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List of Acronyms and Abbreviations

Abbreviation	Definition
ac-ft/yr	acre feet/year
AS	Aqua Strategies
ASR	Aquifer Storage and Recovery
BBASC	Basin and Bay Area Stakeholder Committee
BBEST	Basin and Bay Expert Science Team
cfs	cubic feet per second
CL	Colorado-Lavaca
CMD	Costal Monitoring Database
EFAG	Environmental Flows Advisory Group
EFH	Essential Fish Habitat
EMB	East Matagorda Bay
EMST	Ecological Mapping System of Texas
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FWBIs	Fresh Water Bioindicator(s)
FWI	Fresh Water Inflows
GAM	Groundwater Availability Model
GBHM	Guadalupe Bayou Hydrodynamic Model
GBRA	Guadalupe-Blanco River Authority
GIS	Geographic Information System
GIWW	Gulf lntracoastal Waterway
GSA	Guadalupe-San Antonio
ha	hectares
HB	House Bill
HDR	HDR Engineering
HEC-RAS	Hydrologic Engineering Center – River Analysis System
HEFR	Hydrology-based Environmental Flow Regime
ISF	Instream Flows Regimes
LCRA	Lower Colorado River Authority
LiDAR	Light Detection and Ranging
MAR	Multivariate Autoregressive
MARSS	Multivariate Autoregressive State-Space
MBHE	Matagorda Bay Health Evaluation
MBTA	Migratory Bird Treaty Act
mg	milligrams
NDHM	Nueces Delta Hydrodynamic Model
NWI	National Wetland Inventory
O&M	Operation and Maintenance

List of Acronyms and Abbreviations (concluded)

Abbreviation	Definition
ppt	parts per thousand
RFQ	Request for Qualifications
RRC	Railroad Commission
SAC	Texas Environmental Flow Science Advisory Committee
SAWS	San Antonio Water System
SB3	Senate Bill 3
SNxx	TWDB identified study numbers in the RFQ solicitation and from SN01 to SN33
STF	Strategy Target Frequencies
SWIFT	State Water Implementation Fund for Texas
TAC	Technical Advisory Committee
TCEQ	Texas Commission on Environmental Quality
TIFP	Texas Instream Flow Program
TPWD	Texas Parks and Wildlife Department
TRA	Trinity River Authority
TRWD	Tarrant Regional Water District
TSJ	Trinity and San Jacinto
TSS	Total Suspended Solids
TWDB	Texas Water Development Board
TxBLEND	Texas version of the BLEND model
TxEMP	Texas Estuarine Mathematical Programming model
USACE	United States Army Corp of Engineers
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WAM	Water Availability Model
WMS	Water Management Strategy
WWTP	Wastewater Treatment Plant

Executive Summary

The passage of Senate Bill 3 (80th Texas Legislature, 2007) amended Section 11.0235 of the Texas Water Code to establish a stakeholder-driven process for identifying and quantifying environmental flow regimes needed to maintain sound ecological environments in Texas rivers and estuaries (hereafter referred to as the "environmental flows process"). Environmental flow regimes, which were recommended by Basin and Bay Expert Science Teams (BBEST) and Basin and Bay Area Stakeholder Committees (BBASC), served as the basis for environmental flow standards adopted by the Texas Commission on Environmental Quality (TCEQ) between 2011 and 2014 in seven major river basins and five estuary basin-bay systems. Senate Bill 3 created an adaptive management process (Texas Water Code §11.02362(p)) by which each BBASC could develop a work plan to guide their periodic review and refinement of the environmental flow regime analyses, recommendations, standards, and strategies within their basin-bay area. The TWDB has administered $6 million to implement 56 work plan studies between Fiscal Years 2014 and 2021, however this review represents only the 32 studies that were completed during Fiscal Years 2014 through 2017.

The goal of this statewide synthesis was to evaluate: the applicability of each environmental flow study for meeting the goals of defining a sound ecological environment, the expected variability in ecosystem indicators of a sound ecological environment, the potential need for refining adopted flow standards, and strategies to provide for environmental flows in five basin-bay systems, including the (1) Trinity and San Jacinto Rivers and Galveston Bay, (2) Brazos River and Associated Bay and Estuary System, (3) Colorado and Lavaca Rivers and Matagorda and Lavaca Bays, (4) Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays, and (5) Nueces River and Corpus Christi and Baffin Bays.

Freshwater inflow studies focused on components of freshwater inflows, filling data gaps, refinement of indicator species response to freshwater inflow and salinity, model/tool development, and strategies for achieving standards for freshwater inflows to estuaries and bays. Instream flow studies attempted validation of some component of the adopted environmental flow standards with five of these studies targeting the evaluation of the adopted pulse flow standards. A consistent result in all the instream flow validation studies across four basins (Trinity-San Jacinto, Brazos, Colorado-Lavaca, and Guadalupe-San Antonio) and study sites was that the adopted pulse flow standards do not provide for adequate inundation of riparian zones to support the full complement of native tree species. None of these instream flow validation studies specifically recommend changes to the adopted flow standards. With the exception of the riparian pulse flows, the studies conducted obtained inconclusive evidence to support or refute validation of either instream flow for any river or freshwater inflow adopted standards for any basin or bay.

Implementation of the adaptive management process through funding priority work plan projects resulted in a large volume of high-quality science, especially in estuary/bay systems. Our review found that the TWDB adaptively managed these efforts by providing an evolving focus that targeted studies and monitoring at the statewide level, particularly with respect to freshwater inflow studies, that complemented and leveraged basin specific studies.

We found a general lack of integrated (hydrology, geomorphology, biology, connectivity, and water quality) systematic, long-term monitoring programs focused on instream flows. Integration among these ecosystem components is required for meeting adaptive management objectives. We stress that integration of systematic long-term monitoring programs requires coordinated efforts across aquatic and riparian habitats and indicators of biotic responses as well as hydrologic and geomorphic processes that create and maintain those habitats. It is noted however, that positive steps in this direction have been taken by several river authorities as part of their monitoring programs to complement Senate Bill 3 studies.

We identified four common challenges that emerged across all bays and basins related to the adaptive management process for validation of the instream flow and freshwater inflow standards:

(1) Defining the attributes of a sound ecological environment.
(2) Defining the limits to a sound ecological environment.
(3) Validation of adopted environmental flow standards for instream flows and freshwater inflows.
(4) Establishment of integrated systematic long-term monitoring programs in both basin and bay systems.

From the studies conducted as part of the adaptive management process and reviewed herein, we identified several key scientific themes:

- Refinements in the selection of freshwater indicator species, such as focusing on non-motile benthos or nutrients, (or metrics) may provide better opportunities for targeted monitoring of freshwater inflow responses.
- The focus of freshwater inflow responses should target delta and upper estuary systems rather than open bay systems.
- Fish and invertebrate responses to instream pulse flows show variability at the community level, and study results can inform the expected ranges in the variability of indicators of a sound ecological environment.
- Pulse flow events of the adopted instream flow standards are not likely to maintain species composition of riparian vegetation communities in the long term.
- Integration of geomorphic processes as part of an integrated physical, chemical, and biological monitoring program for instream flows is critical to understand aquatic community dynamics associated with a sound ecological environment.
- Validation of instream flow standards are inherently difficult, but careful selection of indicator taxa, standardized long-term monitoring programs, and use of both state-based and rate-based analyses as discussed by Winemiller *et al.* (2021) demonstrate that it is achievable.

Defining the limits or range to the inherent variability for indicators of a sound ecological environment in rivers requires the integration of flow-ecology responses to subsistence, base flows, pulse flow and overbank events at inter- and intra-annual temporal scales. Additionally, we maintain that a more holistic assessment of the expected range of variability in the characteristics of a sound ecological environment should incorporate linkages between instream flows and freshwater inflows. However, our review found no studies specifically targeting the evaluation of the relationship between adopted instream flow standards and the corresponding downstream adopted freshwater inflow standards, although some preliminary comparisons of the BBEST recommendations were provided in some of the BBEST reports.

Some of the BBASCs evaluated potential strategies to achieve the environmental flow standards as part of their initial recommendation reports, and many of the BBASCs subsequently funded strategy studies. All of the strategy studies focused on providing freshwater inflows to estuaries; none specifically focused on instream flow needs. We acknowledge that some strategies under consideration would require statutory changes and note that some water right holders across the state are amending water rights to add voluntary environmental flows. Identifying and implementing viable strategies remains key to achieving and maintaining a sound ecological environment and is encouraged.

1 Introduction

The passage of Senate Bill 3 (80th Texas Legislature, 2007) amended Section 11.0235 of the Texas Water Code to establish a stakeholder-driven process for identifying and quantifying environmental flow regimes needed to maintain sound ecological environments in Texas rivers and estuaries (hereafter referred to as the "environmental flows process"). Environmental flow regimes, which were recommended by Basin and Bay Expert Science Teams (BBEST) and Basin and Bay Area Stakeholder Committees (BBASC), served as the basis for environmental flow standards adopted by the Texas Commission on Environmental Quality (TCEQ) between 2011 and 2014 in seven major river basins and five estuary systems.

A provision of the environmental flows process (Texas Water Code §11.02362(p)) required each BBASC to develop a work plan for adaptive management that established a schedule for periodic review of the environmental flow regime analyses, recommendations, standards, and strategies within their basin-bay area. The work plans also included recommended studies and activities that, if implemented, were designed to provide additional information for consideration by the BBASCs and the TCEQ during future rulemaking. To date, six of the seven basin-bay systems that were originally scheduled to complete the environmental flows process have submitted work plans to the TCEQ and most BBASCs have actively pursued completing adaptive management studies as outlined in their work plans.

Funding to support adaptive management work plan studies has largely been provided by the Texas Water Development Board (TWDB), though many others have provided both financial and in-kind support to ensure progress in completing work plan studies. Beginning with an initial $2 million in funding provided by the 83rd Texas Legislature (2013), and continuing through the current fiscal year, FY2021, the TWDB has administered $6 million to implement 56 work plan studies between Fiscal Years 2014 and 2021. TCEQ's adopted rules established a schedule for periodic review of the environmental flow standards for each basin-bay system which may not coincide with review periods specified in the developed work plans. Recognizing that BBASCs surpassed or were approaching their first opportunity to evaluate the environmental flow standards adopted by the TCEQ, the TWDB allocated funding in Fiscal Year 2018 to support a review and synthesis of the adaptive management value of the funded work plan studies that were completed as of that time period. This review represents studies that were completed during Fiscal Years 2014 through 2017.

Additional studies in support of the adaptive management process were funded by the TWDB in Fiscal Years 2018 through 2021 but were not completed in time to be reviewed in this report. Studies performed by entities other than TWDB (e.g., river authorities) were not explicitly reviewed in this effort, although studies that were particularly germane to the TWDB funded studies may be included as references. The goal of this statewide synthesis is to evaluate the applicability of work plan studies (individually or in total) in meeting the adaptive management goals of the Senate Bill 3 process. Specifically, we focused on validation efforts for adopted standards in light of maintaining a sound ecological environment; elucidation of expected ranges in indicator species or other physical, chemical, and biological metrics indicative of a sound ecological environment; validity of any recommended changes to existing standards; and development of tools that support the assessment of strategies necessary to meet the adopted environmental flows in the following five basin-bay systems:

(1) Trinity and San Jacinto Rivers and Galveston Bay,
(2) Brazos River and Associated Bay and Estuary System,
(3) Colorado and Lavaca Rivers and Matagorda and Lavaca Bays,
(4) Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays, and
(5) Nueces River and Corpus Christi and Baffin Bays.

The TWDB, with input from the TCEQ and the Texas Parks and Wildlife Department (TPWD), developed a basic rubric to guide the evaluations in the form of the following five questions:

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?
Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow regime and ecological response?
Q3. Did the study evaluate a strategy for achieving environmental flow regimes?
Q4. Did the study develop a tool (*e.g.,* a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?
Q5. Did the study identify additional data or knowledge gaps?

As noted in Section 3.4.2, we adopted this format to report our review of studies (Appendix A) where the assessment of study methods, results and conclusions for each study are embedded within the context of these five questions.

2 Work Plans

Senate Bill 3 (80th Texas Legislature, 2007) recognizes the importance of adaptive management and established an approach by which each BBASC could craft their own timeline and guidance for reviewing and improving upon the environmental flow regimes recommended and subsequently adopted in the TCEQ standards in their basin and the strategies to achieve those standards[1]. The proposed work plan structure, as described in the Texas Water Code, required development of adaptive management work plans with the following content:

> *Section 11.02362(p) In recognition of the importance of adaptive management, after submitting its recommendations regarding environmental flow standards and strategies to meet the environmental flow standards to the commission, each basin and bay area stakeholders committee, with the assistance of the pertinent basin and bay expert science team, shall prepare and submit for approval by the advisory group a work plan. The work plan must:*
>
> *(1) establish a periodic review of the basin and bay environmental flow analyses and environmental flow regime recommendations, environmental flow standards, and strategies, to occur at least once every 10 years;*
> *(2) prescribe specific monitoring, studies, and activities; and*
> *(3) establish a schedule for continuing the validation or refinement of the basin and bay environmental flow analyses and environmental flow*

1 The TCEQ adopted standards for each basin-bay system set the 'official' review timeline which do not necessarily match those recommended in the BBASC work plans.

regime recommendations, the environmental flow standards adopted by the commission, and the strategies to achieve those standards.

Table 1 lists 33 studies funded by the TWDB for each basin and bay; 32 studies were provided for our review and synthesis. Note that one study, SN27, was not provided for review.

Table 1. Environmental flow studies funded by the Texas Water Development Board as part of the adaptive management process between Fiscal Years 2014 – 2017 and reviewed in this report. Study number and title are included for reference.

Study Number (SN)	**Title**
Trinity and San Jacinto Rivers and Galveston Bay	
SN1	Defining bioindicators for freshwater inflow needs studies: Phase I
SN2	LiDAR acquisition and flow assessment for the Middle Trinity River
SN3	Determination of freshwater inflow volume from the Trinity River into Galveston Bay, May 2014 – August 2015
SN4	An evaluation of the variability of sediment and nutrient loading into Galveston Bay from the Trinity River watershed
SN5	Evaluation of adopted flow standards for the Trinity River
SN6	Defining bioindicators for freshwater inflow needs studies: Phase II – The health of the bay
Brazos River and Associated Bay and Estuary System	
SN7	Instream flows research and validation methodology framework and Brazos Estuary characterization
SN8	Validation or refinement of the adopted TCEQ environmental flow standards for the Brazos River
Colorado and Lavaca Rivers and Matagorda and Lavaca Bays	
SN9	Studies to evaluate achievement of freshwater inflow standards and ecological response
SN10	Evaluation of freshwater delivery alternatives to East Matagorda Bay
SN11	Improve simulation of groundwater/surface water interaction in the Groundwater Management Area 12 groundwater availability model
SN12	An evaluation of the variability of sediment and nutrient loading into Matagorda Bay from the Colorado River
SN13	Validation or refinement of the adopted TCEQ standards for the Colorado and Lavaca rivers
SN14	Evaluation of rainfall-runoff patterns in the Upper Colorado River Basin

Table 1(Continued)

Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano Aransas, and San Antonio Bays	
SN15	Instream flows research and validation methodology framework
SN16	Guadalupe Bayou flow and inundation study
SN17	*Rangia* clam investigations
SN18	Assessing the effects of freshwater inflows and other key drivers on the population dynamics of blue crab and white shrimp using a multivariate time series modeling framework: Phase I
SN19	Strategy options for meeting attainment frequencies for the estuaries
SN20	An evaluation of the variability of sediment and nutrient loading into San Antonio Bay from the Guadalupe/San Antonio River
SN21	Continuation of instream flows research and validation methodology framework
SN22	Assessing the effects of freshwater inflows and other key drivers on the population dynamics of blue crab and white shrimp using a multivariate time series modeling framework: Phase II
Nueces River and Corpus Christi and Baffin Bays	
SN23	Re-examination of the 2001 Agreed Order monthly targets and safe yield versus current demand evaluations: Phase I
SN24	Using landform and hydraulic modifications to increase the benefit of freshwater inflows to Nueces Bay and Nueces Delta: Phase I
SN25	Nueces watershed pre- and post-development nutrient budgets
SN26	Modeling salinity fluxes in the Nueces delta
SN27*	Nueces Bay circulation assessment project
SN28	Identify vegetation/marsh changes occurring in the Rincon Bayou Delta and the relationship of those changes to freshwater inflow
SN29	Using landform and hydraulic modifications to increase the benefit of freshwater inflows to Nueces Bay and Nueces Delta: Phase II: Verification and feasibility assessment for landform modifications in the Nueces Delta
SN30	Re-examination of the 2001 Agreed Order monthly targets: Phase 2
SN31	Nutrient Budget for Nueces Bay
SN32	Alternative methods to add freshwater to the Nueces Delta
SN33	An evaluation of the variability of sediment and nutrient loading into Nueces Bay from the Nueces River

*SN27 was not completed and therefore could not be reviewed.

2.1 Work Plan Development

In general, the development of work plan studies reflects an extension of the data and studies identified within the BBESTs and BBASCs environmental flow recommendation reports. Their various reports identified missing data and additional studies needed to define or refine indicators of a sound ecological environment, validating flow-ecology relationships underpinning their flow recommendations and/or identifying strategies to meet the adopted instream flow or freshwater inflow standards.

All work plans highlighted the importance of continued technical support from their respective BBESTs and the continued engagement of state resource agencies (TWDB, TPWD, TCEQ). Work plans universally identified the need for ongoing funding and BBASC/BBEST support. We note however, that no funding was allocated to support the continued work of any of the BBESTs, although in many cases BBEST members continued to participate in BBASC work plan implementations.

We acknowledge that river authorities and other entities have and continue to conduct studies and collect data that support the Senate Bill 3 adaptive management goals and objectives. Review of these supporting efforts however is beyond the scope of this project.

The following section provides a brief introduction to the work plans and serves as a frame of reference to understand elements of our synthesis review. We have excluded the Sabine/Neches adaptive management work plan because this basin elected not to pursue studies outlined in their work plan via Senate Bill 3 funding mechanisms. In this section, we reference review timelines as proposed in their respective work plans but note that these may not coincide with review periods specified in the TCEQ adopted rules as noted above.

2.1.1 Trinity and San Jacinto Rivers and Galveston Bay

Submitted to the TCEQ in May 2012, the work plan identified 64 study elements with a projected timeline of 50 years. This is the most expansive time horizon of any of the submitted work plans. A near-term 5-year horizon identified 30 work plan elements to inform the adaptive management process. Of the 30 recommended near-term studies, six have been completed and are reviewed in this report.

2.1.2 Brazos River and Associated Bay and Estuary System

Submitted to the TCEQ in November 2013, the work plan identified 11 study elements that were categorized into five Priority 1, five Priority 2, and one Priority 3 ranking. Of the 11 recommended studies, two have been completed and are reviewed in this report. The work plan also identified a 10-year review period for developing recommendations on the adopted flow standards. In particular, we note that the Brazos River Authority is funding data collection efforts aimed at directly supporting 10 of the 11 recommended evaluation objectives in the Brazos Basin BBASC Work Plan.

2.1.3 Colorado and Lavaca Rivers and Matagorda and Lavaca Bays

Submitted to the TCEQ in June 2012, the work plan identified 16 priority elements with an additional 20 elements having a lower priority. Of the 36 recommended studies, six have been completed and are reviewed in this report. A 10-year review period with a 5-year interim report prepared by the BBEST was identified during which the priority studies would be completed to guide either flow standard recommendations or modification to work plan study elements or priorities.

2.1.4 Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano Aransas, and San Antonio Bays

Submitted to the TCEQ in May 2012, the work plan identified 21 work plan elements of which 7 were ranked in order as high priority. The work plan did not identify an integrated work schedule for completion of work elements, but it assumed that the high-priority studies would be completed in the first five years. Of the 21 recommended studies, eight have been completed and are reviewed in this report. The plan also identified a five-year review to assess work plan elements and priorities with a final review and recommendation of the adopted flow standards in year 10.

2.1.5 Nueces River and Corpus Christi and Baffin Bays

Submitted to the TCEQ in November 2012, the work plan identified and ranked eight priority work plan elements with an associated implementation schedule to meet a 10-year adaptive management schedule. The plan further identified 12 Tier 2a (instream flows) and 10 Tier 2b (bays) work plan elements that were deemed of equal priority. Of the 30 recommended studies, 11 have been completed and are reviewed in this report. The plan anticipated an interim five-year review and final review at year 10.

The BBASC submitted a formal amendment to the work plan in November 2015, at the completion of the initial two-year funding cycle to specifically target identified data gaps with regards to water circulation in Nueces Bay.

2.2 Work Plan Funding

The TWDB[2], through biennial allocations from the Texas Legislature, has administered funding since 2014 to support adaptive management work plan studies and other environmental flow related study efforts. However, no funding for BBESTs to continue their work has been provided. It is notable that state agencies (*e.g.*, TPWD, TCEQ), river authorities, and other entities have provided collaborative support to the Senate Bill 3 adaptive management process via supplemental funding and technical support.

2014-2015 Biennium (Inaugural Adaptive Management Funding)

The 83rd Texas Legislature adopted Contingency Rider 18.03 for the General Appropriations Bill that appropriated $2 million to the TWDB to continue studies of environmental flows. In accordance with the funding allocation guidelines provided in the rider, the EFAG approved the SAC's recommendations regarding the distribution of funding among basins with prepared work plans (Memo from SAC to EFAG, September 10, 2013, https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/txenvironmentalflowssac.html accessed November 27, 2020):

- *Given the dedication in the Rider of a minimum of $750,000 to the Guadalupe/San Antonio*

[2] September 14, 2017, memo from Dr. Carla Guthrie, Director of Surface Water Studies, TWDB to the Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, Science Advisory Committee, Basin and Bay Area Stakeholders Committees, Basin and Bay Expert Science Teams.

basin, the SAC would suggest that the remainder of the appropriation ($1.25 million) be made available to other basins.

