vulnerabilities and associated flooding effects, and targeted localized studies related to flood management projects.

Findings highlighted the importance of incorporating both upstream and downstream planning perspectives and improving access to resources for rural and isolated communities. The resulting TIFF Recommendations emphasize annual reassessment of planning tools through surveys and outreach with target users, establishing a coordinating flood office with a statewide database of flood-related projects (Texas Flood Coordination Office or TFCO), standardizing project requirements for regional analysis, and fostering inclusive outreach with continuous engagement for vulnerable communities.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

TIFF Structure and Development

Project Identity

Purpose and Need

State and regional flood decisionmakers need a more accurate understanding of coastal flood risks and more effective tools for mitigation planning. Accurate and reliable data is the foundation of change because it supports informed decisions; just as important as knowing what information exists is identifying what is missing. The cornerstones of the TIFF endeavor were the ideas that 1) the best solutions come when institutional barriers are crossed, 2) outcomes should be transparent and guided by the experts in relevant fields, and 3) flood information should be accessible to those who need it.

TIFF gathered the best available information and expertise about coastal flooding to make recommendations and guidelines on how the state could improve the current practices (e.g., spatially, temporally, technologically, periodically, scientifically, and fundamentally) in data gathering/collection, data management/visualization, modeling, planning, and outreach. These science-based recommendations and guidelines are based on the needs of the communities (experts and public) to improve flood risk planning and mitigation. Most importantly, TIFF is forging relationships among state, federal, and local authorities to create a network for solving many of the complex issues that may arise in the future and provide sound, reliable recommendations for the improvement of the development of new products and data that will meet the needs of coastal stakeholders.

The mention of any organization, service, or product in this report and materials is for informational purposes only and does not imply endorsement or sponsorship by TIFF or its partner agencies.

Mission and Vision

> *Mission: TIFF leverages expertise and resources to bring about the best information to enhance coastal flood risk planning and mitigation.*
>
> *Vision: TIFF empowers Texans with reliable information to increase flood resiliency.*

TIFF did not set out to produce specific models or datasets or to solve a particular problem. Instead, TIFF's aim was to create the roadmap to improving the state's modeling, data collection, data management, visualization, planning, and outreach efforts in the future (e.g., recommend the development of data, information, products, or models that don't yet exist). The science-based recommendations included in this report are intended to guide future state initiatives and strengthen Texas' flood resilience. Their purpose is to provide guidance on building infrastructure and policies that support collecting, sharing, and presenting crucial data for decisionmakers.

Geographic Scope

The Scar of Hurricane Harvey

In August 2017, Hurricane Harvey stalled over the Texas coast as a Category Four hurricane. The catastrophic storm dumped 34 trillion gallons of rainfall, sustained wind speeds over 130 miles per hour, and resulted in $218 billion of damages (adjusted for inflation). Nearly 1/3 of the state's population (almost 9 million Texans) were affected across the 49 counties that were designated as impacted areas eligible for CDBG-DR. In response, state disaster and recovery efforts invested resources into efforts prioritizing resiliency and hazard mitigation solutions for future disasters, including TIFF.

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To develop a comprehensive flood planning framework aligned with the state's Harvey plan, TIFF's original scope focused on these 49 CDBG-DR eligible counties:

- Aransas
- Austin
- Bastrop
- Bee
- Brazoria
- Burleson
- Caldwell
- Calhoun
- Chambers
- Colorado
- Comal
- DeWitt
- Fayette
- Fort Bend
- Galveston
- Goliad
- Gonzales
- Grimes
- Guadalupe
- Hardin
- Harris
- Jackson
- Jasper
- Jefferson
- Jim Wells
- Karnes
- Kleberg
- Lavaca
- Lee
- Liberty
- Madison
- Matagorda
- Milam
- Montgomery
- Newton
- Nueces
- Orange
- Polk
- Refugio
- Sabine
- San Augustine
- San Jacinto
- San Patricio
- Tyler
- Victoria
- Walker
- Waller
- Washington
- Wharton

The Unique Hydrology of the Lower Rio Grande Valley

The LRGV encompasses Starr, Hidalgo, Willacy, and Cameron counties and includes a population exceeding 1.3 million. The region is characterized by an international boundary, water scarcity, high salinity levels in both surface and groundwater, rapid urbanization, extensive irrigated agriculture, and a history of severe flooding (e.g., Hurricane Dolly in 2008, the 2018 June floods, and the more recent historic flooding events of June 2021, June 2024, and March 2025). The area's arid/semi-arid climate, ephemeral surface water flows, reliance on reservoirs (Falcon Dam) and diversion infrastructure, as well as known and unknown surface water salinity contributors, complicate water management in the region in ways that may make a one size fits all stormwater approach non-applicable. Additionally, the Rio Grande forms the international boundary with Mexico, requiring binational coordination under the 1944 Water Treaty.

Some of the most common water resource problems experienced within the LRGV are as follows:

- underutilized flood control infrastructure
- loss of natural floodplain function
- increasing water salinity
- lack of integration between local and regional FRM, water supply, water quality, and ecological restoration efforts
- water scarcity and population growth

Where most Texas coastal communities are focused on the speedy channelizing of floodwaters exclusively for rapid removal from populated areas, floodwater planning in the LRGV must consider how these high-flow surface water inputs may be provided back to these populated areas as future drinking and agricultural water supplies during the more frequent times of scarcity. In addition, unique regional opportunities exist for the integration of flood management and ecological improvement projects where lower

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salinity floodwaters can provide synergistic environmental improvements and increase shared funding opportunities.

These complexities, joined with the unique cultural and demographic drivers of the region, prompted GLO to amend TIFF's original scope to specifically address the flood modeling, data collection, data management, visualization, planning, and outreach efforts in the LRGV. As a result, this report presents holistic findings for the Texas coast and highlights special considerations, unique study methodologies, and specific findings related to the LRGV. (Note: Of the 54 final TIFF Recommendations, 12 include specific needs related to the LRGV.)

Project Structure

Funded by the GLO, TIFF is a collaborative planning project developing recommendations, guidelines, and frameworks to improve the modeling, data collection, data management, visualization, planning, and outreach efforts in counties affected by Hurricane Harvey and within the LRGV. GLO, through its CDBG-DR, funded TWDB to serve as the lead agency to coordinate a comprehensive flood risk reduction planning project in partnership with USGS and USACE. The Meadows Center joined the project as process and content facilitators.

TIFF is an innovative multi-level, multi-agency endeavor whose success belongs to the individuals listed below and the many others housed within the partner agencies who provided their support to this ambitious undertaking. The naming of volunteer experts and Study Providers in this report and materials is for acknowledgment purposes only and any mistake in recognizing a contributor does not imply ill intent by TIFF. TIFF is grateful to the numerous experts who supported the project, including research assistants and content developers.

The TIFF Leadership Team

The TIFF Leadership Team is comprised of the Steering Committee (SC) and Facilitation Team (the project's implementing partners): TWDB, USACE, USGS, and the Meadows Center.

STEERING COMMITTEE AND COMPONENT CHAMPIONS

The TIFF planning project was guided by a Steering Committee (SC), which is composed of six members, with two members from each partner agency (TWDB, USGS, and USACE). The SC leveraged the strengths and resources of each partner agency to ensure the project complements the ongoing efforts to enhance flood science, mapping, modeling, and planning in Texas. In addition, the SC helps to facilitate, coordinate, and integrate concerns, ideas, early findings, and recommendations into TIFF's rapidly evolving activities. Specifically, the SC's role includes giving advice and input to the framework and identifying issues in advance for technical discourse and deliberation by each TAT. The SC was composed of the following members:

- Amin Kiaghadi, Ph.D., P.E., Former Coastal Science Manager, TWDB (2021-2025)
- Caimee A. Schoenbaechler, M.E.M., Former Coastal Science Manager, TWDB (2021-2022)
- Coraggio Maglio, P.E., Former Hydraulics and Hydrology Branch Chief, USACE-Galveston District (2021)
- Kristine Blickenstaff, P.E., Integrated Hydrology and Data Science Branch Chief, USGS, Oklahoma-Texas Water Science Center (2023-2025)
- Michael Lee, Gulf Coast Branch Chief, USGS, Oklahoma-Texas Water Science Center (2021-2025)
- Mohammad "Shahidul" Islam, Ph.D., P.E., BC, WRE, Subject Matter Expert, Hydrology & Hydraulic Branch, USACE-Galveston District (2021-2025)
- Patrick Corbitt Kerr, Ph.D., P.E., D.WRE, Former Hydrology and Hydraulics Branch Chief, USACE-Galveston District (2022-2023)

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- Samuel Rendon, Former Hydrologist, USGS, Oklahoma-Texas Water Science Center (2021)
- Saul Nuccitelli, Former Director of Flood Science and Community Assistance, TWDB (2022)
- Srikanth Koka, P.E., Flood Modeling Manager, TWDB (2025)

There are four components to the TIFF Planning Project: 1) Data and Monitoring Gap Analysis, 2) Data Management and Visualization, 3) Integrated Flood Modeling Framework, and 4) Planning and Outreach. The SC identified a member of each partner agency to serve as a "Champion" of at least one Component. Component "Champions" were to provide the leadership, guiding vision, identification of needed expertise, and content for their respective components (including the management of Study Provider contracts and content). As experts in their own right, it was agreed that Champions would participate in the dialogue with their TATs, but also allow the facilitation process to balance any differences presented by team members.

- **Component 1 – Data and Monitoring Gap Analysis (Championed by USGS)**: Identify available data and data gaps and establish a plan for obtaining data critical for successful coastal flood analysis; support the expansion and improvement of data observations for inland, coastal, and ocean systems
- **Component 2 – Data Management and Visualization (Championed by TWDB)**: Ensure that coastal flood-related data and model outcomes can be properly visualized for technical and non-technical end-users; support the effort led by TDIS regarding coastal flood analysis data management and visualization
- **Component 3 – Integrated Flood Modeling Framework (Championed by USACE)**: Develop an integrated modeling framework to support inland and coastal flood hazard identification
- **Component 4 – Planning and Outreach (Championed by TWDB)**: Ensure that data and modeling frameworks incorporate the various end-users' flood planning and mitigation needs; ensure that the findings from various efforts are well communicated; closely collaborate with CHARM, RFPGs, and the GLO's Combined River Basin Flood Studies (RBFS); support the expansion and improvement of flood planning in Texas by incorporating the new findings into the existing planning tools or recommending the creation of new tools; balance and communicate between project-based and regional planning scale solutions

All four Components shared similar overarching objectives:

- Establish SMART (Specific, Measurable, Attainable, Relevant, and Time-based) goals for flood planning
- Guide the selection of best technological solutions to ensure a strategic flood modeling framework
- Provide technical feedback and professional advice
- Review and comment on deliverables

Sunset in Port Aransas, Texas ©Ryan Conine

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FACILITATION TEAM

The Meadows Center served as the Facilitators for TIFF and played a critical role in orchestrating the project's operations. They provided process design and coordination for productive meetings, comprehensive record-keeping, synthesis of expert-elicited data, and the creation of outreach and summary materials, all in alignment with the SC's vision. The facilitation team stayed on the pulse of the project, fine-tuning processes and ensuring that every step taken was in lockstep with our collective goal to elevate Texas' resilience to flooding. Facilitation included conflict management, serving as the public point of contact for the project, balancing inputs so that outside expertise has ample opportunity to influence conclusions, technical interpretation, and ensuring that the project is accountable to its stated objectives.

The Facilitation Team included:

- Carrie Thompson, TIFF Lead Facilitator – Director of Operations, Meadows Center
- Anna Jones, TIFF Co-Facilitator – Deputy Director of Operations – Science Engagement, Meadows Center
- Desiree Jackson, TIFF Facilitator – Science and Stakeholder Engagement Specialist, Meadows Center

Additional facilitation support was provided for several key events by: Sarah Wingfield, Digital Media Specialist (Meadows Center), Nicolas Terasewicz (Meadows Center), and Sara Omar (Kearns and West).

A Window into Facilitation

Some examples of specific facilitation roles are included below to highlight the breadth and complexity of this function.

Lead Facilitator

- Provided guidance and strategic vision for the project, including design of the project's governance (project roles, processes for group decisions, processes for conflict resolution, and processes for TAT member identification and enrollment) and approach to technical expert engagement and elicitation, including process commitments to transparency and communication. Advised the SC through the six years (and multiple personnel changes) to ensure that the project's ultimate consensus-based strategic vision was implemented
- Led all facilitated interactions within the TIFF project, including serving as the project's primary point of contact for external parties and Lead Facilitator for Components 1and 3 throughout the project (and for Components 2 and 4 during later phases of the project)
- Served in an advisory capacity on the TIFF Leadership Team, attending all SC meetings as an accountability and decision-making partner
- Oversaw all aspects of the facilitation, including the management of facilitation personnel, engagement strategies, co-designer for TIFF visual products, and final review/approval/dissemination of all TIFF content
- Added technical expertise to synthesize and translate the technical information provided by Component Champions and Study Providers into accessible formats and contexts that can be used and understood by the full range of potential users of TIFF outcomes
- Provided conflict resolution interventions to address organizational power imbalances, style differences amongst TIFF participants, and differences of opinion amongst technical experts
- Developed and implemented innovative, flexible engagement strategies to meet TIFF's complex technical and scheduling needs
- Created and adapted customized workshop formats, feedback opportunities, and collaborative platforms to maximize input from experts across geographies and disciplines
- Content editor and writer on all TIFF products

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Co-Facilitator

- Provided support for all facilitated interactions within the TIFF projects, including serving as lead facilitator for Components 2 and 4 for much of the project
- Visionary and creator of the TIFF brand and graphic design of TIFF visuals and documents, including the Annual and Final Reports, infographics, outreach materials, and digital graphics
- Developed the vision and content for TIFF-branded website that could serve as a reference point for project content, coordinating with TWDB on implementation and integration into www.texasflood.org
- Co-developed and coordinated the Integrated Flood Modeling Brown Bag Webinar Series with Component 3 Champion, creating a platform for experts to share modeling approaches and needs related to Texas coastal flooding
- Liaison with TWDB to ensure that report content and six years of supporting materials could be successfully housed, maintained, and accessed at TWDB once the project was completed; this included using Adobe InDesign to support accessibility in PDF documents, establishing a dedicated Microsoft Teams channel for file transfer and collaboration, and managing access permissions so that all necessary partners had access
- Content editor and writer on all TIFF products
- Synthesized and translated technical information into accessible formats and contexts that can be used and understood by the full range of potential users of TIFF outcomes
- Developed innovative, flexible engagement strategies to meet TIFF's complex technical and scheduling needs, including workshop formats that leveraged prerecorded expert presentations – a format that became preferred by participants and is now being mimicked by partner agencies
- Created and adapted customized workshop formats, feedback opportunities, and collaborative platforms to maximize input from experts across geographies and disciplines

Facilitator

- Provided support for all facilitated interactions within the TIFF project, including development of interactive activities using innovative software, management of shared documents and live editing, synthesis of meeting learnings and technical information submitted by project experts
- Served as primary accountability manager, documenting and maintaining prioritized action-item lists and ensuring their completion by the project partners; led interactions and project milestone tracking with the program administrators at TWDB
- Served as a liaison to Component Champions and Study Providers and helped to translate their needs and vision into productive engagement opportunities for TAT members (e.g., Model Coupling Workshop, Stakeholder Needs Workshop)
- Temporarily assumed the role(s) normally led by Component Champions or Study Providers during the federal government shutdown to ensure that engagements continued and project milestones were met
- Devised and implemented the collaborative creation and validation of the TIFF Recommendations, including the facilitation of interactive group editing, writing exercises, surveys, document version control, and management
- Provided content editing and writing for the TIFF reports
- Supported contract management for the Meadows Center
- Managed project documents, including tracking and filing of the myriad of technical inputs to the project, including email correspondence from external experts, action items from SC interactions,

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reports and deliverables generated by Study Providers, and iterative report edits from the SC and Facilitation Team

- Added technical expertise to synthesize and translate the technical information provided by Component Champions and Study Providers into accessible formats and contexts that can be used and understood by the full range of potential users of TIFF outcomes

PROJECT MANAGEMENT

TWDB provided grant oversight and oversaw the multitude of state, federal, and private contracts necessary to execute the project. Several additional staff played ongoing key roles in the project, including:

- Aisha Vaz, Contract Specialist
- Amber Rowe, Contract Specialist
- April Weiss, Account Payable & Revenue Manager
- Daniel Cardin, Contract Services Manager
- Eldrisha Eubanks, Financial Operations (Financial Operations Director)
- Jeff Lin, Web Administrator
- Lisa Farrell, Contract Specialist Team Lead
- Luci Cook-Hildreth, Grant Specialist
- Rikki Weaver, Flood Framework Coordinator
- Stephen Ross, Contract Specialist Team Lead
- Steven Artle, Contract Specialist
- Velisa Valk, Contract Specialist

Technical Advisory Teams

The TATs are, in some ways, the most vital part of the TIFF endeavor. Although the SC guided the direction of the project and commissioned research, the TATs served a crucial role in vetting this work and redirecting the SC when necessary.

TIFF employed a truly collaborative approach to engage experts from governmental agencies, academia, and stakeholders with regional experience through the formation of four specialized TATs corresponding to the four Components of the framework. The TAT members include technical experts selected by the SC based on their technical expertise and institutional knowledge of flood mitigation in Texas and beyond. TATs serve as the source of expertise guiding the TIFF project from vision to execution.

The SC initially identified 172 nominees for the four TAT teams based on the project needs, requirements, and suggestions from GLO. After sending out official invitations in March 2021, carefully discussing the expertise and background of the identified nominees, and receiving confirmation from the approached nominees, the SC confirmed initial membership for 96 people in June 2021. The number of people in each TAT changed based on project needs and the availability of experts to continue their participation. In November 2023, TIFF invited 23 additional technical advisors from the LRGV to serve as TAT members to ensure future findings and recommendations reflected the unique hydrologic and coastal behavior of the region. The SC confirmed additional membership for 19 people. In total, 126 experts served as TAT members among the four components (listed below). Advisors marked with as asterisk are those LRGV-specific additions.

The TAT members are highly reputable experts in various aspects of coastal flooding, including data monitoring, new monitoring technologies, data management and visualization, modeling, planning, and outreach. The LRGV TAT members contributed a deeper understanding of tidal interactions, riverine processes, drainage infrastructure limitations, and coastal dynamics unique to Cameron, Hidalgo, Starr, and Willacy Counties. TAT members served voluntarily and participated in meetings and data requests throughout the project based on specific needs and milestones. TAT members received summary information, data, and project materials before TIFF meetings to ensure well-informed and productive discussions. Members were invited to share information and insights on the best available science, state-of-the-art models, methods, and emerging technologies.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

COMPONENT 1 (TEAM CHAMPION: KRISTINE BLICKENSTAFF, USGS)

- Andrew Ernest, Research, Applied Technology, Education, and Service (RATES)
- *Augusto Sanchez, Cameron County
- Chandra Sekharan, TAMU-Corpus Christi
- *Christopher Fuller, RATES
- Craig Glennie, University of Houston
- David Maidment, UT-Austin
- Evan Turner, TWDB
- Gregg Easley, Texas Commission on Environmental Quality (TCEQ)
- Jeff East, USGS
- Jeffrey Danielson, USGS
- Jeremy Justice, Harris County Flood Control District (HCFCD)
- Joey Thomas, TWDB
- John Nielsen-Gammon, TAMU
- Jonathan Thomas, USGS
- Katie Landry-Guyton, National Weather Service (NWS)
- Kayode Atoba, TAMU- Institute for a Disaster Resilient Texas (IDRT)
- Larry Voice, Federal Emergency Management Agency (FEMA)
- Laura Stearns, TAMU-IDRT
- Lydia Fletcher, UT-Austin, TACC
- Philippe Tissot, TAMU-Corpus Christi
- RoseMarie Klee, Texas Department of Transportation (TxDOT)
- Samuel H. Rendon, USGS
- Steve DiMarco, TAMU
- William Butler, USACE- Engineer Research and Development Center (ERDC)
- Witold Krajewski, Iowa Flood Center

COMPONENT 2 (TEAM CHAMPION: AMIN KIAGHADI, TWDB)

- Alan Zunde, Aquaveo, LLC
- Albert Aldana, City of Weslaco
- Andrew Juan, TAMU-IDRT
- *Augusto Sanchez, Cameron County
- *Bill Kirkey, RATES
- Brian Barr, January Advisors
- Bridget Scanlon, UT-Bureau of Economic Geology (BEG)
- *Carlos Sanchez, Cameron County
- Carola Kaiser, Coastal Emergency Risks Assessment-Louisiana State University
- *Christopher Fuller, RATES
- Diane Howe, FEMA
- Federico Antolini, TAMU
- Gordon Wells, UT-Austin, Center for Space Research
- Ibrahim Demir, The University of Iowa
- Jason Fleming, Seahorse Coastal Consulting
- Jeff East, USGS
- Jeff Lindner, HCFCD
- Jeff Reichman, January Advisors
- Jeffrey Horshburgh, Utah State University-Utah Water Research Laboratory
- Justin Terry, HCFCD
- Kayode Atoba, TAMU-IDRT
- Kris Lander, NWS
- Kristine Blickenstaff, USGS
- Laura Stearns, TAMU-IDRT
- Lee von Gynz-Guethle, West Consultants
- Paul Craig, Dynamic Solutions International, LLC
- Russell Blessing, TAMU-IDRT
- Sam Brody, TAMU-College Station
- Steven Mikulencak, TAMU-AgriLife, CHARM
- Taylor Christian, TWDB
- *Velinda Reyes, Office of Hidalgo County Commissioner Ellie Torres

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COMPONENT 3 (TEAM CHAMPION: MOHAMMAD "SHAHIDUL" ISLAM, USACE-GALVESTON DISTRICT)

- Andre Vanderwesthuysen, National Oceanic and Atmospheric Administration (NOAA)
- Andrew Juan, TAMU-IDRT
- Andrew Kennedy, University of Notre Dame
- Arash Taghinezhad, TAMU-IDRT
- Ben Hodges, UT-Austin
- Charles (Landon) Erickson, USACE-Fort Worth District
- Chris Massey, USACE-ERDC
- Clint Dawson, UT-Austin
- David Johnson, Purdue
- Derek Giardino, NWS-West Gulf River Forecast Center
- Don Resio, University of North Florida
- Gabriele Villarini, Princeton University
- Gaurav Savant, USACE-ERDC
- Hugh Roberts, The Water Institute of the Gulf
- Jeff Lindner, HCFCD
- Jim Gibeaut, Harte Research Institute
- *Joseph Gutenson, RATES
- Joseph Zhang, Virginia Institute of Marine Science
- *Jungseok Ho, UT-Rio Grande Valley
- Justin Terry, HCFCD
- Ken Ashe, Wood, PLC
- Mark Jensen, USACE
- Matt Bilskie, University of Georgia
- *Michelle Hummel, UT-Arlington
- Nick Fang, UT-Arlington
- Ning Lin, Princeton University
- Norberto Nadal-Caraballo, USACE ERDC
- Patrick Barnard, USGS
- *Paul Hamilton, USACE-Galveston District
- Richard Wade, Texas Natural Resources Information System
- Rick Luettich, University of North Carolina at Chapel Hill
- Saul Nuccitelli, TWDB
- Suzanne Pierce, UT-Austin, TACC
- Thomas Wahl, University of Central Florida
- *Tushar Sinha, TAMU-Kingsville
- *Unni (Padinare) Unnikrishna, International Boundary and Water Commission (IBWC)
- William Asquith, USGS
- Yu Zhang, UT-Arlington

Flooded streets in the aftermath of Hurricane Harvey © Rex/Shutterstock

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COMPONENT 4 (TEAM CHAMPION: AMIN KIAGHADI, TWDB)

- *Andrew Ernest, RATES
- Ataul Hannan, Harris Country Flood Control District
- *Augusto Sanchez, Cameron County
- Bridget Scanlon, UT-BEG
- *Britt Corley, USACE
- Caroline McCabe, USACE
- Christopher Emrich, University of Central Florida
- Daniel Arriaga, TAMU-IDRT
- Greg Waller, NWS-West Gulf River Forecast Center
- Hanadi Rifai, University of Houston
- *Javier Guerrero, RATES
- Jet Hays, GLO
- *Jianhong-Jennifer Ren, TAMU-Kingsville
- John Kucharski, USACE
- *Jonathan Thomas, USGS
- Katharine Teleki, Teleki Consulting
- Katie Landry-Guyton, NOAA
- Keri Stephens, UT-Austin
- Kiersten Stanzel, Coastal Bend Bays & Estuaries Program
- Lisa Marshall, TCEQ
- Liv Haselbach, Lamar University
- *Melisa Gonzalez, LRGV Development Council
- Mike Quimet, Texas Division of Emergency Management (TDEM)
- Reem Zoun, TWDB
- *Rick Hallman, NWS
- Rose-Marie Klee, TxDOT
- Saji Varghese, USACE
- Siddharth Saksena, Virginia Tech
- Steven Mikulencak, TAMU-AgriLife, CHARM
- Teal Harrison, Adaptation International
- *Tom Jester, USACE
- Tori Johnson, U.S. Naval Academy
- Wes Birdwell, Texas Floodplain Management Association (TFMA)

TIFF Literature Review and Research Partners (Study Providers)

TIFF relied on a diverse network of expertise to advance flood science, communication, and planning across the Texas coast. We gratefully acknowledge the following partners and their contributions to the TIFF literature reviews and research.

UNIVERSITY OF TEXAS-AUSTIN

UT-Austin researchers contributed to multiple aspects of TIFF, advancing both technical modeling, visualization, and communication efforts.

The following researchers supported reviews of hydrodynamic, estuarine, and coupled models for flood hazard characterization, laying the foundation for developing integrated model-coupling workflows on the Texas coast:

- Ben Hodges, Maseeh Department of Civil, Architectural, and Environmental Engineering
- Clint Dawson, Department of Aerospace Engineering & Engineering Mechanics
- Saugata Datta, Department of Earth and Planetary Sciences
- Sina Khani, Mark Loveland, and Erik Valseth, Computational Hydraulics Group at the Oden Institute for Computational Engineering & Sciences

The following researchers carried out literature reviews to identify user groups and best practices for risk communication, informing the development of stakeholder decision maps and guidelines for communicating uncertainty in flood models:

- Elizabeth Le, School of Information

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- Keri Stephens, Jovana Andelkovic, Tara Tasuj, and Samanta Varela from the Department of Communication Studies, Moody College of Communication
- Suzanne A. Pierce, Research Scientist, TACC

TEXAS A&M UNIVERSITY–KINGSVILLE

Jianhong-Jennifer Ren, Tusha Sinha, and Hua Li, from the Department of Environmental Engineering are leading a regional study in the LRGV to identify flood-prone areas and evaluate nature-based flood mitigation strategies through satellite-based remote sensing and machine learning.

PRINCETON UNIVERSITY

Gabriele Villarini and Renato Amorim from the Department of Civil and Environmental Engineering and the High Meadows Environmental Institute collaborated on literature reviews of the state of practice in rainfall and watershed modeling for flood hazard characterization specific to the coastal Texas region.

UNIVERSITY OF IOWA

Felipe Quintero Duque, Marcela Rojas Oliveros, and Nicolás Velásquez Giron from the Iowa Institute of Hydraulic Research led analyses of H&H modeling approaches for flood hazard characterization, helping identify critical data requirements for coastal Texas applications.

UNIVERSITY OF NOTRE DAME

Andrew Kennedy from the Department of Civil and Environmental Engineering and Earth Sciences contributed specialized expertise in coastal wave modeling and compound flooding, supporting both literature reviews and stakeholder workshops on wave data needs.

PURDUE UNIVERSITY

David Johnson and Aaron Dewar from the School of Industrial Engineering performed systematic reviews of probabilistic analysis methods, supporting TIFF's guidance on flood hazard estimation and integration into planning tools.

U.S. ARMY CORPS OF ENGINEERS

Meredith Carr, Fatima Bukhari, Ahmad Tavakoly, Chris Massey, and Gaurav Savant contributed to the coastal compound flood hazard assessment literature review; Gregory S. Karlovits, Meredith Carr, and Avital Breverman are leading the development of bivariate analysis methods for compound flooding in the LRGV.

U.S. GEOLOGICAL SURVEY

Sam Wallace, Glenn Harwell, and Jonathan Thomas led the development of The Coastal Data Surfer (CDS) web-based data availability tool to inventory and visualize coastal flood data, laying the groundwork for a statewide framework for ongoing coastal flood data management.

The Larger TIFF Community

Although not originally designed as an aspect of TIFF, the project engaged hundreds of other interested experts across Texas, the U.S., and internationally. As Technical Advisors and Champions identified interest in specific topics (e.g., Subsidence, Nearshore Wave), the TIFF community began to grow. The project also made several special efforts to engage flood planners and local experts in the LRGV. Over time, individuals asked to be included in TIFF mailings and to stay apprised of the project's activities. The project maintains an email distribution list of more than **500 individuals** and actively engages this coastal flood community in educational brown bags and updates from partners.

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Introduction to Compound Flooding

Wherever society builds towns, cities, farms, and factories, there are sure to be road gutters, ditches, buried stormwater piping, and detention ponds to handle the expected rainfall. Near rivers, flood protection measures (e.g., levees, floodwalls, dams) support the protection of people and property from a river's rise. Similarly, along the coast, flood infrastructure like levees, seawalls, and dunes support the protection of inland areas as the ocean's surge pushes upstream. Floodplains and open spaces (including some roads and highways) are also used to hold and spread the flood waters under extreme conditions. Despite these protection measures, Texas faces significant challenges in managing its water resources and infrastructure along the Texas coast. The region's low-gradient topography, changing long-term hydro-meteorological conditions, combined with both natural and human-induced subsidence, makes it highly vulnerable to flooding. Additionally, the region's seaside appeal has increased urbanization in areas facing rising sea levels and more frequent and intense floods, further increasing the risks and impacts to communities.

High-impact flood events such as Hurricane Ike (2008), the 2015 Memorial Day Flood, the 2018 Independence Day Flood, and Tropical Storm Imelda (2019) have caused billions of dollars in damage and tragic loss of life. Hurricane Harvey (2017) was especially devastating because of the combined occurrence of riverine flooding with nearshore storm surge. This convergence of flood drivers caused widespread impacts across Texas coastal counties, highlighting one of the most destructive state disasters: compound flooding events.

Compound flooding occurs when multiple drivers such as storm surge, heavy rainfall, and river flooding overlap simultaneously or in sequential combination (Figure A-1). The sections below provide a brief overview of the key ideas of compound flooding, discussing the main physical sources of flooding, the different ways flood waters behave, and how the physics behind compound flooding create a more challenging event to understand and model. (See **Appendix C-9** for a more detailed discussion.)

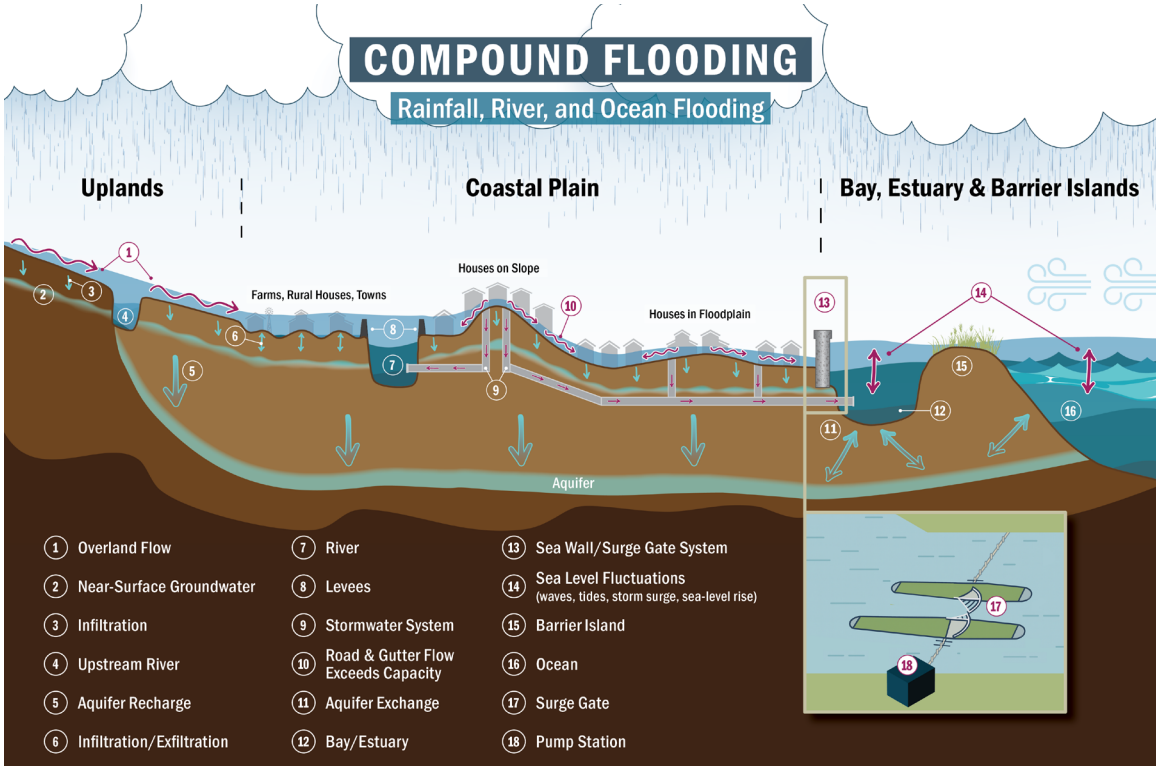

Figure A-1. Compound flooding conditions – multiple and overlapping interactions between flooding types within the design conditions of all infrastructure.

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The overall goal of this section is to provide context for understanding the complexity of compound flooding, and the need for Texas to provide local, regional, and state entities with the compound flood risk information and planning tools necessary for comprehensive regional flood planning and mitigation in the coastal zone.

Flooding Sources

Flooding has four main natural sources (or drivers)[1]: 1) *rainfall* that may overwhelm gutters and storm drains; 2) *rivers* that collect upstream rainfall and may overflow their banks; 3) *the ocean*, whose combination of tides, swell, waves, and storm-driven surges may raise the ocean surface height to overtop natural and man-made defenses, and 4) *groundwater*, which can exacerbate flooding of low-lying areas and extend the drying-out time across relatively flat regions:

1. **Rainfall (pluvial)**: In rainfall flooding, the intense rainfall rate exceeds the combined capacity of infiltration and the stormwater system. Once these capacities are exceeded, the excess rainfall creates streams along street gutters and ponds in low-lying areas. The physics of rainfall flooding are like those of a partially-plugged sink drain with a running water tap: the sink can slowly drain water, but the water level in the sink continues to rise until the water overflows onto the counter and floor.
2. **Rivers (fluvial)**: Rivers collect the rainfall and runoff from the upstream landscape and bring it down to the coast, estuaries, and ocean. In the Texas Coastal Plain, the capacity of a river (the amount of flow it can carry before flooding) is largely dependent on the additional space available between its normal water level and the top of its banks. For example, if a river channel is normally about half full, it can only handle about double that flow rate before overflowing. When a river's capacity to collect upstream rainfall and runoff is exceeded, the lowest points along the banks are the first to flood. The resulting overflows can cause rapid bank erosion and worsen flooding in surrounding areas.
3. **The Ocean (coastal)**: Storm surge flooding is defined as flooding caused by the rise in ocean surface above its expected tide level due to physical forces. Surges are caused by wind blowing across the water's surface and by atmospheric pressure gradients (i.e., the low barometric pressure at the center of a storm). Strong onshore winds cause water to pile up near the shoreline and pushes water inland through estuaries, rivers, and canals. Coastal storm surge flooding is characterized by a rapid rise in sea level that overflows coastal levees, dunes, and flood protection of connected inland waterways.
4. **Groundwater**: A less common form of flooding in coastal areas is groundwater oozing back to the surface in low-lying areas. This phenomenon occurs when the near-surface groundwater aquifers are full and water infiltrating into the upstream aquifer (at a higher elevation) increases the pressure where the downstream aquifer connects to lower-lying land. The pressure difference pushes the water out of the aquifer, which results in ponding or flow in ditches and streams.

When two or more of these flooding sources (or drivers), or other pre-existing conditions such as antecedent soil moisture condition, overlap either simultaneously or in sequential combination, a compound flooding event occurs. Instead of addressing challenges related to one source of flooding, communities are faced with evaluating multiple flooding hazards and behaviors.

1 In the jargon of science and engineering, local rainfall flooding is known as "pluvial" flooding; river overbanking is known as "fluvial" flooding, and oceanic flooding that exceeds expected tides and waves is known as "storm surge". flooding. Groundwater impacts are often discussed in terms of "infiltration" and "exfiltration." To keep this description readable for the widest audience, we will use common words for flooding's primary sources (rainfall, river, ocean, groundwater) in our descriptions.

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Flooding Behaviors

Flooding has three main types of behaviors across the landscape: 1) ponding characteristic of water building up into temporary ponds or lakes in low-lying areas; 2) flash flooding defined as the rapid movement of water, typically in one direction down the steepest local slope; and 3) wind-forced flooding, where ponded water is forced upwind and creates a flood that recedes when the wind decreases:

1. **Ponding**: Ponded flooding occurs when the land is covered by stagnant or slowly moving water. This type of flooding is arguably the most common. Ponding occurs in an area when the local flood inflow (from rainfall, river, ocean) is greater than the outflow to infiltration or an adjacent area. Because of the flatness of the Texas Coastal Plain, ponding can be caused by features of relatively small height. For example, during Hurricane Harvey, the common "Jersey barriers" used in highway medians blocked flow and caused significant ponding.
2. **Flash Flooding**: Flash flooding is the rapid movement of flood waters that typically appears as white-water river rapids, high water velocities, and destructive forces. Flash flooding can easily move cars, destroy roads, collapse bridges, and knock down buildings. Such flooding is typically caused by excessive rainfall on steeply sloped land. The depths in flash floods are often shallow (less than a foot) but can be dangerous and damaging due to high velocities. Flash flooding is arguably the most terrifying form of flooding as it occurs seemingly out of nowhere and creates such rapid flooding that evacuation can be difficult or impossible.
3. **Wind-Forced Flooding**: When we think of ponded water, we usually think of the flat surface of a lake. However, during extreme events, the wind will push the ponded water downwind, which can increase the local flooding level and drive a flow into areas that are nominally upstream. As soon as the wind dies, such waters will run back to ponding in the lowest areas. During Hurricane Harvey, the extensive flooded areas across the Texas Coastal Plain had strong winds blowing across them. These winds pushed the water downwind, causing the water level to be higher for some time on the downwind side of the ponded water.

The primary challenge in analyzing and modeling compound floods is that their individual drivers—such as storm surge, rainfall, and river runoff—interact non-linearly. Because these effects are not simply superimposed, they cannot be analyzed separately and added together to calculate the total flood impact. Each flooding type has interactions with the others, which affect the fate and transport of flood waters.

The TIFF project sought to synthesize the best available information on coastal flooding and identify opportunities to improve existing state flood information, planning, and response procedures. These procedures may be constrained by social, spatial, and temporal considerations, as well as by existing state of technology and the current state of relevant scientific knowledge.

The findings and TIFF Recommendations presented in this report represent the collective expertise of hundreds of the leading experts in coastal and flood science and the rigorous review of the best-available science. These recommendations uniquely address the complex challenges associated with understanding, predicting, and planning for compound flooding in Texas.

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Devastation following Hurricane Harvey ©Erin Gay

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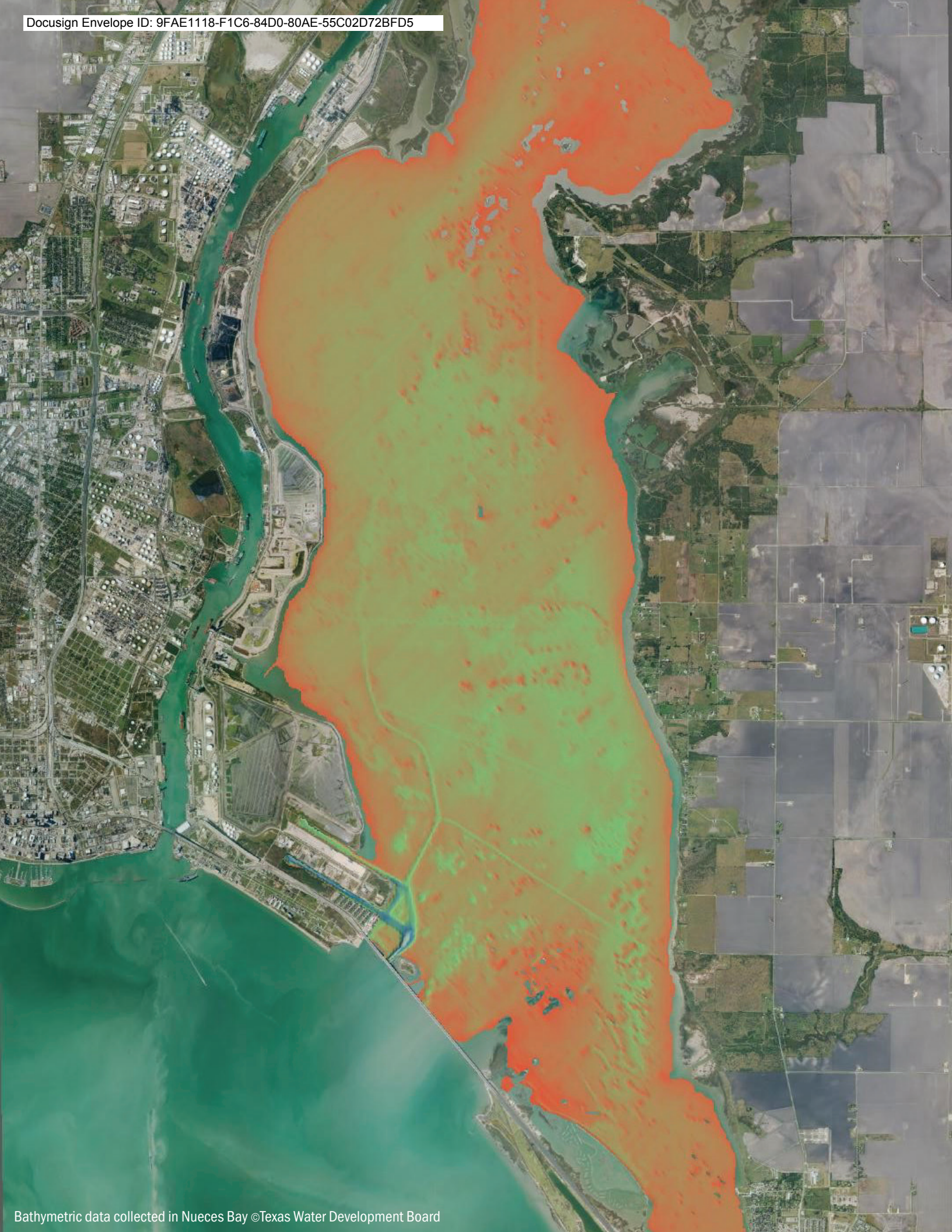

Bathymetric data collected in Nueces Bay ©Texas Water Development Board

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1 Component 1: Data and Monitoring Gap Analysis

The goal of Component 1 is to identify both the available data and the data gaps along the Texas coast and to establish a plan for obtaining data critical for successful coastal flood analysis in this region. This component supports the expansion and improvement of data observations for inland, coastal, and ocean systems.

1.1 What is Data and Monitoring Gap Analysis?

The vision of TIFF is to facilitate access to the accurate flood-related information needed by decision-makers at all levels. This roadmap started by understanding what data, monitoring technology, and practices already exist, what additional resources users need, and what new technologies might bridge those gaps.

Data and monitoring gap analyses play a vital role in assessing whether available information is suitable and ready for flood risk analyses. These evaluations are essential steps in developing an integrated framework that enables decision-makers to better understand and plan for coastal flooding.

Flood models require an appreciable effort to collect data, construct model inputs, and calibrate and validate model parameters to help evaluate risk and potential impacts of flooding. Many models have specific data input requirements that necessitate extensive data collection efforts, whether digital or field-based, before a model can even begin to run. With limited comprehensive data availability assessment tools and constraints on data sharing and visibility, efforts in data collection and qualification are often duplicated. The TIFF gap analyses aim to address this challenge.

1.2 Why Data and Monitoring Gap Analysis Matters to Texas

Information is the foundation of any effort to future-proof Texas. Understanding information gaps is just as important as understanding what data is available in creating a framework to ensure that decision-makers have what they need.

Hurricane Harvey was a wake-up call for flood planners and engineers in Texas, who realized that the available tools were not operating at the scale necessary to predict, understand, or respond to complex flooding events along the Texas coast.

The efforts described under Component 1 were aimed at crossing institutional barriers to catalog, understand, vet, and share the available data and identify additional data needed to fuel the vision for a comprehensive modeling framework to inform the decisions that will shape Texas.

Data analysis is an ongoing process and the recommendations resulting from this endeavor support new infrastructure, policy, and resources to collect, display, and share the data that Texas communities need.

1.3 The Guiding Objectives of TIFF Component 1

TIFF is ultimately an effort towards a comprehensive modeling framework that can be used by decision-makers at all levels. Data is the backbone for models that can deliver on that promise. Data helps us characterize and understand important aspects of modeling flood behavior, such as model grid and definition, model forcing, continuous model validation and improvements, and post-event analysis. TIFF set out to identify available flood-related data, data gaps, new technologies, and establish a plan for obtaining data critical for successful coastal flood analysis.

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This effort consisted of nine stated objectives, which are described in detail below:

1. Establish a TAT to support Component 1
2. Assist TDIS in determining the appropriate data structure for creating a tool to inventory, display, and evaluate the availability of all data applicable to flood-related analyses used for planning and mitigating coastal floods in Texas
3. Provide TDIS with associated data linkages for critical coastal flood analysis use cases
4. Evaluate and provide feedback to GLO on 1) the initial data inventory provided by the RBFS Study Providers and the TWDB RFPGs, and 2) the associated data availability tool provided by TDIS
5. Perform a gap analysis for use cases, with the feedback of the TATs, to identify data needed to improve observations in Texas for coastal flood analysis
6. Recommend a plan to periodically update the data inventory
7. Recommend a plan to periodically perform data gap analyses
8. Evaluate and provide updates on new monitoring technologies and identify locations that could be used as testbeds
9. Provide recommendations pertinent to data and monitoring for coastal flood analysis to GLO

1.4 Approach to Objectives

With the goals of long-term impact, sustainability, and ongoing continuous improvement, Component 1 set out to execute the following steps across traditional disciplinary and organizational divisions:

- identify the leading experts and data practitioners in Texas (23 were selected)
- ask the experts if TIFF is asking the right questions and course-correct as needed
- inventory existing Texas coastal data
- conduct gap analyses to identify what data is missing and needed
- initiate coordination with TDIS to begin displaying and integrating data relevant to coastal flood planning and to establish data linkages for priority datasets
- provide structured feedback to GLO on data availability and tool functionality
- implement a data classification system
- create the Coastal Data Surfer (CDS) platform (https://webapps.usgs.gov/tiff/index.html) (more below)
- produce Recommendations to guide Texas

The effort began in coordination with TDIS and the GLO's RBFS by identifying and periodically updating an inventory of existing applicable datasets for coastal flood analysis. Component 1 Technical Advisors quickly highlighted the challenges of a comprehensive inventory, including the wide variety of data types (and data quality) that ultimately feed the disparate types of models used to evaluate and predict flooding, and set to work to categorize and tier these datasets and consider the challenges associated with metadata inconsistencies (**Appendices A-1** and **A-2**).

To efficiently organize metadata and allow users to filter the coastal flood dataset for their specific needs, data were grouped into 11 coastal flood data classifications (Figure 1-1). For example, to evaluate the flooding associated with Hurricane Harvey, rain gage data from at least 20 types of gage networks and four different sets of rainfall analyses would need to searchable in order to be identified and included in the evaluation.

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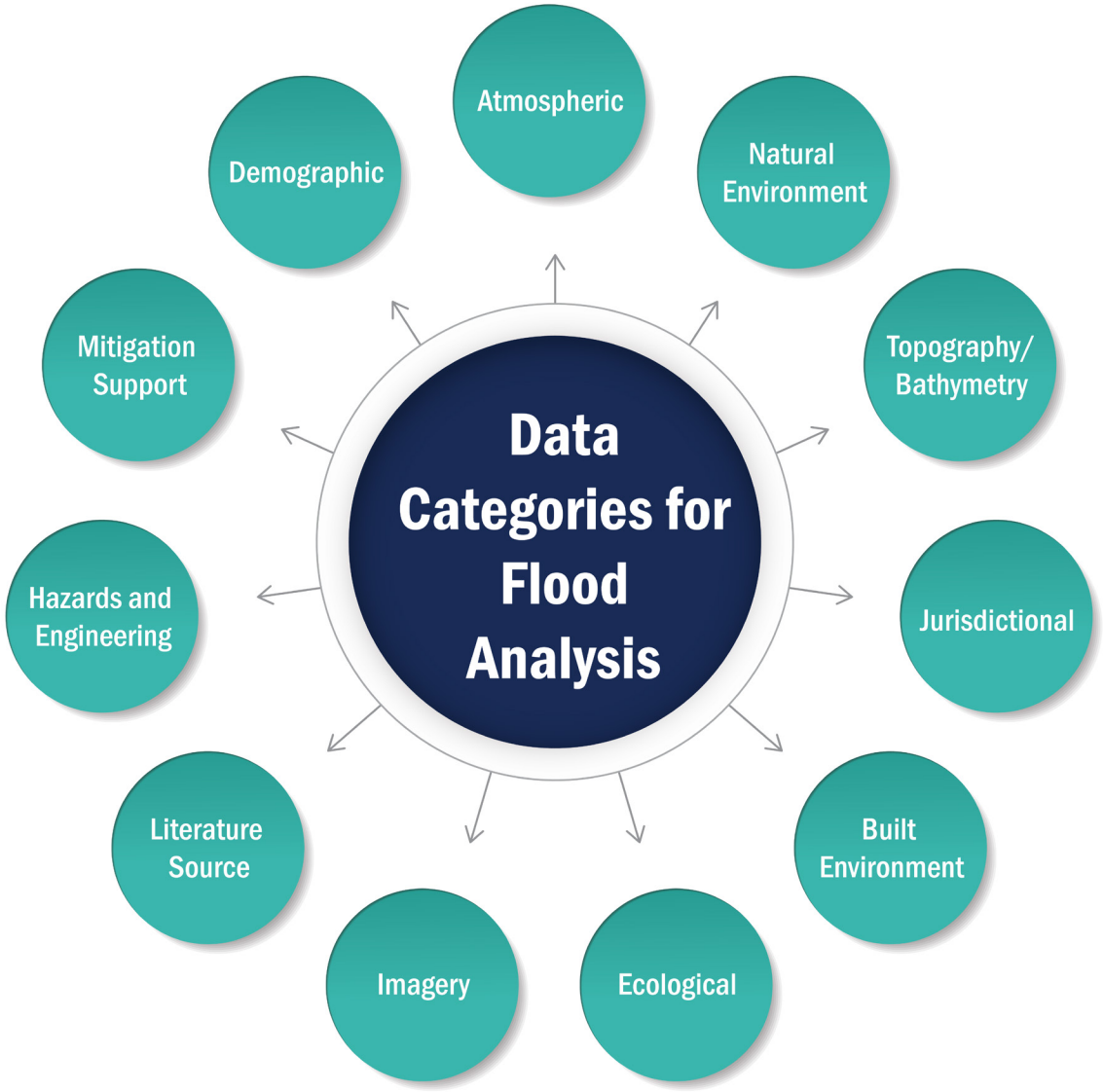

Figure 1-1. Diagram showing the 11 TIFF coastal data classes developed to organize metadata and enable effective filtering of datasets for specific needs.

Component 1 approached its Objectives through a combination of data-related workshops in collaboration with the TAT and other domain experts, a comprehensive data inventory mapping effort in conjunction with TDIS, and the development of a web-based tool for ongoing data gap analysis to serve as a central hub for connecting target users with relevant datasets (the CDS).

TIFF engaged a TAT workgroup to guide the data inventory, then developed a formal data taxonomy and classification map linking datasets to specific use cases and user needs. This classification system supports category-based data gap assessments and enhances user interaction within the CDS.

Several topic-specific workshops were conducted to further articulate data needs and coordinate strategies:

- A virtual Bathymetry Workshop of 90 participants addressed the dynamic nature of bathymetric data and identified acquisition priorities. The workshop provided insights from TAT members, technical experts, and target users, leading to the development of a statewide bathymetry acquisition priority map and a cost estimate for targeted data collection.

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- A virtual Subsidence Workshop drew 177 participants from agencies, universities, and research organizations. The goal was to coordinate subsidence data across Texas and to identify resource needs. The session concluded with a survey to assess continued interest in collaborative subsidence efforts.
- A virtual Nearshore Wave Data Workshop of 75 participants examined the limitations and opportunities of wave data collection. Workshop outcomes included a mapping survey to identify key areas for wave data acquisition and strategies to enhance coordination among researchers and practitioners.

Insights gathered from the workshops, TAT contributions, and coordination with TDIS emphasized the need for a unified, accessible data platform. The CDS was developed to fulfill this need, functioning as a centralized tool for storing, classifying, and linking model input datasets relevant to flood resilience. It allows users to assess data usability, identify data gaps, and access curated datasets in support of planning, mitigation, and research along the Texas coast. The CDS (https://webapps.usgs.gov/tiff/index.html) serves as a one-stop shop for coastal flood-related data and represents a foundational step in strengthening Texas' capacity to respond to increasing coastal flood risks.

Flooded neighborhoods in Surfside Beach, Texas following Tropical Storm Alberto © Brandon Bell, Getty Images

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ZOOMING IN: TIFF'S PRIORITY RECOMMENDATION FOR ONGOING COASTAL FLOOD DATA INVENTORY AND GAP ANALYSIS

The Coastal Data Surfer (TIFF Recommendation C1.2A)

This robust web application, developed in answer to TIFF's data objectives, is built on top of products, tools, and Application Programming Interfaces (APIs) generated by various data service providers. As any inventory (or data repository) is only as current as its latest update, this web interface consistently expands its scope by incorporating publicly available databases from diverse sources, thereby securing its enduring relevance, utility, and sustainability. This information empowers coastal communities to better prepare for future floods and protect lives and property. A suite of critical features for conducting coastal flood analysis includes a user-friendly interface to enable users to seamlessly define desired study areas on interactive maps, ensuring effortless visualization of relevant geographic regions. The scope extends beyond visualization, incorporating a deep understanding of the unique data prerequisites associated with diverse forms of analysis tied to inland and coastal areas—encompassing inundation modeling to risk assessment. The CDS helps address critical coastal flood planning challenges, including:

- identifying data gaps that could impact flood modeling and mitigation planning by highlighting spatial and temporal data gaps that currently prevent informed mitigation planning and modeling efforts
- streamlining the process of finding relevant datasets for specific projects
- enhancing agency and researcher collaboration by providing a centralized, interactive platform for data exploration
- highlighting coastal data needs that could aid in improving the accuracy and efficiency of flood modeling efforts, leading to better flood predictions and risk assessments

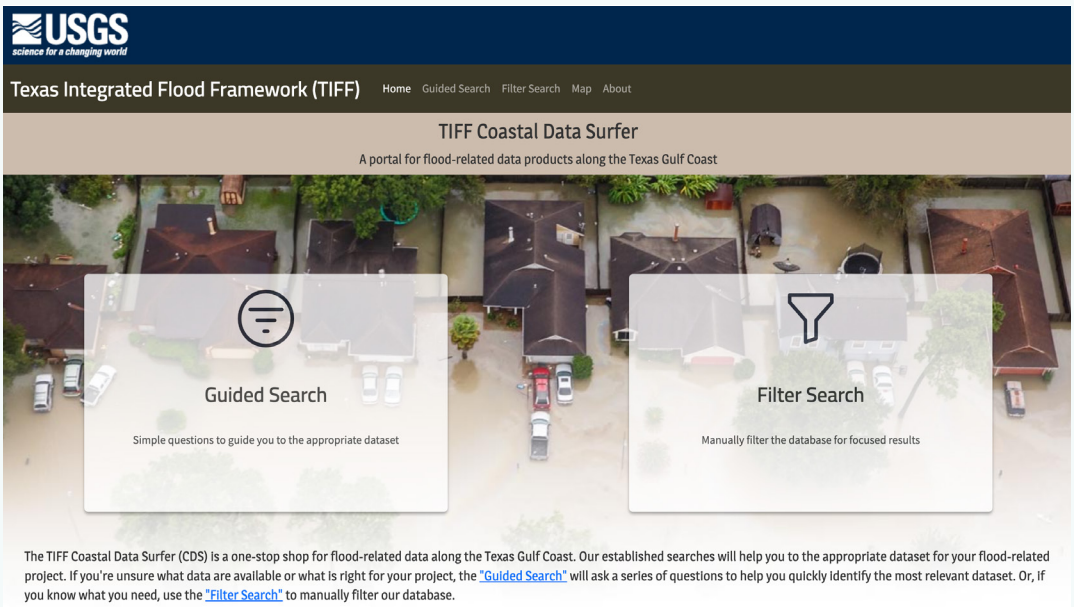

Figure 1-2. A preview of the Coastal Data Surfer landing webpage.

KEY FUNCTIONS OF THE COASTAL DATA SURFER

By integrating interactive mapping, expanded dataset access, and modeling support, the TIFF-informed CDS directly contributes to better flood preparedness, response, and mitigation efforts across Texas, reducing risks to communities, infrastructure, and ecosystems. The CDS serves as 1) an adaptable data and model linkage, 2) a coastal data inventory,

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3) a tool for performing ongoing data gap analysis, 3) an interactive mapper, and 4) a catalog of model inputs:

1. **Adaptable Data and Model Repository**: The CDS aims to help decision-makers identify future data collection needs to support flood assessments and planning by compiling readily available published flood-related datasets into a single, simplified, categorized, and readily accessible database. The TIFF dataset aggregates a diverse set of contributions from federal, state, local, academic, and nonprofit institutions. Each source provides datasets in various formats, such as GIS layers, tabular data, reports, images, and other digital products, which are essential for flood modeling, hazard analysis, and planning. (**Appendix A-3** includes a full list of datasets included in the CDS and their APIs.) Major data sources in the CDS include:
   - USGS – 26 datasets, including reports, GIS layers, tabular data, and images
   - TWDB – 25 datasets, covering reports, GIS layers, tabular data, and images
   - NOAA – 15 datasets, including GIS layers, tabular data, images, and other formats
   - Environmental Information Exchange Network – Seven tabular datasets relevant to environmental and water quality parameters
   - FEMA – Six datasets, comprising GIS layers, tabular data, reports, and images
   - Utah Climate Center – Six datasets, including GIS layers, tabular data, and images useful for climate and weather analysis
   - Texas A&M AgriLife Extension – Six datasets, consisting of GIS layers, tabular data, and images focused on environmental monitoring
   - TxDOT – Five GIS datasets, supporting infrastructure and mobility planning
   - TWDB–Texas Geographic Information Office (TxGIO) – Five GIS datasets focused on statewide water planning
   - TAMU–Corpus Christi-Conrad Blucher Institute – Three datasets, including tabular data and images relevant to coastal hydrology
   - U.S. Fish & Wildlife Service – Three GIS datasets that support ecological and conservation planning
   - U.S. Census Bureau – Three datasets, comprising GIS layers and other demographic or economic data formats
   - TxGIO DataHub – Three datasets, including GIS layers and imagery
   - Integrated Ocean Observing System – Three datasets, including tabular data and oceanographic imagery
2. **Data Inventory**: This public-facing web interface serves a broad audience across various disciplines and flood-related research areas. As a 'one-stop shop' for flood-related data in the study area, the CDS should be equally useful to all user groups and dynamic enough to inform the crucial and rapidly evolving climate of flood research along the Texas coast.

   The CDS facilitates the identification of critical hydrologic, hydrodynamic, and meteorologic observations, essential for improving flood modeling, calibration, and planning along the Texas coast. Users have two options for interaction with the data inventory (illustrated in Figure 1-3): 1) a simple manual filter of the database directed towards more informed users who have a specific dataset in mind, and 2) a guided search modeled after the USGS Coastal Science Navigator (USGS, 2024).

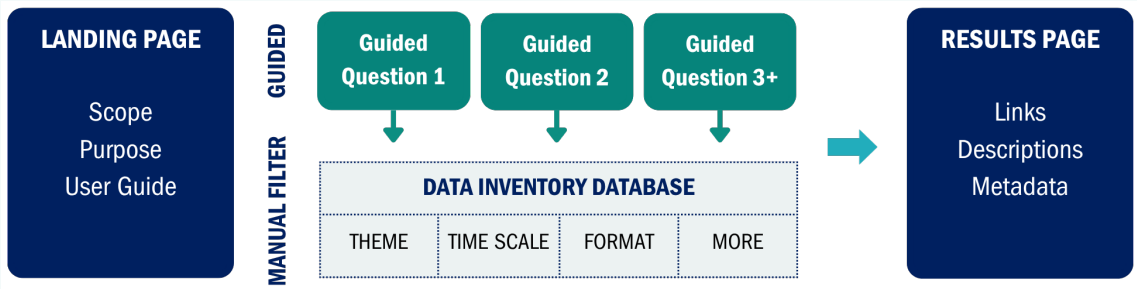

Figure 1-3. A simplified schematic highlighting the web interface's two options for interacting with the data inventory: by a guided questionnaire or through a manual filter of the underlying data inventory database.

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Figure 1-4 captures 'Question 6' in the CDS's Guided Search. Users are prompted to specify which modeling software the data will be used in, enabling more tailored filtering of data products. Users may also choose 'Select All' to view all relevant data, or 'I only want the data, I am not building a particular model' for general use cases. Available options include:

- HEC-RAS 1D / 2D
- HEC-HMS
- MIKE SHE, MIKE 21 HD, MIKE 11 HD, MIKE 11MIKE+ Rivers
- PRMS, SWMM, ADCIRC (ADvanced CIRCulation Model), STWAVE (Steady-State Spectral Wave Model), and others

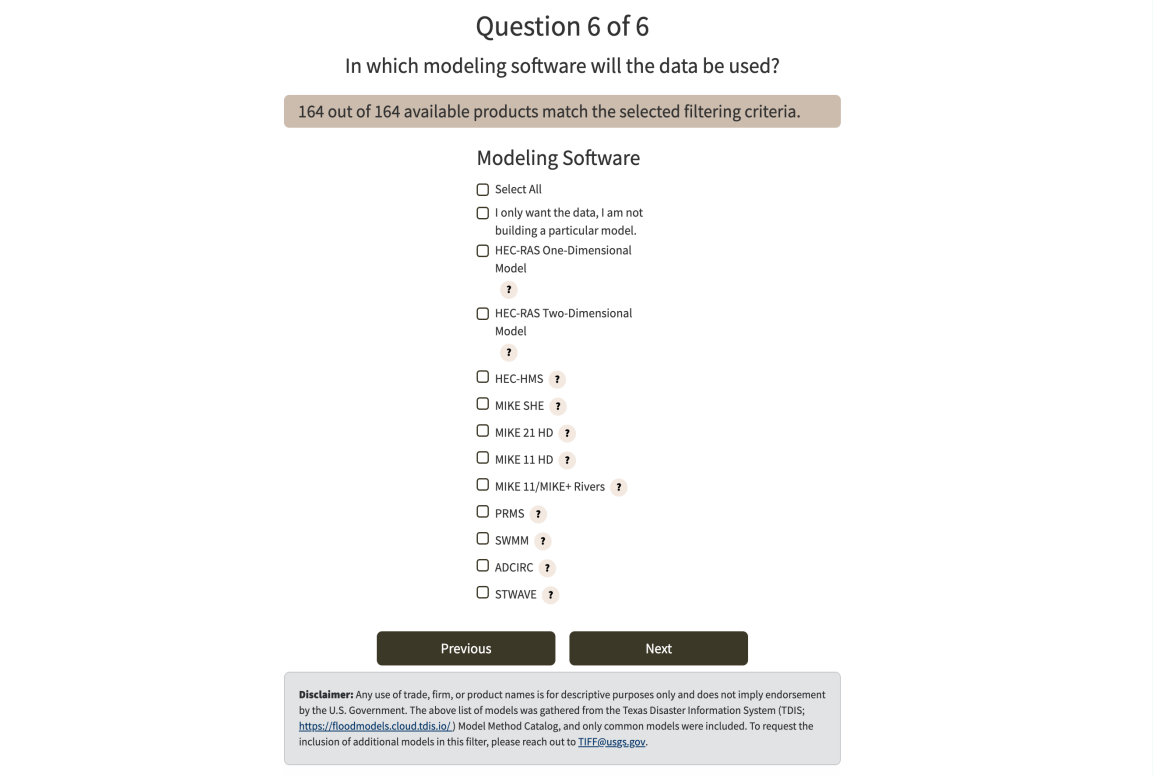

Figure 1-4. A dynamic result count updates based on prior answers and this selection, helping users understand how their criteria refine the dataset and supporting better discovery and relevance for both technical and non-technical users.

3. **Data Gap Analysis**: The CDS also enables data-gap analyses, providing users with a comprehensive overview of crucial data components currently absent within a chosen study area. Tool development must remain an ongoing process, continually incorporating additional functionalities (branches on the decision tree and datasets) to address emerging requirements and technological advancements. Ensuring a broad and deep pool of available data, the tool harnesses the potential of multiple APIs, consolidating data from diverse sources to offer users a comprehensive and up-to-date data landscape.

4. **Interactive Mapping**: The CDS's spatial visualization features enable stakeholders to identify data gaps specific to their needs and utilize resources efficiently to fill these gaps (Figures 1-5, 1-6, 1-7, and 1-8). The interactive map utilizes data services directly from their source, ensuring that datasets remain up to date while reducing the burden of data storage and ongoing maintenance costs. By linking directly to authoritative data providers, such as federal and state agencies, universities, and research institutions, users gain access to the most current and comprehensive flood-related datasets available.

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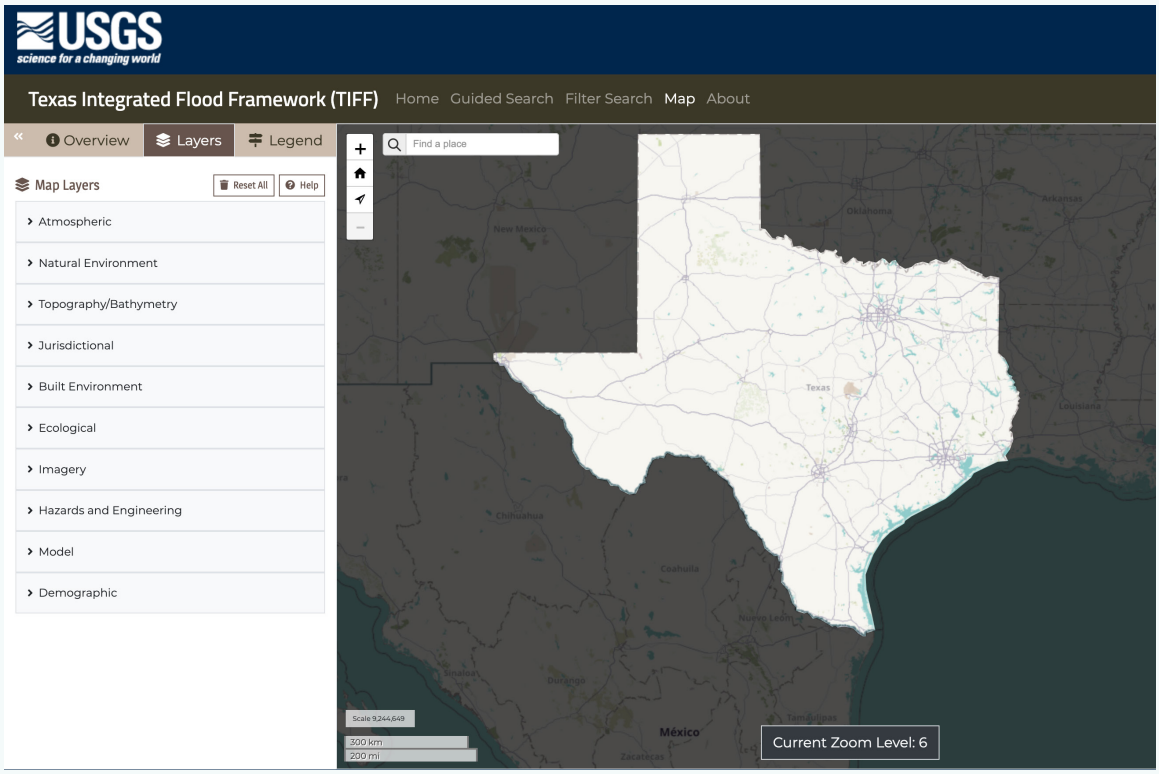

Figure 1-5. Screenshot displaying the interactive map interface where users can explore data layers by thematic category. Users can click on any of the following categories to view and load relevant map layers: Atmospheric, Natural Environment, Built Environment, Ecological, Imagery, Literature Sources, Models, Natural Hazards, Mitigation Support, and Demographics.

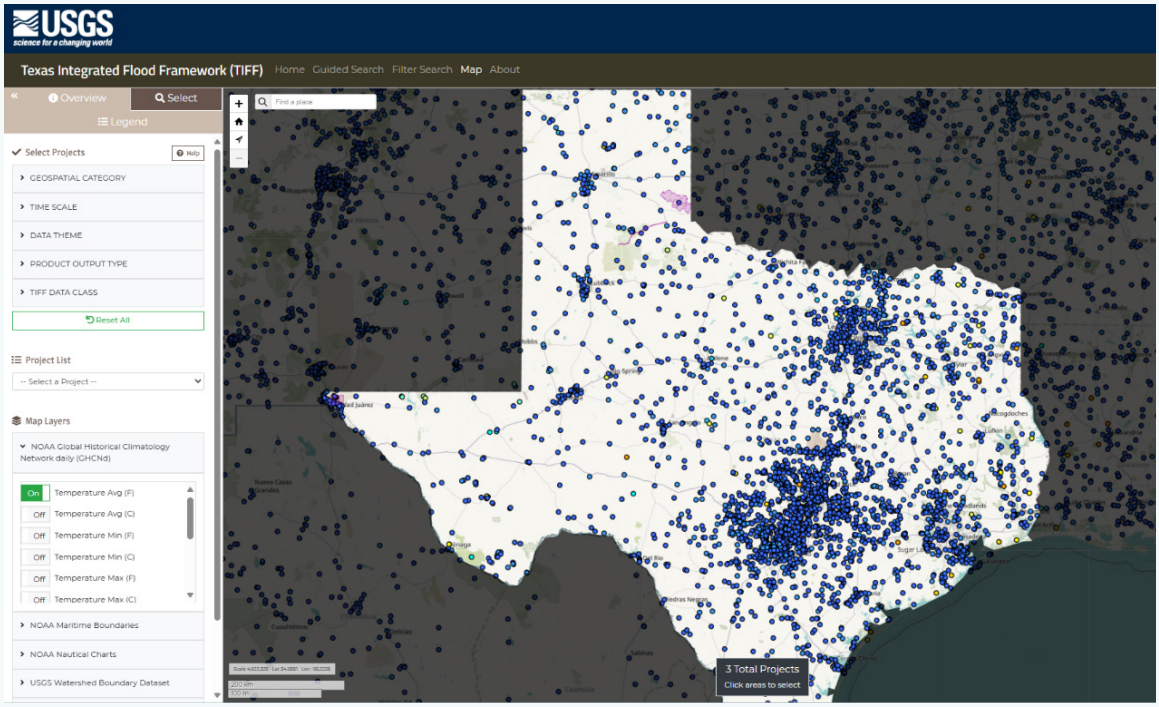

Figure 1-6. Screenshot displaying a visual mask applied around the state of Texas, reducing visual clutter from neighboring states.

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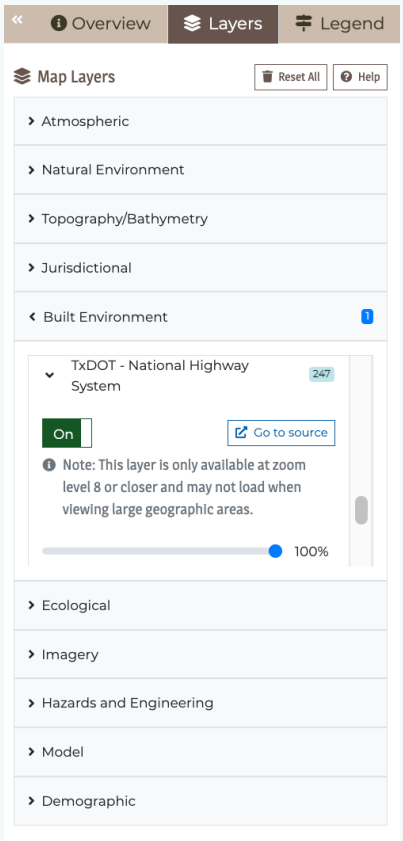

Figure 1-7. Screenshot highlighting map layers that have a '?' icon. When users hover over the icon, a tooltip appears providing helpful information about that specific layer. This improves usability and supports better decision-making.

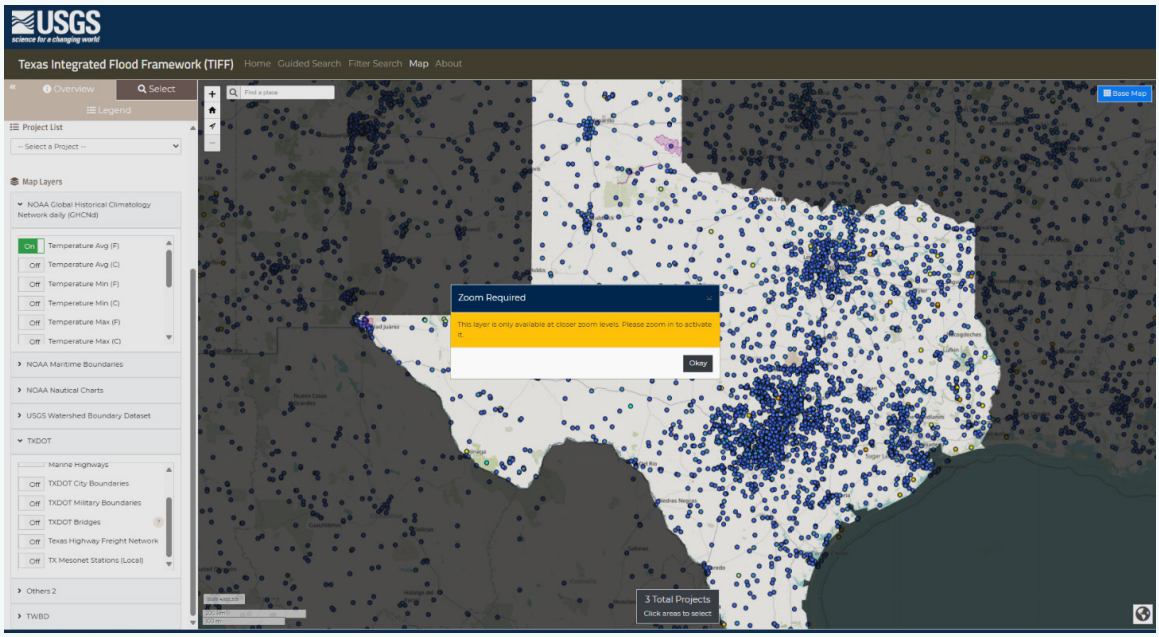

Figure 1-8. Screenshot showing an alert that appears when a user attempts to load layers with high data density without zooming in. The alert advises the user to zoom in closer to avoid long loading times. The final screenshot demonstrates the outcome after zooming in—the relevant data is successfully displayed, improving both performance and user experience.

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5. **Modeling Support**: Another key feature of the CDS is the categorization of available datasets by model type, enabling users to filter data according to their specific modeling needs. This feature was developed in response to stakeholder feedback, recognizing the need for a more direct connection between available datasets and the modeling processes that rely on them. This allows users to select a coastal flood modeling approach from a list of commonly used models and link directly to the relevant input datasets needed for that specific modeling approach. For example, a user may indicate the need to develop a hydraulic model for flood mapping along the coast. The CDS reduces available datasets down to those applicable specifically to hydraulic models and highlight to the user 1) which datasets are readily available within their study area and 2) which datasets have data gaps and need to be collected as part of their modeling effort.

   Where possible, publicly available model extents have been incorporated into the interactive map, further enhancing the usability and efficiency of the CDS. This helps users determine whether existing models can meet their project needs, reducing duplication of effort and saving time and resources. These models may also provide researchers a foundation for more detailed modeling, allowing users to refine and build upon previous work instead of starting from scratch or facilitate model validation and comparison, enabling researchers and decision-makers to cross-check outputs and assess model accuracy. By incorporating model extents into the CDS, users can make more informed decisions about how to approach flood risk assessments, ensuring that their work is grounded in the best available data and modeling resources. With continued refinement and expansion, the CDS will remain a critical tool for coastal flood resilience efforts, helping Texas adapt to changing conditions and improve disaster preparedness strategies.

USGS storm-tide sensor installed near Matagorda, Texas, to collect water-level data during Hurricane Harvey © USGS

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1.5 Implementation of Objectives

Objective 1: Establish a Data and Monitoring TAT

USGS hydrologist Samuel H. Rendon, of USGS' Oklahoma-Texas Water Science Center, was named as the initial Team Champion for Component 1's TAT. Samuel led the effort from 2021-2023. Kristine Blickenstaff, Branch Chief of Integrated Hydrology and Data Science, and Jonathan Thomas, Studies Chief in the Hydrodynamic InFRMatics Section, assumed the Champion role for Component 1 in 2023.

The TATs are responsible for establishing SMART goals to guide the flood modeling framework. Their role includes evaluating and recommending appropriate technologies to support a strategic and scalable flood modeling system, providing expert technical feedback, reviewing project deliverables, and contributing professional guidance throughout the development process. The Component 1 TAT was specifically tasked with a set of focused objectives:

- Identify available datasets and establishing a plan to acquire critical information required for effective flood monitoring and modeling
- Guide the expansion and enhancement of observational data networks and data archives across atmospheric, inland, coastal, and oceanic systems
- Assist in a comprehensive inventory analysis of existing hydrologic, hydrodynamic, meteorological, and planning datasets, including those necessary for model calibration and validation

In addition, the Component 1 TAT supported the development of a gap analysis methodology using geospatial and analytical tools to identify and prioritize data needs across monitoring, modeling, and planning domains. The team was also responsible for helping to develop a prioritized list of recommended monitoring systems and locations. Furthermore, they advised on the identification and evaluation of emerging monitoring technologies, including the creation of a decision matrix to assess these innovations. Finally, the Component 1 TAT provided guidance on data sharing protocols, archiving strategies, and best practices for quality assurance and quality control, working closely with the Component 2 TAT to ensure consistency and integration across the broader TIFF initiative.

To ensure Component 1 addressed the unique hydrologic and coastal behavior of the LRGV, TIFF invited and confirmed the additional membership of two Technical Advisors in November 2023 with firsthand experience in local flooding challenges. The participation of these regional subject-matter experts helped ensure that the technical direction of Component 1 remained aligned with real conditions and hydrological processes experienced in the region and reinforced the scientific reliability of the gap analyses and data-inventory improvements. TIFF engaged these LRGV TAT experts extensively in 2024 and 2025 to review draft methodologies, validate assumptions, and provide targeted feedback that directly improved the accuracy of Component 1 outputs. Their insights shaped revisions to data categorization, model-type requirements, metadata expectations, and the prioritization of datasets incorporated into the CDS. By contributing regional context, these experts helped correct gaps that statewide tools or non-regional specialists were unlikely to detect.

The following advisors were selected to serve as members of the Component 1 TAT based on their expertise in coastal flood data availability, technical data collection requirements, and the interpretation and application of modeling methodologies. Advisors marked with as asterisk are those LRGV-specific additions.

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COMPONENT 1 TECHNICAL ADVISORS

- Andrew Ernest, RATES
- *Augusto Sanchez, Cameron County
- Chandra Sekharan, TAMU-Corpus Christi
- *Christopher Fuller, RATES
- Craig Glennie, University of Houston
- David Maidment, UT-Austin
- Evan Turner, TWDB
- Gregg Easley, TCEQ
- Jeff East, USGS
- Jeffrey Danielson, USGS
- Jeremy Justice, HCFCD
- Joey Thomas, TWDB
- John Nielsen-Gammon, TAMU
- Jonathan Thomas, USGS (TIFF SC Team Champion)
- Katie Landry-Guyton, NWS
- Kayode Atoba, TAMU-IDRT
- Kristine Blickenstaff, USGS (TIFF SC Team Champion)
- Larry Voice, FEMA
- Laura Stearns, TAMU-IDRT
- Lydia Fletcher, UT-Austin, TACC
- Philippe Tissot, TAMU-Corpus Christi
- RoseMarie Klee, TxDOT
- Samuel H. Rendon, USGS (TIFF SC Team Champion)
- Steve DiMarco, TAMU
- William Butler, USACE-ERDC
- Witold Krajewski, Iowa Flood Center

Objective 2: Assist TDIS in determining the appropriate data structure for creating a tool to inventory, display, and evaluate the availability of all data applicable to flood-related analyses used for planning and mitigating coastal floods

TIFF worked closely with TDIS to evaluate coastal datasets, identifying key metadata gaps and recommending improvements based on FEMA standards for flood inundation mapping. Specific to data structure and taxonomy development, TIFF collaborated with TDIS to assess coastal datasets, and it was determined that additional metadata was needed for those data to be fully utilized. Following this assessment, TIFF provided recommendations to TDIS and GLO on data structure and metadata based on the FEMA standards/approaches outlined in their flood inundation map submittal manuals.

TIFF then further developed the spatial component of the CDS to visualize and aid in the evaluation of critical data gaps across individual or multiple datasets in both type and data structure. A 'use inventory' function was added to further identify critical data necessary for modeling and planning needs (critical data includes hydrologic, hydrodynamic, and meteorologic observations vital for model calibration, verification, and simulations to provide informed planning). The inventory and evaluation of data used to support flood planning, modeling, and mapping along the Texas coast continues.

The main objective of the input inventory evaluation was to identify available datasets within the study region that can be used for facilitating model development and supporting gap analysis in regions where improved datasets or models are needed for future flood planning analysis. Furthermore, TIFF assisted TDIS in determining the appropriate data structure and performed an extensive search of flood-related data types available in Texas to inform stakeholders about the available datasets for various model types.

In collaboration, TDIS, Components 1 and 2 TATs, and GLO's RBFS are developing the framework, infrastructure, and software to display and evaluate the availability of all datasets applicable to coastal flood analyses used for planning and mitigation of coastal floods. The first step in this endeavor included developing an inventory of all models and datasets applicable to mitigating coastal floods.

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A data inventory should start with an understanding of what is being inventoried and why. The TAT was asked for volunteers to join a Data Workgroup to determine what datasets apply to coastal flood analysis. A list of approximately 100 datasets was split into ten major data classes, and the Data Workgroup was asked to review each data class and its associated datasets and add any additional datasets that apply to that data class. As a result, an additional 53 datasets were identified. TIFF then curated the results into a list of 143 individual datasets (**Appendix A-4**).

The next step in creating a data inventory was to establish a well-defined organizational structure, known as a data taxonomy. A data taxonomy is the classification of data into hierarchical groups to create structure, standardize terminology, and populate an inventory within an organization. The taxonomy described herein is the initial product of cooperation between TDIS, TIFF, and the TWDB's Regional Flood Planning Groups (RFPGs). The RFPGs, as part of their initial work orders, created Data Collection Plans for each of their four regions. The creation of a database was required to provide centralized access to an authoritative catalog of data for use in their projects. The complex nature of the many types and uses of data required for coastal flood analysis presents challenges for the development of rigid categories.

In many cases, a singular dataset may be categorized differently based on the use case, the background of the data collector, or various other reasons. The RFPGs developed a set of discrete categories to limit this as much as possible using standardized criteria for organizing data. However, after further investigation, TIFF found discrepancies between the RFPGs in critical data, data categorization, and naming conventions. Due to these differences in the taxonomies used by each RFPG, it was determined that a single standardization system was needed.

TIFF then created a single RFPGs-TIFF Data Classification Map, relating the curated list of critical datasets created by the Data Workgroup with the lists and categories developed by the RFPGs, while taking care to mirror as closely as possible the initial schema presented by the RFPGs. This Data Classification Map also included a TIFF Data Themes field to relate datasets that may fall into different categories based on the use case or other reasons. TIFF then asked the Data Workgroup to determine any other names that may apply to each dataset and select the appropriate keywords that best described each of the 143 datasets (**Appendix A-4**). A summary of the TIFF Data Classification Workshop is provided in **Appendix A-5**.

Additionally, TDIS and TIFF have determined that a purpose-driven hierarchical structure is the most effective way of organizing the information needed to create the data availability tool by linking the purpose of analysis to each dataset. An initial iteration of the conceptual schematic for a purpose-driven structure is shown in Figure 1-9, with explanations of each term described below:

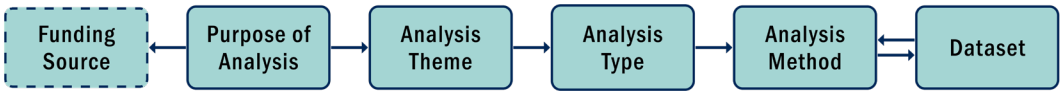

Figure 1-9. Schematic of the purpose-driven inventory structure.

Funding Source – A source of funding that may require particular analyses, such as 'FEMA Grant Application' or a 'USACE Planning Study.' Known funding sources are provided and the addition of a new funding source can be requested where one has been omitted. Information about analyses may be added without relating them to a funding source. 'None' is an option if no funding source is relevant to an analysis.

Purpose of Analysis – A 'Purposes of Analysis' indicates the aim of analyses and may be associated with particular funding sources. For example, an 'USACE Planning Study' could be submitted for 'Infrastructure – Flood Risk Reduction' or 'Improvement in Navigation.'

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Analysis Theme – Designates a broad classification of the topic area to be studied in support of the 'Purpose of Analysis.' For a 'Purpose of Analysis' of 'Infrastructure – Flood Risk Reduction,' a few 'Analysis Themes' include 'Hydrology,' 'Hydraulics,' and 'Cost-Benefit.' Each 'Analysis Theme' can be investigated using one or more 'Analysis Types.'

Analysis Type – A specific type of analysis associated with an 'Analysis Theme.' 'Analysis Types' are not constrained to numerical models; they should include any analyses used for an 'Analysis Theme'. For example, the 'Analysis Theme' of 'Hydrology' includes 'Analysis Types' such as 'Flood Frequency Analysis,' 'Hydrologic Modeling,' and 'Precipitation Analysis.'

Analysis Method – Indicates the methodology used to perform a particular type of analysis. For the 'Analysis Type' of 'Hydrologic Modeling,' many 'Analysis Methods' are possible. Examples of software-dependent analysis methods include 'HEC-HMS,' 'SWAT,' or 'PRMS.'

Dataset – The data that relate to a specific topic and are collected or generated for a particular purpose. Examples include 'Land Use/Land Cover.' A 'Dataset' can be the input to or the output of an 'Analysis Method.'

Figure 1-10 shows a possible example of how the 'Analysis Method' of HEC-HMS may be used in support of a particular 'Purpose of Analysis.' This example generally illustrates the connections to be made and the expected branching structure as each 'Purpose of Analysis,' 'Analysis Theme,' etc., is filled out to correspond to the 'Dataset' inputs and outputs.

TIFF then held a workshop with the Data Workgroup to gather feedback on the framework, focusing on the areas of 'Purpose of Analysis,' 'Analysis Type,' and 'Analysis Method.' The workshop included an interactive, facilitated discussion to solicit feedback on the purpose-driven structure and determine what analysis types and methods are important to workshop participants. TIFF asked participants to answer the questions associated with each framework element and consider whether their contributions are high priority (important in the near term) or low priority (important in the long term). Participants contributed their feedback and responses verbally or by using a virtual and collaborative whiteboarding tool. (**Appendix A-6** includes a summary of this workshop.)

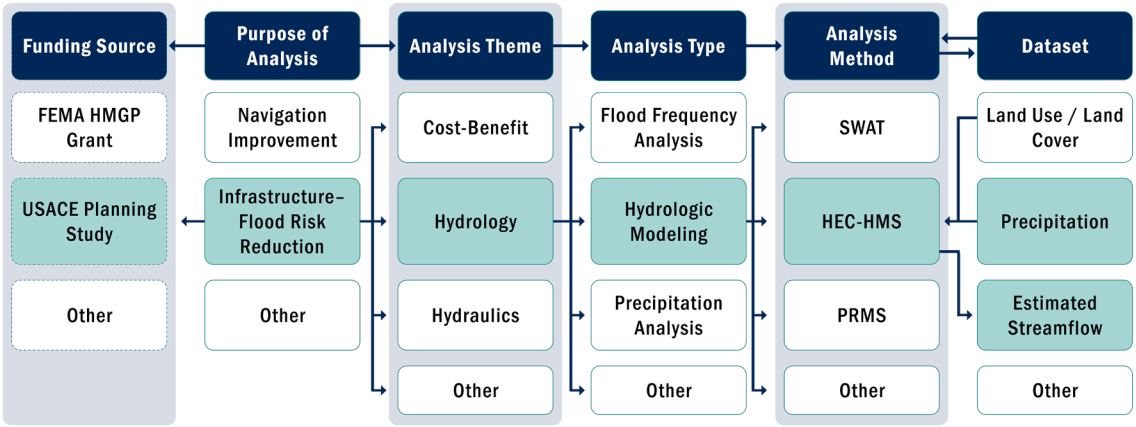

Figure 1-10. Example of hydrologic modeling using the HEC-HMS within the purpose-driven structure.

To further improve the data inventory, TIFF worked closely with TDIS to design a data structure capable of supporting a wide range of coastal, hydrologic, atmospheric, and inland datasets essential for flood-risk analysis in the LRGV. LRGV TAT members provided key insight into the types of datasets used most frequently for regional modeling, highlighting the need for a flexible structure that accommodates datasets with differing temporal resolutions, spatial extents, and formats. Their feedback helped ensure that the data structure could support modeling approaches commonly applied to the LRGV, including coastal surge simulations, riverine hydrologic modeling, and combined inland–coastal interaction assessments.

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The collaboration resulted in a metadata and data-organization framework that can consistently characterize datasets across the region while remaining adaptable for new technologies and evolving flood-analysis needs. The process improved statewide data accessibility and strengthened the foundation upon which the CDS could perform reliable inventory and gap-assessment functions for the LRGV. Additionally, discussions between TIFF and TDIS highlighted a need to ensure that the various flood risk web-tools pointed to other available tools with specific flood risk focuses. Enhancing the data inventory with LRGV datasets included the development of a recommended data-structure framework for TDIS, documented metadata standards informed by LRGV TAT feedback, and technical summaries describing how various LRGV datasets would be indexed and managed. The deliverables improved the consistency and long-term usability of regional datasets and ensured that TDIS could evaluate the completeness and availability of LRGV flood-related information.

Objective 3: Provide TDIS with associated data linkages for critical coastal flood analysis use cases

TIFF collaborated directly with TDIS to ensure that all pertinent, readily available datasets were incorporated while avoiding overlapping efforts. Beyond data inclusion, the partnership emphasized collaboration while developing data linkages to support critical coastal flood analysis use cases. This included aligning metadata structures, standardizing data formats, and coordinating workflows to ensure robust and consistent integration across platforms. Regular communication, including periodic updates and quarterly meetings, ensured progress, accountability, and sustained alignment between both teams. These data linkages were attributed to the compiled datasets using 11 TIFF Classes and subsequently used in the CDS. Additionally, efforts were made to ensure that complementary resources were clearly identified and highlighted within the tools, so users are aware of these additional tools. For example, the CDS directs users to TDIS's Measuring, Mapping, and Managing Flood Risk (M3FR) and the Data & Models Query Tool (DMQT) on the 'About' page with a brief description of the tools. Furthermore, within the model section of the map, the RBFS layer points users to the DMQT for detailed model information and download options.

These classifications were critical in organizing metadata guidance and enabling users to filter the entire data inventory to highlight data availability specific to their needs. This framework enables users to query the full coastal dataset inventory, filter by temporal and format requirements, and directly link to the appropriate data sources.

In its first year, TIFF assisted TDIS in determining the appropriate data structure and conducted an extensive search of flood-related data types available in Texas to inform stakeholders about the available datasets for various model types (TIFF, 2022). Datasets were categorized by data class (Atmospheric, Natural Environment, Topography/Bathymetry, Jurisdictional, Built Environment, Ecological, Imagery, Literature Source, Model, Hazards and Engineering, Mitigation Support, Demographic, and Public Health) as well as thematic category (hydraulic, hydrologic, risk, water quality) to support the review and classification of datasets. Furthermore, digital repositories and APIs for linkage with an eventual interface were identified to support the creation of the CDS. After data categorization and source cataloging, it was determined whether each dataset had a readily accessible digital format for ingestion into the eventual web interface (**Appendix A-5**).

To further improve the CDS, TIFF evaluated the initial LRGV dataset inventory provided by the GLO's study vendor and the TWDB Regional Flood Planning Groups. LRGV TAT members played an essential role in this review by identifying datasets missing from statewide inventories, highlighting inconsistencies in metadata, and noting areas where coverage was insufficient for coastal or riverine flood analysis. Their perspective ensured that local drainage studies, municipal datasets, and smaller-scale monitoring networks were recognized and considered. The evaluation identified both the strengths and deficiencies of the initial inventory and clarified how the CDS could better serve regional planners, engineers, and researchers. TAT feedback was particularly critical in identifying areas where modeling coverage was inconsistent, metadata was unclear, or datasets required reclassification to reflect their true relevance to

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coastal processes. Deliverables included a detailed technical review of the inventory provided, a written set of recommendations for the GLO, and a revised dataset list for integration into the CDS. TIFF also prepared documentation outlining data gaps identified through TAT consultation, ensuring that the improved inventory captured a comprehensive representation of available LRGV datasets.

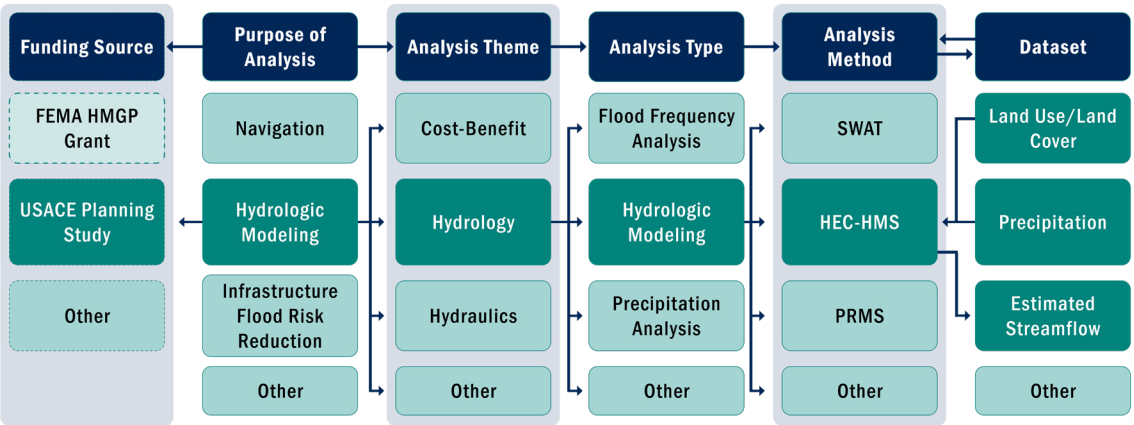

Figure 1-11. A decision tree linking the necessary data for hydrologic analysis using the USACE HEC-HMS. Linkages include FEMA's Hazard Mitigation Grant Program (HMGP), SWAT, and PRMS.

Objective 4: Evaluate and provide feedback to GLO on 1) the initial data inventory provided by the RBFS Study Providers and the TWDB RFPGs, and 2) the associated data availability tool provided by TDIS

The main goal under this Objective was to identify available datasets within the study region that can be used to facilitate model development and support gap analysis in regions where improved datasets or models are needed for future flood planning analysis.

Numerical model users devote an appreciable effort to collecting data, constructing model inputs, and calibrating and validating model parameters to help evaluate risk and potential impacts. Many models also have specific data input requirements that require extensive data collection efforts, whether digital or field-based, before a model can begin to run. Therefore, data collection efforts often comprise a sizable portion of a model's project timeline and are proportional to its size and complexity. With limited data availability, and consequently limited sharing and visibility, there is often duplication of efforts in data collection, which leads to budget increases and delays in project implementation schedules. While many flood models use similar methodologies and input data, this information is often not readily available or shared on a common platform, which forces modelers to spend significant time and effort qualifying the data or even collecting new data when adequate data may already exist. Pragmatically, it is an inefficient use of the modeler's time to reproduce similar model input files to those developed previously.

One way to address these challenges is to create a common platform for sharing and referencing model input datasets. First, an existing inventory of data related to flood analysis studies was needed. This data inventory may not be comprehensive, but TIFF performed an exhaustive search for a myriad of model input data categories, ranging from meteorological to geographic and socioeconomic (**Appendix A-4**). Specifically, TIFF led focused workshops to better understand and assess data classification and linkages along with bathymetric, subsidence, and wave data needs.

DATA CLASSIFICATION WORKSHOP

A Data Classification Workshop was held to review the results of the second TIFF Component 1 Data Monitoring Gap Analysis, specifically the Data Classification Survey, and determine next steps for advancing data taxonomy and ontology to support a comprehensive coastal flood data inventory (**Appen-**

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dix A-5). Participants agreed that improvements to the survey process should inform metadata development, specifically in terms of thematic organization, targeted expert input, and group-based refinement. Regarding the linkage between datasets, models, and analysis types, the group recommended starting with a few base use cases, specific models and analyses, and performing a literature review to identify existing data-model linkages. These initial linkages would later be refined by the TAT, with additional use cases added iteratively.

Objective 5: Perform a gap analysis for use cases with the feedback of the TATs to identify data needed to improve observations for coastal flood analysis

The consideration of use cases led to the exploration of specialized data that are needed for a comprehensive understanding of compound flooding along the Texas coast, including bathymetry, subsidence, and nearshore waves. TIFF held three workshops to explore these topics, bringing national and international experts together to better understand the opportunities and limitations of existing data and identify potential collaborations to advance these areas of monitoring:

BATHYMETRIC WORKSHOP

Bathymetric data is one of the most important datasets for coastal modeling, but there are obstacles to collecting high-quality data. Bathymetry is highly dynamic, meaning data must be collected regularly. As a result, the datasets are sometimes outdated and inaccurate. TIFF hosted a virtual Bathymetry Workshop with 90 participants on May 18, 2022, to improve statewide collaboration and advance bathymetry data in Texas (**Appendix A-7**). The workshop focused on gathering insight from the TAT members and other bathymetry experts and end-users to develop a statewide priority map for bathymetry acquisition needs and target available resources. TIFF used this information to conduct an inventory and gap analysis for bathymetry data, which resulted in a TIFF recommendation for the areas needing immediate bathymetry data acquisition and the associated costs to complete the work.

SUBSIDENCE WORKSHOP

Subsidence is a multi-faceted problem that affects not only land but also groundwater and surface water systems. Many agencies, universities, and organizations across the state are advancing their knowledge and data related to subsidence, but efforts are needed to coordinate these endeavors. TIFF and TWDB cohosted a virtual Subsidence Workshop with 177 participants on September 7, 2022, to improve statewide coordination for subsidence data collection and sharing. The goal of the workshop was to gather insights from subsidence experts, including the TAT members and faculty from various universities, about acquisition and resource needs for advancing subsidence data in Texas. The workshop concluded with a poll to gather participant feedback and gauge interest in their continued involvement with the collaborative subsidence efforts (**Appendix A-8**).

WAVE WORKSHOP

One of the more important datasets lacking along the Texas coast, as identified by the TATs, is wave data. TIFF hosted a virtual Nearshore Wave Data Workshop on November 2, 2023 (**Appendix A-9**). The 75 participants explored the opportunities and challenges of wave data collection methods and data measurement needs to support flood mitigation and response efforts. The workshop gathered insights from TAT members and a diverse mix of wave data experts to identify data gaps for various usages and develop strategies to fill these gaps while promoting collaboration among researchers and practitioners working on nearshore wave data. Following the workshop, the TAT and wave workshop participants were asked to complete a Wave Data Mapping Survey to identify priority areas of interest for nearshore wave data collection. This data inventory provides key information about data coverage, attribute type, and data

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category for the eventual streamlined access and parsing of the data inventory. This initial data inventory laid the foundation for the development of a data inventory mapping interface (described below).

The insights gathered during the wave data workshop underscored a pressing need for a centralized, interactive repository capable of organizing and visualizing coastal flood-related datasets. Participants emphasized that without a streamlined system to access and assess wave data coverage, researchers and planners face significant challenges in identifying critical gaps and coordinating mitigation strategies. The collaborative nature of the workshop revealed a shared demand for tools that not only provide linkages to diverse datasets but also enable dynamic gap analysis to guide decision-making. This recognition directly informed the development of the CDS, which now serves as a resource for ongoing user specific data gap assessments and supports more strategic, data-driven approaches to flood risk management.

The CDS serves as the primary mechanism for ongoing gap analysis. This gap assessment capability enables users to independently or collaboratively analyze data deficiencies, allowing for a more targeted and effective approach to coastal flood planning and mitigation. By eliminating guesswork and providing clear, data-driven insights, these enhancements support smarter decision-making and more effective resource allocation for flood risk management.

Specifically, the map component of the CDS facilitates an ongoing detailed gap analysis by:

1. **Collecting data and metadata for the mapping interface**: A comprehensive search and prioritization of flood-related datasets was performed for the entire study area. This effort identified the spatial extent of these datasets as well as details on the quality of each dataset (e.g., acquisition year, resolution).
2. **Identifying digital repositories (or APIs) for linkage on the web interface**: Earlier data categorization and source cataloging identified whether a dataset contained machine-readable digital data that could be used in this mapping interface. In this way, data gaps accessibility was identified, in addition to gaps in spatial coverage or quality. This next level of analysis allows TIFF to identify efficiencies and cost savings by identifying datasets or coverage areas that may not necessarily need a data collection effort, but rather a data digitization effort instead.
3. **Implementation of the web interface itself**: The 'birds-eye view' provided by combining datasets into a single viewer or catalog that is up to date and populated with pertinent metadata enables consistent and constant data-gap analysis updates by continually updating data or identifying broken links or outdated datasets.
4. **Crowdsourcing further data gap analysis**: A publicly available web interface with a targeted feedback loop creates the potential for an additional 'crowd-sourced' gap analysis. In addition to a formal gap analysis performed by TIFF, public users of the data inventory mapping interface (both lay and technical) can provide feedback on data gaps that meet their unique modeling or flood risk analysis needs. This public-facing approach ensures that TIFF does not overlook data gaps or mis-prioritize data collection efforts that match the public's needs.

The interactive map allows users to toggle datasets on and off, providing a customizable experience. This functionality allows users to visually explore data coverage in specific areas along the Texas coast, evaluate data resolution and availability for various flood-related datasets, and identify gaps in spatial coverage that may impact modeling, forecasting, or risk assessments. The spatial gap assessment feature is particularly valuable for coastal planners, flood modelers, and emergency management officials, as it enables them to quickly identify where data exists and where gaps need to be addressed. By leveraging the interactive map alongside CDS tools, users can perform multi-dimensional gap assessments, including:

- **Spatial gaps**: identifying missing geographic coverage for key datasets
- **Temporal gaps**: determining whether data exists for specific time periods, particularly for long-term

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flood trend analysis or historical modeling

- **Data type gaps**: assessing whether necessary datasets (e.g., hydrologic, hydrodynamic, meteorologic, and topographic data) are available
- **Data format gaps**: ensuring that datasets are provided in compatible formats for integration into various flood modeling and planning tools

DATA GAPS IN THE LOWER RIO GRANDE VALLEY

TIFF conducted use-case-driven gap analyses that incorporated extensive TAT feedback to identify missing, outdated, or inconsistent datasets critical for coastal flood modeling. TAT members provided ground-truth insight into areas where data scarcity or poor quality hindered accurate modeling—such as highly localized drainage networks, areas with limited bathymetric coverage, and coastal inlets subject to frequent geomorphic change. Their expertise helped prioritize where new data collection, digitization, or monitoring infrastructure would have the greatest impact.

The gap analysis process also benefited from TAT input regarding modeling workflows, enabling the team to refine data needs assessments for hydraulic, hydrologic, and coastal models commonly used in the LRGV. This ensured that recommended data collection priorities were tied to real analytical requirements rather than theoretical assumptions. Major deliverables included refined modeling-input requirements and spatial gap maps integrated into the CDS interface and summary documents describing how TAT feedback changed gap analysis findings, ensuring transparency and demonstrating that the results aligned with local expert knowledge.

Objectives 6 and 7: Develop and recommend a plan to periodically update the data inventory and perform data gap analyses

Keeping a web tool up to date is essential for maintaining its functionality and ensuring that any connected datasets remain accurate and reliable. As browsers, APIs, and third-party services evolve, outdated web tools risk losing compatibility, leading to broken features or display issues. Keeping datasets current is crucial for delivering relevant and trustworthy information to target users. To address this need, TIFF developed a recommendation on how to regularly assess and update the CDS (Recommendation C1.2A: Enhance the Coastal Data Surfer).

Periodic data inventory updates include the use of a working group email alias (TIFF@usgs.gov) to enable the science community to send updated sources and add newly published data throughout the year, along with an annual review of the inventory data in detail. Additionally, a review of new methods to fill data gaps and update the inventory tool, as well as management practices for digital data repositories and API infrastructure, is recommended to facilitate easy data utilization and collaboration.

To support long-term model development and adaptability, metadata standards should be designed to accommodate new or customized input data as needed. While current standards may be sufficient for existing methodologies and modeling applications, emerging techniques may require more detailed metadata—such as higher spatial or temporal resolution, or specifications on equipment used. As data formats and usage evolve, metadata requirements also change. Therefore, it is recommended that metadata standards be reviewed and updated annually to ensure continued relevance and usability across applications.

TIFF developed the CDS to allow users to evaluate data gaps based on their specific needs and goals. The spatial and modeling features in the CDS enable users to identify data gaps specific to their needs and allow them to utilize resources efficiently to fill data gaps. TIFF continued working with various stakeholders to ensure that the collected data and findings could be effectively used in flood planning and mitigation efforts across Texas. Additionally, the integration of new monitoring technologies help enhance the overall framework, making flood mitigation more effective and efficient.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

DATA INVENTORY AND GAP ANALYSES FOR THE LOWER RIO GRANDE VALLEY

TIFF created a long-term plan for regularly updating the LRGV data inventory to maintain relevance as new data sources emerge. TAT members were instrumental in identifying regional agencies that routinely generate new datasets and providing guidance on how frequently certain types of data—such as LiDAR updates, sensor records, or flood studies—should be incorporated. Their insight ensured that the plan was realistic, sustainable, and aligned with the data-production cycles of LRGV partners.

The plan established an annual review cycle, ongoing communication channels for scientific contributors, and a strategy for capturing newly published datasets from federal, state, and academic sources. By integrating TAT feedback, TIFF ensured that the plan accounted for the unique pace and diversity of data production in the LRGV. Deliverables included a written update recommendation outlining roles, schedules, and update mechanisms; documentation of TAT-informed revisions; and draft operational procedures for annual review. These materials support the long-term maintenance of the CDS and ensure accuracy and completeness of LRGV data inventories.

TIFF also developed a recurring process for performing periodic LRGV gap analyses, informed heavily by TAT guidance on how flood-risk conditions evolve in the region. TAT members helped identify triggers for interim gap evaluations—such as major storms, rapid urban development, or changes in coastal morphology—that are particularly relevant in the LRGV. Their insight ensured that the plan addressed both predictable and unexpected shifts in regional data needs.

The resulting plan emphasizes the use of the CDS as a dynamic tool for assessing ongoing data deficiencies and outlines how user-driven feedback should be incorporated into future analyses. This approach ensures that gap identification remains continuous and responsive to changing conditions. The plan also included documentation showing how TAT input ensured relevant datasets were included in the tool to confirm accurate data gap assessments can be conducted. These deliverables collectively strengthen the long-term adaptability of the LRGV data-management system.

Objective 8: Evaluate and provide updates on new monitoring technologies

The data gap analysis included the exploration and evaluation of new emerging monitoring technologies that can benefit enhanced coastal flood analysis, as the best data that benefits quality flood planning might not yet exist. This forward-thinking approach ensures the project stays at the forefront of technological advancements, equipping stakeholders with access to the most effective tools available.

TIFF recommends enhancing coastal water monitoring networks as a crucial step in supporting risk assessments and planning analyses (Recommendation C1.5A: Expand Measurement Networks). By leveraging the extensive experience from the TAT members, the importance of improving coastal monitoring has become evident. This step addresses the need for reliable and accurate, real-time data to empower stakeholders to make informed decisions, particularly in response to natural disasters or long-term environmental challenges. Enhanced monitoring systems not only improve decision-making during emergencies but also contribute to proactive planning, allowing coastal regions to better prepare for flooding and other hazards. This recommendation underscores the significance of building resilient infrastructure and data systems that can support both immediate response and long-term sustainability.