- *The SAC further discussed the appropriate allocation of the funds to these four (4) basins, and we have no rationale that would support anything other than an even split of $312,500 to each basin.*

- *Funding from this appropriation would not be allocated to the Sabine/Neches Basin given that the approved Work Plan for that basin, which is focused on monitoring to validate and refine their environmental flows analysis, appears to be adequately funded through existing sources. The SAC understands that the Sabine/Neches BBASC agrees with this assessment.*

Each BBASC submitted a suite of potential work plan studies to be funded from their identified priority work plan elements. The TWDB selected a total of 15 studies from the submitted BBASC work plan studies constrained by the allocation guidance provided in the funding rider (i.e., $750,000 to the Guadalupe/San Antonio basin) and ~$312,500 to be divided approximately equally between the remaining four basins with developed work plans[3] (Table 2). The primary focus on bay and estuary studies reflects the overall priorities identified within the respective BBASC work plans and the TWDB balanced study selections within each basin to achieve an equal split of the remaining funds between the other four basins.

Table 2. Funded studies in the 2014-2015 biennium supporting work plans for adaptive management. Study Number refers to Table 1.

Study Number (SN)	Study Title
Trinity and San Jacinto Rivers and Galveston Bay	
SN1	Defining bioindicators for freshwater inflow needs studies: Phase I
SN2	LiDAR acquisition and flow assessment for the Middle Trinity River
SN3	Determination of freshwater inflow volume from the Trinity River into Galveston Bay, May 2014 – August 2015
Brazos River and Associated Bay and Estuary System	
SN7	Instream flows research and validation methodology framework and Brazos Estuary characterization
Colorado and Lavaca Rivers and Matagorda and Lavaca Bays	
SN9	Studies to evaluate achievement of freshwater inflow standards and ecological response
SN10	Evaluation of freshwater delivery alternatives to East Matagorda Bay

3 We note that not all of these developed work plans have been officially approved by the Environmental Flows Advisory Group (EFAG) as outline in the Senate Bill 3 legislation.

Table 2 (Continued)

Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano Aransas, and San Antonio Bays	
SN15	Instream flows research and validation methodology framework
SN16	Guadalupe Bayou flow and inundation study
SN17	*Rangia* clam investigations
SN18	Assessing the effects of freshwater inflows and other key drivers on the population dynamics of blue crab and white shrimp using a multivariate time series modeling framework: Phase I
SN19	Strategy options for meeting attainment frequencies for the estuaries
Nueces River and Corpus Christi and Baffin Bays	
SN23	Re-examination of the 2001 Agreed Order monthly targets and safe yield versus current demand evaluations: Phase I
SN24	Using landform and hydraulic modifications to increase the benefit of freshwater inflows to Nueces Bay and Nueces Delta: Phase I
SN25	Nueces watershed pre- and post-development nutrient budgets
SN26	Modeling salinity fluxes in the Nueces delta

2016-2017 Biennium

The 84th Texas Legislature appropriated $2 million in general revenue to the baseline budget of the TWDB for the 2016-2017 biennium to support environmental flows studies as described in the agency's strategic plan (*Strategy A.1.1 Environmental Impact Information*). While specific allocation guidelines were not provided with this funding, the TWDB allocated $1.5 million to fund 18 BBASC work plan studies, with equal allocations of funding across basins (Table 3).

Table 3. Funded studies in the 2016-2017 biennium supporting work plans for adaptive management.

Study Number (SN)	Study Title
Trinity and San Jacinto Rivers and Galveston Bay	
SN4	An evaluation of the variability of sediment and nutrient loading into Galveston Bay from the Trinity River watershed
SN5	Evaluation of adopted flow standards for the Trinity River
SN6	Defining bioindicators for freshwater inflow needs studies: Phase II – The health of the bay
Brazos River and Associated Bay and Estuary System	
SN8	Validation or refinement of the adopted TCEQ environmental flow standards for the Brazos River

Table 3 (Continued)

Colorado and Lavaca Rivers and Matagorda and Lavaca Bays	
SN11	Improve simulation of groundwater/surface water interaction in the Groundwater Management Area 12 groundwater availability model
SN12	An evaluation of the variability of sediment and nutrient loading into Matagorda Bay from the Colorado River
SN13	Validation or refinement of the adopted TCEQ standards for the Colorado and Lavaca rivers
SN14	Evaluation of rainfall-runoff patterns in the Upper Colorado River Basin
Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano Aransas, and San Antonio Bays	
SN20	An evaluation of the variability of sediment and nutrient loading into San Antonio Bay from the Guadalupe/San Antonio River
SN21	Continuation of instream flows research and validation methodology framework
SN22	Assessing the effects of freshwater inflows and other key drivers on the population dynamics of blue crab and white shrimp using a multivariate time series modeling framework: Phase II
Nueces River and Corpus Christi and Baffin Bays	
SN27	Nueces Bay circulation assessment project (Not provided)
SN28	Identify vegetation/marsh changes occurring in the Rincon Bayou Delta and the relationship of those changes to freshwater inflow
SN29	Using landform and hydraulic modifications to increase the benefit of freshwater inflows to Nueces Bay and Nueces Delta: Phase II: Verification and feasibility assessment for landform modifications in the Nueces Delta
SN30	Re-examination of the 2001 Agreed Order monthly targets: Phase 2
SN31	Nutrient Budget for Nueces Bay
SN32	Alternative methods to add freshwater to the Nueces Delta
SN33	An evaluation of the variability of sediment and nutrient loading into Nueces Bay from the Nueces River

The TWDB allocated an additional $500,000 in general revenue to support studies with a system-wide monitoring focus (e.g., coast-wide bay water quality monitoring); to expand an existing study of riparian productivity along priority river segments; for strategic data and study needs not covered by BBASC work plan elements; and for scientific peer review of studies from the Texas Instream Flow Program (TIFP) relating to instream flow recommendations for the lower San Antonio, middle and lower Brazos, middle Trinity, and lower Guadalupe river sub-basins. Scientific peer review for these documents was recommended by both the National Research Council in 2005 and the Texas Environmental Flows Science Advisory Committee in 2009 (Table 4).

Table 4. Funded studies in the 2016-2017 biennium supporting both TWDB programs and work plans for adaptive management.

Freshwater inflows
Coast-wide bay water quality monitoring and instrumentation
Development of a hydrodynamic model for the Trinity River Delta
Salinity and ecosystem monitoring in Coastal Bend estuaries
Nutrient and sediment monitoring of Nueces River inputs to Nueces Bay
San Antonio Bay water circulation monitoring
Instream flows
Expand study of riparian productivity along priority river segments
Scientific peer review of reports for priority river segments
Water quality model of the Guadalupe River
Support for two-dimensional hydraulic modeling efforts

2018-2019 Biennium

The 85th Texas Legislature appropriated $2 million in general revenue to the baseline budget of the TWDB for the 2018-2019 biennium to support environmental flows studies as described in the agency's strategic plan (*Strategy A.1.1 Environmental Impact Information* and *Strategy A.1.2 Water Resources Investigations*). The TWDB[4] modified their process for funding studies by implementing a competitive selection process and opening the funding call to expand beyond projects identified in the BBASC work plans. This revision allowed for the TWDB to consider studies outside of the work plans that either supported adaptive management in a basin with adopted environmental flow standards or to assess environmental flow needs or strategies elsewhere within the state. Such studies could be proposed by state agencies, river authorities, or other stakeholders of the environmental flows process. This shift beyond the work plans provided the opportunity for broader engagement of resource agencies and stakeholders as well as recognition of instream flow and freshwater needs in other basins. Requests for studies from the BBASC also were modified to require that the BBASCs submit up to five ranked study topics along with a study description, expected deliverables, anticipated costs, but more importantly an explicit statement as to how the BBASC anticipated the study will meet the goals of either validating or refining analyses, recommendations, and standards or identifying strategies to achieve environmental flows. Studies submitted by non-BBASC entities required this same justification information. Staff further developed clear scoring criteria based on BBASC priority projects, cross-basin studies, and studies which contribute additional funds or in-kind support to further the impact of the available funding. The TWDB proposed to limit individual projects to $75,000 but allowed for some studies to be funded up to $200,000 if they were BBASC identified priority studies focusing on more than one bay-basin area. The change to the process for study requests, selection, and funding formula was clearly articulated:

[4] September 14, 2017, memo from Dr. Carla Guthrie, Director of Surface Water Studies, TWDB to the Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, Science Advisory Committee, Basin and Bay Area Stakeholders Committees, Basin and Bay Expert Science Teams.

This revised process continues to focus funding toward priority work plan studies while ensuring that the applications are competitively ranked among all applications received. Additionally, this process allows for other areas of the state to receive funding for studies recognized to be important for understanding environmental flow needs in those basins. The TWDB is committed to using the $2 million in funding to both support agency strategies to provide water data and environmental impact information as well as to adhere to the intent of the funding to further the environmental flows process laid out by the Texas Legislature.

An initial 29 prioritized study requests were submitted to the TWDB from five of the seven BBASCs who have been engaged in supporting adaptive management in their basins, including the Trinity-San Jacinto, Brazos, Colorado-Lavaca, Guadalupe-San Antonio, and Nueces, as well as recommended topics from other participants in the environmental flows process. TWDB staff expanded one study topic submitted by the Brazos BBASC to evaluate past and current adaptive management studies to include all basins. This study resulted in the current subject of this report, the *Statewide Synthesis of Environmental Flow Studies*, covering funded projects from Fiscal Years 2014-2017. A total of 12 BBASC work plan projects were selected for funding totaling approximately $1.5 million dollars (Table 5) and an additional 6 projects (~ $ 500,000) were funded supporting TWDB programs that contributed to the Senate Bill 3 adaptive management objectives (Table 6). Funding levels were roughly equivalent across the five targeted basins (Trinity-San Jacinto, Brazos, Colorado-Lavaca, Guadalupe-San Antonio, and Nueces).

Table 5. Funded studies in the 2018-2019 biennium supporting work plans for adaptive management.

Environmental flows validation in three river basins (Brazos, Colorado-Lavaca, and Guadalupe-San Antonio)
Statewide synthesis of environmental flow studies from funding cycles I and II.
Monitoring of nutrient and sediment loads from the Trinity-San Jacinto and Guadalupe-San Antonio River basins into Galveston and San Antonio bays
Using comparative long-term benthic data for adaptive management of freshwater inflow to three estuaries (Colorado-Lavaca, Guadalupe, and Nueces)
Influence of freshwater inflow gradients on estuarine nutrient-phytoplankton dynamics in the three estuaries (Guadalupe, Nueces, and Upper Laguna Madre)
Building and testing the Trinity River delta hydrodynamic model
Evaluation of rainfall/runoff patterns in the upper Colorado-Lavaca River basin - Phase II
Trinity River Senate Bill 3 flow assessment, Phase III
Lavaca Bay - development of freshwater inflow biological indicator relationship
Initial data gathering to implement groundwater-surface water interaction field work from GAM improvements study
Guadalupe delta ecological assessment of freshwater inflows
Analysis of riverine estuary of the Brazos basin

Table 6. Funded studies in the 2018-2019 biennium supporting both TWDB programs and work plans for adaptive management.

Monitoring of nutrient and sediment loads from the Colorado and Nueces River basins into Matagorda and Corpus Christi bays
Estuarine water quality monitoring
Development of an environmental flows hydrology model of the Brazos River
Training and support for measuring bedload sediment transport in large, sand-bedded river and hydraulic modeling support
Specialized (bathymetric) LiDAR data collection of the Frio River for use in geomorphic model development
Suspended sediment sampling at TCEQ environmental flows measurement points in four river basins (Trinity, Brazos, Colorado, and Brazos)

2020-2021 Biennium

The 86th Texas Legislature appropriated $2 million in general revenue to the baseline budget of the TWDB for the 2020-2021 biennium to support environmental flows studies as described in the agency's strategic plan (*Strategy A.1.1 Environmental Impact Information* and *Strategy A.1.2 Water Resources Investigations*). As in the two previous biennia, there were no specific funding allocation guidelines or directives to support the adaptive management process. However, the TWDB allocated $1.0 million to fund adaptive management work plan studies.

As before, the TWDB followed a competitive selection process, requesting each BBASC recommend up to four ranked studies for funding consideration. Each project proposal required an explicit study description, expected deliverables, anticipated costs, and articulation of how the anticipated study will meet the goals of either validating or refining analyses, recommendations, and standards or identifying strategies to achieve environmental flows. Studies submitted by non-BBASC entities required this same justification information. Staff retained scoring criteria based on BBASC priority projects, cross-basin studies, and studies which contribute additional funds or in-kind support to further the impact of the available funding. The suggested limit for individual projects was $75,000 with allowance for some studies to be funded up to $200,000 if they were BBASC identified priority studies focusing on more than one bay-basin area.

However, the TWDB explicitly identified critical information gaps that hitherto had not been adequately addressed in the funded adaptive management work plan studies:

- Assessing environmental flow standards and attainment frequencies under existing or future scenarios of water use and climate variability.
- Exploring systematic approaches to linking instream flow and freshwater inflow standards.
- Monitoring temperature and dissolved oxygen at TCEQ environmental flow measurement sites in major river basins.
- Developing targeted monitoring programs to assess ecological indicator response.
- Developing models to forecast ecological outcomes under various flow scenarios.
- Investigating surface water-groundwater interactions.
- Assessing geomorphic processes that sustain long-term channel morphology.

TWDB staff selected 11 of the 15 submitted BBASC projects and 2 projects (combined into one contract) submitted by the Lower Rio Grande Valley Development Council (Table 7). Funding allocations between basins was adjusted with a reduced proportional allocation in the Brazos and Nueces. The Brazos BBASC submitted only one project for consideration, and the Nueces did not submit any projects for consideration because Nueces study interests were covered in the cross-basin study proposals. An additional seven projects ($1 million) were funded supporting TWDB programs that also contributed to the Senate Bill 3 adaptive management objectives (Table 8).

Table 7. Funded studies in the 2020-2021 biennium supporting work plans for adaptive management.

Environmental Flows Assessment, Phase IV (Trinity River)
Assimilative Capacity of Lake Livingston: Nutrients and High Flow Events
Quantifying hydrological connectivity in the Trinity River Delta
Baseline Research in the Brazos River Basin*
Long-Term Benthic Data for Adaptive Management of Three Basins (Colorado-Lavaca, Guadalupe-San Antonio, and Nueces)
Lavaca River Delta Marsh Assessment
Informing Environmental Flow Standards for the Sustainability of Wetlands in East Matagorda Bay: Phase I Big Boggy
Lavaca and Colorado Rivers Small Pulse and Base Flow Connectivity Assessment
Guadalupe Delta Ecological Assessment of Freshwater Inflows
Freshwater Mussels Instream Flow Phased Assessment — Lower Guadalupe River
Surface water-groundwater interaction in part of the Texas Hill Country in the Colorado and Guadalupe basins
River and Estuary Observatory Network: Raymondville Drain, Hidalgo Main Drain, IBWC-North Floodway, and Arroyo Colorado

**Contracting process on hold until active contract for related work is completed.*

Table 8. Funded studies in the 2020-2021 biennium supporting both TWDB programs and work plans for adaptive management.

Evaluating the attainment of environmental flow standards
Assessing cumulative effects of water management strategies on environmental flow standards with a special case study on reuse
Assessment of how trends in the Brazos River Basin may affect surface water availability and attainment of environmental flow standards
Continuation of suspended sediment sampling at TCEQ environmental flows measurement points in seven river basins (Neches, Trinity, Brazos, Lavaca, Colorado, and Guadalupe-San Antonio, and Nueces)
Estuary monitoring program and data collection equipment
Expand evaporation monitoring to coastal waters
Quantifying reservoir firm yield uncertainty due to hydrological variability and long-term change in Texas

3 Review of Work Plan Studies

The goal of this statewide synthesis is to evaluate the applicability of the funded BBASC work plan studies to meet the goals of either validating or refining prior study results, flow recommendations, adopted standards, or identifying strategies to provide for environmental flows in five basin-bay systems, including: the (1) Trinity and San Jacinto Rivers and Galveston Bay, (2) Brazos River and Associated Bay and Estuary System, (3) Colorado and Lavaca Rivers and Matagorda and Lavaca Bays, (4) Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays, and (5) Nueces River and Corpus Christi and Baffin Bays.

The following synthesis of studies is specific to our charge for studies listed in Table 1 and does not reflect work plan studies funded by the TWDB starting with the 2018-2019 biennium and continuing through the present (see Section 2.2). The synthesis does not reflect efforts by the various river authorities or other private, local, regional, or state entities that may be engaged in monitoring or studies that directly or indirectly contribute to the statewide or basin/bay specific environmental flow program objectives. We anticipate the elucidation of many of these supporting efforts during the stakeholder review process, which should provide valuable input to review and modification of work plans. The following sections provide an overview of our synthesis, focusing on addressing the five guiding review questions. Appendix A provides reviews for individual studies.

3.1 Basin and Bay Work Plan Disciplines Considered

The initial two cycles of funding were dominated by studies related to freshwater inflows to estuaries and bays (Table 9). Twenty-nine studies focused on some component of freshwater inflows, eight on instream flows, and six shared some components of both. The relative contribution of scientific disciplines within the studies included hydrology, ecology, and water quality followed by connectivity and flow management with geomorphic processes primarily confined to the Trinity-San Jacinto system. We attribute this as a reflection of the prioritized work plan elements and specific studies selected by the BBASCs and submitted to the TWDB for funding considerations during the first two biennial cycles.

What is also apparent among these studies (Table 9) is the broad absence of multi-disciplinary approaches that simultaneously address geomorphic processes, connectivity, ecology, and water quality. Additionally, our review found a lack of integrated monitoring programs that specifically target assessment of the status or expected ranges in the variability of key indicators of a sound ecological environment. An exception to this is the statewide nutrient and sediment monitoring studies (e.g., SN20) initiated by the TWDB in the FY 2016-2017 biennium. We have stressed the importance of such monitoring efforts to inform both the validation of the adopted standards as well as to characterize the range of conditions indicative of a sound ecological environment. In this case, the TWDB's monitoring program will be able to characterize the range of nutrients and suspended sediments associated with freshwater inflows and the impacts to a sound ecological environment. We believe that any expansion of this monitoring effort should integrate indicator species and water quality metrics that focus on primary productivity and benthic communities given that mobile species can readily relocate in response to changing salinity gradients.

3.2 Basin and Bay Summaries to Review Questions

The TWDB, with input from TPWD and TCEQ, developed five guiding questions for evaluating the applicability of each environmental flow study for meeting the goals of either validating or refining prior analyses, flow recommendations, or adopted standards, or identifying strategies to provide for environmental flows. These questions were contained in the RFQ for TWDB Contract No. 1900012284 as the evaluation guidelines of TWDB-funded environmental flow studies and a condensed version are provided here:

- Q1. Did the study validate the adopted instream flow or freshwater inflow standards?
- Q2. Did the study collect new data or develop a scientific approach for testing cause and effect relationships between flow regimes and components and ecological indicators?
- Q3. Did the study evaluate a strategy for achieving environmental flows?
- Q4. Did the study develop a tool (*e.g.*, a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?
- Q5. Did the study identify additional data or knowledge gaps?

In addition, our scope of work outlined the following evaluation of methodologies for the reviewed studies:

- Study site(s) selection
- Data collection methods
- Analytical methods
- Definitions of terms
- Coherence between data analysis and results
- Coherence between results and discussion with relevant linkage to previous work and open peer reviewed or gray literature
- Coherence between results, discussion, and summary of findings
- Coherence of any recommendations given the specific study or other related studies

During our review process, the study team in coordination with the TWDB concluded that these review elements were best incorporated into the responses to the five evaluation guideline questions in order to inform a broader cross section of the stakeholder community. This approach, based on the five-question format was presented to stakeholders during the July 27th, 2020, Webinar "Update on the Statewide Synthesis of Environmental Flow Studies" (see Stakeholder Presentations - Appendix D). Table 10 provides a high-level summary of whether each of these questions were addressed by a study.

Table 11 summarizes overall how completely each study addressed the five guiding questions. A '**NA**' designation indicates the study did not attempt to address the question. A '**No**' designation generally refers to a study that targeted some element of a specific question but did not succeed. A '**Partially**' designation implies that some element of the question was answered. For example, a study having developed a component necessary for a 'Tool' but not the tool itself would be designated with 'Partially'. A '**Yes**' designation indicates the study addressed the question. We provide an overview of these results in the following sections while detailed comments supporting each designation are found in Appendix A.

Clearly, all studies provided varying amounts of new data and differed in the extent to which they identified the need for additional data, addressed emerging knowledge gaps, or initiated new efforts not identified within their existing work plans. The utility and/or extent to which collected data, analyses, or report findings to inform the status of a sound ecological environment, materially address validation of adopted flow standards or define expected ranges in indicator species or system metrics (e.g., temporal variation in fish community structure) that are indicative of a sound ecological environment are addressed in Section 3.3.

Table 9. Distribution of study topics among bay-basins, instream flows, freshwater inflows, and six categories of technical disciplines, hydrology, geomorphic, connectivity, ecology, water quality, and flow management. See Tables 2 and 3 for titles of the study.

				Disciplines					
Bay and Basin	**Study Number**	**ISF**	**FWI**	**Hydrology**	**Geomorphic**	**Connectivity**	**Ecology**	**Water Quality**	**Flow Management**
TSJ	SN01		X				X		
TSJ	SN02	X		X	X	X			
TSJ	SN03		X	X				X	X
TSJ	SN04		X					X	
TSJ	SN05	X	X		X	X	X		
TSJ	SN06		X				X		
Brazos	SN07	X	X			X	X		
Brazos	SN08	X	X			X	X		
CL&LR M&LB	SN09		X	X			X		X
CL&LR M&LB	SN10		X	X					X
CL&LR M&LB	SN11	X		X					
CL&LR M&LB	SN12		X					X	
CL&LR M&LB	SN13	X	X			X	X		
CL&LR M&LB	SN14	X		X					
GSA	SN15	X	X			X	X		
GSA	SN16		X	X				X	
GSA	SN17		X				X		
GSA	SN18		X				X		
GSA	SN19		X	X					X
GSA	SN20		X					X	
GSA	SN21	X	X			X	X		
GSA	SN22		X				X		
Nueces	SN23		X	X					X
Nueces	SN24		X					X	
Nueces	SN25		X					X	
Nueces	SN26		X					X	
Nueces	SN27 (NA)								
Nueces	SN28		X				X		
Nueces	SN29		X	X					X
Nueces	SN30		X	X					X
Nueces	SN31		X					X	
Nueces	SN32		X	X					X
Nueces	SN33		X					X	
	Totals	9	29	12	2	7	13	10	8

Table 10. Classification of studies according to whether they addressed each of the five guiding questions.

		Primary Review Question				
		Q1	Q2	Q3	Q4	Q5
Bay and Basin	Study Number	Validation	New Data or Approach	Strategies	Tools	Data or Knowledge Gaps
TSJ	SN01		X			
TSJ	SN02		X			X
TSJ	SN03					X
TSJ	SN04		X			X
TSJ	SN05	X	X		X	X
TSJ	SN06		X			
Brazos	SN07	X	X		X	X
Brazos	SN08	X	X			
CL&LR M&LB	SN09	X	X			X
CL&LR M&LB	SN10			X	X	X
CL&LR M&LB	SN11			X	X	
CL&LR M&LB	SN12		X			X
CL&LR M&LB	SN13	X				
CL&LR M&LB	SN14					X
GSA	SN15	X	X		X	X
GSA	SN16				X	
GSA	SN17		X			X
GSA	SN18		X		X	X
GSA	SN19			X	X	X
GSA	SN20		X			X
GSA	SN21	X				
GSA	SN22		X			
Nueces	SN23			X		
Nueces	SN24			X		
Nueces	SN25		X			
Nueces	SN26		X			
Nueces	SN27 (NA)					
Nueces	SN28		X			
Nueces	SN29			X		
Nueces	SN30			X		X
Nueces	SN31		X	X		
Nueces	SN32			X		
Nueces	SN33					X
	Totals	7	18	9	8	16

Table 11. Summary assessment of studies to address each of the five guiding questions.

		Responsiveness to Primary Review Question				
		Q1	Q2	Q3	Q4	Q5
Bay and Basin	Study Number	Validation	New Data or Approach	Strategies	Tools	Data Gaps or Knowledge
TSJ	SN01	No	Yes	NA	No	Yes
TSJ	SN02	Partially	Yes	NA	Partially	Yes
TSJ	SN03	NA	Yes	NA	No	Yes
TSJ	SN04	NA	Yes	NA	NA	Yes
TSJ	SN05	Partially	Yes	NA	Partially	Yes
TSJ	SN06	No	Yes	NA	No	Yes
Brazos	SN07	Partially	Yes	NA	Partially	Yes
Brazos	SN08	Partially	Yes	NA	Partially	Yes
CL&LR M&LB	SN09	Partially	Yes	NA	NA	Yes
CL&LR M&LB	SN10	NA	NA	Partially	Partially	Yes
CL&LR M&LB	SN11	NA	Partially	NA	Partially	Yes
CL&LR M&LB	SN12	NA	Yes	NA	NA	Yes
CL&LR M&LB	SN13	Partially	Yes	NA	Partially	Yes
CL&LR M&LB	SN14	NA	Partially	NA	NA	Yes
GSA	SN15	Partially	Yes	NA	Partially	Yes
GSA	SN16	NA	Partially	NA	Partially	Yes
GSA	SN17	NA	Yes	NA	NA	Yes
GSA	SN18	NA	Yes	NA	Yes	Yes
GSA	SN19	NA	NA	Yes	Partially	Yes
GSA	SN20	NA	Yes	NA	NA	Yes
GSA	SN21	Partially	Yes	NA	Partially	Yes
GSA	SN22	No	Yes	NA	Yes	Yes
Nueces	SN23	NA	NA	Partially	NA	Yes
Nueces	SN24	No	Partially	Partially	No	Partially
Nueces	SN25	NA	Partially	NA	Partially	Yes
Nueces	SN26	NA	Partially	Partially	Yes	Yes
Nueces	SN27 (NA)					
Nueces	SN28	NA	Yes	No	No	No
Nueces	SN29	No	Partially	Partially	No	Partially
Nueces	SN30	NA	NA	Partially	NA	Yes
Nueces	SN31	NA	No	NA	Partially	Yes
Nueces	SN32	NA	NA	Partially	NA	NA
Nueces	SN33	NA	Yes	NA	NA	Yes
Totals	NA	19	5	23	10	1
	Yes	0	19	1	3	28
	Partially	8	7	7	13	2
	No	5	1	1	6	1

3.2.1 Trinity-San Jacinto Basin/Galveston Bay

Flow-ecology relationships are broadly understood to be controlled by interactions between hydrologic forcing and geomorphic setting. Two studies (SN02 and SN05) have documented substantive ongoing changes in channel morphology in response to flow regimes and anthropogenic disturbance (*i.e.*, loss of the historic lock structure in the Trinity River). This is further reinforced by geomorphic modeling of the Senate Bill 2 (2001) Texas Instream Flow Program derived instream flow recommendations in the San Antonio River that indicated the recommended flow regime moves less than 12% of the historic sediment transport rate and is not sufficient to maintain the shape of the channel or the associated aquatic habitats required for a sound ecological environment (Raphelt *et al.*, 2018). Development and implementation of standardized monitoring programs that integrate geomorphic, water quality, and aquatic resources (e.g., fish and benthic macroinvertebrates) are a key foundation to meeting the adaptive management objectives and understanding the acceptable ranges in flow-ecology response metrics associated with a sound ecological environment. We note that geomorphic changes must be considered when assessing acceptable ranges in flow-ecology relationships specific to subsistence and base flow regimes.

Study results clearly demonstrate that the adopted flow standards primarily support sediment movement, hyporheic water table levels, and in-channel habitat functions. However, the authors (SN02 and SN05) noted that the adopted environmental flow regimes provided limited inundation of the riparian communities associated with in-channel willow communities. This was in part attributed to anthropogenic influences at sites containing berms. These analyses, which were supported by WAM modeling, established that the naturally occurring pulse and overbanking flows that exceed the adopted pulse flow standards provide inundation and morphological functions that maintain existing riparian communities. These higher flow pulses also contribute to lateral and vertical changes to channel morphologies. We conclude that these changes in channel topologies and subsequent hydraulic characteristics are sufficient to alter flow-ecology relationships, but it remains unclear if these trends constitute a concern for a sound ecological environment. Finally, the WAM modeling clearly indicated that the *"SB3 flow standard subsistence and base flows are generally lower than flows exhibited at any time of the year in the Trinity River channel as a result of continuous waste-water return flows."* [SN5].

These study results demonstrate the complexity of 'validation' of the adopted flow regimes. Specifically, their assessments show that pulse flows (and higher overbank flows) are sufficient to maintain sediment transport regimes in riffles and pools at study sites but were inadequate to provide necessary inundation levels for the full riparian community due to anthropogenic factors, such as berms, that are inhibiting the ability of pulse and overbank flows to connect to the riparian and floodplain ecosystems. They also noted significant channel morphological changes are occurring at some study sites sufficient to influence existing flow-ecology relationships developed by the BBEST and used in formulating their flow recommendations.

Although TCEQ outlined their rationale for why standards for overbank flows or flood flows were not adopted, these components of the flow regime are required for many riparian species distributed above active channel elevations (Hardy and Davis, 2015). These higher flow components also provide for the lateral connectivity to the extended floodplain necessary for successful episodic recruitment of species such as alligator gar (Winemiller *et al.,* 2021). We note that both subsistence and baseflow regimes in the standards are artificially maintained by anthropogenic induced flow releases in this system, and therefore would imply that these components are likely to be protected into the future. We further note that the study documented that naturally occurring higher-magnitude flows in excess of the adopted standards are maintaining riparian communities and lateral connectivity. Loss of these naturally occurring higher-magnitude flows in excess of the adopted standards in the future would likely result in changes to the riparian community (Hardy and Davis, 2015).

The studies for several rivers (SN07, SN08, SN13, SN15, and SN21) were essentially combined given that their methodological approach and corresponding analytical assessments were the same. The results specific to the aquatics were judged to be indeterminant owing to methodological issues related to evaluating responses of fish and macroinvertebrates to flow pulses (Appendix A). However, an emerging trend across all river basins was evident from the riparian assessments: the pulse flow standards (in the absence of naturally occurring higher-magnitude flows) are likely inadequate to maintain the existing characteristics of the riparian communities. It remains unclear if these changes to the riparian community are within expected ranges of variation associated with a sound ecological environment.

We believe that the integrated assessment methodology developed and refined by the Trinity River studies represent a viable long-term monitoring approach suitable for validation and defining a sound ecological environment. We specifically note their integration of:

- geomorphic assessments based on channel change,
- sediment particle size dynamics in riffles and pools,
- application of HEC-RAS water surface modeling at fixed cross section locations, and
- an integrated standardized aquatic resource sampling approach (*e.g.*, fish).

The Trinity River studies recommended continuing sampling efforts based on their developed methodologies and an expanded effort to provide integrated data for aquatic resources such as fish and benthic macroinvertebrates. Notably, these recommendations were implemented in subsequent adaptive management funded studies and incorporated TPWD standardized sampling methods for aquatics, as noted elsewhere. We also highlight that these monitoring efforts were implemented within a longer-term systematic monitoring program maintained by the Trinity River Authority.

The original deliberation of the BBEST subcommittee on freshwater inflows to the estuary focused on finding indicators of ecological health that are known to be responsive to salinity changes (Trinity-San Jacinto and Galveston Bay BBASC and BBEST, 2012). Two studies (SN01 and SN06) were selected to address data gaps described within The Trinity-San Jacinto Work Plan (Trinity-San Jacinto and Galveston Bay BBASC and BBEST, 2012). The studies would also address whether freshwater bioindicators (FWBI), e.g., certain finfish and shellfish species, that were originally evaluated by the Trinity-San Jacinto (T-SJ) BBEST, were protected by or responsive to the BBEST's recommended inflow regimes. In Galveston Bay, the BBEST originally recommended a flow regime that would support a salinity regime beneficial to wild celery, *Rangia* clams, and Eastern oysters in specific areas (e.g., Trinity Bay). However, the eastern oyster (*Crassostrea virginica*) was not recommended for the SN01 analysis by the TSJ-BBEST on the basis that it is a well-known euryhaline species and adapted to a larger range of salinities.

The SN01 work plan study results provided data to support the conclusion that freshwater inflows influenced oyster disease and parasitism. The authors of SN01 found that the highest number of oysters infected (both juvenile and commercial sized) were collected in lower Galveston Bay where they measured higher salinities. They concluded that while the oysters themselves may not prove to be a useful bioindicators, their predators and occurrence of disease appears to be more sensitive to changing salinity levels.

Wild celery, *Vallisneria americana*, was not found to be a useful indicator because it was, at the time of the study, rare and/or was not found in the target survey areas. The study findings for *Rangia* were also inconclusive due to low encounter rates and problems with low or variable rates of capture in the past by TPWD monitoring gear. During the SN01 study period an additional factor that complicated their analysis was a significant period of drought (2011-2014) which led to higher salinities that is stressful for *Rangia* and wild celery. It should be noted that a later study in 2015-2016 conducted by Guillen *et al.,* (2016) did find multiple patches of wild celery. During these limited surveys, wild celery was detected at several locations in shallow (< 1 m) water within the delta. It is believed the prolonged elevated freshwater inflow during 2015 and early 2016 depressed salinity (< 3 psu) throughout much of the Trinity River delta that led to the recovery of this plant species. Prior to their study, there had not been any detections of wild celery during past field investigations conducted during 2011-2014 (Guillen *et al.,* 2016). This observation of annual variation in plant density and presence seems in phase with changing salinity levels observed and supports the selection of these species as an indicator species.

The study also found that several of the species, used in the older state methodology studies and upon which the adopted standards were based, appear to be useful indicators. These species may be responsive to freshwater inflow; however, these were mostly motile species which are less suitable as indicators because of their ability to avoid unfavorable salinity conditions. Phase 2 of this study reported on recent attainment of historic flow frequencies suggesting inflows are usually above the adopted standards. Phase 2 however, did not specifically address whether the standards are protective for the indicator species.

The Trinity San-Jacinto (SN01, SN06) and Guadalupe-San Antonio (SN18, SN22) work plan studies both relied primarily on the TPWD Coastal Monitoring Database as inputs to their statistical tools. Although Galveston Bay studies collected new data using a boat-mounted water quality sampling system to collect real time data, it is unclear whether those data were incorporated into their statistical analysis. New phytoplankton pigment data also were collected, though conclusions derived from the analysis have not yet been completed. Analyses contained in work plan studies in both basins identified primary factors driving ecological responses, though it is not clear how these findings could be used to evaluate or refine flow recommendations.

3.2.2 Brazos Basin/Estuary

Results from the Brazos Bend study site concluded that all TCEQ flow standards were insufficient to meet the differential inundation levels associated with the riparian community (SN07). Study results from the second study site at Hearne highlight the complex challenges associated with validation. The first-year sampling and analysis (SN07) concluded that no TCEQ flow pulses reached full coverage of the riparian zone. However, the second-year data and analyses (SN08) indicated that only the adopted environmental flow spring wet pulses meet identified inundation levels. The authors attributed these differences to either changes in stream channel geomorphology and the biotic community due to the 2015 and 2016 floods or may indicate differences arising out of different methods employed between the two sampling years.

Several study results from SN07 and SN08 were identified that targeted the pulse flows components of a sound ecological environment related to validation of these adopted instream flow standards. It is notable that results from the studies addressing flow-ecology responses in fish and macroinvertebrates with an emphasis on pulse flow events across three separate basins, Brazos, Colorado-Lavaca, and Guadalupe-San Antonio (SN07, SN08, SN13, SN15, and SN21) found:

- responses by biotic and abiotic components were not detected among flow tiers (i.e., pulse flow levels),
- the predicted ecological values of high-flow pulses could not be validated at the flow levels observed,
- adopted environmental flow tiers and associated observed flow magnitudes were not sufficient to elicit habitat or community responses.

The preliminary study on the Brazos River (SN07) had proposed a 'validation framework'. However, this was removed from subsequent reports (SN08, SN13, SN15, and SN21) at the request of the TWDB. We independently conclude that the framework was unsuitable to address validation of the flow standards. The major strength of the proposed framework was a simple decision tree to guide the potential selection of site-specific studies for a proposed project that could impact the flow regime.

These results underscore the difficulty of the validation process. One interpretation of the study results is that the observed flow regimes simply documented differential responses in the chosen metrics, such as species relative abundance, density, etc., and therefore represent estimates of 'acceptable' ranges in these response variables consistent with maintenance of a sound ecological environment. We note specifically that the authors did not discuss their study results in this light, nor provide an assessment of the observed ranges and differential responses of species in comparison to the broader published literature on the variability of flow-ecology responses to flow regime characteristics.

Prior to the environmental flows process and the adaptive management work plan studies, there has been little data and analysis performed in the Brazos River Estuary. Due to the distance and lack of a well-developed estuarine bay system, and potentially dangerous currents and snags, the TPWD has never conducted systematic surveys of this portion of the Texas coast. Very little fishery-dependent data exist (Lance Robinson TPWD personal communication to G. Guillen). Routine fishery-independent data have never been collected in the Brazos or San Bernard estuarine systems using the routine monitoring gear and protocol. The last comprehensive bottom trawl survey occurred in the mid-1970's when sampling gear differed from the current methods (Johnson 1977). Thus, the work plan studies focused on characterizing and evaluating the underlying relationships between flow and indicators (both water quality and biotic). With regards to water residence time, size, and depth, the Brazos River estuary is unique when compared with other estuaries in Texas (Engle *et al.,* 2007). The Brazos River estuary has extremely short residence times (a few days) compared to some lagoon type estuaries (e.g., Galveston Bay 50 days; Aransas Bay 380 days, Matagorda Bay 100 days). Since the Brazos is a riverine estuary, rather than lagoonal estuary, it was assumed that the instream flow targets would be protective of the estuarine portion of the river. In some ways, the study analysis supported this concept; specifically, that species within the Brazos River estuary respond quickly to changes in flow conditions.

The Brazos studies (SN07, SN08) also collected new data, which is important as this estuary remains data-poor relative to the other estuaries. Further, given the unique characteristics of this riverine estuary, the scientific approach for testing cause and effect relationships in this system will differ from other systems but may have some applicability to evaluating inflow effects in upper estuarine areas of the more typical lagoonal estuaries of the Texas coast. Given the unique geomorphology of the Brazos River, and that it discharges directly into the Gulf of Mexico, it may be useful to consider the other unique functions of the river and how they might be negatively affected if water discharge should change. The important functions provided by the Brazos River include transport of suspended sediments which provides needed material for nourishment of Gulf beaches and maintenance of the Brazos delta. This function is extremely important since the barrier island is the only protection to the Intracoastal Waterway and the multi-million petrochemical industries located in Surfside and Freeport. In addition, the strategic petroleum reserve is located on the mainland. Finally, the river discharge provides nutrients to the nearshore Gulf of Mexico. The primary production and biota in the Gulf of Mexico are therefore closely linked to the dynamics of the river and movement offshore and inshore is occurring constantly. Numerous immature stages of fish and shellfish migrate upstream through the mouth of the Brazos River.

3.2.3 Colorado-Lavaca Basin/Matagorda Bay

Riparian community assessments at four sites showed mixed results. One site revealed that the spring small pulse and large pulse flows and the annual pulse flows of the TCEQ adopted flow standards inundate only portions of riparian communities associated with Level 1 and Level 2 elevations (*i.e.*, two lowest elevation zones). Results from another site suggested that none of the TCEQ adopted flow pulses would inundate large portions of the riparian zones. A third site showed that all TCEQ adopted flow standards for small and large seasonal pulses (except summer) and the annual pulse flows will inundate 100% of the riparian distributions. Finally, a fourth site indicated no TCEQ adopted pulse flow standards inundate large portions of the riparian distribution.

Results for the riparian assessments highlighted within SN07, SN08, SN13, SN15, and SN21 reveal a need for further research. The authors acknowledged uncertainty for the estimated discharge magnitudes given their extrapolation methodology from gage sites. Recommendations related to the ecological requirements for connectivity of lateral habitats necessary to maintain a sound ecological environment are complicated by the evolving nature of channel morphologies over time and the estimated inundation discharges.

We reviewed three freshwater inflow related studies that were completed in this basin. SN09 evaluated achievement of freshwater inflow standards and ecological responses. This study collected and analyzed Dermo (as an indicator of oyster health) and marsh biomass data and statistically related the data to antecedent inflows. SN10 evaluated freshwater delivery alternatives to East Matagorda Bay. This strategy study evaluated options for providing additional freshwater to East Matagorda Bay. SN12 evaluated the variability of sediment and nutrient loading into Matagorda Bay from the Colorado River. This was a data collection only study that measured nutrients and sediment near the mouth of the Colorado River. Collectively, these studies span the range of priorities for the BBASC: a data collection study that may support future evaluations (SB12), an analysis of the adequacy of some aspects of the environmental flows standards (SB09), and a strategy study (SN10). As a result, some progress has been made towards the goals of the Colorado-Lavaca BBASC work plan.

Studies to evaluate the achievement of freshwater inflow standards and ecological responses (SN09) identified a potentially important flow component. The authors stated:

> *The results from this study generally support the existing freshwater inflow standards for Matagorda and Lavaca Bays. The updated Dermo monthly regression, as well as the oyster monthly regression and the Dermo and oyster long-term average regressions, all identify the importance of large freshets, which are not explicitly included in the inflow standards. The BBASC and TCEQ may wish to use these results to consider explicit inclusion of a freshet component in the inflow standards, similar to the high flow pulses that exist in the instream flow standards for the Colorado and Lavaca basins.*

However, we note that this evaluation of the environmental flow standards was limited to two ‘ecosystems components’ (oysters and marsh), both of which exhibit significant scatter in the data that is typical of estuarine systems.

The evaluation of freshwater delivery alternatives to East Matagorda Bay (SN10) considered seven strategies, covering a range of options for providing additional freshwater to East Matagorda Bay. The estimated project costs ranged from $3.8M for the most inexpensive option providing the least amount of water, to $154.9M, for the most expensive option providing the most water (including additional operations and maintenance costs). This strategy study suffered from a lack of consensus regarding ecological goals, and the options evaluated were all expensive, perhaps prohibitively so.

The evaluation of the variability of sediment and nutrient loading into Matagorda Bay from the Colorado River (SN12) was part of a larger effort to measure sediment nutrient loads near the mouths of the Trinity, Colorado, Guadalupe, and Nueces rivers. The Colorado-Lavaca BBASC, like all other BBASCs, has not identified target levels for sediment or nutrients in inflows, hence there is not yet a clear view for how to use these data.

In their work plan, the Colorado-Lavaca BBASC committed to preparing a work plan report by September 1, 2021, for submittal to the TCEQ and EFAG. The BBASC work plan also identified annual reports and a five-year interim report, although we could find no record that these reports were prepared. We note, however, that lack of development of annual reports and the five-year interim report likely reflect the fact that neither the BBASCs nor the BBESTs have funding to support the development of such reports or support BBEST members in providing other technical analyses for the BBASC. The studies completed to date provide information potentially useful for the goals of the work plan and could facilitate preparation of a future report.

3.2.4 Guadalupe-San Antonio Basin/San Antonio Bay

The Guadalupe-San Antonio BBEST Environmental Flows Recommendations Report (2011) reached a consensus that the rivers, streams, riparian, wetland and estuarine habitats of Guadalupe, San Antonio, Mission and Aransas Rivers, and the Mission, Copano, Aransas and San Antonio Bay and estuary systems represent generally sound ecological environments, with a few exceptions. For the riverine systems, this was based primarily on relatively intact fish communities, and for the bays and estuaries, this is more broadly based on the “Status and Trends” reports produced by the Coastal Bend Bays and Estuaries Program (CBBEP) and the Final Programmatic Environmental Impact Statement for approval of the Mission-Aransas National Estuarine Research Reserve. Some of the areas of concern included the steady decline in tarpon, blue crab, and southern flounder populations, although there was no firm evidence that these declining trends were due to changes in freshwater inflows. The Guadalupe-San Antonio BBEST, like the Trinity-San Jacinto BBEST, based their freshwater inflow recommendations in part on salinity preferences for non-motile, *Rangia* clams and oysters.