Recognizing the need for improved coastal monitoring technologies, TIFF evaluated various sensor systems and data collection platforms to determine the most effective solutions for coastal flood monitoring. TIFF developed a recommendation to identify and use a platform to assess various sensors, installation approaches, data transmission options, and power options to identify the most robust options for coastal data collection (Recommendation C1.8A: Operate Testing Sites for Water Monitoring Devices). As water monitoring technologies evolve, the need for robust field testing in challenging environments becomes paramount. TIFF proposes to partner with local, state, and federal agencies to design, install, and operate a testing platform in a coastal environment to evaluate the functionality, environmental resilience, and

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accuracy of new and existing advanced water monitoring equipment. This platform provides real-time data and insights into the equipment's performance under varying coastal conditions, helping to ensure that selected monitoring technologies meet both regulatory standards and practical performance criteria. The platform can be used to:

- evaluate the functionality of water monitoring devices in the coastal environment to determine their reliability and operational effectiveness
- assess environmental resiliency by exposing devices to coastal conditions such as tidal fluctuations, salinity, sedimentation, fouling, and extreme weather events
- test accuracy and calibration to ensure that equipment consistently delivers precise data required for regulatory compliance and environmental management

TIFF also evaluated a broad suite of emerging monitoring technologies for applicability to the LRGV, incorporating TAT insights on environmental conditions and deployment challenges unique to the region (Recommendation C1.8A: Operate Testing Sites for Water Monitoring Devices). TAT members helped identify which technologies would withstand sediment load, salinity fluctuations, and biofouling common in LRGV waterways and which would best support flood forecasting and situational awareness during coastal storms. Their guidance ensured that the evaluation process was grounded in operational realities. Technology assessments included evaluating durability, data quality, installation requirements, and cost-effectiveness. The incorporation of TAT experience improved the reliability of the recommendations and ensured that proposed monitoring enhancements would benefit both long-term planning and emergency response. TAT feedback was documented and incorporated into final selection criteria, ensuring that the proposed monitoring upgrades were both technically feasible and regionally appropriate.

Also guided by TAT expertise, TIFF identified locations across the LRGV suitable for testing new monitoring technologies under real coastal and riverine conditions. TAT members provided essential input on site accessibility, tidal behavior, sedimentation patterns, and hydrologic variability. Their feedback helped ensure that testbed locations accurately represented the full range of environmental conditions experienced in the region. These testbeds were selected to support evaluation of both inland and coastal monitoring technologies, enabling performance comparisons across varied settings. The process ensured that future monitoring investments are grounded in a realistic understanding of equipment behavior under LRGV conditions.

Objective 9: Make recommendations pertinent to future data and monitoring for coastal flood analysis to GLO

As TIFF's ultimate legacy will be the set of recommendations, guidelines, and frameworks to improve the performance, understanding, and communication of flood science, it was imperative that the final recommendations made by TIFF be vetted and optimized by coordinated peer review so that they can be made actionable without hesitation by implementing entities. This coordinated peer review was structured around the component objectives, which were used to query whether the existing list of potential recommendations thoroughly addressed the original vision and intent of TIFF.

Component 1 TAT experts engaged in a series of interactive virtual meetings to systematically review, refine, and discuss draft recommendations (**Appendix A-10**). The primary objective of these meetings was to ensure that every recommendation was aligned with the goals of Component 1, which focused on improving data accessibility, integration, and monitoring for coastal flood planning. The review process was structured to determine whether each recommendation was complete and ready for finalization, in progress (requiring additional work or refinement), or needing new actions (additional objectives, data, or resources were required to fully meet the intended goal).

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Afternoon storms roll in over Galveston Beach, Texas. © Felix Mizioznikov

Each Component 1 Objective was carefully examined during the TAT meetings, ensuring that recommendations fully addressed the intended outcomes. If an Objective was not fully achieved, discussions focused on identifying gaps, defining additional actions, and determining the resources required to close those gaps. This process ensured that no critical aspect of coastal flood data management, modeling, or monitoring was overlooked. The TAT recommendation process followed a structured multi-step approach to ensure that each proposed strategy was optimized for effectiveness:

1. **Initial Review**: Each Recommendation was carefully examined to determine whether it aligned with Component 1 Objectives and whether it addressed the identified data or flood risk assessment challenges.
2. **Optimization**: The TAT worked to refine recommendations by identifying improvements, additional data sources, or technical adjustments that would enhance their practical implementation.
3. **Objective Evaluation**: Each Component 1 Objective was reviewed to assess whether the recommendation fully met the goal or if further work was necessary. If additional steps were required, they were outlined and discussed.
4. **Finalization**: Once a Recommendation was optimized and confirmed to meet its objective, it was finalized as an official TIFF Recommendation, ready for implementation.

Recognizing that not all TAT members could attend every meeting, follow-up surveys were sent after each session to provide an opportunity for additional input and refinements. These emails allowed absent TAT members to review discussion points, provide feedback, and suggest adjustments, ensuring that every recommendation was informed by a broad range of expertise and perspectives.

Beyond reviewing the technical feasibility of recommendations, the TAT also assessed key implementation factors, including:

- **Potential target users**: Who would benefit from or need to implement the recommendation? (e.g., state agencies, researchers, emergency management personnel, policymakers)
- **Time sensitivities**: What are the timeframes? (e.g., urgency, time needed for completion of each task, ongoing)
- **Implementation entities**: Which potential organizations or agencies would be responsible for putting the recommendation into action?
- **Associated costs**: What are the budgetary and funding considerations?

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

By incorporating these practical considerations, the final TIFF Recommendations are not just theoretical solutions, but vetted and actionable strategies that can be realistically implemented to improve Texas' flood planning, mitigation, and response efforts. The rigorous review and optimization process led by the Facilitation Team significantly strengthened the TIFF recommendations, ensuring that they were:

- scientifically sound, rooted in data-driven insights and best practices for flood risk assessment
- technically feasible, designed for practical application in Texas' coastal flood framework implementation
- actionable and implementable, with clearly defined steps, responsible agencies, and resource needs
- capable of driving meaningful improvements in Texas' coastal flood planning analysis and response strategies

A specialized recommendation process was implemented to elicit a set of Recommendations to address the data and monitoring needs of the LRGV (**Appendix A-11**). These TIFF Recommendations address data-collection priorities, monitoring-network enhancements, metadata improvements, and long-term maintenance strategies. TAT contributions ensured that the recommendations were realistic, regionally tailored, and aligned with ongoing efforts by drainage districts, municipalities, universities, and federal partners. The Recommendations serve as a strategic roadmap for improving flood preparedness, planning capacity, and modeling accuracy in the LRGV, emphasizing the need for robust monitoring systems, consistent data updates, and cross-agency collaboration.

By leveraging expert collaboration, structured evaluation, and comprehensive refinement, the TIFF process and Recommendations will help Texas enhance its ability to prepare for, respond to, and mitigate coastal flooding in the years to come. **Ultimately, nine TIFF Recommendations resulted from the research and expertise associated with Component 1.** (See the TIFF Recommendations Handouts which can be used to seek further support for implementation.)

Note: Each Recommendation is designed to articulate implementation needs, and where feasible, approximate costs. These cost estimates are included for planning purposes only and should be understood as preliminary and subject to refinement based on project scope, timing, and local/regional conditions and circumstances. In all cases, implementation of these Recommendations will require the identification and securement of appropriate funding. Additionally, implementation of these Recommendations is subject to the legislative authority and capacity of potential partners. Collectively, the Recommendations are designed to provide funders and policymakers with a clear roadmap for strengthening the state's flood resilience, ensuring that communities, infrastructure, and ecosystems along the Texas coast are better protected for the future.

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THE COMPONENT 1 RECOMMENDATIONS

Table 1-1. Component 1 Objectives for Data and Monitoring Gap Analysis and associated Recommendations.

Component Objective	Associated Recommendation(s)
Establish a Data and Monitoring TAT	Objective met by TIFF. No further Recommendations.
Assist TDIS in determining the appropriate data structure for creating a tool to display and evaluate the availability of all data applicable to flood-related analyses used for planning and mitigating coastal floods	C1.2A: Enhance the CDS
Provide TDIS with associated data linkages for critical coastal flood analysis use cases as determined by the TIFF TATs	Objective met by TIFF. No further Recommendations.
Evaluate and provide feedback to the GLO on 1) the initial data inventory provided by the regional flood groups, and 2) the associated data availability tool provided by TDIS	Objective met by TIFF. No further Recommendations.
Perform a gap analysis for use cases with the feedback of the TATs to identify data needed to improve observations for coastal flood analysis	C1.5A: Expand Measurement Networks C1.5B: Establish a Nearshore Wave Data Collection Network C1.5C: Develop and Maintain a Centralized Subsidence Monitoring Dashboard C1.5D: Compile, Collect, Process, and Integrate High-Resolution Land Cover Data to Enhance Flood Models C1.5E: Collect Bathymetric Data for Priority Areas C1.5F: Integrate Historical Datasets from the Texas Coastal Ocean Observation Network
Develop and recommend a plan to periodically update the data inventory	Objective met and continued with C1.2A: Enhance the CDS
Develop and recommend a plan to periodically perform data gap analyses	Objective met and continued with C1.2A: Enhance the CDS
Evaluate and provide updates on new monitoring technologies	C1.8A: Operate Testing Sites for Water Monitoring Devices C1.8B: Assess the Extent of High-Frequency Radar Accuracy for Wave Measurements
Provide recommendations pertinent to data and monitoring for coastal flood analysis to the GLO	Objective met by TIFF. No further Recommendations.

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C1.2A: Enhance the Coastal Data Surfer for displaying, inventorying, and evaluating data to support flood planning, modeling, mapping, and mitigation along the Texas coast

Researchers, planners, and policymakers need a centralized, web-based tool to access and analyze flood-related data. The CDS serves this role by integrating national, regional, and local datasets covering the entire Texas coast. Designed for a broad audience across disciplines involved in flood planning and mitigation, the CDS will be a dynamic platform that evolves with the rapidly changing landscape of coastal flood research.

Ongoing resources are essential to ensure the CDS goes beyond data visualization. It identifies gaps in existing datasets to improve awareness of available data and past efforts, reduce duplication in data collection and modeling, and enable timely updates to maintain relevance and usability.

Project phases and deliverables should align with other agency flood and hazard mitigation planning cycles, such as the TWDB Regional Flood Plans (https://www.twdb.texas.gov/flood/planning/regions/index.asp) and State Flood Plan (https://www.twdb.texas.gov/flood/planning/sfp/index.asp). Ongoing maintenance costs vary annually and should be allocated across project phases. Agencies can collaborate on funding different phases or use a cost-sharing formula. Key costs include cloud hosting, data storage, production, user interface/user experience (UI/UX) components, security services, and technical debt management.

The CDS is a crucial and ongoing investment that will need to be maintained and updated to ensure it remains a valuable resource. Key implementation actions include:

- **Define Metadata Standards**: Using the TDIS DMQT project as a reference, develop metadata standards in collaboration with partner agencies to categorize hydraulic and hydrologic models in Texas, ensuring consistency for future data input and updates
- **Deploy Beta Version**: Gather user feedback from scientists, modelers, engineers, and other stakeholders; assess usability based on searchability, metadata effectiveness, and dataset availability
- **Integrate Spatial Data**: Facilitate users in performing data gap analysis and improving decision-making; optimize the CDS to support structured data, informing future planning and modeling needs (e.g., identifying where to expand continuous monitoring, improving flood emergency response)
- **Follow-Up Evaluations**: Gather user feedback and refine its functionalities; implement necessary updates and optimizations to improve overall performance
- **Inventory and Gap Analysis**: Conduct an initial inventory to assess dataset availability, followed by targeted gap analyses to prioritize modeling approaches; identify evolving data needs, including critical hydrologic, hydrodynamic, meteorologic, and socio-economic datasets; enhance the CDS to support temporal data searches linked to study requirements
- **Maintenance and Five-Year Updates**: Align updates with State and Regional Flood Planning Cycles; create a dashboard feedback mechanism and working group email alias to facilitate continuous updates; expand API capabilities for improved search functionality, feedback submission, and dataset additions, adhering to FAIR (Findable, Accessible, Interoperable, and Reusable) data principles; validate metadata completeness and system integrity through expert reviews, while integrating new methodologies and datasets to address gaps; catalog machine-readable data with a defined metadata schema and explore opportunities for data digitization
- **Cost-Effective Data Hosting**: Consider shared responsibilities for deploying the CDS, including the potential for long-term hosting by TDIS; align hosting strategies with the USGS-led data gap analyses to maximize efficiency and cost-effectiveness

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

C1.5A: Expand measurement networks to include under-sampled locations, prioritizing areas by flood frequency and severity

In-situ measurements, such as rain gages, often struggle with representativeness, record length, and spatial coverage, but they play a crucial role in monitoring coastal inundation, rainfall, river stages, and nearshore wave conditions–especially in areas where lower-resolution data fail to accurately capture real-world conditions. In regions with insufficient coverage, additional sensors (e.g., gages) may be necessary to enhance data reliability.

TIFF recommends expanding the existing measurement networks to enhance regional flood characterization, particularly in under-sampled areas identified by flood frequency and severity analyses, such as the LRGV. Site selection should also prioritize locations based on their proximity to vulnerable infrastructure and populations–such as Colonias in South Texas, which are disproportionately situated in flood-prone regions–rather than being driven by convenience.

Potential partners include agencies experienced in facilitating regional flood planning and coordination, experience in managing local sensor networks, coordinating emergency management, collecting inundation photos to enhance observations, expertise in socio-economic flood risk factors, and imagery data storage. Key stakeholders include county agencies and non-profits that can serve as community organizers and connectors.

Ongoing maintenance costs vary annually and should be allocated across project phases. Agencies can collaborate on funding different phases or use a cost-sharing formula. Key costs include field operations, hosting the database, and infrastructure development.

The expansion of measurement networks is a cost-effective investment. Key implementation actions include:

- **Inventory and Gap Analysis**: Conduct an initial inventory of existing monitoring infrastructure and activities in the region to identify the gaps between existing and needed monitoring activities; identify under-sampled areas based on flood frequency, severity, and proximity to vulnerable infrastructure and populations; identify priority monitoring and data needs, including critical locations for expanded flood monitoring and prediction
- **Expand Sensor Networks**: Expand local sensor networks and explore funding opportunities through local jurisdictions; locate stations along urbanized and industrial corridors, and near-shore and near-coastal transition zones to capture diverse hydrologic and coastal conditions
- **Data Collection**: Collect and archive continuous historical and real-time data encompassing streamflow, rainfall, groundwater levels, and meteorological forcings such as wind speed, barometric pressure, and tide levels
- **Standardized Data Integration**: Develop best-practice guidelines for verifying and incorporating diverse datasets into flood models, ensuring consistency across studies; one potential resource for this phase is the IDRT pilot community data collection tool, which includes a survey, training process, and web portal for displaying results, and could be adapted for other regions
- **Improve Data Completeness**: Address significant data gaps by integrating anecdotal sources, such as citizen science contributions, local agency data, timestamped inundation photos, and media reports
- **Capacity Building**: Work with local governments, academic partners, state and federal agencies to ensure interoperability, open data access, and long-term system sustainability
- **Prioritize Under-Sampled Locations**: While under-sampled locations, such as the LRGV, have often experienced flood events over the years, resulting from the convergence of different hydrological and meteorological phenomena, current flood monitoring coverage in the region

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is concentrated around major rivers and channels, leaving critical inland and coastal gaps where flood processes are poorly understood; the absence of comprehensive, high-resolution data reduces the accuracy of flood model calibration and limits understanding of local flood dynamics; TIFF recommends deploying additional real-time data collection stations strategically across both coastal and inland zones, prioritizing underserved urbanized and industrial corridors; implementation in the LRGV will expand spatial coverage of real-time hydrologic and meteorologic data, improve model calibration and compound flood simulations, and enhance forecast reliability for emergency management and local planning

C1.5B: Establish a Nearshore Wave Data Collection Network along the Texas coast to address critical data gaps and enhance the understanding of extreme wave events, improve daily flood forecasting, and strengthen coastal risk assessment

Nearshore wave data is essential for designing coastal structures, managing shorelines, assessing hazard risks, and advancing research. However, the availability of such data remains limited due to the challenges of collecting measurements in remote coastal areas. More comprehensive data is needed to refine model forecasts and provide near-real-time updates on wave properties.

TIFF recommends the establishment and ongoing investment in a Nearshore Wave Data Collection Network along the Texas coast to address critical data gaps, enhance the understanding of extreme wave events, improve flood forecasting, and strengthen coastal risk assessment.

Ongoing maintenance costs vary annually and should be allocated across project phases. Agencies can collaborate on funding different phases or use a cost-sharing formula. Key costs include instrumentation, installation, field visits, and data storage.

Key implementation actions include:

- **Inventory and Gap Analysis**: Conduct a comprehensive inventory and gap analysis of nearshore wave data along the Texas coast to improve understanding of extreme wave events and flood forecasting; use existing models and datasets to identify priority regions based on coastal infrastructure, population growth, and risk factors; focus on areas with inconsistent wave measurements, such as Galveston Bay, Port Arthur's Pleasure Island, Keller Bay, Carancahua Bay, and Port Aransas
- **Instrumentation Selection**: Deploy three types of wave measurement instruments: 1) offshore buoys with independent power supplies that report data every 30–60 minutes, 2) nearshore sensors transmitting real-time directional and non-directional wave data, and 3) shore-based sensors activated during inundation events; prioritize cost-effective solutions, such as Spotter buoys, along with integration of a global positioning system into existing systems, like TDIS or TAMU Texas Automated Buoy System (TABS); consider costs of maintenance, data transmission, storage, analysis, and dissemination, which may exceed the costs of instrumentation
- **Deployment of Monitoring Stations**: Identify and secure monitoring station locations, ensuring resilience to extreme weather; assess permitting requirements for buoy deployments and integration with the NOAA National Data Buoy Center (NDBC); develop nearshore and shore-based monitoring infrastructure (may require specialized platforms)
- **Model Integration and Forecasting**: Integrate real-time data into wave, surge, and inland flood models to enhance forecasting; combine observational data with model outputs for hourly forecasts to cover the entire Texas coast, including bays; adapt existing models for seamless integration with new datasets
- **Data Management and Sharing**: Establish a centralized platform for real-time data sharing and long-term storage of high-resolution (15-minute interval) and high-frequency (6 Hz or higher) wave

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

data, including wave height, period, and direction to support model calibration and validation; store raw data in barometric-corrected Network Common Data Form (NetCDF) format per climate and forecast metadata standards, ensuring permanent availability for post-event analysis

- **Long-Term Maintenance and Partnerships**: Build partnerships with federal and state agencies for sustained data collection and funding; engage with contractors, private entities, universities, and industries to support short-term spot measurements; dedicate $100,000–$1,000,000 per year for measurements, $200,000 per year for modeling (with potential increases for model development), and $500,000 for initial buoy deployment; assess additional funding needs for network expansion and explore collaborative funding strategies to distribute maintenance costs

C1.5C: Develop and maintain a centralized Subsidence Monitoring Dashboard to serve as a comprehensive, user-friendly platform to consolidate, analyze, and utilize subsidence data

Subsidence, the gradual sinking of the Earth's surface, presents critical risks to Texas' infrastructure, water resources, and land management. However, current subsidence data is fragmented across various sources, making it challenging for decision-makers to fully understand and address the issue. Additionally, the absence of integrated tools for basic analyses and interpretation limits the ability to apply this data effectively to practical solutions.

TIFF recommends developing a dashboard to integrate innovative remote sensing technologies, such as InSAR (Interferometric Synthetic Aperture Radar), to provide high-resolution, accurate, and timely subsidence rate data. The dashboard would also centralize information from state and federal agencies, universities, and private entities, creating a single repository for easy access. Analysis tools will enable users to assess subsidence trends over time and across geographic areas. Additionally, the dashboard will automate annual InSAR data downloads and processing to ensure consistent updates.

Streamlining access to subsidence information and analyses will empower stakeholders to develop informed, effective strategies for mitigating the risks associated with subsidence in Texas. Subsidence districts can play a key role by utilizing their existing monitoring stations. These stations could also help expand monitoring efforts to other subsidence areas across the state.

The Centralized Subsidence Monitoring Dashboard is a crucial effort with an initial investment estimated at $200,000–$400,000.

Key implementation actions include:

- **Needs Assessment and Planning**: Engage stakeholders to define requirements for data sources, tools, and quality assurance/quality control (QA/QC) processes; collaboration with experts is critical to outline technical specifications for integrating InSAR data and create a detailed project plan with timelines and budgets
- **Data Integration**: Partner with agencies, universities, and private entities to consolidate subsidence data into a centralized repository; the dashboard should be built to meet accessibility standards, incorporate InSAR data, and implement algorithms for calculating subsidence rates
- **Quality Control**: Develop QA/QC protocols to ensure data accuracy and establish ongoing validation with periodic updates
- **User Testing**: Conduct iterative testing with stakeholders, gathering feedback to refine functionality and usability
- **Launch and Support**: Launch the dashboard, promote its use, provide training, and establish systems for regular updates and tool enhancements

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

C1.5D: Compile, collect, process, and integrate high-resolution land cover data to enhance flood models for the entire Texas coast and provide guidelines for implementation into Texas coastal flood modeling systems

Accurate and up-to-date land cover data is critical for coastal flood modeling. This data provides more detailed surface distinctions–such as urban structures, vegetation, and waterbodies–compared to traditional 30-meter datasets, which are essential for flood impact prediction and management.

This data will:

- improve understanding of water flow dynamics and land cover effects
- enhance flood routing simulations for infrastructure and asset risk assessment
- support long-term assessments of sea-level rise and coastal changes
- align flood management with federal standards, fostering better coordination with federal agencies
- improve flood resilience planning tools used by all levels of decision-makers, supporting emergency and long-term response efforts

Key partners include state and local stakeholders to ensure seamless data accessibility and effective implementation. The total budget is estimated to be between $1-$3 million for all Texas coastal counties. The project timeline is 1-3 years, with future updates occurring every 5-10 years, based on funding and demand.

Key implementation actions include:

- Build partnerships with state and federal agencies experienced in providing data access, products, and services to support community resilience such as the TxGIO, NOAA, and research institutions
- Testbed numerical model studies for performance evaluations
- Develop guidelines for integrating high-resolution land cover data into existing coastal flood models to improve flood simulation accuracy
- Integrate existing and new high-resolution data into coastal flood models

C1.5E: Collect bathymetric data for priority areas along the Texas coast to address critical data gaps, strengthen coastal flood modeling efforts, and improve flood forecasting

Bathymetric data is essential for coastal flood modeling, but the availability of high-quality data remains limited due to the challenges of collecting measurements. Bathymetry represents the three-dimensional features of underwater terrain, or bed elevation, which is highly dynamic and frequently changes with natural and anthropogenic influences. As such, data must be collected regularly to ensure it is current, accurate, and useful for coastal modeling.

TIFF recommends the collection of critical bathymetric data at priority areas along the Texas coast to significantly increase the accuracy of coastal flood modeling and forecasting. State and federal agencies and other organizations could collaborate to better coordinate bathymetry data acquisitions and leverage limited funding resources.

The cost of bathymetry acquisition depends on the type of water body (shallow, deep, and rivers), size of project, and method of collection. Partners can collaborate on funding different actions or use a cost-sharing formula, and assess additional funding needs for coastal measurement expansion.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Key implementation actions include:

- **Site Selection**: Begin with priority areas identified by TIFF Technical Advisors: Nueces Bay, Lower Galveston Bay, Sabine Lake, and Laguna Madre
- **Data Integration**: Incorporate data into wave, surge, and inland flood models to enhance forecasting
- **Centralized Sharing**: Create a platform for data sharing and long-term storage
- **Build Partnerships**: Coordinate with federal, state, and local agencies experienced in data collection and management, such as NOAA, USGS, TWDB, and TDIS, for sustained data collection and funding
- **QA/QC Guidelines**: Standardize processes for identifying monitoring station locations and integrating data into flood models

C1.5F: Integrate historical datasets from the Texas Coastal Ocean Observation Network (TCOON) in the National Oceanic and Atmospheric Administration's operational database

Long-term, continuous, and quality-controlled data is essential for understanding compound flood risks and developing reliable tools to prepare for and respond to the state's floods. The Texas Coastal Ocean Observation Network (TCOON) is a network of scientific data collection stations along the Texas coast operated and maintained by NOAA in partnership with the Conrad Blucher Institute (CBI). Historical TCOON data collected by the CBI prior to 2016 was not accepted into the official NOAA database because it was not processed using NOAA quality assurance and quality control (QA/QC) procedures. CBI has this unofficial raw data available through a web portal (https://tamucc-ir.tdl.org/handle/1969.6/89444).

To address this recordkeeping data gap, TIFF recommends acquiring and processing historical TCOON data from CBI for inclusion in NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) official and publicly available dataset.

Based on an approach and cost estimate provided by CO-OPS, a 3-year investment, estimated at $1.352 million, will significantly increase the accuracy of coastal flood modeling and forecasting while supporting flood risk management projects. Key implementation actions include:

- **Tool Enhancement and Automation**: The enhancement will greatly reduce the time required to process stations, allowing CO-OPS to process the entire historical TCOON data record more quickly and deliver updated datums within 12 months; This will require code enhancements for data automation and the creation of automated processing/verification processes of the NOAA Tidal Analysis Datum (TAD) Tool; More accurate code in NOAA's water level processing program will result in better tide picks
- **TCOON Metadata Review and Integration**: Steps include 1) download the data from CBI's data management system, re-format it to CO-OPS specifications, and digitize the metadata paper records (including all site reports, leveling abstracts, benchmark descriptions, benchmark sketches, and INX files for all stations); 2) coordinate with CBI to ingest and validate the data and metadata to CO-OPS standards; and 3) hire two full-time contractors to manually enter and verify any metadata that is in paper record into the system
- **TCOON Data Processing and Verification**: To deliver quality-controlled products, such as updated datums and sea level trends for the Texas coastline, the two full-time contractors will use the enhanced TAD Tool to process 5,400 months of historical TCOON data from 26 long-term water level stations; Each station month is processed individually, compared against neighbors,

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

and appropriate fills are made, then hourly heights and highs and lows are tabulated, as well as the monthly means; These data then go through a verification process

- **TCOON Data Project Management**: This will require the coordination of all data and metadata received from CBI and partners, the development of timely progress reports on the status of the project, and the purchase and updating of standard software licenses needed to complete all tasks for the project
- **Update Additional Flood Analysis Products Used by Texas**: Prioritize products that underpin coastal mapping and flood hazard assessment (e.g., tidal datums, long-term sea-level trends) by 1) extending the five-year data series data to 25 years or more will significantly reduce the uncertainty of the various products supported and will provide the confidence level (> 95%) that users need; and 2) expanding the Inundation Dashboard for the Texas coastline by providing more integrated data on coastal flooding, including real-time alerts, and historic coastal inundation tracked through flood thresholds at the gage locations

C1.8A: Operate testing sites that evaluate water monitoring devices to ensure their reliability, operational effectiveness, and compliance with regulatory standards

Coastal water monitoring networks play a crucial role in flood early warning systems and mitigation planning. Emerging monitoring technologies are essential for improving data accuracy and flood planning. Traditional datasets often fail to capture coastal complexities, but innovative sensing technologies can help bridge these gaps. To ensure reliability, these technologies must be tested against established methods in real-world coastal conditions.

TIFF recommends partnerships with local, state, and federal agencies to design, install, and operate coastal testing sites for evaluating water monitoring devices. These sites will evaluate the performance of existing and prototype monitoring devices under tidal fluctuations, salinity, sedimentation, biofouling, and extreme weather. Key objectives include assessing device reliability, longevity, accuracy, and regulatory compliance. To integrate seamlessly with legacy monitoring programs and regulatory applications, it is essential that data from new technologies align with established sensing methods.

By delivering real-time data and critical insights, these testing platforms will enhance flood analysis, strengthen coastal resilience strategies, and equip stakeholders with effective tools and methodologies.

TIFF encourages building partnerships with traditional monitoring agencies, such as the USGS, where feasible. Organizations experienced in research and data collection, such as universities, flood control districts, and specialized non-profits, should also contribute to this effort. Leveraging existing monitoring sites for technology evaluations can support new methods while filling spatial monitoring gaps with cost-effective solutions.

TIFF recommends a multi-year timeline to evaluate emerging technologies under various weather conditions. Annual costs are estimated to be between $500,000 and $5,000,000, with potential savings from using existing platforms.

Key implementation actions include:

- **Site Selection and Design**: Partner with local experts to identify optimal coastal site(s) and design modular, durable platforms that support multiple devices while meeting permitting requirements
- **Equipment Selection and Installation**: Implement a standardized process to select and install sensors for wave height, water quality, and weather parameters, ensuring proper calibration and accuracy

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

- **Data Collection and Monitoring**: Develop a real-time data acquisition system with remote access and automated alerts for malfunctions
- **Environmental Resilience Assessment**: Evaluate device performance under dynamic coastal conditions, tracking uptime, recalibration needs, and resistance to salinity and biofouling
- **Data Analysis**: Enable stakeholders to analyze data for accuracy, reliability, and operational resilience, ensuring alignment with agency requirements
- **Long-Term Sustainability**: Establish a self-sustaining model through subscription fees, grants, partnerships, and sponsorships
- **Recommended Technologies to Test**: Prioritize testing the monitoring technologies as identified by TIFF Technical Advisors:
    - Disposable, biodegradable flood level sensors, which provide short-term data collection in communities with limited funding; designed to last six months, these sensors offer lower data quality and are not a replacement for traditional gages
    - Next-generation, submersible flood monitoring stations that operate almost entirely underwater in the waterbody being monitored would significantly decrease installation costs, expand monitoring coverage across waterbodies previously considered unsuitable due to installation constraints, and enhance the reliability of real-time data collection during extreme flood events
    - Real-time flood monitors with highly configurable, system-on-module designs that incorporate Reduced-Instruction-Set-Computer-Five (RISC-V) and artificial-intelligence (AI)-enabled processors including graphical processing units (GPUS), neural processing units, tensor processing units, and low-power field programmable gate arrays dramatically increase the speed and fidelity of core pattern-matching algorithms used to adapt machine-learned inferential forecast models, creating a unique opportunity to perform local and on-device analysis and forecasting; examples of this technology already exist at a lower cost than the current generation of single board computers used in real-time monitors
    - Non-contact stream-gaging technological alternatives to submersible sensors for flood monitoring, particularly where debris flows, sediment buildup, and erosion pose damage risks; key benefits include a reduction of buried monitoring infrastructure and damaged stations, and a reduced need for personnel to enter water for routine maintenance along with limitations such as vegetation, wind, turbidity, glare, and streamflow rates
    - Rapid Deployment Gages (RDGs) to supplement existing coastal and riverine gage networks during flood events; can be pre-deployed ahead of forecasted storms to enhance situational awareness, support emergency managers, and provide temporary coverage when permanent stations fail; potential RDG locations should be identified in advance to ensure rapid installation and meaningful data reporting (e.g., water-surface elevation of gage height tied to a reliable local datum such as a bridge); trigger condition criteria to deploy the RDGs and data accuracy needs for various uses should be identified

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

C1.8B: Assess extent of High-Frequency radar accuracy for wave measurements

High Frequency (HF) radar networks, commissioned by the GLO and the Gulf of America Coastal Ocean Observing System (GCOOS), are operational in Sabine Lake, Galveston Bay, and offshore from Bolivar Peninsula to Padre Island National Seashore. These systems provide remote measurements of ocean and estuary surface currents, supporting coastal initiatives like natural resource protection and port security. With an estimated $10 million in capital investment, these networks offer significant potential to enhance wave and current data collection compared to traditional ship- and buoy-based systems.

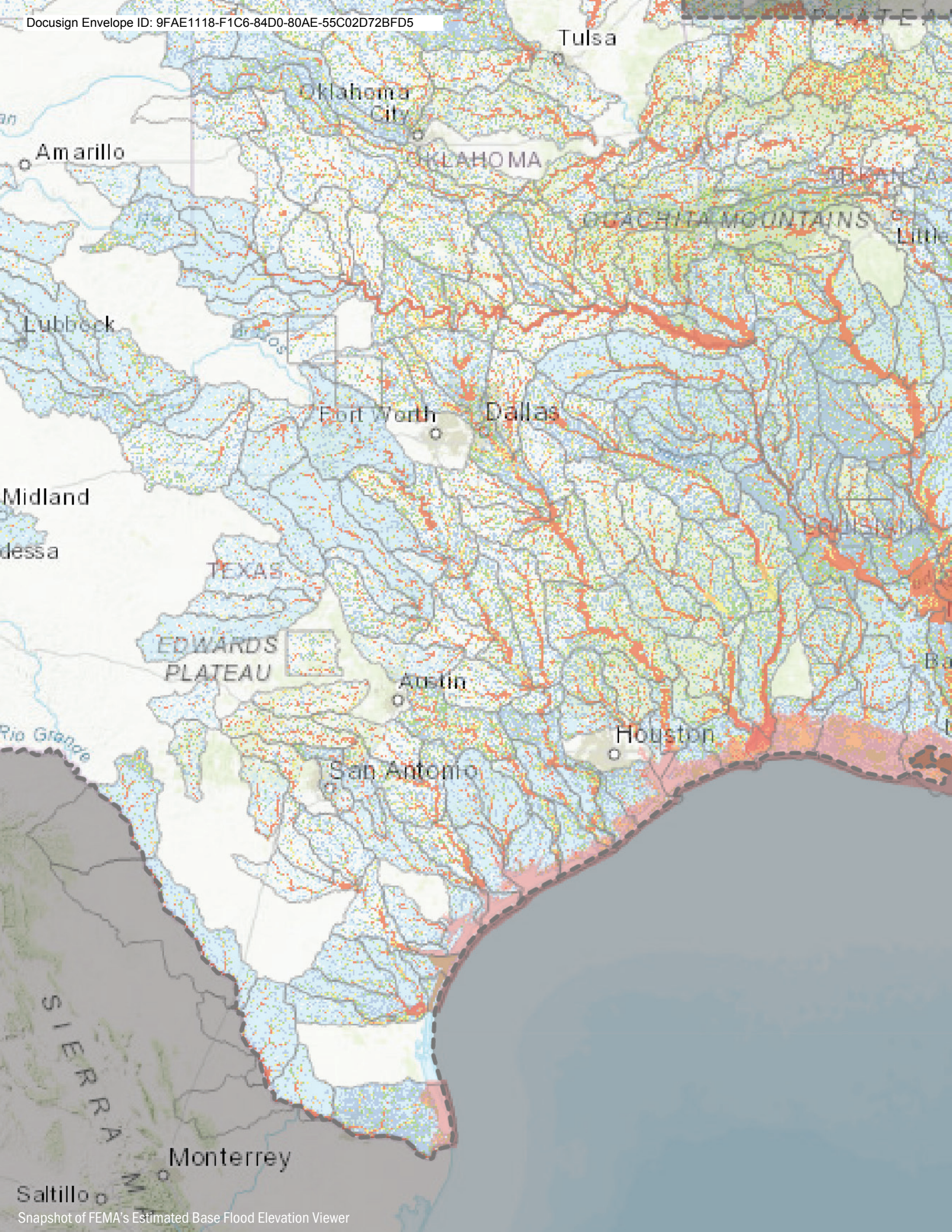
To assess the accuracy of HF radar data, comparative studies with in-situ measurements (e.g., buoy and vessel-based data) are necessary. In Sabine Lake and Galveston Bay, where few buoys are available, offshore studies comparing HF radar data with TAMU TABS and the NOAA buoys are recommended. These studies will help evaluate HF radar performance under varying environmental conditions and establish correlations between different monitoring technologies.

A long-term evaluation is essential to assess the reliability and effectiveness of these systems under changing weather and ocean conditions. If proven dependable, TIFF recommends expanding HF radar coverage to additional Texas bays where such systems are not yet deployed. This expansion would help fill key data gap–particularly in nearshore regions–by providing much-needed surface current measurements to support coastal monitoring and management efforts.

Key implementation actions include:

- **Comparative Studies**: Identify available in-situ monitoring stations, such as the TABS and NOAA buoys, for comparative studies; deploy temporary buoys where necessary, particularly in Sabine Lake and Galveston Bay, where in-situ data is limited; conduct comparative studies between HF radar and buoy-/vessel-based observations to evaluate performance across different environmental conditions
- **Long-Term Evaluation**: Conduct extended studies to assess the reliability of HF radar systems over time; analyze the impacts of seasonal and extreme weather events on HF radar measurements
- **Stakeholder Engagement and Reporting**: Leverage collaborations with coastal management entities, such as the GLO, GCOOS, and NOAA, to share findings; publish interim and final reports summarizing results, challenges, and recommendations; develop guidelines for integrating HF radar data into broader coastal management strategies

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5



Snapshot of FEMA's Estimated Base Flood Elevation Viewer

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

2 Component 2: Data Management and Visualization

The goal of Component 2 is to ensure that coastal flood-related data and model outcomes are properly visualized for both technical and non-technical end-users. TIFF also supports the effort led by TDIS pertaining to data management and visualization related to the Texas coast.

2.1 What is Data Management and Visualization?

Data management and visualization are critical for transforming complex datasets into accessible, usable, and meaningful insights for diverse audiences to make well-informed decisions. Effective systems prioritize clarity, usability, and relevance, achieved through co-design processes that actively involve stakeholders and target users from the outset. This ensures final tools align with real-world needs and decision-making contexts.

In coastal flood planning contexts, data management involves organizing vast datasets (including atmospheric, ecological, demographic, and engineering data) into thematic categories. These datasets must be stored securely, structured consistently, and made digitally accessible for integration into interactive web platforms. Robust data management practices strategically address challenges in storing, accessing, versioning, and sharing model outputs, ensuring data integrity and interoperability across systems. When paired with strong data management, visualization tools can translate complex flood hazard information into actionable insights for planning and mitigation. These tools should support both technical and non-technical users by enabling intuitive exploration of risk scenarios.

2.2 Why Data Management and Visualization Matters to Texas

Communication mechanisms with wide broadcast, appealing delivery methods, and a focus on enhancing decision-making for long-term needs can improve the decision-making process for stakeholders (Mostafiz, 2022). Finding effective ways to share collected data from coastal flood models and tools with various audiences is key to decision processes that rely on accurate and reliable information.

The needs of technical and non-technical user groups in Texas require tailored strategies for information tools and communication approaches. **A central goal of TIFF is improving how flood model results, and associated uncertainties, are communicated and disseminated to non-technical audiences so that they can better plan for and respond to flood.**

There is an urgent need for improved communication strategies that focus on usability, accessibility, and contextual relevance to enhance broader user understanding and experiences. Organizing communication strategies around behavioral archetypes and evaluating user decisions helps tailor messages and improve the impact of visualizations over time.

2.3 The Guiding Objectives of TIFF Component 2

TIFF Component 2 was focused on identifying opportunities for technical and non-technical end-users to properly visualize any coastal flood-related data and model outcomes.

This effort consisted of six objectives:

1. Establish a TAT to support Component 2
2. Assist TDIS with designing and testing the conceptual framework for managing, visualizing, and disseminating large volumes of coastal flood-related datasets, including data visualization system(s)

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

3. Conduct an inventory on coastal flood-related UIs
4. Recommend guidelines for coastal flood UIs, including the level of end-user access, analysis capability, visualizations, and included datasets
5. Assist TDIS with identifying and recommending computational hardware/software requirements for flood-related analysis and visualization
6. Make recommendations pertinent to future data management and visualization needs to the GLO

2.4 Approach to Objectives

TIFF worked in collaboration with partners, the TATs, TDIS, and the Study Providers described below to explore the challenges, goals, and opportunities associated with proper visualization of coastal flood-related data and model outcomes.

Component 2 began by assembling a coastal flood UI inventory (see Objective 3 below) and identifying opportunities to improve coastal flood-related visualization tools. TIFF worked with TDIS and Component 3 Study Providers from the UT-Austin, the University of Iowa, Princeton University, Purdue University, the University of Notre Dame, and USACE's ERDC-CHL to assess the essential components and strategic considerations for 1) designing a conceptual framework for managing, visualizing, and disseminating large volumes of coastal flood-related datasets, and 2) identifying, recommending, and developing computational hardware and software requirements for flood-related analysis and visualization.

Building upon this coastal flood UI inventory, TIFF partnered with Study Providers from the UT-Austin's Moody College of Communications and TACC to recommend guidelines for coastal flood UIs. In identifying effective strategies for communicating flood risk to end-users through data visualizations and other outreach techniques, the Study Providers and TATs found that 1) the term "end-user" should be replaced with "target user," recognizing that these groups should be involved throughout the design process, not just at the end, and 2) objectives of both Component 2 (Data Management and Visualization) and Component 4 (Planning and Outreach) overlap, as data visualization is an impactful way to communicate flood risk. Likewise, to improve coastal flood UIs, it is essential to understand the respective target users.

Through extensive literature reviews, stakeholder collaboration, and surveys with TFMA and TAT members, *The TIFF Communication Guidelines* (**Appendix B-1**) were developed and a statewide survey was administered to assess portions of the guidelines. *The TIFF Communication Guidelines* are meant to function as a strategy for entities designing information visualizations and communication tools to effectively convey flood risk to both general audiences and specific groups affected by coastal flooding. These guidelines are best practices for presenting flood risk in a way that is clear, transparent, and user-friendly. Their adoption and use will ensure that both general audiences and those directly affected by coastal flooding can accurately interpret and respond to the information.

Insights from the surveys, along with stakeholder input from the Best Practices in Identifying Stakeholder Needs around Flooding Workshop (Stakeholder Needs Workshop) (**Appendix B-11**) informed the development of *The TIFF Visualization Guidelines* to enhance flood risk communication for three prioritized target user groups: *Property Owners, Property Renters, and People with Limited English Proficiency (LEP)*, due to their vulnerability to coastal flooding and the potential benefits of improved risk communication. *The TIFF Visualization Guidelines* are meant to serve as a co-design approach, guiding projects to engage target users early and often so visualization tools align with real-world needs. This inclusive process helps ensure that the final products are accessible, meaningful, and capable of supporting informed decision-making across Texas.

Component 2 trialed a community driven, culturally informed approach to improve coastal flood risk communication using the LRGV region as a testbed. Through structured interviews, facilitated work-

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shops, and a Community Learning Exchange, the team worked closely with residents, community organizations, and Spanish speaking audiences to understand how flood information is interpreted, shared, and acted upon. These activities tested tailored communication strategies, including hands on demonstrations and localized flood maps, and contributed to a collaborative multi-modal archive that blends scientific flood modeling resources with community knowledge and cultural memory.

Subsequent sections detail how overlapping Component 2 and Component 4 efforts led to TIFF Recommendations for future work and potential funding.

A Houston resident holds a sign urging passersby to slow down in the aftermath of Hurricane Harvey © Glenn Fawcett

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ZOOMING IN: TIFF'S PRIORITY RECOMMENDATION FOR ONGOING COASTAL FLOOD DATA MANAGEMENT AND VISUALIZATION

The TIFF Guidelines for Coastal Flood Information Design and Communication (TIFF Recommendation C2.4A)

TIFF recommends state coordination and adoption of the developed *The TIFF Communication Guidelines* (**Appendix B-1**) to establish clear objectives for the design of information tools and communication approaches that inform flood risk decisions. Designs should strive to motivate behavior change that is based on the best available knowledge and information.

The TIFF Communication Guidelines convey best practices that address knowledge gaps and propose innovative approaches to leverage technology and information from data collections and coastal modeling for more effective communication of complex flood risk information. Furthermore, these guidelines convey specific insights that can be seamlessly integrated into design processes, from engaging with community members to implementing functional design practices for UIs. *The TIFF Communication Guidelines* emphasize the need to deliver information products that are culturally and contextually adapted to target user groups.

Ultimately, the goal is to incorporate the best available scientific and engineering information into accessible formats, with a strong focus on enhancing the user experience. By tailoring information to meet the specific needs of target user groups, Texas can inspire well-informed decisions and empower communities across the state to navigate flood risks effectively.

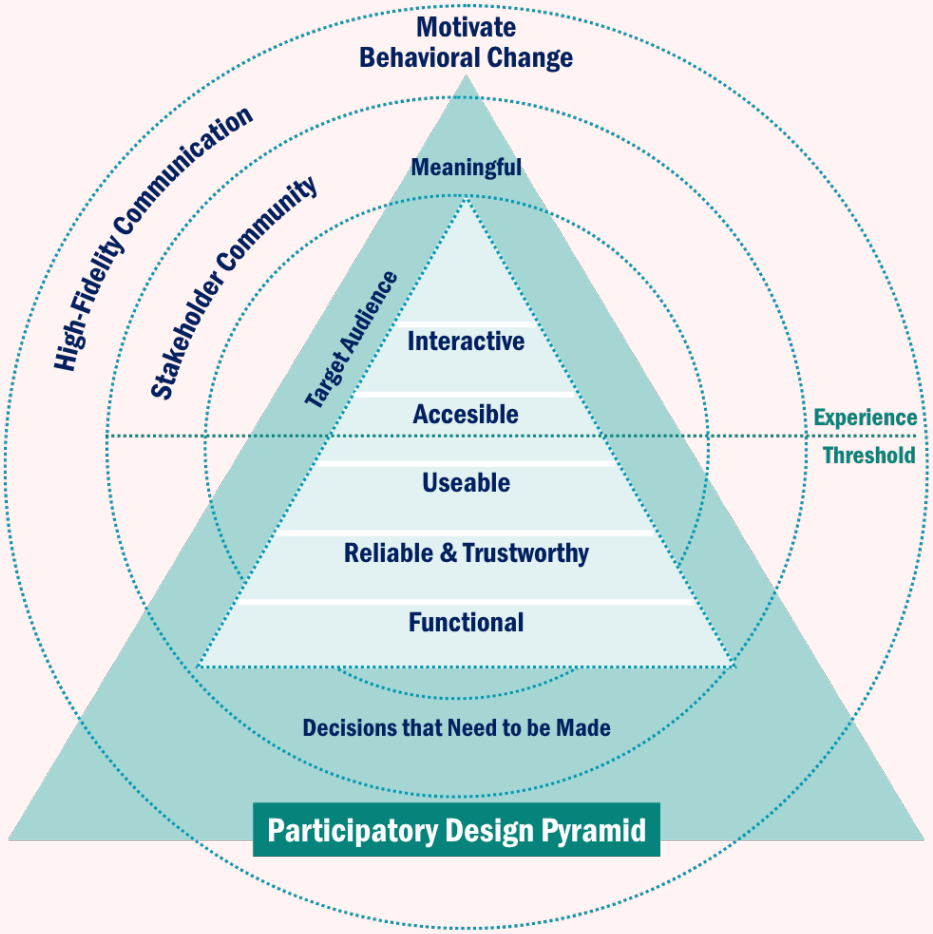

Figure 2-1. Participatory Design Pyramid (prepared by Study Providers Keri K. Stephens, Suzanne A. Pierce, Jovana Andelkovic, Samanta Varela, Ruoxiao Su, and Emaly Aguilar, 2024; and modified after Newbold, 2018).

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Applying the TIFF Communication Guidelines

STEP #1: DETERMINE OBJECTIVE OF THE FLOOD PRODUCT DESIGN

STEP #2: IDENTIFY AND ALIGN WITH TARGET USERS AND INTERESTED ENTITIES TO TAILOR INFORMATION

- Use "Behavioral Archetype" techniques to select target users
- Involve target users via interviews, focus groups, and user experiments
- Confirm target user needs and decision types
- Determine engagement tools, like visualizations, that best communicate the project objectives
- Confirm that selected visualization and communication approaches meet target user needs and project objectives
- Engage with related stakeholders periodically to exchange perspectives and confirm shared understandings

STEP #3: DESIGN PRACTICES THAT LEAD TO MEANINGFUL COMMUNICATION

- Design should address basic functionality, reliability of information, and usability capable of supporting task-oriented activities
- Use human-centered/experiential approaches (e.g., accessibility, interactivity with information) to achieve meaningful representations for target user groups

STEP #4: ACHIEVE HIGH-FIDELITY COMMUNICATION

These adaptive processes result in information and communication products that withstand design testing, can be updated regularly, and integrate the needs and concerns of communities. Information is based on reliable technical data that uses multiple mechanisms to share with the people who need the information most. These approaches can be used across settings and are easily adjusted to support other target user audiences or hazard events.

2.5 Implementation of Objectives

Objective 1: Establish a Data Management and Visualization TAT

To lead the development of a robust data management and visualization framework, the TIFF SC appointed Dr. Amin Kiaghadi, Manager of the Coastal Science Department at TWDB, as the Component 2 Champion. The TAT included experts in geospatial analysis, data architecture, environmental modeling, and user-centered design. Their collective mission was to ensure that data collected across atmospheric, hydrologic, coastal, and human behavior domains are properly curated, stored, and visualized in ways that support both technical and non-technical users. To ensure Component 2 reflected the unique cultural and socioeconomic composition of the LRGV, TIFF invited and confirmed the membership of five Technical Advisors with firsthand experience in developing effective communication strategies for sharing flood-related data and model outcomes. The participation of these regional subject-matter experts helped ensure that the flood-specific challenges and perspectives of the LRGV are reflected in the findings, guidelines, and recommendations of Component 2.

The following advisors were selected to serve as members of the Component 2 TAT based on their expertise in coastal flood data availability, technical data collection requirements, and the interpretation and application of modeling methodologies. Advisors marked with as asterisk are those LRGV-specific members.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

COMPONENT 2 TECHNICAL ADVISORS

- Alan Zunde, Aquaveo, LLC
- Albert Aldana, City of Weslaco
- Amin Kiaghadi, TWDB (TIFF SC Team Champion)
- Andrew Juan, TAMU-IDRT
- *Augusto Sanchez, Cameron County
- *Bill Kirkey, RATES
- Brian Barr, January Advisors
- Bridget Scanlon, UT-BEG
- *Carlos Sanchez, Cameron County
- Carola Kaiser, Louisiana State University-Coastal Emergency Risks Assessment-
- *Christopher Fuller, RATES
- Diane Howe, FEMA
- Federico Antolini, TAMU
- Gordon Wells, UT-Austin, Center for Space Research
- Ibrahim Demir, The University of Iowa
- Jason Fleming, Seahorse Coastal Consulting
- Jeff East, USGS
- Jeff Lindner, HCFCD
- Jeff Reichman, January Advisors
- Jeffrey Horshburgh, Utah State University-Utah Water Research Laboratory
- Justin Terry, HCFCD
- Kayode Atoba, TAMU-IDRT
- Kris Lander, NWS
- Kristine Blickenstaff, USGS
- Laura Stearns, TAMU-IDRT
- Lee von Gynz-Guethle, West Consultants
- Paul Craig, Dynamic Solutions International, LLC
- Russell Blessing, TAMU-IDRT
- Sam Brody, TAMU-College Station
- Steven Mikulencak, TAMU-AgriLife, CHARM
- Taylor Christian, TWDB
- *Velinda Reyes, Office of Hidalgo County Commissioner Ellie Torres

Objective 2: Assist TDIS with designing and testing the conceptual framework for managing, visualizing, and disseminating large volumes of coastal flood-related datasets, including data visualization system(s)

TIFF worked closely with the TATs to provide support to TDIS for data storage, access, and management, with an emphasis on interoperability and long-term sustainability (described in detail in Component 1: Objective 2). This included establishing metadata standards, visualization techniques, data management, and archiving strategies that align with best practices in flood-related data management. TIFF also supported the formation of conceptual frameworks that translate complex flood risk data into actionable insights for planners, decision-makers, and community stakeholders. TIFF met with TDIS leadership and technical teams several times, on a quarterly basis, to offer data collection and flood modeling domain expertise and share updates and collaboration opportunities.

In support of Component 3, TIFF examined the literature (see Component 3: Objectives 3 and 4) and worked closely with the TATs (**Appendix C-10**) and TDIS to assess the essential components and strategic considerations for designing a conceptual framework for managing, visualizing, and disseminating large volumes of coastal flood-related datasets, including data visualization systems. This section provides an overview of the considerations of such a framework, a collaborative software platform for the advancement of coastal flood modeling in Texas known as the Texas Coastal Flood Framework (TxCFF) (**Appendix C-11**). (See Component 3: The Case for a Texas Coastal Flood Framework for a detailed discussion recommending the development such a framework.)

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DATA MANAGEMENT

Data management for Texas coastal compound flood hazard assessment poses a number of challenges associated with storing and archiving model data, accessing external data, and providing data services to users. Both flood inundation modeling (quantifying the combined impact of two or more physical flood forcing processes on the short-term inundation of coastal zones) and flood hazard analysis (the statistical or probabilistic approach to assess the magnitude and likelihood of flood events) include aspects of all three challenges. The key point is that data management is a non-trivial aspect of Texas coastal compound flood hazard assessment and requires careful planning and balancing of costs versus utility of stored data.

For flood inundation modeling, the sheer volume of input data (such as high-resolution topography, land cover, infrastructure, and climate projections) requires significant storage capacity, organization, and metadata documentation. Each model simulation generates large amounts of outputs, including time-varying inundation maps which are often large in file size, and further contributes to storage demands. Attempting to save the data computed at every time step in every flood inundation simulation will quickly overwhelm any available storage capacity. A key aspect of data management will be to determine the short-term and long-term storage needs and provide clear guidance for implementation (e.g., short-term storage during a flood inundation simulation may include higher temporal and spatial resolution than can be practically used for flood hazard analysis or archived in the storage system).

An example of the data storage problem is provided by the U.S. Army Corps of Engineers Coastal Hazards System-Texas (CHS-TX) simulations discussed under Objective 5 (CHS-TX Study: An Example). Data from a typical simulation were approximately 200 gigabytes in size, prior to compression. The data was compressed to save disk space and then archived on a long-term storage system. The total compressed data stored for a single sea level condition for all 660 synthetic tropical cyclones is approximately 80 terabytes. Access to this archived data is restricted to those with accounts on the USACE-ERDC High Performance Computing (HPC) systems which make dissemination and sharing of the full domain data difficult. The compressed state of the data also makes it difficult to quickly use the data, since it first must be brought out of the archive storage, then uncompressed.

It is important to develop workflows and best practices for archiving simulation data with structured organization including naming conventions, sufficient metadata, and other documentation. This effort needs to be closely coordinated among potential users, so that needed data is not discarded nor is unneeded data saved. An example of a collaborative infrastructure for data storage is the DesignSafe (https://www.designsafe-ci.org) portal, which specializes in data management for natural hazards.

Cost-effective long-term storage solutions should be explored to ensure data accessibility for future analysis and validation. Solutions such as Amazon Webservice, Microsoft Azure, or Google Cloud offer flexibility, but cost analyses must include data transfer fees, processing expenses, and long-term data retention strategies. A hybrid approach may be preferred—using on-site HPC clusters (within Texas agencies or universities) for short-term storage associated with model runs and analysis with cloud storage for long-term archival purposes. The storage infrastructure needs must be balanced against project budgets, requiring continuous assessment as storage demands grow with increasing archives. Finally, the infrastructure provided by TACC should be considered before spending major resources on commercial cloud providers.

DATA DISSEMINATION

TIFF is proposing a software framework to address the complexities of Texas compound flooding that encapsulates models and their coupling with analysis tools and workflows. (See Component 3: The Case for a Texas Coastal Flood Framework for a more detailed discussion, along with **Appendix C-11**.)

Data dissemination and data products provided by the proposed framework require substantial planning and resources. The input files and results generated by various models involved in compound flood simulations are too large for a typical user and would require huge bandwidths for routine data transfer.

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Indeed, Google's Earth Engine (https://earthengine.google.com) uses Google servers rather than downloading data to your local machine (costs of in-place data manipulation are much less than the bandwidth costs of data transfer). Thus, in building a software modeling framework, careful consideration must be given to the data products that need to be routinely available to users, as well as to the access workflows for more sophisticated and complete archival data sets. In particular, because flood-hazard modeling requires a large number of flood inundation simulations, there must be a consensus on the time and space resolution that should be archived for each simulation.

Accessing External Data

The sources and formats for external data are varied, so a range of data conversion algorithms must be implemented. As such, a major challenge in any compound flood modeling project is extracting the data from various sources and reformatting it for use within the modeling system. The type and quantity of data required will depend on the models implemented in the framework. Four potential data types are described below: 1) landscape, 2) meteorological, 3) far-field process, and 4) validation/calibration:

1. **Landscape and Infrastructure Data**: Detailed topography, land cover, and built infrastructure data are crucial to the accuracy of a compound flood inundation model. Presently, preparing the necessary data for flood modeling requires extensive engineering/technician time and is done on a case-by-case basis for flood models. There is a need for a systematic approach that ensures that any flood inundation model captures both natural and human-made features that are critical to flood behavior and risk mitigation. Existing federal programs (such as the 3D Elevation Program) and state programs (such as TxGIO) can provide highly accurate light detection and ranging (LiDAR) data for land surface elevations. Other databases (e.g., the National Levee Database, in-development by Coastal and Hydraulics Lab (CHL) Coastal Levee Research initiative) provide information on flood protection infrastructure. Additionally, partnerships with USGS and NOAA for inland hydrology data and NOAA for coastal storm surge data are essential to compiling unified datasets that support compound flood hazard analysis. Unfortunately, the tasks of 1) accessing such data, 2) preparing it for flood modeling, and 3) integrating it with other data sets require specialized expertise and are time-consuming efforts. To further complicate the task of providing landscape geometry, we need to be able to easily introduce "what if" conditions (e.g., What if a specific flood mitigation project is introduced? What if present land use trends continue for the next decade?). Creating such "what if" datasets is challenging and there is little guidance from science on how to build such datasets for compound flood modeling or how to evaluate the uncertainty introduced in the predictions. Thus, there is a data management need to provide systematic and proven workflows to access and translate landscape and infrastructure data.

2. **Meteorological and Climate Data**: Flood inundation models are driven by meteorological data (e.g., wind, rain). Although insight can be gained by modeling a single storm, such as Hurricane Harvey, we need to model a wide range of possible/probable storms to provide foundations for improving future flood protection. Thus, there is a need for model forcing data that covers a range of historical storms and future storms. Traditionally, flood modeling for urban engineering design has been done using spatially uniform rainfall for a storm with a simple constant rainfall rate over a time interval based on a "return period" that reflects the probability of the storm occurring (e.g., the 100-year storm has a 1% chance of occurring in any given year). Such an approach is simply untenable for the hurricanes and tropical storms that drive compound flooding along the Texas coast, as the spatial/temporal patterns of both rain and wind are crucial to the flooding behavior. Datasets for historic storms to drive compound flood models need to include the spatial/temporal patterns of both rainfall and wind, which can be obtained from either direct observations or models. These are typically large datasets that require expertise to extract and prepare for modeling.

   Creating "what if" rainfall and wind fields for possible storms is even more challenging. Presently, there is exciting research going on in creation of "synthetic storms" that are derived by simulation

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models that use the statistical behavior of real storms to generate artificial storm data with similar characteristics. Using such tools, wind/rain data sets can be created to consider "what if" conditions for a range of storms applied at a variety of locations along the coast. Such models may also provide a means of examining how storms might behave under climate change, but such work has yet to be proven.

The main reason for modeling a wide variety of storms is to be able to use the flood inundation model results to build a dataset that can be used for probabilistic flood modeling and uncertainty quantification. The overarching goal of flood hazard analysis is to quantify the probability of specific flood impacts (e.g., the probability that a particular area will flood given the likelihood of a range of storms). Thus, simulations using the flood inundation model need to be driven by the full range of likely storms. This creates a data management issue as the needed meteorological data may come from a wide range of external sources (real world observations, synthetic storms) and need to be translated into data storage schema that are useful to a comprehensive compound modeling system.

The state-of-the-art in developing synthetic tropical cyclones for probabilistic hazard analysis has typically been referred to as Joint Probability Modeling – Optimal Sampling (JPM-OS). These methods have become a standard probabilistic approach for quantifying coastal storm hazards due to tropical cyclones (Nadal-Caraballo et al., 2020). The events, or storms, are developed from combinations of parameters based on historical distributions of meteorological and climate variables recorded during past tropical cyclones. The event parameter sets are used in high fidelity atmospheric and then numerical hydrodynamic and wave models to develop flood water levels. To determine their frequencies curves, they are then integrated with the frequencies and joint probabilities of the inputs to produce the hazard. For instance, ERDC-CHL currently uses a Probabilistic Coastal Hazard Analysis Framework (CHS-PCHA) where a JPM-OS type method is used to quantify coastal hazards. Tropical cyclone atmospheric parameters (e.g., winds, pressure) are determined from Hurricane Database 2 (HURDAT2) climatology, and used to drive numerical atmospheric, hydrodynamic, and wave models to produce surge systems responses which have been traditionally integrated to produce hazard curves. CHS hazard probabilities for surge are hosted publicly on the CHS website (https://chs.erdc.dren.mil/) for regional studies along the Atlantic, the Gulf (including an older Texas study) and the Great Lakes. (More recent detailed study data can be requested there or through USACE.)

Another approach for developing storms from meteorological and climatic data is sampling of Global Climate Model (GCM) storms or ensemble reanalysis datasets. Other examples of probabilistic approaches using synthetic events are described in Dawson et al. (2024a). In compound hazards, the CHS-Compound Framework (CHS-CF) is in development at ERDC-CHL as an extension of the coastal CHS-PCHA with JPM-AMP (Joint Probability Model – Augmented by Metamodel Prediction), and other extended JPM-OS examples are briefly described in Dawson et al (2024b).

3. **Data for Far-Field Processes**: The term "far-field processes" refers to those processes outside of a model that should be considered in developing the model input and boundary conditions. Some key examples are 1) the time/space varying circulation that drives the Gulf outside of the bounds of a coastal ocean circulation model, 2) the soil moisture across the Texas Coastal Plain at the start of a flood simulation, and 3) underground aquifer levels and their interaction with the surface. Data approaches for handling far-field processes are typically customized for any model and are often poorly documented. Building a comprehensive approach to compound flood modeling requires developing and documenting the approaches to handle far-field processes. Creating systematic workflows for introducing far-field processes into the flood inundation modeling system is a critical data management task for building a software framework to address the complexities of compound flood.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

4. **Validation and Calibration Data**: Ideally, model calibration should use (as much as possible) established coefficients and values from literature. Historical observations of flood inundation should be used for validation of flooding modeled from historical storms. A range of data is available from NOAA, USACE, USGS, NDBC, TWDB, and other data sources, but needs to be collated and made available for modeling. Calibration and validation are critical to the validity of modeling yet are often under-reported in the literature. For a software modeling framework to provide foundational information from large infrastructure projects and flood resilience policies, it is critical that the methods for calibration and validation are documented within the framework and workflows are developed to follow accepted practice. Maintaining consistent archives of the data used for calibration/validation and the model comparisons to data in both stages is critical for model transparency and reporting prediction uncertainty. These same datasets and procedures for validation allow for efficient testing during software developments and hardware upgrades as well as intercomparisons of different numerical models or algorithms.

Objective 3: Conduct an inventory of coastal flood-related user interfaces

TIFF convened the TAT members and performed a comprehensive review of the efforts conducted by major agencies responsible for flood data and communication to assemble a coastal flood UI inventory and identify opportunities to improve coastal flood-related visualization tools.

Proper visualization of processed coastal flood-related data and model outputs is critical for enabling technical and non-technical target users to make well-informed decisions. UIs designed for coastal flood risk communication play a crucial role in bridging the gap between complex scientific data and actionable insights. These interfaces must present information engagingly and understandably to facilitate informed decision-making. Furthermore, these can be used to foster collaboration among stakeholders. Ideally, UIs must include features that allow for the sharing of data and insights, enabling communication between government agencies, emergency responders, and coastal communities.

INVENTORY OF COASTAL USER INTERFACES

To design UIs that support decision-making and reduce confusion, it is important to follow both general specifications as well as those tailored to specific target groups. An example of a general specification is Miller's (1956) "seven, plus or minus two" (7±2) visual information capacity limits, which posits that a fundamental aspect of human cognition is that we can only process information in small chunks between five to nine bits. This property of the human brain greatly affects the design aspects of websites, computer programs, and graphic design. Once a collection of items exceeds nine on a website, the design appears 'cluttered' to the user. Therefore, for various target user groups, more specific criteria should be defined (e.g., velocity, water surface elevation, risks). The level of access to data and modeling outcomes (including temporal and spatial resolutions) for each target user group, analysis capability (running scenarios, generating reports), and visualization methods (2D mapping, 3D capability, animations) should be considered.

In addition to the required criteria for coastal flood UI, the TAT members identified some gaps in understanding the visualization methods for 1) demonstrating uncertainty in the models in a way that is understandable for both technical and non-technical end-users, and 2) compound flooding risk that accounts for all components (e.g., storm surge, rainfall, relative sea level rise, king tides) (**Appendices B-3** and **B-4**).

As a first step to filling the identified gaps, TIFF conducted an inventory of flood-related UIs to help create a uniform metadata list of comparable attributes among UI sites. The matrix contains 20 attributes, as shown in Table 2-1 below. The attributes include basic information such as name, interface links, partner

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agencies, mission and vision statements (if any), as well as other properties and characteristics of interfaces, such as spatial and temporal resolution, and the existence of real-time data and the API.

TIFF began the inventory by preparing a list of 44 interfaces with a variety of visualization functionality. Only 34 were related to the inventory and still functional at the time of this report on the TexasFlood.org website (**Appendix B-5**). For the ease of illustration, the original inventory table was paired down into a total of three tables (**Appendix B-6**).

- The inventory revealed the following points and was used as a foundation for the Component 2 tasks:
- The majority of the investigated coastal UIs are only offered in English
- Only two of the UIs let the users upload shapefiles
- None of the UIs let the users conduct new analyses
- There are many overlaps among UIs with regard to the data type, source, and the visualization method they use to present the data
- Many UIs do not have/provide metadata
- Most UIs do not have/provide a coverage map (preferably as a downloadable shapefile)
- An API is only provided in some of the UIs
- Visualization methods are limited to basic functions such as zoom in/out, turn on/off layers, print/share map, pop-up attribute table, legend, charts, base map options, address search, and transparency. There are a few UIs with more advanced methods, such as sliding maps.
- Downloading the data is not offered by many of the UIs

Satellite imagery shows widespread flooding across Texas following Hurricane Harvey's record rainfall © DigitalGlobe

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Table 2-1. Generated inventory matrix for conducting an inventory analysis on the existing coastal UIs.

No.	Criteria	Description
1	Platform Name	The actual name of the platform or website
2	URL	URL address
3	Partner Agencies	Who is/are hosting the interface and actively providing the information to the site? Is it a collaborative effort? If yes, name all partners.
4	Mission	Is there a mission statement for the interface? If yes, what is it?
5	Vision	Is there a vision statement for the interface? If yes, what is it?
6	Available Data	What type of data is available to view/download?
7	Data Sources	ALL sources of data need to be listed. This should be specific (e.g., from a USGS stream gage) 'Various' if there are a lot of sources (4 or more)
8	Data Type	Modeled, measured, reports, or other types of data
9	Real-Time Data?	[Yes/No] If yes, in what intervals (i.e., every 15 minutes, every 2 days)?
10	Data Download Option	Can the user download data from the site? [Yes/No]
11	Spatial Coverage	What areas are covered by the map? (i.e., what counties?, the whole state?, other state(s)?)
12	Spatial Resolution	The lowest resolution the map can go to for information (e.g., county, zip code, property boundary) Needs a value a dimension (e.g., 100m resolution) If points such as gages or stations are used, use 'sparce points'
13	Temporal Coverage	A range of time that the data is available (May be 'varied' if the data is from different sources with no specific time coverage range, may be real time but need specifics on time (e.g., hourly to 2 weeks or steady state))
14	Available Visualization	May include all of the things in the map that one could see and things one could do (e.g., turn on/off layers; transparency/overlay; adding symbols/drawings; base map options; zoom in/out of map; measurements (area/latitude and longitude/distance); tabulate attribute table; swiping function)
15	Flood Scenario Visualization	How is flooding shown in the legend? (e.g., is it 100-year flood, 500-year flood?, is it broken down into flood depth or duration?)
16	User Freedom	Can the user upload data? [Yes/No] Can the user preform independent analysis? [Yes/No]
17	Metadata	Is there metadata? Can the user access it? [Yes/No]
18	Metadata Link	A link, if available to the metadata page/info
19	Coverage Map?	Is there a summary map to show where data is/is not available for whatever data that the interface has? (e.g., an index map to show areas in state where data sets are representing)
20	Ease of Use	How easy is it to get around and find information? [Very Easy/Moderately Easy/Not Easy/Difficult]

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Objective 4: Recommend guidelines for coastal flood UIs, including the level of end-user access, analysis capability, visualizations, and datasets

(Note: Content presented to address this Objective also meets the Objectives associated with TIFF Component 4's Objective 5: "Support the development of flood communications and educational materials". Generally, while identifying effective strategies for communicating flood risk to target users, the TATs and Study Providers found that the objectives of Component 2 (Data Management and Visualization) and Component 4 (Planning and Outreach) overlap, as data visualization is an impactful way to communicate flood risk to target users, and understanding the target users are essential to improving data visualizations, respectively. As a result, the flood communication Recommendations for Components 2 and 4 complement one other.)

To meet Objective 4, TIFF 1) assembled an inventory of existing coastal flood-related UIs as described under the previous Objective, 2) conducted targeted literature reviews to identify best practices, 3) surveyed attendees at a TFMA conference, 4) hosted a Stakeholder Needs Workshop to analyze target user groups and their decision-making needs, 5) defined target user groups (*Property Owners, Property Renters, and People with LEP*), 6) developed *The TIFF Communication Guidelines* and *The TIFF Visualization Guidelines*, 7) tested the recommended guidelines with key stakeholders, and 8) established evaluation metrics designed to assess the effectiveness of coastal flood communication and visualization tools and strategies.

GATHER INFORMATION TO INFORM GUIDELINE DEVELOPMENT

Literature Review of Coastal User Interfaces, User Experience, Visualization, Communication, and Education

To identify best practices, a literature review was conducted on 1) differences between technical and non-technical audiences, 2) rural and urban populations, 3) how uncertainty impacts interpretations of flood risk, 4) audiences at particular risk from floods, 5) stakeholders who support audiences at particular risks, 6) new and innovative visualization approaches to communicate flood risk, and 7) user experience and UI best practices.

In support of the development of flood communication and education materials (TIFF Component 4's Objective 5), TIFF also conducted literature reviews to 1) identify potential target user groups for compound flooding, and 2) determine how to best communicate flood information to those target user groups.

An overview of the findings from the literature reviews can be found in **Appendices B-7**, **B-8**, and **B-9**, and includes the following topics:

- assessing model efficacy in decision-making processes
- non-technical audience needs for flood risk visualizations
- rural/urban populations
- communicating uncertainty for technical and non-technical audiences
- tailoring communication to non-technical target users
- disseminating information to non-technical audiences
- communicating probabilistic information, evidence from hazards other than floods
- the power of visualization: ways to present house-buying decision-making
- visualization, UX, and UI
- identification of target users and needs (including prior relevant research in Texas and lessons learned from other states and countries)

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Literature Review Approach

TIFF used a "Diagnostic Scoping Review" that combined accepted systematic approaches to a literature review together with an iterative Human-Centered Artificial Intelligence (HAI) technique (**Appendix B-10**). HAI approaches are an emerging set of methodologies, tools, and techniques that allow researchers to uncover links across disparate information resources. HAI research relies on strategies that combine "humans-in-the-loop" with machine learning or machine-enabled learning strategies. The human-in-the-loop approach means that people are verifying every finding from the artificial intelligence (AI) system. Combining these approaches provides a more complete evaluation of existing published knowledge on topics related to coastal UIs, visualization, flood communication, and educational materials. This process created a repeatable workflow, as shown in Figure 2-2.

Implementing a semantic search strategy was the first step in developing the diagnostic review. This process identified sets of search terms and identified literature found in academic literature databases that matched these terms. The central aim was to discover relevant publications and collections of information, and to assess the following questions:

1. What are the best ways to disseminate the results of hydrologic, hydraulic, and hydrodynamic model outputs to target audiences?
2. What are the best ways to communicate uncertainties associated with modeled outputs to non-technical users?

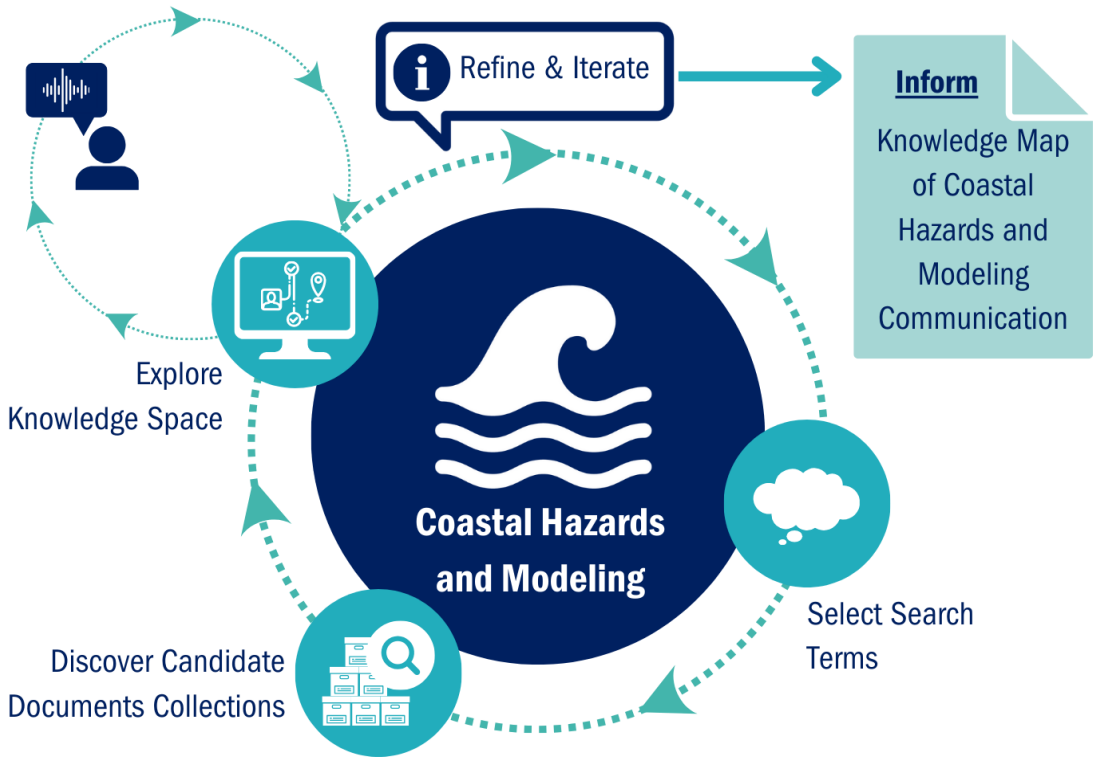

Figure 2-2. Conceptual diagram of a human-in-the-loop process supporting the use of AI applications to accelerate exploration and discovery tasks for systematic and diagnostic literature searches (Pierce, SA 2024).

The remaining steps to identify appropriate literature progressed from discovery tasks to exploratory tasks using the AI-enabled workflow. A total of ten seed articles providing foundational knowledge were closely examined and analyzed using a forward and backward citation process to identify other relevant research. (See **Appendix B-10** for detailed information on the literature review process.)

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The final collection of peer-reviewed research papers focused on communication between scientists and practitioners (Faulkner et al., 2007). There was general agreement that the emphasis should be placed on including stakeholders or "target users" (rather than "end-users") in a co-design process from the beginning of any model product design process. Additionally, the literature suggested that scientific uncertainty can be a serious barrier to progress in communication, and the best practice is to involve stakeholders and include uncertain aspects of information in a transparent and proactive manner.

Key Lessons Learned from Literature Review

Disseminating Information to Non-technical Audiences

- Multiple formats should be used to reach different audiences
- When speaking to an audience with low numeracy, reduce the need to make inferences from numeric data; numbers must be self-explanatory and explain uncertainty; denominators and time periods should be consistent (Peters, 2020; Spiegelhalter et al., 2011, 2017)
- The most important information should be presented first, highlighting the main messages (Peters, 2020)
- Visual communication benefits from using templates, consistency, single hues, **Arial** and **Helvetica** fonts, and little decoration
- For accessibility, a color vision deficiency simulator must be used
- Italics, rainbow-colored maps, red-green or orange-green colored maps must be avoided, and colors that conflict with those commonly used to depict risks or hazards should be avoided; online tools are available to guide colors selection and whether they are color-blind safe (e.g., ColorBrewer 2.0 (Brewer & Harrower, 2013), Adobe Color Wheel (Adobe Express, n.d.)); visuals should focus on communicating when the flood will occur, its impacts, and the actions to be taken (Heggli et al., 2023)
- Avoid overcrowding visuals
- Interactivity and animations may introduce unnecessary complexity
- Acknowledge the limitations of information quality and relevance, and avoid chart junk, such as three-dimensional bar charts (Spiegelhalter et al., 2011, 2017)

Non-technical Audience Needs for Flood Risk Visualizations

- Information must be clear, simple, and specific to geographic areas to improve decision-making
- Framing flood risk in terms of economic loss can lead to more reasoned decisions
- Employ dialogic communication approaches to involve the public in decision-making and build trust
- Involve the audience early on through participatory processes to minimize the risk of producing misleading visualizations to ensure relevance and effectiveness
- Experts should use consistent language and terminology to communicate uncertainty effectively

Rural/Urban Populations

- Urban areas experience more injuries and fatalities per event because of factors in the built environment, while rural areas suffer due to slower emergency response
- Low-income and smaller communities often lack resources for recovery and may not qualify for federal disaster assistance

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Flood Communication Technologies

- Combining visual tools such as virtual reality, 3D animation, videos, and images effectively communicates flood risk by depicting hazards more realistically than 2D maps
- Virtual reality experiences enhance flood risk awareness and preparedness
- Tools that integrate scientific scenarios with local landscapes help residents identify risks and understand complex issues
- Combining maps with 3D animations and textual information helps audiences understand flood threats and guide protective actions
- Using images or videos to show past and future scenarios can educate the public and increase awareness
- Including familiar local elements in visualizations makes them more relatable and effective
- Maintaining an understanding of technologies as they become accessible and usable on common platforms, such as standard mobile devices, is important to ensure quick uptake and appropriate use

User Experience Principles for Flood Interface Design

- UX design should balance usability and emotional responses to create engaging and effective interfaces
- Integrating machine learning into UX design can create more personalized and adaptive user experiences
- Incorporating feedback mechanisms in design helps refine it and improve user satisfaction
- Apply Gestalt principles such as emergence, closure, and proximity to organize content and enhance visual understanding
- Using hierarchy, alignment, and color effectively can improve usability and engagement
- Categorizing information using navigator tabs can display relevant results for different user needs
- Features like zoomable/pannable functions enhance map navigation and information retention

The Interface Design Process

Designing an interface is an iterative process that starts with research on user profiles, prototype building, and testing with users (Martins et al., 2022). Because the process can become disorganized, designers need to focus their efforts and start with a solid understanding of their task, purpose, and the end result. Designers should ask themselves the following questions before starting the process:

- How is the dashboard going to add value to my organization?
- What are the fundamental objectives that will guide my design decisions?
- What type of dashboard am I creating?
- Who is the audience and what are their needs?
- What is the central thought-line of my dashboard story?
- What are the key metrics that will focus users on actionable information?
- In what format is the dashboard delivered?
- How is the dashboard laid out to help users understand the big picture?
- What capabilities will the dashboard include to help users understand and interact with the information? (Juice Analytics, 2015)
- Can the dashboard become accessible well ahead of an imminent event?

Understanding how the dashboard will add value to an organization will align the design process with its strategic goals. Knowing the type of dashboard that will be created allows for tailoring the design to

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meet specific needs, ensuring the information presented is relevant and actionable. Moreover, focusing on key metrics that highlight actionable information helps users quickly identify important trends and insights, leading to more informed decisions. The format and layout of the dashboard are also critical, as those affect how easily users can navigate and comprehend the data. Finally, incorporating capabilities that enhance user interaction with the information, such as filters and drill-down options, makes any dashboard dynamic and user-friendly.

Communicating Flood Risk with High Fidelity

The best practices identified from Peters et al. (2022) are included as part of *The TIFF Communication Guidelines* to address knowledge gaps and propose innovative approaches to leverage technology and information from data collections and coastal modeling for more effective communication of complex flood risk information. These practices outline specific insights that can be seamlessly integrated into the design process, from engaging with community members to implementing functional design practices for user interfaces. They also emphasize the need to deliver information products that are culturally and contextually adapted to the target user group.

(All research conducted, including feedback on communicating and visualizing uncertainty and the specific criteria and UX requirements, was incorporated into the recommended *TIFF Communication Guidelines* (See Approach to Objectives: TIFF Guidelines for Coastal Flood Information Design and Communication for more details, and Recommendation C2.4A.))

Texas City Dike extending into Galveston Bay © Trong Nguyen

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Survey on How Flood Risk is Communicated and Visualized to Stakeholders

TIFF gathered 15 responses from a floodplain manager's survey (**Appendix B-2**) and had informal conversations with 20 attendees at the TFMA Conference in March 2024. The survey explored how flood risk is communicated and visualized to stakeholders. Respondents indicated that stakeholders most frequently ask questions about flood risk assessment, regulatory requirements, and the impact of flooding on properties. Many queries aim to determine if a property is within a floodplain or Special Flood Hazard Area and assess the associated risk. Homeowners and clients often ask about the necessity of flood insurance and property elevation requirements. Additionally, many people find the distinction between ground or base flood elevation and flood frequency confusing.

The TFMA survey also asked about flood visualizations. Respondents believe that 3D models and detailed maps showing rainfall or water flow direction are most effective for explaining flood risk to primary stakeholders compared to simpler flood maps. Respondents also find web applications with uncertainty ranges and color-coded flood depth helpful. Hence, web-based tools, 3D mapping, serious games, and other innovations are appealing delivery methods and can engage people to create two-way and participatory exchanges. These tools are more precise when they communicate uncertainty and are tailored to *People with LEP*, an important audience in Texas.

Responses to the survey most frequently cited FEMA-related platforms, such as the FEMA Flood Maps, FEMA Firm Maps, and FEMA National Flood Hazard Layer Viewer, as the most useful websites, highlighting the importance of official and detailed flood mapping services. Please note that sources not captured in the survey could contribute to biased responses.

Stakeholder Needs Workshop

TIFF hosted a Stakeholder Needs Workshop with 98 participants on June 28, 2024 (**Appendix B-11**). The workshop aimed to differentiate between user personas, user profiles, and behavioral archetypes; understand approaches agencies use to identify flood information target users, and their reasoning; and consider ways to inform communication strategies for selected target user groups.

Creating useful and reliable guidelines, standards, recommendations, and related products to improve the resiliency response of Texans impacted by coastal flooding requires understanding the various flood planning and mitigation needs of target users. It helps ensure researchers and practitioners are asking the right questions when it comes to understanding who the target users of these visualization tools (and data) are, and what those target users ultimately need to make well-informed decisions. However, understanding target users' needs is challenging because related research terms are used interchangeably and frameworks to guide the engagement of target users are sparse.

The workshop gathered insights from TAT members and a mix of agency practitioners experienced in working with different types of potential users of flood information. Its objectives included identifying implementation and evaluation metric needs for target users, highlighting information gaps, and developing strategies to address these challenges. Additionally, the workshop aimed to foster collaboration among practitioners and researchers involved in flood risk planning decisions. (See **Appendix B-11** for workshop materials and additional details.)

The discussion sharpened the focus around ways to identify and prioritize flood-related data and information for target users. Specifically, behavioral archetypes (i.e., identifying ways to cluster groups of users according to their behaviors and the decision they need to make) appeared most relevant for the current effort. User personas are commonly used in marketing and user experience research. They have also been used in flood-related efforts, such as those conducted by CHARM and from the research conducted in Virginia Tech. Personas are a realistic, but fictional representation of a member of each audience segmented group (Kaplan, 2022). The process of crafting a persona likely helps the product designers better think

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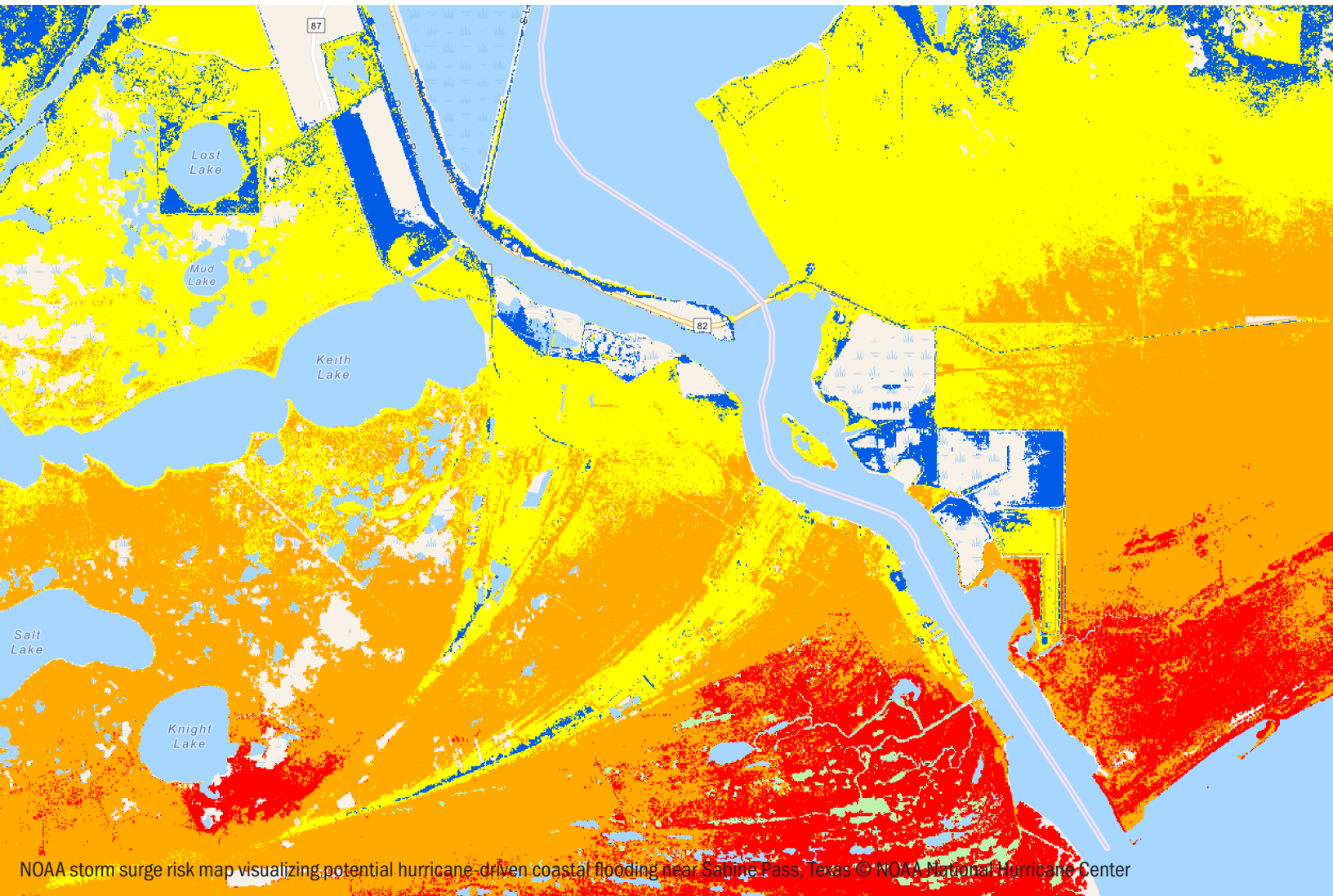
through what members of that group need and the nuances to consider. Given that the persona's main criticisms are that it cannot be "adequately verified or falsified" or proven to be entirely relevant towards its target users (Chapman & Milham, 2006), this tool should ideally be used in conjunction with other methods that involve actual interactions with the people representing the persona (e.g., focus groups, interviews, and other tests) (Nielsen, 2019).

The workshop helped confirm an understanding that "end-user groups" is not an accurate term to use because the users of any flood-related product need to be involved in the development process from the beginning. This reinforced what was found through the literature reviews. Therefore, the term "target user" was adopted. The workshop also refined the focus on three prioritized target groups: *Property Owners*, *Property Renters*, and *People with LEP* instead of the initially proposed four target groups which included meteorologists. The conversation underscored that, while highly technical groups like meteorologists are important, they should not be considered as one of the top three priority groups, with the focus instead shifting to those more vulnerable to flood risk and likely to derive the most significant benefits. The discussion also helped crystallize the importance of including caregiving organizations (broadly defined as organizations responsible for others) in future research, but they needed to be segmented further because these organizations have different types of decisions to make. For that reason, they were not included in the three prioritized groups.

Another key outcome identified that messaging should be framed in a way that is meaningful to the individuals in the target user group. The discussion highlighted different approaches to communicating flood information, including the challenges associated with communicating technical information and uncertainty.



NOAA storm surge risk map visualizing potential hurricane-driven coastal flooding near Sabine Pass, Texas © NOAA National Hurricane Center

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Identifying Target User Groups and Decision-Making Needs

Professionals in the fields of marketing, user-centered design, and user experience have long known that "the public" is not a single entity with definable characteristics. When the goal is to change behavior, information must be personally relevant or people will not pay attention (Lustria et al., 2013). Therefore, identifying specific needs that a group of people have and designing a flood message or a product to meet those specific needs is crucial.

Audience segmentation divides the public into smaller segments that have similar characteristics, needs, or values. It is based on the premise that segments of the population with similar needs will respond in similar ways to a given message. In health communication research, which shares many similarities with coastal flood risk research, this approach is known as targeting, and it is often based on factors such as demographics. Many organizations, including the federal government, recommend a human-centered design approach because it puts people at the center of services that need to reach the general public.

Target users are subsets of stakeholders or user groups that need to be involved in defining requirements during the design process. Using a behavioral archetype approach helps to group audiences according to the types of decisions they need to make. Resulting information visualization or communication products that align with audience needs and decisions will form the narrative crucial for creating a coherent and actionable tool.

→ USER GROUP

A group of people with shared interests that use a particular product or service

→ STAKEHOLDER

A person or group that events, actions, and decisions may impact. Conversely, they may make choices or take actions impacting organizations, other groups, or individuals

→ AUDIENCE

Groups of people who receive messages

→ TARGET USER

A subgroup of people most likely to be interested in and benefit from a product or service; they are a specific segment of the overall population that shares common characteristics, such as demographics, interests, or needs

Figure 2-3. Defining groups involved in the design of flood communication products. These concepts vary according to agency; some people are recipients of information, while others have the capacity to impact decisions. Readers should consider these nuances in meaning.

Using the results of the previously described literature review and Stakeholder Workshop, TIFF chose the behavioral archetype approach, grouped potential target users based on the decisions they might make, and worked to better understand those decisions, as well as the relationships between the different groups. Additional criteria were also used to evaluate which target user group(s) to prioritize:

1. To what extent will having access to appropriate and meaningful flood-related data positively impact the specific group?
2. How homogeneous is the group?
3. How easily can the group be reached with flood risk information?
4. How distinct is the specific group from others?
5. Is there data to measure the size of this particular group?

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

STAKEHOLDER DECISION MAP OF POTENTIAL TARGET USER GROUPS

Informed by research from other states and countries (**Appendix B-9**), the Stakeholder Decision Map clusters important groups in Texas to provide a big-picture understanding of the relationships between target user groups (public and other), decisions they could make, technical level of target user groups, and communication between the groups (Figure 2-4). This figure identifies different stakeholder groups, their technical user levels, communication paths between each other, and the types of decisions they need to make regarding coastal flooding.

For instance, state agencies, federal agencies, elected officials, and local meteorologists all make similar decisions around informing and educating the public. Agencies and elected officials also make decisions around flood control efforts and funding those efforts. However, most of these groups are non-technical. Considerable work is needed to translate technical flood model data and output into meaningful information for these audiences. Understanding the complex relationships among different user groups and between stakeholders is critical for effective flood management and communication in Texas

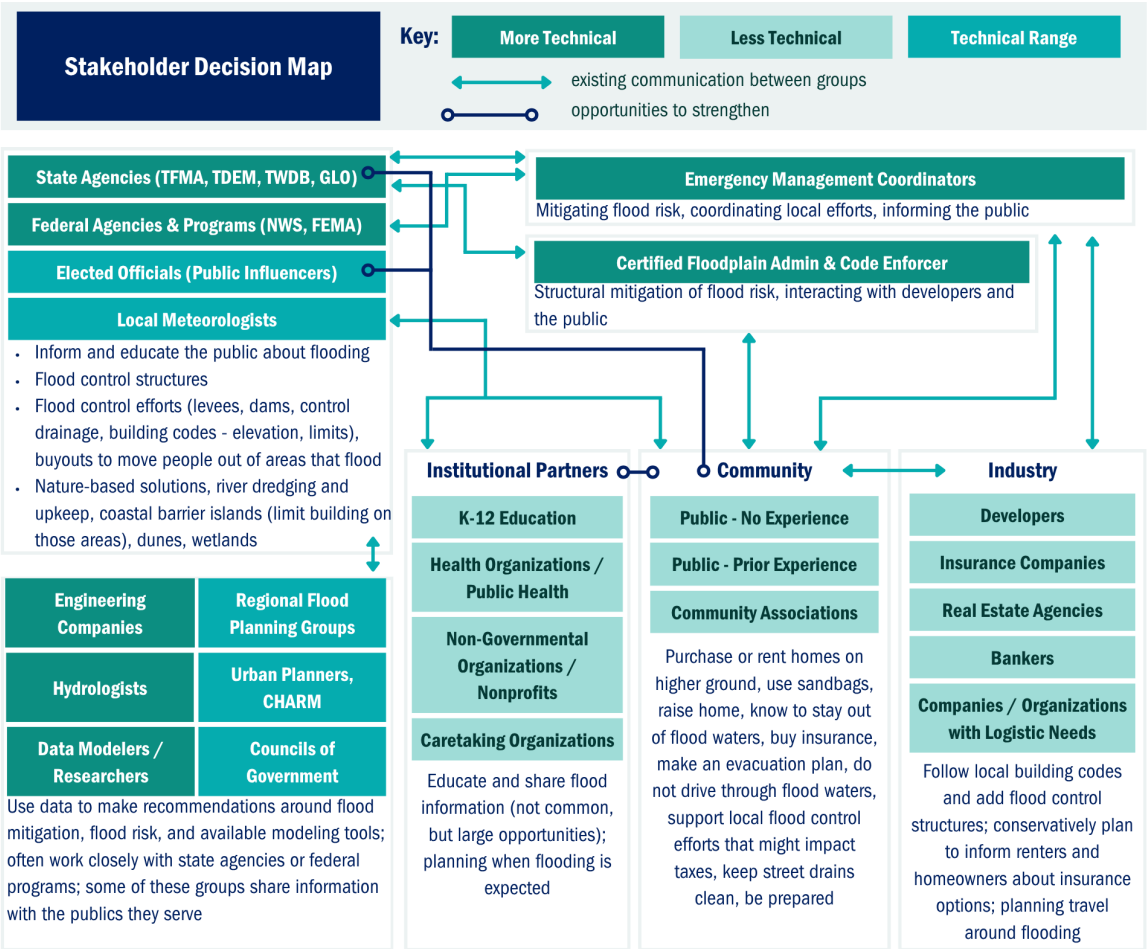

Figure 2-4. The Stakeholder Decision Map summarizes the identified stakeholder groups, their technical user levels, current and future communication paths, and the types of decisions they need to make regarding coastal flooding.

Tables 2-2 through Table 2-5 detail the considered groups and categories of public-related target user groups and the types of decisions they need to make. These decisions revolve around insurance, heightened flood risk, infrastructure-related risk, and responsibility for others. Presenting this information in a clear, organized manner allows state-level stakeholders to better grasp the complex landscape of flood-related decision-making among various public stakeholder groups. This understanding is crucial for developing effective policies and communication strategies to mitigate flood impacts in Texas.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Table 2-2. The types of Texas public target users where flood insurance is a key decision.

Target User Groups	Type of Information Needed and Why
Homeowners	Coastal flood model data to help them make purchase and mitigation decisions
Agricultural asset owners	Where to re-locate livestock during times of flooding, need insurance information for their property and/or their agricultural assets
Business owners who own property	Data to help make purchase and mitigation decisions
Property managers	The history of flooding in an area and how to help their tenants prepare and recover during floods
Renters (*37.6% of Texas properties)	(An often-omitted group that tends to not understand flood risk, constitutes a large percentage of the population, and could purchase insurance for their contents)
Business owners who rent property	(Many small business owners rent a storefront; and do not control the building and rely on property managers/owners. Their biggest concerns are around their contents and inventory.)
Mobile home residents	(This group lives in properties that are especially at-risk to flood waters. They have more limited options for where to place their mobile homes, and some of those locations are in flood hazard areas.)

* per Towncharts, 2022 American Community Survey Census

Table 2-3. Public target users more at-risk to floods due to needs for specific types of information.

Target User Groups	Description
Non-English speakers	~20% of Texans need flood information in other languages, primarily Spanish
People with health constraints	At higher risk during floods (e.g., asthma, heart conditions, mental health concerns, recent surgery)
People with physical mobility conditions	Require assistance during evacuation and have specific shelter needs
Undocumented individuals	Afraid to evacuate, cannot get flood insurance or file claims for recovery assistance
Older adults	Growing population with varying health and information needs
Children	Need education about flood dangers; best channel for disseminating family preparedness information
Males, ages 18-35	Higher risk of driving through floodwaters due to lower sense of vulnerability
Households with no vehicles	Difficulty evacuating, especially in areas with limited public transportation
Unemployed individuals	Financial constraints hinder evacuation and property mitigation
Homeless populations	Difficult to reach with information, making them especially at-risk
People with lower levels of education	Need information communicated through non-print media due to literacy concerns
People living in communities with limited support	Entire communities at-risk due to poverty, education level, and limited access to supportive community groups
Pet owners (58.20% of Texans)	Concerns about evacuating with pets; need help planning for floods while considering their pets

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Table 2-4. Public target users more at-risk due to infrastructure concerns.

Target User Groups	Reasons Why More at Risk
Low-socioeconomic status	Higher likelihood of purchasing and renting a home in a flood hazard area
People living in areas with inadequate drainage	Can be overlooked; includes both rural and urban areas. In places with no drainage, people are more likely to know there is risk, but inadequate drainage could apply in times of extreme rainfall.
People living in colonias	Texas has a large number of people living in colonias, most of which are located in flood hazard areas with limited to no drainage infrastructure.
Logistics organizations	Important part of the supply chain that needs information if there is a chance that roads will be flooded. Many people rely on these organizations.
People living in areas experiencing rapid growth	Development changes how water can flow, which is often not understood by people living in the rapidly expanding communities. Increased impervious cover can change flood risk.
Tourists	One of the most challenging groups to reach with safety information because they often do not know the area and are not registered with any local notifying authorities. Geofencing is the best strategy to inform them because it reaches a specific geography.

Table 2-5. Public target users responsible for others (caretakers).

Target User Groups	Explanation of How They Are Responsible For Others
Nursing/Assisted Care Homes/Group housing	Have particular needs around helping their residents evacuate when needed; need to understand the vulnerability of their location in a given rain/coastal event
Schools	Responsible for keeping children safe and play a role in educating the population; need to understand the vulnerability of their location in a given rain/coastal event and if their school will need to be converted into a shelter
Hospitals	Have dedicated staff who plan for emergencies and likely have needs around evacuation routes, logistics, deliveries, and staffing support
Employers	Often overlooked, but major employers often play a role in helping their employees be prepared for disasters and have a financial reason to get their employees safely to and from work; could be an important group to examine because they provide a metachannel (multiple ways) for reaching many individuals
Food banks	Often involved in the response and recovery effort; need information concerning the vulnerability of their location, logistics, and staffing support
Nonprofits serving the community (including religious organizations)	Often help people in the community recover from flooding and can be involved in sharing preparedness information and in providing temporary shelter during events

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SELECTED PRIORITIZED TARGET USER GROUPS

Building from the extensive list of potential target user groups, the Stakeholder Decision Map, and the audience segmentation criteria, TIFF prioritized three target users (*Property Owners*, *Property Renters*, and *People with LEP*). (See **Appendix B-7**.)

Property Owners

According to academic literature, agency reports, and reports from other countries and states, when people make decisions about purchasing property, they often use a broad spectrum of data sources. A relationship exists between data, information, and knowledge that is especially relevant when discussing translating flood model data into forms usable by non-technical audiences. Information science literature recognizes that there are diverse and interrelated meanings for data, information, and knowledge across the field (Zins, 2007). When there is a perceived gap between a person's knowledge and the amount of knowledge needed to deal with a situation (i.e., information insufficiency), people will seek out information. When people are aware of their knowledge gap, they often desire to reduce uncertainty, especially if the person perceives some kind of risk factor. Uncertainty is recognized as part of this information-seeking behavior, and *Property Owners* often have these knowledge gaps.

The term "property" is used because people may purchase residences, a business property such as a retail building, or land for a farm. The types of flood risk information needed in these contexts are similar, and this information can inform their decision-making. Thus, all these categories of people constitute the same behavioral archetype.

One of the main sources of information for *Property Owners* are flood maps, which enhance public awareness and facilitate informed decision-making regarding property ownership or building (Cooper et al., 2022; Stieb et al., 2019). Despite the availability of maps, many *Property Owners* do not understand the long-term consequences of flooding, including having flood measures in place (Percival et al., 2020). The following recommendations from experts surrounding *Property Owners* are applicable for those in Texas:

- Combining maps with other materials like text, tables, and graphs enhances their effectiveness in disseminating flood hazard information (Stieb et al., 2019)
- Having reference points and local information helps understand specific flood risk and its impact in individual properties or areas of residence (Dransch et al., 2010; Rollason et al., 2018)
- Overall, citizens and flood professionals seek tools that connect personal and community risk, focusing on community-specific metrics for flood communication (Habib et al., 2023)

Scholars highlight the importance of producing detailed spatial reference maps. Maps allow individuals to identify specific locations of interest, such as single houses or neighborhoods. For example, in Habib et al. (2023) workshops, participants zoomed in on locations that were relevant to themselves (e.g., home or work address) and did not look beyond their personal, relevant locations. Pictorial media such as aerial photos, realistic representations, or city models are useful because objects look more realistic and are easier to recognize for non-technical people (Dransch et al., 2010).

The types of information *Property Owners* need include:

- understanding the probability that the property might flood
- whether the property is in a designated flood hazard area
- whether flood insurance is optional or will be required
- whether the property has a history of flooding
- whether surrounding areas have a history of flooding

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

The main mitigation decisions *Property Owners* need to make include:

- choosing the location of property to purchase
- whether to purchase flood insurance or not

The various stakeholders who might support the decisions of Property Owners include people in several groupings that include governmental agencies, such as FEMA, Certified Floodplain Administrators, insurance companies, real estate companies, and banking organizations. If the property owner is seeking information, they might go to their local council of government, if they are aware those resources exist. Figure 2-5 provides an overview of these relationships.

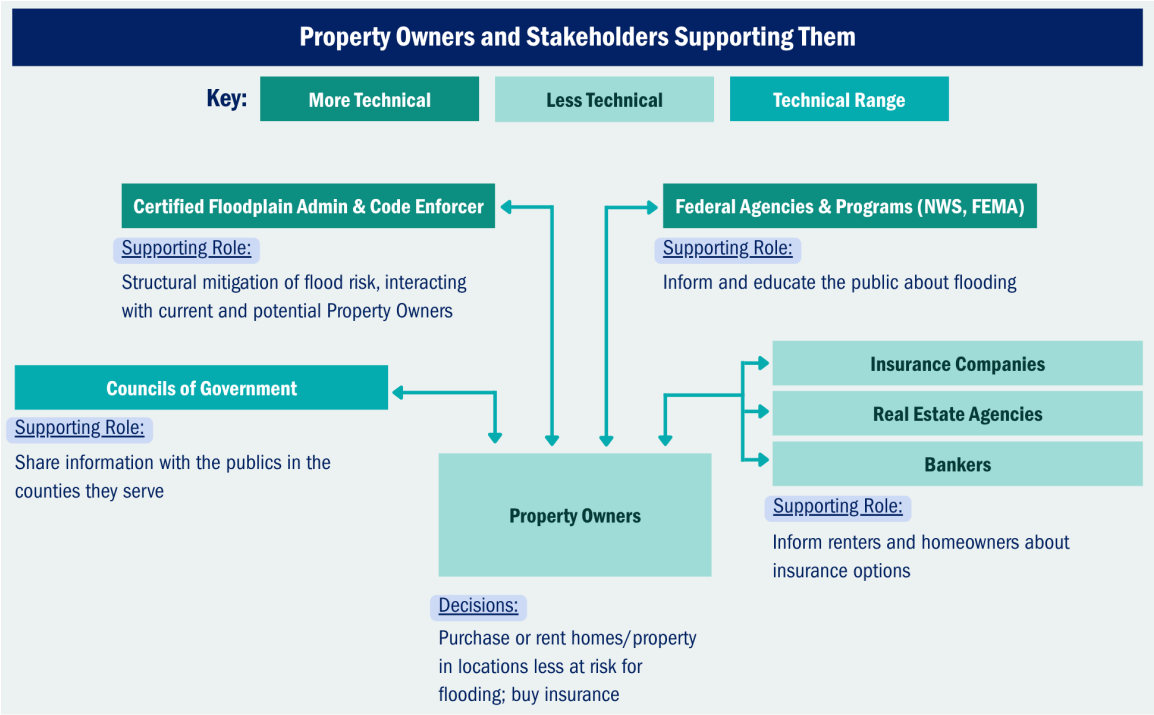

Figure 2-5. *Property Owners* and stakeholders supporting their flood-related decisions.

The main lessons learned about *Property Owners* are:

- It is important to disseminate flood hazard information through detailed maps and personalized tools, illustrating their potential for informing decisions on individual properties or areas of residence.
- Incorporating locally relevant terminology and cultural references will make tools more relatable and culturally applicable. For example, showing audiences buildings and landmarks in their area makes them understand the local relevance of the information.
- Adding actionable information in addition to informing people about flood risk can help empower Property Owners to build safer residences and prepare effectively for floods.
- Ensuring access to locally relevant data supports informed decision-making and avoiding misconceptions.
- Targeted communications support economic decision-making.
- Building community trust and social capital helps Property Owners relate to the risk presented.

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Property Renters

Property Renters are more at-risk for floods than *Property Owners* because they often lack community support, are excluded from funding/intervention programs, have socioeconomic disadvantages, and are less prepared for flood risks (Dundon & Camp, 2021; Lucas & Young; 2022; Shao et al., 2017; Zinda et al., 2021). Rental units tend to be older, more poorly maintained, and not built to the latest building codes. Subpar properties have a higher risk of disaster damage. *Property Renters* also often have difficulty relocating after disaster due to rent increases in the nearby area. Renters are less prioritized for disaster funding/intervention programs than *Property Owners*, and thus, have more difficulty recovering from future disasters (Dundon & Camp, 2021; Lucas & Young; 2022; National Academies of Sciences, Engineering, and Medicine, 2024).

Many existing studies about flood insurance purchase behaviors target homeowners and intentionally exclude *Property Renters* from the sample, and few studies have explored how renters prepare for floods. While the limited findings on flood insurance behavior are mixed, in general, renters have lower intentions to purchase flood insurance and fewer flood risk-reducing actions (Buchanan et al., 2019; Shao et al., 2017).

The types of information *Property Renters* need include:

- understanding the probability that a property might flood
- whether the property is in a designated flood hazard area
- whether flood insurance is advisable for their contents
- whether a property has a history of flooding
- whether surrounding areas have a history of flooding
- ways to recover (including finding new places to live) if floods impact them

The main mitigation decisions *Property Renters* need to make include (some overlap with *Property Owners*):

- the location of property to rent
- whether to purchase flood insurance for their contents

The main lessons learned about *Property Renters* are:

- Ensuring access to locally relevant data supports informed decision-making and avoiding misconceptions.
- Targeting communications to support economic decisions while prioritizing community trust and social capital makes risk more relatable.
- Natural disasters can reinforce socioeconomic inequalities as rental units tend to be in more poorly maintained conditions and have a higher risk of disaster damage.
- Renters are historically underrepresented in studies of flood risk-reducing actions.
- Renters are less likely to purchase flood insurance and participate in flood risk-reduction actions.

People with Limited English Proficiency

Many ongoing projects in Texas concerning flood knowledge and information-seeking have revealed a lack of information targeted at *People with LEP*. For instance, there is a lack of materials in Spanish to help Spanish speakers make informed decisions about coastal flooding. Prior research often identifies groups of people who do not speak English in the U.S. as being especially at-risk to disasters during prepa-

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ration, response, and recovery (Cutter et al., 2010; Teo et al., 2019). Complex document filing procedures that require extensive time, and resources only exacerbate these challenges (Howell & Elliott, 2019).

Risk information offered in other languages (especially Spanish) in the U.S. is often inconsistent due to a lack of standardization (Yas et al., 2021). These inconsistencies can lead to misunderstandings and exacerbate risk for People with LEP, including people in Texas. The gap in direct English to Spanish translation, for example, creates differentiated effects in understanding risk and protective measures (Trujillo-Falcón et al., 2022; 2023). Recent research suggests standardizing terms that communicate urgency in Spanish, e.g., using *vigilancia* for "watch" and *alerta* for "warning" (Trujillo-Falcón et al., 2022), but these will vary depending on the geographic location of the Spanish-speaking audience.

This is more than just a translation issue because careful considerations of culture need to be understood to design messages and visual information to reach and influence a given audience (Maldonado et al., 2015; 2016; Teo et al., 2019). When providing disaster-related information and resources, considering an individual's history and traditions is imperative to tailor messages that are both culturally and linguistically tailored (e.g., Maldonado et al., 2015; 2016). Hispanic families, for example, have especially collectivist cultures and trust their families and friends as sources of disaster information. These familial bonds lend to more informal community networks for information (Teo et al., 2019).

The Hispanic/Latino/a/e population has seen the most transformative growth in Texas. According to the U.S. Census Bureau's 2023 Population Estimates Program, they have edged out Non-Hispanic White Texans (40.2% vs. 39.8%). Hispanic/Latino/a/e (of all races) outnumber White Texans by approximately 129,000 (Ura, 2023). (Figure 2-6 shows this shift in population.)