The results from one study site in the Guadalupe River (SN15) indicated that only 'large seasonal' Senate Bill 3 specified pulse flows are capable of inundating the Level 1 (lowest elevation band) riparian community, whereas results from a second study site indicated that none of the flow standards fully inundated any of the three riparian communities defined by elevation levels. The apparent persistence of the riparian communities at these sites, including recruitment, implies maintenance from naturally occurring high flow events that may or may not correspond to the adopted standards.

Results from the Guadalupe River related to required inundation discharges for lateral overbank habitats changed by over 1000 cfs between the two years of the study and were attributed to flooding events between sampling periods. This level of change underscores the dynamic nature of these riverine systems wherein structural changes in channel topologies may result in different conclusions with regards to validation of flow standards (*i.e.*, requirement to meet a given flow regime component).

A strategy for meeting freshwater inflow attainment frequencies for San Antonio Bay was evaluated using possible aquifer storage and recovery (ASR) approaches (SN19). This would involve storing wastewater return flows and unappropriated water and using ASR methods to meet freshwater inflow goals. Several of the proposed ASR approaches suggested in this study were not allowed under Texas water right statutes and TCEQ rules in effect at the time of these studies. Perhaps the biggest hurdles to this approach are the high cost and method for funding and whether the pumped and released surface water flows can be protected from diversion once discharged back into the river.

Rangia clams were identified as a focal species by the Guadalupe-San Antonio BBEST, however, little information was previously available on salinity requirements for recruitment of *Rangia* clams or the effects of salinity on *Rangia* growth rates in Texas estuaries. Study SN17 collected *Rangia* and determined that they were uncommon in the Guadalupe-San Antonio Estuary systems and may not represent a useful focal species in estuaries exhibiting only intermittent periods of low salinities. This study measured growth rates from live clams using the width of annual shell rings and used the shell ring chronology to determine the year of recruitment into the population. The small sample sizes of live *Rangia* collected hampered this analysis, but the data generally supported the assertion that recruitment events were preceded by high inflow events, but high growth rates occurred during periods of higher salinity. Years when *Rangia* are uncommon would be indicative of extended periods with insufficient freshwater inflow to reduce salinity enough to promote recruitment of this species but may not provide much information on other estuarine ecosystem functions during these drier periods. However, this species may be a sensitive indicator of intermittent periods of high freshwater inflow events that significantly reduce salinity. Continued evaluation of this candidate species is warranted over a longer time period until enough information is collected to make a conclusive decision regarding the utility of this bioindicator.
The Guadalupe-San Antonio work plan studies (SN18 and SN22) developed direct relationships between seasonal freshwater inflow and the abundance of blue crabs and white shrimp and found that

inflow explained between 52% and 64% of the variation in abundance of these species. The BBEST considered but ultimately did not include in the development of their recommendations due to perceived difficulties associated with the use of motile species. Although a simplification, the top line conclusion of the work plan analysis is that the relationship between freshwater inflow and both blue crab and white shrimp were only seen in models with lags of one to two years, indicating that freshwater inflow may positively influence these populations at longer time scales. The other main finding was that the effect of temperature was the most important driver for blue crab while freshwater inflow was the most important driver for white shrimp. Phase 2 of this report did provide an application of the derived relationships to historic flows, including an analysis of four long-term freshwater inflow scenarios ranging from natural conditions to full utilization of surface water and Edwards Aquifer permits without return flows. This analysis found a 6% reduction in average crab abundance and a 9% reduction in average shrimp abundance. The simulations did not, however specifically analyze the impact of the adopted standards on inflows.

3.2.5 Nueces Basin/Nueces Bay

All ten of the work plan studies conducted in the Nueces Basin were related to freshwater inflows. Half of these studies were specifically related to the Nueces Delta. Within this group there was a study to assess changes in the vegetative community within the delta (SN28), to improve the hydrodynamic model to predict salinity fluxes (SN26), and several studies to evaluate strategies to provide ecological benefit to the delta (SN24, SN29 and SN32). Of the other five, three focused on the evaluation of nutrients entering the estuary (SN25, SN31 and SN33) and the other two relate to the existing water management associated with the 2010 Agreed Order (SN23 and SN30).

The first group of studies are related to the Nueces Delta. It has long been acknowledged, including by the BBEST, that the Nueces Delta no longer represents a sound ecological environment, and it is therefore reasonable and appropriate that the Nueces BBASC would focus considerable effort to this ecosystem. As to the specific studies related to the Nueces Delta, the vegetation study (SN28) did not detect a change in the vegetative community between 2005 and 2016 and the hydrodynamic modeling study (SN26) identified additional model refinements which could improve the model performance. However, neither study disputes the basic hypothesis that this ecosystem is currently unsound, and that the unsoundness is a result of reductions in freshwater to the delta. The strategy studies, while they include substantial quantifiable metrics, relied more significantly on expert opinion than originally envisioned. However, the final recommendations result in strategies that would appear to provide ecological benefit to this system. SN29, in particular provides, a wealth of information regarding the process to implement recommendations.

The second group of studies relating to nutrient (and sediment) loading and budgets, also generally confirm the long-standing hypothesis that sediment loads have declined in response to upstream water management. The work plan studies point out significant challenges for developing estimates both due to a lack of pre-regulation data and the challenges to developing flow-load rating curves. The Nueces BBEST recommended an annual high flow event with the goal of resolving some of these loading issues. This recommendation was not adopted by the BBASC or TCEQ and none of the studies directly address the potential nutrient or sediment loading benefits that these high flow events are predicted to provide. An even more significant challenge, highlighted in SN31, is that an optimal loading level is not well defined. This issue is relevant to the freshwater inflow recommendations for all estuaries. This may be an overlooked priority for systems such as the Brazos River where sediment is critically important for maintaining the delta and balancing the erosion and loss caused by offshore currents and storms. This important process has been documented in several geophysical publications (Anderson 2007). All of the BBESTs recognized that nutrient and sediment loading are an important consideration when developing recommendations, but a lack of data limited the analyses that could be performed by the BBEST.

Finally, the two-phase study relating to water management associated with the Agreed Order addresses an important concern: how limited water resources can be managed in the most efficient way to provide firm supplies while maintaining a sound environment. These studies focus on a recommended flow regime that is different than the one developed by the BBEST and adopted by the TCEQ. These two studies make little to no reference to Senate Bill 3 and recommend incorporating analysis (fisheries harvest equations) that were used in earlier studies but not considered in the BBEST analysis.

In summary, a review of ten freshwater inflow studies conducted in the Nueces Estuary leads to the following two conclusions. First, the currently unsound Nueces Delta is a high priority, and there has been significant work in refining flow ecology relationships for important indicators and developing strategies to provide improved ecological benefits. Second, the studies on nutrient loading, while carrying significant caveats, generally confirm that loads have changed, but there remains uncertainty regarding the very challenging question of how to define optimal or desired loadings.

3.3 Statewide Review Summary

In this section we provide a summary overview of the results of funded work plan studies from a statewide perspective to meet key elements supporting the Senate Bill 3 adaptive management goals related to a sound ecological environment:

1. Validating the adopted standards
2. Validating flow-ecology relationships including defining expected ranges
3. Strategies or tools to evaluate the attainment of the adopted instream flow or freshwater inflow standards
4. Tool development
5. Monitoring

3.3.1 Validation of Adopted Flow Standards

Funded studies targeting validation of instream flow related standards were conducted across several basins (see Section A.7 in Appendix A). These validation studies focused on fish, macroinvertebrates, and riparian species targeting the pulse flow components of the standards. These studies were unable to validate or invalidate the adopted pulse flow standards related to fish and macroinvertebrates but clearly documented that the pulse flow components of the adopted standards were inadequate to meet the long-term inundation needs of the full riparian communities in all studied basins. However, none of the basin specific studies provided specific recommendations for revisions to any of the pulse flow standards related to findings for riparian communities.
As noted in Section 3.2, the primary focus of freshwater inflow related studies targeted BBEST/BBASC identified data gaps and refinement or identification of new indicator species and refining their flow-ecology relationships. None of the reviewed studies specifically validated or

invalidated any component of the adopted freshwater inflow standards (Table 11). However, studies did provide important data that can be utilized to inform the characteristics of a sound ecological environment and guide revisions to the existing work plans targeting freshwater inflow validation studies in these bay systems.

3.3.2 Validation of Flow-Ecology Relationships and Delineation of Their Expected Ranges

The suite of instream flow studies (Section A.7 – Appendix A) generated data suitable for informing acceptable ranges in flow-ecology relationships specific to fish and macroinvertebrates (e.g., changes in relative abundance) related to a sound ecological environment. However, interpretation of these study results in this regard were not provided in any of the studies, and results were not discussed in light of published response ranges to different components of the flow regime (i.e., subsistence flows, base flows, pulse flows) reported in the extensive scientific literature. Furthermore, we note that the recommendations in Winemiller *et al.* (2021) clearly outline the criteria for selection of indicator species and the analytical frameworks (state-based and rate-based) capable of validating both the flow-ecology relationships and the assessment of the status and trends in a sound ecological environment.

Most of the indicator species utilized by the BBEST/BBASC in developing proposed freshwater inflow standards during the Senate Bill 3 process were fish and shellfish species contained in TPWD Coastal Monitoring Database. The preference for using TPWD Coastal Fisheries data was due to the lack of any suitable alternative long-term standardized biological dataset. As noted in Appendix A, a number of freshwater inflow related studies evaluated flow-ecology relationships for indicator species or identified alternative indicator species (or metrics) that should be considered when defining a sound ecological environment. At the same time, these freshwater inflow studies suggest a need for more data on key indicator species, such as non-motile benthos within delta and back-bay marsh systems that receive freshwater inflows, that are sensitive to the volumes of water defined by inflow standards. This is noted in study-specific reviews provided in Appendix A.

3.3.3 Strategy Evaluations

Several freshwater inflow studies evaluated strategies to achieve the adopted standards. Studies addressing strategies to achieve the flow standards were lacking for instream flows. Freshwater inflow strategies covered a range of topics, including changes in reservoir management (SN23 and SN30), changes in flow routing (SN24 and SN29), and simple to elaborate infrastructure projects (SN10, SN19, and SN32). Some of these strategies could be implemented at modest costs (e.g., changes in reservoir release schedules as contemplated in SN23 and SN30). Others contemplated large infrastructure projects that could move water from a given time and place where it provides low ecological benefit to a time and place where it provides greater ecological benefit. However, these approaches were associated with high costs. For example, the full build-out of the aquifer storage and recovery project contemplated in study SN19 was estimated to be over $450 million. To the best of our knowledge, none of the strategies have yet been implemented, however some, including modest modifications to inflow volume, timing, and/or routing to the Nueces Delta, have relatively low estimated costs. We discuss this further in Section 4.3.

3.3.4 Tool Development

Relatively few studies developed explicit tools for evaluating environmental flow regimes for instream flows or freshwater inflows as noted below and discussed in detail for individual studies in Appendix A. However, several studies created new tools or adapted existing tools to evaluate various aspects of hydrology, hydrodynamics, and water quality suitable to support the assessment of flow regimes. Some of these tools were developed to support strategy studies (e.g., tools to facilitate hydrologic calculations in SN10 and SN19). As such, these tools are not used to evaluate flow regimes, per se, but are helpful to the overall environmental flows program. Other tools were developed to better link freshwater inflows to salinity (SN16 and SN26) or nutrients (SN25 and SN31). One study (SN22) developed a tool directly relating freshwater inflows to shrimp and crab abundance in the Guadalupe Estuary. As such, these tools may help to inform the BBASCs in the future, should their environmental flow regime discussions revolve around these characteristics. All of the developed tools, including the approaches taken in their development, can clearly be adaptable to other systems and inform the direction and utility of future studies in other systems.

3.3.5 Monitoring

We note that monitoring was identified within all work plans, however, our review found that the priority for monitoring relative to other work plan study elements varied among BBASCs. In many cases, formulation of monitoring strategies was deferred pending outcomes from studies seeking to define/refine bioindicators, selection of target indicator species, or identifying data gaps highlighted in the BBEST/BBASC flow recommendation reports. We recognize that river authorities and other regional entities are implementing a variety of monitoring programs without Senate Bill 3 based funding for various purposes, many of which are relevant to inform Senate Bill 3 adaptive management goals and objectives.

3.3.5.1 Instream Flows

There were no instream flow-specific monitoring programs at the basin or statewide levels that were funded through the Senate Bill 3 process. We note that instream flow validation studies (SN07, SN08, SN13, SN15, and SN21) identify the need for establishing long-term monitoring efforts targeting riparian and aquatic ecosystem components. However, the recommendations were not specific in terms of target indicator taxa, sampling methods or gear types, collection timing or establishment of permanent study sites. Their recommendations were also silent on the need to integrate monitoring data that target changes in sediment characteristics, channel morphologies, mesohabitat availability and responses in aquatic (and riparian) components. Given the focus of these studies on attempted validation of the pulse flow components of the adopted standards, the sampling methods employed are not suitable to meet long-term monitoring protocols.

We note that the Brazos River Authority has implemented long-term data collection aimed at providing information to support the evaluation of the flow regime-ecology relationships and to increase the knowledge of geomorphology, water quality, instream, and riparian biology in relation to environmental flows in their basin. This is being done without specific Senate Bill 3-related funding. Additionally, the studies conducted by the Trinity River Authority (SN02 and SN05) provides another example of an applied adaptive management process where integrated physical (geomorphic), chemical and biological monitoring emerged as a consequence of initial study results funded under Senate Bill 3. Their initial monitoring study focused on geomorphic and riparian components and was subsequently expanded to include water quality and biological monitoring using standardized sampling protocols at several reaches corresponding to the TCEQ adopted flow standards measurement locations.

The importance of defining and implementing relevant long-term monitoring efforts within and across river basins is discussed further in Section 4.1.1.

3.3.5.2 Freshwater Inflows

The study-specific reviews related to freshwater inflows provided in Appendix A clearly show that monitoring efforts varied widely across the bay systems, and as expected, reflect both the inherent variability between these systems and the different work plan priorities adopted by each BBASC. However, it is notable that TWDB-initiated sediment and nutrient monitoring efforts within targeted bay systems (see Section A.6 in Appendix A) that were designed to provide a systematic long-term dataset specifically designed to inform the status of these key metrics informative of a sound ecological environment. These studies also provide important data that will allow the linkage of these flow dependent metrics directly and indirectly to flow-ecology responses for identified indicator species in these systems. These datasets also provide data at spatially relevant scales in the delta and back-bay marsh systems that are most likely impacted by the inflow volumes specific to freshwater inflow standards. We stress that continued monitoring of species of economic and commercial value should continue in the open bay systems. However, these monitoring data are not likely to inform validation of the freshwater inflow standards within the delta and back-bay marsh systems most sensitive to the flow regime.

The importance of defining and implementing relevant long-term monitoring efforts within specific bay systems (delta and back bay marsh areas) is discussed further in Section 4.1.2.

3.4 Challenges

It is important to view the issue of flow standards validation within the context of the adopted definition of a sound ecological environment as well as the expected variability of the system. Specifically, SAC guidance (SAC 2010) noted that a key element necessary for the objective assessment of whether flow standards have been validated or whether recommended changes to the standards are justified requires a clear elucidation of the definition of a sound ecological environment and the expected ecological variability (the range or bounds) that is acceptable within a given ecological system.

> *The validation of flow recommendations/standards/strategies raises additional questions for consideration by the respective BBASC and BBEST (e.g., what does validation consist of? and when is validation considered successful?) The central aspect of validation is to confirm or refute that the recommended standards are protective of a sound ecological environment. Validation is successful when it can be confirmed that the environmental response to flow is as predicted by the flow recommendations.* ***In any event it will be important to identify the range or bounds of acceptable responses to the standard of a sound environment.*** [emphasis added]

Designing a monitoring plan to evaluate whether the system is maintaining a sound ecological environment can be accomplished ***assuming that the work plan has a specific definition for what constitutes a "sound ecological environment".*** [emphasis added]

Our review of studies clearly indicates several systemic challenges to the success of the Senate Bill 3 adaptive management process. In part, these challenges reflect the complexity and variability of the basin and bay systems across Texas, the inherent ecological complexity of these systems, and the challenges reflective of the state of the science used in the assessment of these systems. These universal challenges to the adaptive management process include:

(1) Validation of adopted environmental flow standards.
(2) Defining the limits to a sound ecological environment.
(3) Monitoring the ecological status of rivers and estuaries, and
(4) Integrating instream flows and freshwater inflows.

3.4.1 Validation of Adopted Environmental Flow Standards

Challenges to the successful study and validation of the adopted environmental flow standards is the ability to observe and document the associated system responses to specific components of the instream flow or freshwater inflow regime. This difficulty is due in part to the inherent natural variability of flows as well as water management-induced flow variability, such as diversions, hydropower operations, and reservoir releases. In addition, an adopted flow regime in and of itself may initially provide for a sound ecological environment that can subsequently be compromised by the occurrence of invasive species, changes in land use/land cover, climate-related changes (acidification, increasing temperatures, rainfall frequency, duration, and amounts), and anthropogenic changes in nutrient loading, etc.

An example of these challenges inherent to the validation of standards is clearly demonstrated by the flow assessment studies in the Trinity River (SN02, SN05) that documented how increased baseflows are directly related to changes in return flows due to anthropogenic actions. They note:

Trinity River baseflows are driven by natural rainfall-runoff events and are also influenced by water demand and supply factors that are different upstream and downstream of Lake Livingston. Based on this analysis, seasonal subsistence flows are achieved 100% of time and baseflow targets are expected to be met or exceeded on average 99% of the time above Lake Livingston and 96% of the time below.

Modeling results of studies that assumed 100% water rights usage for the 1940-1996 simulation period showed the reliability of the adopted seasonal baseflows standards were equal to or better than the simulated naturalized flow regimes (SN5) and therefore in the absence of documented negative ecological system responses, provide no basis for recommended changes to these flow components of the adopted standards. We note that these simulations incorporate the drought of record and implies that observability of the adopted baseflow or subsistence flow standards is unlikely during even limited periods of time, much less extended periods, which may impede the ability to empirically test flow regime-ecology relationships at these flow levels. Long-term assessments of previously documented and future anticipated flow regimes are warranted to provide meaningful tests of flow regime-ecology relationships. Similar observability issues are evident in all basins and underscore the importance of establishment of long-term monitoring programs necessary to inform flow-ecology relationships and their expected ranges of variability.

We maintain that validation of a specific component of an adopted flow regime (e.g., subsistence flows or low base flow regime) requires that the specific flow component be observed over a period of sufficient duration to elicit a response (or not) in the underlying flow-ecology relationships affecting a sound ecological environment. This requires the establishment of systematic long-term monitoring programs within river reaches and upper bay systems where the adopted standards have been developed and applied. This is discussed further in Section 4.

While the flows documented in the standards may naturally occur, they are often difficult to observe and to study because the adopted flow values occur infrequently. Notably, adopted instream flow standards for subsistence flow have not occurred in most river systems during the past 10 years of the Senate Bill 3 adaptive management process. The adequacy of the standards to support a sound ecological environment, in a perfect world, would require the specific flow values in the standards to occur with sufficient duration to allow the ecological responses to be measured over time. This would provide the clearest opportunity to understand if the flow standards protect a sound ecological environment. However, such complete control of river flows is not realistic nor necessarily recommended. In the absence of such control, validating any environmental flow standard is a significant challenge, requiring data collected at various flows and at various locations to gain confidence in the conditions likely to occur at the flow standards. This further underscores the need for establishment of systematic long-term monitoring programs that can effectively track the trajectory of a sound ecological environment that can link the observed trends to the causal mechanisms as noted in Section 3.4.3 and Section 4.1.

3.4.2 Defining the Limits of a Sound Ecological Environment

SAC guidance (SAC 2006) defines a sound ecological environment as one that:

1. Sustains the full complement of native species in perpetuity
2. Sustains key habitat features required by these species
3. Retains key features of the natural flow regime required by these species to complete their life cycles, and
4. Sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations.

Given the inherent variability in the physical, chemical, and biological characteristics between bay and basin systems, as well as Senate Bill 3 allowing for basin-specific definitions of a sound ecological environment, it is not surprising that BBEST and BBASC flow recommendation reports demonstrated a wide array of what elements and methods were considered for determining whether a system (instream or estuarine) currently is maintaining a sound ecological environment.

The inherent difficulty in defining acceptable ranges or bounds in ecological responses is pointedly illustrated by existing Senate Bill 3 funded work plan study results. For example, study results

(SN25) showed that within a two-year period, the dynamic nature of the geomorphic processes within a specific river reach required substantially higher pulse flows (e.g., changes of ~ > 1000 cfs) in order to maintain lateral connectivity of off-channel floodplain habitats. Connectivity of these lateral habitats is required for the episodic spawning and recruitment success of several species such as smallmouth buffalo and alligator gar. Additionally, instream flow related studies (SN07, SN08, SN13, SN15, and SN21) clearly showed that year-to-year changes in fish community structure (relative abundance, densities) were tied to the dynamic linkage to these off-channel habitats driven by differences in the antecedent flow regimes.

The dynamic nature of alluvial river channels that result in changes in channel morphology and mesohabitat availability challenges the delineation of acceptable ranges in ecological response metrics driven by subsistence, base, pulse flows and overbank flow components of the flow regime. Clearly, the inherent variability of flow regimes and associated variability in the flow-ecology relationships that are indicative of a sound ecological environment suggests that proposed standards should incorporate a margin of safety into the standards. We acknowledge that this presents its own suite of challenges given the existing legal, institutional and policy constraints associated with granting and administration of water rights and adopted flow standards.

The ability to elucidate the expected bounds in index taxa to the variation in antecedent flow regimes (instream for freshwater inflows) has been impeded by the lack of implemented long-term monitoring programs and is discussed further in Section 3.4.3 and Section 4.