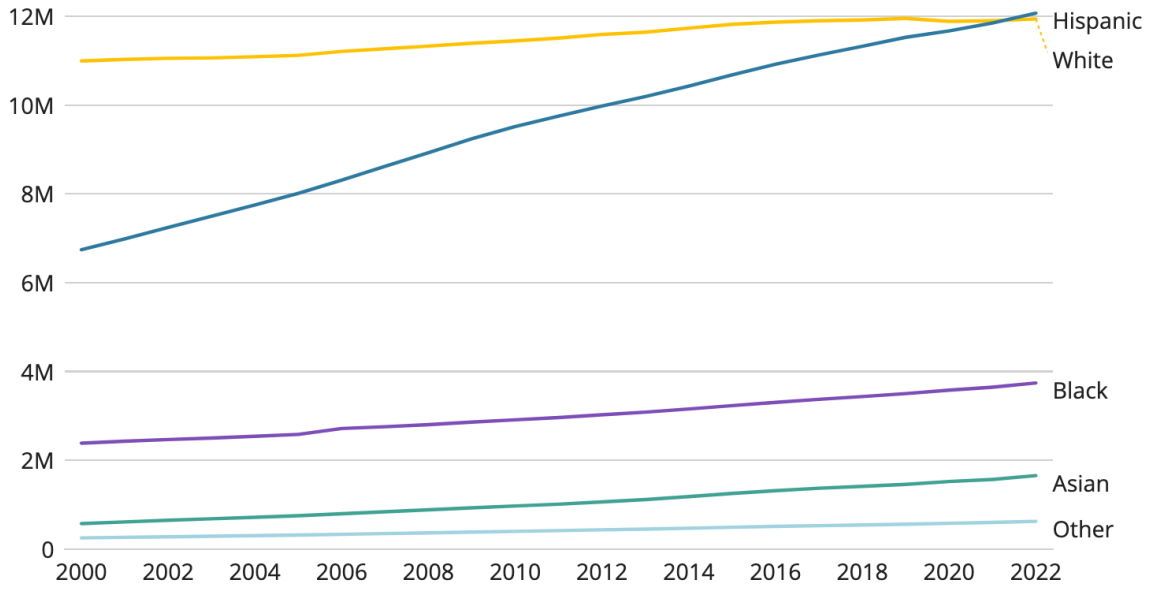

Figure 2-6. Hispanic Texans are the largest demographic group in Texas as of 2022.

Black/African American and Asian are of one race only. Other includes American Indian and Alaska native (of one race only), Native Hawaiian and Other Pacific Islander (of one race only), or people who identify as two or more races (any combination of White, Black/African American, American Indian/Alaska Native, Asian, Native Hawaiian/Other Pacific Islander, or Some Other Race), and does not include Hispanic/Latino/a/e (Ura, 2023).

Table 2-6 ranks the 18 coastal counties according to the number of people who are five years of age and older. Seven of the 18 counties have at least 30% of their population speaking Spanish at home, including two counties located in the LRGV (Cameron County and Willacy County). While that does not mean

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people in those households cannot speak English, it often means English is not preferred and they can better understand information delivered in Spanish.

Table 2-6. Percent and number of Spanish speakers in Texas coastal counties as of 2022. Eighteen coastal counties are listed from highest to lowest population five years and older. The U.S. Census Bureau's margin of error for population estimates and percentages are not noted here (U.S. Census Bureau, 2022; n.d.c).

County	Population 5 Years and Over	Percent of People Who Speak Spanish at Home	Number of People Who Speak Spanish at Home
Harris	4,393,352	35.4%	1,554,270
Cameron	390,450	70.1%	273,744
Brazoria	350,384	20.0%	70,202
Nueces	331,095	31.6%	104,660
Galveston	330,121	15.9%	52,424
Jefferson	237,822	18.1%	43,152
Victoria	85,214	22.5%	19,156
Orange	79,222	5.4%	4,282
San Patricio	64,306	30.2%	19,402
Chambers	43,929	19.1%	8,377
Matagorda	33,585	26.6%	8,933
Kleberg	28,685	34.4%	9,869
Aransas	22,987	16.0%	3,683
Willacy	19,072	61.9%	11,815
Calhoun	18,873	23.1%	4,367
Jackson	14,019	19.4%	2,724
Refugio	6,341	28.5%	1,810
Kenedy	88	85.2%	75

While it is difficult to say how many people along the coast do not speak any English, the 2021 U.S. Census Bureau American Community Survey estimates that 28.7% of Texans speak Spanish at home and 13.1% of Texans speak English less than "very well". While a part of this group is bilingual or relatively bilingual, others are at risk of not being able to understand information that is essential to their safety.

The types of information *People with LEP* need are very broad and include:

- understanding the probability that a property might flood
- whether the property is in a designated flood hazard area
- whether flood insurance is optional or will be required
- whether a property has a history of flooding
- whether surrounding areas have a history of flooding
- proper evacuation routes, the use of sandbags

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- staying out of flood waters
- ways to recover (including finding new places to work) if floods impact them\

The main mitigation decisions *People with LEP* need to make include (some overlap with *Property Owners* and *Property Renters*):

- the location of property to purchase
- planning evacuation routes
- relying on family for trusted information.

The various stakeholders who might support the decisions of *People with LEP* can be seen in Figure 2-4, the large Stakeholder Decision Map.

The main lessons learned about *People with LEP* are:

- Standardizing coastal flood hazard risk terms and using culturally appropriate translations for terms like "watch" and "warning" will improve understanding and encourage preparedness for flooding.
- Consider the culture and dialects of *People with LEP* in the U.S. will increase the effectiveness of messaging.
- Focusing on translating the meaning, not just the words, of key risk statements increases comprehension and encourage action.
- Use slogans that have a similar appeal both in English and other languages.

Caretakers, Business Owners, and Others

Beyond the three prioritized target groups highlighted by TIFF, additional research should be conducted to identify additional vulnerable populations, including:

- Caretakers – Investigating the unique challenges faced by caretakers (groups or individuals) in settings such as schools, daycares, hospitals, nursing homes, assisted care and group homes, foodbanks, as well as nonprofit and community organizations, employers, and individuals caring for others. These groups and individuals have additional barriers that complicate decision-making and heighten risk.
- Business Owners – Exploring how flood risk communication can be tailored to business owners, emphasizing location-specific preparedness and scalable mitigation strategies.

Develop Communication and Visualization Guidelines for Coastal Products

Building upon the key lessons and best practices identified during the literature review, as well as the insights gathered during the floodplain manager survey, the Stakeholder Needs Workshop, and the identification of prioritized target user groups, TIFF developed a framework of guidelines and best practices to support the design of effective coastal flood communication and visualization.

THE TIFF GUIDELINES FOR COASTAL FLOOD INFORMATION DESIGN AND COMMUNICATION (*THE TIFF COMMUNICATION GUIDELINES*)

Understanding the specific needs of both technical and non-technical target users for visualizing data and model outcomes enabled the development of The TIFF Guidelines for Coastal Flood Information Design and Communication (*The TIFF Communication Guidelines*) (**Appendix B-1**) for reaching Texan decision-makers.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

The TIFF Communication Guidelines (Page 1)

1 Determine Goal/Objective of the Flood Product Design

2 Identify and Align with Target Users to Tailor Information

- Use **Behavioral Archetype** techniques, an effective approach, to select target users
- Involve **Target Users** via Interviews, focus groups, and user experiments
- Confirm target users' **needs and decision**s that they make
- Determine engagement tools, like visualizations, that best communicate the project objectives
- **Confirm** that selected visualization & communication approaches meet target users' needs and project objectives
- Engage with **related stakeholders** periodically to exchange perspectives and confirm shared understandings

Tailoring messages and customizing communication strategies to meet the needs of different audiences will raise the level of understanding.

EXPERIENCE THRESHOLD

Moving beyond the fundamental levels of design...
Designs and interactions motivate behavior change when they are built using practices from the participatory pyramid to support people and bridge communication gaps.

3 Design & Co-Design Practices that Lead to Meaningful Communication

- The **foundational levels of design** address basic functionality, reliability of information, and usability capable of supporting task-oriented activities.
- Human-centered approaches are preferred because they provide access to **experience levels** of the pyramid, including accessibility, interactivity with information, and achieve meaningful representations for target user groups.

The words, content, stories and experiences should align with the target user and be grounded in science yet designed to deliver information in digestible chunks.

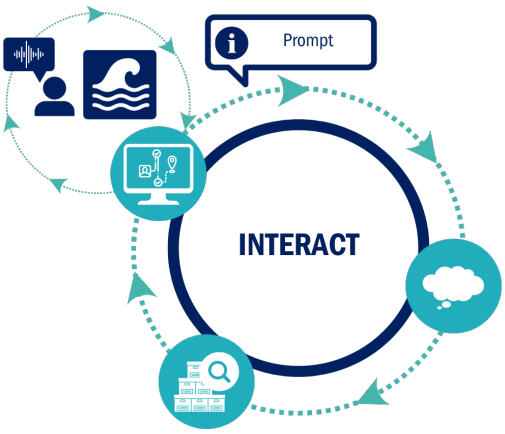

Figure 2-7. The TIFF Guidelines for Coastal Flood Information Design and Communication (*The TIFF Communication Guidelines*).

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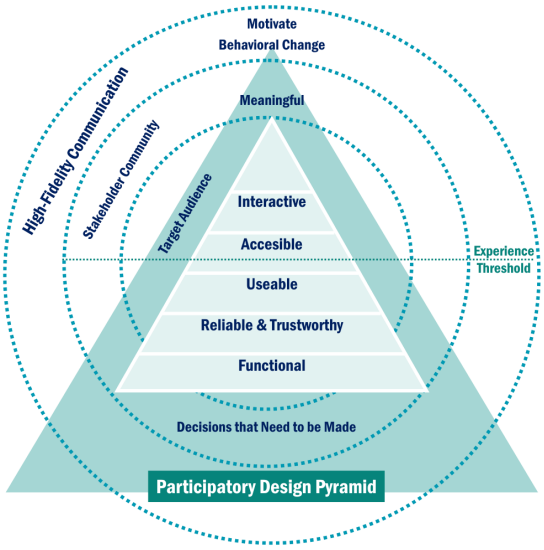
The TIFF Communication Guidelines (Page 2)

4 Achieve High-Fidelity Communication

These adaptive processes result in information and communication products that withstand design testing, can be updated regularly, and integrate the needs and concerns of communities.

Information is based on reliable technical data that uses multiple mechanisms to share with the people who need the information most.

These approaches can be used across settings and are easily adjusted to support other target user audiences or hazard events.



Best Practices for Communicating Flood Risk with High Fidelity (adapted from Peters et al., 2022)

These best practices present key highlights to communicate complex flood risks more effectively by translating the best available science into accessible, user-friendly formats:

1. Communications need to come from trusted sources
2. Leverage social networks and community relationships to understand who is influenced and how they are influenced to make desired decisions
3. Understand and/or utilize social norms (people I trust expect me to engage in these behaviors and/or I see them engaging in these behaviors)
4. Build on community identity and empowerment for target users
5. Use factual/realistic and meaningful language choices that are culturally appropriate.
6. Humanize messages
7. Use effective communication aids that have been vetted with target users
8. Use storytelling to bridge the gap between flood knowledge, understanding, and decision making
9. Present user-appropriate statistics to drive understanding of risk and enable informed decision-making
10. When disseminating flood information, identify common communication barriers to better help target users make informed decisions
11. Periodically vet flood communication with your target users to ensure the mission of the project is met, maintained, and sustained across the project lifecycle
12. Design tools with a view toward sustainability and plan for iteration and regular updates
13. Create evaluation metrics of communication channels to vet the project process

Peters, E., Boyd, P.E., Cameron, L.D., Contractor, N., Diefenbach, M.A., Fleszar-Pavlovic, S., Markowitz, E. Salas, R.N., & Stephens, K.K. (2022). Evidence-based recommendations for communicating the impacts of climate change on health. *Translational Behavioral Medicine*, 12, 543-553. https://doi.org/10.1093/tbm/ibac029.

Texas Integrated Flooding Framework

Prepared by: Keri K. Stephens, Suzanne A. Pierce, Jovana Andelkovic, Samanta Varela, Ruoxiao Su, Emaly Aguilar

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In addition, TIFF recommends several best practices for effective flood visualization and communication, and incorporated these into *The TIFF Communication Guidelines*:

- **User-Centered Design**: Involve target users early and throughout the design process to ensure tools meet their specific needs and preferences
- **Simplicity and Clarity**: Avoid technical jargon and excessive detail, focusing instead on clear, actionable information
- **Visual Effectiveness**: Use intuitive symbols, appropriate colors (avoiding rainbow palettes and checking for color vision deficiency accessibility) and responsive design
- **Uncertainty Communication**: Include both numerical and verbal expressions of uncertainty, prioritizing numerical expressions to reduce subjective interpretations
- **Tailored Approaches**: Adapt information based on audience needs, considering factors such as language, cultural context, and technical literacy
- **Multiple Formats**: Combine various visual elements (maps, videos, 3D animations) to enhance understanding of flood risk, evacuation routes, and decision-making
- **Local Relevance**: Provide detailed spatial reference points and incorporate locally relevant terminology and landmarks

For *People with LEP*, *The TIFF Communication Guidelines* advise presenting information in both English and their language, employing bilingual communicators, providing warnings in both visual and oral formats, using multiple communication channels, ensuring consistency in messaging, and collaborating with trusted community organizations and leaders.

THE TIFF VISUALIZATION GUIDELINES TAILORED FOR SELECTED TARGET USER GROUPS

As described in the previous section, many audiences use coastal flood model data, in various forms, to make a range of decisions, while the design of effective flood communications and visualizations requires an iterative and user-centered approach. Grouping audiences by the types of decisions they make (e.g. purchasing property) helps craft visualizations, communication approaches, and messages that can effectively reach specific audiences.

Following the selection of prioritized target user groups, TIFF recommends that these tailored *The TIFF Visualization Guidelines*, within the overarching framework of guidelines and best practices, be adopted by entities sharing coastal flood products:

Property Owners as a Target User of Coastal Flood Products

Property Owners need information about their current property, properties they are considering purchasing, and decisions related to flood insurance coverage. (Note: Many small business owners rent a storefront; therefore, they do not control the building and rely on property managers/owners. Their biggest concerns are centered around their contents and inventory.) *The TIFF Visualization Guidelines* for these target users include:

1. **Keep the visualization simple and uncluttered**: Avoid overloading the tool with excessive details or competing information so owners can quickly interpret the most important information
2. **Use intuitive symbols and accessible colors**: Select symbols and colors that are easy to understand and have clear meanings for the intended audience, avoid rainbow colors and test colors with a color vision deficiency simulator to improve accessibility
3. **Provide clear context**: Use labels, annotations, and legends to explain flood risk data and help *Property Owners* understand what they are seeing and how it relates to their property
4. **Include interactive features**: Add features such as zooming and panning so users can examine flood conditions at the property and neighborhood scale

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5. **Ensure accessibility across devices**: Design visualizations to function well on mobile phones, tablets, and desktop computers so *Property Owners* can access the information in a variety of settings
6. **Test with the intended audience**: Share the tool with representative users to gather feedback on clarity, usability, and relevance, and refine the visualization with a user-centered approach
7. **Ensure data accuracy and communicate reliability**: Present accurate and reliable data and, when possible, identify the data source so users can better understand and trust the information provided
8. **Clearly communicate uncertainty using numerical and verbal expressions**: Include both quantitative and plain-language descriptions of uncertainty, prioritizing numerical expressions where possible to reduce subjective interpretation (e.g., pairing terms such as "slight," "moderate," or "high," with defined numeric ranges)

Property Renters as a Target User of Coastal Flood Products

Generally, *Property Renters* are in more at-risk social situations, especially as they often have low-to-moderate risk perception. Additionally, *Property Renters* are often uninsured, underinsured, and unaware of flood risk. As *Property Renters* can be more susceptible to flood risk, they are often less prepared for flood events. *The TIFF Visualization Guidelines* for these target users include:

1. **Ensure intuitive navigation and clarity of information**: Design tools so renters can easily find and understand key details about flood risk, insurance, and protections, minimizing confusion and cognitive burden
2. **Provide clear information on insurance implications**: Include accessible explanations of flood insurance benefits, requirements, and consequences of not having coverage to help renters understand their level of protection and financial risk
3. **Incorporate property search and filtering features**: Enable renters to search and filter properties based on criteria such as location, past flood history, and risk levels to support informed housing decisions
4. **Facilitate communication between renters and landlords**: Include features such as messaging tools or shared information portals that encourage transparency and dialogue about flood risk, responsibilities, and mitigation actions
5. **Ensure accessibility across devices**: Design platforms to be fully responsive and functional on desktops, tablets, smartphones, and other mobile devices so renters can access information regardless of device
6. **Use interactive map features to build understanding**: include tools such as zooming and panning to help renters explore risk in their area and better understand how flooding may impact their home and community
7. **Highlight community-level risk and impacts**: Present information that shows how flood risk and lack of insurance affects not only individual properties but also surrounding neighborhoods to increase awareness and contextual understanding

People with LEP as a Target User of Coastal Flood Products

Some non-U.S.-born communities perceive flood risk as a greater general problem compared to U.S.-born people. For example, Spanish speakers have high concern for property damage, injuries, and daily disruptions due to floods. They face several vulnerabilities that make them more susceptible to the damaging effects of coastal flooding. These vulnerabilities include:

1. Potential for lower socioeconomic status limiting access to financial resources and state disaster assistance, impacting their ability to afford insurance and recover from disasters
2. Language barriers prevent access to life-saving information like warnings and educational material
3. Reduced social networks and community support which can impede *People with LEP* from protecting their lives effectively during emergencies.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

4. Low trust in governmental organizations may hamper disaster preparedness and response among *People with LEP*
5. Non-U.S.-born *People with LEP* have, in general, lower levels of mitigation actions and insurance coverage compared to U.S.-born or White people
6. Higher renter status among, for example, non-U.S.-born Hispanics may limit their ability to undertake mitigation actions and maintain flood insurance
7. Less hazard-specific knowledge and greater language barriers, limiting awareness and access to disaster risks and recovery assistance information

These factors collectively result in less effective preparedness, response, and recovery actions in disaster contexts for communities with LEP, leading to disproportionate impacts during calamities. Addressing these vulnerabilities and incorporating appropriate approaches in emergency systems are crucial for reducing them (Maldonado et al., 2015; Trujillo-Falcón et al., 2023). **Before designing a communication tool to address audiences with LEP, ask the following questions**:

1. Are risk communications translated into other relevant languages?
2. Does the translation effectively convey the same meanings as in English?
3. Would you trust that this translation conveys the right level of risk?

If the translation needs improvement, it can be tested with people of different origins with LEP. It should be noted that *People with LEP* in the U.S. come from diverse cultural origins, capturing varied histories, traditions, and experiences. The largest group is of Mexican descent, representing a significant portion of the Hispanic/Latino/a/e population in the U.S. Other major groups include individuals from Puerto Rico, Cuba, El Salvador, Honduras, the Dominican Republic, Guatemala, Venezuela, and Colombia, among others. Each group brings unique influences, such as distinct dialects. For example, Puerto Ricans often bring elements of Caribbean culture, while Cuban communities might share traditions rooted in Afro-Cuban influences. Central American communities, such as those from El Salvador and Guatemala, contribute Indigenous cultural practices alongside Spanish colonial influences. *The TIFF Visualization Guidelines* for these target users include:

1. **Present information in both English and other languages**: Keeping track of two sets of different materials can create organizational pressure and leave some people out
2. **Employ bilingual communicators**: Engage communicators who can effectively translate and disseminate information before and during emergencies when communicating directly to communities
3. **Provide warnings in both visual and oral formats to transcend language and literacy barriers**: Provide demonstrations or simulations of self-protective actions in multimedia formats to enhance understanding
4. **Use different channels**: Share information through television, radio, digital platforms, Facebook, WhatsApp, and/or Instagram
5. **Establish channels for feedback and questions**: Provide opportunities such as hotlines or community meetings
6. **Use simple and clear language in both English and other languages**: Avoid complex jargon to ensure that everyone can understand important updates and instructions during emergencies
7. **Ensure consistency and reliability in preparedness messaging**: Provide consistent and reliable information to build credibility over time
8. **Clearly outline available resources**: Provide information about shelters, insurance options, and emergency assistance in both English and Spanish (including information on how to access these resources and eligibility requirements)

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9. **Be transparent about potential risks and uncertainties**: Clearly communicate the actions authorities are undertaking to mitigate the risk
10. **Collaborate with trusted community organizations and leaders**: Partner with churches and with local language media outlets to disseminate information, as *People with LEP* often rely on informal networks
11. **Recognize and respect the diverse cultural backgrounds and disaster experiences of LEP communities**: Consider regional dialects and colloquialisms to ensure the message is relatable and easily understood
12. **Avoid stereotypes**: Stereotypes may convey a limited effort to understand this diverse audience
13. **Provide training for community leaders in disaster preparedness and response to enhance their ability to relay accurate and timely information to their communities**: Encourage the role of knowledge brokers, such as bilingual community leaders; invite community members to share their experiences and suggestions, fostering a sense of ownership and involvement

TESTING THE NEW TIFF GUIDELINES

In developing *The TIFF Communication Guidelines* and *The TIFF Visualization Guidelines*, TIFF focused on identifying which audiences most need improved flood related decision support and how best to present it. Because effective communication and visualization require an iterative, user centered approach, the draft guidelines and best practices were tested with the selected prioritized target user groups within Texas coastal communities (non-coastal audiences were also tested for comparison). This evaluation of the guidelines and best practices against both scientific evidence and real world user needs, expanded TIFF's understanding of the selected target user groups and strengthened the overall communication framework.

Statewide Survey to Test Aspects of the TIFF Guidelines

A statewide survey was conducted in January and February 2025 to test *The TIFF Communication Guidelines* (**Appendix B-1**) on the selected target user groups: *Property Owners*, *Property Renters*, and *People with LEP*. The survey was administered online, with invitations to participate sent by the company, Centiment. The specified demographics included appropriate coastal areas and demographic representation of Texas: zip codes of Texas coastal counties, age, gender, and race/ethnicity. (Table 2-7 provides the detailed demographics of the full sample.)

TIFF collaborated closely with IDRT to determine the appropriate types of real estate properties to test. The properties tested were not directly beachfront to avoid a bias on property cost, and each home was a three-bedroom two-bath on slab foundation. Real locations were used with modified addresses and visualized using Google Street View images. At the end of the study, participants were informed that no deception was involved and were provided a link to IDRT's Buyer's Aware tool (https://buyersaware.org/) for those interested in learning more about coastal flooding in Texas.

To create a more realistic scenario, participants were asked to examine a property that a family member was considering renting or purchasing, rather than having participants pretend they were interested in the property viewed in the survey. The study participants viewed the following scenario before responding to questions:

> *Assume you have a family member who is considering RENTING/PURCHASING a home that is a 3-bedroom 2-bath modest home close to the Texas coast. They have shared the following information about this home from a website, and they want your help making a decision about RENTING/PURCHASING this home. Please review the information on the map and respond to the questions that follow. You will need to review the content for at least 30 seconds before you can move forward.*

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

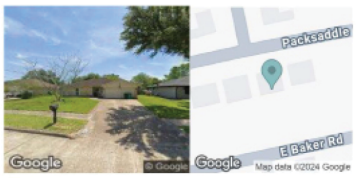
To narrow the specific experimental tests, none of the test properties were in a flood hazard area where flood insurance would be required. IDRT provided the graphics and information for this experimental test showing an example of the most elaborate type of condition study participants viewed (Figure 2-8). Specifically, TIFF tested the following conditions for these two selected target user groups (*Property Owners* and *Property Renters*):

- Higher flood risk property versus lower flood risk property
- Owning a home versus renting a home
- Three ways to indicate property flood risk levels: Qualitative (High or Low), Quantitative (5/5 or 2/5), or both (High, 5/5 or Low, 2/5)
- Viewing just the area around the home versus viewing the neighborhood with the home
- Seeing historical flooding data for the neighborhood versus not seeing that history

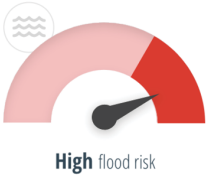
Table 2-7 shows the categorical variables description, with sample sizes and percentage of responses of the whole survey.

Page 1

The flood risk results for 1409 Packsaddle Ln



Flood Risk Report



FEMA Flood Zone

Not in Special Flood Hazard Area

Insurance Not Required

While this property is not in the FEMA regulatory floodplain (sometimes referred to as the "100-year floodplain"), our analysis indicates flood risks may be much higher than what is currently measured by the regulatory maps. These risks could be due to large amounts of historic flood risk nearby, low-lying or poorly drained areas, upstream accumulations of water, or close proximity to surface water sources.

Based on the flood risk variables outlined below, our analysis ranks this site as having a **high, 5/5 flood risk**. This is the highest risk category included in our model.

Our Risk Calculation

This property has a **high flood risk score of 5 out of 5**. The risk score is calculated by factoring the individual hazards below:

Hazard Type	Value
Elevation	29.57 ft
Distance to Coast	5.32 miles
Distance to Stream	0.96 miles
Height Above Nearest Drainage	29.10 ft

Page 2

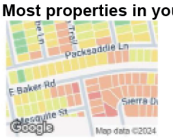
Hazard Risk Description

- **Elevation:** Land elevation at property. Areas that are lower in elevation or flat tend to act like natural paths for water to flow, which can cause them to flood or collect water during times of rain. A lower elevation value increases a property's calculated flood risk.
- **Distance to Coast:** Distance from property to coastline. Areas closer to the coast are more likely to experience flooding from high tides or storm surge. A smaller Distance to Coast value increases a property's calculated
- **Distance to Stream:** Distance from property to nearest stream. Areas close to a stream are more prone to flooding from the stream overflowing its banks. A smaller Distance to Stream value increases a property's calculated flood risk.
- **Height Above Nearest Drainage:** Vertical distance between property and the nearest drainage point (stream, lake, or coastline). A property that has low elevation relative to the nearest drainage path is more likely to experience flooding. A smaller Height Above Nearest Drainage value increases a property's calculated flood risk.

Information provided here is accurate and representative of what is found on a resource being developed for the State of Texas. At the end of the survey, you can follow a link to learn more.

Surrounding Area:

Most properties in your area have a moderate to high level of flood risk



Previous damage claims

$46,108 of flood damage has been paid for under the National Flood Insurance Program in this neighborhood since 2010. In this census block, there have been 9 flood damage claims filed with the National Flood Insurance Program in the last 10 years.

Figure 2-8. Sample flood risk conditions for test properties.

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Table 2-7. Demographics for the Texas survey to test *The TIFF Communication Guidelines*.

Variable	Category	Number	%
Total Sample		2660	100.0%
Region	Coastal	964	36.2%
	Non-Coastal	1696	63.8%
Gender	Woman	1382	52.0%
	Man	1273	47.9%
	Other	5	0.2%
Hispanic	No	1532	57.6%
	Yes	1128	42.4%
Race	White	2004	75.3%
	African/Black	309	11.6%
	Asian	42	1.6%
	Native Hawaiian/Pacific Islander	7	0.3%
	American Indian/Alaskan Native	54	2.0%
	Other/multiple identities	244	9.2%
Household Size	1	519	19.5%
	2	819	30.8%
	3	502	18.9%
	4	463	17.4%
	5	195	7.3%
	6	98	3.7%
	More Than 6	64	2.4%
English Proficiency	Not Very Well	14	0.5%
	Fairly Well	179	6.7%
	Very Well	2467	92.7%
Employment	Full-Time Employment	1086	40.8%
	Part-Time Employment	335	12.6%
	Retired	561	21.1%
	Student Only	107	4.0%
	Student Who Is Also Employed	40	1.5%
	Unemployed and Looking For Work	280	10.5%
	Unemployed and Not Looking For Work	134	5.0%
	Other	117	4.4%
Income	less than $20,000	510	19.2%
	$20,000-39,999	582	21.9%
	$40,000-59,999	522	19.6%
	$60,000-79,999	386	14.5%
	$80,000-99,999	215	8.1%
	$100,000-119,000	156	5.9%
	$120,000-139,999	75	2.8%
	$140,000-159,999	92	3.5%
	$160,000-179,999	44	1.7%
	$180,000 or more	78	2.9%

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Table 2-7. Continued

Variable	Category	Number	%
Major Flood Experience Lifetime	Never	1115	41.9%
	Once	959	36.1%
	More Than Once	586	22.0%
Flood Property Damage	No	1209	45.5%
	Minor	937	35.2%
	Major	392	14.7%
	Lost Everything	122	4.6%
Floodplain Current	No	1630	61.3%
	Floodplain Current	651	24.5%
	I Don't Know	379	14.2%
Neighborhood Flood History	No	1048	39.4%
	Yes	1392	52.3%
	I Don't Know	220	8.3%
Flood Insurance Status	Never Had	1485	55.8%
	Had In the Past but Not Currently	612	23.0%
		563	21.2%

The survey findings included:

Flood perception differences based on *Property Owners* versus *Property Renters*:

- Participants who viewed the property that their family might purchase thought it was less likely to flood than participants who viewed the property as a potential rental.
- If the property they viewed were to flood, participants who viewed the property that their family might purchase thought the depth of flood water would be deeper than participants who viewed the property as a potential rental.
- In all conditions, participants were asked to list three words that came to mind after viewing the property and there were differences between people who saw the property for purchase versus rent.
- Consistent with the survey findings, when examining the three words participants listed after viewing the properties, these also suggest that purchasing the property was viewed as lower flood risk than renting.
- Participants who saw the rental condition listed words that varied more than participants in the home ownership conditions. This suggests there are more diverse views held about flooding when people view the goal as renting property.

Flood perceptions of *People with LEP*:

- Lower perceptions of the probability and severity of flood risks than people who spoke English very well
- Lower intentions to recommend their family buy flood insurance or to advise them to use sandbags to prepare for floods.
- More likely to believe that renting a home has a lower risk than buying it.
- Thought the map was less helpful and they claimed they needed an interactive map significantly less than people who spoke English very well.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Flood perception differences based on coastal versus non-coastal residents in Texas:

- People who did not live in coastal areas had higher perceptions of the probability that flooding would occur, and they were more concerned about flooding. Thus, non-coastal Texans are more sensitive to flooding risks.
- People who lived in noncoastal areas who also saw a low-risk property were even more concerned about flood risk and had a higher perception of the severity of the flood risk than people who lived in coastal areas and saw a high-risk property.
- People who did not live in coastal areas were more likely to believe renting the property shown had a lower risk than buying it.
- People who did not live in coastal areas had a higher intention to recommend their family keep sandbags close for flood preparations, but they had no higher intent to purchase flood insurance than people who live in coastal areas.

General findings not specified for the selected target users:

- Consistent with what was predicted, participants who viewed a property that had a higher flood risk, had a significantly higher perception of flood risk probability, severity, and concern around flooding, and viewed the map as more helpful than participants who viewed the lower flood risk property. Participants had a higher estimation of what insurance would cost for the property, a higher intent to purchase flood insurance, and a higher intent to have sandbags in their garage in case they are needed.
- When testing whether flood risk maps should use numbers only, risk words only, or both numbers and risk words, using both (e.g., High, 5/5 or Low 2/5) increased flood risk perceptions.
- Participants who viewed properties containing only the risk word and flood risk level (High or Low) had a lower perception of probability of floods, expressed lower concerns around flooding, and evaluated the map as less helpful than people who saw both the risk words and numbers together.
- Participants who viewed only the number flood risk level (e.g., 5/5 or 2/5) had slightly lower perceptions of the probability of floods, expressed lower emotions or concerns around flooding, and evaluated the map as less helpful than people who saw both the risk words and number together, but the differences were not statistically significant.
- When testing whether maps should show an area around the home versus viewing the neighborhood with the home, there was no significant impact on risk perception (defined as perceived likelihood, severity, and concern). (Note the experimental checks were successful so people did see the maps differently.)
- Testing whether maps should contain historical flooding data for the neighborhood versus not seeing that history had no significant impact on risk perception (defined as perceived likelihood, severity, and concern). (Note the experimental checks were successful so people did see the maps differently.)
- As expected, people who had major flood experience had higher perceptions of flood probability and severity and expressed higher concerns around flooding than people who did not have flood experience. Those with flood experience also viewed flood insurance as more expensive than those without flood experience, and the first group also were more likely to recommend their family members purchase flood insurance.
- People with major flood experience were more likely to believe that renting a home has lower flood risks than buying it.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

- People who experienced more property damage due to floods had higher estimations of the depth at which flood waters might be if the home they examined were flooded. These people also showed stronger emotional concerns about flood risks and had higher intentions to buy flood insurance.
- Hispanic Texans thought the map was more useful than people who were not Hispanic.
- Hispanic Texans preferred to see more interactive maps than people who did not identify as Hispanic.
- Hispanic Texans were more likely to believe that renting a property had a lower risk than buying it when compared to people who did not identify as Hispanic.

TESTING THE GUIDELINES USING COMMUNITY-DRIVEN RESEARCH IN THE LOWER RIO GRANDE VALLEY

Ineffective communication amplifies uncertainty by excluding information from lived experiences or communicating with messages that do not align with the context of the community members or target audiences. When technical data lacks cultural relevance or local framing, residents struggle to interpret flood maps, understand drainage systems, or act on risk information. These gaps foster misinformation and inaction in flood preparedness, particularly in unincorporated areas where infrastructure and outreach are limited.

TIFF conducted community-driven research in the LRGV aimed at improving flood resilience through culturally informed communication strategies. This research focused on engaging TAT members, local businesses, community organizations, first responder organizations, and food banks in 1) interviews, 2) workshops, and 3) a CLE. See Figure 2-9 for a map of the geographic areas included in the project.

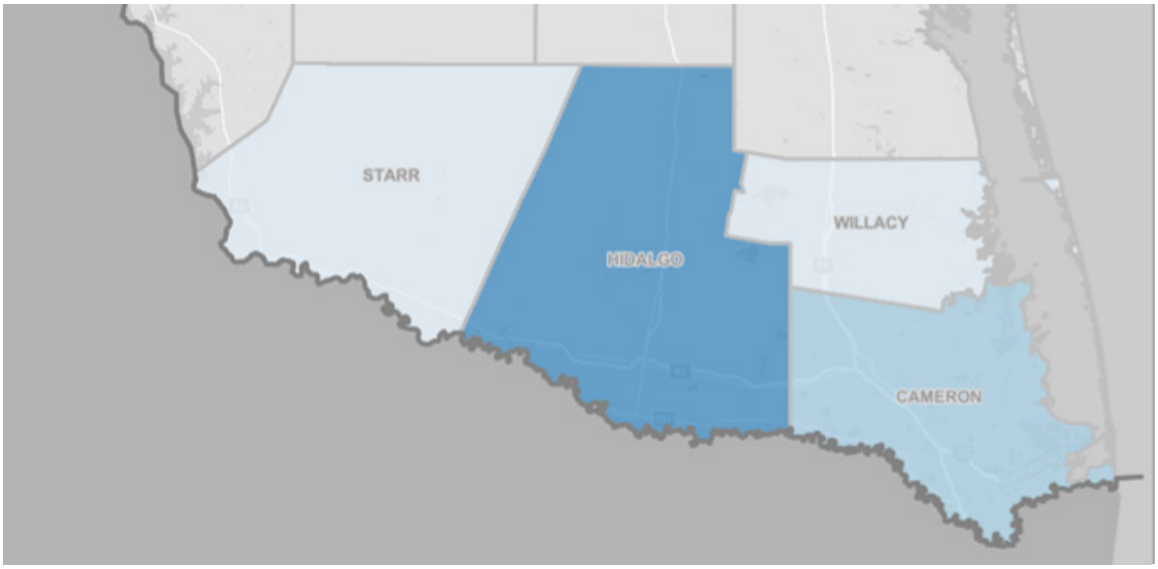

Figure 2-9. A map of the Lower Rio Grande Valley, including Cameron, Hidalgo, Starr, and Willacy Counties. Source: https://www.texasento.net/LRGV.htm.

Interviews to Identify Lower Rio Grande Valley Needs and Decisions

Outreach efforts in the LRGV began with conducting interviews with local stakeholders, which yielded valuable insights about community flood needs. In addition to conducting interviews, TIFF attended community meetings with the LRGV Economic Development Council, the Foodbank of the Rio Grande Valley, and spoke on several occasions with the Hidalgo County Drainage District 1. The meetings outside of the interview space allowed for trust to develop between Study Providers and city leaders and public officials. A total of 19 interviews were completed over the course of three months. The interviews ranged from about 30 minutes to one hour.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Stakeholders included:

- fire and police chiefs
- emergency managers
- local non-profit organizations that work with colonias to address infrastructure and flooding issues
- church pastors heavily involved in providing community resources
- economic development council leadership
- storm water management officials
- homeowners

Conversation topics varied depending on the line of work and the involvement with the community. (Detailed information about each interviewed stakeholder is presented in **Appendix B-14**; Interview questions asked for business/government individuals and community members appear in Table 2-8.)

Table 2-8. Questions asked during interviews.

Business/Government Organizations	Community Members
Can you tell me about how flooding events impact your business/organization?	Can you tell me about how flooding events impact you?
How do you use flood-related messages/information to help you make decisions?	How do you use flood-related messages/information to help you make decisions?
What role does uncertainty play in how you evaluate flood related messages provided to you?	What messages around flooding are most helpful to you?
What flood messages/information do your stakeholders understand best?	What type of flood information do you trust most?
How do you think we can make messaging easier for various members in the community to understand?	
Which type of formats can better help relay flood risk messages in the area (e.g., weather reports, satellite information, modeled outputs, event-based data, testimonies, cuentos (stories), musical recordings telling stories of floods?	
What are some barriers for people with limited English proficiency to understand current flood messages/information?	Which type of formats can better help relay flood risk messages in the area (e.g., weather reports, satellite information, modeled outputs, event-based data, testimonies, cuentos (stories), musical recordings telling stories of floods?
In thinking about creating culturally representative flood messages, what is helpful to include for the LRGV?	
What terminology should be used that translates from English to Spanish to better understand coastal and compound flooding?	
In thinking about the community you engage with, how should messages be shared?	
When your business/organization is facing a flooding event, who are the people you turn to for support?	
When your business/organization is facing a flooding event, who are the people you turn to for support?	When you are facing a flooding event, who are the people you turn to for support?
What is the biggest challenge when translating and describing flood-related information?	What is the biggest challenge when translating and describing flood-related information?

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Stakeholder interviews revealed critical flood-related concerns in the LRGV, including drainage infrastructure challenges, illegal dumping practices, and significant communication gaps (**Appendix B-14**). Initial conversations with emergency managers and fire chiefs expanded into broader stakeholder discussions that provided a comprehensive view of flood-related topics requiring greater community awareness about risk and uncertainty. These interviews highlighted several challenges unique to the LRGV and the flooding the area experiences. (Note: Drainage systems refer to infrastructure designed to control and manage the release and accumulation of water due to topography or climate conditions, such as rain events (Ritzema, 2016). Illegal dumping refers to the unlawful act of disposing of trash on private or public land where such disposal is not permitted (Hidalgo County Drainage District, n.d.).

The findings from the stakeholder interviews include:

- Rapid rainfall is the primary process driver of flooding issues in the LRGV.
- Differences in elevation and variations in local relief across the LRGV impact water flow from county to county, and city to city, over time.
- There is confusion around how the cities and counties are addressing the flooding communities are experiencing.
- People need to understand how the drainage systems in their communities impact flooding patterns and outcomes.
- Sandbags are very useful, but both officials and community members repeatedly mentioned there is no education around how to effectively use sandbags to reduce flooding damage.
- Interviewed officials mentioned the importance of communicating to the public using many different communication channels: trusted local organizations, multiple forms of social media, TV, radio, and flyers.
- Digital forms of communication are missing many people. Of the digital forms, Facebook is dominant, and Instagram is also used by a younger audience.
- People in this region need a greater awareness of how illegal trash dumping behavior impacts flooding-related issues in the LRGV. (These behaviors negatively affect their communities in multiple ways, including some forms of unpredictable flooding.)
- Officials need to better understand the underlying reasons that people participate in illegal dumping.
- Flood-related messages and educational information should be targeted for specific audiences and be phrased in ways non-technical audiences can understand.
- Communities need messages to clearly explain factors that contribute to flooding.
- Crafting messages with language and terminology that are meaningful to a community is essential for effectively communicating with them and motivating behavior change.

Workshops to Test Communication and Visualization Approaches in the Lower Rio Grande Valley

TIFF subsequently designed and conducted two workshops on flooding issues to help residents better understand behaviors that contribute to flooding, providing messages relevant for LRGV communities. Workshop content included materials in both English and Spanish, as well as multiple flood map formats such as FEMA Flood Hazard Maps and the Hidalgo County Drainage District Map. Participants shared positive feedback, and these workshops allowed people in different roles to come together for honest and productive sessions. The workshop events also served as structured space and time for the research team to gather knowledge on how flood-related information is understood, shared, and acted upon.

The community meetings and interviews helped reveal prominent issues in the area, and stakeholder feedback and insights informed the design of workshop materials. Messages developed for the workshops

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leveraged notions of *familismo* (also known as familism), a strong emphasis on family and loyalty (Losada et al., 2006), and aimed to disentangle cultural needs from language needs. Examples include using words/terms relevant to the area, such as water stacking, where flood waters accumulate one to two days later in areas that did not receive excessive rain. TIFF held multiple meetings with the Museum of South Texas History (MOST History) to collect relevant information about past flooding events in the LRGV, and coordinate workshop planning. Two workshops, one for small businesses and one for the general public, were designed to attract participants who live and work in Cameron, Hidalgo, Starr, and/or Willacy Counties.

The workshop-style data collection events were designed to maximize community participation and feedback. Activities included five interactive stations using custom workshop materials, face-to-face focus groups, and informational interviews. A video of the workshop set-up can be found on the TIFF website. This structure allowed researchers to gather comprehensive data on how participants understood and responded to flood risk communication. Attendees moved through stations where messages and visualizations presented flood risk and uncertainty in different formats. Participants offered feedback, joined discussions about the information shared, and completed surveys assessing their comprehension and self-efficacy. The overarching goal was to explore how communication strategies might influence preparedness behaviors and strengthen flood resilience. (Table 2-9 summarizes the workshop stations and their design features.)

Table 2-9. Workshop station and survey design summary.

Station Name	Description	Survey Aspects
Station 1. "The Sandbag Story" Brochure	Read and discussed the brochure to better understand the protective and low-cost use of sandbags with an educational brochure	Compare results between graphic brochure and hands-on activity in Station 2
Station 2. Hands-on Sandbag Preparation	Made sandbags using Ziploc bags, sand, and scoops, emphasizing proper filling and stacking techniques	Hands-on activity to practice proper sandbag preparation in addition to reviewing the brochure
Station 3. FEMA Flood Hazard Map	Displayed FEMA flood hazard maps presented to help participants understand flood risk and decision-making	Compare results between FEMA map and Flood Control District map in Station 4
Station 4. Drainage District Map	Showcased Hidalgo County's flood risk using drainage district maps to help participants understand water flow patterns and connections between different areas in the Valley	Comparison of two map products with differing markers and legends. Also used to compare with Station 3 FEMA map
Station 5. Hands-on Illegal Dumping	Demonstrated flooding impacts from illegal dumping with 3-D models, emphasizing individual actions on flood risk	Pre-test, hands-on activity, post-test, and elaboration of "stacking" concept

The workshop stations incorporated a survey design with the goal of determining if different forms of visualizations and activities have a stronger impact on behavior. TIFF administered a pre-test survey in the hallway before participants entered the workshop room to assess each participant's baseline knowledge about sandbags, maps, and illegal dumping. After the baseline knowledge survey was completed, participants were randomly assigned to interact with one of two different workshop stations and participate in group discussions. Participants received a post-test survey to determine any difference in knowledge and attitude. Baseline knowledge and attitudes (also called a pre-test) were collected and compared to the surveys completed after the participants visited the stations. This allowed the TIFF team to conduct statistical tests to determine which stations best facilitated improved flood-related understanding (See **Appendix B-15** for the complete workshop and message testing findings).

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

The workshops successfully gathered valuable insights from small business owners, local government employees, and the general public, directly contributing to the goal of better understanding how to visualize and communicate flood-related information in culturally appropriate ways. Table 2-10 provide an overview of the statistical workshop findings.

The findings from the workshops include:

- Participants found hands-on activities, collective conversation, and tangible practice highly engaging and educational
- While digital methods (such as online virtual reality or simulations communicating flood risk) need testing in the future, the low-tech approaches used here proved powerful and easily grasped within five to ten minutes per station
- Future communication strategies should include story-based formats that resonate with the LRGV community while effectively conveying critical flood risk information
- Workshop activities with the general public revealed a need to improve communication around proper sandbag filling and stacking, as well as access to obtain sandbags
- Initial results suggested drainage maps (including elevation, drainage information, and direction of water flow) were more effective in enhancing participants' understanding of how flooding occurs in the LRGV than the FEMA flood risk map
- Most participants were aware that illegally dumping waste materials, such as branches, refrigerators, tires, and dead animals, creates further complications around flooding issues in the area
- The workshop supported learning outcomes for decision-makers from local utilities

Houston residents evacuate along I-45 ahead of hurricane © Stan Honda

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Table 2-10. Statistical workshop findings overview.

Survey Item/Station Experience	Was the Change Statistically Significant?	P value (< .05 considered statistically significant)
Increase in knowledge that sandbags should be filled completely full when exposed to the sandbag brochure station only	No (marginally yes)	p = .07
Increase in knowledge that sandbags should be filled completely full when exposed to the hands-on sandbag preparation station only	Yes	p = .003
Increase in knowledge that sandbags are available for free when exposed to the sandbag brochure station only	No	p = 1.0
Increase in knowledge that sandbags are available for free when exposed to the hands-on sandbag preparation station only	No	p = .72
Increase in confidence using sandbags when exposed to sandbag brochure station only	No	p = .35
Increase in confidence using sandbags when exposed to hands-on sandbag preparation station only	Yes	p = .007
Increased perception that sandbags are effective when exposed to the sandbag brochure station only	No	p = .74
Increased perception that sandbags are effective when exposed to the hands-on sandbag preparation station only	Yes	p = .005
Increased plan to use sandbags in the future when exposed to the sandbag brochure station only	No	p = .26
Increased plan to use sandbags in the future when exposed to the hands-on sandbag preparation station only	Yes	p = .001
Increase in knowledge that flooding can happen even when not raining in your area when exposed to the FEMA map station only	No	p = 1.0
Increase in knowledge that flooding can happen even when not raining in your area when exposed to the Drainage District map station only	Yes	p = .001
Increase in knowledge that water in LRGV often drains toward Willacy Co. when exposed to the FEMA map station only	No	p = 1.0
Increase in knowledge that water in LRGV often drains toward Willacy Co. when exposed to the Drainage District map station only	Yes	p = .001
Increased knowledge that grass clippings impact flooding after experiencing the hands-on illegal dumping station	No	p = .38
Increased knowledge that illegal dumping impacts flooding after experiencing the hands-on illegal dumping station	No	p = .76
Increased confidence that they could avoid placing items in ditches after experiencing the hands-on illegal dumping station	Yes	p = .02
Increased perceptions that avoiding putting items in ditches can be effective for flood control after experiencing the hands-on illegal dumping station	No	p = .26
Increased intentions to avoid putting items like yard clippings, tires, and trash in ditches after experiencing the hands-on illegal dumping station	No	p = .52

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Community Learning Exchange

Lastly, TIFF hosted a Community Learning Exchange (CLE), which brought together local stakeholders and resulted in the creation of a museum exhibit and a multi-modal data collection archive that bridges scientific modeling with community knowledge and cultural memory. These resources built upon and added to the LRGV Flood Information Collection developed in collaboration with the Museum of South Texas History.

The public events concluded with a CLE attended by local stakeholders. The event gave the team an opportunity to share what they learned through the workshops and hear participants' feedback on the flood-related education materials (see **Appendix B-16** for the meeting agenda and presentation slides). TIFF re-engaged participants from the initial two workshops and expanded participation to encompass additional stakeholder groups who had provided interviews and contributed to the design of the content used for workshop surveys. The event also welcomed additional stakeholders who had not participated in initial interviews, including community organizations, university researchers, and public officials.

The CLE focused on enhancing local understanding of flood risk and communicating that risk effectively with the community. The event featured live translation services, which were essential to ensure comprehension among all participants, as some spoke English and others spoke Spanish. TIFF presented five different information formats including 1) newly collected drone data including an online interactive geospatial dashboard featuring layers such as building footprints, colonia extents, terrain and elevation layers, water infrastructure, and a base map with roads; 2) paper brochures related to sandbag practices; 3) informational magnets; 4) a musical corrido recording describing the impacts of a historic hurricane; and 5) a photo album containing hard copies of previous hurricane flooding events. The CLE participants shared their preferred formats orally.

Presentations were given by community organizations about ongoing projects aimed addressing flood-related issues in the area. Community members shared recent flood-related experiences with local officials, creating opportunities for positive dialogue. After the presentations, participants were paired with individuals they had not previously met and guided through the museum's galleries. The walk-and-talk activity invited participants to meet others at the event, share stories of their own personal flooding experiences, suggest areas for improvement related to flooding, and learn about other people's experiences. After the walk and talk, participants shared discussion highlights with the broader group. In addition, a local artist attended the CLE and created a live painting. The resulting artwork reflected the themes and insights captured from discussions during the CLE. (See **Appendix B-14** for a more detailed discussion about the event.)

Summary of Findings

The following pitfalls were identified through these workshops, the CLE, and analyses of past flood response efforts in the LRGV and are summarized in Table 2-13:

There is a Communication Disconnect Between LRGV Officials and Residents

Workshop participants and CLE discussions revealed a persistent gap between how officials communicate flood information and how residents receive and interpret it. Many residents lack clear, consistent, and accessible information on flood preparedness, not because information does not exist, but because it fails to reach them in usable forms. Technical language, jargon-heavy documents, and limited outreach channels erode both trust and comprehension. Spanish-speaking residents face compounded barriers. Emergency communications provided only in English or translated without attention to cultural context and local terminology, leave many community members unable to act on critical information. Participants emphasized that effective communication requires more than translation; it demands culturally grounded messaging developed in partnership with community members.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Existing Information is Poorly Integrated and Leads to Information Overload for Residents

The proliferation of flood models, data sources, and agency communications has created a paradox: more information is available than ever, yet residents find it harder to know what to trust or how to act. Multiple overlapping products from different agencies, sometimes presenting conflicting risk assessments, generate confusion rather than clarity. Without coordinated messaging or a recognized authoritative source, residents struggle to reconcile differences. Technical barriers compound this problem. Poor cataloging, inconsistent metadata, and excessive jargon prevent community members from locating or applying relevant information. Workshop participants noted that even motivated residents often abandon searches for flood data after encountering inaccessible formats or unclear guidance on which sources to prioritize.

Communication and Logistics Failures Limit Awareness and Access to Resources in the LRGV

Basic preparedness resources remain out of reach for many LRGV residents, not due to scarcity, but to communication and logistics failures. Sandbags emerged as a focal point: widespread confusion regarding where to obtain them, how to fill them properly, and how to stack them for effective flood protection. Many residents are unaware that free sandbag distribution points exist; others know of them but lack transportation to reach distribution sites during emergencies when timing is critical. This finding highlights how resource availability alone does not ensure preparedness. Without proactive, multi-channel communication that anticipates logistical barriers, physical resources fail to translate into community resilience.

Illegal Dumping and Drainage Infrastructure are Key to Flooding Impacts in the LRGV

Illegal dumping contributes significantly to drainage blockages that amplify flood impacts, yet this connection remains poorly communicated to residents. Current messaging treats dumping primarily as an environmental violation rather than a flood risk behavior, missing an opportunity to link individual actions to community-wide consequences. The potential impact of addressing this gap is substantial. Participants noted that flooding severity increases markedly when drainage infrastructure is compromised by debris accumulation. However, existing outreach lacks the behavioral design elements needed to change dumping practices: clear consequences, convenient alternatives, and community accountability mechanisms. Collaborative efforts between local officials and community organizations could bridge this gap, reframing illegal dumping as a shared flood preparedness concern rather than solely an enforcement issue.

Young People and Cultural Networks are Underutilized Communication Agents

Children and youth demonstrated strong environmental awareness throughout workshop activities, yet they remain largely untapped as agents of community-wide flood communication. Young people often serve as translators and information brokers within multigenerational households, positioning them as potential multipliers for preparedness messaging, a role that current communication strategies overlook. Similarly, established cultural networks remain underleveraged. Promotora networks, trusted local leaders, and community organizations possess the relationships and credibility needed to deliver flood information effectively, yet they are rarely integrated into official communication channels. Schools represent another missed opportunity—educators expressed interest in flood education programs but lack curriculum materials, training, and resources to implement them. Investing in these existing networks could dramatically extend the reach and resonance of flood preparedness efforts.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Table 2-11. Communication pitfalls identified during the TIFF workshops, CLE, and analyses of past flood response efforts with potential strategies to address identified pitfalls.

Pitfalls	Potential Strategies
Disconnect Between Officials and Residents	Develop culturally grounded messaging in partnership with community members; expand Spanish-language communications beyond direct translation; diversify outreach channels to reach often-missed populations
Information Overload and Poor Integration	Establish coordinated messaging protocols across agencies; designate authoritative sources for reconciling conflicting information; improve metadata cataloging for public-facing data products
Limited Awareness and Access to Resources	Implement proactive, multi-channel communication about resource availability; address transportation barriers through mobile distribution or neighborhood-based access points; create clear visual guides for sandbag use
Illegal Dumping and Drainage Infrastructure Issues	Reframe dumping as a flood preparedness issue rather than solely an enforcement concern; develop behaviorally informed messaging linking individual actions to community impacts; foster collaboration between officials and community organizations
Underutilized Youth and Cultural Networks	Integrate youth into communication strategies as household information brokers; partner with promotora networks and trusted local leaders; develop and resource school-based flood education curricula

(For more in-depth discussions on the work carried out in the LRGV, see **Appendix B-14**.)

Data Enhancement for the Lower Rio Grande Valley Flood Information Collection

Effective disaster preparedness requires understanding not only of the physical dynamics of extreme events, but also how communities experience, remember, and respond to them. Traditional approaches often treat scientific data and community knowledge as separate domains, limiting the ability to develop communication strategies that resonate with diverse audiences. Building on insights from the workshops and CLE described in previous sections, TIFF expanded a comprehensive data collection that systematically links multiple forms of resources, enabling users to explore connections between quantitative models and lived experience.

The LRGV Flood Information Collection represents a collaborative effort initiated in 2020 between the MOST and UT-Austin to establish a robust computational infrastructure for data management and analysis via funding from the Planet Texas 2050 program (for more information see https://bridging-barriers.utexas.edu/planet-texas-2050). TIFF expanded this information collection by gathering new data through community engagement events described in previous sections of this report to create a multi-modal archive that bridges scientific modeling and data with social understanding, as reported in interviews and cultural memory. The collection is publicly accessible through the PT2050 Data Portal (https://ptdatax.tacc.utexas.edu/) by searching within the Data Discovery service. Each partner institution maintains an up-to-date registry of the curated "LRGV Flood Collection."

The LRGV Flood Information Collection encompasses seven primary data categories, each serving distinct communication purposes as shown in Table 2-12. The workshops and CLE expanded the collection to include less traditional formats that capture community and cultural dimensions:

- **Musical recordings**: Styles such as corridos common in the LRGV
- **Dendrochronology records**: Demonstrating past wet/dry year conditions (future expansion)
- **Focus group accounts**: Records from community discussions and experiences
- **News and media records**: Descriptions of damages, injuries, and community impacts

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Table 2-12. LRGV Flood Information Collection categories and communication readiness.

Data Category	Example Content	Formats	Communication Use
Community Narratives & Oral Histories	Interview recordings, transcripts, first-person accounts	WAV, MP3, TXT	Cultural preservation, community outreach
Computational Model Outputs	ADCIRC surge models, flooding simulations	NetCDF, GeoTIFF, CSV	Technical analysis, risk assessment
Geospatial Data	LiDAR terrain, interactive 3D visualizations	SHP, GeoJSON, KML	Spatial context, emergency planning
Archival Materials	Historical photos, documents, reports	TIFF, PDF/A, JPEG	Validation, historical reference
Analytical Outputs	Natural Language Processing results, timeline reconstructions	JSON, CSV, XML	Research, pattern identification

The communication gaps revealed by the public events informed the design of a Communication Readiness Framework that TIFF applied to the LRGV Flood Information Collection. Communication-ready data products meet three criteria: Technical Interoperability (standardized metadata, common formats), Contextual Completeness (bilingual descriptors, provenance documentation), and Multi-Modal Accessibility (multiple formats per use case). To ensure the collection provides a foundation for more targeted, effective communication that can evolve as community needs and communication channels change, TIFF embedded implementation classification tags within the data infrastructure itself. Each implementation tag addresses specific barriers uncovered through community engagement.

Use case tags (educational, community outreach, cultural preservation) support integration with schools and cultural networks that are currently underleveraged. Audience tags (technical users, community members, decision-makers, educators) ensure that materials can be filtered to match user needs, reducing information overload. Language and accessibility tags (Spanish/English, audio described/subtitled) respond directly to the barriers facing Spanish-speaking residents.

EVALUATION METRICS AND METHODS TO DESIGN AND ASSESS FUTURE EFFORTS

Designing and planning for evaluation from the beginning of a project is important because that will provide a mechanism to adjust, strengthen, and adapt communication over time. Metrics, or measures of success through indicators, help designers create meaningful, data-rich messages for specific groups and aid diagnosis for any issues, surprises, or aspects of a tool that are unexpected later. A key aspect of communication is identifying the target groups with experiences that can help shape technical information to make it more accessible to communities who need it. Every campaign and evaluation project or program must be tailored to the specific communication goals, target user groups, tools or applications to be assessed, and other constraints, such as budget, time, and available expertise in evaluation.

To effectively evaluate the effectiveness of flood communication and visualization approaches and tools, it is essential to consider various categories of interest that also align with the diverse needs and contexts of target users. By tracking quantitative evaluation metrics, an agency, program, or project can gain valuable insights into how effectively flood risks and coastal modeling information or visualization tools are performing. Together with more tailored metrics for specific target users, an organization should be able to assess performance over time and identify areas for improvement.

This section describes TIFF's work to develop a Target Group Pilot Test (TGP Test) methodology, a useful approach for designing hypothesis-driven tests for target users. The approach is designed to be reusable and adaptable, leveraging insights from previous research and emerging AI tools to create mea-

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

surable performance metrics. Additionally, TIFF consolidated a set of practical measures and quantifiable metrics that can be adapted to fit the goals and objectives of a project, program, or information tool.

Tailored Approach Specifying Testable Hypotheses and Evaluation Metrics

Designing interfaces and information visualizations to effectively communicate coastal flood risk requires multi-faceted approaches to overcome known pitfalls. The complexity of the information requires streamlining the presentation and reducing cognitive loads as people try to make meaning of the information. In particular, communicating uncertainty poses a significant challenge that necessitates adapting messages and visualizations across multiple modes of presentation. Additional challenges arise when target user groups conflate accuracy with accessibility and usability.

TIFF developed a TGP Test methodology for designing hypothesis-driven tests for target users (Recommendation C2.4C). Using a human-AI partnering methodology, the TGP Test approach leverages large language models and structured prompt engineering (Figure 2-10). The step-by-step workflow follows 1) create a user query based on a seed document to ground the search, such as a peer-reviewed article or report about a target audience of interest, 2) prepare and submit structured prompts iteratively to build and improve structured queries over time, 3) elicit a design for evaluating communication and visualization, 4) iterate and revise, and 5) complete an experimental design structure that aligns with a specific user group and topical question of interest. While this approach is conceptual at the time of this report (and AI tools are not yet accessible to all people needing to evaluate flood communication tools/efforts), it represents a workflow to specify testable designs for communication and visualization in the future (Stephens et al., 2023; Trujillo-Falcón et al., 2024; Mobley et al., 2024).

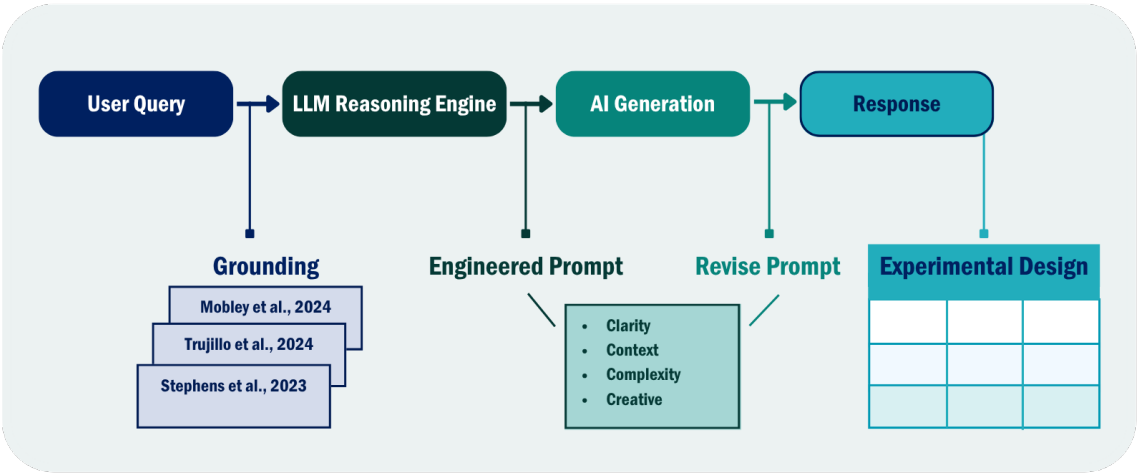

Figure 2-10. Step-by-step TGP Test workflow using artificial intelligence.

The process of designing a prompt and applying it to a problem can enhance the design of communication and visualization experiments. In the case of this report, the applied approach uses an iterative methodology to formulate structured queries and interact with a large language model service to generate a customized TGP Test. Table 2-13 presents the prompt design and example phrasings to frame the design outputs.

The development of evaluation metrics should be guided by the specific goals and objectives of flood communication projects. It is crucial to identify and align with the intended target user group to ensure that the information conveyed is relevant and actionable. An example experimental design is presented in Table 2-14 for a TGP Test Design to Assess Scientific Uncertainty for Flood Visualization and Communication with Property Owners and Property Renters. Testable hypotheses were evaluated around aspects related to communication about access to tools or information, understanding scientific uncertainty in communication about flooding, and the value of data to inform user groups.

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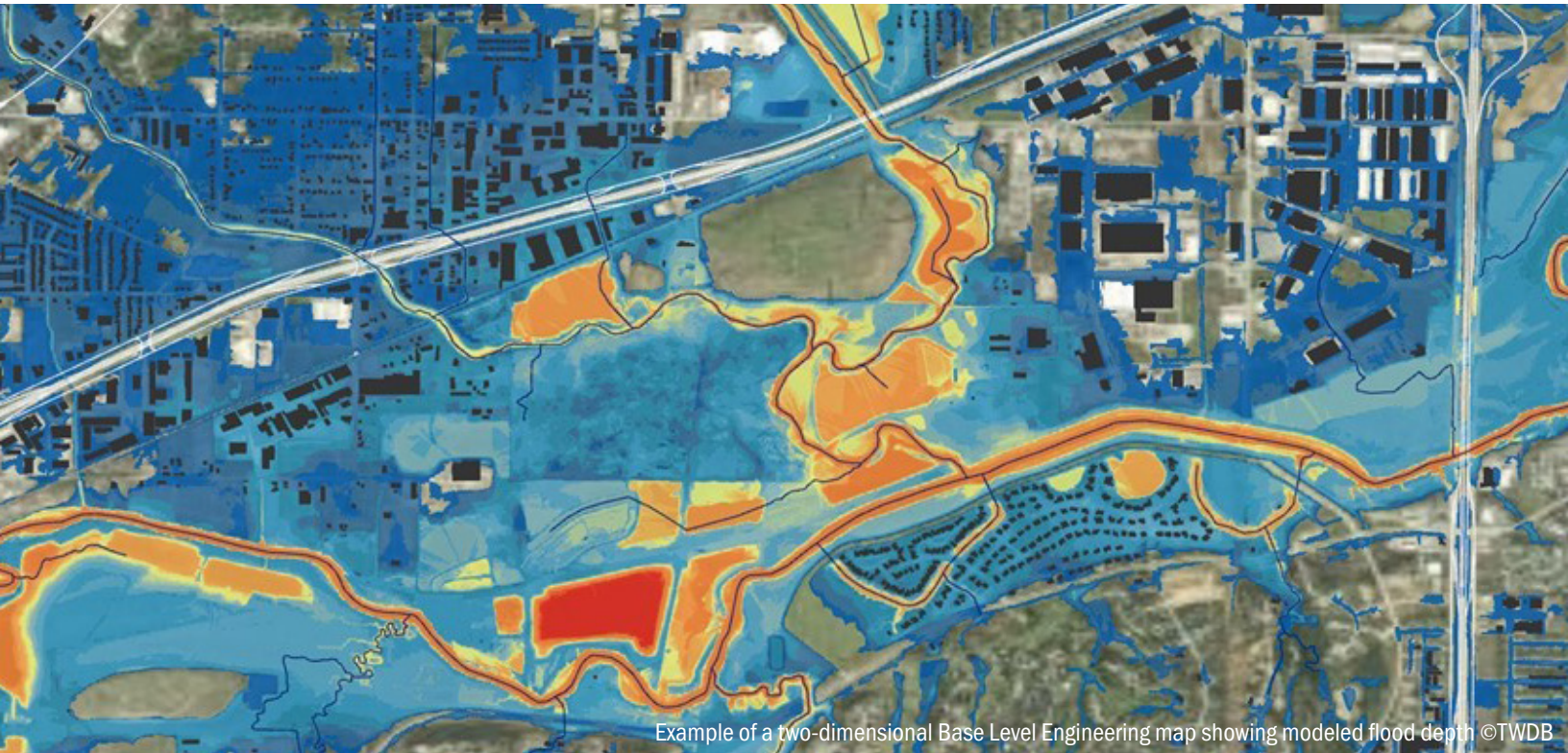
Table 2-13. Design prompts for testable hypotheses, experimental tasks, and observable metrics.

Prompt Design	Example Prompt Phrasing
Define Behavioral Archetype for Target User	"Define <<Target User Group>>" (*e.g., Property Owners, Property Renters, People with LEP*)
Core Information Needs	Example 1 - "What are the main flood-related risks the <<target user>> needs to be aware of?" Example 2 - "What are <<target users>> likely to do or worry about?"
Key Behaviors	Example - "What flood-related actions can <<target users>> take to reduce their risk?"
Identifying Evaluation Design for Target User Groups	Example 1 - "What are the principal challenges for <<target user groups>>?" Example 2 - "What are recommendations for effective communication for the <<target user group>>?"
Generates Testable Hypothesis	Example - "What is a hypothesis about the way <<target user groups>> use information from modeling for flood-related risks?"
Generates Experimental Tasks	Example 1 – Access - "Describe a test that could be designed to evaluate user interfaces for information related to <<core information needs>> for the <<target user group>>." Example 2 – Uncertainty - "What is a test that could evaluate the ability of a target user to assess uncertainty in <<visualization type or data content>>." Example 3 – Data - "What is a test that could evaluate datasets that would be useful when user groups assess <<core information needs>> and please consider multiple information visualization formats."
Generates Observable Metrics	Example - "What is a test that could evaluate the ability of a user to assess <<experimental tasks>> in <<information visualization formats>>?" (e.g., uncertainty in flood maps)
Note: << *brackets* >> are used to denote the locations in the prompts that can be replaced based on the specific user group, risks, or topic of interest. For example, <<Target User Group>> could be "*Property Owner*," "*Property Renter*," or "*People with LEP*."	



Example of a two-dimensional Base Level Engineering map showing modeled flood depth ©TWDB

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Table 2-14. TGP Test designs to assess scientific uncertainty for flood risk visualization and communication with *Property Owners* and *Property Renters*.

Target Groups: Home and Business *Property Owners* and *Renters* in Coastal and Non-coastal Areas		
Decision: Property Purchase Decision Support		
Evaluated: Analysis Capabilities and Uncertainty Representations		
Prompt Design	**Example Prompt Phrasing**	**Measurable Observation**
H1 – Scenario-Based Assessment	Present participants with a series of flood maps that include varying levels of uncertainty indicators, such as probability ranges or confidence intervals	Ask participants to interpret these indicators and make decisions based on the perceived risk to help assess their understanding of uncertainty
H2 – Uncertainty Comprehension Quiz	Develop a quiz that includes questions about the meaning of different uncertainty indicators used in the maps	Ask participants to explain what a "10% chance of flooding" means in practical terms or to compare the risk levels between different areas based on the map's uncertainty data (for example)
H3 – Decision-Making Tasks	Provide participants with tasks that require them to make decisions under uncertainty, such as choosing a location for a new home or deciding whether to purchase flood insurance	Evaluate how participants incorporate uncertainty information into their decision-making process
H4– Feedback and Reflection	After completing tasks H1-H3, ask participants to reflect on their decision-making process and the role that uncertainty information played.	Can provide insights into their thought processes and any difficulties encountered in interpreting uncertainty
H5 – Confidence Rating	Ask participants to rate their confidence in the decisions they made based on uncertainty about flooding	Can help identify whether participants feel certain about the risk of flooding
Designs based on Stephens et al., 2024 with Co-Pilot assistance in configuring designs.		

Key Features to Consider for Evaluation Design

Engaging target user groups is essential to confirm their needs and tailor communication strategies effectively. The recommended general performance measures and customization with the TGP Test aim to enhance the evaluation of flood communication and visualization tools, ensuring they meet the needs of diverse user groups and improve overall flood preparedness and response. For co-design, key recommendations include:

- Consider baseline conditions related to the flood communication issue that a tool is attempting to address
- Assess the baseline knowledge level of expected users with pre- and post-surveys before and after they use the tool
- Request user feedback during the design process to improve the usability and accessibility of the tools as part of a broader design conversation with potential users
- Consider the long-term behavioral changes, such as increased preparedness actions, that the tool is expected to improve

The proposed best practices, evaluation metrics (Table 2-15), and *The TIFF Communication Guidelines* offer a structured approach to assessing the effectiveness of flood risk communication and visualization

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

tools. The general evaluation categories present reliable options to assess user understanding and engagement, effectiveness of communication, usability and accessibility, adaptability and flexibility, visual and aesthetic quality, and impact and reach. For optimal results, design and test tools with specific target users in mind. Tool developers should determine specific target users (e.g., *Property Owners*, *People with LEP*) early and define their unique information needs. Finally, implement testable hypotheses as experimental tasks to refine the tools, adapt evaluation strategies, and assess tool access, uncertainty, and data aspects of flood communication tools.

Continuously evaluating and adapting these strategies is essential to enhance preparedness and response capabilities among communities and organizations. Implementing these evaluation measures can lead to improved flood communication and better outcomes in managing flood risks. Moreover, these suggestions provide insights into how coastal model data and information can be integrated into messaging, dissemination, and communication broadly.

Table 2-15. Evaluation metrics, measurement methods, frequency of measurement, and target outcomes across evaluation metric categories for assessing the effectiveness of communication and visualization tools.

Specific, Quantifiable Metrics	Measurement Method	Frequency of Measurement	Target Outcome
Total Sample			
Clarity and Comprehension	Surveys, comprehension tests, user feedback	Periodic (e.g., quarterly)	High comprehension scores, ensuring information is designed at an appropriate understanding level for each target group
Click-through Rates (CTR)	Tracking clicks on specific links	Continuous	High CTR indicating engagement, showing which content users find relevant
Page Views	Tracking page visits	Continuous	High number of page views, indicating popular content that attracts user interest
Session Duration	Tracking time spent on application	Continuous	Longer session durations, suggesting higher interest in the content
Repeat Visits	Tracking return visits	Continuous	High number of repeat visits, indicating sustained interest and usefulness
Interaction Depth	Feature utilization rates, task completion rates, clickstream analysis, user path analysis, heatmaps, engagement metrics, surveys	Continuous	High interaction depth, indicating users are exploring and interacting with numerous features within the tool
Conversion Rates	Tracking specific actions (e.g., sign-ups, shares, participation in training modules)	Continuous	High conversion rates, indicating users are taking desired actions
User Satisfaction Scores	Surveys, feedback forms	Periodic (e.g., quarterly)	High satisfaction scores, indicating users perceive their experience positively
Comments or Reviews	Qualitative feedback	Continuous	Positive comments and reviews, identifying strengths and areas for improvement

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Table 2-15. Continued

Specific, Quantifiable Metrics	Measurement Method	Frequency of Measurement	Target Outcome
Effectiveness of Communication			
Message Retention	Recall rate via surveys, quiz scores, long-term retention assessment	Periodic (e.g., annually)	High recall and retention rates, indicating users remember key messages over time
Behavioral Change	Action completion rate, preparedness measures, evacuation compliance, behavioral surveys, application usage	Continuous	Positive behavioral changes, indicating practical impact on user actions and safety
Usability and Accessibility			
Ease of Use	Task completion rates, error rates, first-time user success	Continuous	High ease of use, indicating tools are user-friendly and effective
Accessibility	Adherence to accessibility standards, assistive technology usage, visual and auditory access metrics	Continuous	High accessibility compliance, ensuring inclusiveness of design
Adaptability and Flexibility			
Update Frequency	Tracking update logs, user feedback	Continuous	Frequent and relevant updates, ensuring users have access to accurate and current information
Customization Options	Tracking customization feature usage, user feedback	Continuous	High customization usage and satisfaction, allowing users to adapt the tool to their interests or concerns
Visual and Aesthetic Quality			
Design Quality	Surveys of target groups	Periodic (e.g., quarterly)	High design quality ratings, indicating overall appeal and readability of the tool
Consistency and Coherence	Surveys of target groups	Periodic (e.g., quarterly)	High consistency and coherence ratings, indicating uniformity and trustworthiness of the information
Impact and Reach			
Audience Reach	Unique visitors, geographic distribution, demographic data	Continuous	Broad and diverse audience reach, indicating popularity and effectiveness in attracting target groups
Impact Assessment	Tracking actions taken (e.g., sign-ups, downloads), conversion rates, net promoter score	Continuous	High impact on user behavior and decision-making, indicating practical effectiveness of the tool
Information Sharing	Share counts, share rates, referral traffic, virality coefficient, click through rate on shared links, time spent on shared content	Continuous	High information sharing and engagement, indicating effective dissemination of information

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

The activities conducted under Objective 4 underscore the need for coastal flood user interfaces and related communication tools to be developed through a user-centered, participatory process that engages clearly defined target user group(s) early and consistently. Drawing on literature, stakeholder input, and TAT engagement, TIFF applied behavioral archetypes to identify *Property Owners*, *Property Renters*, and *People with LEP* as groups most likely to benefit from improved and targeted coastal flood communications. Designing tools for specific users ensures that interface functionality aligns with their needs and supports informed decision-making. Embedding accessibility, transparency, and iterative usability testing into UI development helps ensure that model outputs and datasets become practical and trustworthy inputs for planning and response.

The TIFF Communication Guidelines and *The TIFF Visualization Guidelines* outline strategies for effective information design and emphasize the importance of culturally and contextually adapted products. Testing these guidelines revealed meaningful differences in flood risk perception across the three selected target users, as well as between coastal and non-coastal users, reinforcing the need for tailored communication products. Additional engagement in the LRGV identified further opportunities to strengthen regional and specific flood risk and preparedness messaging.

To complement the guidelines, TIFF developed evaluation metrics and methods to support continuous improvement of communication products, ensuring messages remain meaningful, actionable, and responsive to user needs. Applying these practices across state efforts will help translate technical flood science into clear, equitable, and usable information that supports informed decision making across Texas.

Objective 5: Assist TDIS with computational hardware/software requirements for flood-related analysis and visualization

TIFF worked closely with the TATs to provide support to TDIS in identifying and recommending computational hardware and software requirements for flood-related analysis and visualization. The literature reviews and Model Coupling Workshop conducted under Component 3 (see Component 3: Objectives 3 and 4 and **Appendix C-10**) informed the following overview of hardware and software considerations necessary to support the flood analysis and visualization needs of Texas.

An example of the typical data management and computational resource needs for a large regional compound flooding study is provided by the 2023 study using the USACE-ERDC Coastal Hazard Systems for Texas, referred to as CHS-TX (See the CHS Studies Repository for more information; https://chs.erdc.dren.mil/Home/Studies). This study included flood inundation modeling results that were integrated into flood hazard analysis and could be hosted in CHS, to make a large amount of the data available to the public. The required computational resource and storage needs are provided in Table 2-17. The numerical modeling involved a dynamically linked storm surge (ADCIRC) and nearshore wave model (STWAVE) that allowed each model to share solution results during the coupled run time steps. A total of 660 synthetic tropical storms and 47 non-tropical events were simulated over three different starting water levels, a base sea level plus two sea level rise scenarios. The synthetic storm events ranged from a 4-day duration up to 13 days, with a typical or average duration being six days. For each storm event, a deep-water wave model known as Wave Model (also referred to as WAM), was used to simulate wave conditions for the entire Texas coast using each of the storm events. The storms were simulated once and used to generate boundary conditions for the nearshore wave model domains. The surge model was run for the entire length of the storm. Wind conditions, pressure conditions, and nearshore wave action were computed for a duration of time that coincided with when the storm forcing winds reached the model domains and lasted until the storm force winds exited the domains. The CHS-TX modeling was performed for the 2016-2018 timeframe using HPC computational resources at USACE-ERDC. A typical run time for the coupled ADCIRC+STWAVE was six hours using approximately 1800 HPC cores, which translates into about 10,000 CPU hours per simulation.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Performing the same simulation using current HPC computing resources at USACE-ERDC would take approximately 3.5 hours with the same number of cores for a total of about 6000 CPU hours. The original study used approximately 40 million CPU hours to complete all the simulations, 660 synthetic tropical cyclones, 47 non-tropical events, and seven historical tropical cyclones repeated for three different sea level conditions, plus time required for calibration and stabilization. The model outputs for storm surge, velocities, winds, pressure, and wave conditions included both peak values for each quantity, along with time series data at every ADCIRC node and every STWAVE grid cell, in addition to values stored at the 18,322 save points. (The data storage requirements for this example simulation are discussed in **Appendix C-7**.)

Table 2-16. Examples of computational and data resources for CHS-TX.

Description	Computational or Data Need
Models	ADCIRC coupled with nearshore wave model STWAVE, and deep-water wave model WAM
Number of Nodes / Number of Elements	4.53 million nodes / 8.98 million elements
Elements Sizing (maximum, minimum, average coastal)	62 km maximum, 24 meters minimum, 150 meters average coastal zone
Number of Save Points	18,332 save points
Number of Tropical Cyclones	660 synthetic tropical cyclones
Number Nontropical Storms	47 non-tropical events
Number of Validation Storms	7 validation storms
Number of Augmented Tropical Cyclone Suite Storms	765,600 synthetic tropical cyclones
Computational Cost	6000 to 12000 CPU Hours per simulation
Model Data Storage	Average of 200 GB not compressed per simulation
Archived Model Data	50 TB compressed for 660 simulations
Data Stored in CHS for Public Access (earlier version)	~ 600 GB (tropical cyclones only)

Potential Computational Resources for Developing a Compound Flooding Software Framework (See TxCFF in Component 3)

Developing a compound flooding software framework will require substantial computational and storage resources to provide the extensive scenario (ensemble) data needed for flood hazard analysis. HPC systems, medium sized local computing clusters or cloud computing infrastructure will be critical for handling the complex and large-scale simulations. Note that few groups in Texas (outside of some universities and federal agencies) have on-premise large-scale computing resources, particularly HPC resources that are necessary for compound flood inundation modeling and the GPU resources that might be needed for future versions of advanced flood hazard modeling. Access is available via cloud-based resources, but they also require significant expertise in selecting the hardware configurations to use and in installing the computational software. Furthermore, the cost of such cloud-based systems may be prohibitive, particularly when compared to shared on-premises HPC resources. Compound flood modeling of large spatial regions that includes all physical components is beyond the capabilities of desktop computers at present. Additionally, the complexity of the models, how to integrate them, and the required expertise in setting up and executing the models is beyond the reach of most users in industry and those involved in policy, emergency response, and planning for the Texas coastal zone.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Some potential paths toward this goal for an effective regional compound flooding modeling software framework include:

1. **WaterWorks OnDemand (WWOD)**: USACE HPC systems could perform the simulations and archive the data. However, access would be restricted to Department of Defense personnel. Thus, the data would need to be transferred to another platform yet to be identified. The USACE WWOD system is being developed with an open-access community usage paradigm to help streamline complex computational workflows such as those required by compound flooding assessments. WWOD uses code as an infrastructure to configure the cloud computing requirements and dockerized containers, to allow (for example) easy installation and setup of the operating system environments and flood modeling computational software. Predefined semi-automated workflows are being developed that guide users through setup and execution of the modeling processes. The WWOD platform is a major delivery mechanism for an overall numerical model modernization effort being led by USACE-ERDC. The goals of that effort are to guide investments in numerical technologies and data management while improving and integrating the modeling and data products as well as improving the accessibility of the data and lowering the entry level threshold for applying the complex numerical models without negatively impacting solution accuracy. Existing workflow within WWOD could serve as the foundations for building even more complex workflows for compound flooding hazards analysis for Texas. Furthermore, this system and its workflows would be able to be deployed in such a way as to make data access and further computing resources available to community partners.
2. **University HPC resources**: University HPC resources (e.g., TACC) can be contracted under Texas interagency agreements. However, for long-term access of industry users as well as state, county, and city employees, it will be necessary to consider long-term hosting requirements for the tool. Commercial products such as AWS, Microsoft Azure, or Google Cloud offer hosting flexibility, but cost analyses must include data transfer fees, processing expenses, and long-term data retention strategies. (See Data Management under Objective 2 for further detail.)
3. **TxGIO or TDIS**: TWDB and GLO might find it more cost-effective to develop suitable HPC capabilities within TxGIO or TDIS (which generates a different cost structure for equipment and maintenance). A hybrid computational approach using on-premises HPC clusters for real-time computation and cloud storage for archival purposes may optimize both cost and operational efficiency. These infrastructure needs must be balanced against project budgets, requiring continuous assessment as the model evolves and computational demands grow. Discussions of possible hosting approaches should proceed in parallel with building the software framework so that the code developers can consider long-term hosting issues in the framework design.
4. **Evolving Computing Architecture (GPU Computing)**: Computing architectures are always changing in response to new ideas and technology. GPU computing is becoming more prominent, especially at modern supercomputer centers and federal agencies where a focus is on AI/ML models that efficiently use GPU systems. This trend may continue but using parallel CPU architecture will likely dominate physics-based models for the next decade. The challenge is that the underlying structure of GPU architecture creates non-trivial coding challenges for physics-based models due to the inherent connectivity within the solutions. Consequently, rewriting physics-based models for GPUs is time-consuming and may not provide sufficient speed-up to justify the costs. However, some components of the compound flooding software system may be better suited for GPU. In particular, both flood hazard analysis and new Flood Inundation Data-Driven (FIDD) data-driven models for flood inundation that are trained on conventional physics-based inundation models may be more efficient when designed on GPU. Thus, there is a need to consider designing for access to both CPU and GPU architectures.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Another option may be to adopt or develop new models that are GPU-optimized and still maintain the required levels of physics to accurately represent the hydrodynamics processes. Cloud storage can also facilitate reuse of the modeling data by making it more accessible and having it alongside computing resources suitable for data manipulation and analysis, which can often be GPU-based. There is a possibility that the wider applicability of the GPU architecture particularly for AI/ML will eventually drive parallel CPU architectures out of the market so that they cannot be cost-effectively maintained and operated. In such a case, it would be necessary at a future date to either adopt new physics-based models or to rewrite the existing physics-based flood inundation models for GPU machines. As mentioned previously, this is a non-trivial task, given the complexity of physics-based flood inundation models that have typically been developed over a decade or more. As a conservative estimate, it would take 3 to 5 years to rewrite a single complex physics-based flood model with an additional 1 to 2 years for full testing, validation, and development of updated graphical UIs as well as supporting software for pre- and post-processing.

Computational Resources for Different Objectives

Computational resource needs for compound flood analysis depend on the overall objective. A comprehensive compound modeling/analysis framework (such as the proposed TxCFF described under Component 3) can support a wide range of uses, including building an inundation database, screening level analysis, operational strategy evaluation, planning strategy evaluation, and detailed infrastructure design. Each of these has different computational resource requirements:

- **Building a flood inundation database**: In general, flood inundation models are too computationally expensive to run in response to custom "what if" scenarios that stakeholders might want to examine. Thus, a key aspect of the software should be running a set of extensive flooding scenarios that can be later accessed for various user purposes and conducting flood hazard analyses. Running these scenarios will be the most computationally intensive part of the framework. Once these have been built for a particular testbed location, updates for additional "what if" cases can be conducted as needed using the full models or surrogate models trained on the full database could be used instead.
- **Screening level analysis**: Agencies often look toward "screening" analyses that require rapid computation of a variety of high-level options. In such analyses a relatively high level of uncertainty is typically tolerated. The ideal framework would include an extensive database of flood inundation scenarios, previously run with high levels of accuracy using full-physics models, that can be used as part of a screening analysis (as discussed above). Where new "what if" scenarios are required, the tool could provide rapid-response reduced-physics modeling (with increased uncertainty) to allow managers to rapidly assess different options and decide whether the additional efforts of full-physics modeling are warranted for a given application.
- **Operational Strategy Evaluation**: The effectiveness of real-time operational strategies can be evaluated using performance metrics such as response times, the accuracy of forecasts, and the efficiency of stakeholder communication during events. Post-event analysis provides critical feedback for improving model accuracy and updating protocols based on lessons learned. Tools to meet such objectives can be built using flood inundation and hazard analysis models within the framework, or as stand-alone desktop or web applications that access the framework's databases. Such tools typically do not have extensive computational resource requirements, although their database access speed can be a critical limitation. Web applications that are executed within the same resources where the database is located, like in a cloud-computing environment, can greatly reduce latency.
- **Planning Strategy Evaluation**: Long-term planning strategies should be evaluated through scenario-based, risk-based, models that incorporate climate projections, land-use changes, and

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

infrastructure developments. Key metrics include cost-benefit analyses, risk management in flood-prone areas, and the impact of planned projects on overall flood resilience. Similar to operational strategy evaluation, the tools to evaluate planning strategies often do not require extensive computational resources, but the speed of their database access to previously run scenarios will control their efficiency. Where such analyses need to create new "what if" conditions, or situations where the project designs are expected to significantly alter flood conditions, then new simulations will be required, and their computational resource requirements will scale on the size of the testbed domain.

- **Detailed Infrastructure Design**: Creating a system that can be used for detailed infrastructure design is the most challenging use-case for computational resources. Inherently, proposed infrastructure will change compound flooding in ways that are not likely included in the existing "what if" scenarios used to build the framework's inundation database. Furthermore, designers typically seek to evaluate a range of design options, each of which might have a different impact and require a different flood inundation model. To make the system useful for design, there needs to be straightforward ways for model users to address a smaller subset of the testbed (e.g., a neighborhood) and setup/run a range of "what if" models for their design vision. Systems such as the USACE's WWOD workflows and USACE's Coastal Storm Modeling and Production Systems (CSTORM) serve as examples that can be expanded to include compound flooding and not just coastal surge and waves. Whether such model of smaller areas can be run on local (non-HPC) workstations or will require access to HPC, or cloud computing remains uncertain and is likely to change over the next 5 to 10 years as computing hardware changes and software and methods evolve.

State, Local Agency, and Stakeholder Involvement

Effective flood resilience efforts require an operational framework that ensures collaboration among key stakeholders, including TWDB, GLO, other state and local agencies, and for-profit and non-profit organizations. Each of these entities brings unique expertise, and their roles in building, maintaining, and using an operational framework should be clearly defined. TIFF could be tasked with overseeing the technical aspects of model implementation and maintenance, ensuring its continuous improvement. TDIS can work with TIFF and Texas agencies to support data management and dissemination effort. Coordinating efforts between these entities will be key to ensuring the flood modeling framework remains operationally sound, continuously updated, and relevant. The involvement of local municipalities and communities, which may provide qualitative insights into flood risk and resilience needs, should also be strongly considered. This integrated stakeholder approach ensures that the flood model supports comprehensive flood management across Texas, meeting both technical and community needs, now and into the future.

Collaboration with Federal Entities

Close collaboration with federal agencies such as NOAA, USGS, FEMA, the U.S. Department of Transportation, and USACE is imperative. NOAA's involvement, especially through its local weather offices, is critical to gaining a localized understanding of watershed dynamics, improving forecast accuracy, and ensuring the models reflect real-world environmental conditions. USGS's efforts, such as the Federal 3D National Elevation Program and other geospatial data acquisition initiatives, are vital to establishing a comprehensive and high-resolution database. USACE contributes critical expertise in hydraulic modeling, flood risk management, and access to detailed datasets from their flood control infrastructure and navigation projects (e.g., levee, dam, reservoir, floodgates). Input from the U.S. Department of Transportation is essential for incorporating transportation infrastructure data and understanding the impacts of flooding on evacuation routes, roadways, and critical transportation assets. These federal collaborations will provide essential datasets, including topographic, bathymetric, infrastructure, and transportation network details, needed to support both inland and coastal flood modeling across the state of Texas. Furthermore, the involvement of these federal entities should extend to continuous model updates and

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

enhancements, ensuring that the latest scientific data and flood risk trends are incorporated into statewide modeling efforts. Coordination with these agencies can also facilitate the sharing of best practices and avoid duplication of efforts, ensuring that resources are used efficiently.

Operations and Maintenance Support for Computational Resources

Long-term support and code maintenance of a model coupling software framework and database management is out of reach for most universities and can only be undertaken or coordinated by agencies or research centers with stable and experienced workforces. Universities can provide crucial manpower for developing and testing new code and algorithms, but there needs to be some means to make the software framework available and ensure integration of updates. We can think of these tasks as operational control and maintenance control. The former is the task of making a software system available online as a functioning user application. The latter is to make sure the code works as desired and is routinely updated for advances in research.

There are three basic paradigms that can be applied to operation and maintenance: 1) centralized, 2) community-based, and 3) hybrid:

1. **Centralized control**: The traditional paradigm where a centralized organization (government, corporation, or individual) controls the software. A good example is the USACE's suite of models built and maintained by HEC without providing open-source code for the community to research and adapt.
2. **Community-based**: Over the past three decades, we have seen the emergence of communities that organize around open-source software to provide code updates and/or operational implementations. True community-based software systems tend to be smaller software applications, simply because as they grow larger, they tend to become fractured into a myriad number of "forked" applications and the project loses coherence. The varying quality of maintenance and code validation over variety of forked applications has led to the development of hybrid control, as described below. The plethora of Linux kernels that are available provides a good example of the natural diffusion of community-based models and the subsequent development of a range of hybrid control organizations. Another example is the Princeton Ocean Model (POM) from the late 1980s, which was open source but predated the GitHub versioning controls that are now standard practice; by the 1990s there were dozens of versions of POM available throughout academia. Today, POM is still somewhat community-based but is arguably hybrid controlled through the POM user group (https://www.pomusers.org/codes).
3. **Hybrid**: Most successful "community-based" applications are actually a hybrid organization, with some central entity (often, but not necessarily, a non-profit foundation) providing control over the "accepted" code updates provided by a broader community. This can be thought of as a "gate keeper." The "R" computing software, run by R Foundation (https://www.r-project.org/foundation/) is an example of a non-profit that has good, centralized control for maintaining and validating code while allowing substantial scope for community involvement. The Modular Finite-Difference Flow Model 6 (MODFLOW 6) groundwater modeling program (https://code.usgs.gov/modflow61/modflow6/-/releases) is an example of hybrid organization where a strong central control is exerted by the USGS, but the code is developed in an open-source repository so that outside model developers/researchers can easily make modifications and advances to the model. The USGS retains absolute control over which outside contributions are incorporated into the model.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

The key problem for long-term maintenance and operation of the model coupling software framework is likely to be maintaining a consistent funding scheme that supports four pillars:

1. Operational availability of the codes
2. Maintenance of the codes and incorporating the latest research
3. Developing and testing algorithm advances for the codes
4. Training users and the next generation of modelers

Operation and maintenance for a comprehensive compound modeling system needs to be either within a government agency or with a long-term contractor (which could be commercial, non-profit, or academic, such as TDIS). Key to the success will be guarantees of funding that ensure stability of the workforce and continued access to models and data. Keeping a flood modeling system operating and available to a wide range of users requires specialized skills that can be difficult to obtain, hence rapid turnover in either agency or contractor personnel due to variability in funding can create problems. Furthermore, there needs to be dedicated funding streams to university programs for developing and testing algorithms that advance the modeling system and keep it up-to-date with the latest research and technology advancements, and training modelers and users that the state, federal agencies, and contractors will need.

Objective 6: Make recommendations for future data management and visualization needs

As TIFF's ultimate legacy will be the set of recommendations, guidelines, and frameworks to improve the performance, understanding, and communication of flood science, it was imperative that the final recommendations made by TIFF be vetted and optimized by coordinated peer review so that they can be made actionable without hesitation by implementing entities. This coordinated peer review was structured around the component Objectives, in that the Objectives were used to query whether the existing list of potential recommendations completely addressed the goals of TIFF (**Appendices B-13** and **B-17**).

Recognizing that effective visualization is central to bridging the gap between complex scientific outputs and actionable decision-making, TIFF worked in collaboration with TDIS, the TATs, and multiple academic and agency partners to establish a comprehensive foundation for advancing coastal flood data management, visualization, and communication in Texas. Through these collaborations, extensive literature reviews, targeted workshops and surveys, and systematic data inventories, TIFF advanced the goal of ensuring that coastal flood-related data and model outcomes are properly visualized for both technical and non-technical users and supported the effort led by TDIS pertaining to data management and visualization related to the Texas coast. These coordinated efforts spanning data infrastructure, visualization, and user-focused design, culminated in a set of vetted recommendations and frameworks intended to guide future flood science initiatives.

Ultimately, 10 TIFF Recommendations resulted from the research and expertise associated with Component 2. (See the TIFF Recommendations Handouts which can be used to seek further support for implementation.)

Note: Each Recommendation is designed to articulate implementation needs, and where feasible, approximate costs. These cost estimates are included for planning purposes only and should be understood as preliminary and subject to refinement based on project scope, timing, and local/regional conditions and circumstances. In all cases, implementation of these Recommendations will require the identification and securement of appropriate funding. Additionally, implementation of these Recommendations is subject to the legislative authority and capacity of potential partners. Collectively, the Recommendations are designed to provide funders and policymakers with a clear roadmap for strengthening the state's flood resilience, ensuring that communities, infrastructure, and ecosystems along the Texas coast are better protected for the future.

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THE COMPONENT 2 RECOMMENDATIONS

Table 2-17. Component 2 Objectives for Data Management and Visualization and associated Recommendations.

Component Objective	Associated Recommendation(s)
Establish a Data Management and Visualization TAT	Objective met by TIFF. No further Recommendations.
Assist TDIS with designing and testing the conceptual framework for managing, visualizing, and disseminating large volumes of coastal flood-related datasets, including data visualization system(s)	Objective met by TIFF. No further Recommendations.
Conduct an inventory on coastal flood-related UIs	C2.3A: Improve Online Tools for User Comprehension C2.3B: Improve Emergency Planning by Better Understanding Evacuation Decisions C2.3C: Identify Effective Language to Communicate Flood Risk C2.3D: Create Flood Risk Planning Cards C2.3E: Standardize Shapefiles for State-Funded Flood Projects
Recommend guidelines for coastal flood-related UIs, including the level of end-user access, analysis capability, visualizations, and datasets	C2.4A: Implement TIFF Communication Guidelines C2.4B: Test Flood Safety Messages in the LRGV C2.4C: Adopt TIFF Target Group Pilot Test Methodology C2.4D: Develop Statewide Tool to Share Texas' Flood History C2.4E: Develop AI Flood Risk Tool to Share Flood Information
Assist TDIS with identifying and recommending computational hardware/software requirements for flood-related analysis and visualization	Objective met by TIFF. No further Recommendations.
Make recommendations pertinent to future data management and visualization needs to GLO as they are identified	Objective met by TIFF. No further Recommendations.

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C2.3A: Improve online tools to maximize user comprehension by studying user gaze patterns and other user responses to different flood risk visualizations and interactive tools

Research is needed to understand how individuals' gaze patterns shift when interacting with various modes of flood risk visualizations. This study will test how different modes of interaction influence user engagement and comprehension of flood risk. This includes in-situ testing, mobile device testing, and using eye-tracking with visualizations, potentially gamifying the process. Results from this study could accelerate understanding of what works for communication and complements efforts to assess emerging technology. This research should focus on testing existing and developing flood risk visualization tools used in Texas, such as the Buyers Aware platform, the CHARM online tool, and dashboards being developed by the IDRT and the UT-Austin. This research should also consider the usefulness of technologies for communicating model outputs. By studying how users interact with these tools, we can refine their design to enhance user comprehension and decision-making, ultimately improving flood preparedness and response efforts.

The estimated cost for this research is $225,000, covering eye tracking software and hardware, virtual and augmented reality equipment, immersive software, and research design and execution. Costs may be reduced if access to existing eye tracking and keystroke tracking equipment is obtained.

Key implementation actions include:

- **Literature Review**: Conduct a full review of interactive and active learning technologies, including user studies and data/analytics workflow; develop serious games and explore how to engage adults in playing these games
- **Eye-Tracking and Virtual Reality Studies**: Conduct eye-tracking and/or virtual reality studies to observe how gaze behavior changes when different visual representations of flood risk are shown to participants
- **Key-Logging Study**: Combine the previous studies with a key-logging study, where participants interact with flood risk information on the web; capture and analyze their search behavior and physical actions while seeking out flood risk data
- **Misinformation Response Studies**: Conduct additional studies to understand how people respond to misinformation about flood risk; compare reactions to a continuum of flood risk levels, ranging from low to high risk, to gauge how misinformation influences decision-making

C2.3B: Improve emergency planning and response by better understanding the decision-making of Texas residents facing evacuation during a flood

TIFF recommends conducting experiments, surveys, and focus groups along the Texas coast to understand how residents use local knowledge, media coverage, and personal experiences when deciding whether to evacuate.

Evacuation decisions are complex and influenced by many factors, including perceived risk, prior disaster experience, and trust in information sources. A critical research question is how past disasters, community knowledge, and media coverage influence decision-making. The research should also assess public trust in local authorities, meteorologists, and emergency managers, and examine how people interpret and act on messages about evacuation orders. A mixed-methods approach should be used to identify barriers to evacuation, common assumptions about risk, and ways to strengthen public communication. Insights from emergency managers and meteorologists should be integrated to ensure recommendations align with operational needs.

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Understanding how Texans decide whether to evacuate or stay can help guide improvements in outreach, communication strategies, and message design during emergencies. The estimated cost for implementation is $450,000. Participants should be compensated to ensure representative data.

Key implementation actions include:

- **Review State Operations Center Practices**: Interview TDEM experts with multi-event experience to identify opportunities to improve evacuation processes by leveraging better information aids, and to provide guidance on messaging strategies to inform the public about evacuation decisions
- **Select Testbed Locations**: Identify testbed sites based on geographic, storm and flood risk, and population characteristics (urban and rural) to capture a range of factors influencing evacuation decisions
- **Select Target User Groups**: Prioritize target user groups based on their vulnerability to coastal flooding and the potential benefits of improved risk communication, such as *Property Owners*, *Property Renters*, and *People with LEP*; beyond the prioritized target groups, additional research should be conducted to identify additional vulnerable populations with barriers that complicate decision-making and heighten risk, including Caretakers and Business Owners
- **Conduct Qualitative Studies in Coastal Communities**: Interview evacuees from the selected target user groups to understand decision drivers (reasons for evacuating, costs, influence of flood models or navigation apps); compare public perceptions with the technical information used by experts
- **Test Tools**: Use the findings from the qualitative study to design experiments testing the effectiveness of flood maps and navigation apps in aiding evacuation decisions; explore how tools can be tailored to each selected target user group

C2.3C: Identify more understandable ways of communicating flood risk to the public than current "frequency-based terminology" (e.g., "100-year Flood")

A significant challenge in flood risk communication is the language used to describe the probability of experiencing a flood. Longer timeframes, such as 100 or 500 years, are difficult for people to grasp, making it harder for them to accurately assess their risk.

TIFF recommends a mixed-methods study to 1) identify how people interpret current flood terminology, 2) develop and test alternative language to improve understanding and accuracy in risk perception, and 3) evaluate how those alternatives perform across languages, especially in English and Spanish given Texas's bilingual population. Future work should also develop relatable examples (e.g., this rainfall amount will carry a child, car, or house away) and assess how linguistic and cultural perspectives affect comprehension of probability and frequency.

The estimated cost of implementation is $750,000. Partner agencies are encouraged to share costs and collaborate on phased funding. Participants should be compensated to ensure representative results across demographic and linguistic groups.

Key implementation actions include:

- **Literature Review**: Examine national and international studies on risk communication, focusing on the United States, Mexico, and China; participation in international workshops is recommended to exchange insights and best practices
- **Interview Target User Groups**: Conduct a systematically designed set of interviews with specific target user groups to identify alternative language and timeframe communication options

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

- **Online Experimental Survey**: Test Texans in these target groups to identify which language options best influence decision-making, attitudes, confidence, response efficacy, and related factors; consider using the subjective numeracy scale and common probability frames used in flood communication
- **Train Language Models**: Based on the interviews and survey findings, train small language models on the specific language used in different coastal and compound flood scenarios, including mapping preferred terms in coastal areas and considering multilingual aspects
- **Evaluate Flood Literacy**: Determine whether alternatives to frequency-based terminology increase flood literacy in target user groups and improve their capacity to respond effectively to risk information

C2.3D: Create Flood Risk Planning Flashcards to support Texas flood planners and decision-makers

Flood risk maps, visualization tools, and coastal management information portals are essential for raising public awareness and driving action at individual, local, and national levels. These tools help residents, policymakers, and emergency responders understand flood risks, prepare for disasters, and make informed decisions about mitigation and adaptation. However, despite their potential, they often fail to effectively communicate flood risk to general audiences. When flood risk information is not clearly presented, non-technical users may misinterpret the data, either overestimating or underestimating the actual risk. Miscommunication can lead to poor decision-making, reducing the effectiveness of flood preparedness and response efforts. To address this issue, a more structured approach is needed to ensure that flood risk information is presented clearly and accessibly.

TIFF recommends the creation of Flood Risk Planning Cards based on *The TIFF Communication Guidelines*. These cards would serve as a toolkit for planners to better organize and prioritize flood risk reduction activities, providing a structured framework for developing and implementing effective strategies to target and reach their specific audiences. The cards would also encourage data-driven discussions during the flood risk planning process and offer a visually appealing, user-friendly design to improve engagement and usability. By integrating these planning cards into flood communication efforts, communities can enhance their ability to interpret flood risk data, plan for future events, and build greater resilience against flooding.

TIFF recommends partnerships between academic institutions, planning organizations, state funding agencies, cities and towns, flood control districts, and regional flood planning groups to develop and implement the Flood Risk Planning Flashcards.

Key implementation actions include:

- **Competitive Analysis & Market Research for Card Deck Development ($50,000-$100,000)**: Conduct a review of existing card decks (e.g., augmented reality 32-card deck), platforms where card decks are marketed (e.g., game crafters), typical costs, and the target audiences that purchase such cards
- **Card Deck Development ($50,000-$100,000)**: Design and create the Flood Risk Planning Flashcards based on insights from the competitive analysis and market research, using *The TIFF Communication Guidelines*
- **User Testing and Evaluation ($50,000-$100,000)**: Evaluate the effectiveness of the cards and gather feedback from users to refine and update the cards for continued improvement

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C2.3E: Require Texas agencies to collect three standardized shapefiles for all state-funded flood-related projects to improve state flood coordination

Flood-related projects in Texas involve various stakeholders, such as local governments, state agencies, and non-profits, working to improve flood management and response. However, a lack of coordination can lead to overlapping efforts, inefficient use of resources, and missed collaboration opportunities.

TIFF recommends a standardized requirement for all funded flood-related projects in the state to submit three critical shapefiles to the funding agency and other relevant recipients. These shapefiles will provide spatial data on the project's location, scope, and impact area. This standardized approach will allow agencies to quickly identify overlaps between projects, assess geographic synergies, and reduce redundancy.

By incorporating these shapefiles into project planning and evaluation processes, stakeholders can better understand the spatial relationships between ongoing and proposed projects, ensuring that funding is directed toward projects that complement each other. This will not only streamline the allocation of resources but also foster comprehensive planning and clarity in project objectives, ultimately enhancing flood preparedness, mitigation, and response across Texas.

Key implementation actions include:

- **Recommended Shapefiles**:
    1. Study Area – This layer delineates the geographic scope of the entire study, providing details on cities, counties, watersheds, or other relevant spatial extents such as the spatial extent of the modeling domain. The purpose of this shapefile is to identify where studies are being conducted, which helps stakeholders locate projects geographically to ensure coverage and prevent redundancy.
    2. Construction Footprint – This layer defines the area directly impacted by construction activities including temporary activities such as traffic control. For permitting, or other reasons, there may be requirements to separately identify specific areas of excavation or ground disturbance. The purpose of this shapefile is to highlight areas where physical interventions are taking place, which facilitates cross-project comparison and mitigates overlapping scopes.
    3. Benefited Area(s) – This layer outlines the projected area influenced by the project's outcomes, such as the area benefitted by flood risk reduction, enhanced resilience, or ecological benefits. This is often an area that is smaller than the total study/model area, but larger than the limit of construction. Sometimes the benefitted areas may be the same as either study area or construction footprint (or both), but it's important to specify these three areas clearly for each project. Also, it is possible the area for flood benefits is significantly different than the area for ecological or other benefits and for certain projects it may be appropriate to delineate multiple benefit areas. The purpose of this shapefile is to provide a visual understanding of the project's anticipated impact, which assists in identifying gaps or overlaps in flood mitigation efforts.
- **Submission Guidelines**: Specify shapefile formats, metadata standards, and protocols; obtain agreement from relevant agencies to adopt the guidelines and standards, such as TWDB, GLO, and TDEM
- **Management**: Assign a state office or database to manage and analyze shapefile submissions; use analyses to enable a clearer understanding of the spatial relationship between ongoing and proposed projects; provide insight into geographic redundancies and opportunities to integrate efforts for maximum impact
- **State Integration**: Add shapefile submission requirements to project scopes and funding application processes

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C2.4A: State and local agencies should implement *The TIFF Communication Guidelines* to enhance consistency, clarity, and accessibility of flood information

To improve the clarity and accessibility of flood risk information, TIFF developed *Guidelines for Coastal Flood Information Design and Communication* (referred to as *The TIFF Communication Guidelines*). These guidelines outline best practices for developing flood risk visualizations and communication tools (e.g., maps and dashboards) in a way that is clear, transparent, and user-friendly. By promoting and applying these guidelines through education and outreach, organizations can ensure that both general audiences and those directly affected by coastal flooding can accurately interpret and respond to shared flood information.

TIFF recommends the TWDB, or other appropriate state agency, lead implementation efforts of *The TIFF Communication Guidelines*. As the state's designated coordinating agency for the National Flood Insurance Program, TWDB has the expertise and relationships necessary for statewide coordination. TWDB can also facilitate partnerships among Texas legislators, funding agencies, local governments, developers, business owners, non-profits, and academic institutions to promote the adoption and consistent application of these guidelines. Partner agencies are encouraged to share costs and collaborate on phased funding.

Key implementation actions include:

- **Collaboration with Regional Stakeholders**: Tailor and optimize the guidelines for Texas's diverse regions and target users. Include special considerations for the LRGV
- **Promotional Campaign**: Produce an asynchronous video walkthrough explaining the guidelines, publish it on the TIFF website, and secure endorsements from subject matter experts and state-level decision-makers
- **Training and Case Studies**: Develop workshops and instructional materials demonstrating effective guideline use, using the Texas Water Data Hub and TDIS as examples of best practices
- **Outreach to Target Users**: Once the guidelines are approved and localized, identify the most effective communication channels (e.g., Facebook ads, local newspapers, radio/television broadcasts) to ensure widespread awareness
- **Evaluation and Feedback**: Host community events and municipal workshops to gather stakeholder feedback and assess guideline effectiveness among both technical and general audiences
- **Flood Literacy Assessment**: Evaluate whether implementing *The TIFF Communication Guidelines* increases public flood literacy, especially among communities vulnerable to coastal flooding

C2.4B: Create and validate flood safety messages that better reach target users in the Lower Rio Grande Valley

Popular flood safety messages, including "Turn Around, Don't Drown," are widely circulated despite the lack of comprehensive impact evaluation beyond their original target audience. Research shows that meaning can shift when messages are shared in different regions, delivered to people from various cultural backgrounds, or translated into other languages.

There is insufficient data on the effectiveness of flood safety messaging for Spanish-speaking populations, immigrants, and residents from states outside of Texas. Without systematic evaluation, organizations cannot reliably claim which flood safety messages work best, under what circumstances, or how they should be adapted for non-English speakers.

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This 2-3-year investment, estimated at $1 million, will produce new flood safety messages that can be adopted by all levels of government.

Key implementation actions include:

- **Capacity Building**: Establish a sustainable annual budget and cost-sharing strategy among local contractors and communities. Secure ongoing state funding and permanent staffing to support long-term implementation and expansion across Texas.
- **Expert Project Team**: Form a team of bilingual or multilingual subject-matter experts to lead rigorous research, evaluation, and message design. At least one member should reside in the region to help implement local events and maintain community presence.
- **Establish Partnerships**: As one of the state's largest data stewards and information sharers related to natural disaster management in Texas, TDIS would be the most beneficial partner in this effort. Other key partners include local non-governmental organizations with expertise in the region to connect the project team with communities, foster trust, and ensure consistent community presence and engagement. Use the Prairie View A&M University Economic Development representatives and TDEM county liaisons as potential resources for best practices.
- **Behavioral Research**: Design and conduct systematic experiments to test message comprehension, retention, and behavioral impact across languages, cultures, and formats.
- **Share Findings**: Develop evidence-based recommendations for message design and deployment. Publicly share results detailing how groups engage with messages, including motivation and behavioral outcomes
- **Develop and Test Tools**: Create prototypes of new messages and visualizations (e.g., maps, graphics, dashboards, infographics, interactive materials) and evaluate their effectiveness across diverse user groups; ensure tools reflect community priorities and lived experiences through continuous user engagement (e.g., "Don't block the drains"; "When thunder roars, go indoors")
- **Implement Inclusive Strategies**: Support multimodal outreach such as storytelling and historical preservation initiatives, regional information sharing forums, post-flood community support, and cross-community collaboration; that builds community connection, collective learning, and emotional resilience
- **Continued Evaluation**: Regularly assess and refine strategies based on community feedback and evolving demographic, environmental, and technological conditions to maintain relevance and effectiveness

C2.4C: State and local agencies should consider adopting the TIFF Target Group Pilot Test methodology to enhance the consistency of designing and evaluating meaningful flood communication tools

To effectively evaluate the effectiveness of flood communication and visualization approaches and tools, TIFF developed the TGP Test methodology for designing hypothesis-driven tests for target users. This approach represents a workflow to specify testable designs for communication and visualization in the future, leveraging insights from previous research and emerging AI tools to create measurable performance metrics. By tracking quantitative evaluation metrics, an agency, program, or project can gain valuable insights into how effectively flood risks and coastal modeling information or visualization tools are performing. Together with more tailored metrics for specific target users, organization will be better equipped to assess performance over time and identify areas for improvement.

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TIFF recommends TWDB, or other appropriate state agency, lead implementation efforts. As the state's designated Coordinating Agency for the NFIP, TWDB has the expertise and relationships necessary for statewide coordination. TWDB can also facilitate partnerships among Texas legislators, funding agencies, local governments, developers, business owners, non-profits, and academic institutions to promote the adoption and consistent application of this human-AI partnering methodology. Partner agencies are encouraged to share costs and collaborate on phased funding.

Key implementation actions include:

- **Collaboration with Regional Stakeholders**: Work with regional planners and decision-makers to identify regional target user groups, core information needs, and key behaviors
- **Promotional Campaign**: Produce an asynchronous video walkthrough explaining the AI-driven step-by-step TGP Test workflow, publish it on the TIFF website, and secure endorsements from subject matter experts and state-level decision-makers
- **Training and Case Studies**: Develop workshops and instructional materials demonstrating effective TGP Test use, using the Texas Water Data Hub and TDIS as examples of best practices
- **Outreach to Target Users**: Once the TGP Test methodology is approved, identify the most effective communication channels (e.g., Facebook ads, local newspapers, radio/television broadcasts) to ensure widespread awareness
- **Evaluation and Feedback**: Host community events and municipal workshops to gather stakeholder feedback and assess the methodology's effectiveness among both technical and general audiences
- **Flood Literacy Assessment**: Evaluate whether implementing the TIFF TGP Test methodology increases public flood literacy, especially among communities vulnerable to coastal flooding

C2.4D: Develop new State of Texas tool to share lessons of Texas' flood history to help residents better predict future flood risks based on historical patterns

Effectively visualizing and disseminating flood-related information is essential for improving public understanding of flood risks. Accurate and accessible flood data can help communities, decision-makers, and emergency responders interpret complex models and datasets, leading to better preparedness, response, and long-term resilience. However, flood information is often scattered across multiple sources, making it difficult for residents to access and use in decision-making.

TIFF recommends the development of a public resource documenting historical floods in Texas hosted by TDIS. This resource would serve as a centralized platform for residents to explore past flood events and understand their potential future risks. An interactive map interface would allow users to visualize flood events by location, making it easier to see where and when major floods have occurred. Each recorded flood event would include key details such as dates, impacted areas, and the extent of flooding, offering a comprehensive historical record.

The resource should also incorporate predictive insights by integrating flood forecasts and return period data. This would provide users with a clearer picture of potential future flood risks based on historical patterns. By combining historical data with predictive modeling, this tool would enhance public awareness and support more effective flood risk management across Texas.

Key implementation actions include:

- **Define "Major Flood"**: Use indicators such as loss of life, property damage, rainfall amounts, and other agreed metrics; these metrics and definition should be agreed upon by agencies and organizations advancing flood science in Texas, such as TWDB, GLO, TDEM, and others

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

- **Generate Event Summaries**: Create tables for each recorded flood event with dates, impacted areas, and extent of flooding; this organization will support improved data comprehension, communication, and informed decision-making
- **Flood Prediction**: Incorporate flood forecasts and return-period data into the public resource
- **Evaluation**: Request user feedback on the interactive map throughout the development process and iterate to improve usability and understanding; consider quantifiable evaluation metrics such as session duration, repeat visits, audience reach, information sharing, and more

C2.4E: Develop a Texas-specific AI Flood Risk Tool to help target users find flood information

Generative AI (GenAI), including prompt engineering and large and small language models, presents an opportunity to modernize flood risk visualization and communication. Human-AI teaming enables more intuitive information retrieval and organization, making critical data more accessible.

TIFF recommends a study to assess how GenAI can better help target users find the flood risk information they need for decision-making. Following the study, a Texas-specific GenAI Flood Risk Tool can be developed for broader implementation. This "Texas GenAI Flood Risk Tool" will feature a prompt coaching system to guide users in writing effective prompts, ensuring they receive accurate and actionable responses. It will also define the necessary datasets for the tool and test how different target users interact with it.

This priority effort is estimated to cost at least $1,000,000. If the resources are not available to implement the entirety of this recommendation at once, the following describes how it could be made into a multi-phase approach:

- **GenAI Flood Tool Proof of Concept (Two Focus Groups costs ~$225,000)**: Identify at least five public target users and two official target users for the study; conduct background research to assess these users' flood information needs, leveraging existing research funded by Texas agencies; carry out initial focus groups of 30-50 participants and in-person lab experiments to analyze how users search for flood information, utilizing methods such as eye-tracking, virtual reality-based eye-tracking, and think-aloud protocols; consider online experiments; conduct a follow-up focus group of 18-36 participants to help participants learn prompt-writing techniques and refine their queries to obtain more effective flood-related information
- **GenAI Flood Tool Development (One Focus Group costs ~$700,000)**: Build on the proof-of-concept findings, applying the insights gained to the same target users; identify necessary datasets, visual information, and flood-specific small language model requirements; conduct usability testing of the designed system using the same research methods from the proof-of-concept study, with a sample size of 30-50 participants per group
- **Post-Implementation Flood Literacy Evaluation**: Assess if the alternatives to menu-driven dashboards increased flood literacy in target users, improving their capacity to respond effectively and appropriately to given flood risk information

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Sun rising over the Gulf on Padre Island © Tim Malek

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Navigation buoy washed up on the beach after a storm on the Texas coast © Michelle, Adobe Stock

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3 Component 3: Integrated Flood Modeling Framework

The goal of Component 3 is to develop an integrated modeling framework to support inland and coastal flood hazard identification for the Texas coast.

3.1 What is an Integrated Flood Modeling Framework?

Current flood modeling practices are siloed, fragmented by discipline (e.g., hydrology, hydraulics, meteorology, coastal ocean dynamics), and inaccessible to many state and local agencies due to the high level of technical expertise required. **Texas needs a unified, scalable, and reusable integrated framework to evaluate compound flood hazards and inform flood mitigation and resilience planning at the local, regional, and state levels.**

Hydrologic, meteorologic, hydraulic, estuarine, and surge models serve as both valuable tools to provide information on flooding hazards and guides in planning and implementing structural and non-structural flood risk mitigation solutions for minimizing flood risk. Various flood process models exist, but each are tailored to address specific challenges related to dominant flooding mechanisms (e.g., pluvial, fluvial, storm surges). While these models have grown in complexity, with many simulating increasingly detailed processes occurring within natural and built systems, an integrated flood modeling framework is needed to better couple different process models (e.g., surge, rainfall-runoff) and accurately resolve total water levels, particularly in the low-lying coastal zones. While FEMA, USACE, NOAA, and other federal agencies have some guidance on this topic, more in-depth guidance and tools are needed for Texas practitioners.

Understanding Flood Modeling

Flood modeling, whether for understanding hazards or to predict inundation, requires a complex set of workflows, data, and models that are created and run by expert modelers. The type of models, their data requirements, and their outputs depend on the user's goals when the model is constructed. Traditionally, such models have been based on what the world looks like right now. However, given the increasing frequency and severity of flood events driven by natural and anthropogenic change, future flood models should integrate changing conditions into data workflows to anticipate more frequent and extreme flooding scenarios. Thus, there is a need for workflows that produce standardized future scenarios based on climate models that consider both inland and coastal impacts (e.g., rising sea levels, higher storm surge hazards, changes in rainfall patterns). These models should also account for probable land use changes driven by population growth and urbanization that can exacerbate flood hazards and risks, particularly in areas where natural drainage is disrupted or where flood-prone areas become more heavily developed. It is crucial to include such projections into flood models to ensure resilience in future infrastructure development, flood mitigation, and adaptive planning/preparedness strategies.

HOW MODELS ENHANCE UNDERSTANDING OF FLOOD RISK

Engineers, scientists, policymakers, and managers use a layered modeling and analysis approach to evaluate and predict flood impacts, or flood risk. Flood risk is an overarching idea that takes into account the flood hazard (the probability of an event), the resilience of the affected systems, and the severity of consequences (e.g., people, property, infrastructure). We can think of this as a bottom-up cascade from specific to general:

FLOOD INUNDATION → FLOOD HAZARDS → HAZARDS + RESILIENCY + CONSEQUENCES → RISK

Figure 3-1. Conceptual cascade of flood risk (flood inundation triggers a flood response from the system; the integration of that flood response across probabilities, or return intervals, is the flood hazard; hazards with resiliency and consequences provide quantification of risk).

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TYPES OF FLOOD MODELING

Flood risk assessments provide the foundations for decision-making in flood protection design, resiliency/recovery analysis, and emergency planning. Flood hazard analysis provides the statistical (or probabilistic) approach to assessing the magnitude and likelihood of flood events. In general, flood hazard analysis can use flood inundation observations and/or inundation modeling to evaluate the flood hazards associated with a range of prior or possible storms. However, observations of large storm events (hurricanes, tropical cyclones) along the Texas coast are insufficient for an observation-only approach. Therefore, flood hazard analysis is based on the modeling of synthetic events built on the science of flood inundation modeling. Flood hazard analysis provides a range of storm conditions based on statistical (or probabilistic) analyses, and then an inundation model predicts the flood water elevation and extents for each storm. The inundation results from the modeled storms are integrated with their probabilities to provide either 1) a map of flood hazard, which is often defined based on the probability of occurrence in a given year that is typically (and misleadingly) expressed as a return interval in years[1], or 2) a single location hazard curve (e.g., a flood frequency curve) that relates specific water levels to their probability of exceedance.

A review of flood risk analysis and planning tools using flood hazards, system resilience, and event consequences is provided in the Component 4: Planning and Outreach section. Here, under the umbrella of Component 3, a narrower focus on two of the key aspects for quantifying flood risk is provided. These two aspects of flood modeling/analysis are 1) determining the probability, risk, and hazards of multiple flood events; and 2) given a single event, determine the resulting flooded areas, depths and durations.

The first, ***flood hazard analysis*** (or probabilistic flood modeling), characterizes flood frequency (how often floods occur in the area of interest), magnitude (size or severity of an event, such as water level and inundated area), duration (how long an event lasts), and the location (including the existing conditions at the start of an event). Flood hazard analysis seeks to quantify the likelihood that a flood will initiate a hazard, which could be a damaging water elevation, a wave height, or an erosive force. This analysis provides the foundation of flood risk assessment[2] used by policymakers and managers throughout the Texas coastal region.

The second, ***flood inundation*** modeling, is event-based modeling representing the time-space evolution of flood physics from a single storm occurring in a region of interest. This analysis provides visualization of the flood depths across the landscape for a particular flood event. Flood inundation modeling seeks to represent extent and depth of flooding caused by a specific single storm or event. In the most sophisticated models, the time-evolution of flooding across the landscape is simulated and can be used to create a movie of how flooding occurs (i.e., how the depth and extent over the land surface changes over time).

These two types of analysis are closely related and incorporate information from each other, as results from flood inundation models often (but not exclusively) provide the water surface elevation data used for flood hazard analysis. Flood hazard analysis is typically conducted with a combination of observed data and a suite of flood inundation models. Both flood hazard analysis and flood inundation models are

1 The flood with 1% chance of occurring in any given year is known as a "100-year flood," which is misleading to those not well-versed in probabilities. To be somewhat less misleading: a 1% or 100-year flood has roughly a 1% chance of occurring at least once in a 1-year period, a 10% chance of occurring at least once in a 10-year period, and a 26% chance of occurring at least once over the course of a 30-year house mortgage. An important concept is that the occurrence of a storm in any given year (or decade) does not affect the probability of a similar storm occurring in following years.

2 Flood risk assessment integrates data from a range of models and observations to estimate the likelihood of an event (with the exposure and vulnerability). Such risk assessments provide the means to evaluate and discuss the cost/benefits of flood protection strategies, decide on flood protection design and emergency management strategies, and communicate to the public of flood risks particular to their location.

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mathematical representations of flooding that typically require extensive computational resources and scientific expertise to create, test, and apply. These tools are complementary and closely coupled in the process of quantifying the flood hazards that determine flood risk.

Flood hazard analysis begins with a statistical analysis of the flood levels and/or the driving forces (meteorological, oceanographic), which are used to drive simulated events using a flood inundation model. Probabilistic models may be used to represent possible future events and statistical models to represent the likelihood of those events, often referred to as synthetic events. Inundation models provide flooding extent, depths, and durations of flooding for a set of individual events. Through flood hazard analysis, the inundation model results are integrated (or aggregated) to develop hazard analysis curves (or flood frequency analysis curves), or maps of flood elevation at different hazard levels (i.e., flood inundation maps).

Flood inundation modeling is a useful tool to evaluate (in detail) what happened in the past and flood scenarios that might occur in the present and future, with and without flood risk management project conditions. Such models are typically (although not exclusively) based on the mathematics of fundamental physical processes (conservation of mass and momentum). These models typically provide a top-down view that divides the landscape and ocean into a horizontal grid mesh where the physics equations are modeled at small scales. The model begins with known initial conditions of landscape elevation, water levels, winds, etc., and future changes in the winds, tides, sea level, etc. are enforced in a step-by-step manner. In effect, the physics equations are marched step-by-step through time to predict how flood inundation in the next time step changes based on the state within the previous time step and the forcing (e.g., rain, wind, tide) that occurs during that time step. Thus, flood inundation models can provide a detailed space-time history of flooding (e.g., a movie of flood depths across the landscape, which is usually called a simulation). Alternatively, the time-space data set can be used for analyses such as maximum flood depths or durations. To understand compound floods, inundation models can be used to isolate different flooding drivers and the effects of multiple drivers in combination. As an example, we can evaluate the impact of rainfall and river overbank flooding can be evaluated by modeling storm impacts both with and without river inflow effects (Figure 3-2). The significant increase in water surface elevations with river flooding caused dramatic changes in the flood inundation area.

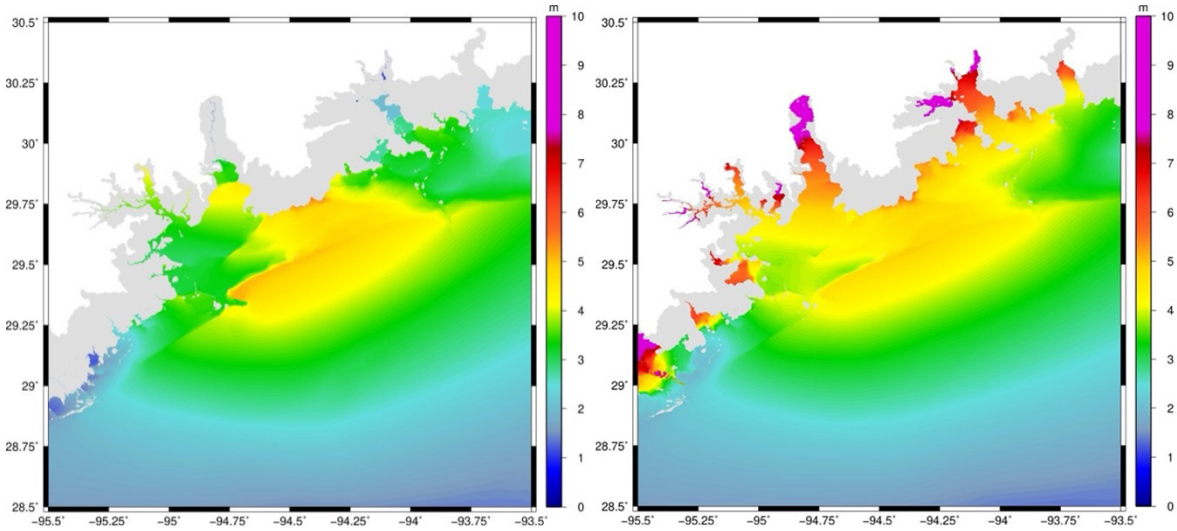

Figure 3-2. Modeled water surface elevation (feet) in the Houston area without river inflow (left), and with synthetic extreme river inflows (right), using winds and oceanic storm surge from Hurricane Ike. Results are from the coastal flood model (ADCIRC).

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Each approach is discussed in more detail below.

(See **Appendices C-1** through **C-7** for key characteristics and computational requirements of the different model types, see. Further details of these models are summarized in Sec. Model Literature and in Dawson et al. 2024a, 2024b.)

1. **Flood Hazard Analysis**: Typically, in a hazard analysis, a long record of flood levels at a location would be ranked and fit to a distribution, from which the probability of occurrence or exceedance could be calculated to define a hazard curve. However, at a specific location, coastal storms (hurricanes, or tropical cyclones, and non-tropical events) do not occur with the same high frequency that inland flood events occur. Compound coastal storm events, where two drivers, such as storm surge and rainfall runoff, raise water levels to flood elevations, are even more under-represented spatially and temporally in the observational record than those for coastal storm surge and wave hazards. To overcome the paucity of coastal storm flood elevations, the state of practice for storm surge/wave is to conduct the hazard analysis on a set of representative synthetic storms numerically modeled in a JPM framework.

   JPM samples regional atmospheric parameter distributions (as opposed to local site water elevations), to develop a set of representative parameters for each synthetic storm and identifies its probability. As compound events can have even less observations, their joint probability is difficult to assess (Gori 2022). Thus, frameworks developed for compound flood hazard analysis can be tiered into different degrees of application difficulty, and the selection of that technical complexity of analysis can be based on a project's data availability, numerical modeling capabilities, details of model realizations, and uncertainty or precision required for a specific application (Gutenson et al. 2021). An example of a tiered probabilistic compound hazard framework, developed by USACE as part of the CHS (Nadal-Caraballo et al. 2020), recommends a set of tiers of increasing complexity: from screening efforts that rely heavily on statistical analysis of paired compound observations, to enhanced JPM-based tiers, which use JPM to quantify coastal hazards induced by storm surge and waves linked to inland drives by increasingly sophisticated joint probability schemes between the compound mechanisms. For example, increasingly complex tiers might link coastal and inland mechanisms based on seasonality at a low tier, while a higher tier might couple coastal and inland models forced by synthetic storm driven, tropical cyclone rainfall models.

   Two main approaches have been advanced in recent years: bivariate copula statistical analysis (e.g., Jane et al. 2022) and enhanced JPMs. Bivariate statistical analyses are direct statistical approaches that are conducted directly on the measurements of the hazard, or response variable, being quantified (e.g., gage height, flow, rainfall, water surface elevation). They are typically based on extreme value analyses (Coles 2001) and can be challenged by limited observations, made more severe by the need for overlapping records (e.g., paired sets) of compound event data. Analyzed using bivariate statistics and representing the relationship between two parameters as a copula, these methods are often used to select joint input pairs for design events to use in numerical models (e.g., hydrologic, hydraulic, coastal storm surge models). Recent efforts in Texas have included the bivariate copula analysis as part of the GLO's RBFS and the Joint Coastal Bivariate Probability Study – Texas (JCBP-TX, Carr et al. 2022c) (See **Appendix C-8** for more regional examples.) The RBFS were conducted by local practitioners following bivariate copula guidelines for several basins in a given region. The JCBP-TX was a coast-wide study across eight large river basins conducted to describe and develop a bivariate copula analysis of the joint probability of compound coincident inland and coastal hazards from recorded observations to assess the interaction of coupled storm surge and rainfall hazards. The reasoning, approaches, and steps for conducting a joint probability bivariate analysis were discussed, and the approach was considered useful for screening level analysis, but sensitive to data availability and assessment choices.

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In enhanced JPMs, synthetic storm parameters are used to drive coupled process-based numerical models for the compound mechanisms (e.g., storm surge, waves, rainfall, rainfall-runoff) (Bass and Bedient 2018; Bartlett et al. 2023; Gori 2022), explicitly accounting for the probabilistic relationship between the driving parameters and the joint probability of the compound response (Abbaszadeh 2022). Application of enhanced JPMs can leverage existing numerical process models, such as hydrological, hydraulic, surge and wave models, as well as results from existing JPM analyses for coastal storm hazards, which can provide large sets of synthetic storm parameters, ocean circulation and wave models, and corresponding storm responses and probability densities (Nadal-Caraballo et al. 2015; Nadal-Caraballo et al. 2022a; Nadal-Caraballo et al. 2022b; Gori and Lin 2022). Recent compound flooding JPM analyses include driving a parametric tropical cyclone rainfall model with JPM synthetic storms and applying that rainfall to hydrologic, hydraulic, and direct flow models (e.g., Bass and Bedient 2018; Bartlett et al. 2023; Gori and Lin 2022; Liu et al. 2025). These studies demonstrate some of the methods, models, and enhanced JPM applications used for compound flood hazard modeling.

2. **Flood Inundation Modeling for Historical Storms**: Traditional engineering flood inundation models are based on physics equations that are well understood and have more than a century of study. These are often referred to as mechanistic models, as they are driven by equations of mechanics rather than by correlations in a data set (see The Emergence of Artificial Intelligence and Machine Learning in Flood Modeling section below). These mechanistic models require extensive data for 1) boundary conditions (the time-space variation of forcing that creates the flood (rainfall, wind, offshore sea level)); 2) the initial conditions of the modeled area at the start (e.g., soil saturation, river and lake water levels); and 3) detailed maps of the landscape that describe elevation, soil type, obstructions, and flow pathways. Combining these data in a mathematical model allows us to create a series of time-marching pictures of the flood extent and depth during an event. The model itself divides the landscape into a grid of boxes (or cells) where mathematics for the physics of forces and water transport are used to compute how much floodwater accumulates and how much moves in/out of each cell in a single time step. We can use the model results to create movies of the flood across the landscape, to evaluate the flood behavior at a particular point, and to create maps of flood statistics (e.g., maximum flood depth, length of time flooded). Inundation models of past storms are used to calibrate and validate models (as discussed below) and to build effective inundation models of "what if" conditions, discussed in the "What If" Flood Inundation Modeling section below.

"What If" Flood Inundation Modeling

Arguably, the most valuable use of the mechanistic models developed for flood inundation modeling is to predict the likely flooding effects of future storms and/or different scenario analysis. For example, "What if Hurricane Harvey had stalled over Corpus Christi rather than Houston?". Another example is, "What if Houston built a system of deep storage tunnels, would that protect against Hurricane Harvey flooding?". These forms of "what if" modeling poses several significant challenges. First, a modeled future (or alternative) storm is a complex variation of rainfall and wind over time and space that is similar to a real-world storm. This issue has been addressed through research over the past decade in development of synthetic storms that mimic the time-space characteristics of real-world storms. A second, more intractable challenge is predicting what the landscape will look like in the future for a "what if" model: how roads will be developed; what areas of farm/ranch land will be converted to housing; how stormwater drainage systems will change; and whether new levees will be built. Finally, "what if" modeling will often use conditions that are outside the formal calibration and validation bounds of the mechanistic model. Such models may be the best possible but will have unknown uncertainty (see Types of Flood Modeling above). In general, "what if" modeling must be done with care and with attention to the uncertainty as to how the landscape will change and the extent to which the models exceed calibration and validation conditions.

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Mechanistic flood inundation models are subject to errors and uncertainties in the forcing data (boundary conditions), the initial conditions, and the underlying landscape data. Furthermore, choices in the model's mathematical design and coding will affect the underlying error behavior. As the model is marched through time from its starting point, it will slowly accumulate error. In general, every mechanistic model has a time horizon beyond which we cannot trust its predictions (even when predicting the past). Modelers use calibration to adjust models to better match observations of a historic event. For example, the flow of flood water over the landscape depends on the roughness of the landscape. Past studies relate the roughness to the type of landscape (e.g., open farmland, buildings, and roadways will all have different values for roughness). Unfortunately, the precise coefficient that correctly represents the real world would require detailed study and data for each grid cell in a model, which is impractical for any large flood model. Thus, calibration is used to adjust roughness coefficients within the accepted bounds of uncertainty to get better agreement between the model and observations. To understand a model's uncertainty and likely error, a model is calibrated with data from one or more storms and then is validated by representing a storm that was not in the calibration data set. This approach allows the modeler to compare the validation model's results to observed data and quantify the error. This validation error represents the uncertainty in the model results for any storm that is similar to those in the validation and calibration data set. This validation error can be used to communicate the uncertainty associated with the model results (e.g., by providing plus/minus values to predicted flood inundation depths).

Table 3-1. Numerical model types of compound flood inundation modeling systems.

Type of Model	Characteristics	Purposes	Computing Requirements	Examples
Flood Inundation Model I (FI-I)	Full physics equations in a single code base	Validation of Water Elevations Engineering Design Sensitivity Studies	High	None
Flood Inundation Model II (FI-II)	Combination of full physics and reduced physics equations in one or more areas in a single code base	Same as Flood Inundation Model I	Medium to High	SCHISM DELFT3D HEC-RAS ADCIRC AdH COASWT
Flood Inundation Model III (FI-III)	Full physics and/or reduced physics in a software framework for coupling codes	Same as Flood Inundation Model I	High	CSTORM-MS NOAA UFS
Flood Inundation Model IV (FI-IV)	Reduced physics and/or low resolution in a single code base	Real-time Forecasting Sensitivity Studies	Low	SFINCS
Flood Inundation Hybrid Models (FI-H)	Combination of physics-based components, surrogate models and/or AI/ML components	Real-time Forecasting Sensitivity Studies Uncertainty Quantification	Variable	Research Codes
Flood Inundation Data-Driven Models (FI-DD)	Surrogate models, probabilistic models, and AI/ML	Forecasting Sensitivity Studies Uncertainty Quantification	GPU capability desirable for AI/ML	Research Codes

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Table 3-2. Current and potential use cases for types of inundation modeling. For model selection for different scenarios, "x" indicates the model is currently in use for this purpose, while "o" indicates it may be applicable depending on engineering judgment. Note that FI-I models do not currently exist but are arguably suitable for all purposes.

Scenario	Operational Forecasting	Hindcasting and Validation	Planning and Design	Uncertainty Quantification
FI-I	-	-	-	-
FI-II	xx	o	xx	o
FI-III	o	xx	xx	xx
FI-IV	o	o	xx	xx
FI-H	o	o	xx	xx
FI-DD	o	o	o	xx

THE EMERGENCE OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN FLOOD MODELING

In contrast to the mechanistic approach of flood inundation modeling (See How Models Enhance Understanding of Flood Risk above), Artificial Intelligence (AI) and Machine Learning (ML) in flood modeling can be thought of as a type of data-driven modeling (where the data may be a combination of observations and results from flood inundation models). That is, the model only understands flooding based on the data (observations, model results) rather than through the fundamental physics of water motion. Over the past 15 years, there have been dramatic advances in AI and ML (subset of AI), which began as pure data-driven models but have recently advanced into quasi-mechanistic models. Managers and policymakers should recognize that AI/ML models are presently research-level tools that do not yet have a strong basis for understanding the uncertainty and likely error associated with its predictions. In particular, AI/ML models used for conditions outside of their training range (i.e., their calibration) are of questionable value. The beauty of AI/ML is that it always provides an answer, no matter how complicated the question—the ugly is that there is no certainty (with today's models) that the answer is correct, and the uncertainty of its predictions cannot typically be estimated.

AI/ML models are arguably an outgrowth of statistical modeling: a large data set is ingested into a model that uses mathematics to correlate observed input behaviors and make predictions about likely output behaviors. The difference between AI/ML and traditional statistical modeling is in the mathematics that underly the treatment of the data. The key point of AI/ML is that it uses its training data to learn the correlations within the data (note that it cannot correlate for conditions that do not appear within the data set itself). Once the model is trained it can rapidly produce predictions for other data sets (which are assumed to be similar). The biggest drawback to AI/ML is that model training can be a long process requiring extensive computer time as well as careful manual cleaning of the input data set. ChatGPT provides a good example—the rapidity with which it can respond to a prompt is phenomenal, but it does not reflect the enormous computational time that it took to train the underlying large language model.

AI/ML has the potential to improve flood hazard analysis in several ways being applied in academic and pilot settings, as well as in application. The JPM-AMP method used by USACE at CHL for regional coastal studies expands the probability and parameter space of the hundreds of regional JPM synthetic storms to many hundreds of thousands of storms and their parameter sets by estimating the model results (i.e. response) through the application of Gaussian process metamodeling (GPM), a ML technique developed in collaboration with the University of Notre Dame. The GPM builds on the high-fidelity storm surge and wave models results by expanding them to cover more possible storms using the lower cost, lower fidelity technique. This method was applied for compound flooding due to Mississippi River flows and hurricane storm surge, expanding both the JPM parameters and seasonal flow through the GPM (Nadal-Caraballo et al. 2022a). Pilot studies, such as the Neches River study conducted by CHL,

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also depended on GPM methods (Carr et al. 2024) while academic efforts have used surrogate modeling in a Bayesian framework to improve storm parameter selection and demonstrate multiple tiers of a Compound Framework in the New Orleans area (Liu et al. 2025).

There are reasons to expect that AI/ML will someday take over for mechanistic models for flood inundation modeling, but not today or even in the next several years (the models simply are not sufficiently mature or trustworthy). The key advantage of AI/ML over mechanistic flood inundation models is that AI/ML, when trained, can run much faster than mechanistic models. However, there are two disadvantages to AI/ML modeling for flood inundation that must be overcome before they can supplant mechanistic models: 1) the AI/ML model training is inherently place-specific, that is, a model trained for Houston cannot be applied to Corpus Christi without repeating the entire training process (in contrast, a mechanistic model built for Houston can be readily adapted to other locations); and 2) an AI/ML cannot be used for "what if" analyses if the "what if" conditions are outside its training data set. For example, "What if Houston had a set of deep stormwater storage tunnels?" cannot be answered by present AI/ML models if they are not trained with relevant datasets. The dataset for flood inundation for all storms in Houston does not contain the effects of stormwater storage so an AI/ML has no way to predict the consequences.

The above should not be taken as a blanket condemnation of the future potential for AI/ML. Much as with any modeling technique, AI/ML can be useful as long as we understand and apply the models within their limits. To continue the "what if" example from above, although present AI/ML cannot use historic data to analyze "what if" for proposed Houston stormwater tunnels, such tunnels could be represented in mechanistic flood models and the resulting data used to train AI/ML. Once the AI/ML is trained with the tunnel data it can be used to quickly model a broader array of storms than is practical for a mechanistic model alone. Such a combined modeling approach can be used to bootstrap our way to fast predictions that retain the underlying accuracy of mechanistic models. Furthermore, development of hybrid AI/ML that incorporate physics constraints directly within their algorithms may provide foundations for better "what if" capabilities.

An important point is that developing, testing, and proving the trustworthiness of future AI/ML models requires extensive data that can only be provided through the existing, well-proven methods for flood hazard analysis and flood inundation modeling.

3.2 Why An Integrated Flooding Framework Matters To Texas

The combination of climate variability, land use change, and recurring tropical systems has significantly increased the vulnerability of the Texas coast. Existing flood modeling frameworks utilized in standard project planning do not adequately capture compound flood hazards. There is a need for integration of natural and anthropogenic changing conditions into the modeling workflows to evaluate project impacts. Compounding this issue is the limited availability of high-resolution data.

In response, Component 3 aims to:

- **advance the science and operationalization of compound flood modeling,**
- **deliver scalable tools** for both screening-level and planning-level risk assessments,
- **promote data-informed decision-making** in flood resilience and infrastructure investments, and
- **integrate innovative and nature-based approaches** into long-term flood mitigation efforts in the LRGV and beyond.

Component 3 supports the creation of a robust, integrated modeling platform to support data-driven, adaptive flood hazard identification, the development of compound flood analysis tools, and the evaluation of testbeds for future flood planning and resilience. Projects, such as these described below, provide

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the impetus and perhaps the avenue to build a reusable computational framework for Texas compound flood modeling (See TxCFF below):

- **Planning Strategy Evaluation**: Federal, state, and local agencies perform site-specific feasibility studies to evaluate proposed projects, identify potential solutions, and recommend suitable solutions for flood hazard reduction. Such feasibility studies may consider either short-term or long-term planning horizons based on the project objectives or goals. The challenge for such studies is that they are inherently "what if" studies that change the conditions under which flooding has been evaluated. Thus, such studies need scenario-based flood inundation models to evaluate impacts of changes. To synthesize inundation model results effectively, a streamlined process is needed to update flood hazard models using outputs from multiple "what-if" scenarios. This will enable systematic cost-benefit analyses, quantification of hazard reduction in flood-prone areas, and assessment of the impact of planned projects on overall flood resilience. Furthermore, long-term planning strategies should be evaluated through models that incorporate climate projections, land use changes, and infrastructure developments. The scale and scope of the required analyses are challenging for any single project to consider. Presently, such feasibility projects do not have the resources or time to build, run, and analyze high-quality compound flooding inundation models (to make the task tractable they resort to simpler reduced-physics models that have relatively wide margins of uncertainty). A reusable computational framework for Texas compound flood modeling could make high-quality modeling more tractable and allow agencies to analyze a broader set of alternatives with greater confidence and reduced uncertainty.
- **Engineering Design**: Communities expend significant funds for engineering consulting firms in developing designs, cost estimates, and feasibility of flood protection features and/or flood impacts of proposed developments. Much is spent on setting up and running river flood inundation models or analyzing storm surge models, which cannot (in isolation) represent the complexities of compound flood modeling. Providing engineering firms with stricter guidance and criteria for including compound flooding would, in the present world, simply increase the costs of such studies and substantially slow development projects. There is a need for an effective compound flood modeling system for Texas that provides engineering firms with the tools and the training to more rapidly evaluate possible designs and compound flood impacts. Building such a framework could allow engineering firms to provide direct feedback on the feasibility and planning strategies discussed above.
- **Operational Strategy Evaluation**: Emergency managers use "what if" scenarios to plan operational strategies for flooding response. The present complexity of flood modeling (in particular for compound flooding) makes it impractical for emergency managers to run a wide range of possible storms and test/evaluate/improve their response strategies against the predicted time/space evolution of flooding. To support emergency planning, a flood modeling system could be used in several ways. First, a modeling system can be used prior to events to evaluate the effectiveness of emergency operational strategies, estimate equipment and personnel required for different conditions, and conduct flooding logistics drills where the flood information from the model is provided in a filtered form for managers to practice making decisions with limited information. Second, during a storm event a modeling system could be used to quickly consider "what if" possibilities with flooding details that are not available in the predictive storm modeling of NOAA. Finally, after an event the flood modeling system could be used as a framework for post-event analysis of emergency response performance metrics such as response times, forecast accuracy, and the efficiency of stakeholder communication during events. In addition to improving future emergency response, such post-event analysis can also provide critical feedback for improving model accuracy and updating protocols based on lessons learned.

Much of our baseline flood protection infrastructure is designed and built in a piecemeal fashion as land is developed. Although this approach is informed by overlapping regulations—from the city/town,

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county, state, and federal agencies that set standards and design guidance based on input from professional societies and the latest research—, there is no guarantee that these individual projects provide the larger community an adequate level of protection. For example, flood protection for an inland river using levees to protect one community may result in shifting the flooding problem to a nearby community. To address this issue, engineers use flood inundation models to predict flood water levels and other impacts (e.g., forces on structure, erosion) across towns, cities, and along the coast for large-scale flood events. When combined with flood hazard analysis, the flood inundation models can be used to identify cost-effective strategies for increasing flood protection across multiple communities, delineate floodplains where development should be discouraged, assist in development of emergency management plans for flood disasters, and provide hazard-based information for stakeholders to decide on design of flood control measures. In common use, probabilistic flood hazard analysis quantifies the known hazards for the existing infrastructure, (i.e., identifying where flooding and damage are deemed more likely) and are used by insurance companies and FEMA to set rates and estimate potential liabilities.

The Challenge of Compound Flooding in Flood Protection Design

Traditionally, flood protection features have been designed for a single flooding source[3]. We protect against commonly expected conditions through flood inundation modeling with 1) a design rainfall rate, 2) a design river elevation, and 3) a design storm-surge height. As a practical matter of costs, time, and resources, we typically cannot build the design level of flood protection infrastructure to protect against an estimate of the maximum expected conditions from any flood source. For example, many cities use a 25-year storm for sizing road gutters—this is a storm that has a 4% chance of occurring in any given year and a 1-in-3 chance of occurring at least once in any decade. Thus, overflowing road gutters should not be an everyday occurrence but can be expected with many extreme rainfall events. This standard design approach links flood hazard and flood inundation modeling—flood hazard modeling is used to set the probabilistic storm conditions for the design standard and then flood inundation models are used to evaluate whether a proposed project meets this standard. The key takeaway is 1) design standards have been traditionally focused on a single type of flooding, and 2) flooding is expected whenever nature exceeds that design standard.

Compound flooding has created a challenge for both flood hazard analysis and flood inundation modeling engineers. CHS-PCHA is the standard of practice for storm surge hazard analysis and applies a method wherein historical information about driving parameters (e.g., central pressure deficit, radius to maximum winds) is used in a JPM to develop synthetic tropical cyclones and drive storm surge models (Carr et al. 2022b). Compound flood hazard analysis is challenging for the same key reason that storm surge hazard analysis is challenging: a limited data record of events (which is even more limited when we seek paired events to characterize the joint probability between the two hazards, e.g., rainfall and surge). Therefore, in seeking to represent the likelihood of a compound event composed of storm surge and rainfall, it would be helpful to have a tropical cyclone rainfall model that is driven by the same parameters of the surge model (i.e., JPM parameters). The Tropical Cyclone Rainfall Model (TCRM) described by Lu et al. (2018), and being applied in research and pilot settings, provides such a method, which is computationally efficient and has the same probability of occurrence as the synthetic tropical cyclone's storm surge.

For flood inundation modeling, engineers traditionally use models designed specifically for one of the major flood sources: rainfall, river, or storm surge. Becoming an expert flood inundation modeler in any one area requires years of practice under the guidance of an expert who has a decade or more of experi-

3 Note that rainfall, rivers, and oceans are the "big three" sources of flooding that are typically considered in engineering design. Groundwater flooding in the Texas coastal region is often neglected as it is usually a small contribution to the events that control the design conditions. Nevertheless, groundwater does play an important role in the effectiveness of urban stormwater systems and is a major contributor in some areas beyond the Texas coast.

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ence. However, the term compound flooding[4] first appears in the science/engineering literature in Wahl et al. (2015). This rather recent focus is reflected in lagging development of integrative expertise and compound flood inundation models across disciplines. Although researchers in academia and government agencies have been actively pursuing better models for both hazard analysis and inundation from compound flooding over the last decade, this area still lacks consensus models that are accepted as state-of-the-science. Furthermore, effective compound flood modeling requires expert modelers to be spread throughout academia, industry, and government. We lack both this broad modeling community and the cadre of experts needed to train and supervise the development of such expertise in both flood hazard analysis and flood inundation modeling.

(See Compound Flooding in **Appendix C-9** for additional details.).

3.3 The Guiding Objectives of TIFF Component 3

The aim of TIFF Component 3 was to address the challenges of developing an integrated modeling framework to support inland and coastal flood hazard identification. This effort consisted of five stated objectives, which are described in detail below:

1. Establish a TAT to support Component 3
2. Evaluate and provide feedback on initial inventory of existing and proposed meteorologic, hydrologic, hydraulic, estuarine and surge models in Texas to support inland and coastal flood hazard identification
3. Perform a literature review to identify potential meteorological, hydrologic, hydraulic, and hydrodynamic models for evaluating and mitigating flood risk for Texas
4. Perform a literature review on probabilistic methods for flood hazard estimation
5. Make recommendations for conceptual model-coupling workflow(s) for assessment of compound flooding hazards in coastal Texas

To achieve these Objectives, a collaborative and systematic approach was adopted in coordination with the TAT, which was established to provide subject matter expertise and guidance throughout the component's execution. After reviewing and providing feedback on the proposed approach of TIFF, the TAT worked closely with Study Providers to evaluate the inventory of existing and proposed meteorological, hydrologic, hydraulic, estuarine, and surge models, ensuring they were suitable for integrated inland and coastal flood hazard identification (**Appendices C-20** and **C-21**). A comprehensive literature review was conducted to identify additional modeling tools capable of capturing complex flood dynamics and informing mitigation strategies specific to Texas. In parallel, a focused review of probabilistic methods was carried out to enhance the understanding and estimation of flood hazard uncertainty. Based on these efforts, the TAT developed recommendations for conceptual model-coupling workflows to support assessment of compound flooding risks in the coastal Texas region, with the goal of enabling a robust and integrated framework (the TxCFF) for flood risk evaluation and decision-making (**Appendices C-22** and **C-23**). The TxCFF is a software framework that encapsulates models and their coupling with analysis tools and workflows. **TIFF recommends the development of the TxCFF as an overarching answer to the goals and objectives nested under Component 3.**

4 The fundamental ideas of hazard and probability associated "compound flooding" can be found in articles on "joint" and "coincident" flooding in the flood risk/hazard literature prior to 2015, but the popularization of the term "compound flooding" and its prominence over the last decade are arguably associated with the Wahl et al (2015) letter to the journal *Nature Climate Change*.

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ZOOMING IN: TIFF'S PRIORITY RECOMMENDATION FOR ONGOING COASTAL INTEGRATED FLOOD MODELING

The Texas Coastal Flooding Framework (TxCFF) (TIFF Recommendation C3.5A)

TIFF recommends the development of the TxCFF, a collaborative software platform for compound flood assessment to facilitate planning, design, development, flood recovery, and supporting emergency response efforts along the Texas coast.

The state-of-the-art and the underlying context of models for coastal and compound flood inundation modeling and hazard analysis lend some insight on the paths forward for Texas. (See Understanding Flood Modeling above and the Model Coupling Workflow Workshop described in **Appendix C-10** for further detail.) These ideas and considerations are generally applicable to any coastal flood modeling/analysis effort but specifically address the complexities of Texas compound flooding. **A critical need is for a software framework that encapsulates models and their coupling with analysis tools and workflows.**

The TxCFF should be a data and modeling system that provides 1) data linkages to existing databases, 2) data transfer between models, 3) a user interface to setup and execute the models as a coupled system, and 4) integration of the output data from component models into a coherent data set for further analysis and visualization. The TxCFF would streamline model coupling workflows, enhance data integration from federal, state, and local sources, and support widespread application through testbeds across the Texas Coastal Plain.

The path forward is ambitious and will require sustained investment, interagency cooperation, and technical innovation. However, the anticipated benefits are profound. A fully realized TxCFF will enable local and state entities to better quantify and manage flood risks, reduce redundancy in engineering efforts, and dramatically lower the costs associated with flood hazard assessments and infrastructure planning. By transforming the current fragmented landscape into a reusable and extensible framework, the TxCFF will not only advance the state-of-the-science—it will redefine the future of flood resilience across the Texas Coastal Plain. The TxCFF would consist of:

- wind and pressure model
- ocean circulation model
- wind/wave model (far field and near field)
- flood inundation (hydraulics) model for river flow and landscape flooding
- upland runoff model (hydrology)
- stormwater drainage model
- groundwater model
- code for input/output
- code for user customization
- code for coupling the various flood inundation component models
- coupling to external meteorological (storm) models/data sets for historic and synthetic storms
- code for calibration, validation, and testing of inundation models
- code for ingesting flood inundation model results into flood hazard analysis
- flood hazard analysis tools
- code for visualizing inundation and hazard analysis results

At the simplest level, the TxCFF could begin as documented workflows for coupling models and data along with codes developed for pre-processing, post-processing and analysis. Over time, the workflows can be codified into a software framework that addresses the key issues of re-usability, access, training, simplification/complexity, and uncertainty. Developing the TxCFF would require a long-term commitment of funds to a consistent project development team that collaborates with agency-sponsored modeling projects to ensure their work can be integrated into the framework. The benefits of integrating hydrologic, hydraulic, meteorologic, estuarine, and coastal models into a single, interoperable system and making advanced compound flood analysis accessible to a broader user base, including planners, engineers, and policymakers far outweigh the costs.

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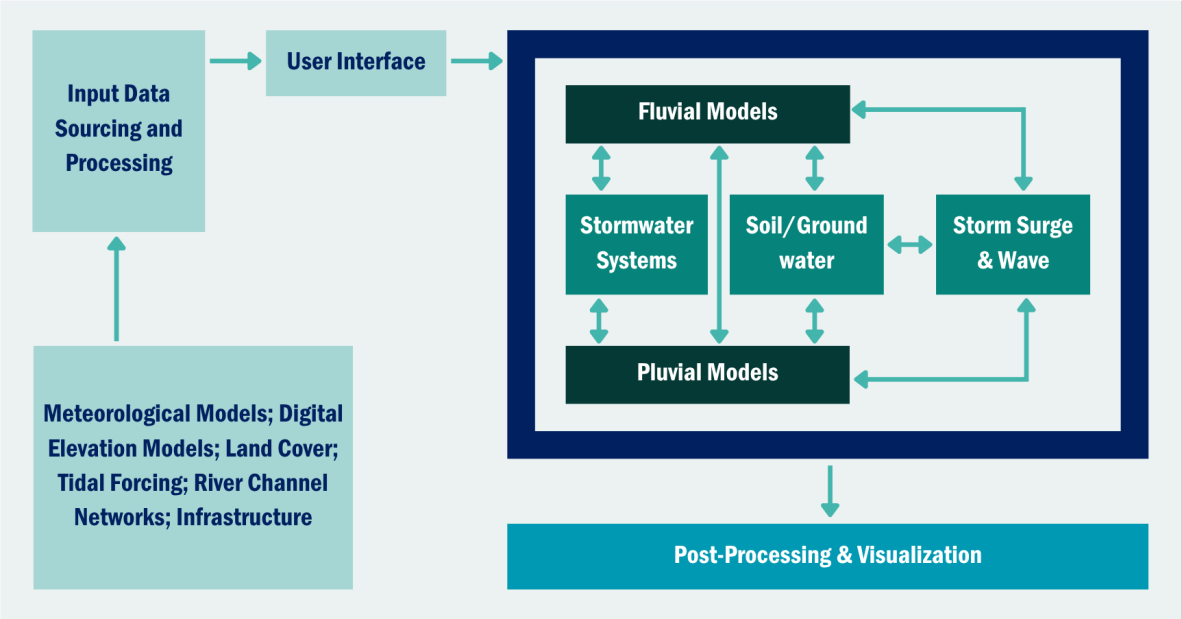

Figure 3-3. Conceptual diagram of model and data couplings within a TxCFF.

For compound flood modeling to become a standard tool in engineering, science, and policy practice, several key points need to be addressed:

1. **Models used within the framework must be validated for Texas, computationally efficient, supported by an active development team and user community, and equipped with graphical user interfaces (GUI) and training documentation**: Community based open source models are preferred to allow for maximum development options within the software, which is likely to be required when integrating with other models. Open-access models do not allow for the same flexibility for code changes but still allow for no-cost usage of the model by a wide range of users. The framework must include coastal surge/circulation and wave models that can be coupled, with the capability to use different hydrodynamic models in the coastal zone for various applications, including three-dimensional baroclinic models and full phase-resolving non-hydrostatic models for wave runup and overtopping. The framework should also include linked H&H models for coastal Texas, building on ongoing initiatives by TWDB, USACE, and others, with options to include wind, pressure, and wave forcing data where these factors are significant (e.g., over large inland lakes).
2. **Models must be re-usable (i.e., the efforts to develop and apply a model to one location should be transferable to another so that each effort is not "reinventing the wheel")**: Currently, flood modeling efforts in the Texas coastal region are custom implementations requiring significant development time, model validation, and specialized skills. A standardized suite of models with coupling software would streamline these projects and allow for consistent engineering decisions based on statistical analysis rather than varying judgments across different basins.
3. **Models need to be widely accessible**: This means flood inundation models and hazard analysis tools within the framework must be accessible to engineers, scientists, and managers across various government levels, academia, and industry. Efficient coastal development requires rapid computation models that meet regulatory standards, supported by user-friendly GUIs and safeguards to prevent misuse. This broad access necessitates robust software and model development. Accessibility is also dependent upon flexibility as well as the availability of training to a broad spectrum of users. The framework should be flexible enough so that individual components can be turned off (e.g., stormwater or groundwater might be unneeded in some scenarios; users might want to evaluate the magnitude of some single forcing, such as storm surge). A user query process or documentation that guides users in best practices for deciding which components to use for their particular application is needed. Comprehensive training is essential for the broad spectrum of users to set up, run, analyze, and communicate model results. Current fragmented approaches make training impractical. Developing standardized workflows and a common computational framework will enable effective training programs for various user levels. The framework's structure should be portable, extensible, and built with plug-and-play

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application programming interfaces, leveraging existing coupling frameworks and adhering to community standards for data curation.

4. **Users should have access to models of varying complexity that fit their particular needs**: The challenge in compound flood modeling lies in the undefined scientific basis for simplification and weak interdisciplinary communication. Simplified models, while faster and useful for feasibility assessments, increase uncertainty. Systematic comparisons between full-physics and reduced-physics models are needed to determine acceptable simplification levels. Future workflows should support full-physics approaches and quantify uncertainties from simplified models. The framework should facilitate inter-model and inter-level hazard analysis approach comparisons, allowing users to evaluate which models and hazard analysis approaches are most useful in different situations.
5. **Model results should be provided with quantification of their uncertainty so that users understand the limits of any prediction/analysis**: Quantifying model uncertainty involves understanding the range of possible results due to various types of uncertainty and their distributions. Flood inundation model uncertainty differs from flood hazard analysis uncertainty, requiring systematic evaluation methods in standard workflows. Better knowledge of uncertainty helps modelers make informed choices about model complexity and simplifications, and effectively communicate uncertainties to managers and policymakers. Flood hazard analysis includes aleatory (irreducible) and epistemic (reducible) uncertainties, while flood inundation model uncertainty arises from multiple sources like forcing data, boundary data, and numerical approaches. Accurate quantification and communication of these uncertainties are essential for reliable modeling. The framework should provide the capabilities to build and test methods for uncertainty quantification, sensitive analysis, hazard analysis, and parameter estimation.
6. **Workflows and computational framework need to be created to support model users, developers, model maintenance, and ongoing modeling improvements with ongoing advances in the state-of-the-art of flood modeling**: Continuous coastal development necessitates ongoing compound flood modeling and analysis. A sustainable approach should systematically incorporate knowledge from each project into future efforts, making subsequent projects cheaper, easier to design, and more robust. Projects used within the framework must document model meshes, tools, and lessons learned to streamline future projects. This includes an assessment of available and develop tools and software for both pre-processing (e.g., mesh generation from Digital Elevation Models, probabilistic driving inputs) and post-processing (e.g., visualization, interactive graphs, communication of results to stakeholders). These secondary software tools should be readily available, shareable, and validated just as the full models are. Additionally, coupling models using existing software packages requires transparent and well-documented code and documentation. Commitment from project managers and funding agencies is essential for maintaining a standardized compound flood modeling framework.

(See **Appendix C-11** for more detailed information on each of these issues.)

3.4 Implementation of Objectives

Objective 1: Establish an Integrated Flood Modeling TAT

To support the development of an integrated modeling framework for inland and coastal flood hazard identification, the SC appointed Dr. Mohammad "Shahidul" Islam of USACE as the Component 3 Champion. Dr. Islam was selected based on his extensive technical background and leadership in hydrologic, hydraulic, and coastal engineering, as well as his national-level experience in flood modeling, risk management, and interagency coordination. His deep expertise and contributions to major federal and state flood mitigation initiatives made him an ideal candidate to lead this effort.

Complementing his leadership, a multidisciplinary TAT was strategically assembled by the SC. Members were chosen for their demonstrated technical excellence and institutional knowledge in areas critical to flood risk modeling and mitigation in Texas and beyond. The TAT includes experts across a range of

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specialties including hydrology, hydraulics, meteorology, estuarine and coastal hydrodynamics, and flood hazard analysis.

To ensure Component 3 reflected the unique hydrologic and coastal behavior of the LRGV, TIFF invited and confirmed the additional membership of six Technical Advisors in November 2023 with firsthand experience in flood modeling in the LRGV region. This inclusive and collaborative approach ensures that the Component 3 framework was informed by the latest science, practical experience, and the diverse perspectives of stakeholders from governmental agencies, academia, and regional institutions. Advisors marked with an asterisk are those LRGV-specific additions.

COMPONENT 3 TECHNICAL ADVISORS

- Andrew Juan, TAMU-IDRT
- Andrew Kennedy, University of Notre Dame
- Arash Taghinezhad, TAMU-IDRT
- Ben Hodges, UT-Austin
- Charles (Landon) Erickson, USACE-Fort Worth District
- Chris Massey, USACE-ERDC
- Clint Dawson, UT-Austin
- David Johnson, Purdue University
- Derek Giardino, NWS-West Gulf River Forecast Center
- Don Resio, University of North Florida
- Gabriele Villarini, Princeton University
- Gaurav Savant, USACE-ERDC
- Hugh Roberts, The Water Institute of the Gulf
- Jeff Lindner, HCFCD
- Jim Gibeaut, Harte Research Institute
- *Joseph Gutenson, RATES
- Joseph Zhang, Virginia Institute of Marine Science
- *Jungseok Ho, UT-Rio Grande Valley
- Justin Terry, HCFCD
- Ken Ashe, Wood, PLC
- Mark Jensen, USACE
- Matt Bilskie, University of Georgia
- *Michelle Hummel, UT-Arlington
- Mohammad Shahidul Islam, USACE-Galveston District (TIFF SC Team Champion)
- Nick Fang, UT-Arlington
- Ning Lin, Princeton University
- Norberto Nadal-Caraballo, USACE ERDC
- Patrick Barnard, USGS
- *Paul Hamilton, USACE
- Richard Wade, Texas Natural Resources Information System
- Rick Luettich, University of North Carolina-Chapel Hill
- Saul Nuccitelli, TWDB
- Suzanne Pierce, UT-Austin, TACC
- Thomas Wahl, University of Central Florida
- *Tushar Sinha, TAMU-Kingsville
- *Unni (Padinare) Unnikrishna, IBWC
- William Asquith, USGS
- Yu Zhang, UT-Arlington

Objective 2: Evaluate and provide feedback on initial inventory of existing and proposed meteorologic, hydrologic, hydraulic, estuarine, and surge models by the Study Providers to support inland and coastal flood hazard identification

Numerical models are essential tools for conducting flood analysis studies. Engineers and scientists invest considerable time and resources in data collection, input preparation, and the calibration and validation of model parameters. Many of these models require complex pre-processing steps, often involving manual and time-consuming workflows. These steps must be repeated each time a new model is developed to

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simulate a particular system. To address this challenge, TIFF prioritized the creation of an initial model inventory aimed at minimizing redundant model development efforts and promoting model sharing and reuse among stakeholders. This effort also supported the identification of geographic areas in Texas where improved model coverage is needed to inform future flood planning initiatives. As part of this effort, TIFF focused on evaluating the model inventories from several ongoing large-scale studies that support flood planning, modeling, and mapping across the state (**Appendix C-13**), including:

- USACE's Flood Risk Management, Coastal Storm Risk Management, and Navigational program for Texas region
- GLO's RBFS
- TWDB's RFPG
- TWDB's Base Level Engineering (BLE) Studies

The intent of this model inventory development and evaluation is to create an existing model catalog with key contextual details for users to leverage when searching for existing information in a particular study area. Key metadata and coverage area shapefiles associated with models were collected (**Appendix C-14**). This information also provides insight into the geographic distribution of information, that is, where pluvial, fluvial, and/or coastal risk information is abundant and where it is lacking. This initial model inventory and associated model metadata lay the foundation for the future development of a detailed model metadata catalog, along with the system for model archiving and sharing with diverse stakeholders.

Storm surge damage caused by Hurricane Ike ©NOAA

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APPROACH TO THE MODEL INVENTORY

The first step to creating and populating the model inventory was to determine what metadata is key to providing sufficient context for the target user to determine the usefulness and/or appropriateness of the existing model for their intended purpose. The metadata requirements were selected by taking into consideration the minimum information needed to characterize flood models with the relevant context to understand their purpose and provide context for use in hazard identification where appropriate. Once the model metadata was collected and categorized, TIFF coordinated with TDIS to compile and disseminate the inventoried information. Geodatabases containing shapefiles that were paired with their respective metadata were also shared with TDIS.

Table 3-3. Inventory matrix metadata fields and their descriptions.

Metadata Field	Description
Study Area	Geographic location where model is based
Software	Type of modeling software used (e.g., Hydrologic Engineering Center Hydrologic Modeling System, Hydrologic Engineering Center River Analysis System, Adaptive Hydraulics, Soil Water Assessment Tool)
Study Title	Title of study associated with model development
Version	Software version the model is currently compatible with (e.g., Hydrologic Engineering Center River Analysis System 6.0)
Focus	The purpose of model development (i.e., what type of analysis or problem the model is expected to inform and/or be leveraged to solve). Categories include: Flood Risk Management; Coastal Storm Risk Management, Water Management, Water Resources, Groundwater, Ecosystem Restoration
Objectives	Summary of study objectives for associated model
Year Developed	Year in which the model was developed
Flow Condition	Specify flow condition of subject model (e.g., steady-modeled variable does not change with time; unsteady-modeled variable changes with time)
Dimension	Dimension(s) of model geometry and associated results
Status	Status of model development (e.g., planning, ongoing, complete)
Model Point of Contact	Point of contact for the model developer
Geo-Referenced?	Specify if the model is spatially referenced through a projection system [Yes/No]
Shp_ID	Shapefile identifier
Report	Specify if a report is available that accompanies the model and includes pertinent details (e.g., modeling methodology and results) [Yes/No]
Location	Location of report and/or model
Calibration Events	Summary of storm events leveraged to calibrate the model
Validation Events	Summary of storm events leveraged to validate the model
Analysis Summary	Summary of what type of analysis the model was used for (e.g., alternatives—with and without—project analysis, sensitivity analysis, scenario analysis)
History	Summary of model update history (e.g., if model was adapted from an existing model)
Additional Comments	Any additional pertinent information related to model

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Although this model inventory matrix can be used for compiling relevant metadata for any flood planning and risk assessment models, the focus of this inventory matrix was to compile metadata for meteorologic, hydrologic, hydraulic, and coastal models, including estuarine, surge, and wave models, which are applied for estimating flooding hazard extent and depth estimations. (Note that this simple model inventory matrix was designed to provide relevant high-level model metadata and does not represent a comprehensive cataloging of model-related metadata sets.) but to. Modelers and other stakeholders can use this high-level metadata and follow up with the model developer(s) for the appropriate level of detailed information based on their project needs. Links to documentation (e.g., reports, publications, web pages) associated with each model are included to provide details related to each modeling effort where applicable and/or available. In addition to the metadata, shapefile coverage areas were obtained where available and are indicated in the metadata table in **Appendix C-14** and on the TIFF website.

THE MODEL INVENTORY

The completed inventory shapefiles of hydrologic, hydraulic, hydrodynamic, meteorological, and coastal models are available for download on the TIFF website.

The inventory was populated by a combination of outreach, literature review, and existing database integration. Numerous models have been developed to support the USACE-Galveston District's diverse Civil Works program and were cataloged through surveys and collaboration with respective modeling points of contact. In addition to models developed within or for the USACE-Galveston District, several models have been developed by local drainage districts, state agencies, universities, and consultants. These models were identified through meetings and discussions with engineers and scientists, and by leveraging existing model and/or publication databases. Other cooperators provided model databases that had previously been cataloged (e.g., BLE models), and that information was integrated into the TIFF Model Inventory format. TWDB provided metadata and coverage areas, as available, for BLE studies, Texas Rainfall-Runoff (TxRR) models, and what was collected as part of the RFPG efforts. Information for the GLO's RBFS models was gathered using TDIS data and the Model Query Tool (https://dmqt.cloud.tdis.io/). Other sources, such as HCFCD's M3 system, allowed for direct referencing and downloading of relevant modeling information. The intent of this model inventory was to create an existing model catalog with key contextual details for users to leverage when searching for existing information in a particular study area. This information also provides insight into the geographic distribution of information, that is, where pluvial, fluvial, and/or coastal risk information is abundant and where it is lacking.

The TIFF Model Inventory was categorized by model type: Inland, Coastal, Meteorological. (See Table 3-4 for a list of software identified for the Inland and Coastal model types.)

1. **Inland Hydrologic and Hydraulic Models**: Numerical models are valuable tools for flood analysis studies. When engineers use models, significant effort is devoted to collecting data, constructing model inputs, and calibrating and validating model parameters. Many models also require sophisticated data pre-processing routines, often with many manual steps. These data pre-processing steps must be repeated each time a new model is created to simulate a system. The limited availability of the model metadata prohibits their sharing and reusing among different stakeholders. The limited metadata availability causes duplication efforts in model development in addition to inducing budget increases and delays in project implementation schedule. While many of these flooding models utilize similar methodology, limited information on the model metadata for the study region of interest often forces modelers to develop a new model from scratch. This causes duplication effort in model development and prevents modelers improving the limitations of previously developed models. From a pragmatic perspective, it is an inefficient use of the modeler's time as a significant amount of time is spent reproducing similar model input files that have been developed previously. One way to begin addressing these challenges is through the development of a basic model metadata template for sharing and referencing or reusing models, where appropriate, built by others. With the objective of making Texas stakeholders aware of the available models, TIFF developed a basic model metadata

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template which was then applied for compiling available models in the study regions. This model metadata template was not comprehensive, but was made to be straightforward and to consider how to minimize efforts of the interested parties who will provide this model information. This simple model metadata will provide key information about the model coverage and the model developer points of contact so that further detailed model metadata information can be gathered on as needed basis during the model development effort. This initial inventory will lay the foundation for future development of detailed model metadata catalog along with the system for model archiving and sharing with diverse stakeholders.

The model inventory identifies available models in the study region for facilitating model sharing and reusing among stakeholders, and for supporting modeling gap analysis for the identification of regions where improved models are needed for future flood planning analysis. This evaluation focused on the ongoing studies for supporting flood planning, modeling, and mapping in Texas.

The efforts also include limited evaluation/compilation of other models' metadata, which were readily available to the TIFF partners from their collaboration with local stakeholders, including Harris County and university partners. (See **Appendix C-14** for further details of these programs and associated large-scale studies being implemented as part of this effort.)

Table 3-4. TIFF Model inventory count by software.

Model Type	Modeling Software	Number of Models
Inland	HEC-HMS	183
	HEC-RAS	529
	SWAT	176
	Riverware	1
	Gridded Surface Subsurface Hydrologic Analysis	5
	TxRR Model	129
	Storm Water Management Model	7
	XP Storm Water Management Model	7
	InfoWorks	9
	Interconnected Channel and Pond Routing Model	2
Coastal	Advanced Circulation Model	5
	Adaptive Hydraulics (Coastal)	7
	Beach-FX	1
	Coastal Modeling System-FLOW and Coastal Modeling System-WAVE	8
	Cornell University Long and Intermediate Wave Modeling	2
	Delft3D	6
	DFLOW-FM/ Delft3D-FM	6
	Fully Nonlinear Phase-Resolving Boussinesq-Type Wave Model	2
	Finite Volume Community Ocean Model	1
	Semi-implicit Cross-scale Hydroscience Integrated System Model	1
	Semi-Implicit Eulerian–Lagrangian Finite-Element Model	2
	Super-Fast Inundation of Coasts Model	1
	TxBLEND	7
	Xbeach	1
	Steady State Spectral Wave	2
	Wind Wave Model	1

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2. **Coastal Models**: Coastal modeling leverages physical attributes and numerical methods to demonstrate and quantify coastal forcings and their consequences. These models simulate hydrodynamics, waves, and sediment transport along coasts and estuaries. Quantifying these forcings provides insight into their impacts associated with coastal inundation (i.e., storm surge), wave action, and/or geomorphological changes (e.g., beach erosion). These models can range in size from targeted locations along a shoreline to entire oceans, depending on the modeling effort needs. (See **Appendix C-15** for brief descriptions of coastal hydrodynamic modeling software applied for coastal hydrodynamic modeling on the Texas coast.)

   The coastal model coverage, shown in Figure 3-4 spans the major Texas bays but varies in complexity and purpose largely based on project needs at the time. Many coastal models are limited to an inland extent since the detail within inland hydrologic/hydraulic models tends to lessen as the riverine environments approach the coast.

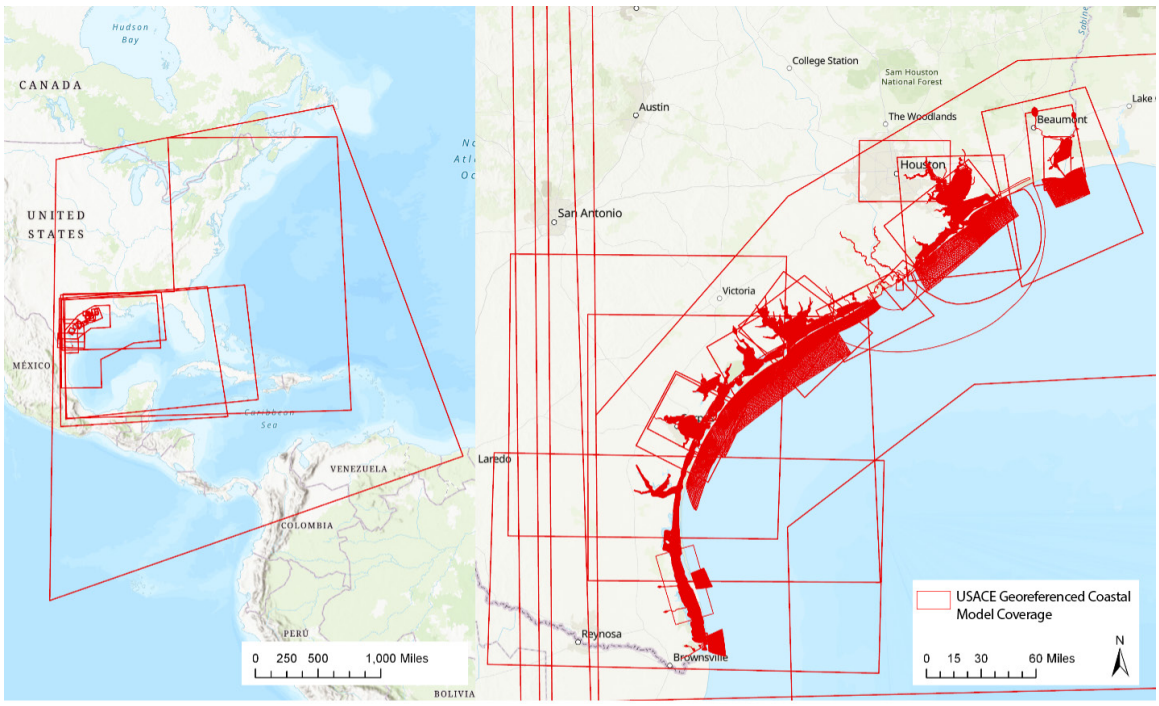

Figure 3-4. Area covered by the USACE Georeferenced Coastal Model.

3. **Meteorological Model Products/Datasets**: TIFF collected meteorological information with a slightly different format than other hydrologic, hydraulic, and coastal information (**Appendix C-1**). The meteorological information consists of models used to develop forecasts as well as datasets that have been modified and/or translated into a format digestible for hydrologic, hydraulic, and coastal modeling purposes. The models and datasets include forecast and/or historical information and range from statewide to global in coverage area (**Appendix C-16**).

Metadata Findings Across Model Types

The extent of the completeness of each line of metadata was dependent upon what information existed and/or was made available at the time of collection. Some existing models were more robustly cataloged than others, and some did not have all relevant metadata available. It is important to note that the cataloged models are included for reference purposes, and care should be taken when leveraging the existing information. This is particularly true when it comes to models developed for specific infrastructure implementation scenarios (i.e., not widely applicable) or those that were created years ago and leverage

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

outdated data inputs (e.g., outdated precipitation inputs, terrain, land cover data). This model metadata catalog may be considered as a preliminary base level model information, which can pave the way for future development of a model repository for sharing with diverse stakeholders.

Although a significant number of model metadata sets were compiled for inland hydrologic, hydraulic, and meteorological models as part of this effort, metadata sets were compiled for a limited number of coastal models. Most of the compiled coastal models were developed to support different USACE projects in Texas. However, a significant number of coastal models were developed or are being developed by different universities for improving understanding of processes controlling coastal flood hazards. Other federal (e.g., NOAA, FEMA), state, county, and local agencies also developed or are developing diverse coastal models for coastal flood hazard estimation in support of their respective program needs. Vendors of GLO's RBFS and TWDB's RFPGs also compiled a very limited number of coastal models through their stakeholder engagement surveys.

To address this gap, TIFF suggests the creation of a comprehensive database of coastal models to facilitate model access and sharing among Texas stakeholders, and to support improved understanding of coastal flood hazard estimation through leveraging existing models and datasets (Recommendation C3.2A: Develop Database of Flood Modeling Studies). This database should use the TIFF Model Inventory (shapefiles of hydrologic, hydraulic, hydrodynamic, meteorological, and coastal models) as the test-case for development. The TIFF Model Inventory should be periodically updated as more models become available. The living inventory will prevent duplication of model development efforts, as huge amounts of flooding analysis are being or will be performed to support a wide range of flood resiliency projects. The key purpose of the database should be facilitating the archiving and sharing of metadata collections, as well as mode input and output files, and providing opportunities for model developers to upload new models for wide dissemination. Further work should consider how the developed models (which vary in resolutions, accuracy, and other factors) can be leveraged and integrated for improved understanding of flood risk along the Texas coast.

Objectives 3 and 4: Perform literature reviews to identify potential meteorological, hydrologic, hydraulic, and hydrodynamic models for evaluating and mitigating flood risk for Texas and probabilistic methods for flood hazard estimation

TIFF performed a literature review on the state-of-practice of modeling and probabilistic analysis for flood hazard characterization for coastal Texas. The literature review was conducted in collaboration with a team of experts in hydrology, hydraulics, and meteorology from the University of Iowa and Princeton University; a team of hydraulics, estuarine, and coastal modelers from UT-Austin; a team of experts in probabilistic compound flood hazard modeling form Purdue University; and a team of wave experts from the University of Notre Dame. An additional grey literature review (especially focused on the latest findings, results, methods of probabilistic hazard, and flood modeling analysis relevant to the USACE studies which may or may not be publicly available) was conducted in collaboration with the ERDC-CHL of the USACE. A final literature review was conducted on nature-based solutions (NBS) for flood mitigation in the LRGV in collaboration with the Texas A&M University-Kingsville. TIFF also organized and hosted a monthly TIFF flood modeling brown bag seminar series to share knowledge among TIFF stakeholders, explore state-of-the-art flood modeling and analysis tools, and discuss the future advancements needed in these tools and/or analysis for Texas coastal flood hazard assessment (**Appendix C-17**).

THE LITERATURE REVIEW APPROACH

Theme I of this literature review covered five topics: 1) meteorology, 2) hydrology/hydraulics, 3) storm surge, 4) waves, and 5) compound flooding. Theme II of this literature review covered probabilistic mod-

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

eling of compound flooding. Theme III focused on the feasibility of integrating NBS into the LRGV's flood management planning.

The summary findings of these literature reviews are provided in the following section. (See **Appendices C-1** through **C-7** for detailed information on these literature reviews.) The findings provided the foundation for the development of conceptual model coupling workflows and assisted in identifying key knowledge gaps in advancing modeling and probabilistic analysis, and development of several future study recommendations to advance flood hazard characterization in coastal Texas.

Figure 3-5. Overview of the literature review of state-of-practice of modeling and probabilistic analysis for flood hazard characterization for coastal Texas.

Literature Review Theme I (Models for Meteorology, Hydrology/Hydraulics, Storm Surge, Waves, Compound Flooding)

To comprehend the impacts of compound flooding, a profound understanding of hydrologic, hydraulic, meteorologic, estuarine, and oceanic processes governing rainfall-runoff flooding, storm surge, and wave action along the Texas coast is essential. Hence, the literature review focused on scrutinizing crucial flooding processes and the state-of-the-art modeling requirements for estimating flood hazards across the Texas coastal study region.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

This literature review encompassed:

- analysis of data sources for topography, bathymetry, land use, and land cover
- integration of data sources for consistent modeling
- examination of upland hydrologic/hydraulic processes and models for rainfall runoff and river flooding
- exploration of processes and models for storm surge and wave action along the coast and their evolution in Texas' bays and estuaries
- investigation into compound flooding processes/models, where waves and storm surge intersect with rainfall and river-induced flooding across the Texas Coastal Plain and its communities

The summarized findings of this literature review are presented in five sections below. (See **Appendices C-1**, **C-2**, **C-3**, **C-4**, and **C-5** for detailed information):

1. **Meteorology Modeling**: Rainfall extent and rates during a tropical cyclone event are critical inputs to any compound flood model. Currently, rainfall is one of the most difficult aspects to model due to its highly localized nature, high variability both spatially and temporally, and other factors. Current deterministic weather models, such as the Weather Research Forecast (WRF) model, simply do not operate at the resolution required to accurately model rainfall. In particular, the clouds that drive rainfall must be modeled as a sub-grid scale effect, and cloud physics are difficult to capture. This section focuses primarily on precipitation models that have been or are being developed to improve precipitation models and discusses both deterministic and probabilistic models. In forecast mode, deterministic weather models may be used, or alternative probabilistic models could be employed. For validation and design studies, datasets such as the Analysis of Record for Calibration (AORC) hold promise as input for hydrologic models. Recommendations include further research into probabilistic models for both forecasting and design, and the use of AI/ML. Deterministic models also have shown continued improvement due to continued development of codes such as NOAA's Global Forecast System.
2. **Hydrology and Hydraulics Modeling**: This section provides details on the characteristics and challenges associated with hydrology and hydraulic modeling in Texas. These include the presence of several complex river systems, tributaries, and watersheds along the Texas coast; complexities due to urbanization, rural versus urban flood modeling, the presence of over 600 dams and river obstructions, uncertainties in channel configurations, width, and depth, soil and groundwater interactions, among others. The section outlines several models currently used in Texas, including:
    - HEC-HMS
    - HEC-RAS
    - SWAT
    - Variable Infiltration Capacity (VIC)
    - National Water Model (NWM), which is based on the WRF-Hydro model
    - U.S. Environmental Protection Agency (EPA) SWMM
    - TxRR model
    - Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) model
    - Watershed Systems of 1D, 2D, and 3D models (WASH123D)

    (Note: AI/ML models are being investigated for hydrology models.)

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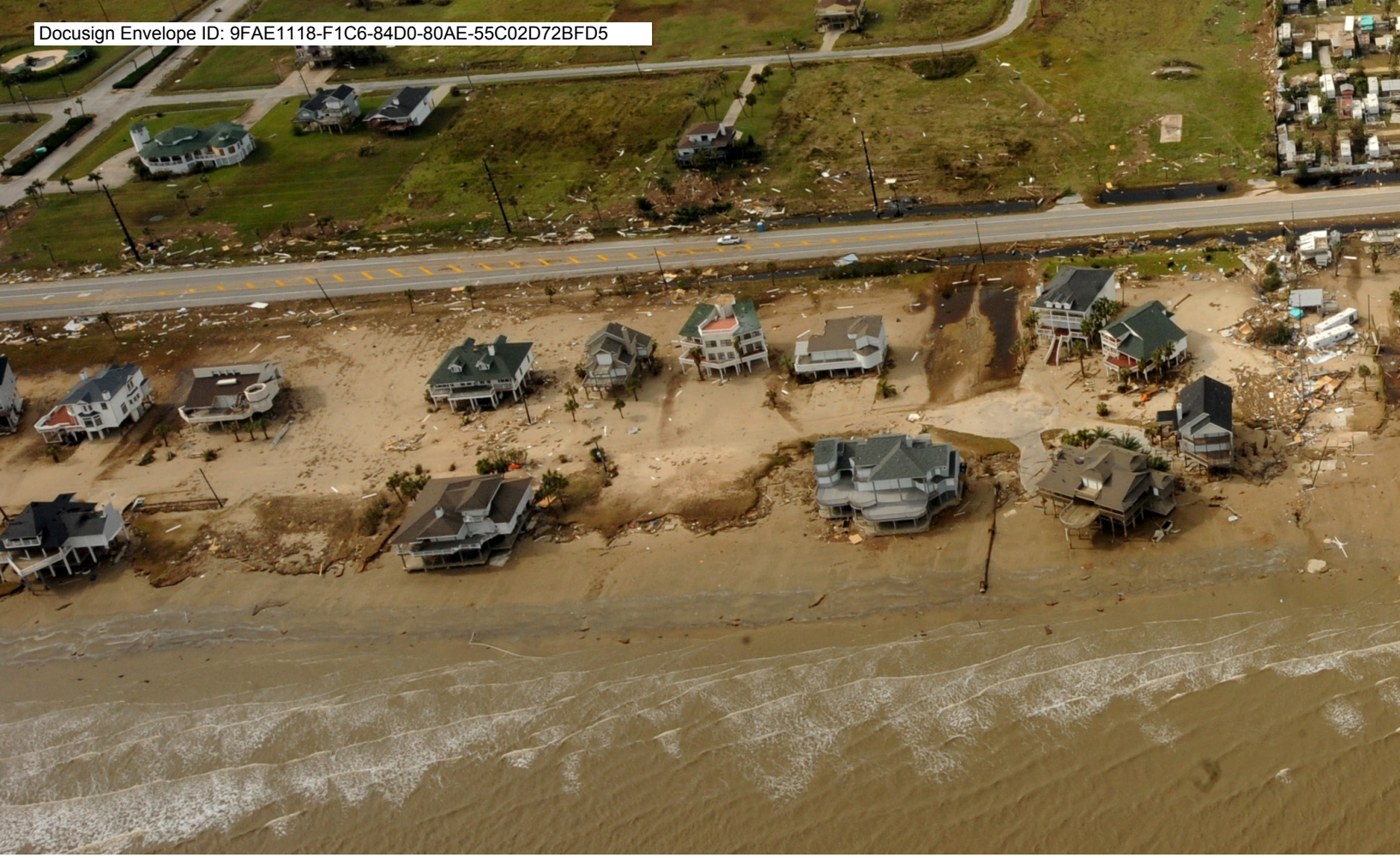

Any, or all, of the above models could be incorporated into workflows or a computational framework for compound flood modeling with consideration of their advantages and disadvantages with respect to the modeling objectives in addition to the other factors. Important considerations for incorporating a particular model include: 1) modeled and/or missing physics, 2) compatibility of programming languages, 3) computing architectures, and 4) the ability to obtain/modify the model source code or access "hooks" in the compiled model application to access relevant data structures and exchange data with other models.

A summary of various hydrologic models is presented by comparing their features in Table 3-5. The comparison includes the complexity of the hydrologic processes, the representation of urban structures, the representation of hydraulic structures, the comparison between planning and operational setups, the ease of use, the available support, and the scale range. Each table category is explained below:

- **Complexity**: the level of detail and sophistication that the model uses to simulate the generation and movement of runoff in the watershed (higher complexity models usually require more input data and parameters, but can capture more hydrologic processes and interactions)
- **Scale Range**: the range of spatial scales that the model can be applied to, from small catchments to large basins, depending on the model assumptions, structure, and data requirements
- **Hydraulics**: the model's ability to simulate hydraulic processes at the channel scale using 1 or 2 dimensions
- **Urban**: the ability of the model to account for the effects of urbanization on hydrology, such as impervious surfaces, stormwater drainage systems, and best management practices
- **Structures**: the ability of the model to represent the effects of hydraulic structures, such as dams, reservoirs, weirs, culverts, and bridges, on the flow and water level in the channels

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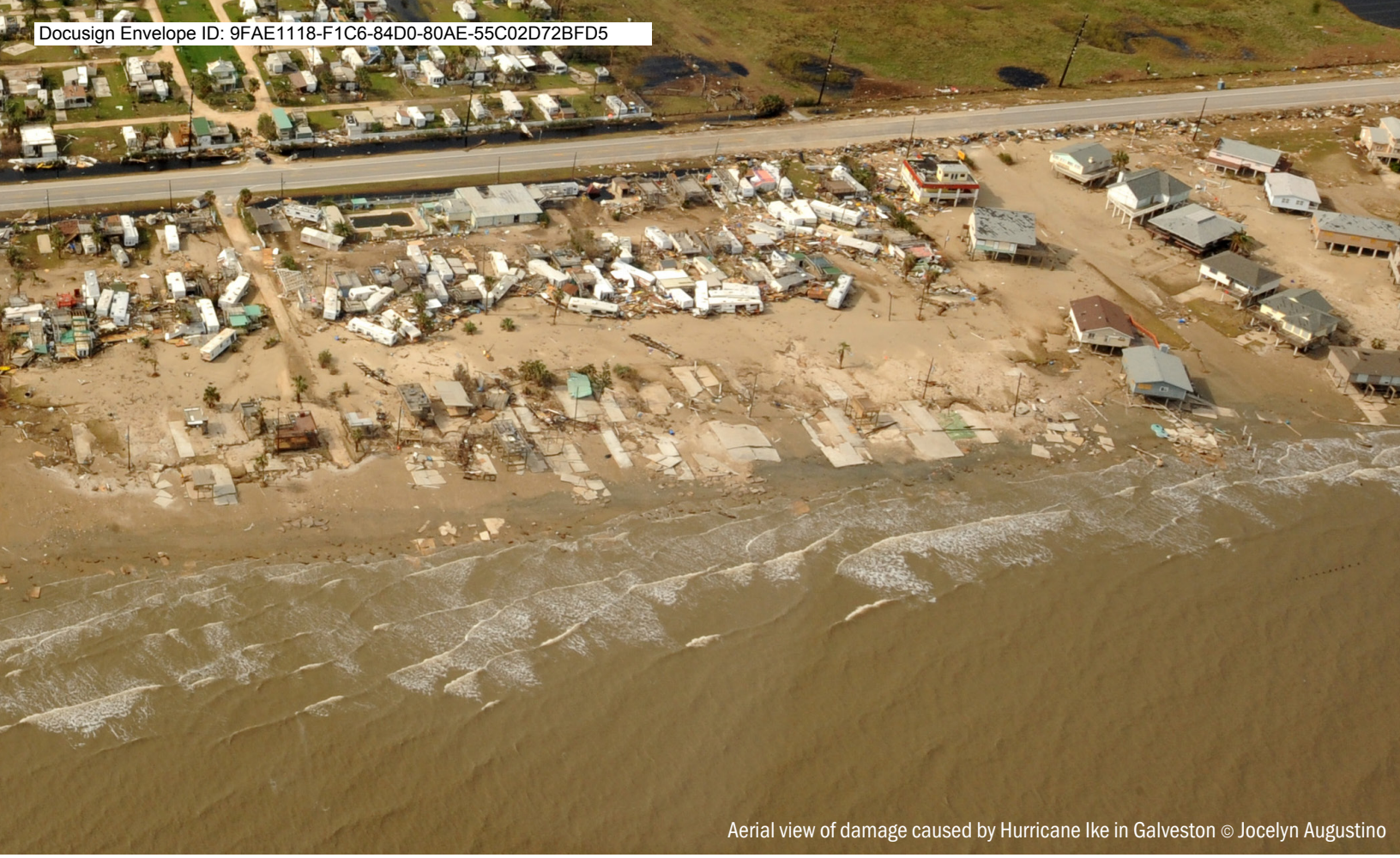

Aerial view of damage caused by Hurricane Ike in Galveston © Jocelyn Augustino

- **Use**: the suitability of the model for different types of applications, such as long-term versus screening-level planning analysis, scenario analysis, impact assessment, or short-term forecasting, warning, and management
- **Ease of Use**: the user-friendliness of the model, such as the availability of graphical user interface, data entry utilities, documentation, and tutorials
- **Support**: the level of support and feedback that the model users can get from the developers, researchers, and other users, such as through forums, websites, publications, and workshops (at the date this report was written)
- **Active**: the current development of the model ([Yes]: developers are still working on improvements or new versions; [No]: there is no current development of the model)

Table 3-5 and Table 3-6, which are related to the hydrologic models, are complemented with Table 3-7 and Table 3-8, which are related to some of the most widely used hydraulic models.

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Table 3-5. A comparison of the process complexity represented in the considered hydrologic models.

Model	Complexity	Scale Range	Hydraulics	Urban	Structures	Use	Ease of Use	Support	Active	Wide Applicability
HEC-HMS	Moderate	Small to Large	No	Good	Good	Planning	High	High	Yes	Yes, suitable for a variety of hydrologic problems, such as flood forecasting, reservoir operations, water quality, and climate change
SWAT	High	Medium to Large	No	Fair	Fair	Planning	Moderate	High	Yes	Yes, suitable for a variety of hydrologic problems (e.g., watershed management, water quality, erosion, nutrient cycling)
VIC	High	Large	No	Poor	Poor	Planning	Low	Moderate	Yes	Yes, suitable for a variety of hydrologic problems, (e.g., drought monitoring, streamflow prediction, land-atmosphere interactions)
WRF-Hydro	High	Large	Yes	Good	Good	Operational	Low	High	Yes	Yes, suitable for a variety of hydrologic problems (e.g., flood forecasting, water resources management, coupled weather prediction)
TxRR	Low	Small	No	Poor	Poor	Planning	High	Low	No	No, mainly designed for Texas watersheds and reservoirs
EPA-SWMM	Moderate	Small to Medium	Yes	Excellent	Excellent	Operational	High	High	Yes	No, mainly designed for urban stormwater runoff and sewer systems
GSSHA	High	Small to Medium	Yes	Fair	Fair	Planning	Low	Low	Yes	No, mainly designed for integrated surface-subsurface flow and transport
WASH123D	High	Small to Medium	Yes	Fair	Fair	Planning	Low	Low	No	No, mainly designed for integrated surface-subsurface flow and transport

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Table 3-6. A description of the hydrologic processes represented by the models. The colors indicate different degrees of complexity of the different processes (green=low complexity, orange=medium complexity, red=high complexity, and grey=not applicable/forced data).

Process	HEC-HMS	SWAT	VIC	WRF-Hydro	NWM	TxRR	EPA-SWMM	GSSHA	WASH123D
ET Pot	Computed	Computed	Computed	Penman	Penman	None	Constant	Penman	Forcing
ET Vegetation	Crop Coefficient	Uses LAI	Uses LAI	Penman	Penman	None	None	Penman	Forcing
ET Surface	After Canopy	None	f(Sat Area)	Penman	Penman	None	None	Penman	Forcing
ET Soil	After Surface	After Canopy	f(Sat Area)	Soil Moisture	Soil Moisture	None	None	Soil Moisture	Forcing
Vegetation	Yes	Yes	Yes	Yes	Yes	None	None	Yes	Yes
Infiltration	Constant	SCS/Green	Linear	Richards eq	Richards eq	SCS mod	Green & Ampt	Green & Ampt	Green & Ampt
Percolation	Constant	Linear	None	Richards eq	Richards eq	Linear	Linear	Richards eq	Richards eq
Subsurface	None	Linear	None	Linear	Linear	None	None	Kinematic	Richards eq
Baseflow	Linear	Linear	Linear	Exponential	Exponential	Linear	Linear	Linear	Topmodel
Tiles	None	Yes	None	None	None	None	None	Yes	Yes
Runoff	Unit Hydrograph	Lag	None	Diffusive	Diffusive	Unit Hydrograph	Linear	Kinematic	Diffusive
Routing	Modified Pulse	Muskingum	None	Muskingum	Muskingum	None	Kinematic	Diffusive	Dynamic
Sewers	None	None	None	None	None	None	Yes	Yes	Yes

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Table 3-7. A comparison of the process complexity represented in the considered hydraulic models.

Model	Complexity	Scale Range	Urban	Structures	Use	Ease of Use	Support	Active	Wide Applicability
HEC -RAS	Moderate	Small to Large	Good	Good	Planning	High	High	Yes	Yes, suitable for modeling full network of natural and constructed channels, over-bank/floodplain areas, levee protected areas
HEC-2	Low	Small to Medium	Good	Good	Planning	Moderate	Low	No	Yes, suitable for river hydraulics, steady gradually varied flow, natural and man-made channels, bridges, culvers, weirs structures
WASH 123D	High	Small to Medium	Fair	Fair	Planning	Low	Low	Yes	Yes, mainly designed for density-dependent water flow, thermal transport, and salinity transport and sediment and water quality transport in watershed systems
GSSHA	High	Small to Medium	Fair	Fair	Planning	Low	Low	Yes	Yes, mainly designed for simulate surface water flows in watersheds with diverse runoff production mechanisms
TUFLOW	Moderate	Small to Large	Excellent	Excellent	Planning	Moderate	High	Yes	Yes, suitable for modeling of rivers and floodplains, wide range of structures with dynamically adjusted energy losses, sediment transport, lake, and coastal hydraulics
MIKE	Moderate	Small to Large	Excellent	Excellent	Planning	Moderate	High	Yes	Yes, suitable for modeling urban or offshore infrastructure, coastal developments, groundwater, water distribution, wastewater

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Table 3-8. A description of the hydraulic processes represented by the considered models.

Process	HEC-RAS	HEC-2	WASH 123D	GSSHA	TUFLOW	MIKE +
Model Type	1D - 2D	1D	1D (Stream River Network)-2D (Overland Regime)-3D (Subsurface Media) – Coupled	1D (Stream Flow and Soil Moisture)-2D (Overland Flow and Groundwater) – Coupled	1D-2D-3D – Coupled	1D-2D (Overland)-3D – Coupled
Geometry	Cross Sections (1D), Terrain Model (2D)	Cross Sections	Cross Sections (1D)	Cross Sections (1D)	Cross Sections (1D)	Cross Sections (Mike 1D River)
Roughness Coefficients	Manning's Roughness	Manning's Roughness	Manning's Roughness	Manning's Roughness	Manning's Roughness, Relative Resistance, Sample Values	Manning's Roughness
Boundary Conditions	Unsteady-state: Upstream and Downstream BC (Stage and Flow Hydrograph - Normal Depth) - Internal BC (Stage/Flow Hydrograph, Lateral and Uniform Lateral Inflow Hydrograph- Rating Curve, Groundwater Interflow, Time Series Gate Openings, Navigation Dam, Elevation Controlled Gate)	-	Global Boundaries (Flows, Thermal, Salinity and Sediment transport); Internal Sources (Junctions, Control Structures); Media Interfaces	Upstream BC: No-Flow Condition, Downstream BC: Normal Depth, Head, Depth	Upstream and Downstream Boundaries, 1D/2D and 2D/2D Links: Outflow, Inflow, Rainfall, Dambreak Hydrograph, Pumps, Infiltration	Open BC, Closed BC, Inflow and Lateral Inflow, Water Level Boundary (Outlet), QH (Inflow/Water Level) Boundary
Type of Flow	Steady (1D-2D) and Unsteady (2D)-state	Steady-state	Steady-state	Steady-state (1D-2D) and Unsteady-state (2D)	Steady-state (1D-2D) and Unsteady-state (2D)	Steady-state
Flow Equations	Backwater Equation (Steady-state), St Venant Equations (Unsteady state) - Diffusive Wave Model	Backwater Equation	St Venant Equations, Kinematic, Diffusive, and Fully Dynamic (MOC) Waves (1D and 2D) - Richards' Equation for Subsurface Media (Vadose and Saturated Zones) (3D)	Saturated Richards' Flow Equations	St Venant Fluid Flow Equations	St Venant Equations-Diffusive Wave Model
Control Structures	Overall Head Losses (Simplified 1D/2D Bridge Modeling and Detailed Bridge Modeling) - Lateral Structures Modeling	Head Losses (Bridge / Culvert) Calculations (Normal Bridge, Special Bridge, and Special Culvert Methods)	Control Structures (Weirs, Gates, Culverts, Levees, Mass, Or Energy Balance) Is Explicitly Enforced by Solving Flux Continuity and State Variable Continuity (or Flux) Equations	Present Version of GSSHA Channel Routing Includes Support for Weirs Future Versions Will Include Bridge Crossings, Culverts, Reservoirs, and Lakes.	Rectangular, Circular, and Irregular Shaped Culverts, Bridges Pressure Flow and Vary Losses with Height. Spillways, Pumps and User Defined Height-Flow Curve or Matrix for Downstream Controlled Condition (1D)	Modeling Of Culverts, Weirs, Bridges, Pumps, Gates, Direct Discharges, Dambreak, Energy Losses, Tabulated Structures
Water Properties	Sediment Transport Capacity Functions (Steady and Unsteady-state): Ackers-White, Engelund-Hansen, Laursen, Meyer-Peter Müller, Toffaleti, Yang	-	Bed and Suspended Sediment Transport Methods (1D and 2D)	Soil Erosion and Sediment Routing (Kilinc and Richardson Equations)	Sediment Transport (2D/3D)	Single-Fraction and Multi-Fraction Sediment Transport and Bed Layer Modeling (MIKE 1D)

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3. **Storm Surge Modeling**: Storm surge could be the dominant process in any compound flood workflow. Storm surge models have reached a mature state and have been routinely applied to forecasting, hindcasting, planning, and design studies for the last two decades. This section of the Theme I Literature Review discussed the basic physics of storm surge and the characteristics of some of the primary codes in this field, including ADCIRC, Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM), Delft3D, Finite Volume Community Ocean Model (FVCOM), and Adaptive Hydraulics (AdH). These codes are written in either Fortran or C programming language and have been parallelized for HPC environments. ADCIRC and SCHISM have been widely applied for large-scale Texas coastal modeling. SCHISM has the advantage of including a 3D component, while ADCIRC has been more thoroughly validated for Texas storms and is being used currently for design studies for USACE, FEMA's coastal flood risk assessment effort, and other groups developing storm mitigation systems. Storm surge models have also been coupled with wave models to simulate wave-circulation interaction. In recent years, surge models have begun to include inland river inflows in a first attempt to account for compound flooding. Some have also added rain-on-mesh to include direct rainfall effects. In the context of workflows for compound flooding, the storm surge model will be of primary importance, since it is the conduit between oceans, coasts, bays and estuaries, and rivers. The interplay between storm surge and river flows will affect the flood inundation both along the conventional coastal region and well upstream along rivers.

   (See **Appendix C-3** and presented in Table 3-9 for findings of strength, weakness, opportunities, and threats (SWOT Analysis) of different storm surge models.)

Table 3-9. A SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis for storm surge models.

Model	Strengths	Weaknesses	Opportunities	Threats
ADCIRC	Validated for Texas storms Large and diverse user base Parallelized for HPC Tightly coupled with SWAN and STWAVE Inputs from many wind products Open source Runs in forecast mode Community GUI available via SurfaceWater Modeling System	Mostly 2D 3D not well developed Limited stabilization for advection Local mass balance issues	Growing user and developer base New global model widely adopted by NOAA, USACE, FEMA, and internationally	Software optimized for traditional HPC CPUs and not GPUs Unstructured meshing can be time consuming (true for all unstructured models)
SCHISM	Validated for recent storms Open source Numerous integrated modules for waves Parallelized for HPC Seamless transition from creeks to deep ocean (2D to 3D) Conserves mass locally and globally	Not as tested for storm surge or large storms	Ongoing Active development Adopted by NOAA and international community User group is growing	Steep learning curve Limited built-in graphic User interface support for model set-up and visualization User base is small compared to other models Unstructured meshing can be time consuming (true for all unstructured models)

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Table 3-9. Continued.

Model	Strengths	Weaknesses	Opportunities	Threats
FVCOM	Solves 3D primitive equations with hydrostatic and non-hydrostatic approximations Coupled with wave model Comparable in accuracy with ADCIRC for storm surge Large user base and well-established model Conserves mass locally and globally	Relatively strict stability constraints Did not show good parallel performance compared to ADCIRC in intercomparison tests Can be overly diffusive due to lower order discretization	Can be employed to study storm surge, internal waves and biogeochemical processes Can include nested spatial domains	Mostly employed for the U.S. East Coast Has not been used for Texas except in intermodel comparison project
Delft3D/ DFLOW-FM	Very large user base Very flexible code with many modeling options including state-of-the-art for morphodynamics/sediment Development supported by a large organization Capable of 2D and 3D modes Relatively easy learning curve Conserves mass locally and globally	No large-scale calibration and validations studies performed for Texas coastal regions Parallelization efficiency is not as good as other models	Sustainable over the long haul Possibility to do beach erosion and 3D	Code development is outside the U.S. Training is expensive Source code is not fully open source
AdH	Validated for storms across U.S. Capable of multiphysics simulations Advanced numerical scheme, robust to advective problems Includes groundwater transport Conserves mass locally and globally GUI available in community version of SurfaceWater Modeling System	Not fully open source Requires sophisticated linear and nonlinear solvers Can be over diffusive	Under active development with effort focused towards multiphysics coupling Still actively used by USACE districts	User base is small compared to other models Development controlled by USACE
ROMS	Sophisticated numerics Open Source 2D and 3D Conserves mass locally and globally	No large-scale calibration and validations studies performed for Texas coastal regions Not validated for storm surge or tides Uses structured grids	Mature model Large user base Stable in 3D	Mostly used for 3D Baroclinic models Not known for storm surge
SLOSH	Efficient Probabilistic framework Conserves mass locally and globally	Simplified model No waves, no advection Tends to overpredict	Wide user base Still used by NHC and NOAA	Old technology User support unknown Future development uncertain

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4. **Waves Modeling**: Wind-induced waves tightly interact with surge models in tropical cyclones. Water velocity and water elevation feeds into wave models and waves increase surface stresses in the coastal ocean. Wave cresting, wave runup, and wave overtopping can impact structures and cause flooding in addition to surge. Wave setup can increase storm surge by up to 1 meter in some cases. For these reasons, most surge models are coupled in some form to wave models. Common wave models are Simulating Waves Near Shore (SWAN), developed at the Delft University of Technology, the STWAVE, developed by the USACE, and WAVEWATCH III, developed by NOAA. Waves should be included as an essential part of a compound flood modeling framework because of the tight interaction between waves and surge. (See **Appendix C-4** for additional findings of wave modeling literature review efforts.)
5. **Compound Flood Inundation Modeling**: The key challenge in compound flood inundation modeling is determining an effective way of quantifying the combined impact of two or more physical flood forcing processes on the short and long-term inundation of coastal zones. This section of Theme I provides a detailed account of the various physical principles and numerical strategies adopted to either 1) couple models representing different physical processes or 2) to develop a fully integrated computational framework. The discussion considers a range of academic and production-level compound flood modeling codes that comprise state-of-the-science. Most compound flood models can be categorized based on either the type of numerical methods (e.g., process-based, reduced physics, and data-driven) and coupling strategies (e.g., one-way coupled, two-way coupled, integrated) or by the intended use cases (e.g., real-time simulation, probabilistic hazard evaluation, high-resolution spatiotemporal modeling).

Physics-based (mechanistic/deterministic) models are well-established in their respective domains as discussed in the preceding sections. Such models are arguably the primary targets for inclusion in a compound flood modeling framework. Using separate domain models requires "model coupling" (i.e., the exchange of data between mechanistic models as they are marched through time). (See Coupling Flood Inundation Models for Compound Flooding, below, for more information.) The complexity of compound flood inundation modeling is driven by the underlying physics that requires high-resolution space and time discretization, high-quality empirical representation of sub-grid scale processes, and extensive computational time for each simulation. Nevertheless, physics-based mechanistic models have been shown to be well-equipped to capture the interaction effects between competing physical processes and can be used to evaluate flood inundation impacts for various engineering "what if" scenarios.

Researchers are attempting to address the issues of high computational cost of mechanistic modeling through "reduced-physics" models and data-driven AI/ML models. Reduced physics models are those which intentionally simplify some portion of the governing physics equations. The goal for reduced-physics models is to achieve a lower computational cost and/or simplified user operability by (hopefully) only marginally sacrificing flood inundation accuracy. Ideally the results from a reduced-physics model should be within the uncertainty envelope of a process-based model. Some notable examples include static flood models such as the Height Above Nearest Drainage (Nobre et al. 2011) methods, simplified momentum models such as LISFLOOD (Large-scale Inundation Simulation using FLOOD) (Van der Knijff et al. 2008), and Super Fast INundation of CoastS (SFINCS) (Leijnse et al. 2021), and downscaled flood models such as Parallel Raster Inundation Model (PRIMo) (Sanders & Schubert 2019).

In theory, data-driven AI/ML models, could be trained to provide rapid flood inundation predictions for specific storm conditions that would be faster than traditional mechanistic flood inundation models. However, such models presently require prohibitive amounts of data and computational time for their training. Furthermore, AI/ML methods have yet to be proven effective in correctly capturing events that are outside their training data. Nevertheless, this is a highly active field of research that is rapidly evolving to overcome these challenges through the development of new physics-informed, hybrid-data, graph-based, operator learning, and generative modeling architectures.

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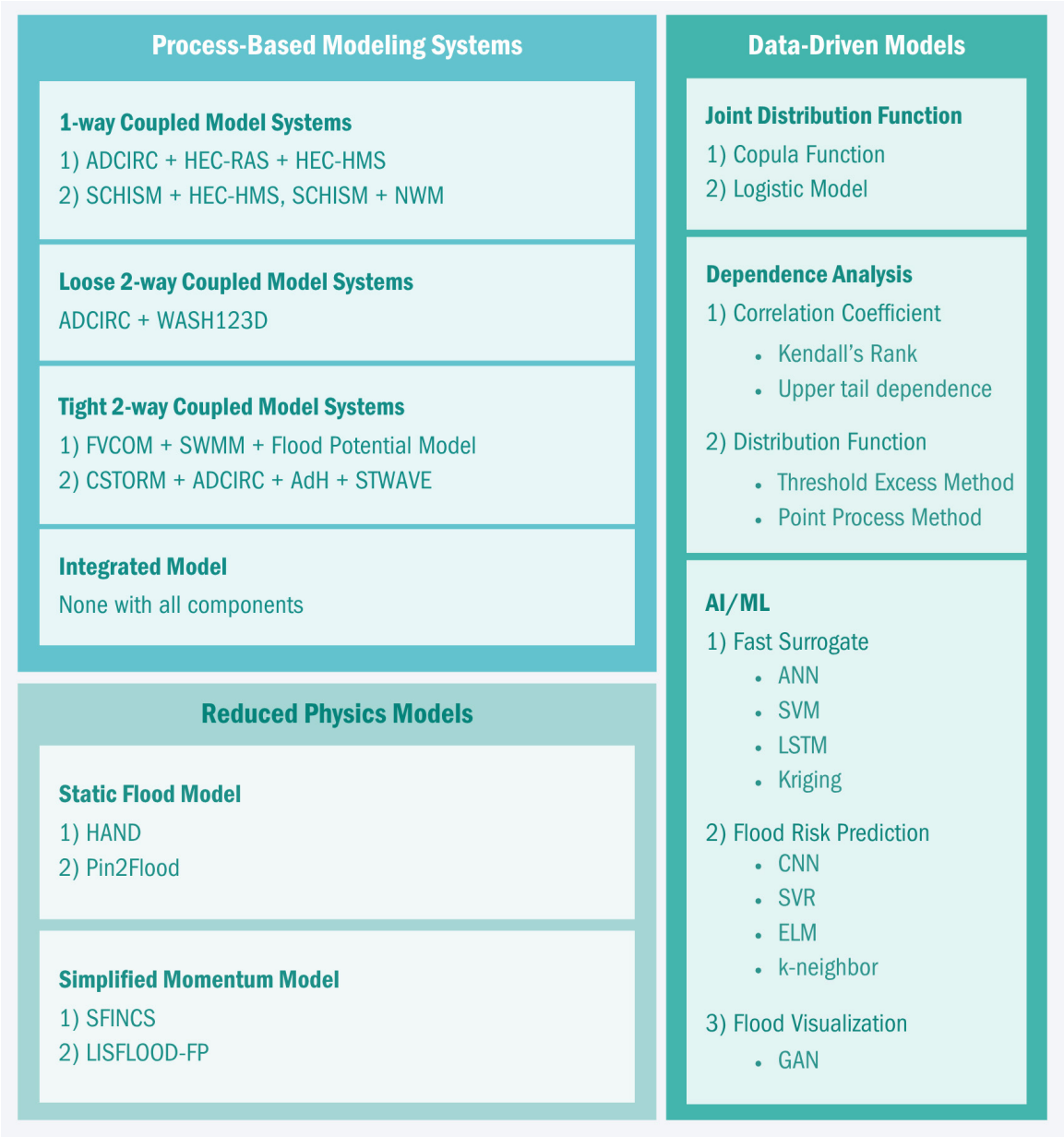

Figure 3-6. Examples of compound flood models found in the literature. Process-based modeling systems include all flood processes (hydrology, hydraulics, ocean, and waves), while reduced-physics models are simplified and may not represent all components. Couplings between process-based models, reduced-physics models, and data-driven models are possible, but are neglected for simplicity in presentation.

Literature Review Theme II (Probabilistic Methods for Flood Hazard Estimation)

The floodplain is a representation of flood risk depicting the extent or water surface elevation with a specified annual probability. Probabilistic studies of flood hazard rely on modeling to overcome the challenge of low spatial and temporal coverage of observational datasets, as well as the need to estimate tail risks outside of the historic record. Model-based studies have traditionally focused on representing the predominant source(s) of flooding in an area independently (e.g., pluvial/fluvial inland, storm surge in coastal zones) without consideration of the interdependencies between different modes. As a result, large disparities occur between floodplain maps based on traditional analyses and actual observations, an indication of the importance of accounting for compound events. TIFF conducted a literature review of techniques for probabilistic compound flood hazard modeling and analysis specific to the coastal Texas

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region, aiming to create a comprehensive field guide. This analysis is crucial for estimating inundation extents and depths at different frequency events, providing insights for evaluating project benefit computations.

The summarized findings of this literature review are presented in five sections below (see **Appendix C-6** for detailed information):

1. **Probabilistic Models**: Probabilistic models are an essential component to any compound flood modeling workflow for a variety of reasons. Such models can be used to develop Probability Density Functions of inputs used to drive compound numerical flood models. Results are used to quantify probabilistic flood hazard analysis caused by different factors. An example is the use of the JPM-OS to generate synthetic storms for modeling flood hazards due to storm surge. Similar approaches are recommended for generation of synthetic storm/rainfall events for probabilistic compound flood hazard analysis. Such methods can also be used in combination with data from measurements or from physics-based models to generate surrogate models for compound flooding. These models are extremely efficient computationally and can be used to estimate impacts from a variety of factors, such as sea-level rise, climate change, etc., over wide ranges of parameter space, which would be computationally prohibitive using high-resolution physics-based models.

2. **Storm Event Generation**: Tropical storms that could potentially lead to meaningful storm surge are relatively rare events, with locations such as Texas having an approximate tropical cyclone frequency rate of only 0.9 storms per year (Zhu et al. 2013). An analysis of 105 years of tropical cyclone observations found that the return period of tropical cyclones to the Texas coast varied from 3 to 5 years along the Texas coast with the return period increasing from 3 years in the northeast to 5 years in the southwest (Keim et al. 2007). By comparison, stream gage observation data have, in many cases, been reported on an hourly basis for decades. As such, many storm events are possible which have combinations of parameters that have never been observed in the historical record. Consequently, most techniques for probabilistic compound flood hazard analysis rely on transformed historic storms (e.g., track-shifted, under different antecedent conditions) or synthetic storms (i.e., tropical cyclones that follow an idealized smooth track and evolution of parameters over time) produced by a physical process-based model.

3. **Sampling Design and Model Coupling multivariate Copula Approaches**: The first step in sampling events for hazard modeling is the selection of thresholds to distinguish what constitutes a hazardous event. For single hazard analysis, only one threshold is required, but compound extreme event analysis contains multiple concurrent or consecutive hazards that interact (Sadegh et al. 2018). As such, compound flood hazard analysis requires consideration of multiple hazard thresholds and the relationships between the hazards and extreme events. The selection of thresholds (or more generally, inclusion and exclusion criteria) impacts every subsequent step in building the flood risk analysis framework. This is complicated by interactions between hazards wherein two hazards that are both below their respective thresholds might occur simultaneously and produce the same or more damage as a single hazard exceeding its threshold would have produced. Once criteria have been established to identify qualifying events, analysts then must also choose what events to simulate and the modeling platform to best simulate the event outcomes.

4. **Combining Independent Hazard Curves**: Recognizing the amplifying effect from the coincidence of multiple flood drivers, several methods are in use that directly combine hazard curves developed from univariate single driver analyses, such as storm surge, rainfall/runoff, river discharge, etc. These approaches assume independence between drivers, and therefore between their hazard curves, which is not ideal (Moftakhari et al. 2017). Combining assumed-independent hazard curves for multiple drivers is typically approached using 1) hazard curve overlay, 2) Monte Carlo simulation, and 3) copula functions.