3.4.3 Monitoring the Ecological Status in Rivers and Estuaries

The SAC guidance document (SAC 2010) specifically highlighted the importance of monitoring to the validation of the flow regimes:

> *In addition to designing detailed research studies and focused surveys to fill data gaps and answer specific flow-ecology linkage questions, long-term monitoring will be a key component of the work plan. This involves monitoring over an extended period of time with the goal of developing a data set that will facilitate periodic review of the basin and bay environmental flow analyses and environmental flow regime recommendations. This will provide for tracking of key indicator variables for validation of standards and evaluation of progress towards management objectives.*

Even when all major components of a natural flow regime are maintained, the introduction of non-native or native invasive species (e.g., salt cedar, zebra mussels, fish) can impact the sustainability of native species and impair a sound ecological environment (Poff *et al.,* 1997). Establishment of a systematic long-term monitoring program for the fisheries in the Virgin River beginning in 1978 and sustained over three decades was critical to understanding and interpreting the mechanisms driving the flow-ecology responses and the expected ranges observed in the fish community that were indicative of the expected variability in the system. Notably, the relative abundance between the six native species fluctuated over 2 to 10 year periods in response to sustained high, average or low water year type flow regimes, showed differences between high spawning success during spring runoff conditions and subsequent poor recruitment during the summer in a given year due to stochastic flooding events associated with summer monsoons and that changes in the fish community structure (composition, relative abundance and density) responded to the establishment of an invasive non-native fish species (Trombley et al., 2018, 2021). Furthermore, as noted in several studies we reviewed here, anthropogenic influences such as berms can impair ecosystem functions within the riparian community by inhibiting the spatial (lateral) connectivity for a given pulse or overbank flow event. These can lead to changes in the riparian community composition with feedback loops that affect aquatic species due to changes in the availability and characteristics of in-channel mesohabitats (Hardy and Davis, 2015).

We elucidate the importance of the establishment of systematic monitoring programs in Section 4 that are necessary to establish a baseline in terms of the specific ecological conditions (community composition, expected species presence or absence, geomorphic characteristics such as mesohabitat types and availability) as a necessary step in the objective assessment of a sound ecological environment. Clearly, this is the implied intent of BBASC work plan monitoring studies outlined in their respective work plans. We stress that if the explicit site-specific baseline ecological conditions are not established for a location with adopted flow standards and there is a lack of an effective long-term monitoring program, there cannot be effective analyses that evaluates the relationship between flow and the ecological conditions at that location. Under this scenario, there can be no objective validation of environmental flow standards or a basis for recommending their modification. Given the inherent complexities of aquatic systems, we acknowledge that an effective adaptive management process is necessary to guide the interpretation of the monitoring data necessary to formulate revisions to the interpretation of site-specific baseline ecological conditions and recommended changes in monitoring techniques as well as to the environmental flow standards as envisioned under the Senate Bill 3 adaptive management objectives.

3.4.4 Integrating Instream Flows and Freshwater Inflows

The challenge of assessing the linkage between instream flow regimes and freshwater inflow regimes was recognized during the development of the various BBEST/BBASC recommendation reports, only the Trinity-San Jacinto work plan specifically highlighted this as a study priority (TSJ 2012, Pages 49-50). We note that Trinity-San Jacinto was the only study (SN06) in our review that attempted to evaluate the linkage between instream and freshwater inflow standards. However, the complex differences in the structure of the two sets of standards ultimately shifted the focus of the study to evaluate the frequency at which the standards were met in the recent record of observed flows. We note specifically, that within a given basin and bay system, study results related to adopted instream flow standards could be interpreted to maintain a sound ecological environment in the river but may not necessarily provide for a sound ecological environment in the bay.

Although there is no requirement for the instream flow standards and freshwater inflow standards to be consistent, we recognize that these connected ecosystems evolved under the same inflow hydrology. It is logical therefore, to expect their flow needs to have some similarities. For the Guadalupe basin, an early attempt was made by Opdyke (2009) to compare draft HEFR outputs against the historical Freshwater Inflow Needs (FINs) values identified by TWDB and TPWD. This comparison identified how the differences in spatial and temporal scales can be partially reconciled to evaluate if instream flow standards are consistent with freshwater inflow standards. The implications of the adopted instream flows and freshwater inflow standards and their implications to support a sound ecological environment in the respective linked basin and bay systems should be considered by the BBASCs as they evaluate their work plans and establish or refine their monitoring programs. As we have noted, the linkage between instream flows and freshwater inflows should focus on the delta and upper bay systems given that the adopted freshwater inflow volumes are likely to impact these key nursery areas more than open bay systems (Browder, 1991; Zarbock *et al.,* 1995, Montagna *et al.,* 2020).

Instream flows have focused on a number of hydrologic, biological, and ecological factors targeting the maintenance of a sound ecological environment by maintaining functional riparian zones, providing appropriate life history cues and levels of connectivity between stream systems and their floodplains, which include maintenance of stream channel morphologies and sediment transport patterns that have been identified as critical elements in the protection of riverine resources (Richter *et al.,* 1996, 1997; Poff *et al.,* 1997; Postel and Richter, 2003). The importance of instream flows and the linkage to freshwater inflows is underscored by the documented changes to freshwater inflows to estuaries that are known to impact the physical and chemical habitat conditions that result in significant impacts on the species composition and productivity of the estuarine biota (Jassby *et al.,* 1995; Sklar and Browder, 1998; Estevez, 2002).

The flow-based ecosystem requirements of instream habitats and estuarine habitats have similarities but are also fundamentally different. For example, both depend on adequate flows to mobilize sediments but whereas an instream fish habitat may benefit by short, high flow pulses that cause scour and removal of fine sediments over a gravel bed used for spawning, an estuarine marsh habitat may benefit by prolonged high inflows that deposit fine sediments and rebuild the marsh platform. As another example, both habitats require freshwater, however instream habitats may run dry, while an estuarine habitat that loses freshwater inflow, water levels remain constant, but salinities increase. These differences lead to flow needs that provide different ecological benefits that differ in space, time, and magnitude.

As noted in Section 3.3, tidal rivers and deltas maintain the low-salinity habitat areas that are most vulnerable to reductions in freshwater inflows given the relatively low volume in these aquatic habitats. Consequently, the relationships between salinity and freshwater inflow tend to be nonlinear and relatively small changes in freshwater inflows can produce large changes in salinity, potentially causing dislocations between favorable salinity regimes and benthic and shoreline habitat characteristics with disproportionate effects on the juvenile stages of many important species that use these areas as nursery habitat (e.g., Browder, 1991; Zarbock *et al.,* 1995; Montagna *et al.,* 2020). Habitats in the open bay appear to be better buffered against ecologically significant salinity fluctuations resulting from changes in freshwater inflows (Zarbock *et al.,* 1995).

3.4.5 Funding

Section 2.2 documented the funding of BBASC work plan elements since the inaugural 2014-2015 biennium through the current 2020-2021 funding cycle. The TWDB allocated approximately $325,000 to each BBASC based on a total of ~ $2,000,000 provided each biennium. This in some respects constrained which and how many of the submitted work plan studies could be funded for a given BBASC. In some cases, the funding constraint associated with the proportional funding paradigm required ‘scaling’ of BBASC specific studies to fit within the available funding targets for a specific work plan element. These funding related constraints were highlighted in basically all BBASC work plans (e.g., Trinity-San Jacinto, Page 59; Colorado-Lavaca, Page 25; Brazos, Page 35; Guadalupe-San Antonio, Page 1 cover letter). All work plans identified strategies for obtaining funding support through other potential collaborative forums but the degree to which these efforts have materially advanced work plan studies is not known and beyond the scope of this project. We note however, than efforts by various river authorities to leverage Senate Bill 3 based funding is evident. For example, the Trinity River Authority has integrated Senate Bill 3 funding of work plan elements for instream flow monitoring into their existing monitoring programs. The sustainability of these integrated efforts remains tied to legislative funding supporting the Senate Bill 3 process in the future biennium.

This is not intended as an indictment of the historical funding over the past decade provided by the legislature or the TWDB allocation strategies to support BBASC priority studies, but rather an objective identification of one of the challenges constraining implementation of the Senate Bill 3 adaptive management process. These challenges in part are a factor in our suggestion for prioritizing long-term monitoring efforts for instream flow and freshwater inflows as a pragmatic cost-benefit strategy supporting the Senate Bill 3 adaptive management objectives based on our synthesis of study results and the work of Montagna et al., (2020, 2021) and Winemiller et al., (2021) as noted in Section 4.

4 Adaptive Management and BBASC Work Plan Suggestions

An objective of our review was to specifically address proposed work plan study components that may be obsolete, require revision necessary to address data or knowledge gaps, or identify studies, monitoring or applied research elements not currently identified or implemented in the BBASC workplans. This included the consideration of specific research or study recommendations that have the potential utility to inform the Senate Bill 3 adaptive management process statewide as suggested by the SAC guidance (SAC 2010). We note that over 30 additional studies related to BBASC work plans have been funded via the Senate Bill 3 process (see Section 2), the review of which is beyond the scope of this project. In many cases, the associated reports for these projects are not yet published. However, a review of these studies as outlined in their respective work plans were used to provide insights in the development of recommendations outlined below.

As noted previously, BBASC work plans uniformly identified continued engagement of their respective BBESTs but were constrained during the Senate Bill 3 process by lack of formal funding targeting their continued involvement. We acknowledge that some BBEST members participated through the adaptive management process, but participation was not uniform nor consistent across all BBASC forums. Although all the BBASC work plans identified monitoring as part of the adaptive management process, the lack of implementation of systematic integrated long-term monitoring programs has impeded validation efforts related to flow-ecology relationships, instream flow and freshwater inflow standards or defining the expected ranges in ecological indicators associated with a sound ecological environment.

We provide several well-established resources on adaptive management to reinforce the importance of well-designed long-term monitoring programs necessary to inform the adaptive management cycle:

- Adaptive Management for Water Resources Project Planning (National Research Council, 2004).
- Adaptive management of natural resources: theory, concepts, and management institutions. (Stankey *et al.*, 2005)
- Adaptive Management: The U.S. Department of the Interior Technical Guide (Williams *et al.,* 2009)
- Open Standards for the Practice of Conservation (2007, 2013). https://cmp-openstandards.org/
- Adaptive management of river flows in Europe: A transferable framework for implementation. (Summers *et al.*, 2015)

At a broad level, these resources provide a consistent view of adaptive management as an iterative process of "plan, do, monitor, and learn" as illustrated in Figure 1.

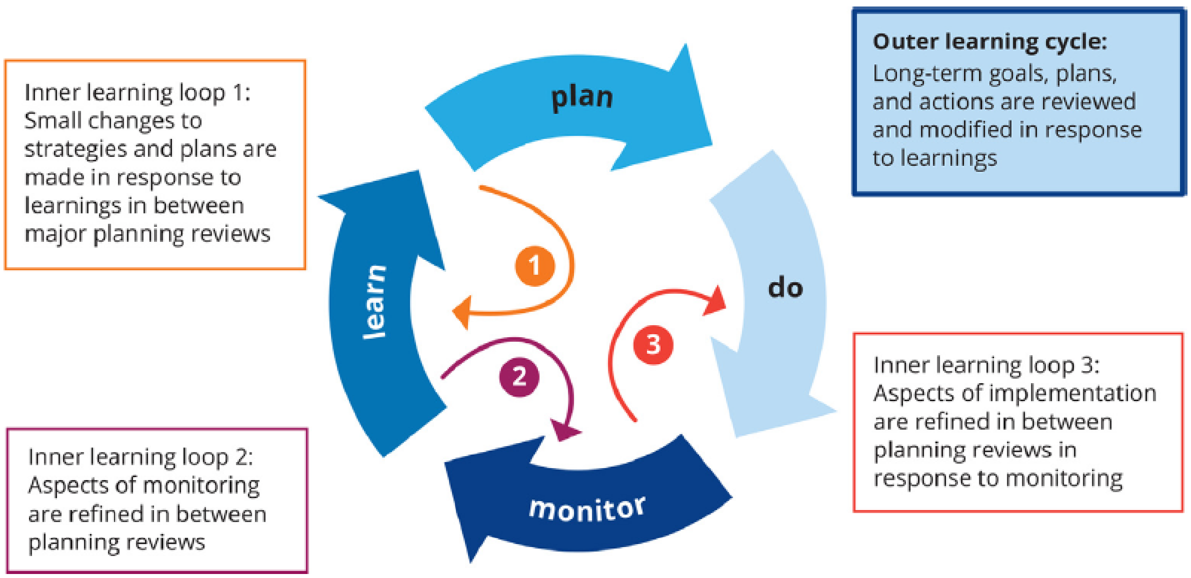

Figure 1. The adaptive management cycles. (Adapted from Webb et al., 2017)

The adaptive management cycle represented by the outer learning cycle highlights the role of knowledge acquisition that informs the next formal phase of planning and implementation (i.e., the Senate Bill 3 10-year review cycle) while the inner learning loops represent changes that are made based on knowledge acquisition that occur between major planning reviews (i.e., interim study or monitoring results that inform revisions to existing work plans targeted for funding during the next biennium).

We note that some work plans were not formally approved by the EFAG, and we could find no direct evidence that specific work plans have materially been revised based on completed study results. However, it is apparent from a review of Tables 2 through 7 that the funded BBASCs study efforts to date have continued to implement studies identified in their work plans, albeit not necessarily based on the assigned priorities. The degree to which specific studies results reflect the learning cycle to modify subsequent work plans (or scopes) remains unknown and undocumented.

A review of the funded work plan studies (see Section 2.2) shows that on balance, freshwater inflow related studies dominate efforts to date (~60 percent of funded studies) relative to instream flow related studies. We attribute this focus based on the emphasis on freshwater inflows evident in the BBEST and BBASC flow recommendation reports that followed through to the developed BBASC work plans priorities.

We acknowledge that work plans often deferred their identified monitoring programs in lieu of either defining or refinement of indicator species and/or elucidation of underlying flow-ecology relationships as identified needs in their respective basin/bay BBEST/BBASC flow recommendation reports. However, we note that the lack of integrated systematic long-term monitoring programs required as part of any adaptive management process (Webb *et al.,* 2017) has hampered validation efforts for both the adopted instream flow and freshwater inflow standards. As noted previously however, progress toward this end is represented by the TWDB funding of annual sediment and nutrient inputs to Gulf Coast bays and estuaries and integrated long-term monitoring efforts related to instream flows by river authorities (e.g., Trinity River Authority, SN02, SN05 and Table 7) and state resource agencies independent of the Senate Bill 3 process.

In general, we believe that targeting revision of work plan studies to specifically focus on addressing the challenges outlined in Section 3.4 within the established adaptive management framework envisioned by Senate Bill 3 should guide BBASC/BBEST discussions. The leveraging of available funding levels by a more collaborative statewide view is strongly encouraged. Summers et al., (2015) provides an example of a flexible framework for the implementation of an adaptive management process targeting the broad evaluation of adopted flow standards under the European Union Water Framework Directive that was designed to be specifically transferable to other regions of the world. This type of transferable framework is suitable to inform statewide efforts across complex estuary and river settings.

4.1 Statewide "Work Plan" Focus

We fully acknowledge that the Senate Bill 3 legislation and SAC guidance resulted in work plan development that was driven at the local level (basin and bay) and work plans reflect these 'site-specific' assessments of data gaps, research needs and identified priorities. Our review did not identify any specific BBASC work plan elements that were invalid in light of existing cumulative study results. However, as noted in Section 4.2, we suggest that some refinement of priorities would be beneficial to meeting the Senate Bill 3 adaptive management objectives across BBASC forums.

Our synthesis when taken in light of the results and recommendations of Montagna et al., (2020, 2021) relative to freshwater inflows and Winemiller et al., (2021) related to instream flows in conjunction with the assumed continuation of historical statewide funding levels and the proportional allocation strategy across all BBASCs clearly suggest that the Senate Bill 3 adaptive management process would benefit all BBASC forums by continuation or initiation of several statewide work plan efforts as noted below:

1. Long-term Riverine Monitoring
2. Long-term Estuarine Monitoring
3. Data Archives
4. Strategy Studies for Environmental Flow Regimes

This is not to suggest that these work plan elements have not been addressed to some degree in funded BBASC specific work plan elements undertaken to date, but rather we suggest these statewide approaches that would provide greater BBASC specific and statewide benefits under a pragmatic cost-benefit view given existing and assumed funding constraints. However, we strongly suggest that implementation of these statewide efforts should be considered given the demonstrated benefits evidenced by numerous national level monitoring and data archive efforts noted in the adaptive management references and other annotated citations in Appendix C.

Webb *et al.,* (2017) provide one of the most cogent statements related to the critical importance of long-term monitoring within an adaptive management framework:

> *"… well-targeted monitoring must be undertaken to justify the public investment and to argue for the value of environmental water in terms of ecological outcomes, ecosystem services provided, and socio-ecological benefits against alternative consumptive uses."*

Webb *et al.,* (2017) make a further compelling argument consistent with BBASC work plans that incorporating targeted research and high-quality monitoring can inform the general understanding of flow-ecology relationships for adopted flow regimes. Notably, Webb *et al.,* (2017) and Winemiller *et al.,* (2021) contend that monitoring will allow prediction of ecological responses under future flow management (*i.e.*, it helps ameliorate the problems associated with (un)observability of adopted flow regimes).

We note that bay systems across the Texas Gulf Coast represent a gradient of salinity and unique conditions that may preclude the direct extrapolation of long-term monitoring results between systems, but results are capable of informing potential future ecological states within a given system given apparent trends detectable from long-term monitoring results. For example, an existing high salinity estuary may be indicative of an ecological 'endpoint' for an another 'freshwater' estuary that long-term monitoring has detected is trending toward increasing saline conditions. The estuary corollary to Webb *et al.,* (2017) to focus on high-quality monitoring at a smaller number of sites is highlighted by (Montagna *et al*., 2020; Wetz *et al*., 2020; Sullivan *et al*., 2020) who advocate a focus on delta/estuary areas that are strongly influenced by freshwater inflows. Montagna *et al.,* (2021) specifically highlights the importance and role of long-term monitoring data to support the Senate Bill 3 adaptive management objectives across multiple estuary systems in Texas. Our synthesis supports this focus on delta/estuary areas in conjunction with targeted long-term monitoring.

The following sections highlight suggested work plan elements at a statewide level that we believe can leverage information/results across basin and bay systems supporting the Senate Bill 3 adaptive management process. We recognize that the legislation implies a 'bottom up' approach specific to each basin and bay system, however we also maintain that ecological processes remain system independent and standardized monitoring approaches in particular are best suited to leverage available resources to inform the adaptive management process at a statewide level. This does not preclude selection of different indicator taxa between systems or differences in sampling gear. For example, the monitoring framework for instream flows outlined by Winemiller et al., (2021) highlights the importance of attributes for selecting indicator taxa, not the necessity to select the same taxa across all basins. It is the consistent application of the monitoring framework using standardized sampling efforts at established reference sites that are the key.

4.1.1 Long-term Riverine Monitoring

Long-term systematic integrated monitoring allows tracking of indicators of a sound ecological environment within a river segment and allows for testing of key flow-ecology relationships for ecosystem indicators. Useful biological indicators should be highly responsive to variation in flow while physical indicators should target aspects of water quality, temperature, and geomorphic properties such as mesohabitat availability, channel topography and bed material characteristics. Other potential indicators of ecosystem status are aquatic and riparian species, functional groups of species, such as habitat guilds and different life history strategies (Winemiller *et al.,* 2021). Additionally, Webb *et al.,* (2017) provide a clear frame of reference to the challenges facing basin (instream flow) specific long-term monitoring programs:

> *Thus, we should not aim to monitor everywhere, but to conduct high-quality monitoring at a smaller number of sites that are a sample of the range of sites to which we wish to extrapolate results. This does not imply that the sampled sites are identical to those to which results will be extrapolated, but are drawn from the distribution of conditions of those sites. Thus, results should be able to be extrapolated to rivers of similar hydrologic regime and geomorphic conditions, in similar climatic zones, and with similar biological communities (Poff et al., 2010).*

We have noted previously that all the BBASC work plans identified monitoring, but that the implementation priorities varied between basins. Additionally, there is a wide variation on the specific approaches outlined on how the monitoring should be conducted. Integrated monitoring approaches were detailed in the Trinity-San Jacinto, Colorado-Lavaca, and Guadalupe-San Antonio BBASC work plans and implied to some degree in the Brazos and Nueces BBASC work plans. However, differences in the details of the approaches are evident and diminish the utility of monitoring results to inform the adaptive management process at a statewide level. We suggest that a collaborative effort between the BBASC/BBESTs to develop and implement a standardized and integrated monitoring framework applied across all basins would provide the most cost-effective benefit to informing the adaptive management process at a statewide level while meeting the basin specific work plan objectives.

Winemiller *et al.* (2021) provide recommendations for survey and monitoring protocols for target indicator taxa (fish, riparian, mussels) and specific analytical methods useful for evaluating flow-ecology relationships and environmental flow standards using both state-based and rate-based assessment methods (see Wheeler *et al.,* 2018). They note that different taxa require different survey methods, and a key factor for long-term monitoring efforts is the use of standard methodologies that are consistently applied during the same time period on an annual basis. The strongest responses by fish communities to flow regime variability are typically detected at annual time scales rather than intra-annual time scales (e.g., Kiernan *et al.,* 2012, Stewart-Koster *et al.,* 2014). Specifically, sampling during September and October is routinely used in flow-ecology research (e.g., Propst and Gido 2004, Kiernan *et al.,* 2012; Winemiller et al., 2021) and the analysis presented in Winemiller *et al.,* (2021) suggests the added benefits of higher persistence and detection during this time period. They further note that although repeated states assessments of flow-ecology relationships are useful for uncovering patterns, understanding the mechanisms that link ecological processes with flow variability are best addressed with rate-based approaches that test specific mechanisms. First, rate-based approaches provide mechanism-based inference into ecological responses, and second, rate-based approaches generate testable, temporally specific predictions for ecological responses to flow variability and alteration.