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5. **Probabilistic Analysis Improvement Needs**: Bivariate analyses of joint probabilities of flooding from two of storm surge, rainfall, and river discharge are relatively common in Texas. The use of copulas to estimate covariance between independently modeled or estimated factors is convenient, given existing software libraries for fitting computationally tractable copula families, but it limits the representation of non-linear, complex dependency structures and nonstationarity in underlying hazards. Modeling and computational capabilities have reached a point where more physically-driven analyses are relatively accessible. As such, it is recommended to pursue studies that extend joint probability methods, historically used to estimate surge hazard, to account for variability in other flooding mechanisms such as rainfall and extreme streamflows. These approaches can also be easily adapted to incorporate stochastic uncertainty in antecedent conditions (e.g., soil saturation, sea level, tides) that vary in importance by local geography. Existing extensions of JPM-OS have generally focused on flooding from tropical cyclones, with some studies incorporating hazard from non-tropical frontal events. The impact of convective storms has been implicitly addressed by empirical analysis of antecedent conditions to which convective storms may have contributed, but more attention could be given to explicitly model interdependencies between such storms and tropical cyclones from the opposite direction (e.g., when flooding from convective systems is impacted by recent cyclonic events).

Literature Review Theme III (Nature Based Solutions for Flood Management Planning)

As flooding becomes a more frequent and severe problem in Texas, combined with populations steadily increasing in and around urban centers, flood mitigation is a growing interest for many communities. In the LRGV—a region vulnerable to hazardous compound flood events due to a combination of factors including its low-lying terrain, rainfall characteristics, drainage systems, and land use—adaptive and robust flood mitigation solutions are needed. NBS, which incorporates natural features or processes into the built environment to promote resilience and sustainability in flood planning, have demonstrated significant benefits over traditional infrastructure. NBS and green infrastructure offer relatively low-cost approaches to mitigating flooding, especially when the uncertainties in flood risks become challenging due to increased climatic variability and land-use change (Uribe, 2017).

TIFF conducted a literature review to understand the effectiveness of NBS under different storm intensities, and to make recommendations for NBS to enhance flood mitigation and resiliency in the LRGV. This review identified existing green infrastructure projects containing NBS (such as pervious pavement systems, biofiltration systems or biofilters, and habitat restoration), while prioritizing projects occurring along the Texas coast and in the LRGV. This review, along with TAT guidance, resulted in TIFF Recommendations for the implementation and performance assessment of NBS in the LRGV (Recommendations C3.3K and C3.3L).

The summarized findings of this literature review are presented in three sections below (**Appendix C-24**):

1. **Types of Green Infrastructure and NBS**: TIFF reviewed existing projects containing low-impact infrastructure alternatives to traditional hard-structure flood defenses and identified the following types of green infrastructure and NBS:
    - Pervious pavement systems are alternatives to traditional pavement and are designed to mitigate stormwater runoff impairment in urban applications (Scholz and Grabowiecki 2007; Perez et al. 2022; Holzer and Poor 2024; Hegemier and Barrett 2021; Le and Petit 2022).
    - Bioretention Cells (BRC), also known as biofiltration systems or biofilters, combine engineered design with natural systems that manage stormwater runoff by reducing peak discharge while improving water quality using low-energy treatment technology (Perez et al. 2022; Hunt et al. 2006; Liu et al. 2014; Mahmoud et al. 2019; Ekka et al. 2021; Hegemier and Barrett 2021).

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- Retention/detention systems manage stormwater by either temporarily storing it and discharging it gradually (Detention Ponds or Dry Ponds) or permanently storing water, allowing it to infiltrate into the ground naturally (Retention Ponds or Wet Ponds) (Bridges et al. 2021).
- River restoration is the process of improving the environmental health of a river or stream by modifying its channel, adjacent riparian zones, and water inputs to restore natural processes and functions.
- Wetland restoration is the process of improving the wetland's water storage system. Wetlands provide improved habitat, flood control, and nutrient uptake from stormwater runoff through chemical and biological processes to treat and improve water quality (Irwin et al. 2018; Hunt et al. 2006; Mahmoud et al. 2019; Bridges et al. 2021).
- Beach and dune restoration is the process of improving those habitats affected by erosion due to wind and wave action. Beaches and dunes provide natural coastal protection against storm surges and high waves, reducing coastal flooding and structural damage and providing ecological habitat.
- A living breakwater is a coastal structure typically located nearshore, and is designed to protect shorelines from erosion and storm damage while also providing habitat for marine life. Unlike traditional breakwaters made of concrete or stone, living breakwaters incorporate natural elements like oysters or reefs to create a more environmentally friendly and sustainable coastal defense system (Bridges et al. 2021; USACE 2021).

2. **Evaluation of NBS in the LRGV**: The evaluation and recommendation of NBS applications was conducted in four hot spots with high flood risk in the LRGV. The selected sites were grouped into three urban cases and one coastal case. The coastal case includes South Padre Island, and the urban cases include the communities of McAllen, Weslaco, and Harlingen. These sites were selected based on flood mapping, which provided evidence that these flood-prone locations could benefit from NBS implementation. Flood mapping integrated multi-sensor satellite datasets, hydrometeorological records, and ML techniques to map historical flood events. (See **Appendix C-24** for a detailed description of the study and methodology.) While many coastal communities exist in the LRGV, South Padre Island stands as an important location due to not only its environmental significance but also its economic impact. However, the area has experienced significant coastal flooding on both the coast and bay sides of the island. With increasing commercial development in this area, a strong dune system is vital for the protection of local businesses. The top recommendation for a coastal community, based on these previous works (e.g., Uddagiri et al. 2024, USACE 2021), is dune/beach restoration. Urban development in the LRGV ranges from small rural towns surrounded by croplands to urban centers housing a majority of the population. It is important to note that in an urban setting, no one NBS can fit each location, and NBS selection should consider site-specific characteristics and features to ensure an effective and positive impact on flood mitigation. For urban centers, three main NBS types can be considered: 1) bioretention systems, 2) retention and detention systems, and 3) pervious pavement systems. In the three urban site locations, all are highly developed and require more area for water infiltration. These areas are also flat with low slopes, meaning storage and detention become a key solution in mitigating flooding.
3. **NBS Decision Support Tree**: The literature review culminated in a decision support tree aimed at simplifying the decision-making process when first identifying and considering a location's suitability for NBS implementation (Figure 3-7). Starting from a broad spectrum of coastal and inland scenarios, the decision support tree defines key attributes to consider while evaluating a location for potential and favorable NBS.

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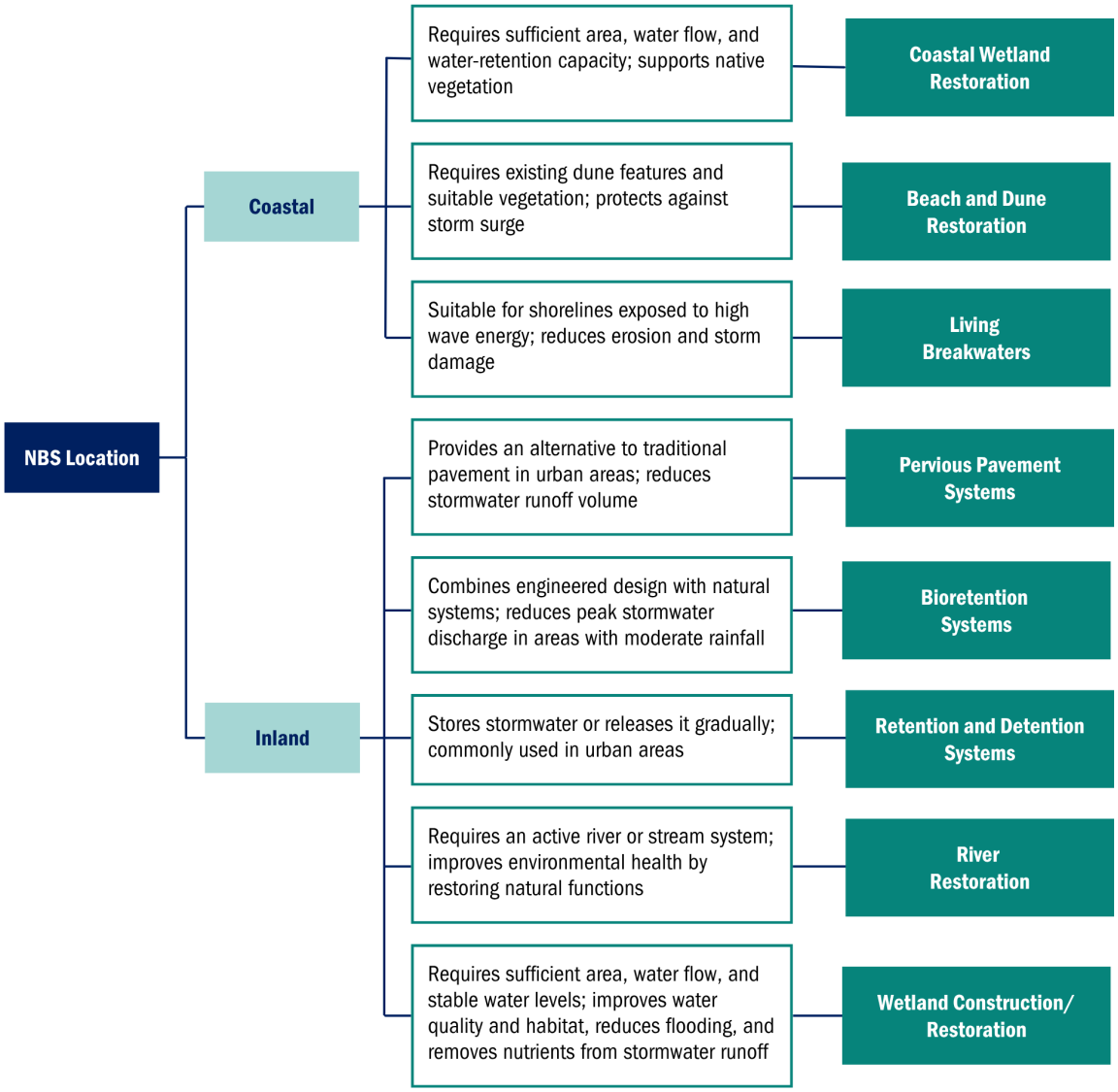

Figure 3-7. Decision support tree for the application of Nature-Based Solutions (NBS) in the LRGV.

Objective 5: Develop recommendations for conceptual model-coupling workflow(s) for assessment of compound flooding hazard in the coastal Texas region

Building on the findings of the model literature review described above, TIFF focused on the development of conceptual model-coupling workflows for assessment of compound flooding hazards in coastal Texas. The goals were to investigate appropriate software, model-coupling frameworks, and conceptual workflows for various simulations with different levels of complexities that may include different types of forces and processes within the GLO's RBFS regions that lead to compound flooding. The major efforts of this work include developing:

A. a conceptual model coupling strategy/workflows (both source code level coupling and using coupling interfaces), including coupling of state-of-the-art meteorologic, hydrologic-hydraulic, wave, and estuarine-surge models for each of the use cases and level of complexities by considering the involved processes/drivers/forces that are present along the Texas coast

B. scenarios and an evaluation matrix to test effectiveness of the conceptual model integration strategy

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C. criteria and recommendations for testbed(s) for workflow evaluation (**Appendix C-18**)

D. a testbed evaluation using the Lower Rio Grande Valley.

A. DEVELOPING A COUPLING STRATEGY FOR FLOOD INUNDATION MODELS FOR COMPOUND FLOODING

The coupling among several, if not all, of the physical processes involved in compound flooding is needed in flood modeling as these processes interact during a compound flood event.

Existing coupled systems[5] are typically centered around a keystone model (e.g., a coastal ocean model (**Appendix C-5**), an H&H model (**Appendix C-2**), or a meteorology model (**Appendix C-1**)). To date, none of these models individually provides a complete physics representation of all the compound flooding processes (e.g., meteorology, hydrology and runoff, river hydraulics, flood inundation, groundwater, stormwater infrastructure, storm surge, waves). The physics-based flood inundation models that incorporate coupled physical processes can be characterized into four categories of increasing level of coupling complexity (Santiago-Collazo et al. 2019): 1) one-way, 2) loose two-way coupled, 3) tightly two-way coupled, and 4) fully coupled (**Appendix C-5**):

> **One-way coupling** is the simplest coupling method from a donor to a recipient model. One-way coupling generally involves coupling two or more models, where one model functions as the receiver of information, whereas the others act as secondary models that provide their outputs to the primary model (Santiago-Collazo et al. 2019). This approach is commonly used for coupling domain models in coastal processes. An example of such coupling is the transfer of upstream or downstream boundary data to or from a HEC-RAS model (Brunner 1994) to or from an ADCIRC model (e.g., Loveland et al. 2021). Such models lack the feedback of physical processes that is provided with two-way coupling.
>
> **Two-way coupling** (tight or loose) involves the independent execution of two or more models, which sequentially exchange information, such as boundary condition data. In two-way couplings, the fundamental characteristic is that the models operate independently and do not share algorithms or solution variables. The objective of two-way coupling is to enable each model to receive feedback from the others in an iterative fashion, thereby overcoming the primary drawback of one-way coupling without necessitating the creation of an integrated model. Loose two-way coupling and tight two-way coupling represent essentially the same basic processes and differ primarily by their software design (Santiago-Collazo et al. 2019).
>
> **Fully coupled** (aka monolithic, integrated) models are those that resolve all physical processes within the same computational framework inherently sharing all necessary solution variables without the need for communication to other models. These represent the closest connection between the physical processes of these coupling methods and thus are less likely to induce numerical issues that can occur in one and two-way coupling.

The State-of-the-Art in Model Coupling

Presently, "one-way" coupling (donor to receiver) is the simplest and most commonly used approach for coastal processes. One-way coupling is a valid approach when changes in the donor caused by the receiver are considered small and such feedback do not substantially change the area of interest (e.g., the flood inundation is presumed[6] to have minimal effect on the storm surge). The assumptions required for one-

5 Existing coupling methods associated with specific models are discussed in **Appendix C-5**.

6 The entire point of compound flooding is that one-way interactions cannot be presumed for extreme events but must be shown to be valid. The use of one-way coupling requires modelers to demonstrate that the uncertainties associated with neglecting two-way effects are understood, quantified, and acceptable for the purposes of the model.

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way coupling can be eliminated by allowing the different models to communicate their results to each other during the time-marching simulation, which is known as "two-way" coupling. Loose and tight two-way coupled models, distinguished primarily by software implementation, allow for feedback between two or more independent models, but may suffer from numerical inconsistency and convergence issues. ADCIRC coupled with WASH123D and the Coastal Storm Monitoring System (CSTORM) are two successful examples of loose and tightly two-way coupled models, respectively (Tritinger & Dillon 2025; Tanaka & Westerink 2011). In contrast to coupled models, it is theoretically possible to build a single model that incorporates all the physical processes (i.e., a fully-integrated compound flood inundation model). However, there are currently no examples such models in either commercial applications or research. Progress is being made in this direction and there are notable examples of partially integrated frameworks that cover different subsets of physical driving processes (e.g., SCHISM, AdH, WASH123D, SFINCS).

Arguably, flood inundation model coupling has been primarily driven by the coastal ocean modeling community, whose models are the most computationally intensive and whose storm surge results are strongly affected by the area available for inundation. The Coupled Systems Centered on Coastal Ocean Modeling section in **Appendix C-19** provides a detailed discussion on a number of coupled systems that have been centered around coastal ocean models. Coupled systems centered on hydraulic inundation models are less common than those centered around coastal ocean models. The two most prominent examples (HEC-RAS and AdH) are discussed in the Coupled Systems Centered on Inundation (Hydraulics) Models section in **Appendix C-19**. The biggest challenge for these models is the two-way coupling with a coastal ocean model such that river flows and river-driven flood inundation interact with storm surge with the correct nonlinear interactions. For compound flood modeling, meteorology is generally treated as a one-way donor model as the feedback from saturated soils to meteorology are arguably on time scales much longer than flood events. Within the meteorological community, modeling systems relevant to compound flooding have been developed, most notably a system for creating spatio-temporal distribution of rainfall from a tropical cyclone and the CSTORM-MS that provides two-way coupling and is already integrated with coastal ocean models ADCIRC and AdH. (See the Coupled Systems Centered on Meteorology section in **Appendix C-19** for more details.)

Coupling in compound flood hazard analysis (and subsequent risk assessment) increases computational burdens due to the need for many flood inundation model runs and are therefore also affected by the choice of coupling, though somewhat differently. In the case of one-way coupling, if the more computationally intensive model needs only to be run once, this can make the approach much more computationally feasible. However, fully coupled models, which are complex in terms of the physical modeling itself, may have the same number of runs as one-way coupling. Two-way coupling, however, can require immense numbers of model runs for hazard analysis, a fact that should be considered when executing coupling approaches for a project where hazard analysis and risk assessment are needed for planning or design (**Appendix C-19**).

Flood Hazard Analysis Category for Compound Flood

Hazard analysis for compound flooding can be categorized by "levels" of increasing complexity as shown in Table 3-10, similar to the CHS-CF tiers (**Appendices C-9** and **C-11**). These levels reflect statistically consistent and increasingly robust probabilistic workflows for quantifying compound coastal hazards.

The foundational stage, Hazard Level 1, consists of a screening-level statistical analysis. This approach uses bivariate statistical methods—typically copulas—to rapidly assess the joint probability of two concurrent flood drivers, such as coastal storm surge and heavy inland precipitation. Instead of relying on computationally intensive dynamic models, this method calculates the statistical correlation and combined return periods of the interacting variables from historical or synthetic data. This allows engineers and planners to efficiently identify highly vulnerable project sites early in the planning process, helping

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them prioritize resources and determine which locations require more rigorous, dynamic compound flood modeling during advanced design phases.

To address this need, TIFF enhanced an existing USACE statistical hydrology tool to integrate this type of bivariate analysis directly within standard H&H modeling workflows, as further detailed in the section Development of a Screening-Level Compound Flood Analysis Tool (Hazard Level 1) below.

Table 3-10. Compound flood hazard framework levels.

Hazard Analysis Level	Characteristics	Purposes	Computing Requirements; Uncertainty	Examples
Hazards Level 0 (HL-0): Independent Scenarios Screening	Combined scenario frequency analysis assuming independence between coincident flood drivers Response matrix used to develop inputs and boundary conditions for flood models	Screening for early feasibility Locations with clear evidence of no correlation between coincident events	Low to medium computing requirements High uncertainty strongly dependent correlation being small and representative of any joint probability	"Response Matrix" HEC-SSP
Hazards Level 1 (HL-1): Screening Statistical Approaches	Data driven statistical approach based on available paired event records Typically statistically represented by a bivariate copula Resulting joint probability curves used to drive flood models	Screening for early feasibility Locations with extensive historical record Projects with limited financial resources or acceptable of high uncertainty	Low to medium computing requirements based on data availability Medium to high uncertainty strongly dependent on number of paired events in historic record	Multivariate analyses Multivariate copula analyses HEC-SSP Bulletin 17C AI/ML approaches
Hazards Level 2 (HL-2): JPM-Hybrid Probabilistic Linking	Synthetic storm driven coastal model linked to simplified inland analysis, such as by correlated parameters and/or random sampling	Areas with highly correlated compound parameters (e.g., seasonality) Independent compound hazards (e.g., river flow and storm surge) Feasibility studies	Medium Uncertainty related to coastal model, correlation and sampling	JPM-OS with Hybrid Monte Carlo JPM hybrid CSTORM-MS
Hazards Level 3 (HL-3): Extended JPM	Coastal model and inland flood model driven by synthetic tropical cyclone parameters Can be linked by tropical cyclone rainfall driven by same parameters One- or two-way model coupling, AI/ML used to expand limited tropical cyclone parameter space Can include additional complexity such as variable antecedent conditions, tropical cyclone rainfall with stochasticity; more complex model coupling; additional hazards (e.g., groundwater)	Feasibility Risk-based design of low to medium to high complexity projects Design or studies for critical infrastructure	Medium to High: Lower uncertainty due to improved modeling and probabilistic rigor May have increase in uncertainty due to additional parameters and models	Extended JPM with CSTORM-MS NOAA UFS Hydrodynamic/ Wave models HEC-HMS, RAS AdH Local H&H models Groundwater models

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Development of a Screening-Level Compound Flood Analysis Tool (Hazard Level 1)

Bivariate analysis techniques (e.g., Santos et al. 2019, Kim et al. 2023) have been applied to assess the joint probability of compound flood hazards, but they are often implemented using ad-hoc custom scripts. Currently, no standardized tool exists that supports the seamless integration of bivariate flood analysis within H&H modeling workflows. To address this gap, TIFF Component 3 is enhancing the USACE-HEC's statistical hydrology application tool, HEC-Neptune, by incorporating bivariate analysis capabilities. These improvements will allow for estimation of dependency between rainfall and surge events, improving hazard estimation compared to current methods that assume independence and support for screening-level joint probability modeling of coastal hazards (essential for feasibility-level flood risk assessments).

HEC-NEPTUNE Copula Analysis

The USACE-HEC is developing HEC-Neptune, the next generation statistical hydrology application. Neptune is the planned successor to the Statistical Software Package (HEC-SSP). A Copula Analysis will be implemented in HEC-Neptune. In addition, technology transfer material, including a User Manual and other tutorials, will be developed to support application of the Copula Analysis in compound flooding analyses.

The Copula Analysis will implement the workflow as documented in **Appendix C-25** and offers advantages over the current ad-hoc custom bivariate analysis scripts by enabling version control, extensibility, and reviewability. Additionally, the GUI reduces the barrier to entry for users by eliminating the need to learn scripting and provides a guided workflow. The Neptune Copula Analysis provides consistency and standardization. Also, HEC-Neptune can be easily integrated with other HEC modeling tools including HEC-HMS and HEC-RAS which have been widely used for flood hazard analysis.

The implementation of the Copula Analysis in HEC-Neptune is underway and snapshots of the tool GUIs, which are preliminary, are presented in **Appendix C-25**.

The Copula Analysis wizard contains six tabs:

1. **General Information tab**: the user enters an analysis name and description
2. **Scenarios tab**: the user selects and labels datasets for use within the result plots and tables; supports a two-sided copula and flexible graph and table labeling options
3. **Marginal Distributions tab**: the user enters the parameterized marginal distributions for the four datasets; the alpha release of HEC-Neptune will not include univariate distribution fitting (Subsequent releases will include the ability to fit univariate distributions using a variety of fitting methods.)
4. **Output Frequency Ordinates tab**: the user specifies the joint probabilities; ordinates can be added, removed, and sorted
5. **Copula Selection tab**: displays the dependence parameter and Akaike Information Criteria (AIC) for each of the fitted copulas; a contour plot for each copula with the observed data pairs are shown; copula models are fit to each of the copula scenarios defined on the Scenarios tab and the user is required to select one copula per scenario
6. **Design Events tab**: the user can examine results, viewing both graphical and tabular results of design events for each copula and the envelope curve

Screening-Level Workflow for Compound Flood Analysis

To meet the project's reporting deadline, an interim bivariate analysis workflow was used for the LRGV testbed application. This interim workflow utilized a specialized, R-based implementation of the intermediate-phase HEC multivariate analysis tool. The analytical methods applied in this study are based on the joint-probability framework developed and implemented in the *R MultiHazard* package by Jane et

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al. (2026). While the theoretical approach is derived from the *R MultiHazard* package, the package itself was not directly executed. Instead, all statistical modeling, bivariate calculations, and copula fitting were performed using custom R scripts. The R code used to perform these analyses is available on GitHub.

The copula bivariate analysis procedure consists of the following steps, which are discussed in detail in **Appendix C-25**:

1. Data acquisition
2. Data Processing (isolating tropical cyclones, detrending, de-tiding)
3. Development of extremal events
4. Fit marginal distributions
5. Dependence assessment
6. Define and fit copulas
7. Generate samples
8. Derive and combine isolines
9. Compute relative density along isolines

Bivariate Copula Analysis for the Lower Rio Grande Valley Testbed

An application of the noted bivariate analysis workflow, as discussed in **Appendix C-25**, was tested in the LRGV. Figure 3-8 shows the basin and nearby long-term surge and precipitation gages. Early steps in the process involving dataset preparation and processing, development of extremal events, and dependence assessment were carried out for the application following USACE-ERDC-CHL developed scripts and tools, which are described in more detail in Carr et al. (2022c) and Carr et al. (2026). The interim workflow and HEC-SSP are then used to produce the application results: fitting marginal distributions, fitting copulas, generating random samples, deriving and combining joint Annual Exceedance Probability (AEP) isolines, and computing density along isolines to identify pairs with the highest likelihood. (See **Appendix C-25** for detailed information.)

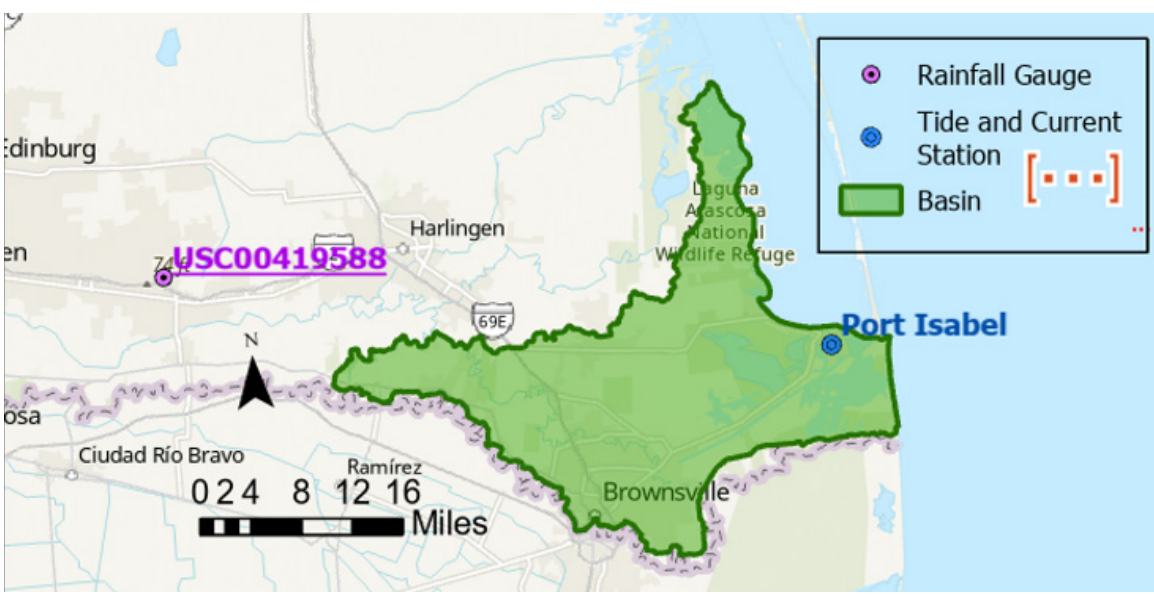

Figure 3-8. Rio Grande drainage basin showing gage locations.

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Figure 3-9 presents the bivariate analysis results. A set of isolines is developed for precipitation conditioned on extreme surge, and a set for surge developed on extreme precipitation. These isolines are then combined using an 'ADD' approach resulting in an envelope joint isoline. Therefore, the plotted isolines define the sets of precipitation and surge combinations that share a joint exceedance frequency corresponding to each AEP. Design events are shown as the most likely event along each isoline, where relatively density of random pairs, shown as grey circles, along the isolines are largest. The relative density is shown as colors along the isoline and the most likely events shown in the redder colors and the most likely event as the red diamond symbols. Table 3-11 details the values of the design events. Though the most likely event is reported, many pairs of precipitation and surge lie along each isoline having the same AEP, so a wide range of precipitation and surge can occur for a given AEP. In addition, the most likely event may not be the event that is critical to the design and should be reviewed and considered by designers in the case of a complex watershed or more sensitivity to either the rain or the surge hazard at the site.

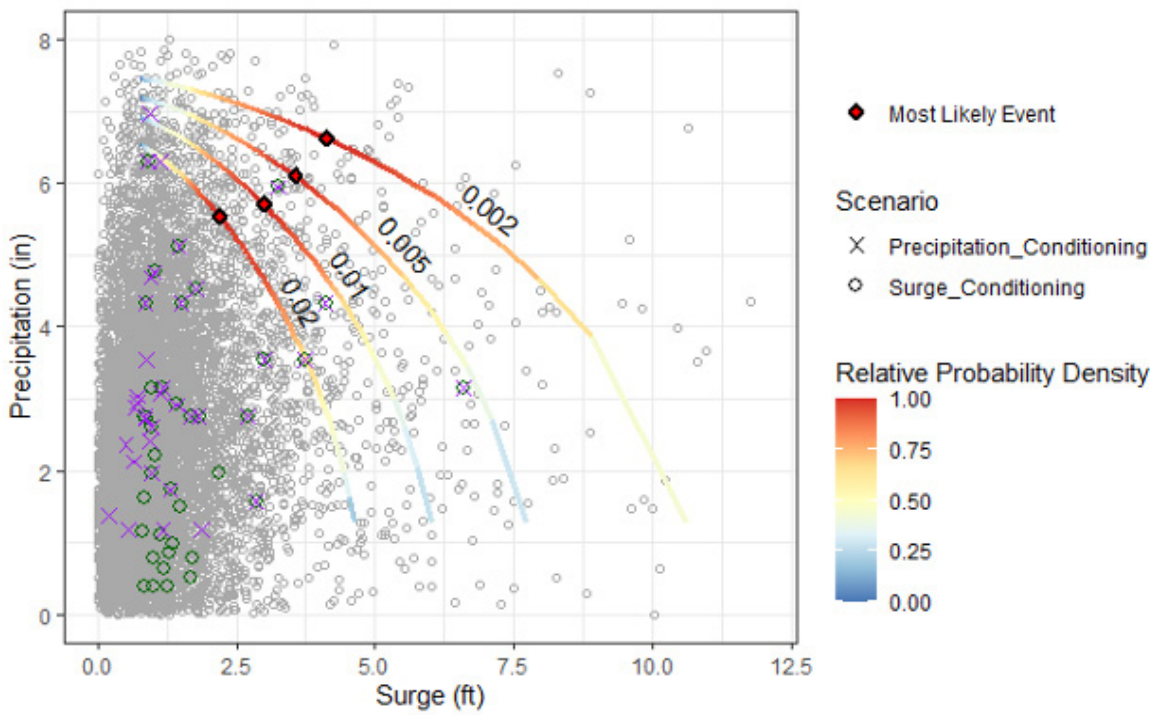

Figure 3-9. Rio Grande isoline envelope curves with relative probability and design events.

Table 3-11. Design events for the LRGV.

Joint Probability	Surge (ft)	Precipitation (in)
0.02	2.981	4.686
0.01	2.905	5.779
0.005	3.609	6.073
0.002	4.603	6.452

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Uncertainties that may be reflected in these results are the locations and representativeness of the rainfall gage and the surge station. In such a flat basin, precipitation is related to riverine and overland water levels with a lot of complexity from storage in drains and ponds, the drainage system, and sensitivity of flooding to cliff's edge effects. Storm surge and rainfall may affect parts of the basin far from a gage and are irregularly distributed, even if a basin-average were considered.

Another consideration is the marginals used to convert the copulas from cumulative density function space to 'real space.' The marginals used to develop these copulas are based on a very small set of observed paired data (green-circle, purple cross in Figure 3-9), which is demonstrated in the bivariate copula plot by only one surge event above the marginal 0.01 AEP surge and only one precipitation event above the marginal 0.01 AEP precipitation. This suggests that use of a more complete marginal, or a published marginal with regional information, may be a better choice for this small dataset.

Flood Inundation Modeling Category for Compound Flood

FI-DD. The model types FI-I through FI-IV are conventional physics-based models (i.e., solving mechanistic equations) whereas FI-H and FI-DD are hybrid and data-driven models focused on flood inundation although they use some of the same underpinnings as probabilistic analysis of flood hazards.

TIFF does not provide specific recommendations for the flood inundation models to be used in particular instances. With the present state-of-the-art, modeler's engineering judgment (backed up by analyses of physical processes, model behaviors and modeling objectives or user needs) must be used to decide on the appropriate models and couplings for various conditions and scenarios. For instance, if soil/groundwater interaction in a given area is known to be a small effect, it may not be worth the added expense and uncertainty to include such a model/module in a particular workflow scenario model coupling.

The Case for a Texas Coastal Flood Framework

The goals of a TxCFF are to provide flexibility for projects, re-usability of workflows and code, and the ability for project manager to determine the "size" that best fits their project. The conceptual organization of flood inundation modeling with the proposed TxCFF is provided in Figure 3-7. Based on the user's modeling objectives, in some cases, prototype codes already exist or are under development to address simplified versions of the conceptual workflow outlined in Figure 3-7. In other cases, extensive research and development would be required to develop and maintain models. There are positive and negative aspects for all of the options -- there is no "one-size-fits-all" solution.

TIFF proposes a variation to be applied as both tiered hazard and flood inundation modeling framework for the TxCFF which is discussed in previous paragraphs. (See Table 3-10 and illustrated in Figure 3-10 for tiered hazard analysis and Table 3-1 for flood inundation model.)

The workflows for flood hazard analysis tools should be built into the TxCFF to couple directly to the output of flood inundation models. The level of complexity for analyzing hazards of a specific project can be chosen to support user needs, such as for coastal risk analysis, design, and mitigation. A critical feature is that the hazard analysis levels should be model agnostic to work with different components of the flood inundation model, as described in (Types of Flood Modeling) depending on which model components are critical to a specific project's focus. Furthermore, the hazard analysis tools must use a basin-agnostic approach that allows location-specific parameters to be defined across the varying geographies in Texas. Implementing hazard analysis within the TxCFF will provide consistency and rigor for site-specific engineering and policy decisions. Increasing complexity of levels within the hazard framework allow for execution to meet different project needs such as speed of execution, data availability/historical record lengths, and computational resource limitations.

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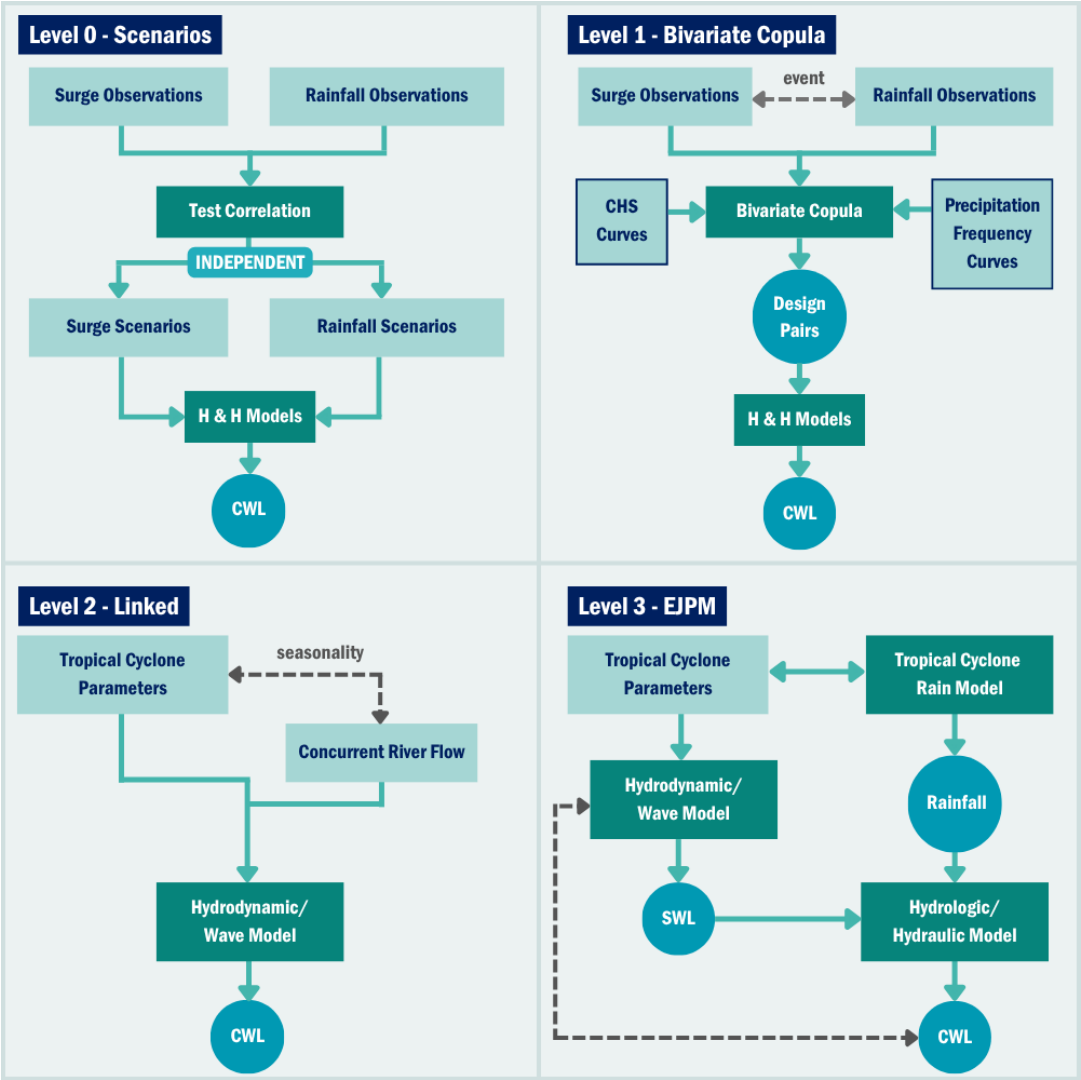

Figure 3-10. Examples of conceptual workflows for a TxCFF (adapted from Liu et al, 2025). SWL and CWL represent surge and compound water elevation, respectively.

Key Considerations for Selecting a Compound Flood Modeling Framework

There are three criteria to be considered before selecting a modeling framework for compound flooding analysis of the Texas coastal region based on project needs:

1. Should flood inundation models use a) the most detailed possible physical equations (FI-I, FI-III), or b) simplified physical equations that allow more rapid solutions (FI-II, FI-IV), or c) data-driven AI/ML models (FI-H, FI-DD) or d) some combination of the above? How do we consider different needs in this choice?
2. Should the model framework be created using a) a monolithic, single model (FI-I, FI-II), or b) as a compound flooding model coupling framework (FI-III)?
3. What hazard analysis level (HL-0, HL-1, HL-2, HL-3) should be used given the data availability and project needs?

To provide background for the following discussions, it is useful to consider the hierarchy of inundation models as presented previously in Table 3-2 and of compound hazard analysis levels in Table 3-1. There

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are positive and negative aspects for all of the options. There are four different options for physics-based models based on level of complexity and code structure:

1. The Flood Inundation models of types FI-II and FI-III are those that engineers typically turn to for planning and design analyses.
2. The key difference between FI-I (which do not exist) and FI-II (which exist) is that FI-II models are designed primarily for a particular purpose so they have the full physics equations accepted by the discipline (e.g., ADCIRC is designed for coastal ocean circulation) whereas the addition of other compound flooding components use some reduced physics (relative to those generally accepted by the adjacent discipline).
3. In contrast, a FI-I or FI-III system could be designed from the ground up to include all physics-based processes with their accepted equations.
4. The FI-IV models are different from FI-II in that the former are designed for fast run times by using simplified physical equations (relative to those accepted by the discipline) across all processes.

The FI-H and FI-DD models are presently undergoing research, but hold promise for eventually providing faster inundation models. However, it is difficult to envision how FI-H and FI-DD models can be trained and validated without first building an FI-I/III system that provides sufficient data.

There are four different compound hazard analysis levels (HL) of increasingly complexity (and typically decreasing uncertainty) meant to meet different projects needs such as speed of executions, and computational resources within the data available and historic record lengths:

1. **HL-0** assumes interdependence between compound drivers (e.g., rainfall, surge) based on a simple correlation. To develop joint probabilities of the compound water levels, a response matrix is population by the compound drivers for different paired scenarios with assumed probabilities from existing univariate analyses (e.g., Atlas 14 Precipitation Frequency Analysis). The response matrix is solved for water level using a near-shore flood inundation model, proving the probabilities and water level responses to develop a compound hazard curve. HL-0 is often applied for screening and fast-paced early feasibility assessments of design.
2. **HL-1** is often applied for similar uses and even for design application, though HL-1 assumes dependence between the compound flood drivers, with their joint probability often represented by a copula (a statistical tool). HL-1 captures more of the joint probability and can reduce uncertainties. However, the method is highly sensitive to the available of a large number of paired historical event with data on both hazards, as well as engineering judgment required for analysis decisions with the statistical method.
3. **HL-2** differs from HL-1 and HL-0 in that synthetic JPM-type hurricane and non-tropical coastal storms are used for the coastal part of the compound hazard analysis. The inland hazard is linked to at least one of the JPM parameters and sample based on the joint probability between them. An example would be a JPM-Monte Carlo hybrid linking storm intensity (as central pressure deficit) to river flow by seasonality. HL-2 is best applied in case where compound drivers can be simply linked and are otherwise nearly independent.
4. **HL-3** builds on the state-of-the-art probabilistic coastal JPM-type hazard analysis, extending it to include compound drivers (e.g., tropical cyclone rainfall) using the same synthetic tropical cyclone parameters to drive flood models and rainfall models with JPM parameter sets and their known probabilities. This approach can be used for complex use cases, as more elements can be incorporated, and uncertainties are reduced by incorporating machine learning type metamodels and a copula to better define the joint probabilities. Computational costs can be reduced by leveraging existing regional models.

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The Question of Simplified or Non-Simplified Flood Inundation Modeling

The question of flood inundation model equations is really a question of what approach should be taken for a baseline model. Neither data-driven (FI-DD) nor hybrid (FI-H) models are appropriate as a baseline because there is not enough data to create and apply such models for accurate predictions of flooding on the coastal plain. That is, any data-driven or hybrid model presupposes the existence of an accurate data set describing flood inundation over a wide range of events and locations, but compound flood events do not happen often enough to provide sufficient data. However, such models remain a useful part of a flood modeling framework.

Type FI-II and FI-IV models (Table 3-2) are inappropriate as baseline approaches models for compound flood inundation modeling. Each flooding discipline (storm surge, rainfall, river overbanking, groundwater) has a cadre of experts that have reached general consensus on the physical equations required to model flooding processes within their specialty. It is inappropriate for compound flood modelers to ignore the decades of work in these areas and implement reduced physics equations simply for faster computational times. If full physics proves too computationally costly for a large storm over large area, then the target should be narrowed until it can be definitively proven that simplified methods are justified. As a matter of science, reduced physics models should only be used in compound flood modeling once comparisons with full-physics models have proven that a discipline's consensus on needed model equations is faulty.

An outcome of building a full-physics modeling system will be the ability to explore this issue and, perhaps, develop well-founded reduced-physics approaches that are appropriate for compound flood modeling. Unfortunately, the present state-of-the-science in compound flood modeling does not support rejecting the existing science of any flood discipline. The need to ensure that the physics equations of the disparate flooding disciplines are included in a baseline model leads us to recommend a compound flooding modeling framework rather than a monolithic model.

A range of flood inundation modeling and hazard analysis approaches are possible for compound flooding, as outlined in Tables 3-1 and 3-2 and discussed in greater detail in Dawson et al (2024). Different types of models have a range of capabilities, computational costs, and examples in the state-of-the-art. In general, a compound flood model framework can be constructed in one of two basic ways:

1. **Develop a monolithic model that incorporates all important physics (i.e., FI-I) and couples with newly designed flood hazard analysis tools.** Although the knowledge and capability exists to build a monolithic compound flood inundation model, the advances in single-discipline inundation models will continue and new advances may be difficult to continually adapt into the monolithic model. The main advantage of a monolithic model is that it provides the best coupling between the different flooding processes. The primary disadvantage is the overall complexity of the code base makes it a challenge to build and maintain unless a dedicated funding stream can guarantee long-term cadre of coders.
2. **Build a compound flood modeling "framework," by developing software to couple existing (or future) model codes so that they can talk to one another and provide consistent predictions with flooding interactions.** A framework is inherently easier to maintain than a monolithic code base, as the individual codes in a framework are maintained within their discipline. The key disadvantages of a coupling framework are that 1) the computations will be less efficient (slower) than the independent models, 2) the coupling algorithms requires methods that are still in research and development in government and academia, and 3) coupling between open-source and closed-source models can be challenging and will require cooperation of the organizations/ agencies maintaining the component models.

Considering the advantages and disadvantages of the two approaches, TIFF recommends a software framework (type FI-III) that can be used to integrate both existing and future flood inundation models with hazard analysis tools in a consistent, supported, and replicable manner. The proposed TxCFF allows

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model developers in discipline areas (river, rainfall, ocean, groundwater) to keep their focus on building/improving their discipline while model integration experts develop the tools and software for coupling models with a TxCFF, simplifying their use, and providing accessible output data. A goal of the FI-III modeling framework should be to provide foundations for future development of FI-H and FI-DD models that can more rapidly compute inundation and thus be more useful for many coastal feasibility, design, and planning purposes.

Building Complex Models Today for Simple Models Tomorrow

Building the flood inundation part of the framework around FI-III models (full physics) puts us in a position to comprehensively evaluate the effectiveness of newly developed approaches in FI-IV, FI-H, and FI-DD models. The number of scenario models that are needed to effectively model flood hazards for long-term planning and impact studies simply cannot be done with full-physics models. However, there does not seem to be any scientifically rigorous path to effective reduced-physics or data-driven inundation models without first developing the full physics models that are needed for training and validation. The way forward is in four steps:

1. Selection of synthetic storm parameters or historical storms and identification of their probabilistic and wind and pressure modeling for input to full-physics modeling
2. Full-physics modeling
3. Training/validation of reduced physics or data-driven models running hundreds to thousands of reduced physics or data-driven models for flood hazard analysis (expanding on high fidelity full-physics results using meta-modeling (machine learning) and copula analysis of hazards)
4. Running hundreds to thousands of reduced physics or data-driven models for flood hazard analysis (expanding on high fidelity full-physics results using meta-modeling (machine learning) and copula analysis of hazards)

Beyond the fourth step, which has incorporated AI/ML into the probabilistic model runs to shortcut the need for more high-fidelity runs, there does not appear to be any shortcut to this stepping-stone path in current model application

Linking Flood Inundation Modeling and Hazard Analysis

Coupling between flood hazard analysis and flood inundation modeling is inherently a different problem than coupling between different physics models within a flood inundation model. The purpose of coupling hazards and inundation is to provide the ability to integrate the results from many inundation scenarios into a unified analysis (**Appendix C-11**). The proposed TxCFF provides the capability to link inundation and hazard analysis. For each of the framework hazard analysis levels, probabilistic inputs for flood inundation models are developed in slightly different ways and then hazard curves should be developed from the resulting compound water levels (also called the response) of the flood inundation models. The described hazard framework levels allow for a selection of approaches based on 1) compound hazard characteristics (dependence, importance of compound effects over univariate hazard), 2) project needs, 3) complexity and resources, 4) data availability and quality, and 5) robustness and level of uncertainty of results:

- **HL-0** links among compound driving hazards are independent scenario pairs over the range of expected univariate hazards. Automation of linking the selected input scenarios to flood inundation models would involve running those models at the specific scenarios, scripting to determine the joint probabilities, and establishing a hazard curve from the probabilities and the outputs of the FI models.
- **HL-1** results in a set of isolines expressing the likelihood of the joint probability of different paired compound hazards and allowing selection of 'design storm' inputs of known probability and

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likelihood established from that joint probability isoline chart. HL-1 follows a bivariate copula approach, for which several possible workflows can be found in the literature (e.g. Santos et al. 2021, Jane et al. 2022, Carr et al. 2022c) and simple tools exist or are in development. Flood inundation models can be run for various design cases of the joint probability isoline chart to develop flood inundation maps or hazard curves at various locations.

- **HL-2** links inland hazards to coastal hazards using simple single parameter sampling, such as seasonality of hurricane intensity and river flow. For each JPM selected storm parameter set, a river flow is linked by random sampling of the seasonality joint probability to storm intensity. The resulting compound water level responses, once these inputs are passed to the flood inundation model, can then be integrated to produce a hazard curve. For HL-2 and HL-3, automation of linking the hazard analysis inputs would include converting wind and pressure model outputs from the JPM-type synthetic storm development as inputs into the coastal and/or inland flood inundation models. This data may also need to be converted into other input models, such as tropical cyclone rainfall models, scripts to link seasonality of parameters and randomly sample from that correlation. This often involves conversion between file types, interpolation between different model grids, and temporal frequency of data for large spatial areas with high temporal resolution.
- **HL-3** has the most complex links, linking the inland drivers (e.g., tropical cyclone rainfall) to the coastal drivers (e.g., storm surge) by driving each model using the same synthetic storm (and its parameters) of known probability. HL-3 can be expanded to include other drivers (e.g., groundwater) if they can be linked to the synthetic storm parameters or applied as model realizations. As with HL-2, automation of linking the hazard analysis inputs would include converting wind and pressure model outputs from the JPM-type synthetic storm development. Synthetic storm selection can be improved using statistical methods and AI/ML surrogate modeling, such as Bayesian methods, to better represent the range of compound hazards of interests for a specific application. As in HL-2, for HL-3, the flood inundation model compound water level responses, or the augmented AI/ML responses built from the FI models, can then be integrated to produce a hazard curve. Outputs of FI models may require conversion to scripts supporting low-fidelity GPM and meta-gaussian copulas, as well as integration of the results into hazard curves. Hazard curves can be used for design, or in development of inundation maps.

B. DEVELOPING AN EVALUATION MATRIX TO TEST THE CONCEPTUAL MODEL INTEGRATION STRATEGY

Modeling compound flooding at large coastal scales is an open problem. However, the research area is rapidly advancing with new models and methods being regularly published. Developing a TxCFF would require a long-term commitment of funds to a consistent project development team that collaborates with agency-sponsored modeling projects to ensure their work can be integrated into the framework.

The TxCFF should provide flood inundation modeling validation against historical data for Texas storms from NOAA, USACE, USGS, NDBC, TWDB, and other data sources. Model performance should be evaluated through quantitative validation metrics, which could include Root Mean Square Error, Pearson's Correlation Coefficient, Mean Absolute Error, and Refined Correlation Coefficient. Inter-model comparisons should also be made to assess accuracy and computational efficiency. Systematic performance studies and computing requirements for various models should be made and reported on for decision-making purposes on which models to use as part of the TxCFF.

Flood hazard analysis uncertainty uses many of the same datasets for validation and assessment of bias and uncertainty. Confidence limits are often based on the assumption of a normal distribution with the number of standard deviations used to assign the limits. For statistical approaches, such as the bivariate copula, correlations are sometimes characterized by a p-value, though this is controversial since it represents the likelihood of the null hypothesis. Different types of correlation coefficients (e.g., Pearson's correlation coefficient r, Spearman's rank correlation coefficient ρ, Kendall's τ) represent linear relation-

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ships or ranked relationships, respectively. Various fitting measures for probability distributions and copula are available to characterize the certainty of those fits. The model performance and evaluation metrics for flood hazard analysis depend on the specific approach and tools used (e.g., hydrological models, hydraulic models, or ML-based models). The matrix below in Table 3-3 lists key important model output parameters, what their performance is assessed against, and metrics that can be used to assess the model's skill and performance. (See **Appendix C-11** for detailed information on each type of component flood inundation models (e.g., hydrologic, hydraulic, storm surge).) Other performance considerations should be on the amount of time and data required to fully set up a model, the computational demands of executing the model to include any parallel computing scaling efficiencies.

Table 3-12. Model skill and performance evaluation matrix.

Model/Analysis	Key Model Outputs for Performance	Validation Data	Metrics
Flood Analysis			
Atmospheric Wind and Pressure Model (Planetary boundary layer model)	Time series of surface winds velocities and atmospheric pressure	Historic storm event gage measurements	Average absolute and relative uncertainty, non-exceedance confidence levels based on unbiased uncertainty
Hydrodynamic Model	Peak still water level, Peak storm surge, time series water levels and depth averaged velocities	Historic storm event water level and current gage measurements and high-water marks	Average absolute and relative uncertainty, non-exceedance confidence levels based on unbiased uncertainty
Combined Wind and Pressure Driven Hydrodynamic Model	Absolute and relative uncertainty of atmospheric and hydrodynamic models	Historic storm event collocated gage measurements	Aggregated error statistics for absolute and relative uncertainty
Wave Model	Hmo = significant wave height, peak period, mean period, and direction	Buoy recorded wave heights	Absolute and relative uncertainty, non-exceedance confidence levels based on unbiased uncertainty
Tropical Cyclone Rainfall Model	Event total precipitation; frequency analysis	Precipitation observations (e.g. Stage IV); Existing precipitation frequency analyses (e.g., Atlas 14)	Mean absolute error, average absolute uncertainty
Hydrologic (Rainfall Runoff) and Hydraulic (River System) Models	Flow and stage hydrograph peak magnitude, time of arrival and duration	Historic storm event flow and/or water level gages	$\overline{R^2}$ = coefficient of determination; RMS = root mean square error; mean absolute error, average absolute or relative uncertainty
Hazard Analysis			
Gaussian Process Metamodel (GPM)	Water level	High fidelity hydrodynamic water levels	$\overline{cc}$ = correlation coefficient; $\overline{R^2}$; $\overline{\sqrt{se}}$ = square root of the squared error (where bar indicates averaged over all storms)
Compound Multi-level GPM (HL-3 and 4)	Water level; peak flow	High fidelity hydrodynamic and flow water level, peak inflow from hydrologic model	$\overline{cc}$, $\overline{R^2}$, $\overline{\sqrt{se}}$
Parameter Independence (HL-0)	Paired event data		Correlation coefficients: Pearson's r, and Spearman's rank correlation coefficient ρ and Kendall's τ
Peaks-Over Threshold Extreme Value Analysis (HL-2)	Water level quantiles	Water level quantiles for different distribution thresholds	WMSE = weighted mean square error; mean excess
Distribution Fits (non-extreme events; HL-2)	Distribution parameters	Water level observations, number of distribution parameters	AIC, log-likelihood of the model, Cramer-von-mises distance.
Copula Fitting (HL-2)	Copula type and parameters		AIC, alpha (Pearson's correlation coefficient converted from Kendall's τ)

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C. DEVELOPING CRITERIA AND RECOMMENDATIONS FOR TESTBEDS FOR STRATEGY EVALUATION AND SELECTION

The successful implementation of the TxCFF will build on lessons learned from testing the models on a diverse set of Texas geographies. The following considerations should guide the selection of these testbeds:

1. Initial sites should be selected based on stakeholder engagement, available resources, storm and flooding scale, data availability, dominant flood hazards (coastal and inland), and geographic characteristics
2. A diverse range of regions should be considered and should include single or multiple watersheds with at least one substantial river system connected to the coast. The range should include regions that:
    - may or may not have records of historical data useful for statistical and model calibration/validation purposes;
    - are urban or rural;
    - may contain coastal bays and barrier islands to provide additional complexity and variety
    - may contain multiple watersheds that converge into other watersheds and coastal area
    - are important for economic purposes such as shipping, fisheries, and tourism
    - have been historically understudied due to compound flooding
3. Ensure prioritized regions represent a balanced mix of hazard types, while allowing flexibility to apply and compare different compound hazard analyses and flood inundation models

Based on these considerations, TIFF identified seven regions as priority locations for building TxCFF capabilities and recommends that the first three receive highest priority (Justification on these selections is provided in Figures 3-11 through 3-17 and **Appendix C-10**.):

1. **Houston/Galveston Region**: TIFF recommends prioritizing this region in the deployment of the TxCFF because it includes several different types of inlet flows into an irregularly shaped bay with complex hydrodynamics, supports a large population with community involvement, has a long history of hurricane impacts, and also has one of the longest tidal gages in the country.
2. **Freeport Region**: TIFF recommends prioritizing this region in the deployment of the TxCFF because the Brazos River empties directly to the Gulf, so it experiences a different kind of compound inundation than the other regions considered. Drainage areas upstream are largely industrial with little infiltration and irregular flood control measures.
3. **Rio Grande/Laguna Madre**: TIFF recommends prioritizing this region in the deployment of the TxCFF because it is a long shoreline bay with several tributaries as well as a large river outlet. The contributing rivers are heavily regulated and international agreements and impacts could be a controlling factor in considering coastal storm risk management. This region is also an excellent example of a data and model-poor watershed of international importance, although TIFF did employ recent advancements in remote sensing applications combined with ML techniques to detect flood prone areas in the LRGV, providing a good foundation for continued efforts (see the Case Study below for more information).
4. **Beaumont/Port Arthur Region**
5. **Corpus Christi Region**
6. **Matagorda Bay Region**
7. **Brownsville/South Padre Island Region**

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PRIORITY TESTBED LOCATIONS FOR BUILDING TXCFF CAPABILITIES

Figure 3-11. The Houston/Galveston priority testbed region.

HOUSTON/GALVESTON REGION TESTBED CHARACTERISTICS

This complex system of bays and backwater estuaries is protected by barrier islands is fed by multiple large and smaller rivers, including the San Jacinto and Trinity Rivers. The coastal area features a gently sloping shoreline connected to a large continental shelf, which has important implications for coastal flooding. The region is well-documented with extensive data available for model validation, including storm surge and fluvial flooding events. Vegetation in the region is primarily composed of marshes and grasslands, which influence local hydrology and need to be considered in flood modeling frameworks. This combination of factors makes Houston/Galveston an ideal location for testing compound flood scenarios involving both coastal surge and riverine inflow.

Serving the fifth largest metro-area in the U.S., the vital hub at the Port of Houston is the second busiest port in the U.S. (by tonnage) supporting a broad industrial base (energy, oil refining, manufacturing, aeronautics, transportation, health care), along with fishing, recreation and tourism.

Problem Recognition	Tropical cyclone impacts normal during fall on Galveston Island and the Bolivar Peninsula, but Hurricane Ike and then Harvey highlighted the inner Bay risk and risk of compound-rainfall hurricane flooding
Dominant Physical Processes	Coastal surge and wave; Rainfall induced riverine flooding; Rainfall induced overland flooding; Poor drainage
Model Types for Dominant Processes	Hydrodynamic and wave models; Rainfall and hydraulic models (including 2D, drainage structures); Rainfall and hydrologic models; Urban drainage models
Coupling and Probabilistic Approaches	1- or 2-way coupling between coastal and inland models; unlikely to have linked compound flooding (HL-2) due to relative size and regulation of rivers; challenge using observation-based approaches (HL-0 and HL-1) due to limited surge records inside the bay, unless high uncertainty acceptable; boundary conditions need to consider that inland model can incorporate urban drainage
Rivers/Streams Causing Fluvial, Pluvial Areas, Groundwater Areas	• Galveston Bay is the seventh largest estuary in the U.S. (1500 km^2), with a maximum natural depth of 3 meters (unusually shallow) (4 areas: Galveston Bay proper, East Bay, West Bay, and Trinity Bay) • Surrounded by marshes, prairies, and urbanized areas • Three outlets from the bay: Bolivar Roads between Galveston Island and the Bolivar Peninsula, San Luis Pass at the West end of Galveston Island, and Rollover Pass across Bolivar Peninsula • The major rivers that outlet into Galveston Bay are the Trinity and San Jacinto Rivers • The Trinity River is 885 kilometers long and drains 46,400 km^2 with an average annual flow of 7 *10^9 m^3/year. • The Trinity River Basin has the largest population and largest number of cities of any watershed in Texas • The San Jacinto River is a short 137 kilometers, draining 10,200 km^2 with an annual flow of 1.68 * 10^9 m^3/year

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Data Availability	• **Water levels and tides**: NOAA Tides and Currents Stations (Morgans Point/Barbours Cut, Rollover Pass, Eagle Point, Galveston Bay, Galveston Pier 21); USGS coastal water levels; Texas Coastal Ocean Observation Network (TCOON) (historical dataset) • **Flow and river stage**: HCFCD Flood Warning System, TWDB Water Data for Texas (TRIN: Mid-Trinity, OLDR: Old River, FISH: Trinity Bay near Baytown, and BOLI: Bolivar Roads), TexMesoNet, USGS National Water Information System (NWIS) • **Precipitation Gages**: HCFCD Flood Warning System, NOAA Global Historical Climatology Network, sub-hourly point gages, Cooperative Observer Network (COOP) • **Precipitation Reanalysis datasets**: PRISM (Parameter-elevation Relationships on Independent Slopes Model), National Centers for Environmental Prediction (NCEP) Stage IV, AORC • **Bathymetry**: TWDB Texas Coastal LiDAR Mapping Project (Upper Coast LiDAR, 04/2018)
Possible Use Cases	Operational for emergency management, regulation of the San Jacinto River; risk-based design and planning use for coastal levee design and other mitigation efforts
Community Support, Model Maintenance, and Distribution	• **National**: CHS for surge hazard curves and model results • **Statewide**: TWDB, Trinity River Authority • **Local**: HCFCD and Flood Warning System • **Non-Profit**: Trinity Improvement Association
Existing Models (Probability and Numerical)	• **Compound Models**: Hurricane Harvey Compound Models: SCHISM, (Huang et. al. 2021), Delft3D-FM (Lee et al. 2024), ADCIRC (Loveland et al. 2021); Lower Clear Creek and Dickinson Bayou Compound Flooding: ADCIRC and HEC-RAS; JCBP-TX at Trinity River Basin; GLO's RBFS: bivariate copula analysis; UT-Austin/TWDB project on transition zones in compound flooding: ADCIRC • **Surge and Wave Models**: CHS-CTX coastal hazard analysis and accompanying CSTORM model water level results: ADCIRC and STWAVE; Coastal Texas Protection and Restoration Feasibility Study (CTXCS): ADCIRC and STWAVE; Sabine Pass to Galveston Bay Coastal Storm Surge and Wave Hazard Assessment: ADCIRC & STWAVE; Hindcast and Validation of Hurricane Ike (2008): SWAN and ADCIRC • **Inland Models**: InFRM Watershed Hydrology Assessment for the Trinity River Basin: HEC-HMS, Riverware, Flood Frequency Analysis; GLO's RBFS: HEC-HMS and HEC-RAS • **Others**: Assessment of Reliability of Levees at Port Arthur: ADCIRC and GSSHA; Galveston Bay Larval Transport Study: AdH model and Particle Tracking Model

Citations:

Lee, W., Sun, A.Y., Scanlon, B.R., & Dawson, C. (2024). Hindcasting compound pluvial, fluvial and coastal flooding during Hurricane Harvey (2017) using Delft3D-FM. *Natural Hazards*, 120(1), 851-880. https://doi.org/10.1007/ s11069-023-06247-9.

Loveland, M., Kiaghadi, A., Dawson, C.N., Rifai, H.S., Misra, S., Mosser, H., & Parola, A. (2021). Developing a modeling framework to simulate compound flooding: when storm surge interacts with riverine flow. *Frontiers in Climate*, 2, 609610. https://doi.org/10.3389/ fclim.2020.609610.

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Figure 3-12. The Freeport priority testbed region.

FREEPORT REGION TESTBED CHARACTERISTICS

West of Galveston Bay, the Brazos River debouches directly to the Gulf without the protection of a barrier island – which is unique to major basins on the Texas Coast. Pluvial mechanisms could interact directly with storm surge from the Gulf in this large coastal area between the extensions of Galveston and Matagorda Bays. The area is heavily industrialized and protected by levees, pumps and stormwater systems withing large industrial areas, which may behave differently than a community-based system.

The economic area is stabilized by chemical plants and hosts a far smaller population than the Galveston area. A hurricane flood protection system (levee system protecting 45 sq mi) was built in the 1960s to protect from riverine flooding and coastal storm surge events from the Gulf. The watershed is managed for flood control both upstream and near the coast.

Problem Recognition	Flooding events within the near coast area are primarily from high river flows after heavy rains upstream and/or hurricanes and tropical cyclones from the Gulf Coast that cause severe flooding; A new flood control project, part of the Sabine Pass to Galveston Bay project, has been in design
Dominant Physical Processes	Tropical cyclones and tropical cyclone induced flooding due to surge and rainfall; Rainfall induced riverine flooding from coastal and upstream storms; Levee and gate controlled near coast, upstream heavily regulated reservoirs
Model Types for Dominant Processes	Hydrodynamic and wave models; Rainfall, H&H models, able to represent flood mitigation controls; Large reservoir models
Coupling and Probabilistic Approaches	• 1-way coupling between coastal and inland models most likely because Brazos River and most of its drainage area outlets directly to the Gulf • Irregular updates to management of flood controls and regulation upstream may challenge observation-based hazard approaches (HL-0 and HL-1), though surge and rainfall records are long • Urban and flood controls need to be well represented by coupled models
Rivers/Streams Causing Fluvial, Pluvial Areas, Groundwater Areas	• Brazos River outlets directly into Gulf, unique on the Gulf coast for major rivers • The Brazos River is 2060 kilometers long (the second longest in Texas) and drains 111,000 km^2 discharging the largest volume to the Gulf of 7.5 * 10^9 m^3/yr • Oyster Creek largest tributary that feeds Brazos River • Areas near the coast are heavily industrialized, largely paved, leveed, and managed for flood control
Data Availability	• **Water levels and tides**: NOAA Tides and Currents Stations (Freeport Harbor), USGS Coastal Water Levels, TCOON (historical dataset) • **Flow and River Stage**: TWDB Water Data for Texas (SURF), TexMesoNet, USGS NWIS • **Precipitation Gages**: NOAA Global Historical Climatology Network, sub-hourly point gages, COOP • **Precipitation Reanalysis datasets**: PRISM, NCEP Stage IV, AORC
Possible Use Cases	Operational for emergency management and operation of flood controls, possibly upstream reservoir releases; Risk based design and planning use for coastal levee design and gate controls

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Community Support, Model Maintenance, and Distribution	• **National**: CHS for surge hazard curves and model results • **Statewide**: TWDB • **Local**: Velasco Drainage District, Brazos River Authority (regulates upper Bravos reservoirs)
Existing Models (Probability and Numerical)	• **Compound Models**: JCBP-TX at Brazos River Basin; Freeport TX Bivariate Joint Probability study; GLO's RBFS: bivariate copula analysis; UT Austin/TWDB project on transition zones in compound flooding: ADCIRC • **Surge and Wave Models**: CHS-CTX coastal hazard analysis and accompanying CSTORM model water level results: ADCIRC and STWAVE; CTXCS: ADCIRC and STWAVE; Sabine Pass to Galveston Bay Coastal Storm Surge and Wave Hazard Assessment: ADCIRC & STWAVE • **Inland Models**: H&H Models: USACE CWMS HEC-RAS, Brazos River Authority 1D, Fort Bend County 1D/2D; GLO's RBFS: HEC-HMS and HEC-RAS

Surfside Jetty County Park sits between the Gulf shoreline and the Freeport navigation channel in Freeport, Texas © Trong Nguyen

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Figure 3-13. The Rio Grande/Lower Laguna Madre priority testbed region.

RIO GRANDE/LOWER LAGUNA MADRE REGION TESTBED CHARACTERISTICS

This complex system of bays and backwater estuaries is protected by barrier islands is fed by multiple large and smaller rivers, including the San Jacinto and Trinity Rivers. The coastal area features a gently sloping shoreline connected to a large continental shelf, which has important implications for coastal flooding. The region is well-documented with extensive data available for model validation, including storm surge and fluvial flooding events. Vegetation in the region is primarily composed of marshes and grasslands, which influence local hydrology and need to be considered in flood modeling frameworks. This combination of factors makes Houston/Galveston an ideal location for testing compound flood scenarios involving both coastal surge and riverine inflow.

Serving the fifth largest metro-area in the U.S., the vital hub at the Port of Houston is the second busiest port in the U.S. (by tonnage) supporting a broad industrial base (energy, oil refining, manufacturing, aeronautics, transportation, health care), along with fishing, recreation and tourism.

Problem Recognition	The effects of a tropical cyclone or hurricane can go well inland past the Texas coast; Heavy rainfall, flooding, and even tornadoes can occur several hundred miles into the interior parts of the state; Large historical impactful historical hurricanes moved slowly down the coast dropping large amounts of rain which ran off as the surge from the wind and storm drove water level up
Dominant Physical Processes	Coastal surge and wave, rainfall induced riverine flooding, rainfall induced overland flooding
Model Types for Dominant Processes	Hydrodynamic and wave models, rainfall models, H&H models (allowing for complex flood control project)
Coupling and Probabilistic Approaches	1-or 2-way coupling between coastal and inland models. May require 2-way coupling because of complexity of transition zone; unlikely to have linked compound flooding (HL-2) due to perennial nature of rivers; challenge using observation-based approaches (HL-0 and HL-1) due to limited data; models may need to include impact of low water and groundwater table
Rivers/Streams Causing Fluvial, Pluvial Areas, Groundwater Areas	• The Rio Grande drains 128,000 km^2 over its 3060 kilometers length but only drains about 0.8 *10^9 m^3/yr due to heavy use for irrigation and impoundment in two large reservoirs. (There is an estimated 11.7-day response time (Jane et al. 2022) of the river to rainfall.) • The LRGFCP covers 180 miles of the Rio Grande from Penitas, Texas to the Gulf, which operates two large diversion dams, levees and lateral drains, and a pumping plant and conveyance channel • Surface water drainage is apportioned by inter-state and international compacts • Large pluvial areas North of the Rio Grande along the coast may produce challenging to model inflow into the Laguna Madre
Data Availability	• **Water levels and tides**: NOAA Tides and Currents Stations (Freeport Harbor), USGS Coastal Water Levels, TCOON (historical dataset) • **Flow and River Stage**: TWDB Water Data for Texas (SURF), TexMesoNet, USGS NWIS • **Precipitation Gages**: NOAA Global Historical Climatology Network, sub-hourly point gages, COOP • **Precipitation Reanalysis datasets**: PRISM, NCEP Stage IV, AORC • **Bathymetry**: USGS South Texas LiDAR (04/2019)

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Possible Use Cases	Operational for emergency management, regulation of canals and reservoirs; risk-based design and planning use for coastal flood protection management
Community Support, Model Maintenance, and Distribution	• **National**: CHS for surge hazard curves and model results • **Statewide**: TWDB • **Local**: Rio Grande Flood Control Project
Existing Model (Probability and Numerical)	• **Compound models**: JCBP-TX at Rio Grande Basin; GLO's RBFS: bivariate copula analysis; UT Austin/TWDB project on transition zones in compound flooding: ADCIRC • **Surge and Wave Models**: CHS-CTX coastal hazard analysis and accompanying CSTORM model water level results: ADCIRC and STWAVE; CTXCS: ADCIRC and STWAVE • **Inland Models**: FEMA BLE; GLO's RBFS (HEC-HMS and HEC-RAS) • **Other**: Transboundary Rio Grande Watershed Model water-balance model using the Basin Characterization Model, and construction of an integrated hydrologic flow model with Modular Finite-Difference Flow Model-One-Water Hydrologic Flow Model (referred to as One Water)

Citation: Jane, R., Wahl, T., Santos, V.M., Misra, S.K., & White, K.D. (2022). Assessing the Potential for Compound Storm Surge and Extreme River Discharge Events at the Catchment Scale with Statistical Models: Sensitivity Analysis and Recommendations for Best Practice. *Journal of Hydrologic Engineering*, 27(3), 04022001. https://doi.org/10.1061/ (ASCE)HE.1943-5584.0002154.

Aerial view of South Padre Island in South Texas © Mathew Risley/Adobe Stock

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Figure 3-14. The Beaumont/Port Arthur priority testbed region.

BEAUMONT/PORT ARTHUR REGION TESTBED CHARACTERISTICS

This region includes the Neches and Sabine Rivers (and their tributaries) feeding into Sabine Lake, which subsequently connects to the Gulf of Mexico. The Beaumont/Port Arthur region is a critical economic zone with urban centers and industrial infrastructure, making it highly vulnerable to both riverine and coastal flooding. The presence of large river systems and the availability of significant historical flood data make this region a prime candidate for testing complex compound flood modeling. Vegetation in the region is a mix of grasslands and forests, and these natural features play a significant role in floodwater retention and runoff dynamics. This region is prone to heavy rainfall events and river flooding, particularly during tropical cyclones and hurricanes. The Sabine River's connection to both Texas and Louisiana makes it an ideal testbed for understanding regional water management, cross-state coordination, and the interaction between riverine and coastal flooding.

Figure 3-15. The Corpus Christi priority testbed region.

CORPUS CHRISTI REGION TESTBED CHARACTERISTICS

This region is characterized by a large bay with inflow from the Nueces River and Osos Creek that is separated from the Gulf by a large barrier island, creating a natural defense against storm surges. Despite limited river inflow from the Nueces River, the Corpus Christi region remains economically significant due to its major ship channel and ports. The region's smaller continental shelf, relative to the upper Texas coast, makes it particularly vulnerable to rapid storm surge events. The mix of urban and rural land use further complicates flood modeling in this area. Given its unique geomorphology and economic importance, Corpus Christi would serve as an important testbed for evaluating coastal flood hazards, particularly those driven by storm surges and limited riverine contributions.

Figure 3-16. The Matagorda Bay priority testbed region.

MATAGORDA BAY REGION TESTBED CHARACTERISTICS

This region is fed by the Colorado River, Lavaca Rivers and smaller creeks, and multiple watersheds including adjacent pluvial areas, the bay and extensions are protected by barrier islands. The Matagorda Bay region is a critical habitat for a wide range of bird species and other wildlife. This area is more rural than the nearby Houston/Galveston and Corpus Christi regions and has significant ecological importance. Furthermore, this region is home to the South Texas Nuclear Power Plant. The region's exposure to both riverine flooding and coastal storm surges makes it a valuable testbed for examining compound flood dynamics, especially where environmental conservation intersects with industrial infrastructure. Testing models here could provide insights into balancing flood protection with habitat preservation.

Figure 3-17. The Brownsville/South Padre Island priority testbed region.

BROWNSVILLE/SOUTH PADRE ISLAND REGION TESTBED CHARACTERISTICS

This southernmost part of coastal Texas is vulnerable to both riverine flooding from the Rio Grande and coastal storm surges. The Brownsville/South Padre Island area is subject to intense tropical cyclones and hurricanes. The area is economically important, with tourism on South Padre Island and international trade through the Port of Brownsville. It is also vulnerable to both riverine flooding from the Rio Grande and coastal storm surges. Although part of the larger Rio Grande/Laguna Madre region, this smaller area could serve as an additional testbed to focus specifically on the effects of tourism, cross-border trade, and the interaction between the Rio Grande's hydrology and coastal hazards.

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These testbeds will expand the geographical and ecological diversity of compound coastal flood modeling studies in Texas. Each region presents unique challenges, from industrial infrastructure and environmental conservation to cross-border considerations and riverine-coastal flood interactions. These areas have distinct characteristics and vulnerabilities, thus offering a comprehensive range of conditions for testing and improving compound flood models and assessing flood hazards. By incorporating both natural and anthropogenic factors (such as urbanization, riverine systems, and coastal features) these testbeds will provide a robust foundation for evaluating and mitigating flood hazards across the Texas coast. Note that these descriptions do not include details such as existing measurements, gages, dominant processes or existing models, but instead focus on the region, its hydro-climatic and coastal characteristics, as well as environmental and economic needs and drivers.

Case Study: Using Remote Sensing Data and Machine Learning to Map Flood Extent and Identify Flood-Prone Areas in the Lower Rio Grande Valley

The LRGV has experienced numerous flood events over the years, often driven by the convergence of various hydrological and meteorological phenomena. The effects of these compound flooding events, which occur due to a combination of multiple sources such as heavy rainfall, storm surge, and riverine flooding, underscore the need for more adaptive and robust flood mitigation strategies in the LRGV region. A challenge to addressing this need is the limited temporal and spatial data available in this region. With the goal of enhancing comprehensive flood probability analyses and future scenario planning in data-limited environments, Component 3 conducted additional targeted research to detect large flood-prone areas in the LRGV and map flood extent.

The key objectives of the case study were to:

- rapidly identify the extent of flood inundation and map flood-prone areas under various rainfall intensities and return periods; and
- provide scalable, low-data alternatives to traditional hydraulic modeling, which is especially valuable for under-monitored and resource-constrained areas like the LRGV.

Recent advancements in remote sensing, particularly when combined with ML techniques, have enabled the detection of large flood-prone areas without the need for highly accurate data inputs or computationally intensive hydrological models. Satellite data can serve as a complementary source to validate and calibrate flood models, especially in the LRGV, where observed data are limited. The study integrated multi-sensor satellite datasets, hydrometeorological records, and ML techniques to map historical flood events for flood mitigation in Cameron, Willacy, Hidalgo, and Starr Counties. (See **Appendix C-24** for the resulting maps and data). These efforts also included the application of new methodologies, such as Bayesian inference and convolutional neural networks, to improve flood extent mapping. These techniques may offer an alternative approach to flood inundation detection, bypassing the need for highly accurate data inputs and computationally intense hydrological processes (**Appendix C-24**). Throughout the study, challenges persisted when processing enhanced satellite imagery. Despite challenges with manual masking, large file sizes, and ArcGIS Pro integration, a robust foundation for flood detection in the LRGV has been built.

D. CONDUCTING A COMPOUND FLOOD MODELING TESTBED EVALUATION FOR COASTAL AND INLAND LOWER RIO GRANDE VALLEY

The implementation of the TxCFF recommendation is driven by several critical phases. These include the identification and prioritization of testbed locations, the rigorous testing of candidate models, and the evaluation of coupling methods for those models. Furthermore, the process involves developing and evaluating boundary placements among disparate numerical models to ensure seamless integration. TIFF specifically explored the options and technical challenges associated with these implementation steps, focusing on the configuration of coastal and inland flood models to analyze compound flooding events within the LRGV.

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To evaluate different modeling configurations, this investigation focused on three representative systems:

1. The coupled ADCIRC (Advanced Circulation) storm surge model with the nearshore wave model STWAVE (Steady State Wave), as implemented in the Coastal Storm Modeling System (CSTORM);
2. The Adaptive Hydraulics (AdH) model; and
3. The Hydrologic Engineering Center's River Analysis System (HEC-RAS).

ADCIRC-STWAVE is a widely utilized coupled surge and circulation model previously applied for storm surge characterization along the Texas coast (Massey et al. 2019). HEC-RAS is the industry standard for watershed and one-dimensional riverine flood modeling. AdH is primarily employed for hydrodynamic characterization in complex estuarine and river environments where 2D and 3D modeling is needed. By testing these models—specifically ADCIRC, STWAVE, AdH, and HEC-RAS—this study aimed to establish a robust framework for analyzing the interaction between coastal and inland flooding drivers.

The foundation for this work built upon previous hazards analysis conducted by the USACE-ERDC. As part of the Coastal Texas Comprehensive Study (CTXCS) (Massey et al. 2019, Melby et al. 2021), ERDC performed extensive coastal storm surge and wave modeling using the CSTORM coupled modeling system and a probabilistic coastal hazards analysis for coastal surge and waves. While this earlier modeling and hazards analysis provided a comprehensive coastal perspective, it did not include compound flooding variables or river forcing data, despite the ADCIRC mesh representing many river geometries. The TIFF study addressed these gaps in the LRGV area by integrating riverine forcing and compound variables into the modeling approach.

Current efforts are further supported by an ongoing USACE Flood and Coastal program research initiative titled "Coastal Physics into HEC-RAS." This research and development effort is investigating the integration of wave radiation stress gradients into the 2D version of HEC-RAS model formulations, alongside the testing of ADCIRC and AdH in compound flooding scenarios. A high-level summary of the testbed study site including the technical approach, modeling results, and findings are included here and more detailed information on the approach and results can be found in **Appendix C-26**.

The LRGV is not a true valley but is a river delta and floodplain around the mouth of the Rio Grande where it enters the Texas Gulf coast. The area is generally flat with a low elevation and is subject to major flooding from both coastal storm surge and pluvial and fluvial flooding.

Regional scale coastal storm surge and wave modeling using the CSTORM coupled ADCIRC and STWAVE models was conducted for this area as part of the CTXCS. In that study, pluvial and fluvial contributions to flooding were not included and it is considered a purely coastal analysis of storm hazards from water levels and waves. The resolution of the ADCIRC and STWAVE domains were considered sufficient for a regional analysis with STWAVE cell sizes being approximately 656 feet (200 meters) and the unstructured elements used in ADCIRC going down to approximately 328 feet (100 meters) along the coastline and gradually increasing inland.

The GLO and USACE-Galveston District have also conducted flood risk assessments in the LRGV using the HEC-RAS model (USACE-SWG 2026, GLO 2025). Lastly, Gutenson et al. (2024) highlights a variety of the HEC tools used in a forecasting mode for the LRGV.

To assess flood modeling in the coastal zone from both coastal forces and inland flooding forces, several relevant processes should be considered. First, topographic and bathymetric data is a critical need for all models. Next are frictional values which are often derived from land use and land cover datasets, and standard values for bottom types within rivers, inlets, and oceans. Coastal forcing processes for flooding include tides, wind speeds and directions, and atmospheric pressure which all serve to drive water surface elevations, currents, and wave conditions. In the coastal zone, coupling coastal circulation and nearshore wave models is critical to accurately predicting depth-averaged waves and wave-induced water level changes, such as wave setup and setdown. Inland processes for flooding include precipitation forcing, temperature, and soil moisture and filtration rates.

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Three historical hurricanes that impacted the LRGV were used to test compound flood modeling analysis: Hurricane Allen, Hurricane Bret, and Hurricane Dolly.

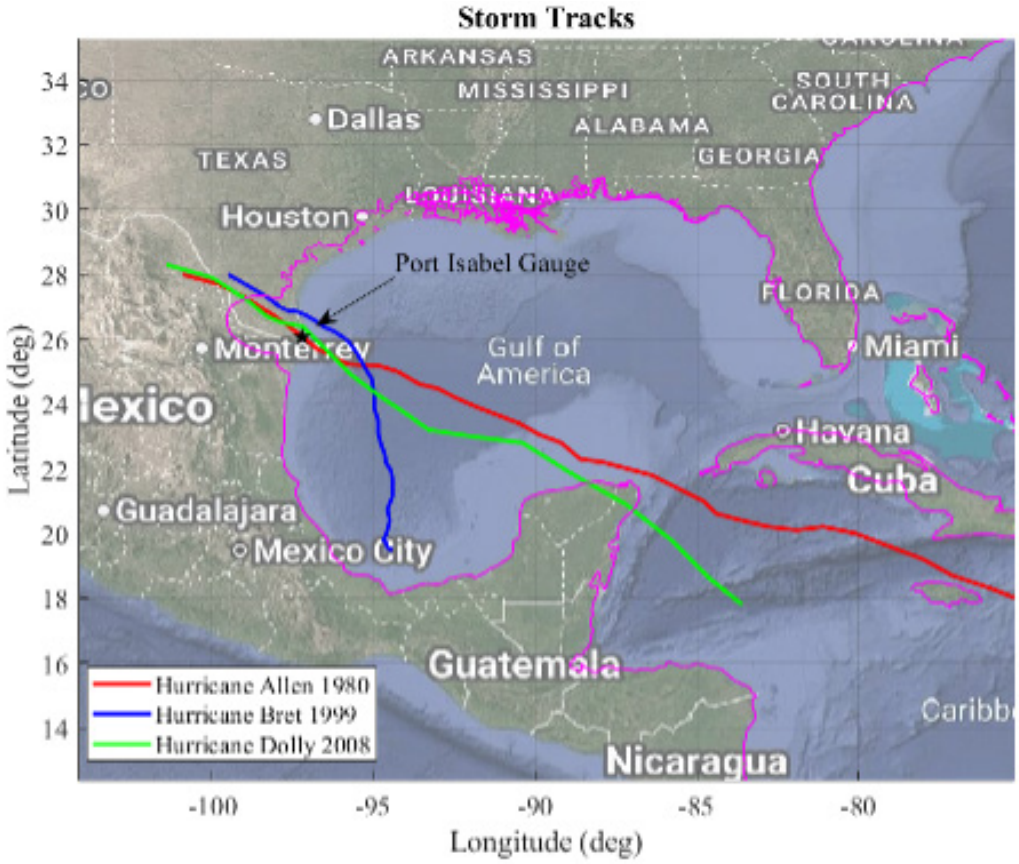

Figure 3-18. Map showing the storm tracks for Hurricanes Allen, Bret, and Dolly in relation to the ADCIRC model domain and the location of the Port Isabel NOAA tides and currents gage location.

Model Development

To advance the state of practice for coastal compound flood modeling, existing and well validated models were leveraged to investigate different coupling frameworks:

- hydrodynamic numerical models, ADCIRC and STWAVE, provided coastal modeling capabilities
- the HEC-RAS model provided inland flood routing and riverine flows
- the AdH model was evaluated as go-between-model linking inputs from ADCIRC and STWAVE with those from HEC-RAS, as well as from original source data for precipitation instead of using routed data from RAS

Further details of this model development including model forcing functions, their simulation results, and associated lessons learned are discussed in **Appendix C-26**.

ADCIRC-STWAVE Model Development

The ADCIRC and STWAVE models used to study compound flooding in the LRGV leveraged the CTXCS Study coupled ADCIRC-STWAVE (Massey et al. 2019, 2021). This CTXCS model was refined to capture local hydrodynamics and overlap with inland models (AdH and HEC-RAS) in the LRGV region. The ADCIRC domain was designed to be large enough to capture basin-to-basin scale hydrodynamic effects, forerunner development, and fully contain tropical cyclone storm forcing, with tidal conditions applied at the easternmost boundary. The STWAVE domains remained unmodified from the original CTXCS study.

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To enable overlapping domain extents with the inland HEC-RAS model, the ADCIRC model domain was extended further westward into the LRGV region. The mesh was highly refined in this area, particularly along the Rio Grande corridor, to improve the representation of channel geometry and hydrodynamic processes.

(See Figure 3-19 for the updated model domain and **Appendix C-26** for detailed discussions on the integration of topographic and bathymetric data, land use and land cover datasets, initial water level conditions, and boundary conditions and forcing data for the three storm events.)

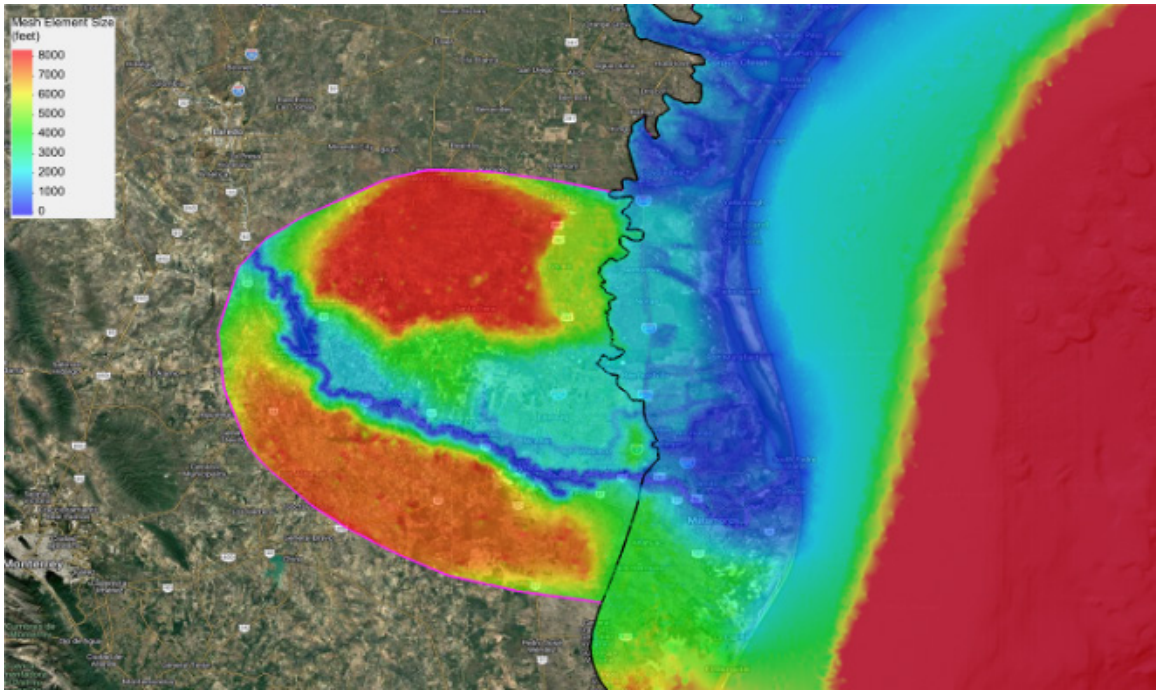

Figure 3-19. Map showing two-dimensional color contours of mesh element resolution (units in feet), for the extended and updated unstructured ADCIRC mesh used in the LRGV study. The black lines indicate the boundary of the original CTXCS Study mesh.

HEC-RAS Model Development

For this study, a pre-existing HEC-RAS 2D unsteady hydraulic model was utilized to simulate rainfall-driven flooding. This model was originally developed for a GLO baseline flood modeling study in the Laguna Madre region (GLO, 2025). The existing model is a 2D rain-on-grid HEC-RAS model, version 6.4.1. It was originally configured to assess the compound effects of storm surge and rainfall-runoff on the coastal communities of Port Isabel, Laguna Vista, and Laguna Heights in the Laguna Madre coastal area. For detailed discussions of the boundary conditions, meteorological forcing, precipitation data, and inherent limitations of the existing HEC-RAS model utilized to simulate compound flooding in the LRGV (**Appendix C-26**).

AdH Model Development

The Adaptive Hydraulics (AdH) numerical model for this study was heavily leveraged from a previously developed ADCIRC model. The AdH domain (Figure 3-21) was created by trimming the larger ADCIRC mesh to focus strictly on the local study area. The resulting unstructured mesh consists of approximately 1.4 million nodes and 2.75 million elements. Resolution ranges from ~10,000 ft in offshore regions to as fine as 20 ft inland to accurately capture flow pathways. By utilizing the existing ADCIRC mesh, bathymetry, and boundary conditions, developers ensured consistency between the two models while streamlining the development process. (See **Appendix C-26** for more information.)

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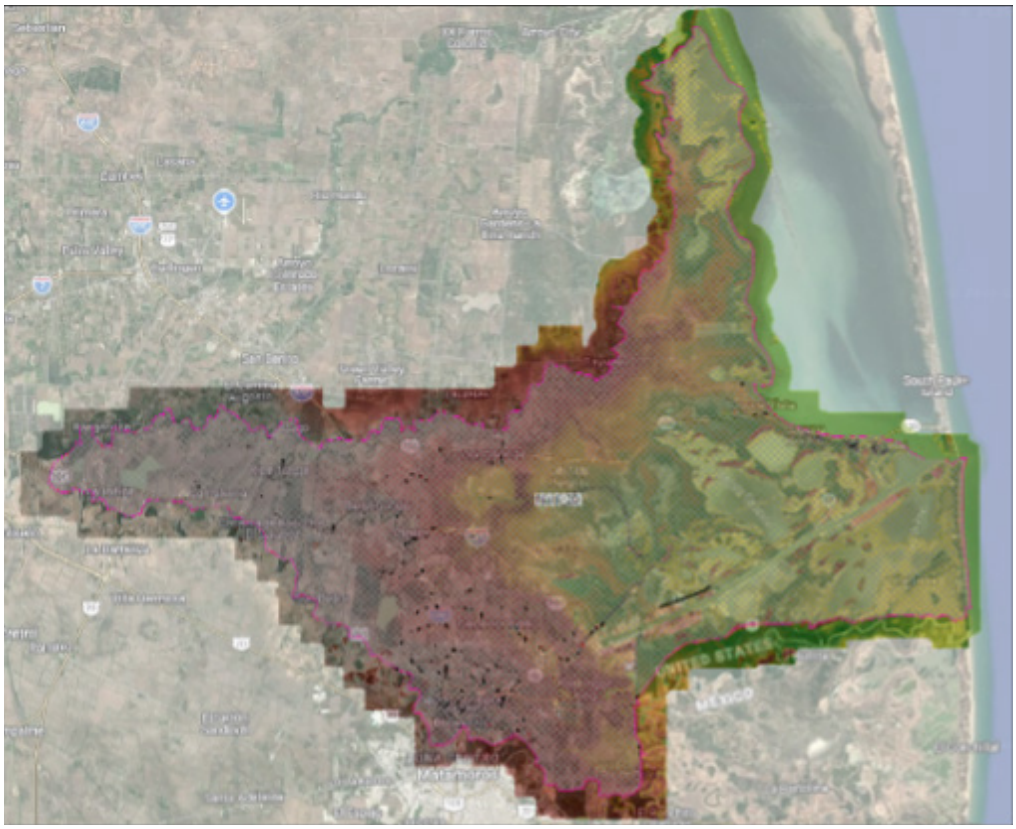

Figure 3-20. Study area and 2D mesh visualized in RAS Mapper.

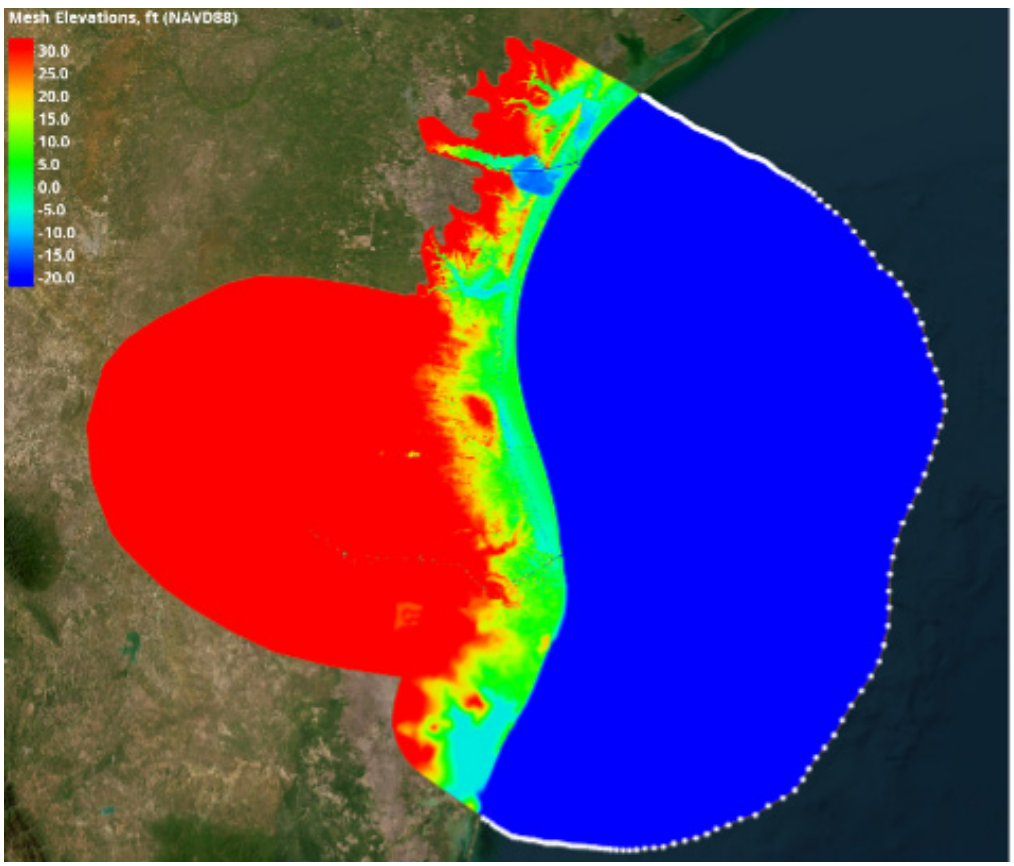

Figure 3-21. AdH model domain and elevations.

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Intra-Comparison of Model Simulation Results

To evaluate model performance, water surface elevation timeseries data for the three historical storm events across the LRGV were compared. Water level simulations from the ADCIRC+STWAVE, uncoupled ADCIRC, AdH, and HEC-RAS models were analyzed on a point-by-point basis to evaluate their performance across coastal, transitional, and inland zones, focusing on representative stations with unique physical dynamics.

Figure 3-22 displays a map of the LRGV with 38 marked comparison locations. Several stations (e.g., 5,6) are located outside the HEC-RAS model domain and are excluded from the HEC-RAS discussion. The HEC-RAS domain used in this study was not originally optimized for complex compound coastal flooding, incorporating only limited coastal boundary inputs. While offshore domain expansion was restricted by the current project timeline, future work will extend the HEC-RAS domain to the open coast to allow for a detailed sensitivity study of coastal boundary placement. (See **Appendix C-26** for detailed discussions comparing the modeling results.)

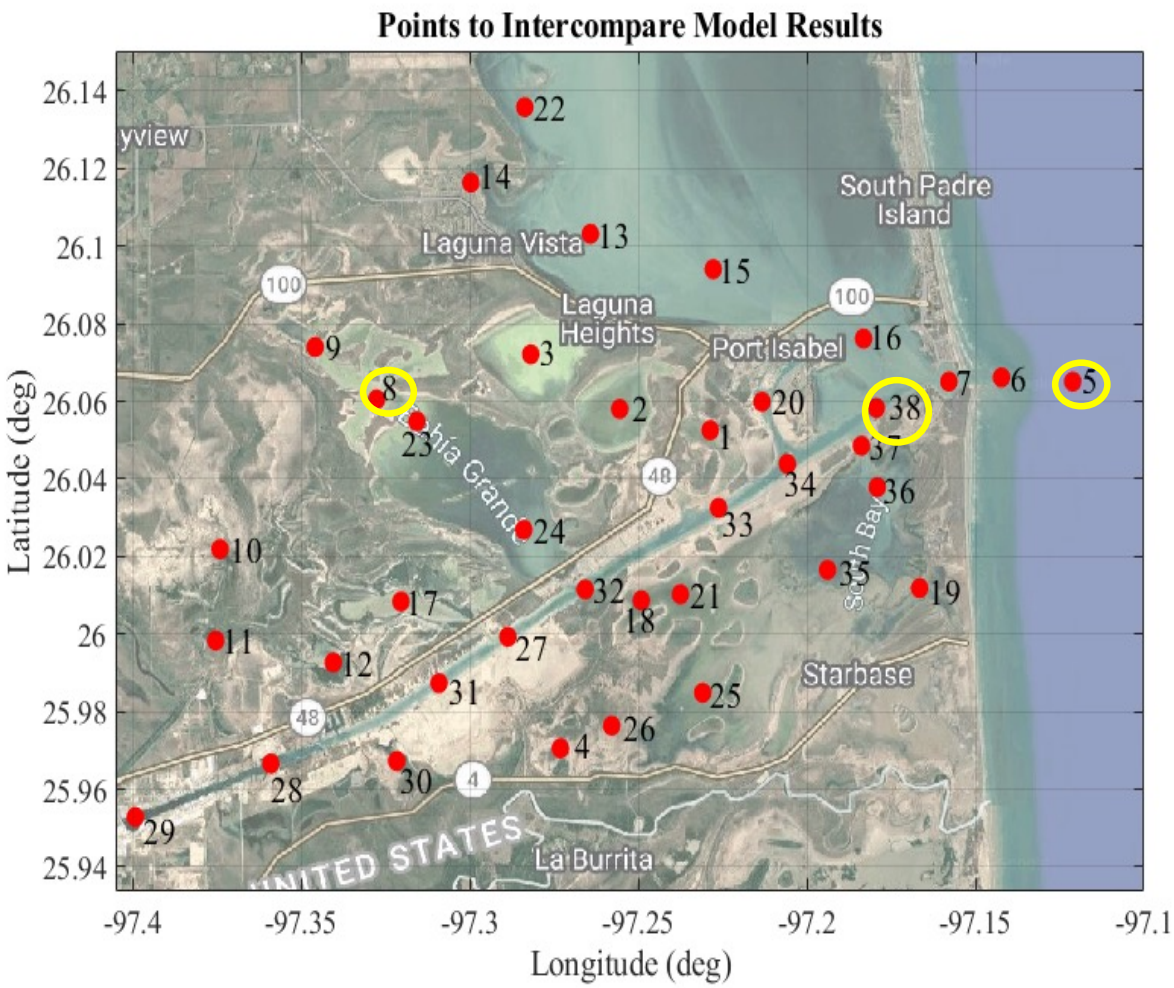

Figure 3-22. Map of the LRGV area with several locations marked and labeled for use in comparing modeling results.

Key Modeling Analysis Findings & Lessons-Learned

The analysis confirmed that flood model performance is highly dependent on the storm's specific forcing mechanisms (e.g., surge, rainfall, wind). Utilizing a multi-model approach proved invaluable for capturing a range of potential outcomes and understanding result uncertainty. All three models produced

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reasonable results that collectively demonstrated the complex behavior of compound flooding in low-gradient coastal areas. However, main findings of the three model results are included here for conciseness of the main report. (See **Appendix C-26** for the detailed model simulation results including observed and model data comparison.)

1. ADCIRC-STWAVE

The ADCIRC model served as the foundational coastal hydrodynamic model. Key findings and lessons learned from its simulations include:

- **Wave Forcing is critical.** For surge-dominated events like Hurricane Allen, simulations that included wave forcing (ADCIRC+STWAVE) predicted peak water levels over a foot higher than those without, underscoring the necessity of including wave effects for accurate surge estimation (Figure 3-23). Omitting wave forcing can lead to a significant underestimation of storm surge and is a critical component for accurate coastal modeling.

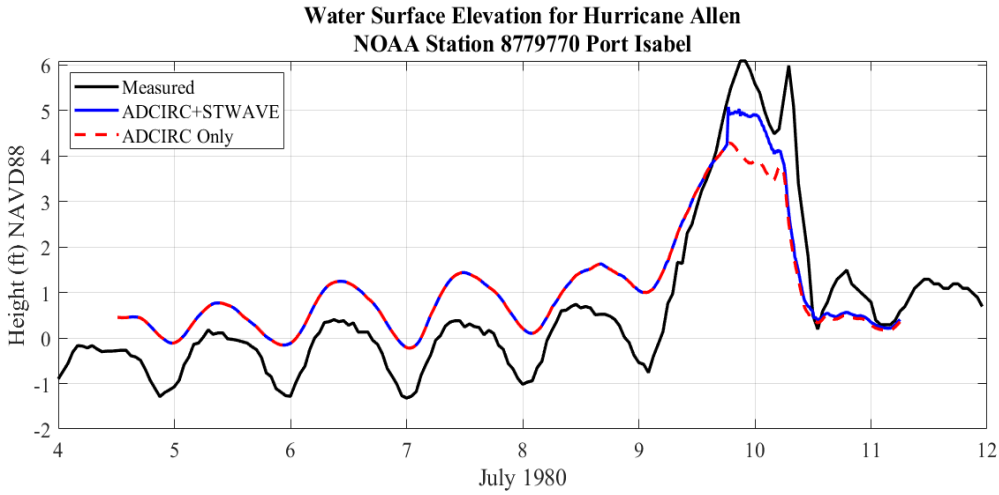

Figure 3-23. Hurricane Allen modeled vs observed water surface elevation (ft.) Port Isabel, Texas.

- **Physics Tuning and localized adjustments are needed.** While effective at capturing the primary coastal signal, the model showed peak water level errors of 1.0 – 1.5 ft at Port Isabel during Hurricane Allen. In follow-on S2G studies (Melby et al. 2022), the CTXCS was updated by increasing the wind multiplier from 1.0 to 1.09—correcting OWI wind field deficiencies for strong storms like Hurricane Allen—and lowering Manning's Roughness friction values across the Gulf, bays, and estuaries. These physics adjustments reduced average model errors to 1.0–1.5 feet and decreased the largest errors observed in the CTXCS by over a foot. This highlighted the need for physics tuning and localized adjustments rather than a single coast-wide setting. Future studies should implement improved physics settings (e.g., adjusted wind multipliers, friction) and localized steric water level adjustments to reduce peak water level errors.
- **Accurate riverine/rainfall-runoff input must be applied.** As a primarily coastal surge model, ADCIRC did not inherently account for direct rainfall or inland runoff contributions, which were significant factors in the Bret and Dolly events. To properly model compound flooding, river forcing data must be applied closer to the coast, or the model must incorporate rain-on-grid capabilities.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

2. **AdH**

The AdH model successfully leveraged outputs from ADCIRC, demonstrating strong capabilities in representing detailed inland hydraulics:

- **Demonstrated inland and coastal hydraulics.** AdH accurately reproduced the tidal and surge signals provided by ADCIRC at its boundaries. Comparisons showed that AdH, like HEC-RAS, effectively captured the rainfall and runoff contributions that ADCIRC missed, providing a more complete picture of inland flooding.
- **Outputs are dependent on flooding forcings.** Analysis confirmed that a combination of wind, barometric pressure, waves, and the Coriolis force drives coastal flooding, with their relative importance varying by storm. For instance, meteorological forcing was essential for capturing accurate flow paths in inland water bodies. The model reinforced the understanding that multiple physical forces drive coastal flooding, and their impact is storm-dependent.
- **Streamlined data processing needed.** The data pipeline from ADCIRC to AdH can be significantly streamlined by developing an automated script to consolidate the data extraction and reformatting process.

3. **HEC-RAS**

HEC-RAS was utilized for its strength in riverine and inland flood routing, though its application to coastal compound events presented challenges. Key findings and lessons learned from its simulations include:

- **Better demonstrated inland hydraulics.** The model was effective in capturing rainfall/runoff contributions to inland flooding. However, comparisons at locations subject to wave effects (Point 38) showed that HEC-RAS sometimes struggled to match the peak water levels predicted by ADCIRC+STWAVE, particularly during the surge-driven Hurricane Allen.
- **Considers wind effects.** During Hurricane Bret, which was characterized by unique wind patterns, the model highlighted variations in how different software handles wind-driven drawdown and initial minimum water depths in wetted areas.
- **Subject to software and data challenges.** Significant effort was required to overcome data interoperability issues, as the model lacks native support for common coastal formats (e.g., ADCIRC outputs). This necessitated custom post-processing for boundary conditions. Furthermore, HEC-RAS version 6.6 or later is required to apply wave forcing as a global boundary condition.
- **Requires optimum computational resource management.** Running multiple concurrent HEC-RAS simulations is resource-intensive and requires careful evaluation of CPU core availability to avoid system overload.

Based on the simulation results, several key best practices emerged for future modeling efforts. First, it is critical to standardize starting water elevations across all coupled models, especially for initially dry areas, to prevent artificial discrepancies in peak surge results. Furthermore, ensuring adequate simulation timing is essential; models require a sufficient "spin-up" period to establish stable tidal dynamics before a storm's arrival and must be run long enough post-storm to fully route rainfall and capture the complete flood event. To better represent pure tidal signals and reduce boundary condition artifacts, future studies should also consider expanding model domains by extending HEC-RAS downstream boundaries further offshore. Ultimately, given that model performance is highly dependent on the dominant storm forcings, utilizing a multi-model approach remains the most effective strategy for understanding the full range of uncertainty and accurately capturing the complex dynamics of compound flooding.

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Objective 5: Make recommendations for conceptual model-coupling workflow(s) for assessment of compound flooding hazard in coastal Texas

As TIFF's ultimate legacy will be the set of Recommendations, guidelines, and frameworks to improve the performance, understanding, and communication of flood science, it was imperative that the final Recommendations made by TIFF be vetted and optimized by coordinated peer review so that they can be made actionable without hesitation by implementing entities. This coordinated peer review was structured around the component objectives, which were used to query whether any potential Recommendations completely addressed the original vision and intent of TIFF.

Ultimately, 23 TIFF Recommendations resulted from the research and expertise associated with Component 3. (See the TIFF Recommendations Handouts, which can be used to seek further support for implementation.)

Note: Each Recommendation is designed to articulate implementation needs, and where feasible, approximate costs. These cost estimates are included for planning purposes only and should be understood as preliminary and subject to refinement based on project scope, timing, and local/regional conditions and circumstances. In all cases, implementation of these Recommendations will require the identification and securement of appropriate funding. Additionally, implementation of these Recommendations is subject to the legislative authority and capacity of potential partners. Collectively, the Recommendations are designed to provide funders and policymakers with a clear roadmap for strengthening the state's flood resilience, ensuring that communities, infrastructure, and ecosystems along the Texas coast are better protected for the future.

Brazos Harbor Inlet in Freeport, Texas ©USACE

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THE COMPONENT 3 RECOMMENDATIONS

Table 3-13. Component 3 Objectives for an Integrated Flood Modeling Framework and associated Recommendations.

Component Task	Associated Recommendation(s)
Establish an Integrated Flood Modeling TAT to support Component 3	Task completed. No associated Recommendations.
Evaluate and provide feedback on initial inventory of existing and proposed meteorologic, hydrologic, hydraulic, estuarine and surge models by the Study Providers to support inland and coastal hazard identification	C3.2A: Develop Database of Flood Modeling Studies C3.2B: Develop New Hydraulic and Hydrologic Models for the Rio Grande
Perform a literature review to identify potential meteorological, hydrologic, hydraulic, and hydrodynamic models and nature-based solutions for evaluating and mitigating flood risk for Texas	C3.3A: Evaluate the Analysis of Record for Calibration C3.3B: Advance Hydraulic Modeling Simulations with HEC-RAS Distributed-Memory Parallelization C3.3C: Advance Artificial Intelligence/Machine Learning Techniques for Flood Modeling C3.3D: Integrate Model Applications Used for Urban Stormwater and Flood Hazard Hydrodynamics C3.3E: Quantify the Impacts of Erosion on Storm Surge C3.3F: Quantify Wind-driven Inland Flows to Enhance Flooding Models C3.3G: Enhance Wave Models and Data to Improve Accuracy in Populated Areas C3.3H: Automate Topography and Bathymetry Data Processing C3.3I: Quantify Sensitivities of Existing Models C3.3J: Develop Guidelines for Nature-based Features to Reduce Flood Risk C3.3K: Assess the Performance of Nature-Based Solutions Using Physics-Based Numerical Modeling C3.3L: Assess the Performance of Nature-Based Solutions Using a Machine Learning Model C3.3M: Study Managed Aquifer Recharge for Flood Risk Reduction in the LRGV C3.3N: Quantify Geomorphic Changes on the Rio Grande and Arroyo Colorado
Perform a literature review on probabilistic methods for flood hazard estimation	C3.4A: Advance the Use of the Joint Probability Method in Compound Hazard Assessment C3.4B: Develop a Tropical Cyclone Rainfall Generator C3.4C: Retrospective Modeling of Historic Landfalling Hurricanes C3.4D: Develop Rapid Predictions of Flooding Hazards C3.4E: Develop a Machine Learning Model to Map Flood Zones in the LRGV C3.4F: Develop a Machine Learning Model to Evaluate Coastal Storm Surges Influence on Flooding in the LRGV
Develop recommendations for conceptual model-coupling workflow(s) for assessment of compound flooding hazard in the coastal Texas region	C3.5A: Texas Coastal Flood Framework (TxCFF) Development

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C3.2A: Develop a database of flood modeling studies to enhance flood risk assessment and emergency response

The results from existing flood modeling studies could significantly enhance flood hazard analysis efforts across Texas. Many existing datasets are underutilized and could immediately benefit professionals in the field if organized in a new cyberinfrastructure.