We stress that an integrated systematic long-term monitoring program requires consideration not only of the spatial and temporal habitats of aquatic and riparian biota, but also the hydrologic and geomorphic processes that have created and maintain those habitats (WMO 2019; Webb *et al.,* 2017). This can only be done by integrating monitoring information that target the five key riverine environmental attributes (hydrology, geomorphology, biology, connectivity, and water quality) into ecological flow assessments (Annear *et al.,* 2004).

We recommend that any integrated, systematic, monitoring program must include at least the following key elements (e.g., see WMO, 2019; Webb *et al.,* 2017; Winemiller *et al.,* 2021):

- geomorphic methods suitable to quantify channel cross-section topology changes over time
- sediment bed material characteristics suitable to model incipient motion and transport
- mesohabitat availability
- permanent monitoring cross-sections for riparian assessments
- standardized seasonal time period and methodological approaches for fish, mussels, and macroinvertebrates
  - recruitment
  - growth
  - population and community dynamics
- water temperature and quality parameters
- annual review of monitoring results and attainment frequencies for the adopted flow standards

Cost

We estimate ~ $120,000/year/basin. This estimate is based on the funded Trinity-San Jacinto integrated monitoring efforts for each of the last two biennium work plan studies funded by the TWDB. However, this estimate could be refined as part of a collaborative effort between the BBASC/BBESTs to develop and implement a standardized and integrated monitoring framework at a statewide level. We note that the data acquisition supporting the first four bulleted items above can be achieved in a cost-effective manner based on access to existing high resolution satellite imagery and/or drone technologies. Channel topological changes and sediment material composition and likewise cost-effective given existing hydro-acoustic sampling technologies. The greatest cost is likely associated with the integrated fish, mussel, and macroinvertebrate sampling and processing. Methodologies developed by Winemiller et al., (2021) can be exploited for the annual review of the monitoring data. Attainment frequencies based on gage station data can also be effectively automated.

4.1.2 Long-term Estuarine Monitoring

Relative to freshwater inflow, we note that the TWDB implemented an important component of a statewide monitoring framework targeting nutrient and sediment dynamics in estuarine systems (e.g., Table 1, SN20 and SN33). The TWDB utilized program funds starting in the 2016-2017 biennium and has sustained this effort to the present. The linkage of these monitoring efforts to key indicator species or other metrics suitable for assessment of a sound ecological environment remains under development.

We suggest that estuarine studies and monitoring should focus on delta and upper estuarine areas rather than bay-wide assessments (see Section 3.3). The maximum inflow standard volumes, and strategies to achieve those volumes, may not provide enough water to impact characteristics throughout an entire bay system. Accordingly, it is appropriate to focus effort where freshwater is expected to have the greatest impact. Research strongly suggests that the main body of bay systems are typically more marine influenced compared to zones in delta/estuary areas that are strongly influenced by freshwater inflow (Montagna *et al*., 2020; Wetz *et al*., 2020; Sullivan *et al*., 2020). Additionally, based on review of work plan studies and scientific literature, we conclude that monitoring efforts and research examining flow-dependent responses of estuarine indicator species should target primary productivity (such as the submerged and emergent plants, macroalgae, or phytoplankton) and benthic species (such as macroinvertebrates, oysters, etc.). Notably Montagna *et al*., (2020), makes a compelling case for this (see also Kinsey,2006; Beseres *et al.,* 2009; Flint and Younk, 1983; Engle *et al.,* 1994; and Engle and Summers, 1999). Mobile species (such as fish and crustaceans) are less suitable indicators of freshwater inflow effects that promote a sound ecological estuarine environment through reduction in salinity as they can migrate to find better conditions when conditions become less suitable through changes in salinity. However, SN18 demonstrated that TPWD Coastal Monitoring Database could be used to detect effects of environmental drivers such as temperature, salinity, and freshwater inflows on populations of blue crab and white shrimp.

As noted for instream flow monitoring, we suggest that a collaborative effort between the BBASC/BBESTs to develop and implement a standardized and integrated monitoring framework applied across all upper bay/estuaries would provide the most cost-effective benefit to informing the adaptive management process at a statewide level while meeting the individual BBASC specific work plan objectives. We maintain that Montagna et al., (2020, 2021) has clearly demonstrated the utility of this approach. We stress the adoption of a standardized framework targeting key areas in each bay/estuary system most sensitive for freshwater inflow volumes associated with the adopted standards. The framework does not preclude a focus on different indicator taxa or other metrics between different upper bay/estuary systems given the known gradient of environmental conditions evident across the Texas Gulf Coast.

We recommend that any integrated systematic, statewide monitoring program for the adaptive management of freshwater inflows must include at least the key elements of:

- A focus on delta and upper estuarine responses where the strongest gradients in salinity are found:
    - standardized annual vegetation monitoring
    - standardized annual habitat mapping
    - establish surface elevation tables to measure sediment accumulation and subsidence
- A continuous, *in situ* water quality monitoring network with:
    - at least one or two stations in the upper estuary, close enough to the river to detect changes in salinity conditions
    - instruments located at multiple depths to detect salinity/freshwater stratification.
    - high frequency (e.g., 15-minute) measurements

    - measurements of water temperature, conductivity/salinity, pH, oxygen concentration and percent saturation, turbidity, chlorophyll-*a*, and pressure/water column depth
- Discrete, monthly sampling of inorganic nutrients (N, P), suspended sediments, and chlorophyll-*a*
- Access to weather data or co-location of monitoring stations with a station meeting World Meteorological Organization or National Weather Service standards
- Derivation of measurements for ecosystem gross primary productivity, respiration, and net ecosystem production
- Monitoring of species to understand short-term population variability and long-term trends due to freshwater inflows and salinity fluctuations:
    - monthly sampling at fixed locations of indicator species that are sensitive to salinity during their life cycle (e.g., submerged aquatic vegetation, benthic invertebrates, oysters, or *Rangia* clams)
    - annual review of TPWD Coastal Monitoring Database for determining population trends of mobile species with requirements for lower salinities (e.g., white shrimp, blue crab)

Cost

We estimate ~ $200,000/bay/year based on allocations of similar studies with an assumed focus on upper bay and estuary systems that target benthos and continues to support the TWDB statewide nutrient and sediment inflow studies.

4.1.3 Data Archives

Numerous examples of the utility of integrating long-term monitoring data through the development of data archives at national and multi-national levels are published and have been used to support advance comparative and synthetic studies, policy-making, and ecological management. Many examples are evident from member state's national programs and/or implementation of the European Union Water Frame Directive (WFD). For example, Feely *et al.,* (2020) report on Ireland's national river monitoring program started in 1971 and adapted to the WFD in 2007 covering 46 river catchments and covering over 8,000 miles of river channels nationwide.

> *"The monitoring program was designed to obtain sufficiently representative information to assess ecological quality for each water body assessed." Consequently, macroinvertebrate data have been collected at over 2,900 river survey stations on a minimum 3-year cycle to fulfill these requirements. While the EPA has collected these data for water quality assessments, we recognize that the data have value beyond this one purpose. We provide a summary of how these 10,987 data records, covering the years 2007 to 2018, have been collected and used to deepen understanding of water quality, biodiversity and general ecological health of Ireland's river network."*

We suggest that from a statewide perspective, the synthesis of instream flow and freshwater inflow monitoring data across different basins can effectively inform the validation of adopted environmental flow standards and contribute to defining the limits to a sound ecological environment by collaboratively adopting a centralized data archive structure. An example relative to instream flows is proposed by the TSJ BBASC (see Appendix A, SN02 and SN05 reviews) for all river basins.

The value of this type of dataset archives is illustrated for multiple bay systems where BBASCs relied on the long-term TPWD CMD to select indicator species and inform flow-ecology relationships. The utility of long-term monitoring datasets is further reinforced by Montagna et al., (2020, 2021) used to support the elucidation of expected limits of a sound ecological environment and guide validation efforts targeting the adopted freshwater inflow standards.

Cost

We estimate an initial one-time cost of ~ $50,000 to define/refine and implement the structure of a data archive using the Trinity-San Jacinto work and the TPWD CMD as starting points. We also note a number of national database structures currently exist at the national level by a variety of monitoring programs and can be leveraged to rapidly meet this objective. We further assumed that the annual population of the data archive with both instream flow and freshwater inflow monitoring efforts are contained in their respective annual budgets for each basin and bay system.

4.1.4 Strategy Studies for Environmental Flow Regimes

Senate Bill 3 (2007) contains language encouraging exploration and use of voluntary and market-based strategies, specifically in areas where unappropriated water is not sufficient to meet the standards. Senate Bill 3 further mandates that each BBASC develop strategies to meet environmental flow standards. At the conclusion of the first round of environmental flow recommendations, which included the Sabine–Neches and Trinity–San Jacinto, the BBASCs expressed considerable uncertainty regarding the development of standards much less the strategies to achieve them. These BBASCs had limited discussion about the use of set asides where unappropriated water was available and the development of market-based and voluntary approaches in fully appropriated areas, including the "purchase and voluntary conversion of selected water rights to environmental flow maintenance, payment for on-farm conservation techniques and an agreement to dedicate for environmental flow purposes the irrigation water conserved, and lease of irrigation water through a "dry year" option, to name a few." (Recommended Environmental Flow Standards and Strategies for the Trinity and San Jacinto River Basins and Galveston Bay, BBASC report submitted to the EFAG on May 28, 2010)

During the second round of environmental flow recommendations, the discussion on strategies was significantly expanded, and each BBASC proposed a list of potential voluntary strategies. The following list is from the Guadalupe-San Antonio BBASC report, but similar lists with additional discussion and strategies specific to their basins were produced by the Colorado-Lavaca, Nueces, and Brazos BBASCs. (The Rio Grande BBASC did not issue a report.)

- Explore the donation, sale, or lease of new or under-utilized water permits
- Dedication of wastewater return flows
- Dry year option (for irrigation permit)
- Increase storage of water for releases for environmental flows
- Dedication of conserved water from current permits to environmental flows
- Facility optimization to enhance environmental flows
- Water rights management
- Set-asides of unappropriated water
- Reduction of groundwater pumping
- Land stewardship programs
    - Riparian zone and wetland restoration and stewardship

    - Watershed or catchment stewardship
- Water dedication from existing permits
- Municipal, industrial, mining, and agricultural conservation to reduce water use and demand
- Develop conjunctive use water projects
- Develop alternate water supplies
- Programs addressing logjam removal

Several BBASCs have investigated potential strategies (Table 12). The Guadalupe-San Antonio BBASC report included a preliminary evaluation of three potential strategies: 1. Wastewater dedication, 2. Dry year option, and 3. Purchase/conversion of under-utilized water rights. Both the Guadalupe-San Antonio and Colorado-Lavaca standards include strategy attainment frequencies associated with their respective freshwater inflow standards. Of these strategy studies, SN32 identifies numerous potential strategies, examines them from a variety of perspectives, and includes relatively small projects, mostly focused on enhancing the limited freshwater inflows to the Nueces Delta. For these reasons, it provides a reasonable template for performing a screening evaluation to identify projects to study further.

The concept of adding freshwater to an area of high habitat value and reduced mixing, in order to retain the freshwater where it is needed most, has been presented elsewhere. For example, the final report of the Texas Environmental Flows Initiative (2019, https://gato-docs.its.txstate.edu/jcr:5580662d-e40c-439c-9b76-687f0abc862d#:~:text=The%20Texas%20Environmental%20Flows%20Initiative%20(TEFI)%20came%20together%20in%20late,transactions%20to%20benefit%20coastal%20estuaries.) states: "[t]he ability to target delivery of inflows to a specific location, such as to a specific marsh habitat or a specific sub-bay or reef, can greatly magnify the benefits realized for a given increment of flow, compared to just allowing the water to flow down a major river or stream into a bay system." Furthermore, Montagna *et al*., (2021) make the case that "focused flows" to estuarine refugia, or nursery areas combines the following advantageous characteristics:

- Such flows entail relatively small volumes of water and are hence more practicable than the large volumes required to freshen an entire bay,
- While such flows are inadequate to maintain the ecosystem health for an entire bay, they may be sufficient to accelerate the recovery of a bay following drought, and The economic value of the accelerated recovery can be used to support the acquisition of the focused flows during drought.

Table 12. Salient Features of Strategy Studies Performed by the BBASCs.

Basin	Study	Donor	Recipient	Notes
Colorado-Lavaca	SN10	Colorado River	East Matagorda Bay	No storage is contemplated, so Colorado River would lose water at the same time as East Matagorda Bay receives water (generally dry periods). East Matagorda Bay has limited exchange with the Gulf but is a large water body. Moderately large volumes of water are contemplated (16,600 ac-ft, one out of every four years, or less frequently), but will result in modest reductions in salinity due to the scale of East Matagorda Bay.
Guadalupe, San Antonio	SN19	Guadalupe and San Antonio Rivers	San Antonio Bay	ASR allows for the rivers to lose water during wet periods and the bay to obtain water during dry periods. San Antonio Bay has limited exchange with the Gulf but is a large water body. Relatively large volumes of water are contemplated (200,934 ac-ft recovered on average one out of every four years)
Nueces	SN32	Nueces River	Nueces Delta	Most strategies do not involve storage, so the Nueces River would lose water at the same times as the Nueces Delta receives water. Nueces Delta has limited exchange with Nueces Bay, so freshwater is well contained. A wide range of volumes of water are contemplated (less than 1 to approximately 100 ac-ft per day, which equates to a maximum of 36,500 ac-ft per year)
Nueces	SN24 and SN29	Nueces Delta	Nueces Delta	Does not add freshwater. Rather, contemplates connecting Rincon Bayou with an adjacent marsh to move freshwater from one area of the Nueces Delta to another area of the delta. Would result in increased salinities in some areas (*e.g.*, Table 3.1.3 of SN24).
Nueces	SN23 and SN30	Nueces Bay	Nueces Bay	Focuses on changing the monthly pattern of pass-through targets and does not increase the annual freshwater inflow. Does not change the freshwater inflow location.

Cost

We estimate between ~ \$50,000 to \$150,000/study given the high variability of potential strategies that can be considered given the wide array of potential constraints related to water availability and physical settings between river and bay/estuary systems.

4.2 Basin/Bay Specific Work Plan Suggestions

As noted in Section 2, the development of work plan elements and their priorities for implementation reflect the individual BBASC synthesis of identified data gaps and research needs derived from the BBESTs and BBASCs environmental flow recommendation reports. We have previously noted that there is a wide array of work plan formats, number of elements, and differential emphasis between instream flow versus freshwater inflow work plan elements between the respective basin and bay systems. There are also wide differences between BBASC specific cost estimates for equivalent work plan study elements that in part reflect differences in these systems and inherent variability in assumed level of effort perceived by each BBASC to achieve study objectives.

Appendix B provides our suggested changes to the published work plan priorities based on our synthesis of reviewed studies (Section 3.3 and Appendix A) and inferences based on work plan descriptions of subsequent funded studies (see Section 2).

Table B.17. Trinity-San Jacinto Basin/Galveston Bay
Table B.18. Brazos Basin/Estuary
Table B.19. Colorado-Lavaca Basin/Matagorda Bay
Table B.20. Guadalupe-San Antonio Basin/San Antonio Bay
Table B.21. Nueces Basin/Nueces Bay

These changes to work plan priorities primarily reflect our suggestion to prioritize long-term monitoring for both instream and freshwater inflows and support efforts targeting validation of flow-ecology relationships and characterizing the expected ranges of a sound ecological environment.

Relevant to all bay and estuary systems, we suggest that the salinity and nutrient monitoring initiated by the TWDB should continue as these data will provide critical information to refine flow-ecology relationships for indicator taxa in the upper bay and estuary system (see Montagna et al., 2020, 2021). Commensurate with our suggestion to focus on upper bay and estuary areas where flow volumes associated with the adopted standards have the greatest potential to affect the status and range of variability in a sound ecological environment is the utilization of these monitoring data to inform the spatial refinement of TxBlend models in these areas. We further suggest that adopting a similar retrospective analysis using a rate-based approach as outlined in Winemiller et al., (2021) should be considered for estuary indicator taxa.

The following sections highlight suggested work plan elements to consider implementing in support of the Senate Bill 3 adaptive management objectives. The suggestions are intended to facilitate BBASC/BBEST discussions as they potentially consider updating/revising their work plans. We recognize that our suggestion to implement long-term monitoring for both instream flows and freshwater inflows in Section 4.1 will likely impact the availability of funds to fully support other BBASC specific work plan elements in any biennium under the ‘historical’ TWDB funding amounts and their objective allocation paradigm (see Section 2) that attempts to equally allocate available monetary resources across all basin/bay systems.

4.2.1 Trinity-San Jacinto Basin/Galveston Bay

We strongly encourage that the existing instream flow related integrated monitoring efforts within the Trinity River system continue (Table 13). These efforts represented by SN02, SN05 and the Phase III (2018-2019 biennium) and Phase IV (2020-2021 biennium) studies are an excellent example of long-term monitoring efforts that have adjusted to completed study results under an adaptive management framework as envision by Senate Bill 3.

Table 13. Suggested long-term instream flow monitoring locations in the Trinity-San Jacinto Basin.

Basin	River	Site	USGS gage ID
Trinity	Trinity River	Grand Prairie	0804860
Trinity	Trinity River	SB3 site at Dallas	0804440
Trinity	Trinity River	Oakwood	0802950
Trinity	Trinity River	Romayor	0800750

We note specifically the integrated monitoring and analysis of geomorphology, fisheries, and riparian related elements of the flow regime targeting both flow-ecology relationships and attributes of a sound ecological environment. We did not identify any technical issues related to these monitoring and analysis efforts and further support their continued broader coordination efforts with resource agencies (e.g., see SN05) in light of the monitoring recommendations outlined in Winemiller et al., (2021). In addition, we suggest that a retrospective analysis as outlined in Winemiller et al., (2021) be undertaken to compliment the analyses undertaken to date in SN02, SN05, and efforts under their Phase III and Phase IV studies (see Section 2).

In addition to the long-term monitoring identified in Section 4.1 and the existing work plan elements in Table B.17, the BBASC should consider support for the following research and monitoring elements:

1. A high-level study to identify potential strategies for providing freshwater inflows, with an emphasis on cost-effective strategies and funding streams to help implement one or more strategies is needed. Partnerships with other non-profit and agency programs who have been working on this topic for the last five years should be explored. Currently the Texas Water Trade (TWT), the Galveston Bay Foundation (GBF), and The Nature Conservancy (TNC) are working together to support monitoring studies associated with future flow restoration projects for Galveston Bay at specific sites in East and West Bay. Coordination between TWT and the BBEST on future projects would provide synergistic opportunities to leverage resources to advance the knowledge base and success of such restoration approaches.
2. Implement focused monitoring in areas of the bay system that are most responsive to changes in freshwater inflows (and which may be suitable locations for freshwater inflow strategies as described in element 1 above).
3. Implement integrated coastal marsh monitoring which using various forms of aerial photography to identify areas that may deteriorate during droughts due to hypersalinity. The integrated use of small, long-term deployable conductivity/salinity probes at multiple sites can be used to spatially track and model patterns in salinity changes. Such approaches have been used to study the Trinity River delta during drought periods and to evaluate changes in salinity at possible water restoration sites (Oakley et al. 2020; Guillen et al. 2016; Guillen et al. 2017a and 2017b; Johns et al. 2017).
4. Consider supporting long-term monitoring of indicator species including Rangia, *Vallisneria*, *Perkinsus marinus* parasites (Dermo Watch) and oyster drill *Thais haemostoma*, although these species were evaluated by multiple TWDB supported investigators (Study 1 and 6) additional monitoring is needed over a range of inflow and salinity levels. For Rangia, this should include population density, condition factors and age-size relationships matched with continuous monitoring inflow and salinity data (e.g., TWDB, USGS other agencies).

4.2.2 Brazos Basin/Estuary

We suggest that the following sites analyzed by Winemiller et al., (2021) based on historical field collections supported by Senate Bill 2 and Senate Bill 3 studies continue as long-term monitoring sites (Table 14).

Table 14. Suggested long-term instream flow monitoring locations in the Brazos Basin.

Basin	River	Site	USGS gage ID
Brazos	Brazos River	Hempstead	08111500
Brazos	Brazos River	Rosharon	08116650
Brazos	Leon River	Gatesville	08100500
Brazos	Little River	Little River Academy	08104500
Brazos	Navasota River	Easterly	08110500
Brazos	San Saba River	San Saba	08146000

Unlike most of the other estuaries in Texas, the tidal portion of the Brazos River remains within confined banks with little delta formation except at the mouth at the Gulf of Mexico. In addition to long-term monitoring needs identified in Section 4.1 and the existing work plan elements in Table B.18, the BBASC may wish to consider the following:

1. Focused monitoring in areas of the estuarine system that are most responsive to changes in freshwater inflows should be examined.
2. Coastal marsh monitoring and review of aerial photography to identify areas that may deteriorate during drought due to hypersalinity. So far, the most extensive coastal marsh exists at the Brazos delta south of the ICWW. Several tidal creeks feed the interior marshes and substantial wading birds are found in this vicinity.
3. Targeted geomorphological and water quality studies in the lower Brazos River are needed to evaluate the influence of river inflow on nutrient and sediment transport, beach nourishment, delta formation, and barrier island integrity including the influence of potential interactions with tropical storms, storm surge and wind, tides and coastal currents.
4. Additional coordinated monitoring of water quality and nekton in lower Brazos River and nearshore Gulf of Mexico and shorelines should continue, in order to facilitate development of a sufficient baseline. Targeted water quality studies in the lower Brazos River are needed to evaluate the influence of river inflow on nutrient and sediment transport. Biological monitoring should be expanded to include larval and juvenile fish use of the river shoreline and mid-channel to evaluate the relative importance of habitats. In addition to density, fish growth using otoliths and total length, condition using weight and length, and possibly RNA/DNA ratios should be measured to evaluate the health and growth (size at age) of each species and how it might be influenced by recent historical river flows.
5. Although the original intent of SB3 was to evaluate the freshwater inflow needs of estuaries, the nearshore Gulf of Mexico falls within the waters of Texas (9 miles), and therefore impacts of reduced flows on the normal environmental functions of this river (sediment and nutrient transport, maintenance of barrier islands; providing nutrients to nearshore phytoplankton and supporting major fisheries) should also be examined. The use of satellite imagery and nutrient data might be useful for examining large scale patterns associated with freshwater plumes, nutrients and sediments into the GOM.
6. Many rivers that discharge into the Gulf of Mexico serve as nursery habitat for juvenile

sharks, including the bull shark (Drymon et al. 2014). According to NOAA, many stocks of sharks have been reduced to extremely low levels. Therefore, an investigation of the shark populations in the lower Brazos should be conducted. This would involve the capture and tagging of juveniles with acoustic tags and installation of acoustic receivers along the riverbanks. This would report their in-river position in relation to river discharge. The tagging process would provide estimates of density and population (mark recapture).