TIFF recommends a comprehensive bibliography and database of numerical grids, computational setups for Texas wave/surge modeling, and data on storms causing coastal flooding, including storm characteristics, wave data, high-water marks, and available measurements. This database will create comprehensive coastal model metadata collections for facilitating model access and sharing among Texas stakeholders and support improved understanding of coastal flood hazard estimation through leveraging existing models and datasets. Standardized computational meshes and setups for wave and surge models should also be provided to facilitate use by researchers and practitioners.

An interactive website should be developed for easy information sharing with Texas stakeholders, and the database must be regularly updated to reflect new findings. Furthermore, the database should also include studies utilizing 3D or hybrid models, ensuring a broader representation, as current models predominantly focus on 2D approaches. This database will prevent duplication of model development efforts as huge amounts of flooding analysis are being or will be performed to support a wide range of flood resiliency projects.

Keys implementation actions include:

- Use the TIFF Model Inventory (**Appendix C-14**) as a test-case to compile a comprehensive bibliography and database of flood modeling studies
- Share findings to support flood risk assessments, emergency planning, and coastal mitigation efforts
- Develop a model management system for storing and sharing numerical grids, computational setups, and storm-related data (this system needs to be made available not only for sharing archived models, but also for the model developers to upload new models for wide dissemination)
- Provide clear guidance on how these datasets impact Texas residents and flood risk management
- Include validated numerical grids and computational setups for Texas wave/surge modeling
- Develop standardized computational meshes to facilitate model reuse by researchers and practitioners
- Build an online database for stakeholders to access and contribute data
- Ensure regular updates to reflect new research and findings as more models become available
- Incorporate studies using 3D or hybrid models to ensure a comprehensive approach beyond traditional 2D modeling
- Investigate how the developed models—which vary in resolutions, accuracy, and other factors—can be leveraged and integrated for improved understanding of flood risk in coastal Texas

C3.2B: Develop one- and two-dimensional hydraulic and hydrologic models for the main stem of the Rio Grande, extending from Peñitas, TX to the Gulf

Hydrologic, meteorologic, hydraulic, estuarine, and surge models are essential tools for understanding flooding hazards and guiding both structural and non-structural flood risk mitigation planning. The 1D hydraulic model currently being used for flood modeling in the LRGV was developed in 2008, meaning it is based on what the region looked like nearly two decades ago, and only extends to the City of Brownsville, meaning the area from the Brownsville to the Gulf Coast is not accounted for in modeling

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processes. In 2021, a 2D base level elevation model was developed and is being used in the region, but an engineering scale 2D model is still needed.

TIFF recommends enhancing the 1D model to improve hydrologic simulations of flows in waterways. TIFF also proposes developing a new 2D model for the region to improve simulations of flow dynamics during flood events. It is crucial that the scope of work is developed jointly by the United States and Mexico, and the initiative carried out jointly.

This 5-year investment, estimated at $3 million, will enhance understanding of hydrodynamic processes in the Rio Grande basin and strengthen binational collaboration to improve flood management and public safety along the border.

Keys implementation actions include:

- Joint collaborations between the U.S. and Mexican sections of the IBWC
- Coordination with organizations experienced in model development, such as USACE, academic institutions, and regional counties
- Identify significant historical flood events and collect corresponding data, where available; compile and examine available datasets from federal, state, and local monitoring and modeling programs
- Use available data to correct uncertainties in the outdated, 1D model, binationally; use the latest software tools to enhance the model's capabilities; integrate coastal boundary conditions, including surge height, tidal phase, and wind forcing, to better simulate nearshore-inland flood dynamics
- Build an appropriate and state-of-the-art 2D model binationally with the Mexican section of the IBWC; integrate coastal boundary conditions, including surge height, tidal phase, and wind forcing, to better simulate nearshore-inland flood dynamics
- Assess model performance using accuracy, precision, recall, and operational reliability metrics
- Develop updated inundation maps for potential failure scenarios of Amistad and Falcon Dams on a periodic basis
- Apply refined modeling to ongoing and future levee design and construction projects, including the Santa Maria to Los Indios reach, which is currently at the pre-final design stage
- Perform joint probability analyses considering simultaneous flood events in both the Rio Grande main stem and the interior drainage basins, such as those observed during the 2018-2019 McAllen-Harlingen storms and the 2025 flood events

C3.3A: Evaluate the Analysis of Record for Calibration across Texas for potential flood hazard analysis uses

TIFF recommends evaluating Texas Analysis of Record for Calibration (AORC) data from 1979 to the near present to provide a comprehensive assessment of the data's accuracy and potential for improving flood hazard analysis and hydrologic modeling in Texas. The evaluation would compare AORC's accuracy against rain gages and benchmark its performance against other hourly rainfall products. Additionally, rainfall events would be categorized by their association with tropical cyclones and by time of year.

The AORC is a high-resolution gridded dataset providing near-surface weather conditions across the United States. With a spatial resolution of approximately 800 meters and a temporal resolution of one hour, it includes data on precipitation, temperature, humidity, pressure, radiation, and wind components. AORC's long history (over 40 years) and fine resolution make it valuable for applications like rainfall frequency analysis and hydrologic modeling. It is particularly useful for areas such as the LRGV, where daily rainfall measurements are often too coarse to capture localized storms, and for regions impacted by tropical cyclones, as seen during Hurricane Harvey in 2017.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

TIFF recommends partnerships with organization experienced in weather data collection, management, and dissemination, such as the TAMU Office of the Texas State Climatologist and other institutions. The project is expected to take 6-12 months, with an estimated budget of $70,000–$100,000.

Keys implementation actions include:

- Analyze AORC data from 1979 to the present (as available) across Texas
- Compare AORC precipitation data against rain gages
- Assess AORC's performance relative to other hourly rainfall products
- Categorize events by association with tropical cyclones and by time of year

C3.3B: Advance hydraulic modeling simulations with HEC-RAS distributed-memory parallelization

The USACE HEC-RAS model is widely used for flood hazard characterization in Texas coastal watersheds but faces computational limitations, especially in flat terrain where inter-basin flow transfers affect flood extent and depth. Current modeling requires breaking very large watersheds into smaller sections, creating edge-matching issues and making real-time flood response impractical.

TIFF recommends a distributed-memory parallelization approach to enable HEC-RAS to run across multiple nodes in a HPC environment, significantly reducing simulation times from days to minutes. Faster computations will improve flood planning, emergency response, and the ability to incorporate high-resolution (1m) Texas LiDAR data for more accurate topographic representation in the model.

Enhancing HEC-RAS with HPC capabilities would also support integration with coastal surge models, improving compound flood hazard assessments critical for the Texas coast, enabling more efficient and accurate result comparisons across modeling scales and platforms for performance benchmarking.

Key implementation actions include:

- Analyze and identify performance bottlenecks in the 2D HEC-RAS computational engine source code
- Develop and validate a small model domain test case for ongoing testing
- Implement message passing interface (MPI)-based parallelization using a single program–multiple data approach
- Perform graphical user interface (GUI) integration and iterative testing for usability and functionality
- Verify code accuracy and scalability with increasing processor counts
- Provide guidance on optimal subdomain sizing for performance and load balancing
- Perform test-bed evaluations of the HEC-RAS parallelized code for evaluating its performance, including result comparisons across modeling scales and platforms for performance benchmarking
- Generate summary tables comparing simulation cost, runtime, and result consistency

C3.3C: Advance artificial intelligence/machine learning techniques for flood modeling

Traditional process-based models for assessing the effects of compound flooding, while accurate, are often time-consuming and resource-intensive, making them less practical for rapid decision-making during emergency events. Coastal infrastructure operations, in particular, require fast evaluations to guide decision-making during floods, which typically necessitate "what-if" scenarios to explore various interventions and outcomes.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Recent advances in AI/ML models demonstrate strong potential to accelerate flood hazard analysis. However, these models are still largely research-level tools that do not yet have a strong basis for understanding the uncertainty and likely error associated with its predictions. To fully leverage their benefits, TIFF recommends advancing AI/ML techniques specifically tailored for compound flood modeling in Texas. By automating and accelerating the modeling process, AI/ML can support faster and more informed decision-making during flood events.

Keys implementation actions include:

- **Collect Ground-Truth Data**: AI/ML models must be trained and validated using high-quality local data to ensure reliability and informed decision-making; invest resources into developing a robust network of gages designed to collect data for future model training and to support real time flood warning systems; link measurements to risk thresholds and operational triggers (e.g., early alerts, road closures, evacuations) (Once trained, AI/ML models can rapidly generate predictions across a wide range of scenarios.)
- **Develop Guidelines for Model Interpretability**: Establish best practices to improve the interpretability of AI/ML models (e.g., moving beyond black-box approaches) to better support decision-making
- **Advance AI/ML Surrogate Modeling**: To enable faster simulation of compound flooding conditions, support ongoing research into AI/ML surrogate models that can replicate the outputs of traditional flood models at a fraction of the computational cost
- **Improve Transparency and Reliability**: Enhance AI/ML approaches to ensure that predictions are transparent, reproducible, and trustworthy; include approaches to quantify uncertainty and communicate model limitations clearly
- **Create "What If" Scenario Tools**: Develop user friendly tools that enable engineers and policymakers to quickly assess intervention strategies during flood events (These tools should enable rapid evaluation of options for protecting and maintaining coastal infrastructure during emergencies and changing conditions.)

C3.3D: Integrate urban stormwater and flood hazard hydrodynamics model applications

Effective modeling should account for both catastrophic hurricanes and more frequent moderate storms, enabling communities to evaluate how engineered infrastructure, such as deep tunnels, can mitigate flooding. While urban stormwater modeling has a long history, it has not been integrated into compound flooding models that consider both coastal and urban flooding.

TIFF recommends the development of an integrated urban stormwater and flood hazard model for Texas' urbanized coastal watersheds. The effort includes evaluating ongoing efforts to model urban flooding, creating multi-scale storm models that simulate both catastrophic and moderate storms, and incorporating 2D flood modeling (e.g., USACE HEC-RAS, Delft-3D, TRITON) into the U.S. EPA SWMM. Coupling SWMM with other open source/freeware flood models will facilitate greater adaptation by diverse stakeholders.

A testbed evaluation of the integrated model and exploring alternative approaches, such as sub-grid-based models, should be performed to enhance its accuracy and application. This integrated system will help assess how urban infrastructure can improve resilience to flooding. TIFF recommends partnerships with flood control districts and cities working on addressing challenges related to urban flooding.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Keys implementation actions include:

- Simulate both tropical and non-tropical storms to assess how urban stormwater systems, such as deep tunnels, enhance flood resilience
- Integrate a 2D flood modeling component into the SWMM
- Couple the SWMM with open-source/freeware flood models like HEC-RAS 2D, TRITON, or Delft3D-FM to facilitate greater adaptation by diverse stakeholders
- Conduct testbed studies in Texas urbanized coastal watersheds to validate model performance
- Explore alternative modeling approaches to improve accuracy and application

C3.3E: Quantify the impacts of erosion on storm surge

Texas bay and estuarine systems connect to the Gulf through narrow inlets that cut across barrier islands and peninsulas. These landforms act as natural buffers, protecting interior waterways from wave action and storm surge. However, their low-lying nature makes them vulnerable to overtopping and erosion during major storms, rapidly altering coastal topography.

Capturing storm-induced erosion in numerical models remains a challenge. During Hurricane Harvey, significant beach erosion near Aransas Bay (Goff et al. 2019) may have allowed additional surge to reach inland areas, leading to potential under-predictions in models like ADCIRC. These models struggle to represent rapid erosion dynamics, as they operate on coarse spatial resolutions (30-40 meters) and lack sediment transport capabilities.

TIFF recommends the enhancement of storm surge models by integrating barrier island and dune erosion processes. A more dynamic approach to modeling erosion would improve flood forecasting and post-storm reconstructions, leading to better risk assessments and coastal resilience planning. By incorporating real-time topographic changes, researchers can more accurately predict storm surge impacts and better protect vulnerable coastal communities in Texas.

Keys implementation actions include:

- **Site-Specific Morphological Modeling**: Identify high-priority sites prone to erosion (e.g., areas impacted by Hurricane Harvey, key dune-protected regions); use nearshore morphology models to simulate dune erosion and establish relationships between erosion and wave/surge conditions
- **Develop Parameterized Erosion Updates**: Conduct multiple simulations to generate datasets linking erosion to storm conditions; utilize regression models, lookup tables, or artificial intelligence/machine learning to create parameterized updates for bathymetry and topography; implement a dynamic system to update dune elevations and erosional areas every 10 minutes based on surge, wave, and current data
- **Integration with Surge Models**: Incorporate erosion-informed updates into large-scale surge models; test the feasibility of using a subgrid-type surge model to represent small-scale coastal features more effectively
- **Expansion**: Apply the developed framework to additional Texas shorelines, accounting for regional variations in sediment characteristics, hard structures (e.g., seawalls), and erosion-resistant layers; develop a methodology for predicting potential barrier island breaches in advance

Citation: Goff, J.A., Swartz, J.M., Gulick, S.P.S., Dawson, C.N., & Ruiz de Alegria-Arzaburu, A. 2019. "An Outflow Event on the Left Side of Hurricane Harvey: Erosion of Barrier Sand and Seaward Transport through Aransas Pass, Texas." *Geomorphology*, 334, 44-57. https://doi.org/10.1016/j.geomorph.2019.02.038.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

C3.3F: Quantify wind-driven inland flows to enhance flooding models

When large areas are flooded (e.g., Hurricane Harvey), strong winds have the ability to provide an additional forcing to tilt the water surface (i.e., pushing water upwind). When the wind stops or changes direction, the water pushed upwind will be redistributed and can cause further flooding.

The problems associated with wind-forcing over shallow water were discussed by Li & Hodges (2019), who implemented an ad hoc increase in drag for shallow marshes to prevent unrealistic acceleration by wind. The underlying problem is that wind-drag models are derived from studies of deep water where only a wind boundary layer exists near the surface. In shallow waters, the wind boundary layer overlaps with the bottom boundary layer, leading to nonlinear turbulent interactions that have not been studied. Although there is perhaps more theory available for waves propagation over shallows, the evolution of waves in shallow waters under short fetches is not well studied. There are no known models that can presently be applied to represent the development of wind-waves in shallow flooded areas.

TIFF recommends the following investments to address this knowledge gap:

- Establish theoretical frameworks for the coupled wind/wave/bottom boundary layer interactions in shallow water environments
- Use laboratory experiments and high-resolution computational fluid dynamics models to validate the theory and gain insights into wind, wave, and bottom boundary layer interactions
- Perform field experiments to examine how theoretical and laboratory results translate to full-scale conditions
- Use theory, laboratory data, computation fluid dynamics results, and field data to create a model equation that links wind speed to effective wind stress, considering water depth, velocity, and bottom roughness
- Integrate both large- and small-scale processes into the model to enhance its accuracy

Citation: Li, Z., & Hodges, B. R. 2019. "Model Instability and Channel Connectivity for 2d Coastal Marsh Simulations." *Environmental Fluid Mechanics*, 19, 1309-38. DOI: 10.1007/s10652-018-9623-7.

C3.3G: Enhance wave models and data to improve accuracy in populated areas

In Texas, wave prediction accuracy is lowest in the region containing the highest population and value: Normally Dry Land (the most important locations for planning and design). The challenges to accurate predictions are threefold:

1. Existing models were developed for conditions vastly different from those found over dry land, such as buildings, diverse vegetation, and rapid changes in land and structure properties.
2. Overland flooding with large waves is rare, resulting in limited datasets for model validation.
3. Significant changes in topography, vegetation, and structures during storms can lead to conditions that differ from pre-storm assumptions, affecting wave and surge properties and reducing model accuracy. This is especially problematic for dune erosion, as protective dunes often vanish during severe storms, exposing developed regions to increased flooding risk.

TIFF recommends enhancing model accuracy and reliability for overland wave prediction in Texas. Key actions include extensive data collection for model parameterization, calibration, and validation; detailed mapping of coastal areas with a focus on buildings and vegetation; detailed inventories of coastal buildings and large vegetation that are likely to withstand flooding; and high-resolution flow modeling over dry land using spectral models like SWAN or WAVEWATCH III. Developing a dedicated overland wave

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

model could establish a new standard for wave predictions, ensuring more reliable forecasts and improved protection for vulnerable areas.

Partners, including state and federal agencies and academic institutions, could execute this initiative over 3-5 years, with an estimated annual budget of $200,000.

Keys implementation actions include:

- Conduct extensive data collection to improve wave model parameterization, calibration, and validation
- Develop detailed inventories of coastal structures and vegetation likely to withstand flooding
- Use high-resolution mapping of Texas coastal areas, focusing on buildings, vegetation, and land characteristics
- Incorporate dynamic changes in topography, vegetation, and structures before, during, and after storms
- Implement high-resolution wave modeling over dry land using spectral models like SWAN or WAVEWATCH III
- Establish a dedicated overland wave model to enhance predictive capabilities

C3.3H: Automate topography and bathymetry data processing

TIFF recommends the development of automated methods to improve and standardize the representation of topo-bathymetric datasets, including engineering features like levees, in flood hazard models. This should include the creation of a standard vector representation for features such as levees, where polylines with varying widths and elevations along the line can be used for topographic processing.

Additionally, automated topographic processing methods should be developed to extract engineering features (e.g., levee, ship channel, bridge) from high-resolution LiDAR data without requiring human intervention except performing quality assurance and quality control of the final topographic products. To further enhance the process, model grid generation programs that can effectively incorporate vector polylines into model topography should be developed. A comprehensive standard database for accessing data on such features throughout Texas is also crucial for consistency and ease of use.

This initiative should leverage the NOAA Continuous Updated Digital Elevation Model (though it is limited in representing engineering structures like levees). The resulting tool should ensure that its derived products are easily usable across a range of flood hazard models, providing a more efficient and consistent means of incorporating engineering features into flood hazard assessments.

Keys implementation actions include:

- Establish a vector-based representation for levees and similar features, using polylines with varying widths and elevations
- Develop automated processing methods to extract engineering features from high-resolution LiDAR without human intervention
- Create grid generation programs capable of incorporating vector polylines into model topography
- Establish a standardized database for consistent access to topo-bathymetric data across Texas
- Prioritize bathymetric data improvements in small channels to refine flood models

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

C3.3I: Quantify sensitivities of existing models to wind forcing, bathymetry, bottom friction, and turbulence, with an initial emphasis on bathymetry

TIFF recommends the improvement of bathymetric data (particularly for small-scale features like channels and barrier islands) to resolve the associated computational challenges in flood hazard models. Errors in bathymetry and topography also contribute to significant inaccuracies inland hydraulics, coastal hydrodynamic and storm surge models. While higher-resolution data like LiDAR and satellite imagery enhance accuracy, they provide only a snapshot in time, leading to potential errors in areas undergoing frequent changes, especially in urban regions. Computational challenges arise in resolving small-scale features, such as channels and barrier islands, impacting model performance.

Additionally, TIFF recommends research to improve regional models like WRF for operational forecasting to enhance wind predictions in storm surge models. The primary source of uncertainty in storm surge simulations is attributed to wind forcing, which is a major driver for both surge and waves. Accurate wind predictions are crucial for reliable surge forecasts, especially when hurricane track and intensity are uncertain. Operational meteorologic models, despite improvements in numerical precision and higher resolution, do not guarantee error-free results. For instance, Hurricane Ian (2022) deviated from its predicted landfall location, showcasing the challenge in forecast accuracy. Regional models like WRF, tested at 1-5 km resolution in the Gulf, reveal fine-scale features but are not yet operational for forecasts.

TIFF also recommends the development of a framework for quantifying uncertainty in bottom friction, using measured data, to improve flood hazard model predictions. Bottom friction, determined by formulations like Manning's Roughness, introduces another source of error in storm surge predictions. The Manning's Roughness, dependent on sea-surface bottom characteristics, becomes more pronounced in shallow waters, influencing flooding severity over inundated land. Despite recent efforts to estimate bottom friction from measured data, this research is in its early stages and lacks a comprehensive framework for uncertainty quantification and parameter estimation.

C3.3J: Develop guidelines for nature-based features to reduce flood risk

Traditional benefit-cost analysis (BCA) focuses on economic metrics, making it less effective for evaluating nature-based solutions (NBS) that provide broader environmental and social benefits. As advancements continue, there is a need to refine BCA methodologies to better capture the full value of Natural and Nature-Based Features (NNBFs) within coastal infrastructure systems.

TIFF recommends that guidelines be developed for implementing NNBFs along the Texas coast and that their effectiveness in coastal flood risk reduction be assessed.

This approach will provide valuable insights into how NNBFs mitigate surge and dissipate waves, ensuring that site selection aligns with physical and local conditions while maximizing cost efficiency. Additionally, long-term monitoring systems should be implemented to quantify the lifespan and ongoing benefits of NNBFs. This will allow for data-driven assessments of their effectiveness in reducing coastal risk and evaluating cost feasibility over time. This fuller accounting of benefits can better support the adoption of NNBFs as viable, cost-effective flood mitigation strategies.

Keys implementation actions include:

- Update BCA methodologies to better account for the full range of NNBF benefits, including social and environmental factors
- Establish criteria/metrics to assess NNBF efficiency in mitigating storm surge and wave energy, incorporating social, environment, and economic factors

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

- Optimize site selection and feature sizing based on local coastal conditions
- Identify and implement pilot projects to evaluate NNBF effectiveness under varying conditions
- Establish a testbed to help determine the best locations, timing, and configurations for maximum flood risk reduction
- Develop monitoring systems to track NNBF lifespan and performance over time
- Use data-driven assessments to refine NNBF designs and improve cost efficiency
- Collaborate with federal, state and other agencies, and universities to leverage on-going efforts and the lessons-learned of NNBF implementations

C3.3K: Use physics-based numerical modeling to evaluate the coastal flood risk reduction performance of nature-based solutions applied in Lower Rio Grande Valley watersheds

The LRGV is vulnerable to hazardous compound flood events due to its low-lying terrain and combination of factors including, rainfall characteristics, drainage systems, land use, and water management. As flooding becomes a more frequent and severe problem in the region, many are looking to NBS as a potential strategy to mitigate flood risk. To date, comprehensive evaluation of NBS contributions within coastal infrastructure systems in the LRGV has yet to be done.

TIFF recommends using physics-based numerical modeling to evaluate the coastal flood risk reduction performance of NBS applied in LRGV. This initiative will support adaptive flood management by applying physics-based numerical modeling to analyze the effectiveness of NBS strategies and generating data-driven insights into how green infrastructure enhances flood hazard resilience along the Texas coast.

This proposal will:

- Develop and validate physics-based models that quantify the performance of NBS in reducing coastal flood severity and frequency
- Model hydrodynamics for a set of NBS feature designs to assess how different NBS configurations perform across varying site and hazard conditions
- Evaluate NBS feature effectiveness, cost, and benefits as compared with traditional hardened infrastructure measures, under design-level and historic events
- Establish a data-driven catalog of feasible NBS interventions tailored to the LRGV's coastal hazard risk

Success requires coordination between agencies and organizations experienced in advancing flood science, such as the USACE, GLO, TWDB, other federal and state agencies, academic institutions, and other stakeholders. Depending on existence of already-proposed NBS projects to evaluate in the region, other stakeholders and the general public may be needed for a project solicitation and/or concept design phase.

This 3-4 year investment, estimated at $2 million, will enhance understanding of green infrastructure performance within the LRGV and support local agencies in integrating NBS into regional flood management frameworks. Cost is highly dependent on the number of modeled scenarios, ease of implementation of NBS project concepts into numerical models, availability of site-specific information and data, and the amount of field data collection needed.

Keys implementation actions include:

- Conduct a comprehensive literature review of all existing coastal NBS projects in the LRGV region, as well as high-priority flood risk sites where NBS could feasibly be implemented in the future

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

- Collaborate with state and local agencies and stakeholders to gather relevant information associated with current and potential future project sites, such as performance assessments, lessons learned, and historical hydrodynamic and hazard data
- Identify key project performance indicators such as wave energy reduction, inundation extents, and erosion mitigation; consider mitigation scope of NBS (e.g., mitigate repeated low- to medium- intensity flooding, mitigate low-probability/high-intensity flooding)
- Use findings from literature review to develop a matrix of NBS scenarios to be simulated with physics-based models; NBS scenarios at several different sites are recommended, including at an existing project site to aid in validation; ideal scenarios for inclusion are those for which findings can be readily applied to other site locations; select a set of design-level and historic storm events to be simulated based on the NBS feature(s) and specific hazard risks associated with each site
- Assess the matrix of NBS scenarios and determine the most appropriate numerical model(s) to use for performance quantification; develop model for each scenario and incorporate up-to-date bathymetry/topography and land cover information into model frameworks
- Use hydrodynamic data (from water level gages and wave buoys), morphological data (such as beach profiles and sediment analysis), and hydrologic information (such as discharge) to validate the model outputs and refine predictive accuracy
- Collect field data at NBS scenario site locations if there is a lack of measured validation data at the modeled sites (Validated physics-based model frameworks can be leveraged for future projects and analyses.)
- Conduct model simulations and develop standardized metrics to assess NBS performance, including wave energy, current velocity, and inundation extent reduction and erosion mitigation; include performance measures needed to support probabilistic risk assessment along with model outputs from storm event simulations
- Compare the cost-effectiveness, long-term maintenance needs, and ecological co-benefits of NBS versus traditional hardened infrastructure, potentially using life cycle risk assessment and environmental benefits models
- Evaluate opportunities to replace or complement hardened infrastructure with natural or hybrid infrastructure that improves ecosystem function and community resilience at modeled site locations
- Create a decision-support catalog of NBS strategies optimized for LRGV conditions that links site characteristics, hydrologic profiles, and land-use types with the most effective NBS interventions; The catalog should align with forthcoming NBS Guidance Manual from the TWDB and promote reproducibility through open-source AI workflows to encourage collaboration among local agencies and researchers; Include interactive visualizations and design tools to refine project concepts and dynamically reevaluate NBS impacts

C3.3L: Develop a machine learning model that leverages artificial intelligence to evaluate the flood risk reduction performance of nature-based solutions applied in Lower Rio Grande Valley watersheds

AI/ML models, which began as pure data-driven models, have recently advanced into quasi-mechanistic models with the potential to improve flood hazard analysis in several ways, including through the comprehensive evaluation of NBS contributions within coastal infrastructure systems.

TIFF recommends the development of a ML model that leverages AI and physics-based modeling to evaluate the flood mitigation performance of NBS across the LRGV. This initiative will support adap-

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

tive flood management by analyzing the effectiveness of NBS strategies and providing data-driven insights into how green infrastructure enhances hydrologic resilience along the Texas coast.

This proposal will:

- Develop and validate a machine learning model that quantifies the performance of NBS in reducing flood severity and frequency
- Integrate hydrologic, land use, and climatic datasets to optimize the model's capacity to assess how different NBS configurations perform across varying conditions
- Develop recommended best-practice workflows for evaluating proposed NBS interventions using ML models
- Establish a data-driven catalog of feasible NBS interventions tailored to the LRGV's environmental and urban characteristics
- Evaluate opportunities to replace or complement grey infrastructure with green alternatives that improve ecosystem function and community resilience

Success requires coordination between agencies and organizations that supported the development of the USACE HEC-RAS models for various counties and cities in the ongoing LRGV Regional Flood Study, including the USACE, GLO, academic institutions, and contractors. Depending on existence of already-proposed NBS projects to evaluate in the region, other stakeholders and the general public may be needed for a project solicitation and/or concept design phase.

This 2-4 year investment, estimated at $2 million, will enhance understanding of green infrastructure performance within the LRGV, identify the most effective flood mitigation strategies, and support local agencies in integrating NBS into regional flood management frameworks. Cost is highly dependent on the number of modeled scenarios, ease of implementation of NBS project concepts into numerical models, availability of site-specific information and data, and the amount of field data collection needed.

Keys implementation actions include:

- Conduct a comprehensive review of AI-based modeling approaches for NBS performance evaluation and flood mitigation analysis; identify key performance indicators such as runoff reduction, infiltration rates, and storage capacity
- Build and train the model using learning techniques that integrate observed hydrologic and meteorological data, land-cover maps, and field monitoring results
- Incorporate environmental variables such as soil permeability, vegetation type, roughness, and rainfall intensity to simulate NBS effectiveness across multiple scenarios
- Conduct an analysis of feature importance to streamline model training
- Identify appropriate suites of events and landscape scenarios to support evaluation of NBS performance using surrogate models; events should include historic storms, design-level storms, and a corpus of synthetic storms suitable for probabilistic risk analysis; scenarios should include realizations of sea levels and land-use change plausible over the useful lifetime of NBS projects and equivalent hardened infrastructure measures to support both probabilistic risk analysis and analysis of epistemic uncertainties (This item should involve coordination with a team developing physics-based modeling workflows to simulate NBS performance.)
- Develop standardized metrics to assess NBS performance, including reduction in peak discharge, delay in runoff timing, and enhancement of infiltration; performance measures should be based on probabilistic risk assessment and also outcomes from selected design-level and recreated historic storm events

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

- Compare the cost-effectiveness, long-term maintenance needs, and ecological co-benefits of NBS versus traditional grey infrastructure
- Create a decision-support catalog of NBS strategies optimized for LRGV conditions that links site characteristics, hydrologic profiles, and land-use types with the most effective NBS interventions; the catalog should align with forthcoming NBS Guidance Manual from the TWDB and promote reproducibility through open-source AI workflows to encourage collaboration among local agencies and researchers; include interactive visualizations and design tools to refine project concepts and dynamically reevaluate NBS impacts

C3.3M: Study the viability of using managed aquifer recharge as a flood risk reduction strategy in the Lower Rio Grande Valley

Managed aquifer recharge refers to the process of moving water underground, either through natural infiltration or engineered systems designed to enhance recharge. This process can help replenish groundwater reserves, prevent saltwater intrusion, and slow down land subsidence.

TIFF recommends a two-year pilot program to test small-scale floodwater injection systems at select sites throughout the LRGV. Specifically, this pilot will evaluate whether injecting excess floodwater directly into underground aquifers at strategic locations in the LRGV can reduce surface flooding, prevent saltwater intrusion into freshwater supplies, and protect critical public infrastructure like wastewater and stormwater systems from corrosion and overloading.

This 2-year investment, estimated at $1 million, will guide region-wide decisions on the use of aquifer storage as a tool for (or limitation of) flood management, supporting state and local infrastructure planning, investment strategies, and regional resilience initiatives.

Keys implementation actions include:

- Use modeling techniques to detect and map optimal locations and methods for groundwater injection and storage
- Determine the technical and geological viability of injecting stormwater into existing aquifer formations without compromising water quality or structural integrity
- Quantify the potential reduction in surface flooding in nearby communities during heavy rainfall or hurricane events
- Evaluate how sustained aquifer recharge can reduce saltwater intrusion and limit corrosion in wastewater and stormwater collection systems

C3.3N: Conduct sediment transport and channel capacity analyses on the Rio Grande and Arroyo Colorado to quantify geomorphic changes and vegetation growth that may impair flood conveyance

The Rio Grande has experienced substantial hydrologic and geomorphic transformation over the past century, largely due to land-use changes and water management practices. Once a wide and multi-channel system, the river is now characterized by a narrowing channel because of the accumulating sediment and encroaching vegetation. Unfortunately, this channel narrowing is threatening important wildlife habitat and has increased flood risk for local communities. Similarly, the Arroyo Colorado (a former outlet of the Rio Grande), experiences accumulated sedimentation which reduces the river's capacity to carry floodwaters. These evolving river conditions pose challenges for flood management and ecosystem health across the LRGV.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

TIFF recommends evaluating sediment transport processes, geomorphic changes, and vegetation encroachment that contribute to altered flow capacity in the Rio Grande and Arroyo Colorado. This includes identifying critical channel reaches where sediment accumulation and vegetation have significantly reduced flood conveyance efficiency.

This 2-year investment, estimated at $1 million, will enhance regional understanding of how sediment transport and vegetation growth are altering the Rio Grande and Arroyo Colorado's hydrologic behavior, and generate actionable insights to guide river restoration and flood mitigation planning across the LRGV.

Keys implementation actions include:

- Obtain existing LiDAR and bathymetric datasets to capture both overbank and in-channel geometries
- Compile and examine available datasets from federal, state, and local monitoring and modeling programs
- Measure spatial and temporal trends in sediment transport, deposition, and erosion to understand how these processes shape channel morphology
- Compare new bathymetric data against previous surveys to quantify narrowing, aggradation, and loss of flood capacity along the river corridor
- Map and evaluate vegetation growth patterns that restrict channel capacity or alter local hydrology
- Apply sediment transport and H&H models to estimate flow capacity, sediment yield, and areas at risk of future aggradation; identify reaches with the greatest sedimentation and flow restrictions, prioritizing areas for potential restoration, sediment management, or vegetation clearing
- Develop detailed channel capacity and sedimentation maps
- Make recommendations for managing sediment buildup and vegetation encroachment

C3.4A: Advance the use of the Joint Probability Method in compound hazard assessment

Current coastal flood hazard assessments often underestimate water levels by neglecting the compound effects of storm surge and precipitation-driven flooding. This is particularly critical in Texas coastal watersheds, where hurricane storm surge and hurricane-induced rainfall riverine flooding interact in complex ways. Traditional statistical methods, such as bivariate copulas, are limited by data constraints and basin variability, making them insufficient for capturing the full range of flood hazards.

TIFF recommends expanding the CHS-PCHA model agnostic framework to improve compound flood hazard characterization. This enhancement would integrate high-resolution numerical modeling, machine learning, and stochastic uncertainty (e.g., antecedent conditions like soil saturation, which vary based on local geography). Leveraging synthetic storm results from prior regional studies would also support a framework that can be consistently applied across Texas coastal basins.

Key implementation actions include:

- Improve the CHS-PCHA framework by integrating additional probability methods beyond observation-based approaches, such as the use of Hurricane Rainfall Models and the use of seasonal correlation between flow and intensity applied in the JPM framework
- Develop a flexible, model-agnostic framework that can be applied consistently across Texas coastal basins

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

- Incorporate variability in antecedent conditions (e.g., soil saturation) to refine flood risk estimates based on local geography
- Utilize synthetic storm results from prior coastal hazard studies to reduce computational cost and apply widely-accepted regional storm surge information and statistics; explicitly represent interactions between tropical cyclone storm surge and rainfall-induced water levels to capture compound flood hazards
- Apply the improved JPM framework in select Texas coastal watersheds to assess accuracy and reliability
- Conduct validation studies with historical and synthetic storm events to refine methodology

C3.4B: Develop a Tropical Cyclone Rainfall Generator

TIFF recommends the development of a high-resolution (hourly, 0.05-degree) rainfall generator for statewide application in Texas to generate rainfall fields for all synthetic tropical cyclones used in compound flood hazard assessments for the coastal Texas region. Building on the USACE 2023 study which established a set of 660 synthetic tropical cyclones for evaluating flood risks, the effort involves quantifying uncertainty and bias in tropical rainfall models by leveraging historical rainfall datasets. This high-resolution rainfall generator will support improved flood hazard assessments.

TIFF recommends partnerships with organizations experienced in weather data collection, management, and dissemination, such as the Office of the Texas State Climatologist (housed at TAMU) and other academic institutions. The project timeline is expected to range from 6 months to 3 years, depending on the required level of detail and prior experience with similar developments. The estimated total cost is between $100,000 and $200,000.

Keys implementation actions include:

- Use historical rainfall data to assess and correct biases in existing tropical cyclone rainfall models
- Create an hourly (0.05-degree) tropical cyclone rainfall generator tailored for Texas
- Produce bias-corrected and probabilistic rainfall datasets for all 660 synthetic tropical cyclones in the CTXCS
- Utilize artificial intelligence/machine learning to analyze rainfall distribution relative to storm tracks and generate realistic rainfall patterns within hurricane rain bands

C3.4C: Conduct retrospective modeling of historic landfalling hurricanes using high-resolution weather models

Understanding historical storm impacts is crucial for improving predictive models and better protecting lives and infrastructure. However, hurricane modeling is limited by the lack of high-resolution observational data before the 2000s, reducing the accuracy of flood and wind hazard assessments, particularly in data-scarce regions. While many flood models rely on modern datasets, validating them against past events enhances their reliability.

TIFF recommends a retrospective analysis of major landfalling hurricanes from the early 1960s to the 1990s using high-resolution modeling techniques. This analysis will provide data to calibrate and validate flood models while also supporting wind hazard assessments for periods before the availability of the High-Resolution Rapid Refresh weather forecasting model. Simulating past hurricanes will offer insights into their potential impact on today's coastal infrastructure, aiding in the refinement of evacuation plans, resilience strategies, and building codes. Additionally, understanding historical hurricane behavior will contribute to long-term assessments of storm intensity and frequency, informing climate adaptation efforts.

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TIFF recommends partnerships with organizations experienced in weather data collection, management, and dissemination, such as the Office of the Texas State Climatologist (housed at TAMU), other academic institutions, federal and state agencies, industries, and consulting firms for the implementation of this effort. The effort is expected to take 1 to 3 years, depending on the historical scope. The estimated cost ranges from $100,000 to $350,000, with the higher end supporting simulations of additional storms, such as Hurricanes Carla (1961) and Beulah (1967), and alternative storm path scenarios. (Hurricane Carla is particularly important for wind analysis, while Hurricane Beulah is significant for rainfall impacts.) TIFF recommends prioritizing these hurricanes for analysis and incorporating perturbed simulations to assess potential storm impacts under alternative tracks. Deliverables should include high-resolution wind and rainfall data, validated against historical observations, to improve understanding of past hurricane impacts and enhance future modeling efforts.

C3.4D: Develop rapid predictions of flooding hazards

Effective flood hazard prediction is crucial for ensuring public safety and optimizing emergency response during storm events along the Texas coast. Currently, rapid and accurate forecasting of storm surge and wave impacts is limited, making it challenging to issue timely warnings to at-risk communities. The ability to predict flooding hazards quickly enhances emergency response efforts by enabling authorities to issue evacuation orders, mobilize resources, and reduce casualties and property damage. Furthermore, these predictions aid in managing coastal flood protection systems, such as pumps, dams, and surge barriers, to protect vulnerable areas.

TIFF recommends the development of a robust, reliable, and accurate storm surge and coupled wave model for the Texas coast. This model should build on previous studies to provide enhanced predictions for total water levels and flood inundation. By incorporating large- and small-scale 3D processes, the model would improve the accuracy of simulations, ultimately supporting better decision-making in flood preparedness and response.

TIFF also recommends the evaluation of the suitability of existing web tools, such as the Interagency Flood Risk Management (InFRM) Flood Decision Support Toolbox (https://webapps.usgs.gov/infrm/fdst/) and the NWS National Water Prediction Service (https://www.weather.gov/ewx/NWPSInfo), for disseminating information to emergency managers and relevant statewide parties. The evaluation should aim to determine whether these platforms can effectively convey the complexities of coastal and compound flooding risks or if a separate platform is necessary for improved communication and visualization.

C3.4E: Collect ground-truth data to develop a machine learning model that leverages artificial intelligence and remote sensing to detect and map high-risk flood zones across the Lower Rio Grande Valley

Flood risk in the LRGV is especially hazardous due to the threat of compound flooding, or the combined effects of riverine flooding and nearshore storm surge. While historical records specific to compound flooding in the LRGV region may be limited, the area has experienced various flood events over the years, often resulting from the convergence of different hydrological and meteorological phenomena. Recent advancements in applying remote sensing, especially when combined with ML techniques, have made possible the detection of large flood-prone areas without the need for highly accurate data inputs and computationally intense hydrological processes.

TIFF recommends developing and validating a scalable ML model for automated flood detection and risk mapping. This requires integrating multi-sensor and multi-scale data to calibrate models and improve detection precision with a validated artificial intelligence-driven approach.

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This 2-3-year investment, estimated at $1 million, will support adaptive flood management by mapping flood-prone areas, analyzing contributing risk factors, and providing data-driven insights for infrastructure planning and mitigation strategies across the Texas coast.

Keys implementation actions include:

- Collaborate with local universities and partners to assist with drone data collection and analysis, remote sensing and associated analysis, ML development, and model validation
- Collaborate with federal and state agencies to integrate historical coastal and hydrological data
- Consider an existing state agency as the potential data host
- Identify significant historical flood events and collect corresponding high-water marks and satellite imagery, where available
- Assess data gaps and synthesize available datasets, and consider challenges related to cloud-free satellite data availability
- Conduct a literature review to build on TIFF's previous review of AI-based flood modeling and remote sensing techniques
- Identify best practices for data selection, pre-processing, and algorithm design; incorporate LRGV-specific factors such as debris accumulation, stormwater stacking, and drainage obstruction
- Build and train an appropriate and state-of-the-art ML model applied to Sentinel-1/2, Synthetic Aperture Radar (SAR), InSAR, LiDAR, drone imagery, and historical ground-truth data
- Automate classification of water bodies, impervious surfaces, and flood-affected zones for improved early detection
- Expand labeled datasets through supervised learning and iterative refinement based on historical and field-verified data
- Integrate key environmental variables, including stormwater accumulation, drainage networks, and soil saturation
- Conduct spatial analyses using GIS-based workflows to identify regularly flooded areas
- Deploy drones to collect high-resolution, post-event imagery and validate model predictions at site-specific scales
- Combine three data layers (remote sensing imagery, drone data, and field survey inputs) to calibrate and verify the model's outputs
- Assess model performance using accuracy, precision, recall, and operational reliability metrics; evaluate predictive capabilities under varying climatic and meteorological scenarios; compare results against historical flood maps and municipal drainage datasets
- Develop a decision-support catalog highlighting flood risk levels, contributing factors, and spatial trends across the LRGV that aligns with the forthcoming NBS Guidance Manual from the TWDB to ensure consistency with statewide flood infrastructure strategy
- Publish shareable and reusable AI workflows using emerging computational infrastructure ("pods") to support cross-agency collaboration, transparency, and repeatability
- Integrate models and datasets into external state and federal systems and share outputs with local LRGV counties through clear data-sharing protocols
- Conduct training sessions and workshops to support local adoption and capacity building

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C3.4F: Leverage historical and real-time monitoring data to develop a machine learning model that evaluates how coastal storm surges influence flood dynamics in the Lower Rio Grande Valley

Coastal storm surge is driven by at least two distinct flooding processes: slow-moving inland flooding (low energy, inundation) and rapid coastal flooding from bays and estuaries (high energy, destructive). When these floods interact, their differing energy regimes pose challenges for analysis and modeling, often resulting in computational singularities that make it difficult to estimate compound flood impacts along the shoreline.

TIFF recommends developing and validating a ML model designed to integrate inland stream gage observations (e.g., water surface elevation, discharge) with advanced bay and estuary measurements (e.g., tidal depth, 3D velocity fields, and salinity gradients) to estimate compounded flood depth and energy loss.

This 3-year investment, estimated at $1 million, will quantify the spatial and temporal influence of coastal surge on inland river stages; estimate compound flood depth, duration, and flow energy losses across the LRGV; and support the calibration of detailed hydraulic models for regional planning applications.

Keys implementation actions include:

- Compile and examine available datasets from federal, state, and local monitoring and modeling programs
- Train a one-year model using multivariate data inputs (e.g., streamflow, tidal stage, offshore wave height, barometric pressure) and adapt the system for continuous learning and procedural evaluation using the remaining historical datasets and evolving real-time data
- Introduce independent datasets such as stream network node connectivity for assessing data resource requirements at the Hydrologic Unit Code (HUC)-8 scale and extrapolate results by hydrographic type
- Use ML-generated insights to calibrate and validate hydraulic models; validate models at both sub-regional (multi-watershed) and urban (municipal drainage system) scales to test scalability and transferability
- Integrate models and datasets into external state and federal systems and share outputs with local LRGV cities and counties to support local adoption

Alberto storm surge in Surfside Beach, Texas ©Surfside Beach EMS

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C3.5A: Develop the Texas Coastal Flood Framework (TxCFF) for compound flood assessment to support flood recovery and emergency response efforts along the Texas coast

Texas has the opportunity to set a national standard for compound flood modeling. As the largest economy among hurricane-prone states, and second only to Florida in population at risk, Texas faces urgent challenges from hurricane and tropical cyclone flooding. To address these challenges, TIFF recommends establishing the TxCFF: a sustainable, updateable, and state-of-the-art system for compound flood assessment. The TxCFF will integrate models, analysis tools, and workflows to support planning, development, recovery, and emergency response along the Texas coast. This framework will provide linkages to existing databases, seamless data transfer between models, a user interface for setting up and executing coupled models, plug-and-play APIs, and integrated output datasets from component models into coherent datasets for analysis and visualization. Over time, it will evolve into a robust platform for evaluating and managing compound flooding across multiple projects.

The TxCFF would consist of:

- wind and pressure model
- ocean circulation model
- wind/wave model (far field and near field)
- flood inundation (hydraulics) model for river flow and landscape flooding
- upland runoff model (hydrology)
- stormwater drainage model
- groundwater model
- flood hazard analysis tools
- code for coupling the various flood
- inundation component model
- coupling to external meteorological (storm) models/data sets for historic and synthetic storms
- code for calibration, validation, and testing of inundation models
- code for ingesting flood inundation model results into flood hazard analysis
- code for visualizing inundation and hazard analysis results
- code for input/output
- code for user customization

Initially, the TxCFF could start as documented workflows for coupling models and data, supported by pre- and post-processing tools. These workflows can then be codified into a software framework emphasizing reusability, accessibility, scalability, training, and uncertainty management. Development will require long-term funding, a consistent project team, and collaboration with agency-sponsored modeling projects. By building on vetted workflows and testbeds, the TxCFF can grow incrementally into a central resource for scalable and integrated flood modeling across Texas with an active user community supported with training resources.

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Tasks/steps to developing the TxCFF are outlined in Figure 3-24 and below:

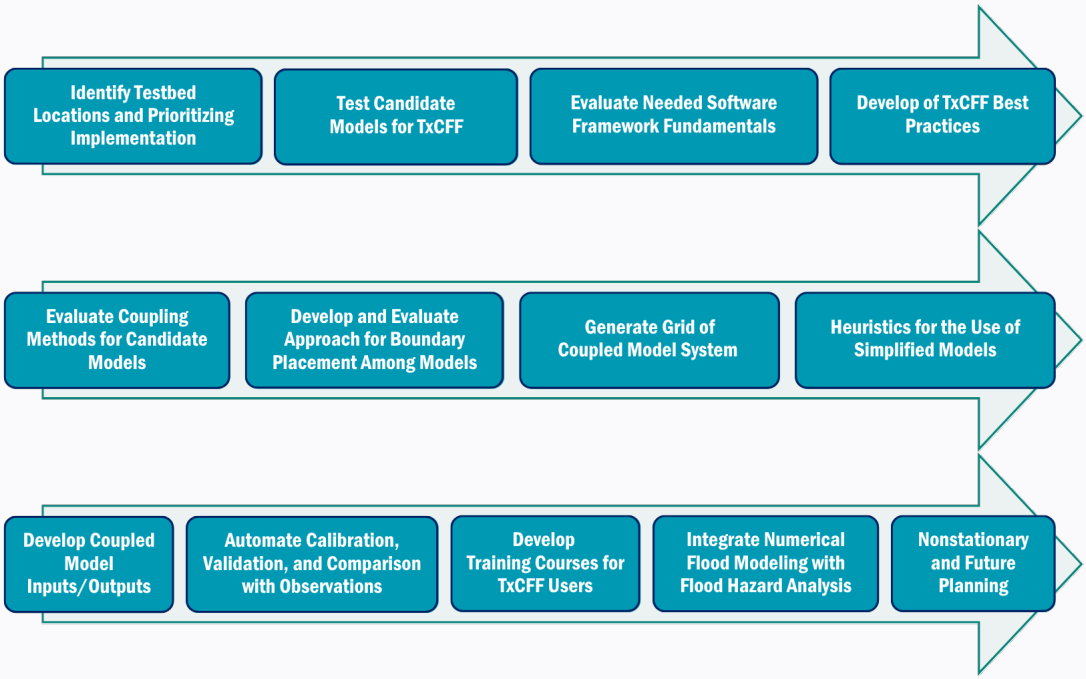

Figure 3-24. Tasks/steps to build the TxCFF.

1. **Identify and Prioritize Testbed Locations**: TIFF identified seven regions as priority locations for building the TxCFF capabilities and recommends that the first three receive highest priority (See Figures 3-11 through 3-17 and **Appendix C-10** for more details on each location.).

    1. Houston/Galveston Region – TIFF recommends prioritizing this region in the deployment of the TxCFF because it includes several different types of inlet flows into an irregularly shaped bay with complex hydrodynamics, supports a large population with community involvement, has a long history of hurricane impacts, and also has one of the longest tidal gages in the country.
    2. Freeport Region – TIFF recommends prioritizing this region in the deployment of the TxCFF because the Brazos River empties directly to the Gulf, so it experiences a different kind of compound inundation than the other regions considered. Drainage areas upstream are largely industrial with little infiltration and irregular flood control measures.
    3. Rio Grande/Laguna Madre – TIFF recommends prioritizing this region in the deployment of the TxCFF because it is a long shoreline bay with several tributaries as well as a large river outlet. The contributing rivers are heavily regulated and international agreements and impacts could be a controlling factor in considering coastal storm risk management. This region is also an excellent example of a data and model-poor watershed of international importance, although TIFF did employ recent advancements in remote sensing applications combined with ML techniques to detect flood prone areas in the LRGV, providing a good foundation for continued efforts.
    4. Beaumont/Port Arthur Region
    5. Corpus Christi Region
    6. Matagorda Bay Region
    7. Brownsville/South Padre Island Region

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Making the final decision on the sites to be implemented and order of implementation should carefully consider the level of stakeholder engagement and resources that can be allocated, the scale of the storms and adjacent flooding area that require modeling, data availability, the dominate flood hazards to ensure a balanced mix between the different drivers, e.g. coastal and inland, the geographic characteristics, both land and water, of the area, and the overall resources available to the project. Flexibility to employ and compare different compound hazard analyses levels and flood inundation models would be an added benefit.

2. **Test Candidate Models for a TxCFF**: Select relevant models based on the findings of the TIFF literature review and input from scientists/engineers familiar with the testbed site. (This selection should take into consideration the existing models and hazard analyses in the testbed study region for leveraging resources.) Develop and apply testing strategies to evaluate each discipline model with respect to:
   - How the model algorithm influences the practical coupling algorithms
   - Whether implementation is through source code changes or in/out data stream
   - Stability and convergence conditions for coupling
   - Whether an interface region is needed between models
   - Identifying model boundaries and handling boundary movement
   - Handling disparities in model time steps and grid size
   - Effectiveness of parallelization of the model; test cases for proving coupling viability
   - Availability of graphical user interfaces
   - User guides, documentation, and training material

   (This action should connect discipline scientists/engineers with framework software engineers to ensure analyses consider both model-specific and framework-level impacts.)

3. **Evaluate Software Framework Fundamentals**: Identify the critical methods for model integration and data exchange (e.g., selection of coding language for the framework) considering:
   - The utility of existing frameworks like the Earth System Modeling Framework
   - Needs for coupling data communication
   - Standard data libraries and metadata standards to be included
   - The approach used for parallelization across different models to ensure efficient computing
   - The definition of "best practices" to be used in writing framework code
   - Systematic approaches and supporting data for testing and code validation

   (This work should proceed in parallel with candidate model testing to ensure framework and coupling decisions are aligned. The deliverables will be an alpha version of the TxCFF and guidelines on coding conventions, libraries, and inter-team communication to ensure project compatibility.)

4. **Develop TxCFF Best Practices**: Develop best practices and training materials to broaden adoption of the TxCFF. These should emphasize basin or location-agnostic approaches by using probabilistic methods for inputs and boundary conditions, consistently sampled from fitted distributions. For example, engineers might suggest a certain infiltration sub-model, but the input parameters could be selected by sampling distributions fit to historical records.

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5. **Evaluate Coupling Methods for Candidate Models**:
    - Select and test candidate models
    - Investigate coupling interfaces across:
        - ocean and flood inundation
        - upland runoff and flood inundation
        - stormwater system and flood inundation
        - stormwater system and upland runoff
        - groundwater with flood inundation, stormwater system, and upland runoff
        - wind/wave with flood inundation
        - meteorological forcing with all models

    (Coupling must be developed and coded by multidisciplinary teams, working collaboratively and transparently to ensure consistency across interfaces. Each project team should coordinate directly with the compound flooding framework team to define input/output data, manage spatial and temporal interpolation, and guide development.)

6. **Develop and Evaluate Boundary Placement Among Models**: Develop a methodology and code to automatically set and adjust coupling boundaries as needed. This requires analyzing diverse testbeds under different modeling scenarios and establishing guidance on which model outputs to use in overlapping regions. From a compound hazard perspective, boundaries should be positioned within a single model wherever possible, ensuring that boundary conditions represent only one driver at a time.

7. **Grid Generation for Coupled Model System**: Develop a consistent, automated methodology for creating and testing coupled model grids to support multiple testbed sites along the Texas coast. This approach should leverage existing initiatives and focus on efficiency, reliability, and standardized practices. Key tasks include automating extraction of ground elevation data (e.g., TxGIO LiDAR) into grid meshing systems; updating grids routinely to reflect geomorphic changes and urban growth; and providing guidance on discretization resolutions and standardized parameters (e.g., Manning's Roughness). These measures will streamline model development, maintain up-to-date domains, and ensure consistency in model configuration and application, supporting faster innovation and more reliable outputs for coastal resilience planning.

8. **Heuristics for the Use of Simplified Models**: Develop heuristic algorithms to guide users on the relative importance of different compound flooding components under specific conditions. For example, if upland rainfall is low and soils are unsaturated, a heuristic might recommend disabling hydrological modeling. These heuristics can rely on general knowledge of forcing scales and landscape characteristics and may suggest pre-defined workflows for users. Heuristics may need to be customizable for specific locations, with different parameters for areas such as Houston-Galveston Bay versus Brownsville. Screening hazard tools (e.g., HL-0, HL-1) can help identify major drivers, and bivariate copulas can be extended to trivariate analyses to assess additional factors, such as groundwater, in compound flooding.

9. **Develop Coupled Model Inputs/Outputs**: Models within the framework will have varying input and output formats that must be standardized by the framework. This action involves collaborating with hazard analysts, discipline engineers/scientists, and potential users to define flexible, practical

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data methods. Wherever possible, standard libraries and file formats (e.g., NetCDF, Hierarchical Data Format 5, JavaScript Object Notation) should be used. Metadata should follow community standards, such as the Climate Forecast Metadata conventions. Data cataloging and curation practices should ensure proper access and retrieval. Tools for community-based visualization and analysis should also be developed.

10. **Automate Calibration, Validation, and Comparison with Observations**: Traditionally, calibration, validation, and comparison with observations have relied on user expertise. For TxCFF testbed sites, automated approaches should be developed to standardize these tasks, preventing model adjustments outside their intended scope. This system will increase confidence in model outputs, especially for users lacking expertise in specific compound flood disciplines.

11. **Develop Targeted Training Courses for TxCFF User Groups**: Include an introduction to compound hazard analysis, covering probabilistic inputs, synthetic storms, and integration of model outputs to generate hazard curves and flood maps.

    - Training For Modelers – Focus on using testbed models to create, run, and analyze compound flooding cases, including making "what-if" changes to assess storm scenarios, land development, and other impacts
    - Training For Testbed Model Developers – Expand expertise to extend testbed models and hazard analyses to other regions and more complex scenarios, supporting the broad adoption of TxCFF across the Texas Coastal Plain
    - Training For Managers (academia, industry, government) – Provide guidance on the capabilities and limitations of TxCFF, interpreting model outputs, and formulating relevant "what-if" questions for planning and decision-making

12. **Integrate Numerical Flood Modeling with Flood Hazard Analysis**: Evaluate compound flood hazards at different hazard levels using the testbed and/or its sub-basins. Analyses can leverage existing models, new TxCFF models, or published compound hazard studies. These results can be compared with individual hazard models such as CHS for storm surge/waves or inland flood frequency analyses. Integrated model outputs can be used to generate hazard curves and flood inundation maps. Additionally, multi-level meta-model approaches tested in pilot studies can be applied to characterize basin-specific impacts on event probabilities (e.g., HL-3 Extended JPM). Uncertainty in inputs, model outputs, and hazard estimates can be incorporated to improve overall hazard assessment.

13. **Address Nonstationarity and Future Planning**: To account for natural and anthropogenic factors, the framework should include inland and coastal impacts that can exacerbate flood risk (e.g., sea-level rise, higher storm surge risks, and shifting rainfall patterns, as well as land-use changes from population growth and urbanization). Incorporating these projections ensures resilience in infrastructure development and flood mitigation planning. Several methods exist to characterize future conditions. Numerical physical models currently incorporate sea-level rise for JPM-based models (Nadal-Caraballo et al. 2020). Statistical approaches, such as Bayesian networks, surrogate modeling, and Bayesian updating, can quantify changes in tropical cyclone frequency, rainfall patterns, and land-use impacts, providing insights into evolving risks. These methods help stakeholders prioritize interventions and adapt flood protection strategies over time (Liu et al. 2025).

Citations:

Liu, Z., Carr, M.L., Nadal-Caraballo, N.C., Yawn, M.C., & Bensi, M. 2025. "A Bayesian Network Method for Deaggregation: Identification of Tropical Cyclones Driving Coastal Hazards." http://arxiv.org/abs/2505.14374.

Nadal-Caraballo, N.C., Campbell, M.O., Gonzalez, V.M., Torres, M.J., Melby, J.A., & Taflanidis, A.A. 2020. "Coastal Hazards System: A Probabilistic Coastal Hazard Analysis Framework." *Journal of Coastal Research*, 95, 12111216. https://doi.org/10.2112/SI95-235.1.

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Flooding along the Texas coast from Hurricane Ike in 2008 © Smiley N. Pool/Getty Images

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Hurricane warning sign on a Houston freeway ©Andrea Quintero Olivas, Adobe Stock

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4 Component 4: Flood Planning and Outreach

Component 4 worked to bridge the gap between technical modeling and community priorities, ensuring flood mitigation strategies are informed by and communicated with the people and places they are designed to protect. This component considers the influence of compound flooding on planning efforts and supports the expansion of comprehensive flood risk management that reconciles local interventions with regional solutions.

4.1 What is Flood Planning and Outreach?

Planning and outreach in the context of TIFF involved the thoughtful development of communication strategies, educational materials, and planning tools that support decision-making for compound flooding and coordinate planning across jurisdictions. By combining technical expertise with stakeholder engagement, planning and outreach helps shape flood risk solutions that are inclusive, scalable, and grounded in the lived experiences of Texas communities.

TIFF aims to ensure that flood mitigation efforts are informed by the needs of both technical and non-technical stakeholders, that the results of such efforts are effectively communicated to stakeholders, and that the realities of compound flooding are appropriately considered during the planning phase. This involves integrating target user perspectives into data and modeling frameworks, refining tools to reflect community vulnerabilities, and aligning planning scenarios with regional and state-level priorities.

4.2 Why Flood Planning and Outreach Matters to Texas

Texas faces a wide range of flood risks—from coastal surge to inland flash flooding—affecting communities that vastly differ in geography, infrastructure, and vulnerability. In this context, planning and outreach becomes a cornerstone of effective flood resilience. Effective strategies ensure that technical solutions are not developed in isolation, but are shaped by the priorities and knowledge of local stakeholders.

Planning and outreach is not just about disseminating information; it is about building trust, fostering collaboration, and ensuring that flood mitigation strategies are informed by the people and places they are designed to protect. By engaging communities early and often, this approach helps create more equitable, transparent, and durable flood planning outcomes across the state.

4.3 The Guiding Objectives of TIFF Component 4

The overarching goal of TIFF Component 4 was to ensure that flood planning and mitigation needs are incorporated into data and modeling frameworks, and the findings from various efforts are well communicated to stakeholders. Achieving this goal required close collaboration between TIFF, CHARM, the RFPGs, and the GLO's RBFS Study Providers.

This effort consisted of eight objectives:

1. Establish a TAT to support Component 4
2. Coordinate with the RFPGs and stakeholders to identify flood planning and mitigation scenarios consistent with regional flood planning efforts, beginning by establishing a working relationship with RFPGs or their Coastal Liaisons to identify TIFF end-users
3. Develop and implement a comprehensive outreach plan to engage RFPGs and other stakeholders regarding flood planning and mitigation efforts. Annually reassess user needs regarding flood planning and mitigation efforts and requirements and provide the results by updating the comprehensive outreach plan and preparing an annual progress report

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A rainbow over the Gulf of Mexico as a boat passes offshore © USACE

4. Evaluate and provide feedback on the initial inventory of planning datasets (e.g., parcel data, structure characteristics, first-floor elevation, building codes, demographics) provided by GLO RBFS Study Providers
5. Perform a literature review on planning tools and develop a list of data modeling needs for planning tools
6. Support the development of flood communications and educational materials
7. Investigate the opportunities to balance local cost-effective flood risk management analysis with regional flood risk considerations
8. Make recommendations pertinent to flood planning and outreach/communication to GLO

4.4 Approach to Objectives

Efforts began by building relationships with the RFPG Coastal Liaisons, CHARM, TDIS, and the GLO's RBFSs. This sustained engagement guided the development of the TIFF Outreach Plan, a multi-year strategy emphasizing inclusivity, transparency, and strategic coordination to avoid redundancy and maximize impact within the TIFF planning project.

The TAT worked closely with Study Providers to inventory planning datasets, tools, and resources available for flood analysis and project evaluation. This inventory distinguished between resource tools, data access platforms, and planning models—each serving a unique role in defining affected areas, estimating consequences, and assessing the likelihood of achieving desired outcomes. Concurrently, TIFF conducted a review of planning tools to develop a list of data modeling needs for tools in Texas.

The TAT found that Objectives of Component 4 (Planning and Outreach) and Component 2 (Data Management and Visualization) overlap, because effectively communicating flood risk over time requires

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

an understanding of the respective target users as well as meaningful data visualizations. (See Component 2 for details about literature reviews and outreach events related to *The TIFF Communication Guidelines*.)

Notably, the TAT identified the need to bridge and communicate between project-based solutions and regional planning-scale strategies to enhance statewide planning efforts with more adaptive approaches. This insight directly informed the direction of Component 4, leading TIFF to investigate the balance between local cost-effective flood mitigation and broader regional considerations. This work underscored the importance of multidisciplinary planning frameworks capable of reconciling project specific needs with regional-scale strategies—an approach further illustrated through a case study in the LRGV, where flood risk and stormwater management, water scarcity, international interests, and socioeconomic factors intersect in uniquely complex ways. (See Objective 7 for details regarding the LRGV case study.)

Establishing cost-effective FRM initiatives that reflect both current and future conditions requires long-term partnerships, coordinated budgeting, sustained funding, and extensive consensus-building to define shared objectives. Despite the dedication of numerous entities working to address flood risk across Texas, TIFF consultations with flood planners revealed the need for a centralized coordinating entity to unify the state's flood-related efforts. In response, TIFF recommends the establishment of a Texas Flood Coordination Office (TFCO) within an existing state agency to serve as a central hub to streamline flood planning efforts, provide technical support, and foster collaboration across jurisdictions (Recommendation C4.7A: Establish a Texas Flood Coordination Office (TFCO)).

Subsequent sections describe how the work and findings under Component 4 led to TIFF recommendations to address critical gaps in communication, data integration, and alignment between local and regional planning efforts.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

ZOOMING IN: TIFF'S PRIORITY RECOMMENDATION FOR ONGOING COASTAL FLOOD PLANNING AND OUTREACH

Establish a Texas Flood Coordination Office (TFCO) (TIFF Recommendation C4.7A)

Flooding poses a persistent and growing threat to communities, infrastructure, and ecosystems across Texas. To better prepare for and respond to these challenges, state and regional flood planners need coordinated access to information, planning tools, and technical support.

Currently, multiple state and federal agencies, private and non-profit organizations, and academic institutions are engaged in efforts to raise awareness and respond to floods. However, without a centralized coordinating body, the extensive work being done often overlaps, creating redundancies, inefficiencies, and missed opportunities to leverage project outcomes.

TIFF recommends Texas legislators establish a Texas Flood Coordination Office (TFCO) within an existing state agency. The TFCO would:

- centralize and streamline flood-related efforts
- create and maintain an official statewide database of past and ongoing projects
- provide technical support to state and regional planners
- enhance collaboration among agencies, institutions, and stakeholders
- reduce redundancy and maximize the impact of state and federal investments
- formalize and expand beyond the current volunteer-based efforts

KEY OBJECTIVES OF THE TEXAS FLOOD COORDINATION OFFICE

By centralizing information and oversight, the TIFF-informed TFCO will enhance the state's ability to manage and mitigate flood risks efficiently. The TFCO will 1) centralize state and federally funded flood projects in one central body, 2) facilitate collaboration among stakeholders to build partnerships and shared solutions, 3) maintain a central archive of project outcomes and share findings with stakeholders, 4) reduce redundancy to ensure efficient use of state and federal resources, and 5) report to the Legislature on the state of flood projects and recommend improvements for flood management.

1. **Centralized Oversight of Flood Projects**: The TFCO will oversee all state and federally funded flood-related projects, ensuring that efforts are aligned, complementary, and not duplicated. The Office will maintain a central database of ongoing and completed projects (including information on scope, funding, and progress) to improve coordination and transparency. This oversight will help decision-makers allocate resources more effectively and ensure future flood projects address the state's most pressing needs.
2. **Facilitation of Collaboration**: The Office will actively encourage collaboration among state agencies, academic institutions, non-profits, and private sector organizations to promote innovation and more effective flood management. It will serve as a neutral convener, bringing stakeholders together to foster partnerships and shared solutions. This coordinated approach will help break down silos, align diverse expertise towards state goals, and lead to more efficient project implementation.
3. **Archiving and Dissemination of Findings**: All project outcomes, data, reports, and findings will be archived in a central repository managed by the TFCO. This information will be made accessible to all relevant parties, promoting transparency and knowledge sharing. The TFCO will ensure that results from projects are effectively disseminated among key stakeholders and can be leveraged in future flood mitigation efforts. By disseminating project findings, the Office will ensure that valuable insights from past projects inform future flood mitigation efforts.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

4. **Reduction of Redundancy**: Through its oversight and coordination roles, the TFCO will reduce unnecessary duplication of effort by identifying overlaps among projects and redirecting resources to unmet state needs. This leveraging of project outcomes will prevent wasted investments in repetitive research or narrowly scoped projects and inform new initiatives. This efficient use of state and federal resources will maximize the impact of available funding and ensure that flood management efforts address a broader range of needs across Texas.
5. **Legislative Reporting and Recommendations**: The TFCO will provide regular reports to the Texas Legislature that highlight the status of flood projects, identify gaps in the state's approach, and recommend improvements for flood management and response. These reports will ensure that decision-makers are equipped with up-to-date, evidence-based information. The Office will work closely with legislators, providing the latest research and field-tested solutions to help shape policies that are more responsive, effective, and sustainable in reducing flood risks statewide.

ORGANIZATIONAL STRUCTURE AND RESOURCES

The TFCO could be housed within a state agency involved in flood science, flood planning, flood funding, and floodplain management. Although the Office could be established as a separate entity, utilizing an existing agency may reduce the overhead and administrative burden. The TFCO would be staffed by a small team of experts in flood management, project coordination, and data archiving. This team would work in close collaboration with existing staff at TWDB (or other selected agency), leveraging existing resources and expertise. Initial funding for the TFCO could come from state appropriations, with additional support from federal grants or partnerships with non-profit organizations and private companies involved in flood-related efforts.

Flooding is an urgent and ongoing threat in Texas, and the current landscape of flood-related efforts is fragmented and inefficient. By establishing the TFCO, the state can enhance its flood management efforts, streamline coordination across sectors, and ensure that all projects contribute to a more resilient and prepared Texas.

4.5 Implementation of Objectives

Objective 1: Establish a Planning and Outreach TAT

To advance the goals related to planning and outreach, the TIFF SC appointed Dr. Amin Kiaghadi, Manager of the Coastal Science Department at TWDB, as the Component 4 Champion. The TAT included experts in stakeholder engagement, public communication, urban planning, and community resilience. The TAT was tasked with bridging the gap between technical modeling and community priorities to ensure that flood mitigation strategies are informed by the people and places they are designed to protect. Ultimately, the TAT served as a strategic engine for elevating flood planning across Texas, investigated local to balance local cost-effective solutions with broader regional resilience, and fostered planning frameworks built on trust, equity, and shared purpose.

The TAT worked closely with CHARM, TDIS, the RFPGs, and the GLO's RBFS Study Providers to identify key stakeholders, assess user needs, and align flood mitigation scenarios with regional planning efforts. The TAT also worked in collaboration with Component 2 (Data Management and Visualization), as data visualizations can be an impactful way to communicate flood risk to target users. To ensure Component 4 reflected the unique flood planning needs of the LRGV, TIFF invited and confirmed the membership of nine additional Technical Advisors with firsthand experience in the design and delivery of flood-related outreach and educational tools. The participation of these regional subject-matter experts helped ensure that the needs of both technical and non-technical stakeholders in LRGV are reflected in the findings and Recommendations of Component 4.

The following advisors were selected to serve as members of the Component 4 TAT based on their expertise in behavioral science, regional and community planning, and data visualization. Advisors marked with an asterisk are those LRGV-specific additions.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

.COMPONENT 4 TECHNICAL ADVISORS

- *Andrew Ernest, RATES
- Ataul Hannan, Harris Country Flood Control District
- *Augusto Sanchez, Cameron County
- Bridget Scanlon, UT-BEG
- *Britt Corley, USACE
- Caroline McCabe, USACE-SWF
- Christopher Emrich, University of Central Florida
- Daniel Arriaga, TAMU-IDRT
- Greg Waller, NWS-WGCRFC
- Hanadi Rifai, University of Houston
- *Javier Guerrero, RATES
- Jet Hays, GLO
- *Jianhong-Jennifer Ren, TAMU-Kingsville
- John Kucharski, USACE-HEC
- *Jon Thomas, USGS
- Katharine Teleki, Teleki Consulting
- Katie Landry-Guyton, NOAA
- Keri Stephens, UT-Austin
- Kiersten Stanzel, Coastal Bend Bays & Estuaries Program
- Lisa Marshall, TCEQ
- Liv Haselbach, Lamar University
- *Melisa Gonzalez, LRGVDC
- Mike Quimet, TDEM
- Reem Zoun, TWDB
- *Rick Hallman, NWS
- Rose-Marie Klee, TxDOT
- Saji Varghese, USACE
- Siddharth Saksena, Virginia Tech
- Steven Mikulencak, Texas AgriLife- CHARM
- Teal Harrison, Adaptation International
- *Tom Jester, USACE

Objective 2: Coordinate with the RFPGs and stakeholders to identify flood planning and mitigation scenarios consistent with regional flood planning efforts, beginning by establishing a working relationship with RFPGs or their Coastal Liaisons to identify TIFF end-users

TIFF incorporated a collaborative approach by engaging experts from governmental agencies, academia, and stakeholders with regional experience. To initiate a foundation for identifying target user needs and aligning with regional flood planning priorities, TIFF hosted a virtual meeting with the RFPG Coastal Liaisons with 36 participants on September 1, 2021. (See **Appendix D-1** for meeting invitation, agenda, and notes.)

The Liaisons identified and discussed many important issues that were considered during the development of the TIFF deliverables. The liaisons also expressed their willingness to be informed on TIFF milestones and to continue providing feedback to the TIFF. During the meeting, various participants shared their thoughts and concerns related to flood planning for the communities they serve and talked about the challenges, both unique to their region and/or the ones that are common across the coast, to flood planning efforts throughout the state.

Major discussion points included:

- Regional and local flood planning decisions made by groups upstream often cause challenges for downstream groups; Guidance for how to integrate or complement these upstream decisions into downstream flood planning efforts is needed
- Redundancy and duplication in flood planning efforts must be minimized; Avoiding these pitfalls requires careful documentation and cataloging of flood planning activities throughout the state, as well as building relationships at local, regional, state, and federal levels

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

- Isolated and rural communities struggle to receive financial or planning assistance from state or federal sources, often due to the complex application process for grants, and the lack of resources available to those communities

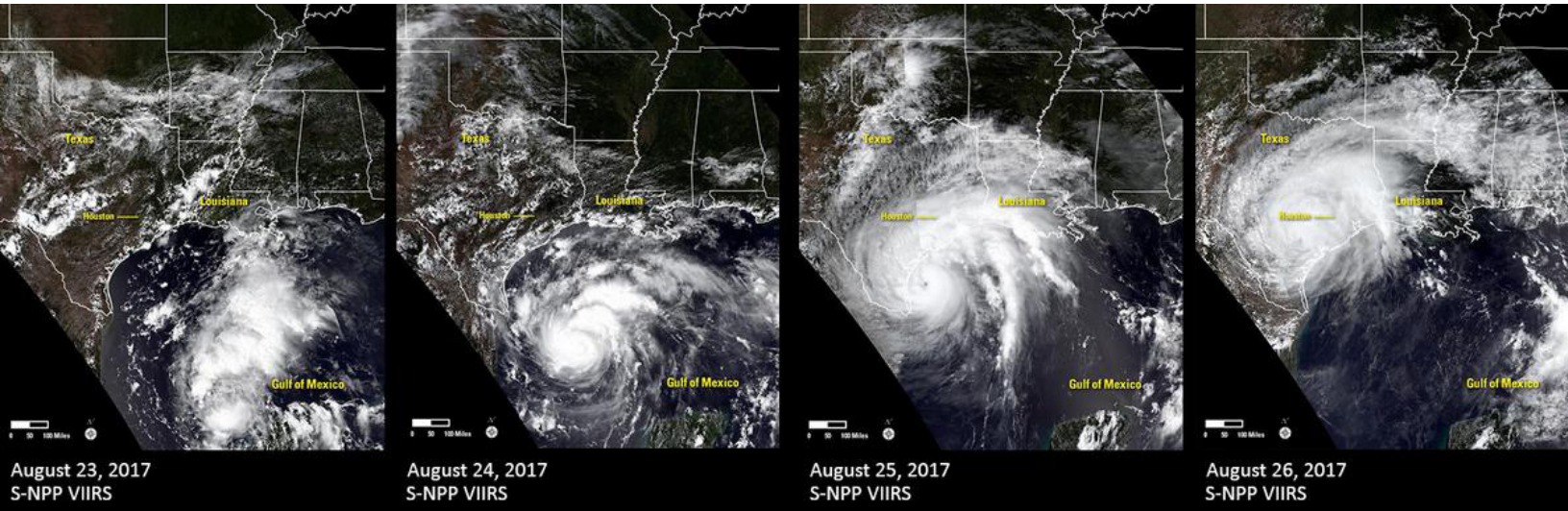
The dialogue revealed a critical need to better understand the broader impacts of local and regional flood planning efforts, particularly the upstream/downstream dynamics and interactions across adjacent watersheds. This insight directly informed the direction of Component 4 and informed the creation of Objective 7, which focuses on investigating opportunities to bridge and communicate between project-based solutions and regional planning-scale strategies. Notably, this is a highly complex and challenging topic, especially when considering the implications of compound flooding where multiple flood drivers interact. The nonlinear consequences of such events can significantly alter both the planning phase and the effectiveness of solutions at different scales. These dynamics underscore the need for deeper understanding and more adaptive approaches, which will be discussed further in subsequent sections. More research is required in this domain to successfully add coordination and impact evaluations into planning matrices.

This engagement marked the beginning of a long-term relationship aimed at integrating local insights into the development of flood planning and mitigation scenarios consistent with broader regional efforts. Several participants from this initial meeting later joined the TAT, further strengthening the connection between regional expertise and the technical direction of the TIFF project.

Objective 3: Develop and implement a comprehensive outreach plan to engage the RFPGs and other stakeholders regarding flood planning and mitigation efforts, reassessing user needs annually regarding flood planning and mitigation efforts and requirements, and providing the results by updating the comprehensive outreach plan and preparing an annual progress report

TIFF developed an Outreach Plan to be applied to the project process. This multi-year plan was refined through ongoing collaboration with the TAT (**Appendices D-2** and **D-3**). The approach was designed to serve both technical and non-technical stakeholders, emphasizing inclusivity and strategic alignment.

The TIFF Outreach Plan outlined the following process elements that would define the TIFF project: expert collaboration; an inclusive bottom-up approach; an inclusive and transparent scientific approach; and a commitment to avoiding redundancy (Figure 4-1). These elements were designed to ensure TIFF would create useful and reliable guidelines, standards, Recommendations and related products relevant to both technical and non-technical target users. (See **Appendix D-4** for more on the Outreach Plan.)



Satellite progression of Hurricane Harvey as it made landfall on the Texas Gulf Coast © USGS/NASA

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Figure 4-1. The TIFF Star shows the five major elements of trust for building a reliable brand among the selected target users.

EXPERT COLLABORATION

The ultimate goal of TIFF is the pioneering of a new collaborative effort to address compound flooding impacts in Texas and establishing the TIFF project as a benchmark for future efforts in this field. The state and federal agencies that support the TIFF efforts are recognized leaders in flood science, planning, and mitigation (e.g., GLO, USACE, USGS, TWDB) and have a strong history of partnering with state and local organizations to improve the safety and lives of the communities they serve. TIFF collaborated with experts in the field of coastal flooding and engaged specialists across multiple disciplines to leverage key knowledge, incorporate target user feedback, and ensure the development of valued and relevant TIFF products. The TAT members (100+ advisors among the four components) are well-known experts in various aspects of coastal flooding including data monitoring, data management and visualization, modeling, planning, and outreach. TIFF interacted with technical target users through interactive meeting opportunities and other direct forms of communication (e.g., surveys, workgroups, emails). Figure 4-1 lays out the general execution approach used by TIFF to execute all TIFF project efforts and shows where in the process the TATs will be consulted for feedback.

INCLUSIVE BOTTOM-UP APPROACH

It is well established that the engagement of target users in the creation of any new product or idea will lead to a higher likelihood of the use of new products once they are available to a community at large. The early engagement and inclusion of target users in development of project deliverables is one way to build trust among technical and non-technical target user groups. TIFF sought to connect with non-technical target users through leveraged assistance from existing agency programs already engaged with these communities on similar topics. Once perspectives were collected, the process of creating solutions in the form of guidelines and Recommendations to meet target user needs progressed. TIFF worked closely with Study Providers from the Moody College of Communication at UT-Austin to conduct surveys and interviews with technical advisors, and representative members of target user groups. The research gathered valuable feedback on user needs, concerns, and priorities, which was incorporated into the development of TIFF products, guidelines, and recommendations, as discussed in more detail in Selected Prioritized Target User Groups.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

SCIENTIFIC APPROACH, INCLUSION AND TRANSPARENCY

As mentioned earlier, the SC was comprised of individuals and agencies that have made valuable contributions to the field of flood science and are committed to using a sound scientific approach to develop recommendations that will be useful to target users. Additional expert collaboration in all four components of the TIFF planning project ensured that the guidelines, Recommendations, and all related TIFF products were created through a holistic scientific approach.

To create useful products, it was imperative to first understand the needs of those target users that will use the product in future applications. To this end, the SC looked to include input at all possible target user levels (through direct and indirect outreach) and to consider feedback on the needs of both technical and non-technical target users in the development of TIFF guidelines, recommendations, and related products. Inclusion of the perspectives and needs of target users will ensure that the TIFF products are useful, helpful, and trusted by the communities they are intended to assist. The project remained committed to transparency made final products available to the public via the project webpages (https://www.glo.texas.gov/disaster-recovery/planning-studies and https://tiff.texasflood.org/) and project data through TDIS and the CDS.

AVOID REDUNDANCY

TIFF was committed to avoiding redundancy and duplicative efforts as a key to creating useful and relevant products. Through an extensive effort to communicate with project managers across Texas about planned and ongoing flood related data and model driven projects, TIFF cataloged many important projects related to flood preparedness in Texas (**Appendix C-12**). This inventory of statewide projects was initially developed through discussions with the TATs and further refined from meetings with various stakeholders. Meetings included The Texas Flood Organizing Group, Galveston Bay Council, Southeast Texas Flood Coordination Study, and GLO's RBFS. The intention was to enhance the inventory into a publicly accessible database through methods that will be further developed. The existence of a comprehensive database to reference flood science projects that are currently ongoing or completed will significantly improve efforts to avoid project redundancy and provide target users with a helpful comprehensive project overview.

UPDATES AND OUTCOMES OF THE OUTREACH PLAN

To fulfill the goals of this objective, TIFF developed and implemented a comprehensive outreach strategy that engaged regional planning groups, technical experts, and non-technical stakeholders throughout the duration of the project. This strategy was continuously refined through annual reassessments of user needs and feedback mechanisms, ensuring that outreach efforts remained responsive, inclusive, and effective.

(See **Appendix D-4** for more information related to the Outreach Plan and the selected target users.)

Objective 4: Evaluate and provide feedback on the initial inventory of planning datasets provided by the GLO Regional Flood Study Groups

Planning datasets include a range of local and regional flood risk data often used to develop flood models, conduct risk assessments, and evaluate potential flood mitigation projects and solutions. These datasets not only require the collection of meaningful data to support future mitigation efforts but must also be carefully organized and managed for effective storing and sharing.

To evaluate and provide feedback on the initial inventory of planning datasets, TIFF leveraged the CDS web application developed under Component 1. The CDS is an inventory and data gap analysis tool used to centralize coastal flood-related data for planning and mitigation. Development involved careful classification of datasets to carry out an interactive assessment of key planning datasets (e.g., parcel boundaries, structure characteristics, first-floor elevations, building codes, demographic indicators) by

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

integrating them into a centralized, user-friendly interface. The CDS streamlined data exploration and gap identification and laid the groundwork for improved flood modeling, planning, and collaboration to ensure that coastal communities are better equipped to prepare for and respond to future flood events.

As part of this effort, and to support state flood risk reduction decision-making, TIFF undertook a targeted inventory analysis of existing planning tools used by federal, state, and local agencies in flood risk reduction efforts. The goal was to assess how these planning models evaluate and compare the performance of flood mitigation alternatives, and to identify opportunities for aligning H&H model outputs with planning support needs. This approach supported both the evaluation of the initial dataset inventory and the following objective of reviewing planning tools and developing a list of data modeling needs.

THE PLANNING MODEL INVENTORY

The full inventory of planning and economic tools, models, and resources are in **Appendix D-5**, while relevant H&H modeling resources are discussed in **Appendix C-5**.

The inventory was populated by a combination of outreach, review of planning tools, and existing database integration. Numerous models and tools have been developed by the USACE to support flood risk reduction and were catalogued in collaboration with coastal flood modeling engineers. In addition to these USACE models and tools, several resources have been developed by state and federal agencies, universities, and consultants. These resources were catalogued through meetings and discussions with flood planners and scientists and leveraged from existing model and/or publication databases.

This effort focused on cataloging tools based on their purpose, applications, data requirements, limitations, key takeaways, and publicly available resources or websites (see Table 4-1 for a sample). The inventory categorizes available resources into data access tools, area-specific resources, and planning models. Data tools provide information on area characteristics and future scenarios to support alternative development and identification of affected zones, while planning models estimate the consequences of specific alternatives and assess the likelihood of achieving desired outcomes.

Table 4-1. Planning model inventory example: HEC's Flood Damage Reduction Analysis.

Attribute	Description
Main Purpose	Conducts integrated hydrologic engineering and economic analysis of flood risk management plans using risk analysis procedures for formulating and evaluating flood risk management measures
Applications	This model is appropriate for evaluation of performance of a non-erodible, solid feature, such as a wall or levee. The software 1) stores hydrologic and economic data necessary for an analysis, 2) provides tools to visualize data and results, 3) computes expected annual damage and equivalent annual damages, 4) computes assurance of annual exceedance probability and as required for National Flood Insurance Program Accreditation Recommendation, and 5) implements the risk analysis procedures described in EM 1110-2-1619.
Data Needs	H&H profiles of water depth for 8 flood frequencies (2-yr, 5-yr...500-yr) flood events and study reaches and index points Structure inventory that details types, condition, elevation, size and location of assets, Depreciated Replacement Cost Estimate Geographic extent of study area
Limitations	This model is appropriate for evaluation of performance of a non-erodible, solid feature, such as a wall or levee. Analysis relies on an events-based evaluation framework
Takeaway	This is an approved tool for USACE project that supports in depth feasibility studies.
Website	https://www.hec.usace.army.mil/software/hec-fda/

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Objective 5: Perform a literature review on planning tools and develop a list of data modeling needs for planning tools

TIFF performed a review of planning tools by identifying practical applications and technical considerations to develop a list of data modeling needs in Texas. The review was conducted in collaboration with coastal flood modeling engineers and planners, ensuring that technical insights were grounded in practical planning contexts, and aimed to align H&H model outputs with planning needs.

This TIFF review encompasses:

- implications of compound flood events on planning efforts
- the mechanics of consequence modeling, the value in calculating consequences, and risk driven by compound flooding
- the planning formulation process, including subtopics such as problem identification, alternative evaluation, approved economic models, and benefit categories
- how compound risk can be incorporated into planning frameworks

Through this process, TIFF identified several critical opportunities to enhance planning decisions by integrating compound flood risk modeling. Compound flood model outputs must be formatted consistently to integrate effectively with planning models. The interface between flood planners and modelers is critical during model design, where underlying assumptions shape the relevance and applicability of outputs. Future agency coordination should ensure the inventory reflects the types of planning decisions and models in use.

The review identified opportunities to enhance planning through compound flood modeling by:

1. Improving problem identification by better accounting for all flood sources and ensuring model boundaries encompass the full area of impact
2. Addressing life safety risks through considerations for how timing, duration, and extent of flooding from multiple sources affect safety outcomes
3. Defining comprehensive benefit measurements to better quantify the community and economic impacts of flooding (including effect on income, mobility, access, and property value)
4. The summarized findings of this review are presented in the sections below. (See **Appendix D-7** for detailed information.)

KEY LESSON LEARNED FROM LITERATURE REVIEW

Planning for Compound Flood Events: Flooding in coastal and riverine areas does not always stem from a single, isolated hazard. In many systems, compound flooding, the convergence of different flood drivers such as storm surge, riverine flows, and intense rainfall, can produce inundation depths that exceed those from individual events. These overlapping processes become particularly significant in areas where inland flooding meets coastal tides or storm surge, known as transition zones. Traditional methods of evaluating flood risk often focus on either riverine or coastal hazards independently, potentially underestimating the true extent of flood exposure. Thoroughly modeling compound flooding improves understanding of where and when higher flood levels may occur, offering vital insights for planning, design, and policy decisions. From both an economic and engineering standpoint, accurately capturing these overlapping hazards is crucial for effectively diagnosing and evaluating the overall hazard. If economic models (and subsequent analyses) that estimate consequences of flooding fail to account for and reflect the extra water contributed by another flood source, several serious risks may arise, such as inaccurately capturing damages, inaccurately defining the extent of the flood vulnerability, and misinforming communities of the overall life safety hazard.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Consequence Modeling: Economic models estimate flood consequences by combining H&H output, such as flood depth and extent of inundation, with damageable assets in the study area. Each agency applies its own procedures to define benefits and quantify damage reduction from proposed solutions, with the level of modeling rigor often reflecting the significance of the decision and agency priorities. Any consideration of how to best account for compound flood risk within models requires an understanding of how risk is estimated within the models. An integrated approach that accounts for different types of events, along with their associated probabilities, is needed. In general, there are two main ways to account for compound flooding: 1) a stepwise (sequential) approach, and 2) a simultaneous (joint) analysis. A stepwise (sequential) approach is straightforward and avoids double counting of damages from two events which may not have occurred independently. However, a stepwise analysis does not capture what happens if the water surfaces from each source combine to produce even deeper flooding in certain areas, and therefore, does not include the maximum damage. Another alternative would be to sum the damages or to pick a value in between the maximum from one and the summed damages. Each solution has an issue. Using the maximum will undercount damages; using the summed value will overcount damages; and selecting a value between the two is likely to be arbitrary. Alternatively, a simultaneous analysis seeks to combine the multiple sources of flooding into a single hazard event. Simultaneous analysis will likely provide a better representation of the compound hazard, in that it explicitly captures the interplay of water from multiple sources. This may demonstrate higher calculable damages in transition zones, potentially shifting the alternatives that are considered and selected, and may also show the need for more robust, comprehensive measures.

Incomplete Compound Flood Representation in Flood Planning: Planning decisions are made by comparing the overall performance of potential alternatives against relevant metrics to identify the best action (applications obviously differ across the types of decisions to be made and the agency authority). If the modeling results misdiagnose the initial flood risk or the expected risk reduction of one or more alternatives, the ramifications of that decision may be more serious than time and funds spent on the analysis. Structural FRM solutions are typically justified by balancing study objectives with cost-effective design and scale of conveyance or detention features. Compound flood modeling supports more informed planning decisions with a more accurate portrayal of when and where higher flood levels can occur, and provides critical insights for planning, design, and policy decisions. If comparisons are made with an inaccurate depiction of the flood hazard, it may only justify a scale or design that is based on underestimated consequences. Smaller features may perform less reliably in practice and may not provide the level of protection to property and life safety than was expected. The risk is multiplied if land use decisions increase the investment in the area under the expectation that flood risk has been managed for current and future conditions. Contributing factors to the decision risk include inaccurately capturing benefits, limited geographic boundaries and regional interventions, and understated real-world risk to those that live and work in a given project area.

Planning Applications: Planning applications can be considered in two broad categories to assess the intersection of the compound flood modeling framework:

- Technical Analysis – The technical analysis category includes the planning steps that apply H&H model outputs to study area conditions to characterize flood risk and consequences, develop potential solutions, and support flood risk management plan comparisons. State, regional, or local agencies conduct planning studies in cooperation with federal agencies or may develop flood studies, plans for funding, or coordination with relevant funding sources to establish and address regional flood priorities. This category of analyses compares the necessary model inputs to ensure compatibility of planning tools with new H&H output data and where compound flood model outputs can better support planning decisions. These analyses are the "plan formulation" efforts of the USACE or other federal agencies, such as FEMA and HUD. These efforts typically follow standard processes to ensure consistent and fair evaluation and comparison of potential FRM/CSRM projects. (See **Appendices D-5** and **C-15** for more information.)

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

- Target User Considerations – This category reflects the broader consideration of target users who incorporate flood risk considerations in various policy decisions, such as infrastructure investment, land use, public safety, insurance, and more. Target user considerations informs data development and supports the inclusion of compound flood risk in multiple contexts. Outreach efforts will seek an understanding of existing target users to improve the type of information that can support current planning decisions and expand consideration of flood risk across multiple applications.

Planning Formulation and Evaluation: Planners conduct technical plan formulation efforts with methods to support the comparison of alternative performance and selection. Performance assessment methods differ in overall function and specificity across agencies based on the project authority, funding source or program, and the scale of the proposed project. Planners supporting plan formulation within a flood risk study combine H&H model outputs with study area conditions to produce relevant information to support the plan formulation phases, including:

- Problem Identification and Preliminary Alternative Formulation – Identifying the water resources problem to be solved is a critical first step in formulating and defending a flood risk management project. A key aspect of the problem identification phase is to characterize the flood risk mechanism with sufficient detail to recognize the actual risk mechanism and not a symptom of the flood risk. The baseline condition combines H&H and physical conditions to define the flood risk exposure of study area assets, populations, and physical conditions, and diagnose applicable risk mechanisms. The problem identification step is an opportunity for the modelers and planners to clarify whether compound flood modeling is necessary for the study. A compound flood risk modeling system will support a thorough definition of the applicable risks and their interrelationship. The relative impact of coastal flooding may dominate inland flooding contributions (or vice versa), and a complex model may only be necessary for some study areas. To support Texas state flood planning proposals over time, future detailed modeling studies are needed to identify the criteria and areas where tidally influenced waterways (whether now or in projected future conditions), significant riverine flood heights, or physical conditions warrant the additional time and specificity of compound flood modeling. Until those detailed modeling studies are performed, planning for modeling coastal floods may consider the following three sources of coastal flood extents for the Texas coast as an initial estimate of the extent of regions to investigate compound flooding:
    - CTXCS ADCIRC model domain (Melby et al, 2021)
    - FEMA 0.2% AEP coastal limit of inundation (FEMA, 2011)
    - NOAA Maximum of the Maximum (MOM) Envelope of High Water based on the Sea, Lake, and Overland Surges for Hurricanes (SLOSH) hurricane modeling
- Alternative Performance Evaluation – Although models and analyses differ across agencies and authorities, all flood risk studies will combine the H&H model outputs with a structure inventory of damageable resources and assets in the study area to quantify baseline damages in the existing and future without project conditions. **Appendix D-5** lists the most frequently used planning models. USACE studies require approved models to translate the H&H conditions in the study area into quantified consequences by integrating the H&H conditions with an inventory of assets, such as structures, contents, and other infrastructure. The economic models that complete this analysis vary based on several characteristics, which include the flood risk mechanism, the function of the structure proposed to manage the flood risk, and the physical conditions in the study area. (See **Appendix D-7** for a description of approved economic models used in USACE studies.)
- Cost Benefit Analysis – Cost benefit analysis is the most common way to measure the performance of flood risk management. It quantifies the flood damage reduction in dollars to structures and contents in the study area. Cost-effectiveness is reflected by the benefit-to-cost ratio and net benefits, which demonstrate whether anticipated benefits from the alternative are greater than the implementation

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

cost. Benefit categories reflect agency priorities and include fundamental benefits measured in dollars and non-dollar-denominated metrics. Plan performance and cost-effectiveness are measured with dollar-denominated benefits with the same planning and H&H tools applied to characterize the flood risk problem. Benefit categories represent monetary and non-monetary beneficial outputs of alternative plans. Additional metrics are applied to capture broader benefits categories, quantified in dollars or other units, or qualitative comparisons of effectiveness. Agencies evaluate proposed flood risk management projects against different benefit standards based on the applicable authority and funding source. Therefore, benefit types across different agencies may capture similar effects but with slightly different definitions and guidance for tabulation. The current emphasis within the USACE and multiple agencies presents an opportunity to define additional metrics to assess broader agency and societal objectives. TIFF outreach included an interagency workshop (**Appendix D-6**) to clarify shared evaluation criteria and explore additional impacts informed by more detailed H&H model outputs.

- Integrating Planning Tools into the TxCFF – The first focus of evaluating the integration of planning tools into the framework was to confirm that the H&H model output would be compatible with continued application of most agencies existing planning and economic models. In other words, any H&H output for compound flooding that improves the specificity of flood risk information can only improve the study outcome if it is clearly understood and compatible with the existing planning tools and models. If the output is produced in new or different units or formats, it would not readily support planning and economic analysis since it would not be compatible with the existing planning tools and models. Consultation with H&H modelers clarified that the compound flood modeling system output format would not differ from the current H&H modeling (e.g., rainfall, rivers, ocean) output format. The H&H output will reflect the flood risk from compound events but will be ready for import into the planning models in the necessary format, and compatibility is not a concern. Rather, the assumptions underlying the H&H model development will reflect the additional aspects of compound flood risk in the analysis. The H&H model design will require collaboration between the planner and the hydraulic modelers to reflect the appropriate boundary conditions and the H&H conditions that produce the best H&H output to support the planning considerations. Customizing the H&H model design presents an opportunity to base decisions on the most applicable hydraulic and hydrologic conditions that will require exploration of the types of decisions that planners make in different flood studies across different agencies.

Objective 6: Support the development of flood communications and educational materials

While identifying effective strategies for communicating flood risk to target users, the Study Providers and TAT members found that objectives of Component 2 (Data Management and Visualization) and Component 4 (Planning and Outreach) overlap. Flood communication efforts to meet this objective were conducted jointly by Components 2 and 4, and the resulting recommendations work together and build upon each other.

Together, these components developed *The TIFF Communication Guidelines* (**Appendix B-1**). The Guidelines document clear objectives for the design of information tools and communication approaches that inform flood risk decisions. The goal was to incorporate real-world perspectives into outreach efforts to support both technical and non-technical user needs from the outset. This integrated approach ensures that flood risk information is not only scientifically accurate but also accessible, actionable, and tailored to the communities it aims to serve.

Accordingly, the conclusions of this Objective are presented under Component 2 Objective 4 (focused on recommending guidelines for coastal flood UIs).

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Objective 7: Investigate the opportunities to balance local cost-effective flood risk management analysis with regional flood risk considerations

Access to accurate and understandable information about compound floods is crucial for making informed flood risk planning decisions. It helps to broaden the understanding of the model output, provides valuable insights for planners and agencies responsible for managing flood risks, enhances existing planning tools, minimizes residual risk, and advances research. Yet, understanding compound flooding is challenging because of the simultaneous occurrence of multiple flood hazards, often in close succession, and their combined impacts on the Texas coastal zone.

Compound flooding amplifies the consequences of flood events and introduces nonlinear impacts that complicate both the planning phase and the effectiveness of mitigation strategies. This complexity is further heightened when trying to reconcile project-specific interventions with regional-scale solutions, each presenting distinct tradeoffs in terms of cost, feasibility, and long-term resilience. While project-specific outcomes may offer timely relief in constrained areas, regional approaches can layer mitigation strategies, reduce inundation across broader footprints, support critical infrastructure, and potentially reduce the overall cost at larger spatial scales. However, regional solutions often require extensive coordination, consensus-building, and shared investment across jurisdictions.

This insight directly informed the direction of Component 4, leading TIFF to investigate the balance between local cost-effective flood risk management and broader regional considerations. For example, TIFF hosted a Compound Flood Planning Decision Support Workshop with 16 participants on April 18, 2024. The purpose of the workshop was to 1) evaluate existing decision-support tools and models currently used in flood risk management studies or planning decisions, and 2) identify the needs related to H&H model outputs for Compound Risk Analysis. This group helped to identify planning decision needs and information gaps, recommended strategies to address these challenges, and emphasized collaboration among practitioners and researchers working on flood risk planning decisions. (See **Appendix D-6** for additional details.)

In addition to the workshop, the Component 4 TAT asked TIFF to examine current flood risk management programs, FRM policy opportunities, the benefits of local versus regional project scales, and the decision support tools available for FRM. These findings further support the need for the type of enhanced local and regional coordination that could be provided by the TFCO (Recommendation C4.7A).

CURRENT FLOOD RISK MANAGEMENT PROGRAMS

While Texas agencies have long partnered with federal entities to fund and advance flood risk management programs, the Texas Legislature established the first statewide regional flood program in 2019, following the aftermath of Hurricane Harvey, to be administered by TWDB. The program adopts a bottom-up approach by convening 15 Regional Flood Planning Groups to develop regional flood plans that collectively inform the Texas State Flood Plan, updated every five years (TWDB 2024).

Concurrently, the GLO launched the RBFS, a one-time, CDBG-funded effort that provides detailed risk information and mitigation strategies for 49 counties. RBFS delivers modeling and technical support for region-specific project development, supports implementation through authorities such as USACE, and ensures proposals meet agency standards to maximize the potential for advancement. The data and analyses produced through RBFS supports the Texas State Flood Plan and is hosted within TDIS through an accessible online dashboard, alongside other critical flood risk information for the state.

Together, these programs illustrate Texas' transition to a coordinated statewide strategy that strengthens a regional focus. TIFF's review of the current planning processes, partnerships, and recommended solutions highlights opportunities to further enhance this system and better balance local, cost-effective flood risk analysis with broader regional considerations.

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FLOOD RISK MANAGEMENT POLICY DEVELOPMENT OPPORTUNITIES

After evaluating the targeted coordination and outreach efforts conducted by current flood risk management programs in Texas, TIFF identified opportunities for larger FRM policy development. Opportunities exist to:

1. **Refine risk considerations across agencies to improve infrastructure siting and decisions including site selection, design, and resilience planning**

   The state flood planning program and other flood mitigation efforts may not be limited to specific business lines that confine the focus of federal participation and funding. Within the agencies implementing FRM solutions, policy considerations should include broadening study authorization types, refining cost share decisions, and funding appropriations. For example, many federal projects only address flooding along the main stem of a bayou and could leave residual risk in tributaries or risk related to unaddressed pluvial flooding. While several federal projects have successfully reduced flood damage, many areas remain vulnerable to multiple hazards. A coordinated evaluation of the latest data will identify priority locations for interagency efforts to address compound flooding from riverine and coastal risk, and where pluvial and riverine flooding coexist.

2. **Expand awareness of risk exposure and residual risk where projects have been implemented via emergency planning strategies, such as evacuation advisories, pre-storm preparation, resource positioning to support response, and post-event recovery**

   When it comes to identifying and communicating flood hazards, a primary method is the use of floodplain delineations on flood insurance rate maps (FIRMs). While FIRMS represent coastal and fluvial hazards, they do not include pluvial hazards. This is concerning because some areas are exposed to multiple flood sources. Additionally, while FIRMs are a useful tool, they are based on models with embedded assumptions. They present a single base flood elevation associated with the 1% ACE event, but there is a range of potential outcomes for a rainfall event. Flood inundation during a rainfall event depends on various hydrologic and hydraulic conditions which can vary. Furthermore, most strategies are necessarily backward-looking and ingest observed information. The duration of the observational record and the nature of the observations impact the accuracy of the statistical rainfall or flow estimates. Future communication strategies must develop tools and methods to effectively describe risk associated with flood hazards, potential insurance needs, and costs of flood risk.

3. **Characterize specific sources of flood hazard and associated risk using compound flooding analysis**

   Compound flooding analysis can improve larger policy considerations of flood risk. Compound flooding rarely respects administrative or hydrologic boundaries; in many cases, the confluence of surge and river flows can push flooding well beyond the immediate coastline or the typical floodplain. If planning focuses narrowly on one hazard in a localized area, broader solutions (e.g., upstream detention areas, integrated levee systems that extend to coastal barriers, regional water management strategies) might be overlooked. This also means that opportunities for larger regional management measures may be overlooked, such as partnerships between cities or counties. Missing these solutions not only impedes comprehensive flood mitigation but may also increase costs over the long term by requiring piecemeal fixes for compound flooding after the fact. By recognizing and mapping where overlapping flood sources are likely, planners can identify a more expansive set of opportunities for reducing risk across wider geographic extents. A thorough compound flood analysis forces communities, state agencies, federal entities, and other stakeholders to consider how floodwaters move across geographic and administrative boundaries.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

REGIONAL VERSUS PROJECT-SPECIFIC CONSIDERATIONS

Flood risk frequently manifests most acutely in geographically constrained areas where water accumulation or flow restriction becomes pronounced (e.g., topographic low points, narrow river passages). These localized vulnerabilities may appear straightforward to address through targeted interventions, such as enhancing channel conveyance capacity or implementing diversion strategies to protect critical assets. However, regional approaches, which evaluate solutions within a larger area (e.g., a watershed versus a more discrete area like a specific stretch of river, tributary, or confluence) may be more cost-effective than localized approaches by considering all sources of water and combining multiple strategies to reducing flood risk.

Evaluating and proposing FRM solutions traditionally centers on identifying a cost-effective feature and scale that will perform under a certain range of statistically likely events for the study area. Cost-effectiveness is typically assessed via cost benefit analysis, including construction, real estate, and operation and maintenance costs of the proposal to the expected economic benefits of its operation (typically flood damage reduction benefits). With the project in place, the largest component of economic benefits accrues as estimated reductions in flood damage and other losses. However, the pursuit of a cost-effective project can often result in the selection of a smaller project area with dense development that can produce benefits that exceed the construction and operation cost of the structure. As a result, the traditional comparison of alternative solutions may overlook regional approaches to reduce flood risk. Likewise, regional consequences of flood risk can impact individual and economic circumstances that are not easily captured in a typical cost benefit analysis.

Recent statewide and regional flood planning initiatives such as those led by TWDB and GLO illustrate the value of expanding FRM evaluations beyond local boundaries. Requirements to avoid negative downstream impacts and the inclusion of drainage issues in the State Flood Plan encourage the consideration of watershed scale conveyance, detention, and integrated structural and natural features (some of which may provide additional benefits such as reduced erosion and wave attenuation). These regional perspectives help identify solutions that address multiple flood drivers—pluvial, fluvial, coastal, and groundwater—and better capture the consequences of compound flooding, which often transcends administrative and hydrologic boundaries.

Regional approaches can also reveal system level benefits that localized projects may miss. By reducing inundation across a broader area, regional solutions can preserve evacuation routes, maintain economic activity, and support long term community resilience. Layered systems of measures, such as upstream detention, integrated levee and coastal barrier systems, or regional water management strategies, can adapt more effectively to changing conditions and increasing flood risk. In some cases, regional projects also allow cost sharing across jurisdictions or agencies, reducing the economic burden on flood prone communities or subdivisions. (See Objective 6 for additional information on the estimation of consequences of compound flooding as it provides additional insights in evaluating FRM solutions with the larger consideration of regional risk and impacts.)

While regional solutions offer the potential for broad-scale impact and can be more cost-effective in the long term, they often require compromise, coordinated budgeting, sustained funding, and relocation logistics. Achieving alignment across jurisdictions demands extensive consensus-building to define shared objectives and clarify problem statements, particularly when structural measures (e.g., walls, culverts, overflow areas) span multiple boundaries and introduce complexity in feature design, and cost-sharing. These collaborative efforts can also result in uneven distribution of aesthetic impacts, dislocation, or real estate acquisition requirements. To address these challenges, adaptive strategies (e.g., phased buyouts, incremental elevation of protective features, staged implementation) can help mitigate initial disruptions. Over time, these actions support lower-risk community growth while preserving the integrity and scalability of regional flood mitigation efforts.

Each geographic location and flood source presents distinct challenges, requiring tailored approaches to flood risk reduction. The tradeoffs between regional and local-scale solutions should be carefully evaluat-

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ed throughout key stages of the flood study process—including problem characterization, alternative development and screening, and assessment of potential impacts. No study area or hazard is identical, and the appropriate scale of intervention will depend on a range of factors, including hydrologic complexity, community priorities, and long-term resilience goals. Larger study areas may support extended periods of analysis and accommodate greater variability in flood risk over time, particularly as storm intensity and frequency increase. In contrast, localized solutions may offer timely protection and help preserve critical assets, though they must be considered within the broader context to ensure compatibility with regional strategies and future adaptation needs.

To balance local cost effectiveness with regional considerations, flood studies should be scoped with a clear understanding of surrounding land uses, flood sources, interconnected hazards, and potential downstream effects under multiple conditions. Multidisciplinary teams should evaluate alternatives across multiple spatial scales, ensuring that localized interventions do not inadvertently increase risk to neighboring areas. To support this effort, TIFF recommends that future agency coordination efforts should include a standardized requirement for all funded flood-related projects to submit three critical shapefiles (location, scope, and impact area) to the funding agency and other relevant recipients (See Recommendation C2.3E: Standardize Grantee Shapefiles). Additionally, TIFF also recommends the establishment of a Texas Flood Coordination Office within an existing state agency to centralize flood efforts, reduce redundancy, and optimize state and federal project impact beyond current volunteer-based efforts (Recommendation C4.7A: Establish a Texas Flood Coordination Office).

FLOOD RISK MANAGEMENT DECISION SUPPORT TOOLS

Developing cost effective FRM projects that reflect both current and future conditions requires tools that help communities evaluate the full range of relevant flood drivers. While no study can feasibly model every surrounding interaction within typical schedules or budgets, existing engineering and economic resources can still meaningfully inform investment decisions.

Understanding flood hazards begins with assessing how multiple flood sources interact. In many cases, H&H modeling will show that one damage driver dominates, reducing the need for full compound flood simulations. However, secondary drivers can exacerbate impacts and should not be underemphasized, particularly in transition zones where coastal and riverine processes overlap. These zones vary widely across watersheds due to local physical characteristics, and recent analyses show that compound effects can extend farther inland than expected. This may be due to lack of drainage capability, where the water cannot flow out of the receiving body/ocean during a coastal storm event. While transition zones are important considerations, they must be evaluated within the larger context of interacting flood processes.

Evolving modeling tools can help planners evaluate multiple flood sources more efficiently. The CHART model, under development by the USACE, aims to provide modular, or scalable, applications of H&H modeling and economic analysis that adjust in complexity across FRM study phases. Once operational, the H&H module will provide data that supports the economic evaluation of planning considerations, including expected flood damages with detailed consideration of depth and timing of inundation, and life safety risks, by characterizing flow depth, direction, and velocity. Once complete, CHART will combine engineering and economic analysis, and improve the efficiency of data collection, input, and model setup of FRM studies.

While CHART will be in development for several years, this model, or a similar interface, could assist communities to better understand the surrounding and interrelated flood hazards at the beginning of a flood study. In the meantime, a standardized checklist should be developed and adopted to support consistent, scalable, and context-sensitive flood modeling for H&H modelers and economists. This checklist would guide model design based on study location and dominant flood sources and use GIS shapefiles and bivariate analysis to ensure thorough assessment of data needs and hazard complexity.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

CASE STUDY: OPPORTUNITIES TO BALANCE AND COMMUNICATE BETWEEN PROJECT-BASED AND REGIONAL PLANNING SCALE SOLUTIONS IN THE LRGV

Component 4 conducted additional targeted research specific to the LRGV to improve the planning and outreach efforts in the region. The geographic and flood management complexities in the LRGV necessitate integrative flood planning approaches to mitigate flood risk in this unique and growing area. In particular, TIFF recommends formalizing cooperative agreements between regional stakeholders to support long-term flood risk management and planning. (See Recommendation C4.7C and **Appendix D-8** for more information.)

When conducting FRM planning processes in the LRGV, key considerations include:

- **Transboundary Coordination**: International boundaries necessitate close collaboration with Mexico on watershed-wide management. Political sensitivities, treaty obligations (e.g., 1944 Water Treaty), and historical adherence to established commitments must be carefully considered for a comprehensive (multi-use) regional water resource plan to be effective. TIFF suggests the use of existing IBWC channels to 1) further foster relationships with Mexican scientists and engineers to improve communication, cooperation, and data sharing, and 2) implement consistent modeling and regulatory standards across the river. Coordinated planning with Mexico might involve:
  - Developing joint H&H (hydrologic, hydraulic, and coastal surge) models utilizing shared data
  - Enhancing infrastructure project communications to better coordinate reservoir operations
  - Identifying, creating, or otherwise utilizing a centralized database containing geographic data and information on flood hazards, infrastructure, land use, and environmental resources to support informed FRM decision-making, such as the geoportal hosted by the International Spatial Technology and Research Lab (https://www.istar.igg.unam.mx/lab/geoportal-about)
- **Socioeconomic Factors**: The region has a diverse population with varying levels of vulnerability to flooding and ability to recover from extreme events. Socioeconomically disadvantaged urban and rural communities—and potential language barriers—may require creative approaches to ensure FRM measures are available in high-risk communities.
- **Water Rights & Water Supply**: The region's arid/semi-arid climate leads to water scarcity being a constant and overarching concern. FRM alternatives and solutions must be weighed in consideration of the specific water rights system that applies in the region, water supply enhancements, and ecological needs. Planning might consider:
  - Novel approaches to avoid proposing measures that could reduce water availability for agriculture and other "beneficial" uses that might be claimed under existing water rights allocations in the region
  - Regulatory requirements regarding interbasin flow transfers to ensure additional authorization requirements are not inadvertently triggered as part of proposed plan implementation
- **Agricultural Dependence**: Irrigated agriculture is a significant regional economic driver. The impacts of FRM strategies on agricultural water availability and operations must be considered. Conversely, agricultural activities must incorporate practical and efficient water use methodologies in consideration of water supply needs and salinity reduction efforts if a regional water resource plan is to be functional and effective. FRM strategies should support research and development of salt-tolerant and absorbing crop varieties and improvement of irrigation techniques to reduce the impact of salinity on agriculture.
- **Salinity Management**: Increasing water salinity is a significant and unique challenge in this region and comprehensive flood water planning in this region must take this significant issue into

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account and consider all potential corrective measures. Salinity issues stem from several sources, some well-known and others currently less understood due to data gaps. Additional study of this subject is needed to further identify, eliminate, effectively contain, or treat specific sources causing increased water salinity. An enhanced network of in situ and mobile real-time salinity sensors should be implemented and supported throughout the region to improve data collection and inform management decisions.

- **Ecological Restoration and Historic Preservation**: The region is a vital corridor for migratory birds and other wildlife. Opportunities to integrate NBS and ecological restoration into FRM projects should be explored and consider restoring riparian habitats, enhancing wetlands, and creating green infrastructure. When restoring historic riverbed features, resacas, and estuarine systems, be mindful of potential cultural resources and historical sites and conduct appropriate archaeological assessments, surveys, and mitigation measures as necessary.
- **Loss of Historic Riverbed Geomorphology**: Channelization and development have altered the river's historic and contemporary natural geomorphology, reducing its ability to attenuate floodwaters and provide flood stage freshwater inflows into historic scars and former oxbows known regionally as resacas. Reconnecting the river (specifically during flood stages) to various channels and elements of its historic floodplain presents potential FRM, aquifer recharge, and surface ecological opportunities. Leveraging these naturally occurring formations may provide significant opportunities for stormwater infrastructure development cost savings for local governments when compared to creating stormwater overflow systems from exclusively upland areas as is often done in other regions where such geomorphology is not so extensively naturally occurring. Special considerations should be taken to evaluate the feasibility of integrating specific resacas into a comprehensive systems approach, with the goal of optimizing flood control, water quality, and ecological improvements along designated corridors while avoiding unintended negative consequences.
- **Integration of the Lower Rio Grande Flood Control Project (LRGFCP)**: The IBWC was established in 1889 and operates under the foreign policy guidance of the Department of State. Along the Lower Rio Grande, part of the IBWC interest is to operate the LRGFCP, a flood control system network of flood control and water detention infrastructure. Comprehensive FRM planning efforts should integrate the LRGFCP into a broader regional floodwater usage and FRM framework. A detailed evaluation of the LRGFCP could help identify areas for improvement, optimization, and novel approaches to floodwater diversion and use integration. This plan should address improved operational protocols, maintenance schedules, funding mechanisms, flood notification systems, floodwater utilization, and coordination with other FRM stakeholders.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Objective 8: Make recommendations pertinent to flood planning and outreach/communication to GLO

As TIFF's ultimate legacy will be the set of Recommendations, guidelines, and frameworks to improve the performance, understanding, and communication of flood science, it was imperative that the final recommendations made by TIFF be vetted and optimized by coordinated peer review so that they can be made actionable without hesitation by implementing entities. This coordinated peer review was structured around the component objectives, which were used to query whether the existing list of potential recommendations thoroughly addressed the original vision and intent of TIFF (**Appendices B-13** and **B-17**).

TIFF engaged with the TATs, CHARM, TDIS, the RFPGs Coastal Liaisons, and the GLO's RBFSs to identify state planning needs, identify significant data gaps impacting planning initiatives, and support the development of recommendations in support of the improvement and expansion of flood planning in Texas. **Ultimately, 12 TIFF Recommendations resulted from the research and expertise associated with Component 4.** (See the TIFF Recommendations Handouts for summary handouts that can be used to seek further support for implementation.)

Note: Each Recommendation is designed to articulate implementation needs, and where feasible, approximate costs. These cost estimates are included for planning purposes only and should be understood as preliminary and subject to refinement based on project scope, timing, and local/regional conditions and circumstances. In all cases, implementation of these Recommendations will require the identification and securement of appropriate funding. Additionally, implementation of these Recommendations is subject to the legislative authority and capacity of potential partners. Collectively, the Recommendations are designed to provide funders and policymakers with a clear roadmap for strengthening the state's flood resilience, ensuring that communities, infrastructure, and ecosystems along the Texas coast are better protected for the future.

Storm Alberto at Surfside Beach, Texas ©Brandon Bell

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THE COMPONENT 4 RECOMMENDATIONS

Table 4-2. Component 4 Objectives for Flood Planning and Outreach and associated Recommendations.

Component Objective	Associated Recommendation(s)
Establish a TAT to support Component 4	Objective met by TIFF. No further Recommendations.
Coordinate with the RFPGs and stakeholders to identify flood planning and mitigation scenarios consistent with regional flood planning efforts, beginning by establishing a working relationship with RFPGs or their coastal liaisons to identify TIFF end-users	Objective met by TIFF. No further Recommendations.
Develop and implement a comprehensive outreach plan to engage regional planning groups and other stakeholders regarding flood planning and mitigation efforts	Objective met by TIFF. No further Recommendations.
Evaluate and provide feedback on the initial inventory of planning datasets (e.g., parcel data, structure characteristics, first-floor elevation, building codes, demographics) provided by GLO RBFS Study Providers	Objective met by TIFF. No further Recommendations.
Perform a literature review on planning tools and develop a list of data modeling needs for planning tools	C4.5A: Develop a Flood Tool for Hazard and Loss Assessments C4.5B: Teach Stakeholders how to Use Flood Risk Maps
Support the development of flood communications and educational materials	C4.6A: Establish Online Learning Center within TDIS C4.6B: Expand K-12 Flood Education C4.6C: Understand Stakeholder Social Norms Related to Flood Decision-Making C4.6D: TexasFlood.org Branding Campaign C4.6E: Address Flooding Caused by Illegal Dumping in the LRGV
Investigate the opportunities to balance local cost-effective flood risk management analysis with regional flood risk considerations	C4.7A: Establish a Texas Flood Coordination Office C4.7B: Establish a State Flood Communication Officer C4.7C: Formalize Cooperative Local and Regional Flood Planning in the LRGV C4.7D: Enhance Regional Flood Early Warning Systems in the LRGV C4.7E: Develop "Safe Pass", a Transportation Flood Resilience Initiative in the LRGV
Make recommendations pertinent to flood planning and outreach/communication to GLO as they arise	Objective met by TIFF. No further Recommendations.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

C4.5A: Develop a flood tool for hazard and loss assessments to improve state flood planning and prediction

Flooding and other natural disasters in Texas cause significant damage each year, impacting communities, infrastructure, and economic stability. To improve planning, insurance assessments, and predictive capabilities, TIFF recommends the development of a comprehensive hazard and loss assessment framework for Texas.

Currently, hazard and loss assessments are fragmented, relying on disparate data sources, costly post-disaster inspections, and varying building codes across communities. A structured, statewide framework would provide consistent, high-quality data to inform decision-making, reduce uncertainties, and support mitigation planning.

By implementing this framework, Texas can move toward a data-driven, proactive approach to flood risk management with a comprehensive framework that accounts for a wide range of losses, beyond just structural inundation. This includes social impacts and disruptions to essential services, providing a more holistic understanding of disaster consequences.

Key implementation actions include:

- **Database Development and Enhancement**: Develop and maintain a centralized, regularly updated database to support hazard and loss assessments; this database will include essential information such as building age, construction standards, and historical flood regulations (e.g., National Flood Insurance Program adoption, freeboard requirements, International Building Code compliance); TIFF recommends various agencies partner to enhance TWDB's building footprint database, ensuring improved data accuracy and coverage
- **Flood Risk Model Development**: Establish model functionality requirements and certification criteria for accurate risk assessment; this development includes assessing the feasibility of creating a Texas-specific flood model that incorporates local flood level data, damage estimates, and loss metrics; design the models to ensure compatibility with BCA requirements, supporting state and federal grant applications
- **Post-Disaster Data Collection Strategy**: Improve data collection following disaster events; strategies will be developed to address challenges such as lost high-water marks and overwhelmed local officials; encourage community participation in recording flood depths using simple methods like photo documentation and height measurements
- **Cumulative Impact and Mitigation Tracking**: Expand assessments beyond catastrophic events to include the cumulative impact of minor flooding, which often goes unrecorded but can still degrade infrastructure and property values over time (this tracking will also improve tracking of mitigation efforts and loss avoidance, ensuring that valuable data is preserved for future analysis)

C4.5B: Teach stakeholders how to use flood risk maps for preparedness to enhance community flood resilience

As floods become more frequent and severe, Texas must enhance community resilience by ensuring local stakeholders understand and act on flood risk information. Flood maps are essential for assessing risks, but many residents and local officials struggle to interpret them accurately, hindering preparedness and response efforts.

TIFF recommends coordinating workshops that help local emergency managers, community coordinators, and residents learn how to read and interpret flood maps. The workshops should engage community members by encouraging feedback and updating local data. Involving the community in data

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collection and decision-making will foster a sense of shared responsibility. TIFF recommends partnering with organizations experienced in flood planning, coordination, and mitigation, such as TDEM.

By the end of the project, stakeholders, including residents and officials, will collaborate effectively on flood preparedness, with flood risk maps becoming a common tool in decision-making and community resilience planning.

Keys implementation actions include:

- **Establish Partnerships**: The planning and development phase should include multiple meetings with TDEM's Assistant Chiefs, Regional Section Chiefs, District Chiefs, and County Liaison Officers; use existing datasets and expert observations to identify priority locations based on flood history, flood severity, population size, critical infrastructure, and other variables
- **Stakeholder Outreach**: Promote the workshops through partner websites; reach out to agencies and organizations advancing flood science, such as TWDB, TDIS, and GLO to promote the workshops through their engagement channels; advertise the workshops locally to connect with residents
- **Workshops**: Conduct at least two workshops in each of TDEM's eight regions to engage participants in flood-preparedness activities with the goal to 1) strengthen participant understanding of flood risk map symbols and associated uncertainties, and 2) build participant ability to assess the impacts of various flood scenarios; each workshop should integrate flood-risk maps with complementary data, such as demographic information and land use trends, to provide a more comprehensive understanding of community flood risks

Matagorda Harbor during Hurricane Nicholas © Supportstorm, Flickr

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C4.6A: Establish online learning center within the Texas Disaster Information System to improve sharing of flood education resources

State and federal agencies, along with academic institutions, offer a wealth of educational resources on flood-related topics, including compound flood modeling, data gathering, visualization, and management. These resources include workshops, webinars, and expert-led seminars that provide valuable insights into research, data, and ongoing flood-related projects. However, despite the abundance of available content, there is no centralized platform where these materials are systematically stored and easily accessible for future reference. As a result, critical knowledge is often scattered across different organizations, making it difficult for professionals, policymakers, and researchers to efficiently access and utilize these resources.

To address this gap, it would be beneficial to create an online learning center within TDIS. This platform would serve as a comprehensive repository for flood-related educational materials, including recorded webinars, research presentations, and training modules. A centralized resource hub would enhance accessibility to critical flood-related knowledge, provide professional education credits continuing education hours which are required for various professional license renewals such as PE and CFM, and foster greater collaboration among agencies, academic institutions, and flood management professionals.

This Recommendation can be implemented for an estimated annual cost of $85,000 – $108,000. The estimated cost for initial implementation is $300,000. The project team must have established connections with the Texas Education Agency (TEA) and a strong understanding of the Texas Essential Knowledge and Skills (TEKS) requirements. TIFF recommends the TFMA help coordinate this effort because it has established a national program for professional certification of floodplain managers.

By establishing this learning center, Texas can strengthen workforce education, improve flood preparedness, and ensure that critical expertise remains readily available for researchers, decision-makers, and practitioners.

Key implementation actions include:

- **Planning and Development**: Conduct a survey to identify priority content and existing educational resources from agencies, academic institutions, and professional organizations; define technical requirements for content hosting, search functionality, and credit tracking; select a video hosting platform will be selected; build a searchable library with keyword tagging and design an intuitive interface for easy navigation
- **Content Collection and Integration**: Gather existing videos, slides, and presentations from past workshops and seminars, collaborating with relevant agencies and experts and leverage any existing flood educational materials developed/collected by federal and state agencies; materials should be tagged, categorized, and updated quarterly for continued relevance; conduct beta testing with key users and refine the platform based on feedback
- **Launch and Ongoing Maintenance**: Promote the platform through TDIS, TWDB, professional organizations, and academic networks, with a virtual kickoff webinar; employ one full-time employee for content management and updates; maintain cloud storage, engage with stakeholders, and ensure the platform evolves with user needs
- **Flood Literacy Evaluation**: Determine if the online learning center increased flood literacy in target user groups, improving their capacity to respond effectively and appropriately to given flood risk information

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

C4.6B: Expand K-12 flood education to help students better understand and respond to flooding

K-12 students in Texas schools (public, charter, homeschool) currently learn about the water cycle and drought. However, despite the state's high vulnerability to flooding, most students receive little to no instruction on how floods occur, the risks they pose, or how to prepare for them. This differs greatly compared to topics like fires and tornadoes, where schools and fire departments often collaborate to conduct drills and teach preparedness (e.g., "Stop, Drop, and Roll").

Texas should adopt a flood education plan that develops culturally and linguistically appropriate flood education content for its K-12 system using tools like virtual and augmented reality and serious games to build students' critical decision-making skills in emergencies. This initiative should embed flood awareness in science, geography, and emergency preparedness curricula, using interactive and technology-driven learning tools, to engage students effectively. This initiative should also develop programs that integrate children and youth into community-based flood preparedness and response activities, fostering intergenerational learning and stronger awareness networks.

Piloting this effort is estimated to cost $300,000 over two years. Success requires close coordination with the TEA, along with a solid understanding of the TEKS standards. Collaborating with Independent School Districts, homeschool and online education programs, and family and community organizations is essential. Partners should also include coordination with state agencies experienced in producing flood education resources, such as TDEM, TWDB, and TFMA.

Key implementation actions include:

- **Determine Feasibility and Timeline**: Assess the process, feasibility, and realistic timeline for integrating flood education into the Texas K-12 curriculum; develop materials suitable for children, youth language brokers, and their families, recognizing Texas's bilingual communities
- **Review Best Practices**: Conduct a literature review of flood education initiatives both within Texas and internationally; identify effective models, gaps, and grade-level opportunities for integration; adapt existing materials games from successful programs and include activities that engage parents and caregivers to broaden community flood awareness
- **Develop Educational Tools**: Recommend and design content such as interactive modules, serious games, and augmented reality experiences aligned with TEKS learning standards; plan for long-term support needs such as maintenance and regular updates
- **Flood Literacy Assessment**: Measure whether incorporating flood education increases flood literacy among students

C4.6C: Better understand stakeholder social norms related to flood decision-making

Research consistently shows that social norms—being influenced to engage in a behavior because of trusted others—are a strong predictor of Texans' flood-related decisions. These trusted individuals are often peers rather than experts, highlighting the need for a deeper understanding of how social influence shapes decision-making in flood preparedness, response, and recovery.

TIFF recommends targeted experiments, surveys, and focus groups to explore the various forms of flood-related decision-making. By analyzing how different social groups influence perceptions and actions, these studies can identify the most effective ways to disseminate flood information. Insights from this research can then be used to develop communication strategies that leverage peer networks, ensuring that critical flood-related messages resonate with and motivate communities to take protective action.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

The estimated cost is $245,000, which includes participant compensation to ensure representative data. Testing *People with LEP* should be prioritized to improve accessibility and effectiveness. A key research objective should be to assess how well individuals understand the documentation involved in purchasing a home. For example, do they know whether the home is located in a designated flood zone?

Key implementation actions include:

- **Social Norms Studies (Two Experiments)**: Study how social norms impact flood-related decisions (e.g., buying insurance, creating evacuation plans, home selection); examine the role of information sources will be examined, including trust and domain-specific trust; test evidence-based messaging strategies that integrate social norms, assessing their effects on risk perception and cognitive load
- **Key-Logging Study**: Analyze how peer-shared flood experiences influence decisions and identify the most effective messengers; explore community-driven approaches, such as using *promotoras* (lay health workers) for flood communication; conduct surveys, interviews, and focus groups reflecting Texas' demographics, with a focus on *People with LEP*

C4.6D: Use a branding campaign to enhance online engagement with key flood information on TexasFlood.org

TIFF research showed that TexasFlood.org, despite being a key resource for flood information, has limited engagement with its target audiences. To increase awareness, graphics should be finalized and a comprehensive campaign promoting the website and its resources should be launched to emphasize flood preparedness and risk management.

The campaign will incorporate clear metrics to track website traffic and user engagement, ensuring measurable success and ongoing improvement. TIFF research also suggests evaluating the impact of the messages after launch to ensure they resonate with the target audiences and effectively drive engagement. Regular assessments will help refine the approach and keep the materials relevant.

TIFF recommends establishing a branding campaign for TexasFlood.org, including the finalization of graphics tailored to the identified audiences, strategic outreach to increase awareness, and a robust evaluation process to track the effectiveness of the campaign. By integrating a clear branding strategy with evaluation and metrics, this effort aims to enhance the website's visibility and ensure that flood-related resources are accessible and actionable for Texans across the state.

Key implementation actions include:

- **Branding Campaign**: Develop and execute a comprehensive campaign aimed at raising awareness of TexasFlood.org and its flood-related resources; use finalized graphics to create outreach materials and advertisements tailored to the TIFF prioritized three target users (*Property Owners*, *Property Renters*, and *People with LEP*); leverage multiple channels, such as social media and partnerships with relevant agencies, to maximize reach and engagement with the public
- **Website Metrics and Tracking**: Establish clear metrics to track website traffic, engagement, and user interactions; use metrics to help monitor the campaign's effectiveness, refine strategies, and identify any gaps in outreach efforts
- **Evaluation**: Periodically evaluate the messages and materials post-launch; gather feedback from target audiences and analyze data to assess whether the graphics and messages resonate with each group; adjust and updated materials based on the findings to ensure they remain relevant and impactful

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C4.6E: Address flooding caused by illegal dumping in the Lower Rio Grande Valley by simplifying drainage education and applying behavioral intervention strategies

Drainage systems in the LRGV play a critical role in managing floodwaters but are often strained by the region's flat topography, rainfall characteristics, land use, and water management. These conditions cause rainfall and floodwater to stagnate and recede slowly, increasing flood risks. Illegal dumping exacerbates this problem by clogging drainage ditches and channels which worsens flooding, public health hazards, and property damage. Many residents are unaware of how local drainage systems function or how illegal dumping directly obstructs water flow between neighborhoods, cities, and counties. During heavy rain events, even minor blockages can cause "stacking," where backed-up water accumulates and floods areas days after rainfall.

TIFF recommends combining simplified drainage education with innovative behavioral interventions that integrate environmental design, community education, and incentive-based strategies. This 2-year investment, estimated at $950,000, aims to make drainage concepts relatable to residents' daily experiences, reduce illegal dumping, strengthen community engagement in flood prevention, and foster long-term stewardship of local drainage systems.

Key implementation actions include:

- **Establish Partnerships**: Collaborate with local law enforcement (including state-licensed peace officers, code enforcement, and local prosecutors), drainage districts, governments, universities, schools, and nonprofits with expertise in the region; use Hidalgo County's drainage mapping expertise as a guide to co-develop public education and incentive programs; align activities with environmental-social-governance principles to promote community responsibility; work with the local partners mentioned above (as well as county commissioners and colonia-focused nonprofits) to conduct workshops, educational programs on control measures, and an annual conference that incorporates youth education; coordinate with state agencies and existing local environmentally-focused nonprofits to enhance cleanup efforts and data collection through community and citizen science networks
- **Behavioral Intervention Study**: Fund a behavioral study to identify barriers and motivators influencing illegal dumping; compare attitudes and behaviors between incorporated and unincorporated areas, homeowners, and renters; test messaging strategies to identify which most effectively promote compliance and awareness
- **Strengthen Deterrence and Compliance**: Implement a dual-approach pilot combining deterrents and convenience measures; increase friction at dumping hotspots with strategic environmental design (e.g., vegetation buffers, fencing, art, lighting); reduce friction for proper disposal by offering mobile drop-offs, easy quick response/text scheduling, and well-marked "clean zone" windows; measure dumping rates before and after interventions across neighborhoods
- **Enhance Local Law Enforcement**: Provide funding and incentives (potentially through Councils of Government and TWDB) for local law enforcement agencies to educate and empower state-licensed peace officers, code enforcement officials, and local prosecutors to more effectively enforce and publicize existing illegal dumping and water quality-related laws (including criminal penalties under the Texas Litter Abatement Act and the Texas Water Code)
- **Incentive Credit Program**: Create a points-based system rewarding residents for positive behaviors such as reporting clogged drains, using authorized disposal sites, or joining cleanup events; allow credits to be exchanged for household goods or service vouchers, reinforcing long-term community engagement
- **Pilot Implementation and Evaluation**: Test interventions in at least two or three colonias or unincorporated areas; track results using metrics such as dumping frequency, resident participation,

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

program costs, scalability, equity impacts, and illegal disposal and water pollution-related enforcement and arrest statistics

- **Simplify Drainage Education**: Replace technical flood maps with accessible visuals showing neighborhood-level drainage flow and impacts of illegal dumping; use hands-on demonstrations, such as interactive CHARM simulations, to show how local dumping contributes to regional flooding; publicize existing illegal dumping and water quality-related laws; deliver education through workshops, community cleanups, and updated, plain-language drainage materials developed with local partners

C4.7A: Establish a Texas Flood Coordination Office (TFCO) to optimize local, state, and federal project impacts

Currently, multiple state and federal agencies, private and non-profit organizations, and academic institutions are engaged in efforts to raise awareness and respond to floods. However, without a centralized coordinating body, the extensive work being done often overlaps, creating redundancies, inefficiencies, and missed opportunities to leverage project outcomes. TIFF recommends Texas legislators establish a Texas Flood Coordination Office (TFCO) within an existing state agency. Initial funding for the TFCO could come from state appropriations, with additional support from federal grants or partnerships with non-profit organizations and private companies involved in flood-related efforts.

By centralizing information and oversight, the TIFF-informed TFCO will enhance the state's ability to manage and mitigate flood risks efficiently. The TFCO will 1) centralize state and federally funded flood projects in one central body, 2) facilitate collaboration among stakeholders to build partnerships and shared solutions, 3) maintain a central archive of project outcomes and share findings with stakeholders, 4) reduce redundancy to ensure efficient use of state and federal resources, and 5) report to the Legislature on the state of flood projects and recommend improvements for flood management.

These key objectives are described in detail below include:

- **Centralized Oversight of Flood Projects**: The TFCO will coordinate all state and federally funded flood-related projects, ensuring that efforts are aligned, complementary, and not duplicated. The Office will maintain a central database of ongoing and completed projects (including information on scope, funding, and progress) to improve coordination and transparency. This coordination will help decision-makers allocate resources more effectively and ensure future flood projects address the state's most pressing needs.
- **Facilitation of Collaboration**: The Office will actively encourage collaboration among state agencies, academic institutions, non-profits, and private sector organizations to promote innovation and more effective flood management. It will serve as a neutral convener, bringing stakeholders together to foster partnerships and shared solutions. This coordinated approach will help break down silos, align diverse expertise towards state goals, and lead to more efficient project implementation.
- **Archiving and Dissemination of Findings**: All project outcomes, data, reports, and findings will be archived in a central repository managed by the TFCO. This information will be made accessible to all relevant parties with appropriate access level (e.g., emergency responders, the general public) to promote transparency and knowledge sharing. The TFCO will ensure that results from projects are effectively disseminated among key stakeholders and can be leveraged in future flood mitigation efforts. By disseminating project findings, the Office will ensure that valuable insights from past projects inform future flood mitigation efforts.
- **Reduction of Redundancy**: Through its oversight and coordination roles, the TFCO will reduce unnecessary duplication of effort by identifying overlaps among projects and redirecting resources to unmet state needs. This leveraging of project outcomes will prevent wasted investments in repetitive research or narrowly scoped projects and inform new initiatives. This efficient use of state and federal

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

resources will maximize the impact of available funding and ensure that flood management efforts address a broader range of needs across Texas.

- **Legislative Reporting and Recommendations**: The TFCO will provide regular reports to the Texas Legislature that highlight the status of flood projects, identify gaps in the state's approach, and recommend improvements for flood management and response. These reports will ensure that decision-makers are equipped with up-to-date, evidence-based information. The Office will work closely with legislators, providing the latest research and field-tested solutions to help shape policies that are more responsive, effective, and sustainable in reducing flood risks statewide.

Flooding is an urgent and ongoing threat in Texas, and the current landscape of flood-related efforts is fragmented and inefficient. By establishing the TFCO, the state can enhance its flood management efforts, streamline coordination across sectors, and ensure that all projects contribute to a more resilient and prepared Texas.

Key actions when implementing this recommendation include:

1. **Establishment**: Embed the TFCO within an existing state agency involved in flood science, planning, and/or funding; although the TFCO could be established as a separate entity, utilizing an existing agency may reduce the overhead and administrative burden; form a small interdisciplinary team of flood management experts supported by 1-2 administrative staff; this team must build long-term partnerships with external agencies, academic institutions, and stakeholders; TIFF recommends either TDEM or TWDB as the potential state agency to house the TFCO
2. **Build Partnerships**: Coordinate with regional data collection and monitoring organizations, non-profit organizations, counties, municipalities and special-purpose districts, consulting firms, engineering firms, academic institutions, and state and federal agencies advancing flood monitoring and modeling to promote adaptive flood management strategies
3. **Engagement and Outreach**: Sustain engagement with technical and non-technical stakeholders to inform the development of shared goals and priorities that guide regional partners:
    - Workforce Development – Offer a suite of educational and vocational programs to address the current and near-term future needs of public and private sector organizations investing in each region
    - Translational Research – Conduct targeted flood-related research with an immediate operational benefit that supports the needs of public and private sector regional investors and recruits further investment in the area
    - Academic Evolution – Establish an exemplary institute to serve as the foundation for recruiting traditional research-extensive institutions to further knowledge-based economic development
    - Regional Resiliency – Emphasize socio-economic resiliency as a core precept in the promotion of technological advances and production of associated workforce, by identifying and adapting for likely hazards and potential risks through technological advancement and workforce responsiveness
    - Economic Development – Advance each region's knowledge-based economy by being an integral part of the economic development engine, serving current workforce and technology development needs and proactively adapting the changing economic landscape
4. **Database Management**: Compile a public and statewide archive of state and federally funded flood projects through structured outreach and data collection; adopt consistent metadata and quality-control standards for project documentation, tagging, and categorization; maintain and

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

update the database annually to reflect new projects and evolving priorities; utilize data analytics to identify research gaps, emerging risks, and priority investment areas

5. **Reporting**: Disseminate project outcomes and data to the public and stakeholders to promote transparency and coordination; facilitate workshops, briefings, and inter-agency meetings to foster collaboration; provide regular progress reports and policy recommendations to the Texas Legislature

C4.7B: Appoint a State Flood Communication Officer to facilitate interorganizational coordination in flood research

Effective coordination among agencies involved in flood-related projects is essential for improving preparedness, response, and mitigation. As floods become more frequent and severe, Texas needs a centralized communication strategy. However, without clear leadership, agencies may operate in silos, reducing efficiency and policy alignment. Texas already employs state experts, such as the State Demographer, who provide policy guidance. A similar role focused on flood communication coordination would bridge gaps between agencies and ensure a unified approach.

This individual would serve as a liaison among agencies, organizations, and policymakers to streamline communication and advise the Governor and Legislature on science-based flood policies. Additionally, they would coordinate efforts between scientific research, insurance, and policy sectors to ensure alignment in mitigation planning and response. Drawing from successful models in other states, they would also develop best practices for interagency collaboration.

With the establishment of this impactful role, Texas can enhance interagency coordination, strengthen flood preparedness, and foster a unified flood management strategy. A dedicated expert will ensure that science, policy, and risk mitigation strategies work together, ultimately improving the state's resilience to flooding.

Key implementation actions include:

- **Research Comparable Roles and Craft Proposal**: Review the guidelines and responsibilities of similar state advisory roles, such as the State Demographer and Chief Resilience Officers, to inform the structure and best practices for the new position.
- **Role Definition and Options for Organizational Integration**: Define the Officer role's scope and authority within the TFCO; integrate the role within an existing state flood agency while expanding its authority and responsibilities; assist organizations in developing effective flood preparation plans and materials; align and incentivize local, regional, and state flood projects for cohesive efforts; establish data-sharing mechanisms with academic institutions and funding agencies, such as through open science platforms; ensure every agency with a flood-related mission designates a representative to support coordination efforts
- **Allocate Resources**: Focus on securing the necessary funding and resources to ensure the position is adequately staffed and supported

C4.7C: Formalize cooperative local and regional flood planning in the Lower Rio Grande Valley

The LRGV is comprised of over 40 local, state, and federal jurisdictions with overlapping and intersecting interests in flood prevention, protection, and planning. To effectively coordinate local and regional flood projects between historically competing jurisdictions and economic sectors, a structured and formal agreement between key stakeholders is needed to guide flood risk management planning targeting shared goals.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

TIFF recommends that the State of Texas create a Texas Flood Coordination Office (TFCO) and prioritize coordination efforts between traditional flood planning interests and those of supply and demand-related entities, agencies, and representatives specifically in the LRGV. TIFF also recommends that until such time that such an office can be established, state and federal agencies may enter into inter-local or memoranda of agreements with partnering counties and/or other entities, as appropriate, to focus integrative flood planning activities consider and maximize opportunities for shared areas of interest in the LRGV and/or participate in other regional coordination initiatives such as the envisioned Applied Coastal Water Intelligence for Regional Resilience and Economic Development (ACWIRRED) Institute (a consortium of 30+ local and independent jurisdictions have been meeting to discuss the envisioned ACWIRRED Institute as a natural evolution of their cooperative efforts).

A three-year investment, estimated at $1,000,000 annually, would enable the TFCO to serve as a facilitator to synergistically produce flood resilience-specific outcomes in the LRGV—an integrative water resources planning testbed—that may be replicated, re-used, or served as models for other regions. This regional priority might alternatively be addressed by local partners such as RATES and the LRGV Stormwater Task Force in the interim while the TFCO is being established (see **Appendix D-8** for implementation ideas and partnership opportunities presented by TAT members for inclusion in this report).

Key aspects of these cooperative agreements should include specific commitments to improve:

- flood data collection and sharing
- cross-jurisdictional contracting
- international trans-boundary coordination
- consistent public engagement and community flood education
- flood monitoring and modeling
- decision-maker education and engagement
- education and outreach to small to mid-sized communities
- academic curriculum and research outcomes that address local needs
- cloud-computing services to support local and regional environmental data collection and gap analyses
- regional coordination of flood planning projects and research
- identification of local and regional flood mitigation goals and objectives
- coordination of City ordinances to local/state/federal standards, etc.
- pooling and alignment economic resources to implement innovative stormwater solutions
- stakeholder input into potential FRM strategies potentially not previously identified in assessments of existing literature or studies
- targeted local studies to leverage the data, maps, and findings from the latest regional flood assessments such as the GLO RBFS and the LRGFCP
- balance and integration of regional water supply and demand interests to maximize innovation, funding opportunities, and a comprehensive approach to water resources challenges in the LRGV

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

C4.7D: Enhance regional Flood Early Warning Systems in the Lower Rio Grande Valley by centralizing existing flood monitoring and forecasting efforts

Texas has faced several federally declared flood disasters over the past decade, resulting in billions of dollars in damages and tragic loss of life. Communities often respond with structural mitigation measures like drainage improvements, levees, and floodwalls without having the necessary planning and guidance in place to ensure their effectiveness.

To strengthen flood resilience in the LRGV, TIFF recommends enhancing existing regional Flood Early Warning Systems (FEWS) in collaboration with local communities. By centralizing ongoing and local emergency management efforts, a bilingual alert framework can be improved to enable timely and protective responses while honoring the region's cultural and linguistic diversity.

This 1-2-year investment, estimated at $700,000, will increase regional flood preparedness, provide more equitable and strategic dissemination of flood information, and enhance engagement between public agencies and local communities.

Key implementation actions include:

- **Establish Partnerships**: Collaborate with federal agencies, regional organizations, academic institutions, drainage districts, city departments, schools, faith-based groups, community leaders, and other local partners
- **Educate Local Officials**: In addition to following the TWDB guidance documents (see action Enhance Flood Management below), coordinate with TDEM and use professional networks to train local officials and appropriate emergency responders on effectively managing and acting on flood early warning systems; training should cover how to interpret risk-signaling data, actions to take during the preparedness phase before public alerts are issued, and appropriate steps during emergency response; incorporate education, hands-on practice, and peer experience-sharing to help build confidence in decision-making during emergency events
- **Engage Stakeholders**: Conduct surveys, workshops, and public meetings to assess how residents receive and act on flood warnings; evaluate communication methods, including bilingual alerts, visual cues (e.g., rain gages, public displays), and community-based media; work with at least three pilot communities to define goals that reflect local flood challenges to inform system complexity, equipment, and data modeling needs
- **Technology, Data, and Models**: Promote collaboration between academic and local partners to design, develop, and integrate sustainable (low-total-cost) and potentially innovative flood monitoring technology; use existing monitoring and forecasting tools from state, federal, and local agencies to guide future data collection and modeling improvements
- **Financing**: Secure sustainable funding through state and federal grants, private foundations, and local cost-sharing strategies; conduct cost-benefit analyses to demonstrate long-term value and reliability
- **Enhance Flood Management**: Follow TWDB's FEWS Guidance Document, Alternative FEWS Guide, and Flash Flood Warning Siren Guide to integrate localized monitoring and forecasting components into one centralized system; consider features such as warning sirens and expanded sensor networks; gather feedback from technical experts and community users before full deployment
- **Public Outreach**: Create or attain culturally and linguistically appropriate educational materials; conduct outreach campaigns to build public awareness, trust, and effective response behavior
- **Evaluation**: Collect user feedback and performance data to refine system features, strengthen functionality, and improve long-term effectiveness

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

C4.7E: Develop Safe Pass, a Transportation Flood Resilience Initiative in the Lower Rio Grande Valley

Evacuation and response planning is critical to effective flood resilience in the LRGV, a region facing a wide range of flood risks, from coastal surge to inland flash flooding. Emergency managers need adequate data, resources, and operational tools to deliver timely and accurate preparedness messaging and alerts to local communities making transportation decisions. As such, there is a need to incorporate transportation infrastructure data to better understand the impacts of flooding on evacuation routes, roadways, and critical transportation assets.

TIFF recommends the development of Safe Pass, a transportation flood resilience initiative designed to systematically reduce roadway flooding risk across the LRGV. Safe Pass integrates flood hotspot analytics, flood monitoring and analysis system observations, structured stakeholder outreach, and coordination with TxDOT to:

- Establish an LRGV-wide roadway flooding inventory and standardized crossing classification based on roadway inundation behavior that is repeatable and defensible;
- Improve roadway closure decision-support and public situational awareness at flood-prone crossings
- Prioritize investments using a BCA framework informed by TxDOT roadway demand/use and local operational knowledge
- Deploy resilient, high-visibility flood monitoring systems that reduce flood risk and improve storm response outcomes

Success requires coordination with TxDOT. Other potential partners include state and federal agencies, and regional organizations experienced in flood planning and mitigation. Organizations managing local sensor networks should also contribute to this effort. Other potential partners include county agencies and non-profits that can serve as community organizers and connectors.

This 2-year investment, estimated at $1,400,000, will support consistent messaging and response protocols across jurisdictions, reduce stranded-vehicle risk and exposure to swift-water incidents, and create a defensible basis for future capital mitigation projects and grant competitiveness. Agencies can collaborate on funding different phases or use a cost-sharing formula.

Key implementation actions include:

1. **Identify and Classify Over-Water Intersections and Flood-Prone Roadways across the LRGV (~$300,000)**:
    - Classification – This effort will identify over-water roadway intersections and classify each into one of three operational categories based on exceedance expectations, observed performance, and validated local knowledge: 1) Dry Pass: crossings that should not flood during a 1,000-year storm event, 2) Submersible Pass: crossings expected to flood during a 500-year storm event, and 3) Inundated Pass: crossings that flood during a 100-year storm event.
    - Evaluation – Execute a structured evaluation using TWDB Flood Infrastructure Fund guidance documents (https://www.twdb.texas.gov/financial/programs/fif/index.asp); this evaluation will include hotspot analyses, transportation infrastructure data, available hydrologic/hydraulic indicators, and event documentation; convene private technical sessions (cities/engineers/drainage stakeholders) and public meetings to validate known and emerging hotspots; these meetings will be targeted on known recurring issues including expressway entrance/exit ramps (notably in Cameron County), FM 495 (Hidalgo County), and other locally identified flooding locations

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

- TxDOT Coordination – As inundated zones and candidate crossings are identified, coordinate with TxDOT to confirm roadway functional classification, usage/demand, detour feasibility, and consequence-of-failure considerations; this information will support the development of a defensible BCA

2. **Develop BCA and Prioritize Three to Five High-Impact Locations; Harden Hydrological and Meteorological Monitoring (HydroMet) Systems for High-Risk Zones (~$600,000)**:
   - BCA Development – Using outputs from the prior step, develop a defensible BCA framework incorporating (as available) roadway demand, flood frequency/severity, incident history, detour impacts, emergency response exposure, damage avoidance, and operational benefits of improved warning/closure decisioning; produce a ranked shortlist of 3–5 priority deployment sites supported by BCA results and stakeholder concurrence
   - Harden Monitoring Infrastructure – In parallel, harden the HydroMet design for the identified high-risk installations to increase longevity and resilience (e.g., reinforced enclosures, anti-tamper hardware, debris-resistant mounting, protected cabling, survivability in extreme hydraulic conditions, safe maintenance access)
   - Support Timely Alerts – Develop and validate multilingual alerting (e.g., English/Spanish) aligned with the field equipment (lighting states/signage) and digital communications (e.g., SMS, email, web, dashboard messaging), ensuring terminology is consistent with the Dry/Submersible/Inundated framework
3. **Install High-Visibility Flood Roadway Monitoring and Depth-Awareness Assets (~$400,000)**: Install and commission category-appropriate, high-visibility infrastructure at priority on-road staff-gage interfaces, including light emitting diode illumination and/or beacon elements tied to rainfall or stage thresholds; this improved visibility will provide motorists and responders with direct and interpretable depth information, enhance rapid public recognition of potential flood risk during storm events and low-light conditions, and support consistent warning alerts
   - Submersible Pass Deployments – Install visible on-road staff gages to support public depth awareness at the roadway interface, with illumination/lighting where appropriate to improve visibility during rainfall events and nighttime conditions
   - Inundated Pass Deployments – Install high-visibility staff gages plus shell transducers to capture continuous, real-time water level/depth conditions affecting roadway inundation, with robust telemetry and integration into FEWS alerting/decision-support workflows
4. **Program Management (~$100,000)**: Hire a dedicated program manager for adequate permitting, reporting, ensuring compliance with quality assurance and control procedures, and contingency planning

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Sunrise over Matagorda Bay the day after Hurricane Beryl © Gage, Adobe Stock

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5 TIFF Facilitation

Facilitation has been called an art, a science, and a skill backed by research suggesting that successful facilitators are active bridging agents, interlocutors, or innovation brokers who are respected and trusted in their specialist area. A facilitator can play many roles, including providing visionary leadership, nurturing a network, getting things organized, selling a new idea, creating space for dialogue, and running effective meetings. Notably, there are three main roles a facilitator plays: convener, moderator, and catalyst. A convener brings together the relevant actors and stimulates interaction. A moderator gets the actors to collaborate by managing their differences and supporting processes of mutual learning. A catalyst stimulates the actors to think outside the box and develop and implement new and bold solutions (Brouwer et al., 2015).

To support the needs of the TIFF project, facilitation included these three main roles in addition to expert elicitation (to engage more than 100 technical advisors) and science communication (to involve and resource the variety of audiences who will hopefully utilize the information resulting from the TIFF process). Early in the partnership, TIFF's partner agencies embraced the importance of third-party facilitation in meeting this mission and navigating some of the inevitable challenges of a large multi-agency research and engagement effort. Some key areas of the project were identified for the role of project facilitator:

- serve as an equal member of the TIFF Leadership Team
- elicit the needed expertise to inform the future of Texas flood science, ensuring that all voices were represented in the process and final outcomes
- design processes to ensure that all TIFF decisions maximize input from experts and ultimately represent consensus of the Leadership Team
- create a unique, overarching identity for TIFF outside of the identities of the sponsoring agencies
- design and implement engagement activities to maximize inputs to the project
- resolve conflicts within the SC and partner agencies, amongst TAT members, and between TAT members and SC members
- address conflicts of interest or conflicting opinions within the various external expert communities
- create communication tools and documents to convey project milestones and gathered expertise
- interpret technical information so that it could be received by target audiences
- streamline the delivery and implementation of the project
- synthesize and present technical content for continuity across Components and coherence for the eventual consumers of the project's outcomes

TIFF centered on expert engagement and elicitation and getting feedback from key scientific and user communities. "Expert elicitation is a formal and systematic process for obtaining and quantifying expert judgment in order to characterize the uncertainty about decision critical quantities. It does not create new knowledge; instead, it characterizes the state of knowledge about some issue or quantity that is uncertain" (USACE, 2018). The vision was to create communities of expertise to guide and vet the research and recommendations resulting from the TIFF effort. These expert communities were also meant to serve their respective areas of research and support the eventual implementation of recommendations that might result from the TIFF findings. Internally, it was often said that more than anything, TIFF is about relationships.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Effective elicitation and synthesis of collective expertise benefits from neutral third-party facilitation, which provides an unbiased check on project sponsors whose expertise and familiarity with the subject matter may introduce bias or limit the potential scope of topic exploration. A third-party facilitator is also beneficial in collaborative governance structures where parties are working together to make decisions outside of (and in addition to) their typical decision-making hierarchies (e.g., the TIFF SC). Facilitation provides structure and guides the process of group interactions to help teams work effectively and make high-quality, inclusive decisions. Rather than directing content or outcomes, the facilitator's role is to create an environment that supports participants in doing their best thinking and working together to achieve (and be accountable to) their shared goals. As the lead process designer, the facilitator can help to balance or override power dynamics or resolve conflicts that might otherwise result from non-facilitated partner collaborations.

As noted above, facilitation is both an art and a science: the art lies in the facilitator's ability to identify and understand desired outcomes and creatively adapt and respond to changing information and group dynamics; the science involves understanding how individuals and groups think, learn, behave, and develop in order to design effective processes. In addition to guiding the process, the facilitator also serves as a process steward and accountability partner, maintaining focus on the group's commitments, tracking progress, and ensuring that next steps and deliverables are clear and acted upon. While they remain neutral on content, facilitators reinforce alignment with group objectives and timelines, supporting momentum and accountability across complex, multi-stakeholder efforts.

One often overlooked role of a Facilitator is that of process designer. Once the project goals and stakeholder needs are identified and understood, it is the Facilitator who creates the process to meet the project's needs. "Process" is designed to maximize three elements to ensure a satisfying outcome: 1) trust, 2) data/information, and 3) operating structure (Moore, 2014). For TIFF, trust-building was an element in the work of the SC as well as a target for communications with the TATs; transparency and accountability around shared data and information was emphasized throughout; a comprehensive outreach plan to engage regional planning groups and other stakeholders regarding flood planning and mitigation efforts was created; and special care was given in designing roles and responsibilities amongst the SC and Facilitation Team as well as with the external participants of TIFF.

The Meadows Center for Water and the Environment

The Meadows Center at Texas State University served as the Facilitators for TIFF, playing a critical role in project operations by staying on the pulse of the project to fine-tune processes and ensure every step advanced our collective goal to elevate Texas's resilience to flooding. The Meadows Center is unique in its facilitative capacity. Established as trusted neutral convener for more than 20 years, as well as an applied research center that brings technical expertise to communities across the state to address water challenges, the Meadows Center occupies a unique niche in science communication.

Carrie Thompson was identified as the Lead Facilitator for the TIFF project with Anna Jones serving as a co-facilitator and communications lead. Desiree Jackson joined the effort in 2024 as co-facilitator, joining Rikki Weaver (Flood Framework Coordinator, TWDB) in shepherding the effort. Implementation of the project also included key contributions from Sara Omar (Kearns and West), Nic Terasewicz (Program Associate, Meadows Center), Sarah Wingfield (Digital Media Specialist, Meadows Center), and Luci Cook-Hildreth (Grant Specialist, TWDB).

The TIFF Project Charter

Successful facilitation requires that project sponsors share power and authority with the Facilitator, deferring to their expertise as a key element of the project's design and delivery.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

The Meadows Center led the development of the TIFF Charter, establishing the project's Leadership Team as the SC (made up of sponsoring agencies) plus the Facilitation Team, and clarified expectations for the roles:

1. *The **Steering Committee** helps to facilitate, coordinate, and integrate concerns, ideas, and early findings and recommendations into rapidly evolving TIFF activities. This includes giving advice and input to the framework and identifying issues in advance for technical discourse and deliberation by the TATs. The SC is scheduled to meet on a bi-weekly basis, commits to working diligently to keep the process on schedule, and to bring forth as quickly as possible any concerns that may affect the schedule.*
2. *The **Facilitation Team** is responsible for providing pre- and post-meeting facilitation support and to prepare for, facilitate, debrief, and support offline collaboration and stakeholder engagement. This includes:*
    - *Coordinate, draft, and finalize meeting agendas and meeting materials in consultation with the SC*
    - *Assist in developing meeting handout packets when necessary*
    - *Shepherd content development, maintain and provide records of agendas and action items*
    - *Provide and operate webinar platforms*
    - *Identify scheduling needs and notify participating members of scheduling needs in a timely manner*
    - *Facilitate TAT meetings, including meetings to prepare and debrief TAT meetings*
    - *Take notes during TAT meetings, summarize decisions and action items at the end of the meeting, and develop internal and external facing meeting and summary reports*
    - *Provide conflict resolution and process design services as needed*
    - *Provide additional outreach materials as agreed upon with the SC. This may include, but is not limited to interviews, surveys, polls, fact sheets, handouts, webpages, or videos.*
    - *Develop supporting tools (e.g., meeting agendas, facilitation plans, logistics, and coordination plans)*
    - *Provide a process that supports constructive and productive dialogue, helping groups remain focused on their charges and agreed-upon scopes of work*
    - *Offer process skills to support open, balanced, respectful dialogue and problem-solving*

    The Facilitation Team is also responsible for providing quarterly progress reports, including:
    - *descriptions of tasks completed and in-progress*
    - *percent completion of tasks in-progress*
    - *updates to overall project schedule as warranted*
    - *descriptions of potential issues or challenges encountered and strategies to mitigate issues affecting the scope, budget, or timeline*
    - *invoices at the satisfactory completion of each task*
    - *detailed schedule based on project milestones*

The Charter and related discussions also guided decisions around the TIFF Mission and Vision, TIFF Components, TIFF membership, Charter purpose and objectives, roles and responsibilities, ground rules for interaction, SC and TIFF decision-making process, information management and sharing, general communication protocols, TAT meeting schedule targets, and goals for the Final Report.

Docusign Envelope ID: 9FAE1118-F1C6-84D0-80AE-55C02D72BFD5

Facilitation Deliverables

The Facilitation Team played a critical role in orchestrating TIFF's operations, providing an objective perspective on project outcomes, and allowing the SC to fully participate in technical discussions with the TATs. Throughout the project, the Facilitation Team maintained close coordination and frequent communication with the SC to ensure that all activities remained aligned with TIFF's vision, while also adapting to shifting needs, timelines, and deliverables.

For the purposes of this project, facilitation tasks were organized under five core areas:

1. **Convening Stakeholders**: To support engagement across technical experts and stakeholders, the Facilitation Team led the planning and facilitation of technical workshops and TAT meetings. This included coordinating logistics for both virtual and in-person events, developing meeting agendas and process outlines, and supporting offline collaboration before and after each session. The team also prepared executive summaries to capture and communicate the technical information generated through these engagements and maintained clear communication with TAT members and other stakeholders. Planning and debrief meetings with the SC helped ensure that each session was well-supported with tailored materials and resources.

2. **Process Management**: The Facilitation Team advised the SC on strategic, efficient, and effective approaches to engage technical experts and gather their feedback on technical considerations, methodologies, and recommendations across all four project components. This included organizing meetings to convene the Leadership Team for team building and strategic project planning, as well as arranging meetings with the SC and collaborating agencies. The team helped coordinate the peer-review process between the SC and TAT members, ensuring that draft project materials and recommendations were reviewed collaboratively, and also maintained a centralized cloud-based filing system (via Microsoft Teams) for shared access to project materials.

3. **Communications and Branding**: To support cohesive and consistent communication, the Facilitation Team led the design and production of project materials aligned with the TIFF brand (e.g., executive summaries, fact sheets, infographics, flyers/handouts, and other materials as needed). This work involved developing a comprehensive brand and style guide that defined the project's visual identity. The guide outlined the use of project and partner logos, established primary color palettes for text and headers, secondary color palettes for backgrounds and supporting graphics, and specified fonts for headline, subheadline, and body text. This attention to detail helped present a unified, professional face to both internal and external audiences.

4. **Preparing Annual and Final Reports**: The Facilitation Team led the compilation and development of reports for each of the four project components, as prepared by the SC, for inclusion in the TIFF annual and final reports. This involved the creation of outlines and content guidelines coordinated with the SC as well as the creation and editing of both written content and visual elements to combine and synthesize the findings of the TIFF Study Providers, the TATs, and the Component Champions – ultimately ensuring that TIFF's outcomes were presented with one voice. The Meadows Center also led the digital design and layout, creating visual elements to bring coherence to the highly technical information and ensure its accessibility to a Texas audience.

   The team also finalized the formatting of the print reports, ensuring appropriate acknowledgment and inclusion of logos and branding for co-authoring entities and funders. Electronic versions of the annual and final reports were shared with co-author entities for use on their websites or distribution channels, in addition to submitting the final deliverables to GLO.

5. **Website Updates**: The Facilitation Team lead creative design work to ensure consistent use of TIFF's branding elements and information as agreed upon with the SC (e.g., webpages, visuals and graphic design, file organization, and other materials as needed). This included optimizing webpage appearance to enhance user experience and accessibility. A workflow was also established with the SC for web content creation, review, approval, and publishing.

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Facilitation Strategies

TIFF's ultimate legacy is the articulation of disciplinary and organizational cross-cutting priorities for understanding and communicating compound flooding, vetted for immediate implementation. As such, it was crucial to ensure consistent TIFF communications and branding, execute productive and engaging meetings that encourage democratic decision-making, and report progress towards achieving the project's desired outcomes.

Establishing a "TIFF" Identity and Branding for Enhanced Coherence and Consistency

As illustrated in the TIFF Structure and Development section of this report, TIFF has a very complex structure. An early (and key) facilitation strategy was to create a "TIFF" identity that could be recognized by participants – separate from the identities of is partner agencies.

The Facilitation Team worked closely with the SC to develop the TIFF Brand Guide, which outlined guidance on logos, color palettes, and font styles. This mechanism established a consistent visual project identity and ensured that all project communications and materials (e.g., executive summaries, fact sheets, infographics, flyers, handouts) aligned with the TIFF brand. To promote consistent communication ex-ternally, a lead facilitator was designated to communicate with TAT members using a single email address. This approach minimized confusion, reduced the risk of mixed messages, and fostered more personal-ized relationships between the Facilitation Team and TAT members. Rather than relying on partner agen-cies to promote the project through various channels, the team developed a dedicated website to serve as the central hub for TIFF materials. This ensured a single point of access for project reports, recommendations, and resources. By applying the TIFF Brand Guide, the team created a consistent and professional appear-ance across all project materials.

Equally important was the use of a singular email address and a centralized point of contact for all TIFF-related communication. The TIFF Charter established that the Facilitation Team would lead all email communications and established the Lead Facilitator as the singular voice of TIFF. This served three important purposes: 1) hearing from one individual simplified and humanized the project for external audiences, created a more streamlined experience for stakeholders, and promoted a sense of personal accountability among participants engaging with the process; 2) this allowed SC members to participate more fully as expert members of their respective TATs; and 3) provided additional accountability to the stakeholders by ensuring that responses were representative of the entire SC (and not subject to a potential imbalance of influence that might have occurred had inquiries gone to a single member of the SC).

Accessible Communication of Complex Information

The outcomes of TIFF reflect the engagement of more than 500 experts. Technical content was generat-ed by the partner agencies, Team Champions, the four TATs, and contracted Study Providers represent-ing more than 15 universities across a multitude of disciplines. **Ultimately, it was the facilitators who transformed these disparate inputs into the organized and unified voice of TIFF presented in this report.**

Along the way, facilitators helped make technical material more understandable by synthesizing dense content into summaries, visuals, and plain-language explanations. Curated presentation materials, workshop summaries, and structured feedback loops helped stakeholders understand highly technical content and contribute meaningfully. This enabled broader engagement and ensured that the project's outcomes were communicated in accessible and actionable formats. Additionally, to foster participatory learning and greater engagement in key elicitation exercises, the Facilitation Team tested and utilized a variety of multi-modal interactive tools and formats to best meet the needs of participants with different learning styles and asynchronous availability.

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Neutrality, Transparency, and Responsiveness to Advisor Input

The promise of TIFF was to gather the best minds in each discipline related to coastal flooding and ask for their critical review of the project's goals, implementation, and ultimate outcomes. To ensure that the advisors had the promised influence, the project consistently embraced change in response to the feedback, worked with power imbalances between the participating experts and the partner agencies, and dealt with any arising conflict.

Process documentation is an often-underestimated component of successful facilitation and is key to demonstrating neutrality and providing the transparency necessary to keep all participants on equal footing. Significant effort went into distilling the technical deliberations and making all materials accessible to the TAT members.

Designing and Delivering Effective Meetings

Facilitation can be a powerful tool to help groups work together more effectively, resulting in improved knowledge exchange and enhanced learning. Through intentional process design, the Facilitation Team made a lasting impact in achieving TIFF's desired outcomes by reinforcing alignment, sustaining engagement and communication, and serving as an accountability partner to the SC. These efforts helped TIFF maintain momentum and consistency throughout a multi-year, multi-agency planning process.

Engagement Tools for Participation and Feedback

The facilitation approach provided space for authentic engagement. Through carefully designed meetings, adaptive tools, and inclusive communication strategies, the team ensured that TAT expert feedback was effectively incorporated into the development of TIFF's 54 draft recommendations. This feedback loop grounded the final recommendations in real-world expertise and positioned TIFF as both a technically sound and stakeholder-informed initiative.

Together, these efforts built a strong, recognizable brand identity that reinforced TIFF's mission and vision.

A home damaged by Hurricane Dolly on South Padre Island © FEMA

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Facilitation Activities

To support engagement across technical experts and stakeholders, the Facilitation Team led the planning and facilitation of four types of meetings:

1. **Leadership Team Meetings** were used to establish and clarify project outcomes and deadlines. The Facilitation Team leveraged Microsoft Teams and SharePoint (cloud-based, centralized collaboration and filing platforms compatible with SC requirements) to host regular coordination and planning/debrief meetings with the SC. These platforms also supported team building, strategic planning, and broader project management efforts. Early on, the Facilitation Team gathered information about the project and participants, collaborating with the SC to refine the project's purpose and identify desired outcomes. Based on these discussions, the team developed a TIFF Leadership Team Charter. The Charter was a process design that served as a blueprint for how the group would work together, manage conflicts (e.g., scheduling tensions), and stay aligned on goals. The Charter outlined the project scope, roles, responsibilities, and norms of collaboration. Although not a legal agreement, it represented a shared commitment among team members to participate and contribute meaningfully to the project. It was treated as a living document, updated as needed to reflect evolving agreements and needs.

2. **Component Champion Meetings** were used to prepare for each Component's TAT engagements. The Facilitation Team worked closely with Champions to confirm the TAT's requirements and co-develop meeting agendas aligned with Component objectives. This included identifying the necessary materials (e.g., reports, surveys), ensuring that crucial support roles were in place (e.g., speakers, panelists, moderators), and tying each agenda item to specific outcomes. The goal was to ensure each meeting was purposeful, well-supported, and results-driven.

3. **Component TAT Meetings** convened technical experts to synthesize knowledge, share feedback, and guide the project from vision to execution. The Zoom virtual platform was utilized to facilitate technical workshops and TAT meetings/events. Zoom polls and Whiteboards, Qualtrics Surveys, Survey123 (for mapping areas of priority), Miro boards, Mentimeter, Google Jamboards, and more were used to elicit TAT expertise and ensure engagement.

   Before each meeting, the Facilitation Team organized meeting logistics and developed meeting materials (such as meeting agendas, facilitation plans, and logistics and coordination plans) to ensure the limited time was effectively used. At the start of each meeting, the Facilitation Team clarified its role to support the TAT in navigating its work and staying focused on its objectives. Facilitators remained responsive to group dynamics and unexpected challenges, adjusting as needed while maintaining forward momentum. Through steady presence and confidence in the process, the Facilitation Team helped TATs build a shared understanding, navigate through project complexities, and make informed decisions. The goal was to ensure that each meeting concluded with a sense of progress and gratitude, reinforcing the TAT's contribution to the project's overarching goals and outcomes.

   The Facilitation Team prepared executive summaries of technical information discussed or produced during TAT meetings and technical workshops hosted by TIFF, or as requested by the SC. The Facilitation Team also led communications and information distribution to technical experts and TATs and other stakeholders, to support online and offline collaboration and stakeholder engagement. Outreach strategies and materials beyond meetings included interviews, surveys, polls, fact sheets, handouts, infographics, videos, and other educational tools.

4. **Ad Hoc Workshops and Brown Bag Webinars** were used to ensure that priority topics, questions, and challenges identified by the TAT were acknowledged and addressed accordingly. Although not initially envisioned, these customized sessions provided the flexibility needed to

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adapt to unforeseen needs that arose for each Component's TAT and project changes that resulted from ongoing coordination with other statewide flood planning initiatives.

5. **Coordination Meetings** were organized by the Facilitation Team when the complexities of project delivery resulted in deviations from the original schedule (specifically the scheduling of component contract deliverables). These meetings included coordination sessions with the Leadership Team and individual calls with Component Champions to clarify workshop objectives.

PROJECT SCHEDULE

The Meadows Center's facilitation activities evolved over the course of the TIFF project to support its dynamic needs and maintain momentum (Figure 5-1). Below is a year-by-year summary of key milestones.

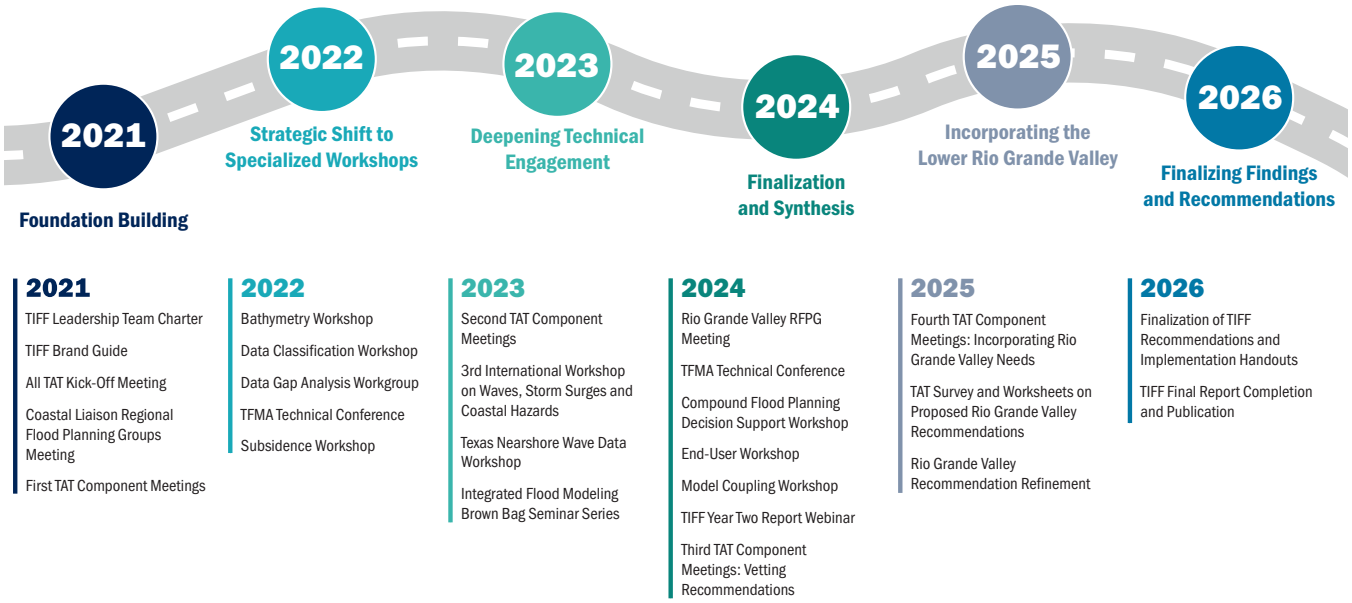

Figure 5-1. Timeline illustrating key project milestones.

2021: Foundation Building

In its first year of implementation, TIFF strategically focused on establishing a strong foundation for stakeholder engagement, project identity, and collaborative governance. The Facilitation Team worked closely with the SC to co-develop critical structures and launch the first series of TAT and stakeholder engagements.

Key activities and engagements included:

- **TIFF Leadership Charter**: Defined the project's mission, vision, and general execution approach; established targets for TAT meeting schedules; and clarified the roles and responsibilities of the SC, Facilitation Team, and Components 1–4.
- **TIFF Brand Guide**: Created a consistent project identity by outlining guidance on logos, color palettes, and font styles for all communications and materials.
- **TIFF Components (1–4)**: Finalized a membership list of 96 confirmed TAT participants across all components, including details on initial TAT nominees and final membership as of June 2021, as confirmed by the SC.

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- **TAT Kick-Off Meeting, all components (April 5)**: TIFF's first meeting brought together participants from federal and state agencies, academia, and regional entities to introduce the TIFF partners and Facilitation Team, and to orient attendees to TIFF's scope, timeline, and structure.
- **Coastal Liaison Meeting with RFPGs (September 1)**: Held a virtual session with RFPG representatives to discuss how TIFF tools and data could support ongoing regional planning.
- **First Round of Component-Specific TAT Meetings (December 6-9)**: Convened four virtual meetings for each component, marking the beginning of sustained technical engagement.

2022: Strategic Shift to Specialized Workshops

The second year of TIFF was marked by a responsive approach that directed focus to areas where momentum is gathering in the technical communities around data collection, integrated modeling, flood communication, and flood planning. This included ongoing coordination with the project's key Texas stakeholders, such as the GLO River Basin Study Groups, CHARM, TDIS, and TWDB's RFPGs, as well as distinguished academics and experts serving as TAT members. These efforts led TIFF to adopt a workshop model focused on emerging priorities within each component, which in turn broadened national engagement around cutting-edge flood science.

A total of four topic workshops were held across all Components (1-4):

- **Bathymetry Workshop (May 2022)**: Participants explored needs and standards for bathymetric data along the Texas coast.
- **Data Classification Workshop (May 2022)**: This workshop engaged TAT members in identifying consistent classification schemes for flood-related data.
- **Data Gap Analysis Workgroup (July 2022)**: TIFF facilitated a TAT workgroup to analyze and prioritize gaps in coastal flood data across Texas.
- **Subsidence Workshop (September 2022)**: This workshop convened experts to discuss coastal land subsidence and its role in flood risk.

2023: Deepening Technical Engagement

In its third year, TIFF undertook outreach efforts to clarify data needs for incorporating compound flood modeling outputs into traditional tools and models, and proposed guidelines to best balance scheduling and practical application concerns. TIFF engaged regional planners, stakeholders, and technical end-users to better understand the planning needs and tools required for more informed regional decision-making. Additionally, TIFF worked with priority end-user groups (*Property Owners*, *Property Renters*, and *Individuals with LEP*) to identify their decision-making needs regarding datasets, modeling, and visualization.

Major facilitation activities included:

- **Second Round of TAT Component Meetings (March 22-23)**: Held virtually, these meetings leveraged interactive platforms, such as Google Jamboard and Poll Everywhere, to review and prioritize technical recommendations.
- **International Workshop on Waves, Storm Surges, and Coastal Hazards (October 1-6)**: TIFF designed and presented a project poster and gathered expert input on coastal dynamics and modeling frameworks.
- **Texas Nearshore Wave Data Workshop (November 2)**: A virtual session was hosted to evaluate wave monitoring needs for coastal flood modeling.
- **Integrated Flood Modeling Brown Bag Seminar Series (July 2023-April 2024)**: TIFF led a seven-part seminar series on integrated flood modeling, featuring expert discussions on innovative modeling strategies and tools.

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2024: Finalization and Synthesis

The fourth year of TIFF centered on synthesizing the questions, feedback, and findings gathered from all components, TATs, and stakeholders engaged throughout the effort's first three years. This comprehensive synthesis, combined with ongoing outreach and engagement, led to the initial development of 42 potential TIFF recommendations. These recommendations aim to improve flood hazard characterization in the Texas coastal region, help coastal communities better prepare for future floods and safeguard lives and property, and support regional flood planning and mitigation efforts. This initial set of potential TIFF recommendations would be later expanded into 54 TIFF recommendations after incorporating specific considerations for the LRGV in 2026.

Engagement highlights included:

- **TFMA 36th Annual Meeting (2024)**: TIFF was featured via an exhibitor booth and direct engagement with regional flood professionals.
- **Compound Flood Planning Decision Support Workshop (April 18)**: The team facilitated a session focused on aligning TIFF outputs with planning needs at the local and regional level.
- **Stakeholder Needs Workshop (June 28)**: TAT members gathered to discuss best practices for communicating flood information to end-user groups.
- **Model Coupling Workflow Workshop (August 6)**: The Facilitation Team guided a technical discussion around integrating inland and coastal flood models.
- **TIFF Year Two Report Webinar (August 8)**: TIFF delivered a virtual presentation of the Year Two Report, showcasing progress and setting the stage for final TAT engagements.
- **Third Round of TAT Component Meetings – Vetting Recommendations (September-December)**: Hosted final meetings for each component to vet, refine, and confirm the 41 TIFF recommendations based on expert and stakeholder input.

2025: Incorporating the Lower Rio Grande Valley

The final year of TIFF focused on incorporating the LRGV into the TIFF study area with region-specific objectives.

Key activities and engagements included:

- **TIFF TAT Meetings (October 15 and 22)**: Meeting the Flood Visualization, Planning, and Outreach needs of the LRGV
- **TIFF TAT Meetings (October 17 and 24)**: Meeting the Integrated Flood Modeling Needs of the LRGV
- **TIFF Component 3 Team Champion's Call (November 20)**: Refine LRGV Recommendations
- **TIFF Components 2 and 4 Team Champion's Call (November 25)**: Refine LRGV Recommendations

2026: Finalizing Findings and Recommendations

A coordinated peer review between the Steering Committee and TATs was conducted to vet and optimize the final recommendations made by TIFF to meet the data and monitoring gap analysis, data management and visualization, integrated flood modeling, and flood communications needs of the LRGV.

Key activities and engagements included:

- TIFF TATs Survey on New Proposed Recommendations for the LRGV
- TIFF TATs Worksheets on New Proposed Recommendations for the LRGV

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The TIFF Recommendations Process

The Facilitation Team coordinated two series of individual TAT Component meetings in 2024 and 2025 (TIFF Original and TIFF LRGV). These meetings served as a culminating step in the TIFF engagement process, bringing together TAT members to revisit their original and LRGV-revised Component objectives, refine draft Component recommendations that resulted from TIFF's research partners and the Annual Reports, and propose additional Recommendations to more fully meet the original and LRGV-revised TIFF objectives.

TIFF Recommendations for the Footprint of Hurricane Harvey

From September to December 2024, the Facilitation Team coordinated the third series of individual TAT Component meetings, bringing together TAT members to revisit their original Component objectives, refine draft Component recommendations that resulted from TIFF's research partners and the Years One and Two Reports, and propose additional Recommendations to more fully meet the original TIFF objectives.

The TATs were guided through a rigorous review and refinement process to finalize the TIFF Recommendations included in this report:

1. Reintroduction to Objectives: Meetings began with a review of the component's original objective list, highlighting two to three objectives as the focus for that meeting
2. Review of Supporting Material: Champions or Study Providers presented relevant background information and led Q&A sessions to ensure participants were prepared to engage thoughtfully
3. Review existing recommendations
    a) Facilitators posed the question live and collected feedback via chat or audio: Is the recommendation sufficient as written, or do enhancements need to be made? If not, the group collaborated to revise the language.
    b) The question was then re-asked to confirm consensus on the updated version.
4. Optimize recommendation language
5. Evaluate whether the recommendations fully addressed the highlighted objective. If any participant answered "No," facilitators supported the development of additional recommendation proposals.
6. Propose new recommendations, as needed
7. Once all proposals were gathered, or if all agreed the objective was considered addressed, facilitators guided the group in defining implementation details (partners/stakeholders, resources/ costs, and time considerations).
8. Consider key partners or stakeholders; estimated resources or costs; and time sensitivities, deadlines, and deliverables.
9. If any additional recommendations required further context or clarification, the Component Champion or Study Provider(s) would present supporting materials and lead a Q&A discussion.
10. This process was repeated for all recommendations under the highlighted objective.
11. Once consensus was reached, the TAT Review phase concluded for that objective.
12. For participants unable to attend, or needing more time, follow-up surveys were distributed after select meetings. These surveys mirrored the meeting discussions and included the same TAT Review and Certification questions.
13. Once all necessary recommendations and implementation details were complete, the TAT Certification phase concluded.

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The TAT Review and Certification phases were repeated for each set of highlighted objectives throughout the September-December meetings, covering as many objectives and recommendations as time allowed.

Following this third series of TAT individual component meetings, a *TIFF Components 1-4 Survey: Technical Advisor Feedback on Potential Recommendations* was distributed to capture the final TAT review of all potential recommendations for all Components (1-4). Additionally, the SC identified 20 key technical advisors across the four components to conduct a more in-depth review of recommendations identified as SC priorities. All collected feedback throughout this engagement process was used to shape the final set of TIFF Recommendations. Every recommendation was reviewed by the SC, which made the final decision on whether to incorporate the TATs' input.

After collecting all feedback, the SC had a debriefing with the Facilitation Team to discuss the findings. Together, they used the insights from TAT members and coordinating agencies to refine the TIFF Recommendations. The final recommendations were then formatted into one-page handouts for sharing with potential funders. See the TIFF Recommendations section for detailed handouts.

TIFF Recommendations for Lower Rio Grande Valley

From October 2025 to March 2026, the Facilitation Team 1) coordinated the final series of individual TAT Component meetings, bringing together TAT members to clarify their new LRGV Component objectives; 2) refined draft Component recommendations that resulted from TIFF's research partners and the Year One LRGV Report, and 3) proposed additional Recommendations to more fully meet the new LRGV TIFF objectives.

The TATs were guided through a similar review and refinement step-by-step process used in 2024 to finalize the TIFF Recommendations; but this process was less formal and provided a space for open dialogue.

Meetings opened with Champions or Study Providers presenting relevant background information to ensure participants were prepared to engage thoughtfully. The TAT reviewed existing recommendations that resulted from the Component work and proposed new recommendations to meet the flood information needs of the LRGV, as needed. Once all proposals were gathered, facilitators guided the group in defining implementation details (partners/stakeholders, resources/ costs, and time considerations). This process was repeated for all new recommendations. For participants unable to attend, or needing more time, follow-up worksheets were distributed after select meetings. These worksheets mirrored the meeting discussions and included the same prompts for TAT review.

Following this final series of TAT individual component meetings, a *TIFF Components 1-4 Survey: Technical Advisor Feedback on LRGV Recommendations* was distributed to capture the final TAT review of all potential recommendations. After collecting all feedback, the SC had a debriefing with the Facilitation Team to discuss the findings. Together, they used the insights from TAT members and coordinating agencies to refine the TIFF Recommendations. The final recommendations were then formatted into one-page handouts for sharing with potential funders. See the TIFF Recommendations Handouts which can be used to seek further support for implementation.

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Interagency Collaboration Lessons Learned

While the TIFF project stands out as a breakthrough for collaborative science and the advancements it will bring to Texas' ability to plan and respond to floods, the project has also offered some important lessons for future interagency collaborative efforts. This section reflects on both what worked well and where limitations surfaced, offering actionable insights for future efforts involving cross-disciplinary collaboration and facilitation. These lessons point to the importance of embedding facilitation early on, clearly defining roles, and maintaining open communication across teams:

1. **Flexibility in facilitation strategies is essential**: The process designed for the implementation of TIFF centered around a feedback loop. An initial vision was presented to the identified Technical Advisors with the hope and expectation that the advisors would guide the project in new directions. While the project was greatly enhanced by its flexibility and responsive approach, the contracts, staffing, and deadlines governing the project did not allow for the degree of influence and adaptation that best suited the outcomes.

   When project deliverables and timelines evolved, the Facilitation Team had to continually adapt its approach, shifting from general engagement to more specialized workshops, adjusting meeting formats, and revisiting timelines. Flexibility proved critical in maintaining engagement despite uncertainty.

- **Interactive tools increase engagement across audiences**: The use of tools like Qualtrics, Miro, Zoom Whiteboards, Poll Everywhere, and Survey123 helped engage both technical and non-technical participants in virtual settings. These platforms allowed for real-time feedback, continuous input, and visual collaboration, making complex content more accessible and inter-active. It is important to note that time should be spent teaching participants how to use the interactive tools, along with regular check-ins to assist with any difficulties. Other considerations for future projects interested in using these or similar tools include: 1) time should also be built in to allow facilitators to learn and test tools, 2) costs for tools should be considered in project budgets, and 3) workarounds may be needed to include participants who have security restrictions that prevent them from accessing these tools.
- **Consistent documentation supports continuity**: Meeting notes, executive summaries, and synthesis materials helped maintain momentum and institutional memory, especially when staff turnover, shifting roles, or timeline extensions occurred. Reliable documentation became a key tool for knowledge transfer and decision-making.
- **Long-term expert collaboration sustains momentum**: TIFF was designed to build a cross-disciplinary, multi-institutional network of experts. When regular engagement was possible, expert input greatly improved the quality of technical outputs. Sustained collaboration must be prioritized to retain continuity, trust, and momentum over time. Identifying the Lead Facilitator as the TIFF Point of Contact also enhanced accessibility and accountability of the project to the Technical Advisors and broader network of experts and stakeholders.
- **Facilitation role should be embedded into the project design from the start**: While TIFF recognized the importance of the facilitation role from the start, there were implications from having the Facilitation Team brought on as contractors after some of the initial project decisions had already been made. The SC successfully folded the Facilitation Team into the Leadership Team and fully supported the facilitation role, but the process continued to be constrained by some of the early structural decisions that were made before the engagement strategy could be developed.

Challenges That Shaped These Lessons

TIFF is a model for science collaboration and eliciting expertise to guide public decision-making. The project brought together experts who might not have otherwise had an avenue to engage in this kind of collaborative work, placing them directly in the driver's seat to shape TIFF's outcomes. This interagency

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and interdisciplinary coordination responded to an immediate need, enhancing Texas's coastal flood resiliency, and condensed what might have taken decades into a quick and efficient cycle of research and peer review. This pace, at times, came at the expense of facilitation. Over the course of the multi-year endeavor, several challenges emerged that limited the full potential of facilitation. Consideration of these obstacles offers design opportunities for future collaborative, multi-agency projects.

- **Divided coordination roles between the SC and the Facilitation Team**: There is a natural tension between the project management role and the facilitation role. This can create redundancies, slow communication, and dilute accountability. The partner agencies each carried multiple project roles (e.g., Component management, contract management, research coordination) which, at times, resulted in canceled planning sessions and gaps in internal coordination. Project delays led to delayed outreach to TATs and reduced opportunities for expert review and stakeholder engagement.
- **Traditional task-based contracts are not the best tools for "flying the plane as we build it"**: True to its word, TIFF is an adaptive endeavor, responding to the input and guidance of the experts engaged in the project. Additionally, while the project's contracts set out with a clear vision, other statewide initiatives related to flood planning and science were simultaneously evolving (e.g., RBFS, TDIS) and influenced significant changes in the TIFF scope over the life of the project. The TIFF Leadership Team stayed committed to delivering the optimal outcomes and absorbed mounting calls for changed schedules, additional workshops, and enhanced coordination with study providers. This came at the cost of internal budgets, delayed project timelines, and ultimately reductions in the frequency and planning available for TAT engagement.
- **Underestimation of the facilitation needs**: If facilitation is viewed as a delivery function only (versus a guiding principle in overall process design), the associated work can be underestimated and undervalued resulting in a lack of sufficient funding, delayed inclusion in planning conversations, and missed opportunities for strategic alignment. When practical, the Facilitation Team should be included as an equal decision partner in all of the scoping and planning from the very beginning of a collaborative endeavor, rather than being hired in service to a partial vision already constrained by contracts and commitments.
- **Conflict of interest concerns challenged crucial coordination with the Facilitation Team**: Because the Meadows Center was a contracted entity that hypothetically could have competed for other project contracts, the SC developed procurement processes for key aspects of the project without the participation of the Facilitation Team. (Note: A "non-compete" clause in the Meadows Center's facilitation contract (disallowing any additional TIFF contracts with the Center) could have allowed the facilitators to more fully participate and guide the scoping, planning, and integration of the contracted technical work conducted by Study Providers.)

  Due to the timing and contracting pressures of the overall TIFF project, the deadlines of these contracts were independent of the deadlines associated with the TAT engagement and annual report deadlines. This provided a key challenge in regard to having the engagement goals be the driving influence on sequencing/timing of technical work and expert review. Ultimately, the structural limitations around potential conflicts of interest undermined the facilitators' ability to serve as process stewards, co-creating in collaboration with the SC. This model also limited the project's ability to seek input from Technical Advisors as Scopes of Work were developed, which may have enhanced the work of Study Providers.

Power sharing has inherent challenges, and there are trade-offs with any collaborative process design. Based on these learnings, some recommendations to consider for facilitated interagency collaboratives include: 1) when possible, facilitation considerations should be included from the start and before final process decisions are made and should be informed by the facilitator, 2) facilitation contracts should be as flexible as possible to allow for changes in project delivery that best suit the project, and 3) non-compete clauses should be considered for all interagency partner contracts to eliminate unnecessary complexity and ensure that all project partners are unencumbered and can be fully participatory in key decisions.

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Storm over South Padre Island, Texas © David, Adobe Stock

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6 Texas Integrated Flooding Framework Recommendations Handouts

ACTIONABLE RECOMMENDATION SUMMARIES THAT CAN BE PRINTED AS HANDOUTS TO GUIDE DECISION-MAKING

The TIFF Recommendations are the culmination of five years of collaborative research, technical engagement, and expert consensus. More than 125 national experts representing state and federal agencies, academic institutions, and local governments contributed to this integrated framework that seeks to equip local, regional, and state entities—along with other stakeholders and households—with the compound flood risk information and tools needed for comprehensive flood planning and mitigation.

These 54 actionable Recommendations are organized by focus area:

1. Improved Data and Monitoring Gap Analysis
2. Improved Data Management and Visualization
3. Improved Integrated Flood Modeling
4. Improved Flood Planning and Outreach

Each TIFF Recommendation can be funded and pursued independently or aligned within broader, multi-agency initiatives to advance integrated flood resilience across the state. The TIFF Recommendations have been formatted for convenient printing and distribution to support advocacy for their implementation, either individually or as a part of a coordinated effort.

The Recommendations are designed to articulate implementation needs, and where feasible, approximate costs. These cost estimates are included for planning purposes only and should be understood as preliminary and subject to refinement based on project scope, timing, and local/regional conditions and circumstances. In all cases, implementation of these Recommendations will require the identification and securement of appropriate funding. Additionally, implementation of these Recommendations is subject to the legislative authority and capacity of potential partners. Collectively, the Recommendations are designed to provide funders and policymakers with a clear roadmap for strengthening the state's flood resilience, ensuring that communities, infrastructure, and ecosystems along the Texas coast are better protected for the future.

Suggested citation and additional context: Texas Integrated Flooding Framework, *2026 Final Report Recommendations to GLO* (Texas Water Development Board, U.S. Army Corps of Engineers at Galveston District, U.S. Geological Survey, Meadows Center for Water and the Environment) https://texasflood.org/tools-library/tiff/reports.html.

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ENHANCE THE COASTAL DATA SURFER (CDS)

Enhance the Coastal Data Surfer for displaying, inventorying, and evaluating data to support flood planning, modeling, mapping, and mitigation along the Texas coast

Researchers, planners, and policymakers need a centralized, web-based tool to access and analyze flood-related data. The Coastal Data Surfer (CDS) serves this role by integrating national, regional, and local datasets covering the entire Texas coast. Designed for a broad audience across disciplines involved in flood planning and mitigation, the CDS will be a dynamic platform that evolves with the rapidly changing landscape of coastal flood research.

Ongoing resources are essential to ensure the CDS goes beyond data visualization. It identifies gaps in existing datasets to improve awareness of available data and past efforts, reduce duplication in data collection and modeling, and enable timely updates to maintain relevance and usability.

Project phases and deliverables should align with other agency flood and hazard mitigation planning cycles, such as the Texas Water Development Board Regional Flood Plans and State Flood Plan. Ongoing maintenance costs vary annually and should be allocated across project phases. Agencies can collaborate on funding different phases or use a cost-sharing formula. Key costs include cloud hosting, data storage, production, user interface/user experience (UI/UX) components, security services, and technical debt management.

The CDS is a crucial and ongoing investment that will need to be maintained and updated to ensure it remains a valuable resource.

KEY IMPLEMENTATION ACTIONS

- **Define Metadata Standards**: Collaborate with partner agencies to categorize hydraulic and hydrologic models in Texas and ensure consistency for future data input and updates; use the Texas Disaster Information System (TDIS) Data Management Query Tool as a potential reference
- **Deploy Beta Version**: Gather user feedback from scientists, modelers, engineers, and other stakeholders; assess usability based on searchability, metadata effectiveness, and dataset availability
- **Integrate Spatial Data**: Guided by the data gap analysis performed by users, optimize the CDS to highlight those data gaps to inform future planning and modeling needs (e.g., identifying where to expand continuous monitoring, improving flood emergency response)
- **Follow-Up Evaluations**: Gather user feedback and refine its functionalities; implement necessary updates and optimizations to improve overall performance
- **Inventory and Gap Analysis**: Conduct an initial inventory to assess dataset availability, followed by targeted gap analyses to prioritize modeling approaches; identify evolving data needs, including critical hydrologic, hydrodynamic, meteorologic, and socio-economic datasets; enhance the CDS to support temporal data searches linked to study requirements
- **Maintenance and Five-Year Updates**: Align updates with State and Regional Flood Planning Cycles; create a dashboard feedback mechanism and working group email alias to facilitate continuous updates; expand application programming interface capabilities; validate metadata completeness and system integrity; catalog machine-readable data with a defined metadata schema and explore opportunities for data digitization
- **Cost-Effective Data Hosting**: Consider shared responsibilities for deploying and hosting the CDS, including the potential for long-term hosting by TDIS; align hosting strategies with the U.S. Geological Survey-led data gap analyses

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EXPAND MEASUREMENT NETWORKS

Expand measurement networks to under-sampled locations, prioritizing by flood frequency and severity

In-situ measurements, such as rain gages, often struggle with representativeness, record length, and spatial coverage, but they play a crucial role in monitoring coastal inundation, rainfall, river stages, and nearshore wave conditions–especially in areas where lower-resolution data fail to accurately capture real-world conditions. In regions with insufficient coverage, additional sensors may be necessary to enhance data reliability.

TIFF recommends expanding the measurement networks to enhance regional flood characterization, particularly in under-sampled areas identified by flood frequency and severity analyses, such as the Lower Rio Grande Valley (LRGV). Site selection should also prioritize locations based on their proximity to vulnerable infrastructure and populations–such as Colonias in South Texas, which are disproportionately situated in flood-prone regions.

Potential partners include agencies experienced in facilitating regional flood planning and coordination, experience in managing local sensor networks, coordinating emergency management, collecting inundation photos to enhance observations, expertise in socio-economic flood risk factors, and imagery data storage. Key stakeholders include county agencies and non-profits that can serve as community organizers and connectors.

Ongoing maintenance costs will vary annually. Key costs include field operations, hosting the database, and infrastructure development.

KEY IMPLEMENTATION ACTIONS

- **Inventory and Gap Analysis**: Inventory existing monitoring infrastructure and activities in the region to identify the gaps between existing and needed monitoring activities; identify under-sampled areas based on flood frequency, severity, and proximity to vulnerable infrastructure and populations; identify priority locations for expanded flood monitoring and prediction
- **Expand Sensor Networks**: Expand local sensor networks along urbanized and industrial corridors, and near-shore and near-coastal transition zones; explore funding opportunities through local jurisdictions
- **Data Collection**: Archive continuous historical and real-time data encompassing streamflow, rainfall, groundwater levels, and meteorological forcings (e.g., wind speed, barometric pressure, and tide levels)
- **Standardized Data Integration**: Develop best practices for verifying and incorporating diverse datasets into flood models, ensuring consistency across studies; one potential resource for this action is the Institute for a Disaster Resilient Texas pilot community data collection tool
- **Improve Data Completeness**: Address data gaps by integrating anecdotal sources from local and expert stakeholders (e.g., community and citizen science contributions, local agency data, timestamped inundation photos, media reports)
- **Capacity Building**: Build interagency partnerships to ensure interoperability, open data access, and long-term system sustainability
- **Prioritize Under-Sampled Locations**: While under-sampled locations, such as the LRGV, have often experienced flood events over the years, current flood monitoring coverage in the region is concentrated around major waterways, leaving critical gaps where flood processes are poorly understood. Use the LRGV as a testbed to guide measurement network expansion in other under-sampled and hydrologically unique regions in Texas; deploy strategically placed real-time data collection stations and enhance forecast reliability for emergency management and local planning

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NEARSHORE WAVE DATA COLLECTION NETWORK

Establish a Nearshore Wave Data Collection Network along the Texas coast to address critical data gaps and enhance the understanding of extreme wave events, improve daily flood forecasting, and strengthen coastal risk assessment

Nearshore wave data is essential for designing coastal structures, managing shorelines, assessing hazard risks, and advancing research. However, the availability of such data remains limited due to the challenges of collecting measurements in remote coastal areas. More comprehensive data is needed to refine model forecasts and provide near-real-time updates on wave properties.

Ongoing maintenance costs will vary annually. Key costs include instrumentation, installation, field visits, and data storage.

KEY IMPLEMENTATION ACTIONS

- **Inventory and Gap Analysis**: Conduct an inventory and gap analysis of nearshore wave data along the Texas coast to improve understanding of extreme wave events and flood forecasting; use existing models and datasets to identify priority regions based on coastal infrastructure, population growth, and risk factors; focus on areas with inconsistent wave measurements, such as Galveston Bay, Port Arthur's Pleasure Island, Keller Bay, Carancahua Bay, and Port Aransas
- **Instrumentation Selection**: Deploy 1) offshore buoys with independent power supplies that report data every 30-60 minutes, 2) nearshore sensors transmitting real-time directional and non-directional wave data, and 3) shore-based sensors activated during inundation events; prioritize cost-effective solutions and integrate a Global Positioning System into existing systems (e.g., Texas Disaster Information System or Texas A&M University Texas Automated Buoy System)
- **Deployment of Monitoring Stations**: Identify and secure monitoring station locations, ensuring resilience to extreme weather; assess permitting requirements for deployments; develop nearshore and shore-based monitoring infrastructure (may require specialized platforms)
- **Model Integration and Forecasting**: Integrate real-time data into wave, surge, and inland flood models; combine observational data with model outputs for hourly forecasts to cover the Texas coast; adapt existing models for seamless integration
- **Data Management and Sharing**: Establish a centralized platform for real-time data sharing and long-term storage of high-resolution (15-minute interval) and high-frequency (6 Hz or higher) wave data; store raw data in barometric-corrected Network Common Data Form format per climate and forecast metadata standards
- **Long-Term Maintenance and Partnerships**: Build interagency partnerships for sustained data collection and funding; dedicate $100,000–$1,000,000 per year for measurements, $200,000 per year for modeling (with potential increases for model development), and $500,000 for initial buoy deployment

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A CENTRALIZED SUBSIDENCE MONITORING DASHBOARD

Develop and maintain a Subsidence Monitoring Dashboard to serve as a centralized, comprehensive, user-friendly platform to consolidate, analyze, and utilize subsidence data

Subsidence, the gradual sinking of the Earth's surface, presents critical risks to Texas' infrastructure, water resources, and land management. However, current subsidence data is fragmented across various sources, making it challenging for decision-makers to fully understand and address the issue. Additionally, the absence of integrated tools for basic analyses and interpretation limits the ability to apply this data effectively to practical solutions.

TIFF recommends developing a dashboard to integrate innovative remote sensing technologies, such as InSAR (Interferometric Synthetic Aperture Radar), to provide high-resolution, accurate, and timely subsidence rate data. The dashboard would also centralize information from state and federal agencies, universities, and private entities, creating a single repository for easy access. Analysis tools will enable users to assess subsidence trends over time and across geographic areas. Additionally, the dashboard will automate annual InSAR data downloads and processing to ensure consistent updates.

Streamlining access to subsidence information and analyses will empower stakeholders to develop informed, effective strategies for mitigating the risks associated with subsidence in Texas. Subsidence districts can play a key role by utilizing their existing monitoring stations. These stations could also help expand monitoring efforts to other subsidence areas across the state.

The Centralized Subsidence Monitoring Dashboard is a crucial effort with an initial investment estimated at $200,000–$400,000.

KEY IMPLEMENTATION ACTIONS

- **Needs Assessment and Planning**: Engage stakeholders to define requirements for data sources, tools, and quality assurance/quality control (QA/QC) processes; collaboration with experts is critical to outline technical specifications for integrating InSAR data and create a detailed project plan with timelines and budgets
- **Data Integration**: Partner with agencies, universities, and private entities to consolidate subsidence data into a centralized repository; the dashboard should be built to meet accessibility standards, incorporate InSAR data, and implement algorithms for calculating subsidence rates
- **Quality Control**: Develop QA/QC protocols to ensure data accuracy and establish ongoing validation with periodic updates
- **User Testing**: Conduct iterative testing with stakeholders, gathering feedback to refine functionality and usability
- **Launch and Support**: Launch the dashboard, promote its use, provide training, and establish systems for regular updates and tool enhancements

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DEPLOY HIGH-RESOLUTION LAND COVER DATA TO ENHANCE FLOOD MODELS

Compile, collect, process, and integrate high-resolution land cover data to enhance flood models for the Texas coast and provide guidelines for implementation into Texas coastal flood modeling systems

Accurate and up-to-date land cover data is critical for coastal flood modeling. This data provides more detailed surface distinctions—such as urban structures, vegetation, and waterbodies—compared to traditional 30-meter datasets, which are essential for flood impact prediction and management.

This data will:

- improve understanding of water flow dynamics and land cover effects
- enhance flood routing simulations for infrastructure and asset risk assessment
- support long-term assessments of sea-level rise and coastal changes
- align flood management with federal standards, fostering better coordination with federal agencies
- improve flood resilience planning tools used by all levels of decision-makers, supporting emergency and long-term response efforts

Key partners include state and local stakeholders to ensure seamless data accessibility and effective implementation. The total budget is estimated to be between $1-$3 million for all Texas coastal counties. The project timeline is 1-3 years, with future updates occurring every 5-10 years, based on funding and demand.

KEY IMPLEMENTATION ACTIONS

- Build partnerships with state and federal agencies experienced in providing data access, products, and services to support community resilience such as the TxGIO, NOAA, and research institutions
- Testbed numerical model studies for performance evaluations
- Develop guidelines for integrating high-resolution land cover data into existing coastal flood models to improve flood simulation accuracy
- Integrate existing and new high-resolution data into coastal flood models

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ACQUIRE BATHYMETRIC DATA FOR PRIORITY AREAS

Collect bathymetric data for priority areas along the Texas coast to address critical data gaps, strengthen coastal flood modeling efforts, and improve flood forecasting

Bathymetric data is essential for coastal flood modeling, but the availability of high-quality data remains limited due to the challenges of collecting measurements. Bathymetry represents the three-dimensional features of underwater terrain, or bed elevation, which is highly dynamic and frequently changes with natural and anthropogenic influences. As such, data must be collected regularly to ensure it is current, accurate, and useful for coastal modeling.

TIFF recommends the collection of critical bathymetric data at priority areas along the Texas coast to significantly increase the accuracy of coastal flood modeling and forecasting. State and federal agencies and other organizations could collaborate to better coordinate bathymetry data acquisitions and leverage limited funding resources.

The cost of bathymetry acquisition depends on the type of water body (shallow, deep, and rivers), size of project, and method of collection. Partners can collaborate on funding different actions or use a cost-sharing formula, and assess additional funding needs for coastal measurement expansion.

KEY IMPLEMENTATION ACTIONS

- **Site Selection**: Begin with priority areas identified by TIFF Technical Advisors (Nueces Bay, Lower Galveston Bay, Sabine Lake, and Laguna Madre)
- **Data Integration**: Incorporate data into wave, surge, and inland flood models to enhance forecasting
- **Centralized Sharing**: Create a platform for data sharing and long-term storage
- **Build Partnerships**: Coordinate with federal, state, and local agencies experienced in data collection and management, such as the National Oceanic and Atmospheric Administration, the U.S. Geological Survey, the Texas Water Development Board, and the Texas Disaster Information System, for sustained data collection and funding
- **Quality Control/Quality Assurance Guidelines**: Standardize processes for identifying monitoring station locations and integrating data into flood models

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INTEGRATE HISTORICAL TCOON DATA INTO NOAA'S DATABASE

Integrate historical datasets from the Texas Coastal Ocean Observation Network (TCOON) in the National Oceanic and Atmospheric Administration's operational database

Long-term, continuous, and quality-controlled data is essential for understanding compound flood risks and developing reliable tools to prepare for and respond to the state's floods. The Texas Coastal Ocean Observation Network (TCOON) is a network of scientific data collection stations along the Texas coast operated and maintained by NOAA in partnership with the Conrad Blucher Institute (CBI). Historical TCOON data collected by the CBI prior to 2016 was not accepted into the official NOAA database because it was not processed using NOAA quality assurance and quality control (QA/QC) procedures. CBI has this unofficial raw data available through a web portal (https://tamucc-ir.tdl.org/handle/1969.6/89444).

To address this recordkeeping data gap, TIFF recommends acquiring and processing historical TCOON data from CBI for inclusion in NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) official and publicly available dataset.

Based on an approach and cost estimate provided by CO-OPS, a 3-year investment, estimated at $1.352 million, will significantly increase the accuracy of coastal flood modeling and forecasting while supporting flood risk management projects.

KEY IMPLEMENTATION ACTIONS

- **Tool Enhancement and Automation**: Enhance the NOAA Tidal Analysis Datum (TAD) Tool with more accurate code for data automation and the creation of automated processing/verification processes; enhancement will allow CO-OPS to process the entire historical TCOON data record more quickly and deliver updated datums within 12 months
- **TCOON Metadata Review and Integration**: Steps include 1) download the data from CBI's data management system, re-format it to CO-OPS specifications, and digitize the metadata paper records (including all site reports, leveling abstracts, benchmark descriptions, benchmark sketches, and INX files for all stations); 2) coordinate with CBI to ingest and validate the data and metadata to CO-OPS standards; and 3) hire two full-time contractors to manually enter and verify any metadata that is in paper record into the system
- **TCOON Data Processing and Verification**: Two full-time contractors will use the enhanced TAD Tool to process 5,400 months of historical TCOON data from 26 long-term water level stations; each station month is processed individually, compared against neighbors, and appropriate fills are made, then hourly heights and highs and lows are tabulated, as well as the monthly means; these data then go through a verification process
- **TCOON Data Project Management**: organize all data and metadata received from CBI and partners; develop timely progress reports on the status of the project; purchase and update standard software licenses needed to complete all tasks for the project
- **Update Additional Flood Analysis Products Used by Texas**: Prioritize products that underpin coastal mapping and flood hazard assessment (e.g., tidal datums, long-term sea-level trends) by 1) extending the five-year data series to 25 years or more to reduce the uncertainty of the various products supported with a confidence level (> 95%) that users need; and 2) expanding the Inundation Dashboard for the Texas coast with more integrated data on coastal flooding such as real-time alerts, and historic coastal inundation tracked through flood thresholds at the gage locations

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DEVELOP TESTING SITES FOR WATER MONITORING DEVICES

Test water monitoring devices for reliability, effectiveness, and compliance with regulatory standards

Coastal monitoring networks play a crucial role in flood early warning systems and mitigation planning. Innovative sensing technologies can bridge the gaps left by traditional datasets, but must be tested against established methods in real-world coastal conditions.

TIFF recommends testing sites for evaluating existing and prototype water monitoring devices under tidal fluctuation, salinity, sedimentation, biofouling, and extreme weather conditions. Objectives include assessing device reliability, longevity, accuracy, and regulatory compliance. To integrate with legacy monitoring programs and regulatory applications, data from new technologies must align with established sensing methods. Recommended technologies to test include:

- Disposable, biodegradable flood level sensors for short-term data collection in communities with limited funding; designed to last six months, these sensors offer lower data quality and are not a replacement for traditional gages
- Next-generation, submersible flood monitoring stations operate almost entirely underwater, expand monitoring coverage across waterbodies previously considered unsuitable due to installation constraints, and decrease installation costs
- Real-time flood monitors with highly configurable, System-on-Module designs that incorporate Reduced-Instruction-Set-Computer-Five and artificial-intelligence-enabled processors that would dramatically increase the speed and fidelity of core pattern-matching algorithms used to adapt machine-learned inferential forecast models
- Non-contact stream-gaging alternatives to submersible sensors for flood monitoring in areas where debris flows, sediment buildup, and erosion pose damage risks
- Rapid Deployment Gages (RDGs) to supplement existing coastal and riverine gage networks during flood events; can be pre-deployed ahead of forecasted storms to enhance situational awareness, support emergency managers, and provide temporary coverage when permanent stations fail

Partnerships with organizations experienced in monitoring (e.g., U.S. Geological Survey) and research/data collection (e.g., universities, flood control districts, specialized non-profits) can leverage existing monitoring sites to support new methods while filling spatial monitoring gaps with cost-effective solutions.

TIFF recommends a multi-year timeline to evaluate emerging technologies under various weather conditions. Annual costs are estimated to be between $500,000 and $5,000,000, with potential savings from using existing platforms.

KEY IMPLEMENTATION ACTIONS

- **Site Selection and Design**: Identify optimal coastal site(s) with local experts; design platforms that support multiple devices and meet permitting requirements
- **Equipment Selection and Installation**: Use a standardized process to select and install sensors for wave height, water quality, and weather parameters
- **Data Collection and Monitoring**: Develop a real-time data acquisition system with remote access and automated alerts for malfunctions
- **Environmental Resilience Assessment**: Evaluate device performance under dynamic coastal conditions
- **Data Analysis**: Enable stakeholders to analyze data for accuracy, reliability, and operational resilience aligned with agency requirements
- **Long-Term Sustainability**: Establish a self-sustaining model through subscription fees, grants, partnerships, and sponsorships

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ASSESS ACCURACY OF HIGH-FREQUENCY RADAR FOR WAVE MEASUREMENTS

Assess extent of High Frequency radar accuracy for wave measurements

High Frequency (HF) radar networks, commissioned by the Texas General Land Office (GLO) and the Gulf of America Coastal Ocean Observing System (GCOOS), are operational in Sabine Lake, Galveston Bay, and offshore from Bolivar Peninsula to Padre Island National Seashore. These systems provide remote measurements of ocean and estuary surface currents, supporting coastal initiatives like natural resource protection and port security. With an estimated $10 million in capital investment, these networks offer significant potential to enhance wave and current data collection compared to traditional ship- and buoy-based systems.

To assess the accuracy of HF radar data, comparative studies with in-situ measurements (e.g., buoy-/vessel-based data) are necessary. In Sabine Lake and Galveston Bay, where few buoys are available, offshore studies comparing HF radar data with Texas A&M University's Texas Automated Buoy System (TABS) and the National Oceanic and Atmospheric Administration's (NOAA) buoys are recommended. These studies will help evaluate HF radar performance under varying environmental conditions and establish correlations between different monitoring technologies.

A long-term evaluation is essential to assess the reliability and effectiveness of these systems under changing weather and ocean conditions. If proven dependable, TIFF recommends expanding HF radar coverage to additional Texas bays where such systems are not yet deployed. This expansion would help fill key data gaps–particularly in nearshore regions–by providing much-needed surface current measurements to support coastal monitoring and management efforts.

KEY IMPLEMENTATION ACTIONS

- **Comparative Studies**: Identify available in-situ monitoring stations, such as the TABS and NOAA buoys, for comparative studies; deploy temporary buoys where necessary, particularly in Sabine Lake and Galveston Bay, where in-situ data is limited; conduct comparative studies between HF radar and buoy-/vessel-based observations to evaluate performance across different environmental conditions
- **Long-Term Evaluation**: Conduct extended studies to assess the reliability of HF radar systems over time; analyze the impacts of seasonal and extreme weather events on HF radar measurements
- **Stakeholder Engagement and Reporting**: Leverage collaborations with coastal management entities, such as the GLO, GCOOS, and NOAA, to share findings; publish interim and final reports summarizing results, challenges, and recommendations; develop guidelines for integrating HF radar data into broader coastal management strategies

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STUDY USER INTERACTIONS WITH FLOOD RISK VISUALIZATIONS

Improve online tools to maximize user comprehension by studying user gaze patterns and other user responses to different flood risk visualizations and interactive tools

Research is needed to understand how individuals' gaze patterns shift when interacting with various modes of flood risk visualizations. This study will test how different modes of interaction influence user engagement and comprehension of flood risk. This includes in-situ testing, mobile device testing, and using eye-tracking with visualizations, potentially gamifying the process. Results from this study could accelerate understanding of what works for communication and complements efforts to assess emerging technology. This research should focus on testing existing and developing flood risk visualization tools used in Texas, such as the Buyers Aware platform, the Community Health and Resource Management online tool, and dashboards being developed by the Institute for a Disaster Resilient Texas and the University of Texas-Austin. This research should also consider the usefulness of technologies for communicating model outputs. By studying how users interact with these tools, we can refine their design to enhance user comprehension and decision-making, ultimately improving flood preparedness and response efforts.

The estimated cost for this research is $225,000, covering eye tracking software and hardware, virtual and augmented reality equipment, immersive software, and research design and execution. Costs may be reduced if access to existing eye tracking and keystroke tracking equipment is obtained.

KEY IMPLEMENTATION ACTIONS

- **Literature Review**: Conduct a full review of interactive and active learning technologies, including user studies and data/analytics workflows; develop serious games and explore how to engage adults in playing these games
- **Eye-Tracking and Virtual Reality Studies**: Conduct eye-tracking and/or virtual reality studies to observe how gaze behavior changes when different visual representations of flood risk are shown to participants
- **Key-Logging Study**: Combine the previous studies with a key-logging study, where participants interact with flood risk information on the web; capture and analyze their search behavior and physical actions while seeking out flood risk data
- **Misinformation Response Studies**: Conduct additional studies to understand how people respond to misinformation about flood risk; compare reactions to a continuum of flood risk levels, ranging from low to high risk, to gauge how misinformation influences decision-making

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ASSESS PUBLIC EVACUATION DECISION-MAKING

Improve emergency planning and response by better understanding the decision-making of Texas residents facing evacuation during a flood

TIFF recommends conducting experiments, surveys, and focus groups along the Texas coast to understand how residents use local knowledge, media coverage, and personal experiences when deciding whether to evacuate.

Evacuation decisions are complex and influenced by many factors, including perceived risk, prior disaster experience, and trust in information sources. A critical research question is how past disasters, community knowledge, and media coverage influence decision-making. The research should also assess public trust in local authorities, meteorologists, and emergency managers, and examine how people interpret and act on messages about evacuation orders. A mixed-methods approach should be used to identify barriers to evacuation, common assumptions about risk, and ways to strengthen public communication. Insights from emergency managers and meteorologists should be integrated to ensure recommendations align with operational needs.

Understanding how Texans decide whether to evacuate or stay can help guide improvements in outreach, communication strategies, and message design during emergencies. The estimated cost for implementation is $450,000. Participants should be compensated to ensure representative data.

KEY IMPLEMENTATION ACTIONS

- **Review State Operations Center Practices**: Interview Texas Division of Emergency Management experts to identify opportunities to improve evacuation processes, and to provide guidance on public evacuation and emergency communications strategies
- **Select Testbed Locations**: Identify testbed sites based on geographic, storm and flood risk, and population characteristics (urban and rural) to capture a range of factors influencing evacuation decisions
- **Select Target User Groups**: Prioritize target user groups based on their vulnerability to coastal flooding, such as *Property Owners*, *Property Renters*, and *People with Limited English Proficiency (LEP)*; additional research should be conducted to identify additional vulnerable populations with barriers that complicate decision-making, including Caretakers and Business Owners
- **Conduct Qualitative Studies in Coastal Communities**: Interview evacuees from the selected target user groups to understand decision drivers (reasons for evacuating, costs, influence of flood models or navigation apps) and compare public perceptions with the technical information used by experts
- **Test Tools**: Use the findings from the qualitative study to design experiments testing the effectiveness of flood maps and navigation apps in aiding evacuation decisions; tailor tools to each selected target user group

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REPLACE THE "FREQUENCY-BASED TERMINOLOGY" CURRENTLY USED TO CONVEY FLOOD RISK (E.G., "100-YEAR FLOOD")

Identify more understandable ways of communicating flood risk to the public than current "frequency-based terminology"

A significant challenge in flood risk communication is the language used to describe the probability of experiencing a flood. Longer timeframes, such as 100 or 500 years, are difficult for people to grasp, making it harder for them to accurately assess their risk.

TIFF recommends a mixed-methods study to 1) identify how people interpret current flood terminology, 2) develop and test alternative language to improve understanding and accuracy in risk perception, and 3) evaluate how those alternatives perform across languages, especially in English and Spanish given Texas's bilingual population. Future work should also develop relatable examples (e.g., this rainfall amount will carry a child/car/house away) and assess how linguistic and cultural perspectives affect comprehension of probability and frequency.

The estimated cost of implementation is $750,000. Partner agencies are encouraged to share costs and collaborate on phased funding. Participants should be compensated to ensure representative results across demographic and linguistic groups.

KEY IMPLEMENTATION ACTIONS

- **Literature Review**: Examine national and international studies on risk communication, focusing on the United States, Mexico, and China; participation in international workshops is recommended to exchange insights and best practices
- **Interview Target User Groups**: Conduct a systematic set of interviews with specific target user groups to identify alternative language and timeframe communication options
- **Online Experimental Survey**: Test Texans in these target groups to identify which language options best influence decision-making, attitudes, confidence, response efficacy, and related factors; consider using the subjective numeracy scale and common probability frames used in flood communication
- **Train Language Models**: Based on the interviews and survey findings, train small language models on the specific language used in different coastal and compound flood scenarios, including mapping preferred terms in coastal areas and considering multilingual aspects
- **Evaluate Flood Literacy**: Determine whether alternatives to frequency-based terminology increase flood literacy in target user groups and improve their capacity to respond effectively to risk information

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CREATE FLOOD RISK PLANNING CARDS

Create Flood Risk flashcards to support Texas flood planners and decision-makers

Flood risk maps, visualization tools, and coastal management information portals are essential for raising public awareness and driving action at individual, local, and national levels. These tools help residents, policymakers, and emergency responders understand flood risks, prepare for disasters, and make informed decisions about mitigation and adaptation. However, despite their potential, they often fail to effectively communicate flood risk to general audiences. When flood risk information is not clearly presented, non-technical users may misinterpret the data, either overestimating or underestimating the actual risk. Miscommunication can lead to poor decision-making, reducing the effectiveness of flood preparedness and response efforts. To address this issue, a more structured approach is needed to ensure that flood risk information is presented clearly and accessibly.