4.2.3 Colorado-Lavaca Basin/Matagorda Bay

We suggest that the following sites analyzed by Winemiller et al., (2021) based on historical field collections supported by Senate Bill 2 and Senate Bill 3 studies continue as long-term monitoring sites (Table 15).

Table 15. Suggested long-term instream flow monitoring locations in the Colorado-Lavaca Basin.

Basin	River	Site	USGS gage ID
Colorado	Colorado River	Bend	08147000
Colorado	Lampasas River	Kempner	08103800
Colorado	Onion Creek	Driftwood	08158700

In addition to the long-term monitoring identified in Section 4.1 and the existing work plan elements in Table B.19, the BBASC may wish to consider the following:

1. A high-level study to identify potential strategies for freshwater inflows, with an emphasis on cost-effective strategies and funding streams to help implement one or more strategies.
2. Focused monitoring in areas of the bay system that are most responsive to changes in freshwater inflows (and which may be suitable locations for freshwater inflow strategies).
3. Coastal marsh monitoring and review of aerial photography to identify areas that may deteriorate during drought due to hyper salinity.

4.2.4 Guadalupe-San Antonio Basin/San Antonio Bay

We suggest that the following sites analyzed by Winemiller et al., (2021) based on historical field collections supported by Senate Bill 2 and Senate Bill 3 studies continue as long-term monitoring sites (Table 16).

Table 16. Suggested long-term instream flow monitoring locations in the Guadalupe-San Antonio Basin.

Basin	River	Site	USGS gage ID
Guadalupe-San Antonio	Cibolo Creek	Cestohowa	08186000
Guadalupe-San Antonio	Guadalupe River	Comfort	08167000
Guadalupe-San Antonio	Guadalupe	Gonzales	08173900
Guadalupe-San Antonio	Medina River	Bandera	08178880
Guadalupe-San Antonio	San Antonio River	Goliad	08188500
Guadalupe-San Antonio	San Marcos River	Luling	08172000

In addition to the long-term monitoring identified in Section 4.1 and the existing work plan elements in Table B.20, the BBASC may wish to consider the following:

1. Salinity and nutrient monitoring should be performed in the upper estuary near the river delta on a continuous basis with salinity values recorded at least hourly, and nutrient samples collected at least once per month. The Texas Water Development Board's Estuary Monitoring Program maintains one non-live reporting water quality station in San Antonio Bay near the Guadalupe River Delta (DELT) https://waterdatafortexas.org/coastal. Additionally, the TWDB rehosts water quality data from three stations maintained by Texas Parks and Wildlife Department (CHKN, SOPA, MOSQ). Major parameters collected at all stations include hourly water temperature and conductivity, although the DELT station also reports multi-dimensional pH, dissolved oxygen, and chlorophyll-a. The BBEST Environmental Flows Recommendation Report proposed using oysters and *Rangia* clams as focal species for evaluation of freshwater inflow standards. However, TWDB study SN17 demonstrated that *Rangia* were too rare in this estuary to be effective as a focal species. Furthermore, oysters are fairly tolerant of a wide range of salinities, and are heavily harvested, making their use as the sole or major focal species less than ideal. We suggest that there needs to be further discussion of suitable focal species for evaluating freshwater inflows in San Antonio Bay.

4.2.5 Nueces Basin/Nueces Bay

Instream flow related work plan elements have been deferred with an initial effort to collect Specialized (bathymetric) LiDAR data from the Frio River for use in geomorphic model development during the 2018-2019 biennium. We are unaware of any integrated monitoring efforts for geomorphology, riparian or fisheries data from Senate Bill 3 BBASC environmental flow quantification sites funded through the Senate Bill 3 process. We suggest that the BBASC/BBESTs consider adopting the monitoring recommendations provided in Winemiller et al., (2021) at a prioritized number of study sites. Given the current efforts to develop a geomorphic model in the Frio River, we suggest monitoring at this site be considered. As noted in Section 4.2, we suggest that adopting a similar retrospective analysis using a rate-based approach as outlined in Winemiller et al., (2021) should be considered for estuary indicator taxa developed for the Nueces Bay.

5 Summary and Conclusions

We found that the funding sustained by the Texas Legislature, and managed by the TWDB, provided critical support for selected BBASC work plan studies that targeted previously identified data needs and generated key research results that to some degree support the adaptive management objectives of Senate Bill 3 (2007). This includes the identification and refinement of key indicator species (or metrics) related to freshwater inflows, focus on indicator responses within delta and estuary systems in lieu of open bay assessments, the importance of large freshets, and that existing pulse flow standards of the instream flow regimes are not sufficient to maintain the full species complement of the existing riparian systems. In addition, there needs to be recognition of the diversity of riverine and estuary types that are being evaluated, including the large lagoon systems consisting of multiple side bays. Specifically, targeted research efforts (and monitoring) need to consider estuary type (major bay, river, lagoon) when developing specific methodologies given how differently these estuary types respond to freshwater inflow volumes and regimes.

The instream flow related research documented that existing pulse flow and lower overbank flows were insufficient to maintain connectivity with the full suite of the riparian community at almost all study sites. The instream flow study results also clearly documented that year-to-year variability in the flow regimes induce geomorphic changes in channel topographies that affect the required magnitude of flows necessary to maintain lateral connectivity of key off-channel habitats. However, none of the studies proposed specific changes to any of the flow recommendations.

Instream flow related study results also documented the differential responses in the fish and invertebrate communities in response to pulse flow events. Although study results focused on statistical testing of the responses within and between study sites (and times) as part of their validation efforts for pulse flows, no interpretation of these study results in light of the broader ecological literature was undertaken or framing of the results within the context of expected variation in a sound ecological environment. The existing data can be compared to the broader literature and can be revisited in light of defining acceptable ranges indicative of a sound ecological environment. Furthermore, Winemiller *et al.,* (2021) provide recommendations on indicator species related to fish, mussel and riparian species and successfully demonstrated analytical methods (state-based and rate-based) suitable for defining the expected range of a sound ecological environment, validating flow-ecology relationships, and key factors to consider when implementing long-term monitoring programs in river basins.

We maintain that an assessment of whether specified components of the flow regime for an adopted standard have (or have not) been observed does not in and of itself constitute any form of validation or whether a system maintains a sound ecological environment. It is notable that we could find no specific effort in the work plans to standardize what constitutes validation of an adopted environmental flow standard. Furthermore, there has been no demonstrated effort within individual basins or at a statewide level to elucidate acceptable ranges or bounds to what constitutes a sound ecological environment. This in part, is a function of the lack of implementing standardized integrated monitoring programs as noted elsewhere in this report. From a statewide perspective, we believe this is a critical refinement to the adaptive management process going forward.

Several BBASCs investigated potential strategies for achieving the adopted freshwater inflow standards. No work plan studies were identified for evaluating potential strategies for instream flows.

Our review suggests that the priority for monitoring relative to other work plan study elements varied by BBASC and in many cases has been deferred pending the outcome of studies to better define bioindicators, target indicator species, or other identified data gaps. Establishment of integrated long-term monitoring programs are clearly warranted based on study results from Winemiller *et al.,* (2021) and supporting literature cited in Section 4 of this report.

Senate Bill 3 (2007) recognizes the importance of an adaptive management process now codified in statute (Texas Water Code § 11.02362) and anticipated at 10-year review intervals. It is the purview of individual BBASCs to review and formulate potential recommendations to revise the adopted flow standards based on their work plan study results. Our review of the work plan studies and synthesis across basins indicate that results at the basin or statewide level are currently not able to inform or support possible changes to subsistence flows and base flows. This does not imply that the existing studies have validated these components of the flow regime. In most cases, these flows have not been observed. However, all instream flow related studies reviewed provided evidence of the need for reconsidering flow regime recommendations necessary to support the full range of species within the riparian communities in all basins although no studies made any specific recommendations.

For freshwater inflow standards, our synthesis suggests that their recommendations supporting substantive changes to the adopted flow standards will generally require a reanalysis of the existing recommendations based on using revised indicator species (or metrics) and focusing on the delta and upper estuary systems (Montagna *et al.,* 2020, 2021).

6 References

The following list of references are specific to citations contained within the body of this report. Appendix C provides an annotated bibliography of selected studies identified to support the ongoing Senate Bill 3 adaptive management process.

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Appendix A: Specific Study Reviews

The Appendix provides more detailed reviews for each identified study (Table 1) specific to the five main questions posed by the TWDB. These five questions frame the utility of specific studies toward meeting the Senate Bill 3 adaptive management goals, strategies for attainment or validation of adopted flow standards, and defining limits of a sound ecological environment. We stress that specific studies represent competent science which generated useful data to inform knowledge gaps but their utility to inform the needs of the Senate Bill 3 adaptive management goals vary widely.

We provide a synopsis of the study objectives for each study. For transparency, we stress that the material in each Study Objective section is taken from the original reports with some editing to condense the material and improve readability. The reader is referred to the provided weblinks for each study to access the original, unedited study objectives.

A.1 Trinity and San Jacinto Rivers and Galveston Bay

SN01: Defining bioindicators for freshwater inflow needs studies: Phase I

Quigg, A., and J. Steichen. 2015. Defining bioindicators for freshwater inflow needs studies: Phase I. Texas Water Development Board Contract No. 1400011695. 139 pp. (www.twdb.texas.gov/publications/reports/contracted_reports/doc/1400011695_bioindicators.pdf)

SN06: Defining bioindicators for freshwater inflow needs studies: Phase II – The health of the bay

Quigg, A., and J. Steichen. 2018. Defining bioindicators for freshwater inflow needs studies – Phase 2: Defining a sound ecological environment for Galveston Bay. Texas Water Development Board Contract No. 1600011941. 109 pp. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600011941.pdf)

Study Objectives

Phase I: This study focused several study elements identified for Trinity-San Jacinto River Basin and Galveston Bay as a result of the Senate Bill 3 process to determine freshwater inflows needs for this ecosystem using data collected from various agencies from 1980 to 2010. These were (i) to test the conclusion that the bioindicators identified were appropriate for representing the health of Galveston Bay and (ii) to consider the addition of new bioindicator species which were previously not recognized during the studies.

Phase II: One of the goals of the Phase II study was to determine the freshwater inflows required to maintain the salinity regime necessary to accommodate a healthy ecosystem or a sound ecological environment within Galveston Bay based on the ability of the inflow regime to sustain the full complement of native species in perpetuity as suggested by the SAC (2006) guidance. Phase I defined the full complement of native species as the dominant fish and invertebrates found in the 5,226 bag seine sampling events conducted from 1992 to 2015 by TPWD. Based on their findings, they conclude that it is reasonable to assert that the inflows into the bay currently provides a sound ecological environment for the species captured using this sampling approach.

A second part of this study focused on evaluation of the instream flow and freshwater inflows standards for Galveston Bay. The original objective of the study was to determine whether the instream flow and freshwater inflow standards align to support a sound ecological environment in Galveston Bay. However, due to the complex differences in the structure of the two sets of standards (e.g., instream flow standards are comprised of subsistence, base, and pulse flows, but freshwater inflow standards are comprised of seasonal and annual inflow quantities and annual attainment frequencies), it was determined that a comparison analysis was not appropriate. As such, the focus of the study shifted to evaluate the frequency at which the standards were met in the recent record of observed flows. The TCEQ adopted instream flows standards were compared to stream gage data collected by the U.S. Geological Survey (USGS) while the TCEQ adopted freshwater inflow standards were compared to freshwater inflow data compiled by the TWDB. Their analysis found the Trinity River and San Jacinto River basins were receiving the recommended freshwater inflow volumes and frequencies. This project contributes to several priority activities identified in the Trinity, San Jacinto Basin and Bay Area Work Plan for Adaptive Management (Trinity-San Jacinto BBASC 2012), including to test the conclusion that the bioindicators were appropriate for representing the health of Galveston Bay and to consider the addition of new bioindicator species which were previously not recognized.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

No. The study did not validate the adopted flow standards; however, it did provide analyses to validate that some of the bio-indicators used to derive part of the BBESTs recommendations are useful while others are not and still others should be considered in future analysis.

In the development of the freshwater inflow recommendations, the BBEST focused most of its analysis and effort on applying the salinity zonation approach recommended by the SAC (2009) which in its very simplest form contains two major tasks. The first is to define the relationship between estuarine conditions (salinity) and ecological response (a selection of species with specific geographic and salinity preference ranges serve as indicators). This first task was accomplished at two workshops at which experts reviewed available data, primarily from the TPWD Coastal Monitoring Database (CMD), and reached consensus on a suite of species, their geographic ranges and preferred salinity zones for which subsequent analysis was to be performed. The second task was to define the inflow to estuarine conditions relationship. This was accomplished by applying the TWDB TxBLEND model and developing statistical relationships between freshwater inflow and preferred salinity zones in specific geographic areas. The BBEST eventually decided to only include flow recommendations derived to produce preferred salinity conditions for wild celery and to a lesser extent Atlantic *Rangia* for Trinity River freshwater inflow and Atlantic *Rangia* and oyster parasites/disease for San Jacinto River freshwater inflow. The reasons for this limited selection of species were related to a concern that mobile species will move to better salinity location or because the relationships between inflow and desired conditions was weak. The results of this analysis were endorsed by about half of the BBEST members (regime group).

The other half of the BBEST (conditional group) endorsed freshwater inflow recommendations based on results derived from an earlier set of studies, commonly referred to as the state methodology. While the state methodology and resulting recommendations were developed before the Senate Bill 3 process was initiated and though it was not a major focus of the BBEST process, it is worth noting since this approach informed the TCEQ adopted standards. Although the BBEST could not reach consensus on freshwater inflow recommendations, there was broad consensus that the salinity zonation approach was promising but also that there remained significant uncertainty regarding the selection of suitable indicator species. The selection of suitable species is the main focus of Phase I of this work plan study.

> *Evaluate the effect of the appropriate flow recommendations on salinity zones for additional indicators starting with, but perhaps not limited to, those initially identified by the TSJ B&E subcommittee.*

The current work plan studies are primarily focused on this question of validating the bio-indicators for freshwater inflows, although a small portion of the Phase II study addresses instream flows in rivers. With respect to the freshwater inflow analysis, the Phase I study concluded that some of the biological indicator species identified by the BBEST (blue catfish and Dermo and oyster drill impacts on oysters) show statistically significant response to freshwater inflow and thus are useful for evaluating estuarine health; some are not (Wild Celery, Gulf menhaden, Mantis shrimp, and Eastern Oyster); while the utility of others is inconclusive (Atlantic *Rangia* and Pinfish); and still other species not considered by the BBEST could be useful (Blue Crab, Southern Flounder, Atlantic Croaker, and several groups of phytoplankton).

This study did not directly address the adopted flow standards however the results of the study do suggest that some of the species considered in these earlier studies could serve as useful indicators of estuarine health.

The Phase II study took a community, rather than species, level approach based on metrics composed of the 30 most dominant species collected in bag seines as part of the TPWD CMD and concluded that Galveston estuarine health has remained stable for the period from 1992-2015. The Phase II study also provided an analysis of the frequencies that freshwater inflows for the period from 1992-2015 exceeded the annual and seasonal inflows included in the TCEQ adopted standards.

This analysis, provided additional information to support or refute the selection of indicator species, demonstrated recent period ecological stability, and calculated that the adopted flow standards are met, and actually exceeded in recent years. However, it does not directly address the question of whether the adopted flow standards protect a sound environment. What could be concluded from this analysis is that the freshwater inflows that have occurred over the last 20 years have resulted in a stable estuarine community. The adopted flow standards, as the attainment frequency analysis demonstrates, represent significantly lower inflows than those that have occurred over the last 20 years.

The attainment frequency analysis does not address the validity of the statement that the adopted flow standards are protective of a sound environment, rather the study concludes that the current estuarine community is stable and that the current flow in both rivers and into the estuary are generally higher than the values in the adopted standards.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

Yes. The study collected new data and developed a scientific approach for testing relationships between flow (or rather salinity as a surrogate for flow) and ecological response. These relationships described the strength and direction of effects but did not attempt to quantify a cause and effect relationship or identify thresholds.

Two categories of new data were collected as part of this study. The first is data collected with a boat mounted Dataflow® apparatus. This data was used to produce high spatial (bay wide) and temporal (13 sampling events approximately monthly between January 2014 to July 2015) maps of water quality parameters. Descriptive results were provided. As would be expected, temperature showed a strong seasonal effect, and salinity decreased, and turbidity increased following large freshet inflows. Dissolved organic matter concentrations in Galveston Bay were relatively low during the study period which was assumed to be associated with low freshwater inflows. Chlorophyll *a* concentration, which is known to respond positively to nutrient inputs via freshwater inflows were surprisingly higher on the western, San Jacinto side than the eastern Trinity side of the estuary. The two pigments phycoerythrin and phycocyanin commonly associated with cryptophytes and cyanobacteria, respectively, both responded positively to high freshets.

While the data and maps provide insight into the seasonal and inflow response, it is not clear from the report if this data was used in any of the analysis to identify bio-indicators or otherwise serve to validate the relationship between freshwater inflows and ecological health of the estuary.

The second new data collection reported in this study is the collection of phytoplankton pigment concentration and associated water quality data. These data have been collected by Texas A&M University-Galveston (the Quigg Lab[5]) since 2008 and were collected during this study (2014-2015) though the 2013-2015 data had not been analyzed as of the publication of the Phase 1 report. These data were used to determine whether phytoplankton pigments could serve as a useful bio-indicator. Much of the period during which data was collected was during a drought, and thus there was a decrease in overall phytoplankton concentration across all phytoplankton taxonomic groups analyzed, while spikes were observed in the spring and fall due to increased nutrient availability during those times. While the analysis suggests relationships between phytoplankton and freshwater inflow, or water quality parameters associated with freshwater inflow, the study concluded that that "*… phytoplankton pigments have the potential to be included as FWBI* [freshwater bioindicator] *in Galveston Bay but more data must be obtained covering a longer period of time to make a better assessment"*.

In terms of scientific approach, the Phase I study is focused on applying three standard and established statistical tests to evaluate the strength of the response of select species to freshwater inflows or water quality parameters associated with freshwater inflow. The Phase II study however took a community level approach. While this approach has been employed by others to investigate Texas estuaries, community level studies have not been widely used in the Senate Bill 3 or previous statewide analyses of freshwater inflow needs. The Phase II study concluded based on these community metrics (Shannon diversity (H'), Pielou's evenness measure (J'), species richness (S) and total number of individuals (N)) that the health of Galveston Bay has been stable over the period from 1992-2015. The community level approach could serve as useful template for other systems, both riverine and estuarine, to test this hypothesis in other systems.

This community level approach however does not specifically address the question of whether the adopted flow standards are sufficient to maintain a sound environment.

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[5] Dr. Antonietta Quigg, Phytoplankton Dynamics Lab at Texas A&M University, Galveston Campus

Q3. Did the study evaluate a strategy for achieving environmental flows?

NA. This was not one of the project deliverables for either study.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

No. It is unclear how much of the information in these reports could be used effectively in an adaptive management process as there is essentially no predictive analysis of how incremental changes in flow or changes in the flow regime and salinity might influence the abundance of freshwater bioindicator(s) (FWBI's) or overall species composition (nekton, plankton, or benthos). The response of plankton communities to alterations in freshwater inflow as measured by pigment composition is hard to use for defining a healthy ecosystem versus other possible states. Future development of the approach using pigments should be pursued. Tying these changes to upper level trophic impacts or potential harmful algal blooms would be a useful addition that would help describe how the overall health of the estuary is affected.

Q5. Did the study identify additional data or knowledge gaps?

Yes. The Phase I study, in addition to considering several finfish and shellfish species that were not included in the BBEST analysis, added the analysis of phytoplankton, and concluded that phytoplankton are a good candidate as an indicator of freshwater health. The new finfish and shellfish species were in fact considered at the BBEST workshops but were not included in the analysis to determine flow standards largely because they are mobile and therefore believed that they will simply seek more preferable habitats when conditions are unsuitable. The analyses suggest that several species be reconsidered, though the outstanding issue, which is generic to all estuarine settings, of how to incorporate mobile species in the analysis remains unaddressed. We believe that the analysis of phytoplankton holds significant promise and should be pursued further.

SN02: LIDAR acquisition and flow assessment for the Middle Trinity River (Phase I)

Mangham, W., T. Osting, and D. Flores. 2015. LiDAR acquisition and flow assessment for the middle Trinity River. Texas Water Development Board Contract No. 1400011696. 128 pp. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1400011696_MiddleTrinity.pdf)

SN05: Evaluation of adopted flow standards for the Trinity River (Phase II)

Mangham, W. T. Osting, and D. Flores. 2017. Evaluation of adopted flow standards for the Trinity River, Phase 2. Texas Water Development Board Contract No. 1600011940. 56 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600011940_TRA.pdf)

Study Objectives

Phase I: This project collected site-specific field data and analyzed river characteristics at three Senate Bill 3 measurement sites in the Trinity River basin to determine system responses to the adopted standards. River study sites were in the vicinity of the Dallas (river mile 444, USGS stream gage #08057000), Oakwood (river mile 295, USGS stream gage #08065000), and Romayor (river mile 85, USGS stream gage #08066500) Senate Bill 3 study locations.