TIFF recommends the creation of Flood Risk Planning flashcards based on *The TIFF Communication Guidelines for Coastal Flood Information Design and Communication* (*TIFF Communication Guidelines*). These cards would serve as a toolkit for planners to better organize and prioritize flood risk reduction activities, providing a structured framework for developing and implementing effective strategies to target and reach their specific audiences. The cards would also encourage data-driven discussions during the flood risk planning process and offer a visually appealing, user-friendly design to improve engagement and usability. By integrating these planning cards into flood communication efforts, communities can enhance their ability to interpret flood risk data, plan for future events, and build greater resilience against flooding.

TIFF recommends partnerships between academic institutions, planning organizations, state funding agencies, cities and towns, flood control districts, and regional flood planning groups to develop and implement the Flood Risk Planning flashcards.

KEY IMPLEMENTATION ACTIONS

- **Competitive Analysis & Market Research for Card Deck Development ($50,000-$100,000)**: Conduct a review of existing card decks (e.g., augmented reality 32-card deck), platforms where card decks are marketed (e.g., game crafters), typical costs, and the target audiences that purchase such cards
- **Card Deck Development ($50,000-$100,000)**: Design and create the Flood Risk Planning Flashcards based on insights from the competitive analysis and market research, using *The TIFF Communication Guidelines*
- **User Testing and Evaluation ($50,000-$100,000)**: Evaluate the effectiveness of the cards and gather feedback from users to refine and update the cards for continued improvement

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STANDARDIZE GRANTEE SHAPEFILES STATEWIDE TO SUPPORT INTERAGENCY COORDINATION

Require Texas agencies to collect three standardized shapefiles for all state-funded flood-related projects to improve state flood coordination

Flood-related projects in Texas involve various stakeholders, such as local governments, state agencies, and non-profits, working to improve flood management and response. However, a lack of coordination can lead to overlapping efforts, inefficient use of resources, and missed collaboration opportunities.

TIFF recommends a standardized requirement for all funded flood-related projects in the state to submit three critical shapefiles to the funding agency and other relevant recipients. These shapefiles will provide spatial data on the project's location, scope, and impact area. This standardized approach will allow agencies to quickly identify overlaps between projects, assess geographic synergies, and reduce redundancy.

By incorporating these shapefiles into project planning and evaluation processes, stakeholders can better understand the spatial relationships between ongoing and proposed projects, ensuring that funding is directed toward projects that complement each other. This will not only streamline the allocation of resources but also foster comprehensive planning and clarity in project objectives, ultimately enhancing flood preparedness, mitigation, and response across Texas.

KEY IMPLEMENTATION ACTIONS

- **Recommended Shapefiles**:
  - Study Area Layer – Delineates the geographic scope of the entire study, providing details on cities, counties, watersheds, or other relevant spatial extents such as the spatial extent of the modeling domain; the purpose of this shapefile is to identify where studies are being conducted, which helps stakeholders locate projects geographically to ensure coverage and prevent redundancy
  - Construction Footprint Layer – Defines the area directly impacted by construction activities including temporary activities such as traffic control; for permitting, or other reasons, there may be requirements to separately identify specific areas of excavation or ground disturbance; the purpose of this shapefile is to highlight areas where physical interventions are taking place, which facilitates cross-project comparison and mitigates overlapping scopes
  - Benefited Area(s) Layer – Outlines the projected area influenced by the project's outcomes (e.g., the area benefited by flood risk reduction, enhanced resilience, or ecological benefits); it is important to clearly specify the benefited area(s) for each project because the benefited area(s) could be 1) smaller than the total study/model area, 2) the same size as the total study/model area, or 3) delineated into multiple benefit areas; the purpose of this shapefile is to provide a visual understanding of the project's anticipated impact, which assists in identifying gaps or overlaps in flood mitigation efforts
- **Submission Guidelines**: Specify shapefile formats, metadata standards, and protocols; obtain agreement from relevant agencies to adopt the guidelines and standards, such as the Texas Water Development Board, Texas General Land Office, and the Texas Division of Emergency Management
- **Management**: Assign a state office or database to manage and analyze shapefile submissions; use analyses to enable a clearer understanding of the spatial relationship between ongoing and proposed projects; provide insight into geographic redundancies and opportunities to integrate efforts for maximum impact
- **State Integration**: Add shapefile submission requirements to project scopes and funding application processes

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IMPLEMENT THE TIFF GUIDELINES FOR COASTAL FLOOD INFORMATION DESIGN AND STATEWIDE COMMUNICATION

State and local agencies should implement *The TIFF Communication Guidelines* to enhance consistency, clarity, and accessibility of flood information

To improve the clarity and accessibility of flood risk information, TIFF developed *The TIFF Guidelines for Coastal Flood Information Design and Communication* (referred to as T*he TIFF Communication Guidelines*). These guidelines outline best practices for developing flood risk visualizations and communication tools (e.g., maps and dashboards) in a way that is clear, transparent, and user-friendly. By promoting and applying these guidelines through education and outreach, organizations can ensure that both general audiences and those directly affected by coastal flooding can accurately interpret and respond to shared flood information.

TIFF recommends that the Texas Water Development Board (TWDB) lead implementation efforts. As the state's designated coordinating agency for the National Flood Insurance Program, TWDB has the expertise and relationships necessary for statewide coordination. TWDB can also facilitate partnerships among Texas legislators, funding agencies, local governments, developers, business owners, non-profits, and academic institutions to promote the adoption and consistent application of these guidelines. Partner agencies are encouraged to share costs and collaborate on phased funding.

KEY IMPLEMENTATION ACTIONS

- **Collaboration with Regional Stakeholders**: Tailor and optimize the guidelines for Texas's diverse regions and target users; include special considerations for the Lower Rio Grande Valley
- **Promotional Campaign**: Produce an asynchronous video walkthrough explaining the guidelines, publish it on the TIFF website, and secure endorsements from subject matter experts and state-level decision-makers
- **Training and Case Studies**: Develop workshops and instructional materials demonstrating effective guideline use, using the Texas Water Data Hub and the Texas Disaster Information System as examples of best practices
- **Outreach to Target Users**: Once the guidelines are approved and localized, identify the most effective communication channels (e.g., Facebook ads, local newspapers, radio/television broadcasts) to ensure widespread awareness
- **Evaluation and Feedback**: Host community events and municipal workshops to gather stakeholder feedback and assess guideline effectiveness among both technical and general audiences
- **Flood Literacy Assessment**: Evaluate whether implementing the TIFF Guidelines increases public flood literacy, especially among communities vulnerable to coastal flooding

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CREATE FLOOD SAFETY MESSAGING TARGETING USERS IN THE LOWER RIO GRANDE VALLEY

Create and validate flood safety messages that better reach target users in the Lower Rio Grande Valley

Popular flood safety messages, including "Turn Around, Don't Drown," are widely circulated despite the lack of comprehensive impact evaluation beyond their original target audience. Research shows that meaning can shift when messages are shared in different regions, delivered to people from various cultural backgrounds, or translated into other languages.

There is insufficient data on the effectiveness of flood safety messaging for Spanish-speaking populations, immigrants, and residents from states outside of Texas. Without systematic evaluation, organizations cannot reliably claim which flood safety messages work best, under what circumstances, or how they should be adapted for non-English speakers.

This 2-3-year investment, estimated at $1 million, will produce new flood safety messages that can be adopted by all levels of government.

KEY IMPLEMENTATION ACTIONS

- **Capacity Building**: Establish a sustainable annual budget and cost-sharing strategy among local contractors and communities; secure ongoing state funding and permanent staffing to support long-term implementation and expansion across Texas
- **Expert Project Team**: Form a team of bilingual or multilingual subject-matter experts to lead rigorous research, evaluation, and message design; at least one member should reside in the region to help implement local events and maintain community presence
- **Establish Partnerships**: Key partners include the Texas Disaster Information System and local non-governmental organizations with expertise and community trust in the region; use the Prairie View A&M University Economic Development representatives and Texas Division of Emergency Management county liaisons as potential resources for best practices
- **Behavioral Research**: Design and conduct systematic experiments to test message comprehension, retention, and behavioral impact across languages, cultures, and formats
- **Share Findings**: Develop evidence-based recommendations for message design and deployment, and publicly share research results
- **Develop and Test Tools**: Create prototypes of new messages and visualizations (e.g., maps, graphics, dashboards, infographics, interactive materials) and evaluate their effectiveness across diverse user groups; ensure tools reflect community priorities and lived experiences through continuous user engagement
- **Implement Inclusive Strategies**: Support multimodal outreach (e.g., storytelling and historical preservation initiatives, regional information sharing forums, post-flood community support) that builds community connection, collective learning, and emotional resilience
- **Continued Evaluation**: Regularly assess and refine strategies based on community feedback and evolving demographic, environmental, and technological conditions to maintain relevance and effectiveness

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ADOPT TIFF TARGET GROUP PILOT TEST TO ENHANCE FLOOD COMMUNICATION TOOLS

State and local agencies should consider adopting the TIFF Target Group Pilot Test methodology to enhance the consistency of designing and evaluating meaningful flood communication tools

To effectively evaluate the effectiveness of flood communication and visualization approaches and tools, TIFF developed the Target Group Pilot Test (TGP Test) methodology for designing hypothesis-driven tests for target users. This approach represents a workflow to specify testable designs for communication and visualization in the future, leveraging insights from previous research and emerging artificial intelligence tools to create measurable performance metrics. By tracking quantitative evaluation metrics, an agency, program, or project can gain valuable insights into how effectively flood risks and coastal modeling information or visualization tools are performing. Together with more tailored metrics for specific target users, the organization will be better equipped to assess performance over time and identify areas for improvement.

TIFF recommends that the Texas Water Development Board (TWDB), or other appropriate state agency, lead implementation efforts. As the state's designated coordinating agency for the National Flood Insurance Program, TWDB has the expertise and relationships necessary for statewide coordination. TWDB can also facilitate partnerships among Texas legislators, funding agencies, local governments, developers, business owners, non-profits, and academic institutions to promote the adoption and consistent application of this human-AI partnering methodology. Partner agencies are encouraged to share costs and collaborate on phased funding.

KEY IMPLEMENTATION ACTIONS

- **Collaboration with Regional Stakeholders**: Work with regional planners and decision-makers to identify regional target user groups, core information needs, and key behaviors
- **Promotional Campaign**: Produce an asynchronous video walkthrough explaining the artificial-intelligence-driven step-by-step TGP Test workflow, publish it on the TIFF website, and secure endorsements from subject matter experts and state-level decision-makers
- **Training and Case Studies**: Develop workshops and instructional materials demonstrating effective TGP Test use, using the Texas Water Data Hub and the Texas Disaster Information System as examples of best practices
- **Outreach to Target Users**: Once the TGP Test methodology is approved, identify the most effective communication channels (e.g., Facebook ads, local newspapers, radio/television broadcasts) to ensure widespread awareness
- **Evaluation and Feedback**: Host community events and municipal workshops to gather stakeholder feedback and assess the methodology's effectiveness among both technical and general audiences
- **Flood Literacy Assessment**: Evaluate whether implementing the TIFF TGP Test methodology increases public flood literacy, especially among communities vulnerable to coastal flooding

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SHARE THE LESSONS OF TEXAS' FLOOD HISTORY

Develop new State of Texas tool to share lessons of Texas' flood history to help residents better predict future flood risks based on historical patterns

Effectively visualizing and disseminating flood-related information is essential for improving public understanding of flood risks. Accurate and accessible flood data can help communities, decision-makers, and emergency responders interpret complex models and datasets, leading to better preparedness, response, and long-term resilience. However, flood information is often scattered across multiple sources, making it difficult for residents to access and use in decision-making.

TIFF recommends the development of a public resource documenting historical floods in Texas hosted by the Texas Disaster Information System. This resource would serve as a centralized platform for residents to explore past flood events and understand their potential future risks. An interactive map interface would allow users to visualize flood events by location, making it easier to see where and when major floods have occurred. Each recorded flood event would include key details such as dates, impacted areas, and the extent of flooding, offering a comprehensive historical record.

The resource should also incorporate predictive insights by integrating flood forecasts and return period data. This would provide users with a clearer picture of potential future flood risks based on historical patterns. By combining historical data with predictive modeling, this tool would enhance public awareness and support more effective flood risk management across Texas.

KEY IMPLEMENTATION ACTIONS

- **Define "Major Flood"**: Use indicators such as loss of life, property damage, rainfall amounts, and other agreed metrics; these metrics and definition should be agreed upon by agencies and organizations advancing flood science in Texas, such as the Texas Water Development Board, Texas General Land Office, Texas Division of Emergency Management
- **Generate Event Summaries**: Create tables for each recorded flood event with dates, impacted areas, and extent of flooding; this organization will support improved data comprehension, communication, and informed decision-making
- **Flood Prediction**: Incorporate flood forecasts and return-period data into the public resource
- **Evaluation**: Request user feedback on the interactive map throughout the development process and iterate to improve usability and understanding; consider quantifiable evaluation metrics such as session duration, repeat visits, audience reach, information sharing, etc.

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DEVELOP ALTERNATIVES TO MENU-DRIVEN DASHBOARDS TO BETTER REACH TARGET USERS

Develop a Texas-specific AI Flood Risk Tool to help target users find flood information

Generative Artificial Intelligence (GenAI), including prompt engineering and large and small language models, presents an opportunity to modernize flood risk visualization and communication. Human-AI teaming enables more intuitive information retrieval and organization, making critical data more accessible.

TIFF recommends a study to assess how GenAI can better help target users find the flood risk information they need for decision-making. Following the study, a Texas-specific GenAI Flood Risk Tool can be developed for broader implementation. This "Texas GenAI Flood Risk Tool" will feature a prompt coaching system to guide users in writing effective prompts, ensuring they receive accurate and actionable responses. It will also define the necessary datasets for the tool and test how different target users interact with it. This priority effort is estimated to cost at least $1,000,000.

KEY IMPLEMENTATION ACTIONS

- **GenAI Flood Tool Proof of Concept (Two Focus Groups costs ~$225,000)**: Identify at least five public target users and two official target users for the study; conduct background research to assess these users' flood information needs, leveraging existing research funded by Texas agencies; carry out initial focus groups of 30-50 participants and in-person lab experiments to analyze how users search for flood information, utilizing methods such as eye-tracking, virtual reality-based eye-tracking, and think-aloud protocols; consider online experiments; conduct a follow-up focus group of 18-36 participants to help participants learn prompt-writing techniques and refine their queries to obtain more effective flood-related information
- **GenAI Flood Tool Development (One Focus Group costs ~$700,000)**: Build on the proof-of-concept findings, applying the insights gained to the same target users; identify necessary datasets, visual information, and flood-specific small language model requirements; conduct usability testing of the designed system using the same research methods from the proof-of-concept study, with a sample size of 30-50 participants per group
- **Post-Implementation Flood Literacy Evaluation**: Assess if the alternatives to menu-driven dashboards increased flood literacy in target users, improving their capacity to respond effectively and appropriately to given flood risk information

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DEVELOP A DATABASE OF FLOOD MODELING STUDIES

Develop a database of flood modeling studies to enhance flood risk assessment and emergency response

The results from existing flood modeling studies could significantly enhance flood hazard analysis efforts across Texas. Many existing datasets are underutilized and could immediately benefit professionals in the field if organized in a new cyberinfrastructure.

TIFF recommends a comprehensive bibliography and database of numerical grids, computational setups for Texas wave/surge modeling, and data on storms causing coastal flooding, including storm characteristics, wave data, high-water marks, and available measurements. This database will create comprehensive coastal model metadata collections for facilitating model access and sharing among Texas stakeholders and support improved understanding of coastal flood hazard estimation through leveraging existing models and datasets. Standardized computational meshes and setups for wave and surge models should also be provided to facilitate use by researchers and practitioners.

An interactive website should be developed for easy information sharing with Texas stakeholders, and the database must be regularly updated to reflect new findings. Furthermore, the database should also include studies utilizing three-dimensional (3D) or hybrid models, ensuring a broader representation, as current models predominantly focus on two-dimensional (2D) approaches. This database will prevent duplication of model development efforts as huge amounts of flooding analysis are being or will be performed to support a wide range of flood resiliency projects.

KEY IMPLEMENTATION ACTIONS

- Use the TIFF Model Inventory found in the TIFF Final Report (Appendix C-14) as a test-case to compile a comprehensive bibliography and database of flood modeling studies
- Share findings to support flood risk assessments, emergency planning, and coastal mitigation
- Develop a model management system for storing and sharing numerical grids, computational setups, and storm-related data (this system needs to be made available not only for sharing archived models, but also for the model developers to upload new models for wide dissemination)
- Provide clear guidance on how these datasets impact Texas residents and flood risk management
- Include validated numerical grids and computational setups for Texas wave/surge modeling
- Develop standardized computational meshes to facilitate model reuse by researchers and practitioners
- Build an online database for stakeholders to access and contribute data
- Ensure regular updates to reflect new research and findings as more models become available
- Incorporate studies using 3D or hybrid models to ensure a comprehensive approach beyond traditional 2D modeling
- Investigate how the developed models—which vary in resolutions, accuracy, and other factors—can be leveraged and integrated for improved understanding of flood risk in coastal Texas

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ENHANCE BINATIONAL FLOOD MODELING IN THE LOWER RIO GRANDE VALLEY

Develop one- and two-dimensional hydraulic and hydrologic models for the main stem of the Rio Grande, extending from Peñitas, TX to the Gulf

Hydrologic, meteorologic, hydraulic, estuarine, and surge models are essential tools for understanding flooding hazards and guiding both structural and non-structural flood risk mitigation planning. The one-dimensional (1D) hydraulic model currently being used for flood modeling in the Lower Rio Grande Valley (LRGV) was developed in 2008, meaning it is based on what the region looked like nearly two decades ago, and only extends to the City of Brownsville, meaning the area from Brownsville to the Gulf Coast is not accounted for in modeling processes. In 2021, a two-dimensional (2D) base level elevation model was developed and is being used in the region, but an engineering scale 2D model is still needed.

TIFF recommends enhancing the 1D model to improve hydrologic simulations of flows in waterways. TIFF also proposes developing a new two-dimensional (2D) model for the region to improve simulations of flow dynamics during flood events. It is crucial that the scope of work is developed jointly by the United States and Mexico, and the initiative carried out jointly.

This 5-year investment, estimated at $3 million, will enhance understanding of hydrodynamic processes in the Rio Grande basin and strengthen binational collaboration to improve flood management and public safety along the border.

KEY IMPLEMENTATION ACTIONS

- Joint collaborations between the U.S. and Mexican Joint collaborations between the U.S. and Mexican sections of the International Boundary and Water Commission (IBWC)
- Coordinate with organizations experienced in model development, such as U.S. Army Corps of Engineers, academic institutions, and regional counties
- Identify significant historical flood events and collect corresponding data; compile and review datasets from federal, state, and local monitoring and modeling programs
- Use available data to correct uncertainties in the outdated binational 1D model and apply the latest software tools to enhance its capabilities; integrate coastal boundary conditions (surge height, tidal phase, and wind forcing) to better simulate nearshore-inland flood dynamics
- Build a state-of-the-art binational 2D model with the Mexican section of the IBWC, integrating coastal boundary conditions (surge height, tidal phase, and wind forcing) to improve simulation of nearshore-inland flood dynamics
- Assess model performance using accuracy, precision, recall, and operational reliability metrics
- Periodically update inundation maps for potential Amistad and Falcon Dams failure scenarios
- Apply refined modeling to ongoing and future levee design and construction projects, including the Santa Maria to Los Indios reach
- Perform joint probability analyses of simultaneous flood events in the Rio Grande main stem and the interior drainage basins, such as the 2018-2019 McAllen-Harlingen storms and 2025 flood events

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EVALUATE THE ANALYSIS OF RECORD FOR CALIBRATION

Evaluate the Analysis of Record for Calibration across Texas for potential flood hazard analysis uses

TIFF recommends evaluating Texas Analysis of Record for Calibration (AORC) data from 1979 to the near present to provide a comprehensive assessment of the data's accuracy and potential for improving flood hazard analysis and hydrologic modeling in Texas. The evaluation would compare AORC's accuracy against rain gages and benchmark its performance against other hourly rainfall products. Additionally, rainfall events would be categorized by their association with tropical cyclones and by time of year.

The AORC is a high-resolution gridded dataset providing near-surface weather conditions across the United States. With a spatial resolution of approximately 800 meters and a temporal resolution of one hour, it includes data on precipitation, temperature, humidity, pressure, radiation, and wind components. AORC's long history (over 40 years) and fine resolution make it valuable for applications like rainfall frequency analysis and hydrologic modeling. It is particularly useful for areas such as the Lower Rio Grande Valley, where daily rainfall measurements are often too coarse to capture localized storms, and for regions impacted by tropical cyclones, as seen during Hurricane Harvey in 2017.

TIFF recommends partnerships with organizations experienced in weather data collection, management, and dissemination, such as the Texas A&M University Office of the Texas State Climatologist and other institutions. The project is expected to take 6-12 months, with an estimated budget of $70,000–$100,000.

KEY IMPLEMENTATION ACTIONS

- Analyze AORC data from 1979 to the present (as available) across Texas
- Compare AORC precipitation data against rain gages
- Assess AORC's performance relative to other hourly rainfall products
- Categorize events by association with tropical cyclones and by time of year

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ADVANCE HYDRAULIC MODELING SIMULATIONS WITH HEC-RAS DISTRIBUTED-MEMORY PARALLELIZATION

The U.S. Army Corps of Engineers Hydrologic Engineering Center River Analysis System (HEC-RAS) model is widely used for flood hazard characterization in Texas coastal watersheds but faces computational limitations, especially in flat terrain where inter-basin flow transfers affect flood extent and depth. Current modeling requires breaking very large watersheds into smaller sections, creating edge-matching issues and making real-time flood response impractical.

TIFF recommends a distributed-memory parallelization approach to enable HEC-RAS to run across multiple nodes in a High-Performance Computing (HPC) environment, significantly reducing simulation times from days to minutes. Faster computations will improve flood planning, emergency response, and the ability to incorporate high-resolution (1m) Texas light detection and ranging (LiDAR) data for more accurate topographic representation in the model.

Enhancing HEC-RAS with HPC capabilities would also support integration with coastal surge models, improving compound flood hazard assessments critical for the Texas coast, enabling more efficient and accurate result comparisons across modeling scales and platforms for performance benchmarking.

KEY IMPLEMENTATION ACTIONS

- Analyze and identify performance bottlenecks in the two-dimensional HEC-RAS computational engine source code
- Develop and validate a small model domain test case for ongoing testing
- Implement message passing interface (MPI)-based parallelization using a single program–multiple data approach
- Perform graphical user interface integration and iterative testing for usability and functionality
- Verify code accuracy and scalability with increasing processor counts
- Provide guidance on optimal subdomain sizing for performance and load balancing
- Perform test-bed evaluations of the HEC-RAS parallelized code for evaluating its performance, including result comparisons across modeling scales and platforms for performance benchmarking
- Generate summary tables comparing simulation cost, runtime, and result consistency

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ADVANCE ARTIFICIAL INTELLIGENCE/MACHINE LEARNING TECHNIQUES FOR FLOOD MODELING

Improve the speed, transparency, and reliability of AI/ML-based compound flood modeling

Traditional process-based models for assessing the effects of compound flooding, while accurate, are often time-consuming and resource-intensive, making them less practical for rapid decision-making during emergency events. Coastal infrastructure operations, in particular, require fast evaluations to guide decision-making during floods, which typically necessitate "what-if" scenarios to explore various interventions and outcomes.

Recent advances in artificial intelligence/machine learning (AI/ML) models demonstrate strong potential to accelerate flood hazard analysis. However, these models are still largely research-level tools that do not yet have a strong basis for understanding the uncertainty and likely error associated with its predictions.

To fully leverage their benefits, TIFF recommends advancing AI/ML techniques specifically tailored for compound flood modeling in Texas. By automating and accelerating the modeling process, AI/ML can support faster and more informed decision-making during flood events.

KEY IMPLEMENTATION ACTIONS

- **Collect Ground-Truth Data**: Train and validate AI/ML models using high-quality local data to ensure reliable, informed decision-making; invest in a robust gage network to collect data for model training and support real-time flood warning systems; link measurements to risk thresholds and operational triggers (e.g., early alerts, road closures, evacuations); once trained, AI/ML models can rapidly generate predictions across many scenarios
- **Develop Guidelines for Model Interpretability**: Establish best practices to improve the interpretability of AI/ML models (e.g., moving beyond black-box approaches) for decision-making
- **Advance AI/ML Surrogate Modeling**: To enable faster simulation of compound flooding conditions, support ongoing research into AI/ML surrogate models that replicate traditional flood model outputs at a fraction of the computational cost
- **Improve Transparency and Reliability**: Enhance AI/ML approaches to ensure that predictions are transparent, reproducible, and trustworthy; include approaches for quantifying uncertainty and clearly communicating model limitations
- **Create "What If" Scenario Tools**: Develop user-friendly tools that help engineers and policymakers to rapidly assess intervention strategies during flood events to protect and maintain coastal infrastructure during emergencies and changing conditions

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INTEGRATE URBAN STORMWATER AND FLOOD HAZARD HYDRODYNAMICS MODEL APPLICATIONS

Couple an urban stormwater model and a flood hazard hydrodynamic model and assess the effectiveness through test-bed evaluations in Texas urbanized coastal watersheds

Effective modeling should account for both catastrophic hurricanes and more frequent moderate storms, enabling communities to evaluate how engineered infrastructure, such as deep tunnels, can mitigate flooding. While urban stormwater modeling has a long history, it has not been integrated into compound flooding models that consider both coastal and urban flooding.

TIFF recommends the development of an integrated urban stormwater and flood hazard model for Texas' urbanized coastal watersheds. The effort includes evaluating ongoing efforts to model urban flooding, creating multi-scale storm models that simulate both catastrophic and moderate storms, and incorporating two-dimensional (2D) flood modeling (e.g., U.S. Army Corps of Engineers Hydrologic Engineering Center River Analysis System (HEC-RAS), Delft-3D, TRITON) into the U.S. Environmental Protection Agency Storm Water Management Model (SWMM). Coupling SWMM with other open source/freeware flood models will facilitate greater adaptation by diverse stakeholders.

A testbed evaluation of the integrated model and exploring alternative approaches, such as sub-grid-based models, should be performed to enhance its accuracy and application. This integrated system will help assess how urban infrastructure can improve resilience to flooding. TIFF recommends partnerships with flood control districts and cities working on addressing challenges related to urban flooding.

KEY IMPLEMENTATION ACTIONS

- Simulate both tropical and non-tropical storms to assess how urban stormwater systems, such as deep tunnels, enhance flood resilience
- Integrate a 2D flood modeling component into the SWMM
- Couple the SWMM with open-source/freeware flood models like HEC-RAS 2D, TRITON, or Delft3D-FM to facilitate greater adaptation by diverse stakeholders
- Conduct testbed studies in Texas urbanized coastal watersheds to validate model performance
- Explore alternative modeling approaches to improve accuracy and application

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QUANTIFY THE IMPACTS OF EROSION ON STORM SURGE

Texas bay and estuarine systems connect to the Gulf through narrow inlets that cut across barrier islands and peninsulas. These landforms act as natural buffers, protecting interior waterways from wave action and storm surge. However, their low-lying nature makes them vulnerable to overtopping and erosion during major storms, rapidly altering coastal topography.

Capturing storm-induced erosion in numerical models remains a challenge. During Hurricane Harvey, significant beach erosion near Aransas Bay (Goff et al. 2019) may have allowed additional surge to reach inland areas, leading to potential under-predictions in models like ADvanced CIRCulation Model (ADCIRC). These models struggle to represent rapid erosion dynamics, as they operate on coarse spatial resolutions (30-40 meters) and lack sediment transport capabilities.

TIFF recommends the enhancement of storm surge models by integrating barrier island and dune erosion processes. A more dynamic approach to modeling erosion would improve flood forecasting and post-storm reconstructions, leading to better risk assessments and coastal resilience planning. By incorporating real-time topographic changes, researchers can more accurately predict storm surge impacts and better protect vulnerable coastal communities in Texas.

KEY IMPLEMENTATION ACTIONS

- **Site-Specific Morphological Modeling**: Identify high-priority sites prone to erosion (e.g., areas impacted by Hurricane Harvey, key dune-protected regions); use nearshore morphology models to simulate dune erosion and establish relationships between erosion and wave/surge conditions
- **Develop Parameterized Erosion Updates**: Conduct multiple simulations to generate datasets linking erosion to storm conditions; utilize regression models, lookup tables, or artificial intelligence/machine learning to create parameterized updates for bathymetry and topography; implement a dynamic system to update dune elevations and erosional areas every 10 minutes based on surge, wave, and current data
- **Integration with Surge Models**: Incorporate erosion-informed updates into large-scale surge models; test the feasibility of using a subgrid-type surge model to represent small-scale coastal features more effectively
- **Expansion**: Apply the developed framework to additional Texas shorelines, accounting for regional variations in sediment characteristics, hard structures (e.g., seawalls), and erosion-resistant layers; develop a methodology for predicting potential barrier island breaches in advance

Citation: Goff, J.A., Swartz, J.M., Gulick, S.P.S., Dawson, C.N., & Ruiz de Alegria-Arzaburu, A. 2019. "An Outflow Event on the Left Side of Hurricane Harvey: Erosion of Barrier Sand and Seaward Transport through Aransas Pass, Texas." *Geomorphology*, 334, 44-57. https://doi.org/10.1016/j.geomorph.2019.02.038.

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QUANTIFY WIND-DRIVEN INLAND FLOWS TO ENHANCE FLOODING MODELS

Address the lack of inland flooding models that include wind and wave stresses via a coordinated research effort to quantify the physics of wind-driven flows in shallow flooding

When large areas are flooded (e.g., Hurricane Harvey), strong winds have the ability to provide an additional forcing to tilt the water surface (i.e., pushing water upwind). When the wind stops or changes direction, the water pushed upwind will be redistributed and can cause further flooding.

The problems associated with wind-forcing over shallow water were discussed by Li & Hodges (2019), who implemented an ad hoc increase in drag for shallow marshes to prevent unrealistic acceleration by wind. The underlying problem is that wind-drag models are derived from studies of deep water where only a wind boundary layer exists near the surface. In shallow waters, the wind boundary layer overlaps with the bottom boundary layer, leading to nonlinear turbulent interactions that have not been studied. Although there is perhaps more theory available for waves propagation over shallows, the evolution of waves in shallow waters under short fetches is not well studied. There are no known models that can presently be applied to represent the development of wind-waves in shallow flooded areas.

KEY IMPLEMENTATION ACTIONS

TIFF recommends the following investments to address this knowledge gap:

- Establish theoretical frameworks for the coupled wind/wave/bottom boundary layer interactions in shallow water environments
- Use laboratory experiments and high-resolution Computational Fluid Dynamics (CFD) models to validate the theory and gain insights into wind, wave, and bottom boundary layer interactions
- Perform field experiments to examine how theoretical and laboratory results translate to full-scale conditions
- Use theory, laboratory data, CFD results, and field data to create a model equation that links wind speed to effective wind stress, considering water depth, velocity, and bottom roughness
- Integrate both large- and small-scale processes into the model to enhance its accuracy

Citation: Li, Z., & Hodges, B. R. "Model Instability and Channel Connectivity for 2d Coastal Marsh Simulations." *Environmental Fluid Mechanics*, vol. 19, 2019, pp. 1309-38. https://doi.org/10.1007/s10652-018-9623-7.

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ENHANCE WAVE MODELS AND DATA TO IMPROVE ACCURACY IN POPULATED AREAS

Better represent overland wave transformation by enhancing wave models and data collection overland

In Texas, wave prediction accuracy is lowest in the region containing the highest population and value: Normally Dry Land (the most important locations for planning and design). The challenges to accurate predictions are threefold:

1. Existing models were developed for conditions vastly different from those found over dry land, such as buildings, diverse vegetation, and rapid changes in land and structure properties.
2. Overland flooding with large waves is rare, resulting in limited datasets for model validation.
3. Significant changes in topography, vegetation, and structures during storms can lead to conditions that differ from pre-storm assumptions, affecting wave and surge properties and reducing model accuracy. This is especially problematic for dune erosion, as protective dunes often vanish during severe storms, exposing developed regions to increased flooding risk.

TIFF recommends enhancing model accuracy and reliability for overland wave prediction in Texas. Key actions include extensive data collection for model parameterization, calibration, and validation; detailed mapping of coastal areas with a focus on buildings and vegetation; detailed inventories of coastal buildings and large vegetation that are likely to withstand flooding; and high-resolution flow modeling over dry land using spectral models like Simulating Waves Near Shore (SWAN) or WAVEWATCH III. Developing a dedicated overland wave model could establish a new standard for wave predictions, ensuring more reliable forecasts and improved protection for vulnerable areas.

Partners, including state and federal agencies and academic institutions, could execute this initiative over 3-5 years, with an estimated annual budget of $200,000.

KEY IMPLEMENTATION ACTIONS

- Conduct extensive data collection to improve wave model parameterization, calibration, and validation
- Develop detailed inventories of coastal structures and vegetation likely to withstand flooding
- Use high-resolution mapping of Texas coastal areas, focusing on buildings, vegetation, and land characteristics
- Incorporate dynamic changes in topography, vegetation, and structures before, during, and after storms
- Implement high-resolution wave modeling over dry land using spectral models like SWAN or WAVEWATCH III
- Establish a dedicated overland wave model to enhance predictive capabilities

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DEVELOP AUTOMATION TOOL FOR HIGH-RESOLUTION TOPOGRAPHY AND BATHYMETRY DATA PROCESSING

TIFF recommends the development of automated methods to improve and standardize the representation of topo-bathymetric datasets, including engineering features like levees, in flood hazard models. This should include the creation of a standard vector representation for features such as levees, where polylines with varying widths and elevations along the line can be used for topographic processing.

Additionally, automated topographic processing methods should be developed to extract engineering features (e.g., levee, ship channel, bridge) from high-resolution light detection and ranging (LiDAR) data without requiring human intervention except performing quality assurance and quality control of the final topographic products. To further enhance the process, model grid generation programs that can effectively incorporate vector polylines into model topography should be developed. A comprehensive standard database for accessing data on such features throughout Texas is also crucial for consistency and ease of use.

This initiative should leverage the National Oceanic and Atmospheric Administration Continuous Updated Digital Elevation Model (though it is limited in representing engineering structures like levees). The resulting tool should ensure that its derived products are easily usable across a range of flood hazard models, providing a more efficient and consistent means of incorporating engineering features into flood hazard assessments.

KEY IMPLEMENTATION ACTIONS

- Establish a vector-based representation for levees and similar features, using polylines with varying widths and elevations
- Develop automated processing methods to extract engineering features from high-resolution LiDAR without human intervention
- Create grid generation programs capable of incorporating vector polylines into model topography
- Establish a standardized database for consistent access to topo-bathymetric data across Texas
- Prioritize bathymetric data improvements in small channels to refine flood models

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QUANTIFY SENSITIVITIES OF EXISTING MODELS

Address some of the known computational challenges of existing models by quantifying the sensitivities of model results to uncertainties in wind forcing, bathymetry, bottom friction, and turbulence, with an initial emphasis on bathymetry

TIFF recommends the improvement of bathymetric data (particularly for small-scale features like channels and barrier islands) to resolve the associated computational challenges in flood hazard models. Errors in bathymetry and topography also contribute to significant inaccuracies inland hydraulics, coastal hydrodynamic and storm surge models. While higher-resolution data like light detection and ranging (LiDAR) and satellite imagery enhance accuracy, they provide only a snapshot in time, leading to potential errors in areas undergoing frequent changes, especially in urban regions. Computational challenges arise in resolving small-scale features, such as channels and barrier islands, impacting model performance.

Additionally, TIFF recommends research to improve regional models like Weather Research and Forecasting (WRF) for operational forecasting to enhance wind predictions in storm surge models. The primary source of uncertainty in storm surge simulations is attributed to wind forcing, which is a major driver for both surge and waves. Accurate wind predictions are crucial for reliable surge forecasts, especially when hurricane track and intensity are uncertain. Operational meteorologic models, despite improvements in numerical precision and higher resolution, do not guarantee error-free results. For instance, Hurricane Ian (2022) deviated from its predicted landfall location, showcasing the challenge in forecast accuracy. Regional models like WRF, tested at 1-5 km resolution in the Gulf, reveal fine-scale features but are not yet operational for forecasts.

TIFF also recommends the development of a framework for quantifying uncertainty in bottom friction, using measured data, to improve flood hazard model predictions. Bottom friction, determined by formulations like Manning's Roughness, introduces another source of error in storm surge predictions. The Manning's Roughness, dependent on sea-surface bottom characteristics, becomes more pronounced in shallow waters, influencing flooding severity over inundated land. Despite recent efforts to estimate bottom friction from measured data, this research is in its early stages and lacks a comprehensive framework for uncertainty quantification and parameter estimation.

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DEVELOP STATEWIDE GUIDELINES FOR NATURE-BASED FEATURES TO REDUCE FLOOD RISK

Traditional benefit-cost analysis (BCA) focuses on economic metrics, making it less effective for evaluating nature-based solutions (NBS) that provide broader environmental and social benefits. As advancements continue, there is a need to refine BCA methodologies to better capture the full value of Natural and Nature-Based Features (NNBFs) within coastal infrastructure systems.

TIFF recommends that guidelines be developed for implementing NNBFs along the Texas coast and that their effectiveness in coastal flood risk reduction be assessed.

This approach will provide valuable insights into how NNBFs mitigate surge and dissipate waves, ensuring that site selection aligns with physical and local conditions while maximizing cost efficiency. Additionally, long-term monitoring systems should be implemented to quantify the lifespan and ongoing benefits of NNBFs. This will allow for data-driven assessments of their effectiveness in reducing coastal risk and evaluating cost feasibility over time. This fuller accounting of benefits can better support the adoption of NNBFs as viable, cost-effective flood mitigation strategies.

KEY IMPLEMENTATION ACTIONS

- Update BCA methodologies to better account for the full range of NNBF benefits, including social and environmental factors
- Establish criteria/metrics to assess NNBF efficiency in mitigating storm surge and wave energy, incorporating social, environment, and economic factors
- Optimize site selection and feature sizing based on local coastal conditions
- Identify and implement pilot projects to evaluate NNBF effectiveness under varying conditions
- Establish a testbed to help determine the best locations, timing, and configurations for maximum flood risk reduction
- Develop monitoring systems to track NNBF lifespan and performance over time
- Use data-driven assessments to refine NNBF designs and improve cost efficiency
- Collaborate with federal, state and other agencies, and universities to leverage on-going efforts and the lessons-learned of NNBF implementations

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USE PHYSICS-BASED MODELING FOR EVALUATION OF NATURE-BASED SOLUTIONS IN THE LOWER RIO GRANDE VALLEY

The Lower Rio Grande Valley (LRGV) is vulnerable to hazardous compound flood events due to its low-lying terrain and combination of factors including, rainfall characteristics, drainage systems, land use, and water management. As flooding becomes a more frequent and severe problem in the region, many are looking to nature-based solutions (NBS) as a potential strategy to mitigate flood risk. To date, comprehensive evaluation of NBS contributions within coastal infrastructure systems in the LRGV has yet to be done.

TIFF recommends using physics-based numerical modeling to evaluate the coastal flood risk reduction performance of NBS applied in LRGV. This initiative will support adaptive flood management by applying physics-based numerical modeling to analyze the effectiveness of NBS strategies and generating data-driven insights into how green infrastructure enhances flood hazard resilience along the Texas coast.

This proposal will:

- Develop and validate physics-based models that quantify the performance of NBS in reducing coastal flood severity and frequency
- Model hydrodynamics for a set of NBS feature designs to assess how different NBS configurations perform across varying site and hazard conditions
- Evaluate NBS feature effectiveness, cost, and benefits as compared with traditional hardened infrastructure measures, under design-level and historic events
- Establish a data-driven catalog of feasible NBS interventions tailored to the LRGV's coastal hazard risk

Success requires coordination between agencies and organizations experienced in advancing flood science, such as the U.S. Army Corps of Engineers, Texas General Land Office, Texas Water Development Board (TWDB), other federal and state agencies, academic institutions, and other stakeholders. Depending on existence of already-proposed NBS projects to evaluate in the region, other stakeholders and the general public may be needed for a project solicitation and/or concept design phase.

This 3-4 year investment, estimated at $2 million, will enhance understanding of green infrastructure performance within the LRGV and support local agencies in integrating NBS into regional flood management frameworks. Cost is highly dependent on the number of modeled scenarios, ease of implementation of NBS project concepts into numerical models, availability of site-specific information and data, and the amount of field data collection needed.

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USE PHYSICS-BASED MODELING FOR EVALUATION OF NATURE-BASED SOLUTIONS IN THE LOWER RIO GRANDE VALLEY

KEY IMPLEMENTATION ACTIONS

- Conduct a comprehensive literature review of all existing coastal NBS projects in the LRGV region, as well as high-priority flood risk sites where NBS could feasibly be implemented in the future
- Collaborate with state and local agencies and stakeholders to gather relevant information associated with current and potential future project sites, such as performance assessments, lessons learned, and historical hydrodynamic and hazard data
- Identify key project performance indicators such as wave energy reduction, inundation extents, and erosion mitigation; consider mitigation scope of NBS (e.g., mitigate repeated low- to medium- intensity flooding, mitigate low-probability, high-intensity flooding)
- Use findings from literature review to develop a matrix of NBS scenarios to be simulated with physics-based models; NBS scenarios at several different sites are recommended, including at an existing project site to aid in validation; ideal scenarios for inclusion are those for which findings can be readily applied to other site locations; select a set of design-level and historic storm events to be simulated based on the NBS feature(s) and specific hazard risks associated with each site
- Assess the matrix of NBS scenarios and determine the most appropriate numerical model(s) for performance quantification; develop model for each scenario and incorporate up-to-date bathymetry/topography and land cover information
- Use hydrodynamic data (from water level gages and wave buoys), morphological data (such as beach profiles and sediment analysis), and hydrologic information (such as discharge) to validate the model outputs and refine predictive accuracy
- Collect field data at NBS scenario site locations if there is a lack of measured validation data at the modeled sites; leverage validated physics-based model frameworks for future projects and analyses
- Conduct model simulations and develop standardized metrics to assess NBS performance, including wave energy, current velocity, and inundation extent reduction and erosion mitigation; include performance measures needed to support probabilistic risk assessment along with model outputs from storm event simulations
- Compare the cost-effectiveness, long-term maintenance needs, and ecological co-benefits of NBS versus traditional hardened infrastructure, potentially using life cycle risk assessment and environmental benefits models
- Evaluate opportunities to replace or complement hardened infrastructure with natural or hybrid infrastructure that improves ecosystem function and community resilience at modeled site locations
- Create a decision-support catalog of NBS strategies optimized for LRGV conditions that links site characteristics, hydrologic profiles, and land-use types with the most effective NBS interventions; the catalog should align with forthcoming NBS Guidance Manual from the TWDB and promote reproducibility through open-source artificial intelligence workflows to encourage collaboration among local agencies and researchers; include interactive visualizations and design tools to refine project concepts and dynamically reevaluate NBS impacts

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DEVELOP ARTIFICIAL INTELLIGENCE-DRIVEN FLOOD RESILIENCE IN THE LOWER RIO GRANDE VALLEY

Develop a machine learning model that leverages artificial intelligence to evaluate the flood risk reduction performance of nature-based solutions applied in Lower Rio Grande Valley watersheds

Artificial intelligence (AI) and machine learning (ML) models, which began as pure data-driven models, have recently advanced into quasi-mechanistic models with the potential to improve flood hazard analysis in several ways, including through the comprehensive evaluation of nature-based solutions (NBS) contributions within coastal infrastructure systems.

TIFF recommends the development of a ML model that leverages AI and physics-based modeling to evaluate the flood mitigation performance of NBS across the Lower Rio Grande Valley (LRGV). This initiative will support adaptive flood management by analyzing the effectiveness of NBS strategies and providing data-driven insights into how green infrastructure enhances hydrologic resilience along the Texas coast.

This proposal will:

- Develop and validate a machine learning model that quantifies the performance of NBS in reducing flood severity and frequency
- Integrate hydrologic, land use, and climatic datasets to optimize the model's capacity to assess how different NBS configurations perform across varying conditions
- Develop recommended best-practice workflows for evaluating proposed NBS interventions using ML models
- Establish a data-driven catalog of feasible NBS interventions tailored to the LRGV's environmental and urban characteristics
- Evaluate opportunities to replace or complement grey infrastructure with green alternatives that improve ecosystem function and community resilience

Success requires coordination between agencies and organizations that supported the development of the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center River Analysis System models for various counties and cities in the ongoing LRGV Regional Flood Study, including the USACE, Texas General Land Office, academic institutions, and contractors. Depending on existence of already-proposed NBS projects to evaluate in the region, other stakeholders and the general public may be needed for a project solicitation and/or concept design phase.

This 2-4 year investment, estimated at $2 million, will enhance understanding of green infrastructure performance within the LRGV, identify the most effective flood mitigation strategies, and support local agencies in integrating NBS into regional flood management frameworks. Cost is highly dependent on the number of modeled scenarios, ease of implementation of NBS project concepts into numerical models, availability of site-specific information and data, and the amount of field data collection needed.

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DEVELOP ARTIFICIAL INTELLIGENCE-DRIVEN FLOOD RESILIENCE IN THE LOWER RIO GRANDE VALLEY

KEY IMPLEMENTATION ACTIONS

- Conduct a comprehensive review of AI-based modeling approaches for NBS performance evaluation and flood mitigation analysis; identify key performance indicators such as runoff reduction, infiltration rates, and storage capacity
- Build and train the model using learning techniques that integrate observed hydrologic and meteorological data, land-cover maps, and field monitoring results
- Incorporate environmental variables such as soil permeability, vegetation type, roughness, and rainfall intensity to simulate NBS effectiveness across multiple scenarios
- Conduct an analysis of feature importance to streamline model training
- Identify appropriate suites of events and landscape scenarios to support evaluation of NBS performance using surrogate models, including historic storms, design-level storms, and a corpus of synthetic storms suitable for probabilistic risk analysis; scenarios should include realizations of sea levels and land-use change plausible over the useful lifetime of NBS projects and equivalent hardened infrastructure measures to support both probabilistic risk analysis and analysis of epistemic uncertainties; involve coordination with a team developing physics-based modeling workflows to simulate NBS performance
- Develop standardized metrics to assess NBS performance, including reduction in peak discharge, delay in runoff timing, and enhancement of infiltration; performance measures will be based on probabilistic risk assessment and also outcomes from selected design-level and recreated historic storm events
- Compare the cost-effectiveness, long-term maintenance needs, and ecological co-benefits of NBS versus traditional grey infrastructure
- Create a decision-support catalog of NBS strategies optimized for LRGV conditions; link site characteristics, hydrologic profiles, and land-use types with the most effective NBS interventions; align the catalog with recommendations from the Texas Water Development Board and promote reproducibility through open-source AI workflows to encourage collaboration among local agencies and researchers; include interactive visualizations and design tools to refine project concepts and dynamically reevaluate NBS impacts

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MANAGE AQUIFER RECHARGE IN THE LOWER RIO GRANDE VALLEY

Study the viability of managed aquifer recharge for flood risk reduction in the Lower Rio Grande Valley

Managed aquifer recharge refers to the process of moving water underground, either through natural infiltration or engineered systems designed to enhance recharge. This process can help replenish groundwater reserves, prevent saltwater intrusion, and slow down land subsidence.

TIFF recommends a two-year pilot program to test small-scale floodwater injection systems at select sites throughout the Lower Rio Grande Valley (LRGV). Specifically, this pilot will evaluate whether injecting excess floodwater directly into underground aquifers at strategic locations in the LRGV can reduce surface flooding, prevent saltwater intrusion into freshwater supplies, and protect critical public infrastructure like wastewater and stormwater systems from corrosion and overloading.

This 2-year investment, estimated at $1 million, will guide region-wide decisions on the use of aquifer storage as a tool for (or limitation of) flood management, supporting state and local infrastructure planning, investment strategies, and regional resilience initiatives.

KEY IMPLEMENTATION ACTIONS

- Use modeling techniques to detect and map optimal locations and methods for groundwater injection and storage
- Determine the technical and geological viability of injecting stormwater into existing aquifer formations without compromising water quality or structural integrity
- Quantify the potential reduction in surface flooding in nearby communities during heavy rainfall or hurricane events
- Evaluate how sustained aquifer recharge can reduce saltwater intrusion and limit corrosion in wastewater and stormwater collection systems

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ASSESS CHANNEL CAPACITY IN THE RIO GRANDE AND ARROYO COLORADO

Conduct sediment transport and channel capacity analyses on the Rio Grande and Arroyo Colorado to quantify geomorphic changes and vegetation growth that may impair flood conveyance

The Rio Grande has experienced substantial hydrologic and geomorphic transformation over the past century, largely due to land-use changes and water management practices. Once a wide and multi-channel system, the river is now characterized by a narrowing channel because of the accumulating sediment and encroaching vegetation. Unfortunately, this channel narrowing is threatening important wildlife habitat and has increased flood risk for local communities. Similarly, the Arroyo Colorado (a former outlet of the Rio Grande), experiences accumulated sedimentation which reduces the river's capacity to carry floodwaters. These evolving river conditions pose challenges for flood management and ecosystem health across the Lower Rio Grande Valley (LRGV).

TIFF recommends evaluating sediment transport processes, geomorphic changes, and vegetation encroachment that contribute to altered flow capacity in the Rio Grande and Arroyo Colorado. This includes identifying critical channel reaches where sediment accumulation and vegetation have significantly reduced flood conveyance efficiency.

This 2-year investment, estimated at $1 million, will enhance regional understanding of how sediment transport and vegetation growth are altering the Rio Grande and Arroyo Colorado's hydrologic behavior, and generate actionable insights to guide river restoration and flood mitigation planning across the LRGV.

KEY IMPLEMENTATION ACTIONS

- Obtain existing light detection and ranging and bathymetric datasets to capture both overbank and in-channel geometries
- Compile and examine available datasets from federal, state, and local monitoring and modeling programs
- Measure spatial and temporal trends in sediment transport, deposition, and erosion to understand how these processes shape channel morphology
- Compare new bathymetric data against previous surveys to quantify narrowing, aggradation, and loss of flood capacity along the river corridor
- Map and evaluate vegetation growth patterns that restrict channel capacity or alter local hydrology
- Apply sediment transport and hydrologic and hydraulic models to estimate flow capacity, sediment yield, and areas at risk of future aggradation; identify reaches with the greatest sedimentation and flow restrictions, prioritizing areas for potential restoration, sediment management, or vegetation clearing
- Develop detailed channel capacity and sedimentation maps
- Make recommendations for managing sediment buildup and vegetation encroachment

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ADVANCE USE OF THE JOINT PROBABILITY METHOD IN COMPOUND HAZARD ASSESSMENT

Expand probabilistic modeling to better capture the combined effects of storm surge, rainfall, riverine flooding, and local watershed conditions across Texas coastal basins

Current coastal flood hazard assessments often underestimate water levels by neglecting the compound effects of storm surge and precipitation-driven flooding. This is particularly critical in Texas coastal watersheds, where hurricane storm surge and hurricane-induced rainfall riverine flooding interact in complex ways. Traditional statistical methods, such as bivariate copulas, are limited by data constraints and basin variability, making them insufficient for capturing the full range of flood hazards.

TIFF recommends expanding the Coastal Hazards System Probabilistic Coastal Hazard Analysis (CHS-PCHA) model agnostic framework to improve compound flood hazard characterization. This enhancement would integrate high-resolution numerical modeling, machine learning, and stochastic uncertainty (e.g., antecedent conditions like soil saturation, which vary based on local geography). Leveraging synthetic storm results from prior regional studies would also support a framework that can be consistently applied across Texas coastal basins.

KEY IMPLEMENTATION ACTIONS

- Improve the CHS-PCHA framework by integrating additional probability methods beyond observation-based approaches, such as the use of Hurricane Rainfall Models and the use of seasonal correlation between flow and intensity applied in the Joint Probability Model (JPM) framework
- Develop a flexible, model-agnostic framework that can be applied consistently across Texas coastal basins
- Incorporate variability in antecedent conditions (e.g., soil saturation) to refine flood risk estimates based on local geography
- Utilize synthetic storm results from prior coastal hazard studies to reduce computational cost and apply widely-accepted regional storm surge information and statistics; explicitly represent interactions between tropical cyclone storm surge and rainfall-induced water levels to capture compound flood hazards.
- Apply the improved JPM framework in select Texas coastal watersheds to assess accuracy and reliability
- Conduct validation studies with historical and synthetic storm events to refine methodology

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DEVELOP A HIGH-RESOLUTION STATEWIDE PARAMETRIC TROPICAL CYCLONE RAINFALL GENERATOR

TIFF recommends the development of a high-resolution (hourly, 0.05-degree) rainfall generator for statewide application in Texas to generate rainfall fields for all synthetic tropical cyclones used in compound flood hazard assessments for the coastal Texas region. Building on a U.S. Army Corps of Engineers 2023 study that established a set of 660 synthetic tropical cyclones for evaluating flood risks, the effort involves quantifying uncertainty and bias in tropical rainfall models by leveraging historical rainfall datasets. This high-resolution rainfall generator will support improved flood hazard assessments.

TIFF recommends partnerships with organizations experienced in weather data collection, management, and dissemination, such as the Office of the Texas State Climatologist (housed at Texas A&M University) and other academic institutions. The project timeline is expected to range from 6 months to 3 years, depending on the required level of detail and prior experience with similar developments. The estimated total cost is between $100,000 and $200,000.

KEY IMPLEMENTATION ACTIONS

- Use historical rainfall data to assess and correct biases in existing tropical cyclone rainfall models
- Create an hourly (0.05-degree) tropical cyclone rainfall generator tailored for Texas
- Produce bias-corrected and probabilistic rainfall datasets for all 660 synthetic tropical cyclones in the Coastal Texas Comprehensive Study
- Utilize artificial intelligence/machine learning to analyze rainfall distribution relative to storm tracks and generate realistic rainfall patterns within hurricane rain bands

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CONDUCT RETROSPECTIVE MODELING OF HISTORIC LANDFALLING HURRICANES USING HIGH-RESOLUTION WEATHER MODELS

Understanding historical storm impacts is crucial for improving predictive models and better protecting lives and infrastructure. However, hurricane modeling is limited by the lack of high-resolution observational data before the 2000s, reducing the accuracy of flood and wind hazard assessments, particularly in data-scarce regions. While many flood models rely on modern datasets, validating them against past events enhances their reliability.

TIFF recommends a retrospective analysis of major landfalling hurricanes from the early 1960s to the 1990s using high-resolution modeling techniques. This analysis will provide data to calibrate and validate flood models while also supporting wind hazard assessments for periods before the availability of the High-Resolution Rapid Refresh weather forecasting model. Simulating past hurricanes will offer insights into their potential impact on today's coastal infrastructure, aiding in the refinement of evacuation plans, resilience strategies, and building codes. Additionally, understanding historical hurricane behavior will contribute to long-term assessments of storm intensity and frequency, informing climate adaptation efforts.

TIFF recommends partnerships with organizations experienced in weather data collection, management, and dissemination, such as the Office of the Texas State Climatologist (housed at Texas A&M University), other academic institutions, federal and state agencies, industries, and consulting firms for the implementation of this effort. The effort is expected to take 1 to 3 years, depending on the historical scope. The estimated cost ranges from $100,000 to $350,000, with the higher end supporting simulations of additional storms, such as Hurricanes Carla (1961) and Beulah (1967), and alternative storm path scenarios. (Hurricane Carla is particularly important for wind analysis, while Hurricane Beulah is significant for rainfall impacts.) TIFF recommends prioritizing these hurricanes for analysis and incorporating perturbed simulations to assess potential storm impacts under alternative tracks. Deliverables should include high-resolution wind and rainfall data, validated against historical observations, to improve understanding of past hurricane impacts and enhance future modeling efforts.

KEY IMPLEMENTATION ACTIONS

- Develop partnerships with organizations experienced in weather data collection, management, and dissemination, such as the Texas A&M University Office of the Texas State Climatologist, other academic institutions, federal and state agencies, industries, and consulting firms
- Support simulations of additional storms such as Hurricanes Carla (1961) and Beulah (1967), and alternative storm path scenarios (Hurricane Carla is particularly important for wind analysis, while Hurricane Beulah is significant for rainfall impacts)
- Prioritize modeled hurricanes for analysis and incorporating perturbed simulations to assess potential storm impacts under alternative tracks
- Deliverables should include high-resolution wind and rainfall data, validated against historical observations, to improve understanding of past hurricane impacts and enhance modeling efforts

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DEVELOP RAPID PREDICTIONS OF FLOODING HAZARDS TO SUPPORT FLOOD PLANNING AND RESPONSE

Effective flood hazard prediction is crucial for ensuring public safety and optimizing emergency response during storm events along the Texas coast. Currently, rapid and accurate forecasting of storm surge and wave impacts is limited, making it challenging to issue timely warnings to at-risk communities. The ability to predict flooding hazards quickly enhances emergency response efforts by enabling authorities to issue evacuation orders, mobilize resources, and reduce casualties and property damage. Furthermore, these predictions aid in managing coastal flood protection systems, such as pumps, dams, and surge barriers, to protect vulnerable areas.

TIFF recommends the development of a robust, reliable, and accurate storm surge and coupled wave model for the Texas coast. This model should build on previous studies to provide enhanced predictions for total water levels and flood inundation. By incorporating large- and small-scale three-dimensional (3D) processes, the model would improve the accuracy of simulations, ultimately supporting better decision-making in flood preparedness and response.

TIFF also recommends the evaluation of the suitability of existing web tools, such as the Interagency Flood Risk Management Flood Decision Support Toolbox (https://webapps.usgs.gov/infrm/fdst/) and the National Weather Service National Water Prediction Service (https://www.weather.gov/ewx/NWPSInfo), for disseminating information to emergency managers and relevant statewide parties. The evaluation should aim to determine whether these platforms can effectively convey the complexities of coastal and compound flooding risks or if a separate platform is necessary for improved communication and visualization.

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GROUND-TRUTH DATA FOR FLOOD RISK MODELING ACROSS THE LOWER RIO GRANDE VALLEY

Develop a machine learning model that leverages artificial intelligence and remote sensing to detect and map high-risk flood zones across the Lower Rio Grande Valley

Flood risk in the Lower Rio Grande Valley (LRGV) is especially hazardous due to the threat of compound flooding, or the combined effects of riverine flooding and nearshore storm surge. While historical records specific to compound flooding in the LRGV region may be limited, the area has experienced various flood events over the years, often resulting from the convergence of different hydrological and meteorological phenomena. Recent advancements in applying remote sensing, especially when combined with machine learning (ML) techniques, have made possible the detection of large flood-prone areas without the need for highly accurate data inputs and computationally intense hydrological processes.

TIFF recommends developing and validating a scalable ML model for automated flood detection and risk mapping. This requires integrating multi-sensor and multi-scale data to calibrate models and improve detection precision with a validated artificial intelligence-driven approach.

This 2-3-year investment, estimated at $1 million, will support adaptive flood management by mapping flood-prone areas, analyzing contributing risk factors, and providing data-driven insights for infrastructure planning and mitigation strategies across the Texas coast.

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GROUND-TRUTH DATA FOR FLOOD RISK MODELING ACROSS THE LOWER RIO GRANDE VALLEY

KEY IMPLEMENTATION ACTIONS

- Collaborate with local universities and partners to assist with drone data collection and analysis, remote sensing and associated analysis, ML development, and model validation
- Collaborate with federal and state agencies to integrate historical coastal and hydrological data
- Consider an existing state agency as the potential data host
- Identify significant historical flood events and collect corresponding high-water marks and satellite imagery, where available
- Assess data gaps and synthesize available datasets, and consider challenges related to cloud-free satellite data availability
- Build on TIFF's previous literature reviews of artificial intelligence (AI)-based flood modeling and remote sensing techniques
- Identify best practices for data selection, pre-processing, and algorithm design; incorporate LRGV-specific factors such as debris accumulation, stormwater stacking, and drainage obstruction
- Build and train an appropriate and state-of-the-art ML model applied to Sentinel-1/2, Synthetic Aperture Radar, Interferometric Synthetic Aperture Radar, light detection and ranging, drone imagery, and historical ground-truth data
- Automate classification of water bodies, impervious surfaces, and flood-affected zones for improved early detection
- Expand labeled datasets through supervised learning and iterative refinement based on historical and field-verified data
- Integrate key environmental variables, including stormwater accumulation, drainage networks, and soil saturation
- Conduct spatial analyses using GIS-based workflows to identify regularly flooded areas
- Deploy drones to collect high-resolution, post-event imagery and validate model predictions at site-specific scales
- Combine three data layers (remote sensing imagery, drone data, and field survey inputs) to calibrate and verify model outputs
- Assess model performance using accuracy, precision, recall, and operational reliability metrics; evaluate predictive capabilities under varying climatic and meteorological scenarios; compare results against historical flood maps and municipal drainage data
- Develop a decision-support catalog highlighting flood risk levels, contributing factors, and spatial trends across the LRGV that aligns with the forthcoming NBS Guidance Manual from the Texas Water Development Board to ensure consistency with statewide flood infrastructure strategy
- Publish shareable and reusable AI workflows using emerging computational infrastructure ("pods") to support cross-agency collaboration, transparency, and repeatability
- Integrate models and datasets into external state and federal systems and share outputs with local LRGV counties through clear data-sharing protocols
- Conduct training sessions and workshops to support local adoption and capacity building

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MODEL STORM SURGE IMPACTS IN THE LOWER RIO GRANDE VALLEY

Leverage historical and real-time monitoring data to develop a machine learning model that evaluates how coastal storm surges influence flood dynamics in the Lower Rio Grande Valley

Coastal storm surge is driven by at least two distinct flooding processes: slow-moving inland flooding (low energy, inundation) and rapid coastal flooding from bays and estuaries (high energy, destructive). When these floods interact, their differing energy regimes pose challenges for analysis and modeling, often resulting in computational singularities that make it difficult to estimate compound flood impacts along the shoreline.

TIFF recommends developing and validating a machine learning (ML) model designed to integrate inland stream gage observations (e.g., water surface elevation, discharge) with advanced bay and estuary measurements (e.g., tidal depth, three-dimension velocity fields, and salinity gradients) to estimate compounded flood depth and energy loss.

This 3-year investment, estimated at $1 million, will quantify the spatial and temporal influence of coastal surge on inland river stages; estimate compound flood depth, duration, and flow energy losses across the LRGV; and support the calibration of detailed hydraulic models for regional planning applications.

KEY IMPLEMENTATION ACTIONS

- Compile and examine available datasets from federal, state, and local monitoring and modeling programs
- Train a one-year model using multivariate data inputs (e.g., streamflow, tidal stage, offshore wave height, barometric pressure) and adapt the system for continuous learning and procedural evaluation using the remaining historical datasets and evolving real-time data
- Introduce independent datasets such as stream network node connectivity for assessing data resource requirements at the Hydrologic Unit Code (HUC)-8 scale and extrapolate results by hydrographic type
- Use ML-generated insights to calibrate and validate hydraulic models; validate models at both subregional (multi-watershed) and urban (municipal drainage system) scales to test scalability and transferability
- Integrate models and datasets into external state and federal systems and share outputs with local LRGV cities and counties to support local adoption

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IMPLEMENT THE TEXAS COASTAL FLOODING FRAMEWORK (TXCFF)

Develop the Texas Coastal Flood Framework (TxCFF) assessment system for compound flood assessment to support flood recovery and emergency response efforts along the Texas coast

Texas has the opportunity to set a national standard for compound flood modeling. As the largest economy among hurricane-prone states, and second only to Florida in population at risk, Texas faces urgent challenges from hurricane and tropical cyclone flooding. To address these challenges, TIFF recommends establishing the TxCFF: a sustainable, updateable, and state-of-the-art system for compound flood assessment. The TxCFF will integrate models, analysis tools, and workflows to support planning, development, recovery, and emergency response along the Texas coast. This framework will provide linkages to existing databases, seamless data transfer between models, a user interface for setting up and executing coupled models, plug-and-play application programming interfaces, and integrated output datasets from component models into coherent datasets for analysis and visualization. Over time, it will evolve into a robust platform for evaluating and managing compound flooding across multiple projects.

The TxCFF would consist of:

- wind and pressure model
- ocean circulation model
- wind/wave model (far field and near field)
- flood inundation (hydraulics) model for river flow and landscape flooding
- upland runoff model (hydrology)
- stormwater drainage model
- groundwater model
- flood hazard analysis tools
- code for coupling the various flood
- inundation component model
- coupling to external meteorological (storm) models/ data sets for historic and synthetic storms
- code for calibration, validation, and testing of inundation models
- code for ingesting flood inundation model results into flood hazard analysis
- code for visualizing inundation and hazard analysis results
- code for input/output
- code for user customization

Initially, the TxCFF could start as documented workflows for coupling models and data, supported by pre- and post-processing tools. These workflows can then be codified into a software framework emphasizing reusability, accessibility, scalability, training, and uncertainty management. Development will require long-term funding, a consistent project team, and collaboration with agency-sponsored modeling projects. By building on vetted workflows and testbeds, the TxCFF can grow incrementally into a central resource for scalable and integrated flood modeling across Texas with an active user community supported with training resources.

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IMPLEMENT THE TEXAS COASTAL FLOODING FRAMEWORK (TXCFF)

KEY IMPLEMENTATION ACTIONS

Tasks/steps to development the TxCFF are outlined in Figure 3-24 and below:

1. **Identify and Prioritize Testbed Locations**: TIFF identified seven regions as priority locations for building the TxCFF capabilities and recommends that the first three receive highest priority (See TIFF Final Report Figures 3-11 through 3-17 and Appendix C-10 for more details on each location.):
   a. Houston/Galveston Region – This region includes several different types of inlet flows into an irregularly shaped bay with complex hydrodynamics, supports a large population with community involvement, has a long history of hurricane impacts, and also has one of the longest tidal gages in the country.
   b. Freeport Region – This region is prioritized because the Brazos River empties directly to the Gulf, so it experiences a different kind of compound inundation than the other regions considered. Drainage areas upstream are largely industrial with little infiltration and irregular flood control measures.
   c. Rio Grande/Laguna Madre – This region is a long shoreline bay with several tributaries as well as a large river outlet. The contributing rivers are heavily regulated and international agreements and impacts could be a controlling factor in considering coastal storm risk management. This region is also an excellent example of a data and model-poor watershed of international importance, although TIFF did employ recent advancements in remote sensing applications combined with machine learning techniques to detect flood prone areas in the Lower Rio Grande Valley, providing a good foundation for continued efforts.
   d. Beaumont/Port Arthur Region
   e. Corpus Christi Region
   f. Matagorda Bay Region
   g. Brownsville/South Padre Island Region

   The final decision on the sites to be implemented (and order of implementation) should carefully consider 1) the level of stakeholder engagement and resources that can be allocated, 2) the scale of the storms and adjacent flooding area that require modeling, 3) data availability, 4) the dominate flood hazards to ensure a balanced mix between the different drivers (e.g. coastal and inland, the geographic characteristics, both land and water, of the area), and 5) the overall resources available to the project. Flexibility to employ and compare different compound hazard analyses levels and flood inundation models would be an added benefit.

2. **Test Candidate Models for a TxCFF**: Select relevant models based on the findings of the TIFF literature review and input from scientists/engineers familiar with the testbed site. (This selection should take into consideration the existing models and hazard analyses in the testbed study region for leveraging resources.) Develop and apply testing strategies to evaluate each discipline model with respect to:
   - How the model algorithm influences the practical coupling algorithms
   - Whether implementation is through source code changes or in/out data stream
   - Stability and convergence conditions for coupling
   - Whether an interface region is needed between models
   - Identifying model boundaries and handling boundary movement

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IMPLEMENT THE TEXAS COASTAL FLOODING FRAMEWORK (TXCFF)

- Handling disparities in model time steps and grid size
- Effectiveness of parallelization of the model; test cases for proving coupling viability
- Availability of graphical user interfaces
- User guides, documentation, and training material

(This action should connect discipline scientists/engineers with framework software engineers to ensure analyses consider both model-specific and framework-level impacts.)

3. **Evaluate Software Framework Fundamentals**: Identify the critical methods for model integration and data exchange (e.g., selection of coding language for the framework) considering:
   - The utility of existing frameworks like the Earth System Modeling Framework
   - Needs for coupling data communication
   - Standard data libraries and metadata standards to be included
   - The approach used for parallelization across different models to ensure efficient computing
   - The definition of "best practices" to be used in writing framework code
   - Systematic approaches and supporting data for testing and code validation

   (This work should proceed in parallel with candidate model testing to ensure framework and coupling decisions are aligned. The deliverables will be an alpha version of the TxCFF and guidelines on coding conventions, libraries, and inter-team communication to ensure project compatibility.)

4. **Develop TxCFF Best Practices**: Develop best practices and training materials to broaden adoption of the TxCFF. These should emphasize basin or location-agnostic approaches by using probabilistic methods for inputs and boundary conditions, consistently sampled from fitted distributions. For example, engineers might suggest a certain infiltration sub-model, but the input parameters could be selected by sampling distributions fit to historical records.

5. **Evaluate Coupling Methods for Candidate Models**:
   - Select and test candidate models
   - Investigate coupling interfaces across:
     - ocean and flood inundation
     - upland runoff and flood inundation
     - stormwater system and flood inundation
     - stormwater system and upland runoff
     - groundwater with flood inundation, stormwater system, and upland runoff
     - wind/wave with flood inundation
     - meteorological forcing with all models

   (Coupling must be developed and coded by multidisciplinary teams, working collaboratively and transparently to ensure con-

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sistency across interfaces. Each project team should coordinate directly with the compound flooding framework team to define input/output data, manage spatial and temporal interpolation, and guide development.)

6. **Develop and Evaluate Boundary Placement Among Models**: Develop a methodology and code to automatically set and adjust coupling boundaries as needed. This requires analyzing diverse testbeds under different modeling scenarios and establishing guidance on which model outputs to use in overlapping regions. From a compound hazard perspective, boundaries should be positioned within a single model wherever possible, ensuring that boundary conditions represent only one driver at a time.

7. **Grid Generation for Coupled Model System**: Develop a consistent, automated methodology for creating and testing coupled model grids for multiple testbed sites along the Texas coast, leveraging existing initiatives and focus on efficiency, reliability, and standardized practices. Key tasks include automating extraction of ground elevation data (e.g., Texas Geographic Information Service light detection and ranging) into grid meshing systems; updating grids routinely to reflect geomorphic changes and urban growth; and providing guidance on discretization resolutions and standardized parameters (e.g., Manning's Roughness). These measures will streamline model development, maintain up-to-date domains, and ensure consistency in model configuration and application, supporting faster innovation and more reliable outputs for coastal resilience planning.

8. **Heuristics for the Use of Simplified Models**: Develop heuristic algorithms to guide users on the relative importance of different compound flooding components under specific conditions. For example, if upland rainfall is low and soils are unsaturated, a heuristic might recommend disabling hydrological modeling. These heuristics can rely on general knowledge of forcing scales and landscape characteristics and may suggest pre-defined workflows for users. Heuristics may need to be customizable for specific locations, with different parameters for areas such as Houston-Galveston Bay versus Brownsville. Screening hazard tools (e.g., Hazard Level-0, Hazard Level-1) can help identify major drivers, and bivariate copulas can be extended to trivariate analyses to assess additional factors, such as groundwater, in compound flooding.

9. **Develop Coupled Model Inputs/Outputs**: Models within the framework will have varying input and output formats that must be standardized by the framework. This action involves collaborating with hazard analysts, discipline engineers/scientists, and potential users to define flexible, practical data methods. Wherever possible, standard libraries and file formats (e.g., Network Common Data Form, Hierarchical Data Format 5, JavaScript Object Notation) should be used. Metadata should follow community standards, such as the Climate Forecast Metadata conventions. Data cataloging and curation practices should ensure proper access and retrieval. Tools for community-based visualization and analysis should also be developed.

10. **Automate Calibration, Validation, and Comparison with Observations**: Traditionally, calibration, validation, and comparison with observations have relied on user expertise. For TxCFF testbed sites, automated approaches should be developed to standardize these tasks, preventing model adjustments outside their intended scope. This system will increase confidence in model outputs, especially for users lacking expertise in specific compound flood disciplines.

11. **Develop Targeted Training Courses for TxCFF User Groups**: Include an introduction to compound hazard analysis, covering probabilistic inputs, synthetic storms, and integration of model outputs to generate hazard curves and flood map.
    - Training For Modelers – Focus on using testbed models to create, run, and analyze compound flooding cases, including making "what-if" changes to assess storm scenarios, land development, and other impacts
    - Training For Testbed Model Developers – Expand expertise to extend testbed models and hazard analyses to other regions and more complex scenarios, supporting the broad adoption of TxCFF across the Texas Coastal Plain
    - Training For Managers (academia, industry, government) – Provide guidance on the capabilities and limitations of TxCFF, interpreting model outputs, and formulating relevant "what-if" questions for planning and decision-making

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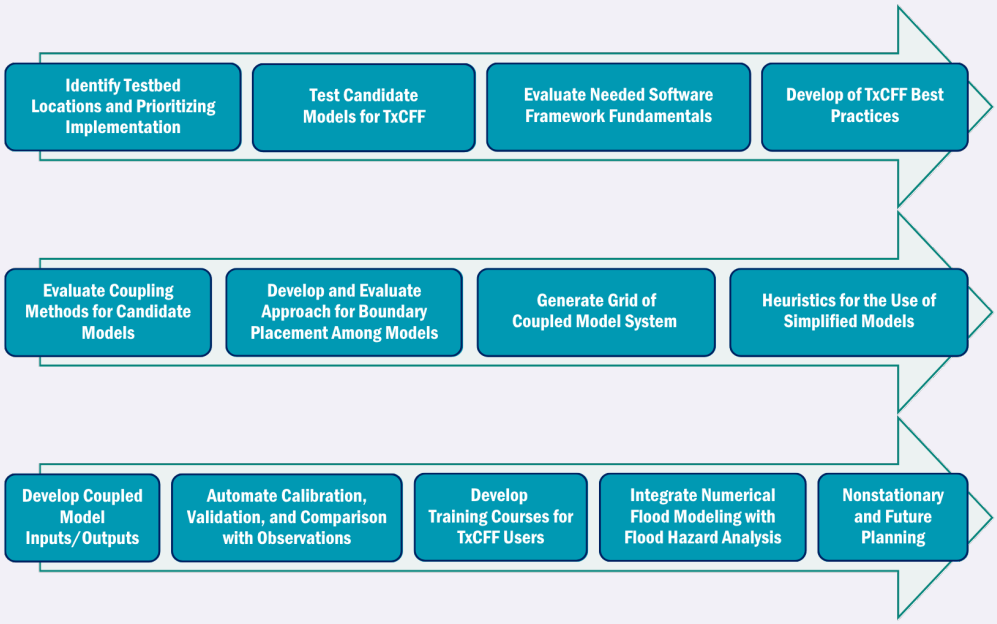
IMPLEMENT THE TEXAS COASTAL FLOODING FRAMEWORK (TXCFF)

12. **Integrate Numerical Flood Modeling with Flood Hazard Analysis**: Evaluate compound flood hazards at different hazard levels using the testbed and/or its sub-basins. Analyses can leverage existing models, new TxCFF models, or published compound hazard studies. These results can be compared with individual hazard models such as the Coastal Hazards System for storm surge/waves or inland flood frequency analyses. Integrated model outputs can be used to generate hazard curves and flood inundation maps. Additionally, multi-level meta-model approaches tested in pilot studies can be applied to characterize basin-specific impacts on event probabilities (e.g., Hazard Level-3 Extended Joint Probability Model (JPM)). Uncertainty in inputs, model outputs, and hazard estimates can be incorporated to improve overall hazard assessment.

13. **Address Nonstationarity and Future Planning**: To account for natural and anthropogenic factors, the framework should include inland and coastal impacts that can exacerbate flood risk (e.g., sea-level rise, higher storm surge risks, and shifting rainfall patterns, as well as land-use changes from population growth and urbanization). Incorporating these projections ensures resilience in infrastructure development and flood mitigation planning. Several methods exist to characterize future conditions. Numerical physical models currently incorporate sea-level rise for JPM-based models (Nadal-Caraballo et al. 2020). Statistical approaches, such as Bayesian networks, surrogate modeling, and Bayesian updating, can quantify changes in tropical cyclone frequency, rainfall patterns, and land-use impacts, providing insights into evolving risks. These methods help stakeholders prioritize interventions and adapt flood protection strategies over time (Liu et al. 2025).



Task/steps to build the TxCFF.

Citations:

Liu, Z., Carr, M.L., Nadal-Caraballo, N.C., Yawn, M.C., & Bensi, M. 2025. "A Bayesian Network Method for Deaggregation: Identification of Tropical Cyclones Driving Coastal Hazards [Unpublished Manuscript]." http://arxiv.org/abs/2505.14374.

Nadal-Caraballo, N.C., Campbell, M.O., Gonzalez, V.M., Torres, M.J., Melby, J.A., & Taflanidis, A.A. 2020. "Coastal Hazards System: A Probabilistic Coastal Hazard Analysis Framework." *Journal of Coastal Research*, 95, 12111216. https://doi.org/10.2112/SI95-235.1.

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CREATE A FLOOD TOOL FOR HAZARD AND LOSS ASSESSMENTS

Develop a flood tool for hazard and loss assessments to improve state flood planning and prediction

Flooding and other natural disasters in Texas cause significant damage each year, impacting communities, infrastructure, and economic stability. To improve planning, insurance assessments, and predictive capabilities, TIFF recommends the development of a comprehensive hazard and loss assessment framework for Texas.

Currently, hazard and loss assessments are fragmented, relying on disparate data sources, costly post-disaster inspections, and varying building codes across communities. A structured, statewide framework would provide consistent, high-quality data to inform decision-making, reduce uncertainties, and support mitigation planning.

By implementing this framework, Texas can move toward a data-driven, proactive approach to flood risk management with a comprehensive framework that accounts for a wide range of losses, beyond just structural inundation. This includes social impacts and disruptions to essential services, providing a more holistic understanding of disaster consequences.

KEY IMPLEMENTATION ACTIONS

- **Database Development and Enhancement**: Develop and maintain a centralized, regularly updated database to support hazard and loss assessments; include essential information such as building age, construction standards, and historical flood regulations (e.g., National Flood Insurance Program adoption, freeboard requirements, International Building Code compliance); TIFF recommends various agencies partner to enhance Texas Water Development Board's building footprint database, ensuring improved data accuracy and coverage
- **Flood Risk Model Development**: Establish model functionality requirements and certification criteria for accurate risk assessment; include assessing the feasibility of creating a Texas-specific flood model that incorporates local flood level data, damage estimates, and loss metrics; design the models to ensure compatibility with benefit-cost analysis requirements, supporting state and federal grant applications
- **Post-Disaster Data Collection Strategy**: Improve data collection following disaster events; strategies will be developed to address challenges such as lost high-water marks and overwhelmed local officials; encourage community participation in recording flood depths using simple methods like photo documentation and height measurements
- **Cumulative Impact and Mitigation Tracking**: Expand assessments beyond catastrophic events to include the cumulative impact of minor flooding, which often goes unrecorded but can still degrade infrastructure and property values over time; improve tracking of mitigation efforts and loss avoidance, ensuring that valuable data is preserved for future analysis

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DEPLOY A STATEWIDE PREPAREDNESS EDUCATION CAMPAIGN ON HOW TO USE FLOOD RISK MAPS

Teach stakeholders how to use flood risk maps for preparedness to enhance community flood resilience

As floods become more frequent and severe, Texas must enhance community resilience by ensuring local stakeholders understand and act on flood risk information. Flood maps are essential for assessing risks, but many residents and local officials struggle to interpret them accurately, hindering preparedness and response efforts.

TIFF recommends coordinating workshops that help local emergency managers, community coordinators, and residents learn how to read and interpret flood maps. The workshops should engage community members by encouraging feedback and updating local data. Involving the community in data collection and decision-making will foster a sense of shared responsibility. TIFF recommends partnering with organizations experienced in flood planning, coordination, and mitigation, such as the Texas Division of Emergency Management (TDEM).

By the end of the project, stakeholders, including residents and officials, will collaborate effectively on flood preparedness, with flood risk maps becoming a common tool in decision-making and community resilience planning.

KEY IMPLEMENTATION ACTIONS

- **Establish Partnerships**: The planning and development phase should include multiple meetings with TDEM's Assistant Chiefs, Regional Section Chiefs, District Chiefs, and County Liaison Officers; use existing datasets and expert observations to identify priority locations based on flood history, flood severity, population size, critical infrastructure, and other variables
- **Stakeholder Outreach**: Promote the workshops through partner websites; reach out to agencies and organizations advancing flood science, such as the Texas Water Development Board, Texas Disaster Information System, and the Texas General Land Office to promote the workshops through their engagement channels; advertise the workshops locally to connect with resident
- **Workshops**: Conduct at least two workshops in each of TDEM's eight regions; the workshops will engage participants in flood-preparedness activities with the goal to 1) strengthen participant understanding of flood-risk map symbols and associated uncertainties, and 2) build participant ability to assess the impacts of various flood scenarios; each workshop should integrate flood-risk maps with complementary data, such as demographic information and land use trends, to provide a more comprehensive understanding of community flood risks

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ESTABLISH A TDIS ONLINE LEARNING CENTER

Establish an online learning center within the Texas Disaster Information System to improve sharing of flood education resources to strengthen workforce education, improve flood preparedness, and ensure that critical expertise remains readily available for researchers, decision-makers, and practitioners

State and federal agencies (and academic institutions) offer a wealth of educational resources on flood-related topics, including compound flood modeling, data gathering, visualization, and management. These resources include workshops, webinars, and expert-led seminars that provide valuable insights into research, data, and ongoing flood-related projects. Despite the abundance of available content, there is no centralized platform where these materials are systematically stored and easily accessible for future reference. As a result, critical knowledge is often scattered across different organizations, making it difficult for professionals, policymakers, and researchers to efficiently access and utilize these resources.

To address this gap, it is beneficial to create an online learning center within the Texas Disaster Information System (TDIS). This platform would serve as a comprehensive repository for flood-related educational materials, including recorded webinars, research presentations, and training modules. A centralized resource hub would enhance accessibility to critical flood-related knowledge, provide professional education credits continuing education hours which are required for various professional license renewals (e.g., Professional Engineer, Certified Facility Manager) and foster greater collaboration among agencies, academic institutions, and flood management professionals.

This recommendation can be implemented for an estimated annual cost of $85,000-$108,000. The estimated cost for initial implementation is $300,000. The project team must have established connections with the Texas Education Agency and a strong understanding of the Texas Essential Knowledge and Skills requirements. TIFF recommends the Texas Floodplain Management Association help coordinate this effort because it has established a national program for professional certification of floodplain managers.

KEY IMPLEMENTATION ACTIONS

- **Planning and Development**: Conduct a survey to identify priority content and existing educational resources from agencies, academic institutions, and professional organizations; define technical requirements for content hosting, search functionality, and credit tracking; select a video hosting platform; build a searchable library with keyword tagging and design an intuitive interface for easy navigation
- **Content Collection and Integration**: Gather existing videos, slides, and presentations from past workshops and seminars, collaborating with relevant agencies and experts and leverage any existing flood educational materials developed/collected by federal and state agencies; materials should be tagged, categorized, and updated quarterly for continued relevance; conduct beta testing with key users and refine the platform based on feedback
- **Launch and Ongoing Maintenance**: Promote the platform through TDIS, Texas Water Development Board, professional organizations, and academic networks, with a virtual kickoff webinar; employ one full-time employee for content management and updates; maintain cloud storage, engage with stakeholders, and ensure the platform evolves with user needs
- **Flood Literacy Evaluation**: Determine if the online learning center increased flood literacy in target user groups, improving their capacity to respond effectively and appropriately to given flood risk information

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EMBED FLOOD LITERACY TO K-12 EDUCATION

Expand K-12 flood education to help students better understand and respond to flooding

K-12 students in Texas schools (public, charter, homeschool) currently learn about the water cycle and drought. However, despite the state's high vulnerability to flooding, most students receive little to no instruction on how floods occur, the risks they pose, or how to prepare for them. This differs greatly compared to topics like fires and tornadoes, where schools and fire departments often collaborate to conduct drills and teach preparedness (e.g., "Stop, Drop, and Roll").

Texas should adopt a flood education plan that develops culturally and linguistically appropriate flood education content for its K-12 system using tools like virtual and augmented reality and serious games to build students' critical decision-making skills in emergencies. This initiative should embed flood awareness in science, geography, and emergency preparedness curricula, using interactive and technology-driven learning tools, to engage students effectively. This initiative should also develop programs that integrate children and youth into community-based flood preparedness and response activities, fostering intergenerational learning and stronger awareness networks.

Piloting this effort is estimated to cost $300,000 over two years. Success requires close coordination with the Texas Education Agency, along with a solid understanding of the Texas Essential Knowledge and Skills (TEKS) standards. Collaborating with Independent School Districts, homeschool and online education programs, and family and community organizations is essential. Partners should also include coordination with state agencies experienced in producing flood education resources, such as the Texas Division of Emergency Management, the Texas Water Development Board, and the Texas Floodplain Management Association.

KEY IMPLEMENTATION ACTIONS

- **Determine Feasibility and Timeline**: Assess the process, feasibility, and realistic timeline for integrating flood education into the Texas K-12 curriculum; develop materials suitable for children, youth language brokers, and their families, recognizing Texas's bilingual communities
- **Review Best Practices**: Conduct a literature review of flood education initiatives both within Texas and internationally; identify effective models, gaps, and grade-level opportunities for integration; adapt existing materials and games from successful programs and include activities that engage parents and caregivers to broaden community flood awareness
- **Develop Educational Tools**: Recommend and design content such as interactive modules, serious games, and augmented reality experiences aligned with TEKS learning standards; plan for long-term support needs such as maintenance and regular updates
- **Flood Literacy Assessment**: Measure whether incorporating flood education increases flood literacy among students

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BETTER UNDERSTAND THE FLOOD DECISION-MAKING OF PUBLIC STAKEHOLDERS

Better understand stakeholder social norms related to flood decision-making

Research consistently shows that social norms—being influenced to engage in a behavior because of trusted others—are a strong predictor of Texans' flood-related decisions. These trusted individuals are often peers rather than experts, highlighting the need for a deeper understanding of how social influence shapes decision-making in flood preparedness, response, and recovery.

TIFF recommends targeted experiments, surveys, and focus groups to explore the various forms of flood-related decision-making. By analyzing how different social groups influence perceptions and actions, these studies can identify the most effective ways to disseminate flood information. Insights from this research can then be used to develop communication strategies that leverage peer networks, ensuring that critical flood-related messages resonate with and motivate communities to take protective action.

The estimated cost is $245,000, which includes participant compensation to ensure representative data. Testing *People with Limited English Proficiency* should be prioritized to improve accessibility and effectiveness. A key research objective should be to assess how well individuals understand the documentation involved in purchasing a home. For example, do they know whether the home is located in a designated flood zone?

KEY IMPLEMENTATION ACTIONS

- **Social Norms Studies (Two Experiments)**: Study how social norms impact flood-related decisions (e.g., buying insurance, creating evacuation plans, home selection); examine the role of information sources will be examined, including trust and domain-specific trust; test evidence-based messaging strategies that integrate social norms, assessing their effects on risk perception and cognitive load
- **Key-Logging Study**: Analyze how peer-shared flood experiences influence decisions and identify the most effective messengers; explore community-driven approaches, such as using *promotoras* (lay health workers) for flood communication; conduct surveys, interviews, and focus groups reflecting Texas' demographics, with a focus on *People with Limited English Proficiency*

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DEPLOY A STATEWIDE TEXASFLOOD.ORG BRANDING CAMPAIGN

Use a branding campaign to enhance online engagement with key flood information on TexasFlood.org

TIFF research showed that TexasFlood.org, despite being a key resource for flood information, has limited engagement with its target audiences. To increase awareness, graphics should be finalized and a comprehensive campaign promoting the website and its resources should be launched to emphasize flood preparedness and risk management.

The campaign will incorporate clear metrics to track website traffic and user engagement, ensuring measurable success and ongoing improvement. TIFF research also suggests evaluating the impact of the messages after launch to ensure they resonate with the target audiences and effectively drive engagement. Regular assessments will help refine the approach and keep the materials relevant.

TIFF recommends establishing a branding campaign for TexasFlood.org, including the finalization of graphics tailored to the identified audiences, strategic outreach to increase awareness, and a robust evaluation process to track the effectiveness of the campaign. By integrating a clear branding strategy with evaluation and metrics, this effort aims to enhance the website's visibility and ensure that flood-related resources are accessible and actionable for Texans across the state.

KEY IMPLEMENTATION ACTIONS

- **Branding Campaign**: Develop and execute a comprehensive campaign aimed at raising awareness of TexasFlood.org and its flood-related resources; use finalized graphics to create outreach materials and advertisements tailored to the TIFF prioritized three target users (*Property Owners*, *Property Renters*, and *People with Limited English Proficiency*); leverage multiple channels, such as social media and partnerships with relevant agencies, to maximize reach and engagement with the public
- **Website Metrics and Tracking**: Establish clear metrics to track website traffic, engagement, and user interactions; use metrics to monitor the campaign's effectiveness, refine strategies, and identify any gaps in outreach efforts
- **Evaluation**: Periodically evaluate the messages and materials post-launch; gather feedback from target audiences and analyze data to assess whether the graphics and messages resonate with each group; adjust and update materials based on the findings to ensure they remain relevant and impactful

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IMPROVE DRAINAGE EDUCATION TO REDUCE ILLEGAL DUMPING IN THE LOWER RIO GRANDE VALLEY

Address flooding caused by illegal dumping in the Lower Rio Grande Valley by simplifying drainage education and applying behavioral intervention strategies

Drainage systems in the Lower Rio Grande Valley (LRGV) play a critical role in managing floodwaters but are often strained by the region's flat topography, rainfall characteristics, land use, and water management. These conditions cause rainfall and floodwater to stagnate and recede slowly, increasing flood risks. Illegal dumping exacerbates this problem by clogging drainage ditches and channels which worsens flooding, public health hazards, and property damage. Many residents are unaware of how local drainage systems function or how illegal dumping directly obstructs water flow between neighborhoods, cities, and counties. During heavy rain events, even minor blockages can cause "stacking," where backed-up water accumulates and floods areas days after rainfall.

TIFF recommends combining simplified drainage education with innovative behavioral interventions that integrate environmental design, community education, and incentive-based strategies. This 2-year investment, estimated at $950,000, aims to make drainage concepts relatable to residents' daily experiences, reduce illegal dumping, strengthen community engagement in flood prevention, and foster long-term stewardship of local drainage systems.

KEY IMPLEMENTATION ACTIONS

- **Establish Partnerships**: Build interagency partnerships to co-develop incentive programs, workshops, educational programs on control measures, cleanup efforts, and an annual conference that incorporates youth education; use Hidalgo County's drainage mapping expertise as a potential guide
- **Behavioral Intervention Study**: Fund a behavioral study to identify barriers and motivators influencing illegal dumping; compare attitudes and behaviors between incorporated and unincorporated areas, homeowners, and renters
- **Strengthen Deterrence and Compliance**: Implement a dual-approach pilot combining deterrents (e.g., vegetation buffers, fencing, art, lighting) and convenience measures (e.g., mobile drop-offs, easy quick response/text scheduling, and well-marked "clean zone" windows); measure dumping rates before and after interventions across neighborhoods
- **Enhance Local Law Enforcement**: Provide funding and incentives (potentially through Councils of Government and Texas Water Development Board) for local law enforcement agencies to educate and empower enforcement public servants to more effectively enforce and publicize existing illegal dumping and water quality-related laws (including criminal penalties under the Texas Litter Abatement Act and the Texas Water Code)
- **Incentive Credit Program**: Create a points-based system rewarding residents for positive behaviors (e.g., reporting clogged drains, using authorized disposal sites, joining cleanup events); allow credits to be exchanged for household goods or service vouchers
- **Pilot Implementation and Evaluation**: Test interventions in at least two or three colonias or unincorporated areas; track results using metrics (e.g., dumping frequency, resident participation, program costs, arrest statistics)
- **Simplify Drainage Education**: Replace technical flood maps with accessible visuals showing neighborhood-level drainage flow and impacts of illegal dumping; use hands-on demonstrations, such as interactive simulations by Texas A&M AgriLife's Community Health and Resource Management Program, to show how local dumping contributes to regional flooding; publicize existing illegal dumping and water quality-related laws; deliver education through workshops, community cleanups, and updated, plain-language drainage materials developed with local partners

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ESTABLISH A TEXAS FLOOD COMMUNICATION OFFICE (TFCO)

Establish a statewide Flood Coordination Office (TFCO) to optimize local, state, and federal project impacts

Currently, multiple state and federal agencies, private and non-profit organizations, and academic institutions are engaged in efforts to raise awareness and respond to floods. However, without a centralized coordinating body, the extensive work being done often overlaps, creating redundancies, inefficiencies, and missed opportunities to leverage project outcomes. TIFF recommends Texas legislators establish a Texas Flood Coordination Office (TFCO) within an existing state agency. Initial funding for the TFCO could come from state appropriations, with additional support from federal grants or partnerships with non-profit organizations and private companies involved in flood-related efforts.

By centralizing information and oversight, the TIFF-informed TFCO will enhance the state's ability to manage and mitigate flood risks efficiently. The TFCO will 1) centralize state and federally funded flood projects in one central body, 2) facilitate collaboration among stakeholders to build partnerships and shared solutions, 3) maintain a central archive of project outcomes and share findings with stakeholders, 4) reduce redundancy to ensure efficient use of state and federal resources, and 5) report to the Legislature on the state of flood projects and recommend improvements for flood management.

These key objectives are described in detail below:

1. **Centralized Oversight of Flood Projects**: The TFCO will maintain a database of all state and federally funded flood-related projects to improve coordination and transparency, help decision-makers allocate resources more effectively, and ensure efforts are not duplicated.

2. **Facilitation of Collaboration**: The TFCO will encourage a collaborative approach to promote adaptive flood management strategies, including interagency collaboration and stakeholder engagement for the purpose of developing shared solutions.

3. **Archiving and Dissemination of Findings**: To inform future flood mitigation efforts, the TFCO will archive project outcomes and resources. The information will be made accessible to all relevant parties with appropriate access level (e.g., emergency responders, the general public).

4. **Reduction of Redundancy**: The TFCO will reduce unnecessary duplication of effort by identifying overlaps among projects. This leveraging of project outcomes will prevent wasted investments in repetitive research or narrowly scoped projects and inform new initiatives.

5. **Legislative Reporting and Recommendations**: The TFCO will provide regular reports to the Texas Legislature that highlight the status of flood projects, identify gaps in the state's approach, and recommend improvements for flood management and response.

Flooding is an urgent and ongoing threat in Texas, and the current landscape of flood-related efforts is fragmented and inefficient. By establishing the TFCO, the state can enhance its flood management efforts, streamline coordination across sectors, and ensure that all projects contribute to a more resilient and prepared Texas.

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ESTABLISH A TEXAS FLOOD COMMUNICATION OFFICE (TFCO)

KEY IMPLEMENTATION ACTIONS

- **Establishment**: Embed the TFCO within an existing state agency involved in flood science, planning, and/or funding; although the TFCO could be established as a separate entity, utilizing an existing agency may reduce the overhead and administrative burden; form a small interdisciplinary team of flood management experts supported by 1-2 administrative staff; this team must build long-term partnerships with external agencies, academic institutions, and stakeholders; TIFF recommends either Texas Division of Emergency Management or Texas Water Development Board as the potential state agency to house the TFCO
- **Build Partnerships**: Coordinate with regional data collection and monitoring organizations, non-profit organizations, counties, municipalities and special-purpose districts, consulting firms, engineering firms, academic institutions, and state and federal agencies advancing flood monitoring and modeling to promote adaptive flood management strategies
- **Engagement and Outreach**: Sustain engagement with technical and non-technical stakeholders to inform the development of shared goals and priorities that guide regional partners:
  - Workforce Development – Offer a suite of educational and vocational programs to address the current and near-term future needs of public and private sector organizations investing in each region
  - Translational Research – Conduct targeted flood-related research with an immediate operational benefit that supports the needs of public and private sector regional investors and recruits further investment in the area
  - Academic Evolution – Establish an exemplary institute to serve as the foundation for recruiting traditional research-extensive institutions to further knowledge-based economic development
  - Regional Resiliency – Emphasize socio-economic resiliency as a core precept in the promotion of technological advances and production of associated workforce, by identifying and adapting for likely hazards and potential risks through technological advancement and workforce responsiveness
  - Economic Development – Advance each region's knowledge-based economy by being an integral part of the economic development engine, serving current workforce and technology development needs and proactively adapting the changing economic landscape
- **Database Management**: Compile a public and statewide archive of state and federally funded flood projects through structured outreach and data collection; adopt consistent metadata and quality-control standards for project documentation, tagging, and categorization; maintain and update the database annually to reflect new projects and evolving priorities; utilize data analytics to identify research gaps, emerging risks, and priority investment areas
- **Reporting**: Disseminate project outcomes and data to the public and stakeholders to promote transparency and coordination; facilitate workshops, briefings, and inter-agency meetings to foster collaboration; provide regular progress reports and policy recommendations to the Texas Legislature

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CREATE THE OFFICE OF THE STATE FLOOD COMMUNICATION OFFICER

Appoint a State Flood Communication Officer to facilitate interorganizational coordination in flood research

Effective coordination among agencies involved in flood-related projects is essential for improving preparedness, response, and mitigation. As floods become more frequent and severe, Texas needs a centralized communication strategy. However, without clear leadership, agencies may operate in silos, reducing efficiency and policy alignment. Texas already employs state experts, such as the State Demographer, who provide policy guidance. A similar role focused on flood communication coordination would bridge gaps between agencies and ensure a unified approach.

This individual would serve as a liaison among agencies, organizations, and policymakers to streamline communication and advise the Governor and Legislature on science-based flood policies. Additionally, they would coordinate efforts between scientific research, insurance, and policy sectors to ensure alignment in mitigation planning and response. Drawing from successful models in other states, they would also develop best practices for interagency collaboration.

With the establishment of this impactful role, Texas can enhance interagency coordination, strengthen flood preparedness, and foster a unified flood management strategy. A dedicated expert will ensure that science, policy, and risk mitigation strategies work together, ultimately improving the state's resilience to flooding.

KEY IMPLEMENTATION ACTIONS

- **Research Comparable Roles**: Review the guidelines and responsibilities of similar state advisory roles, such as the State Demographer and Chief Resilience Officers, to inform the structure and best practices for the new position
- **Role Definition and Options for Organizational Integration**: Define the Officer role's scope and authority within the Texas Flood Coordination Office; integrate the role within an existing state flood agency while expanding its authority and responsibilities; assist organizations in developing effective flood preparation plans and materials; align and incentivize local, regional, and state flood projects for cohesive efforts; establish data-sharing mechanisms with academic institutions and funding agencies, such as through open science platforms; ensure every agency with a flood-related mission designates a representative to support coordination efforts
- **Allocate Resources**: Focus on securing the necessary funding and resources to ensure the position is adequately staffed and supported

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COORDINATE TARGETED FLOOD PLANNING EFFORTS ACROSS THE LOWER RIO GRANDE VALLEY

Formalize cooperative local and regional flood planning in the Lower Rio Grande Valley

The Lower Rio Grande Valley (LRGV) is comprised of over 40 local, state, and federal jurisdictions with overlapping and intersecting interests in flood prevention, protection, and planning. To effectively coordinate local and regional flood projects between historically competing jurisdictions and economic sectors, a structured and formal agreement between key stakeholders is needed to guide flood risk management planning targeting shared goals.

TIFF recommends that the State of Texas create a Texas Flood Coordination Office (TFCO) and prioritize coordination efforts between traditional flood planning interests and those of supply and demand-related entities, agencies, and representatives specifically in the LRGV. TIFF also recommends that until such time that such an office can be established, state and federal agencies may enter into inter-local or memoranda of agreements with partnering counties and/or other entities, as appropriate, to focus integrative flood planning activities consider and maximize opportunities for shared areas of interest in the LRGV and/or participate in other regional coordination initiatives such as the envisioned Applied Coastal Water Intelligence for Regional Resilience and Economic Development (ACWIRRED) Institute (a consortium of 30+ local and independent jurisdictions have been meeting to discuss the envisioned ACWIRRED Institute as a natural evolution of their cooperative efforts).

A three-year investment, estimated at $1,000,000 annually, would enable the TFCO to serve as a facilitator to synergistically produce flood resilience-specific outcomes in the LRGV—an integrative water resources planning testbed—that may be replicated, re-used, or served as models for other regions. This regional priority might alternatively be addressed by local partners such as RATES and the LRGV Stormwater Task Force in the interim while the TFCO is being established. (See TIFF Final Report Appendix D-8 for implementation ideas and partnership opportunities presented by TAT members for inclusion in this report.)

KEY IMPLEMENTATION ACTIONS

Key aspects of these cooperative agreements should include specific commitments to improve:

- flood data collection and sharing
- cross-jurisdictional contracting
- international trans-boundary coordination
- public engagement and community flood education
- flood monitoring and modeling
- decision-maker education and engagement
- education and outreach to small/mid-sized communities
- academic curriculum/research that address local needs
- cloud-computing services to support local and regional environmental data collection and gap analyses
- regional coordination of flood planning projects/research
- identification of local and regional flood mitigation goals and objectives
- coordination of City ordinances to local/state/federal standards, etc.
- pooling and alignment economic resources to implement innovative stormwater solutions
- stakeholder input into potential FRM strategies not previously identified in existing literature or studies
- targeted local studies to leverage data/maps/findings from the latest regional flood assessments such as the Texas General Land Office's Combined River Basin Flood Studies and the Lower Rio Grande Flood Control Project
- balance and integration of regional water supply and demand interests to maximize innovation, funding opportunities, and a comprehensive approach to water resources challenges in the LRGV

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IMPROVE REGIONAL FLOOD MONITORING AND FORECASTING

Enhance regional Flood Early Warning Systems in the Lower Rio Grande Valley by centralizing existing flood monitoring and forecasting efforts

Texas has faced several federally declared flood disasters over the past decade, resulting in billions of dollars in damages and tragic loss of life. Communities often respond with structural mitigation measures like drainage improvements, levees, and floodwalls without having the necessary planning and guidance in place to ensure their effectiveness.

To strengthen flood resilience in the Lower Rio Grande Valley (LRGV), TIFF recommends enhancing existing regional Flood Early Warning Systems (FEWS) in collaboration with local communities. By centralizing ongoing and local emergency management efforts, a bilingual alert framework can be improved to enable timely and protective responses while honoring the region's cultural and linguistic diversity.

This 1-2-year investment, estimated at $700,000, will increase regional flood preparedness, provide more equitable and strategic dissemination of flood information, and enhance engagement between public agencies and local communities.

KEY IMPLEMENTATION ACTIONS

- **Establish Partnerships**: Collaborate with federal agencies, regional organizations, academic institutions, drainage districts, city departments, schools, faith-based groups, community leaders, and other local partners
- **Educate Local Officials**: In addition to following the TWDB guidance documents (see action Enhance Flood Management below), coordinate with the Texas Division of Emergency Management and use professional networks to train local officials and appropriate emergency responders on effectively managing and acting on flood early warning systems; training should cover how to interpret risk-signaling data, actions to take during the preparedness phase before public alerts are issued, and appropriate steps during emergency response; incorporate education, hands-on practice, and peer experience-sharing to help build confidence in decision-making during emergency events
- **Engage Stakeholders**: Conduct surveys, workshops, and public meetings to assess how residents receive and act on flood warnings; evaluate communication methods, including bilingual alerts, visual cues (e.g., rain gages, public displays), and community-based media; work with at least three pilot communities to define goals that reflect local flood challenges to inform system complexity/equipment/data modeling needs
- **Technology, Data, and Models**: Promote collaboration between academic and local partners to design, develop, and integrate sustainable (low-total-cost) and innovative flood monitoring technology; use existing monitoring and forecasting tools from state, federal, and local agencies to guide future data collection and modeling improvements
- **Financing**: Secure sustainable funding through state and federal grants, private foundations, and local cost-sharing strategies; conduct cost-benefit analyses to demonstrate long-term value and reliability
- **Enhance Flood Management**: Follow the Texas Water Development Board's FEWS Guidance Document, Alternative FEWS Guide, and Flash Flood Warning Siren Guide to integrate localized monitoring and forecasting components into one centralized system; consider features such as warning sirens and expanded sensor networks; gather feedback from technical experts and community users before full deployment
- **Public Outreach**: Create or attain culturally and linguistically appropriate educational materials; conduct outreach campaigns to build public awareness, trust, and effective response behavior
- **Evaluation**: Collect user feedback and performance data to refine system features, strengthen functionality, and improve long-term effectiveness

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DEVELOP SAFE PASS, A TRANSPORTATION FLOOD RESILIENCE INITIATIVE IN THE LOWER RIO GRANDE VALLEY

Reduce roadway flooding risk across the Lower Rio Grande Valley by improving monitoring and forecasting

Evacuation and response planning is critical to effective flood resilience in the Lower Rio Grande Valley (LRGV), a region facing a wide range of flood risks, from coastal surge to inland flash flooding. Emergency managers need adequate data, resources, and operational tools to deliver timely and accurate preparedness messaging and alerts to local communities making transportation decisions. As such, there is a need to incorporate transportation infrastructure data to better understand the impacts of flooding on evacuation routes, roadways, and critical transportation assets.

TIFF recommends the development of Safe Pass, a transportation flood resilience initiative designed to systematically reduce roadway flooding risk across the LRGV. Safe Pass integrates flood hotspot analytics, flood monitoring and analysis system observations, structured stakeholder outreach, and coordination with the Texas Department of Transportation (TxDOT) to:

- Establish an LRGV-wide roadway flooding inventory and standardized crossing classification based on roadway inundation behavior that is repeatable and defensible
- Improve roadway closure decision-support and public situational awareness at flood-prone crossings
- Prioritize investments using a benefit-cost analysis (BCA) framework informed by TxDOT roadway demand/use and local operational knowledge
- Deploy resilient, high-visibility flood monitoring systems that reduce flood risk and improve storm response outcomes

Success requires coordination with TxDOT. Other potential partners include state and federal agencies, and regional organizations experienced in flood planning and mitigation. Organizations managing local sensor networks should also contribute to this effort. Other potential partners include county agencies and non-profits that can serve as community organizers and connectors.

This 2-year investment, estimated at $1,400,000, will support consistent messaging and response protocols across jurisdictions, reduce stranded-vehicle risk and exposure to swift-water incidents, and create a defensible basis for future capital mitigation projects and grant competitiveness. Agencies can collaborate on funding different phases or use a cost-sharing formula.

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DEVELOP SAFE PASS, A TRANSPORTATION FLOOD RESILIENCE INITIATIVE IN THE LOWER RIO GRANDE VALLEY

KEY IMPLEMENTATION ACTIONS

- **Identify, Classify, and Evaluate Flood-Prone Roadways (~$300,000)**:
  - Identify and Classify Flood-Prone Roadways – Identify over-water roadway intersections and classify each into one of three operational categories based on exceedance expectations, observed performance, and validated local knowledge: 1) Dry Pass: crossings that should not flood during a 1,000-year storm event, 2) Submersible Pass: crossings expected to flood during a 500-year storm event, and 3) Inundated Pass: crossings that flood during a 100-year storm event
  - Conduct Flood Management Evaluations – Execute a structured evaluation following the Texas Water Development Board Flood Infrastructure Fund guidance documents as a step toward securing financial assistance; convene private technical sessions (cities/engineers/drainage stakeholders) and public meetings to validate the findings from the evaluations (such as known and emerging hotspots, recurring flooding issues, and other locally identified flooding locations)
  - Coordinate with TxDOT – As inundated zones and candidate crossings are identified, coordinate with TxDOT to confirm roadway functional classification, usage/demand, detour feasibility, and consequence-of-failure considerations; this information will support the development of a defensible BCA
- **Develop a BCA to Prioritize Flooding Locations (~$100,000)**: Develop a defensible BCA framework incorporating (as available) roadway demand, flood frequency/severity, incident history, detour impacts, emergency response exposure, damage avoidance, and operational benefits of improved warning/closure decisioning; produce a ranked shortlist of three to five priority sites for deploying flood monitoring systems supported by BCA results and stakeholder concurrence
- **Harden Hydrological and Meteorological (HydroMet) Monitoring Systems for Priority Locations (~$400,000)**: Harden HydroMet monitoring systems for prioritized, high flooding risk locations with reinforced enclosures, anti-tamper hardware, debris-resistant mounting, protected cabling, and other strategies
- **Install High-Visibility Flood Monitoring System Equipment for Priority Locations (~$400,000)**: Install high-visibility infrastructure at priority on-road staff-gage interfaces, including light emitting diode illumination and/or beacon elements tied to rainfall or stage thresholds; this improved visibility will provide motorists and responders with direct and interpretable depth information, enhance rapid public recognition of potential flood risk during storm events and low-light conditions, and support consistent warning alerts
  - Submersible Pass Deployments – Install visible on-road staff gages to support public depth awareness at the roadway interface, with illumination/lighting where appropriate to improve visibility during rainfall events and nighttime conditions
  - Inundated Pass Deployments – Install high-visibility staff gages plus shell transducers to capture continuous, real-time water level/depth conditions affecting roadway inundation, with robust telemetry and integration into FEWS alerting/decision-support workflows
- **Support Timely Alerts (~$100,000)**: Develop and validate multilingual alerting (e.g., English/Spanish) aligned with the field equipment (lighting states/signage) and digital communications (SMS/email/web/dashboard messaging), ensuring terminology is consistent with the Dry/Submersible/Inundated framework
- **Program Management (~$100,000)**: Hire a dedicated program manager for adequate permitting, reporting, ensuring compliance with quality assurance and control procedures, and contingency planning

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