The project developed (1) a Light Detection and Ranging (LiDAR) topographic dataset, (2) a site-specific field dataset and (3) a final report detailing field work, modeling results, and analysis relative to the TCEQ adopted Senate Bill 3 environmental flow standards for these river locations.

Phase II: The goal of the Phase II project was to use empirical data, field observations, and modeling results to understand and document instream conditions and/or functions of the Senate Bill 3 flow standards. The study and accompanying data deliverables were not intended to recommend flows or provide an exhaustive explanation of each flow possibility but was designed to serve the following purposes:

1. Summarize field and analysis methods used for this project;
2. Document existing data;
3. Provide a data archive deliverable that the Trinity and San Jacinto Basin and Bay Area Stakeholder Committee (BBASC) can use to answer questions during the upcoming adaptive management phase of Senate Bill 3;
4. Provide the morphology, hydrology, riparian, sediment, and connectivity backdrop for the incorporation of upcoming biological data collection results;
5. Provide an overview of selected results; and
6. Characterize the system at different flows.

The combined studies focus on high flow pulses and address data gaps identified in the Senate Bill 3 BBASC Work Plan Report (Trinity-San Jacinto 2012).

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

Partially. The study provided important data and modeling results for the relationship between discharge (i.e., pulse flows and overbank flows) and water surface elevation, inundation, lateral connectivity, channel topography changes, and bed material dynamics at each study site. In addition, the study utilized a modified version of the TCEQ Water Availability Model (WAM) to test the reliability of the Senate Bill 3 baseflows under current and near-future conditions (see Appendix 6, Phase II report).

The study demonstrated that Senate Bill 3 high flow pulses primarily support (1) sediment transport dynamics, (2) recharge of the riverine water table, and (3) in-channel topography dynamics. Inundation of riparian areas by Senate Bill 3 flows is limited to in-channel willow habitats at several study sites. Riparian communities exhibit different species as a function of inundation elevation and reflect regional characteristics (Hardy and Davis 2015). As expected, study sites reflect flow-dependent differential recruitment. The study noted that naturally occurring pulse and overbanking flows that are higher than the adopted Senate Bill 3 flows occur; this provides for inundation that supports riparian communities as well as providing lateral and vertical changes to channel morphology.

WAM modeling indicated that seasonal Senate Bill 3 subsistence flows are achieved 100% of the time above Lake Livingston and 96% of the time below. The modeling also indicated that projected baseflow levels are expected to be achieved more frequently. The study did not characterize base flows or instream habitat.

These analyses document the likelihood of Senate Bill 3 flows being observed in the system but do not validate if the flows will maintain a sound ecological environment. Furthermore, the observed dynamics in channel morphology, which reflect habitat quantity and quality for aquatic species was not evaluated. The implications of channel changes, especially the large-scale changes occurring within the reach downstream of Dallas, on the relationship between discharge and aquatic habitat quantity and quality remain unknown.

We note that these 'validation' efforts were not part of the study objectives. WAM modeling demonstrated that Senate Bill 3 subsistence and base flows are not likely to be 'observable' and therefore difficult if not impossible to validate in terms of their ability to maintain the ecological integrity of the system.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

Yes. The study collected data on floodplain topography (LiDAR), in-channel cross section geometries, sediment composition, and riparian species age-structure and channel elevation relationships with discharge. It is notable that the data collection was conducted within the context of both the Senate Bill 3 adaptive management process and in support of the established long-term monitoring programs of the Trinity River Authority (TRA) and the Tarrant Regional Water District (TRWD). The collected data on cross-section geometries and bed material composition was especially informative on how discharge regimes influence channel geometry and initiation of bed material particle sizes. These data can be used to infer changes in the quantity and quality of aquatic habitat driven by channel responses to flow regimes.

The study demonstrated application of a variety of field data collection strategies that materially address the requirements of an adaptive management monitoring program that ties channel responses to flow regimes suitable for supporting the evaluation of ecological responses in the future.

Q3. Did the study evaluate a strategy for achieving environmental flows?

NA. This was not an objective of the study.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

Partially. The study developed HEC-RAS water surface profile models for the selected study sites corresponding to approximate locations of the Senate Bill 3 measurement points. The modeling examined water surface elevations at selected cross sections that included several target pulse and overbank discharges. The simulated water surface elevations were examined in light of channel elevation dependent riparian vegetation distributions. The modeling also assessed the expected incipient motion of bed material to inform channel geometry changes and bed material composition. The water surface modeling and associated inundation analyses were used to assess the relationship between flow levels and overbank inundation areas. Although no analyses were conducted on the ecological implications of the field measurements or modeled water surface elevations, the data collected represents important monitoring data that can be exploited to evaluate ecological responses to flow regimes over time. The study also developed a modified WAM model in order to evaluate the expected occurrence of Senate Bill 3 subsistence and base flow discharges.

Q5. Did the study identify additional data or knowledge gaps?

Yes. The study provided a variety of next steps for each of the three study sites as well as a broad overview perspective. In particular, we note the need to collect and integrate ecological data on fish, benthic macroinvertebrates, mussels, and riparian communities in response to ongoing and predicted channel changes under existing (and future) flow regimes. We support the identified recommended additional work which is provided below:

- Riparian cross-sections should be completed at each site since high flows prevented data collection during this project.
- Senate Bill 3 flow standards profiles at study sites should be projected upstream and downstream of the sites and linear survey field work should be completed to determine if the flow standards would inundate tributary confluences or other low lying junctions, especially at near known oxbow lakes.
- Game-cams can be installed to capture water level during pulse flow events to estimate riparian inundation; installation would be beneficial within a mile of Senate Bill 3 measurement point USGS stations and/or near tributary confluences, low lying junctions or oxbow lakes.
- Repeat channel monitoring should be completed at these sites to determine the effects of the 2015 flood events on the morphology of the channel.
- Biological data should be collected and compared with the 2012 Supplemental Biological Data Collection effort to determine the effects of extended high flow scouring events on fish, benthic macroinvertebrates, and native mussels.
- Additional LiDAR should be collected, especially in locations where the existing LiDAR is outdated or inaccurate.
- Another channel monitoring site should be installed to represent the most upstream Senate Bill 3 measurement point at USGS gage 08049500 - West Fork Trinity River at Grand Prairie.
- Develop a historical timeline for each of the Trinity River study segments identified in the TRA Long-term Study, identifying flood control, navigation, and other pertinent characteristics.
- The historical USACE cross-section data from 1899 and 1939 should be location-referenced to facilitate comparison to modern-day survey data.
- Measure pre-failure baseline conditions upstream at Lock #2 in anticipation for a future dam failure.
- The Data Archive Structure should be adopted by other entities working on instream flow studies in order to assist in sharing data across platforms.

SN03: Determination of freshwater inflow volume from the Trinity River into Galveston Bay, May 2014 – August 2015

USGS. 2015. Determination of freshwater inflow volume for the Trinity River into Galveston

Bay, May 2014 – August 2015. Texas Water Development Board Contract No. 1400011697. 27 pp. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1400011697_USGS.pdf)

Study Objectives

This study attempted to determine tidally affected discharge on the lower reaches of the Trinity River using the index velocity method and evaluated the variability of nutrient and sediment concentration entering Galveston Bay over a range of hydrologic conditions. Additionally, the study intended to investigate possible correlations between in situ field measurements of acoustic backscatter and discrete nutrient and sediment concentrations.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

NA. This was not an objective of the study.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

Yes. The study developed a new real time discharge estimation technique that refined the estimated discharge from the Trinity River into the delta region of Galveston Bay. The use of an index velocity rating methodology was also used as a surrogate method to estimate suspended sediment concentrations. Additional data was obtained on several water quality parameters (ammonia, nitrate, nitrite, orthophosphate, phosphorus, total nitrogen, dissolved oxygen, pH, specific conductance, water temperature, and turbidity). Bed sediment data was also collected when the acoustic doppler readings indicated bedload transport was evident. These data in mass, represent important characteristic properties of the freshwater inflow regime to the delta region of Galveston Bay that can inform future analyses of ecological responses.

Q3. Did the study evaluate a strategy for achieving environmental flows?

NA. This was not an objective of the study.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

No. However, we note that the development of the index velocity rating method at the USGS station for the Trinity River at Wallisville (08067252) provides updated real time discharge estimates for the lower Trinity River. These data provide improved discharge estimates for freshwater inflows to Galveston Bay for upstream discharge ranges less than about 20,000 cfs. The study found that this flow rate appears to be the maximum flow at this station even though higher discharges are estimated at the two upstream gage locations. The route and destination of the unaccounted flow remains unknown. These flows are important as they influence the delta region's complex array of wetlands, channels, and lakes that likely impact the water quality of Galveston Bay inflows. We further note that the preliminary assessment of use of the index velocity rating method to estimate suspended sediment concentrations is promising and likely important to inform the flow dependent contribution of suspended sediment and water quality constituents to the delta region of Galveston Bay. Refinement of this surrogate methodology for suspended sediment is ongoing.

Q5. Did the study identify additional data or knowledge gaps?

Yes. This study provided important updates to the quantitative real time estimates of freshwater inflow characteristics in terms of discharge, water quality, and suspended sediment to the delta region of Galveston Bay. It also defined the upper discharge range after which inflows to the delta are not occurring via the Trinity River at this location. The pathway and location of these flows into the delta and ultimately Galveston Bay remain unknown.

SN04: An evaluation of the variability of sediment and nutrient loading into Galveston Bay from the Trinity River watershed

This is a data only study and SN04, SN12, SN20, and SN33 are combined under the discussion in Section A.6 given that they were methodologically the same.

SN05: Evaluation of adopted flow standards for the Trinity River (Phase II)

Mangham, W. T. Osting, and D. Flores. 2017. Evaluation of adopted flow standards for the Trinity River, Phase 2. Texas Water Development Board Contract No. 1600011940. 56 pp + Appendices.
(https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600011940_TRA.pdf)

SN05 is discussed under the SN02 section above since it was a continuation of the SN02 work.

SN06: Defining bioindicators for freshwater inflow needs studies: Phase II – The health of the bay

Quigg, A., and J. Steichen. 2018. Defining bioindicators for freshwater inflow needs studies – Phase 2: Defining a sound ecological environment for Galveston Bay. Texas Water Development Board Contract No. 1600011941. 109 pp.
(https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600011941.pdf)

SN06 is discussed under the SN01 section above since it was a continuation of the SN01 work.

A.2 Brazos River and Associated Bay and Estuary System

SN07: Instream flows research and validation methodology framework and Brazos Estuary characterization

Bonner, T., J. Duke, G. Guillen, K. Winemiller, Bio-West, Inc. 2015. Instream flows research and validation methodology framework and Brazos Estuary characterization. Texas Water Development Board Contract No. 1400011722. 159 pp + Appendices.
(https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1400011722%20BIO-WEST.pdf)

SN08: Validation or refinement of the adopted TCEQ environmental flow standards for the Brazos River (estuary only)

Bonner, T., J. Duke, G. Guillen, and Bio-West, Inc. 2017. Instream flows research and validation methodology framework 2016-2017: Brazos River and Associated Bay and Estuary System. Texas Water Development Board Contract No. 1600012009. 120 pp +

Appendices.
(https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600012009.pdf)

The estuary components of these studies are discussed here. The instream flow components of SN07, SN08, SN13, SN15, and SN21 are combined under the discussion in Section A.7 given that they were methodologically and analytically combined by the authors across basins.

Study Objectives (Estuary Only)

The Brazos estuary component described water quality and nekton community patterns and quantified estuary salinity regime, nutrients, suspended solids, and utilization by estuarine-dependent nekton.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

Partially. Estuarine ecological needs were not directly estimated by the Brazos BBEST. Due to both the lack of data to support an analysis of relationships between freshwater inflow and ecological responses and the fact that the Brazos estuary is a riverine estuary, in contrast to the lagoon-type estuaries (shallow bays) that dominate the Texas coast, the BBEST made an initial assumption that environmental flows developed for riverine segments upstream of the estuary would be sufficient to maintain the health of the estuary. Consequently, the TCEQ did not adopt freshwater inflow standards specifically for the Brazos Estuary.

The question of validation thus becomes: are riverine flow standards a valid method for protecting the health of this estuary specifically? This raises a more general question as to how the natural flow paradigm, upon which most (all) of the instream flow recommendations were based, might be developed, and applied to make recommendations for estuaries.

In Section 1.4 the authors present their basic concepts of the flow-ecology hypothesis recommended by the SAC for freshwater inflows. As there was insufficient data to develop flow-ecology relationships, the focus on this study was the collection of basic chemical and biological data. Flow-ecology hypotheses and regression relationships were developed; however, given the paucity of data, its variability and interactions between sites and flow tiers, interpretations are difficult and conclusions tenuous. Clearly many of the water quality results aligned with expectations, e.g., inverse relationship between flow and salinity. This study was part of a larger series of studies on validation (see section A.7), and the methodological issues we discuss therein should be considered here particularly with respect to nekton response to antecedent flow conditions.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

Yes. During November 2014 to May 2015 and December 2016 to May 2017, a total of 12 sampling events were conducted at multiple monitoring sites for water quality, nutrients, nekton, and zooplankton. For each sampling event, flows at USGS gage #08116650 in Rosharon, Texas, was monitored and classified into tiers (subsistence, base, pulse) relative to the adopted instream flow standards. "Regression models were used to describe potential relationships between river inflow and the response of salinity, water quality, and primary production as measured by chlorophyll-α (RFU)…. Spatial and flow tier mediated effects on nekton community composition were analyzed using the PRIMER 6 statistical package" (SN08).

Statistically significant relationships were detected between discharge (cfs) measured at the Rosharon gage and resulting flow tier levels and salinity, chlorophyll- α, TSS, N-NO2+3, TSS, TKN and TP. A weak but significant negative relationship was detected between proportion of estuarine dependent species and stream discharge at the Rosharon gage and resulting flow tiers. Interactions between site location and flow magnitude and the limited number of data point confounded results and made them difficult to interpret and potentially apply to suggest refinements to flow standards.

Q3. Did the study evaluate a strategy for achieving environmental flows?

NA. This was not part of the study objectives.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

NA. This was not part of the study objectives.

Q5. Did the study identify additional data or knowledge gaps?

Yes. The paucity of data for the Brazos Estuary was a limiting factor in the BBEST analysis and this study only begins to address this deficiency. Much of the text in Phase I is repeated in Phase II, and with the exception of the additional collections in 2017-2016, it is somewhat difficult to identify the impact of the new data on the models or results.

Many responses were better explained by when the flow magnitude, rather than flow tier was used as the predictor variable, since the flow tier collapses the variability observed in flow magnitude. "Further research is needed to evaluate the relationship and statistical properties observed between actual flow values and flow tiers (e.g., subsistence flows; low, medium and high base flows; pulse and overbank flows) and the dependent variables." (SN07)

SN08: Validation or refinement of the adopted TCEQ environmental flow standards for the Brazos River (instream only)

Bonner, T., J. Duke, G. Guillen, and Bio-West, Inc. 2017. Instream flows research and validation methodology framework 2016-2017: Brazos River and Associated Bay and Estuary System. Texas Water Development Board Contract No. 1600012009. 120 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600012009.pdf)

Review of studies SN07, SN08, SN13, SN15, and SN21 are combined given that they were methodologically and analytically combined by the authors across basins and are discussed in Section A.7 of Appendix A.

A.3 Colorado and Lavaca Rivers and Matagorda and Lavaca Bays

SN09: Studies to evaluate achievement of freshwater inflow standards and ecological response

Anchor QEA, LLC, Bio-West, Inc., J.F. Trungale Engineering and Science., and T. Soniat.

2015. Studies to evaluate achievement of freshwater inflow standards and ecological response. Texas Water Development Board Contract No. 1400011715. 85 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1400011715_Matagorda&Lavaca.pdf)

Study Objectives

This report describes scientific investigations regarding freshwater inflows and associated ecosystem responses for Matagorda and Lavaca Bays (Anchor QEA, LLC, *et al.,* 2015). Since the end of the Matagorda Bay Health Evaluation (MBHE) effort, which used data through 2007, additional data related to marsh habitat and productivity, and oyster abundance and parasitism, have been collected. The purpose of this study was to compile and collect new data (through the end of 2014) and to update and expand upon the marsh productivity and oyster evaluations that were performed in support of the MBHE. In addition to extensive oyster and dermo analyses, a series of biological field sampling activities were conducted in Matagorda and Lavaca Bays (specifically, the Colorado River Delta [CRD] and Lavaca River Delta [LRD]) during summer and fall 2014, which included data analysis and interpretation. Field activities beyond oyster collection included the following ecological categories: 1) marsh vegetation, 2) juvenile finfish and shellfish, and 3) *Rangia* clams. This information was expected to either corroborate the existing inflow standards or suggest new relationships between freshwater inflows and ecosystem responses that the BBASC and TCEQ could use to guide a potential re-evaluation of the original standards.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

Partially. The marsh biomass results confirmed that marsh vegetation does serve as an important ecological indicator, with a detectable response to freshwater inflow. The marsh vegetation results also support a multi-level flow criteria and achievement guideline approach as is currently in place for both bays. However, the authors state that due to the limited duration (1 year) of the study, they could not address all the complexities associated with recommended multi-season, multi-site inflow standards (Anchor QEA, LLC 2015). The BBEST recommended a freshwater inflow regime for Matagorda Bay that was adopted from the Matagorda Bay Health Evaluation (MBHE) inflow criteria, which were designed to cover the full range of inflow conditions into Matagorda Bay (Colorado Lavaca River and Colorado-Lavaca Bay/Basin Expert Science Team, 2011). The inflow suite for the MBHE inflow criteria included long-term inflow conditions (presented as long-term volume and variability), an inflow regime (presented as MBHE 1–4), and extremely low and infrequent inflow events (termed Threshold) (Colorado-Lavaca Bay/Basin Expert Science Team, 2011).

The MBHE study relied on historical flow data, salinity data, TxRR rainfall-runoff modeling, hydrodynamic modeling of the bay and marshes, nutrient and primary productivity modeling, habitat modeling, benthic community analysis, and biostatistical analysis of TPWD coastal fisheries data (MBHE 2008). The BBEST also considered findings from previous freshwater inflow need studies (Martin *et al.,* 1997, LCRA, 2006). Martin *et al.,* (1997) recommendation was based on five years of data collected after the 1991 diversion channel opening, relying on flow, salinity and biological productivity based on commercial harvest data. LCRA (2006) recommendation was based on an additional eight years of new data since Martin *et al.,* (1997), relying on flow, salinity, and TPWD coastal fisheries data.

The authors acknowledged that the limited 2014 field sampling and analysis associated with their current study represented only a snapshot in time for each bay system and should be interpreted with caution (Anchor QEA, LLC *et al.,* 2015). As noted throughout their report, complexities with antecedent inflow conditions and ecological responses of the marsh and juvenile finfish and shellfish communities makes additional long-term monitoring and statistical analysis necessary prior to being able to conduct a rigorous validation of the inflow criteria. In order to start alleviating the caveats in this limited biological evaluation for the species studied, several recommendations for future monitoring and applied research were provided in the final section of their report for BBASC consideration. The final report provided suggestions for future efforts that would enhance the BBASC's assessment of freshwater inflow standards for Matagorda and Lavaca Bays (Anchor QEA, LLC *et al.,* 2015).

Specific recommended monitoring efforts included 1) Re-establishment of Dermo monitoring in Matagorda and Lavaca Bays, and 2) Development of marsh productivity monitoring in each delta system. The marsh productivity monitoring program should include measurement of marsh vegetation biomass as well as spring and fall throw trap sampling in each delta to establish the condition of habitats, their inhabitants, and the relationship of each to freshwater inflow over time. Having annual end of growing season marsh vegetation biomass data for 5 to 10 years and corresponding juvenile finfish and shellfish data from these areas would be invaluable in teasing out the complexities with antecedent inflow conditions. The authors state that this type of simplified, long-term monitoring data with an emphasis towards documenting and understanding the intermediary link of habitat is essential, in their opinion, to truly test the applicability of multi-tiered, achievement guideline-based freshwater inflow criteria (Anchor QEA, LLC *et al.,* 2015).

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

Yes. An additional year of data of bay hydrology, water quality, and specific indicators including oyster health were collected. Since the culmination of the MBHE effort (which used data through 2007), additional data related to marsh habitat and productivity, and oyster abundance and parasitism, has been collected. The purpose of this study was to compile and collect new data (through the end of 2014) and to update and expand upon the marsh productivity and oyster evaluations that were performed in support of the MBHE. This information was expected to either corroborate the existing inflow standards or suggest new relationships between freshwater inflows and ecosystem response that the BBASC and the TCEQ could use to guide a potential re-evaluation of those standards.

Q3. Did the study evaluate a strategy for achieving environmental flows?

NA. This was not part of the study objectives.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

NA. This was not part of the study objectives.

Q5. Did the study identify additional data or knowledge gaps?

Yes. The study (SN9, Section 6.4) provided suggestions for future efforts that would enhance the BBASC's assessment of freshwater inflow standards for Matagorda and Lavaca Bays. The authors noted that future monitoring should focus on sessile organisms including dermo, oysters, and marsh vegetation. These organisms once established are relatively easy to sample and cannot move as salinity varies. They therefore provide useful indicators for ecosystem health. In addition, some of these species (marsh vegetation and oysters) provide structural habitat for other species (e.g., immature finfish and shellfish in wetlands) and ecosystem services (e.g., reduction of storm wave intensity and protection of shoreline habitats, water filtration, primary production).

The investigators recommended re-establishment of dermo monitoring in Matagorda and Lavaca Bays. Their rationale was that Dermo provides a robust indicator of ecological condition and is strongly influenced by inflows and salinity (high infection rates correlated with elevated salinity and reduced inflows). While previous monitoring information was utilized and considered sufficient to estimate future dermo conditions, the authors concluded that any new data would be helpful as part of a continuing corroboration and validation effort. Future dermo data would also help identify dermo epizootics when they occur.

SN10: Evaluation of freshwater delivery alternatives to East Matagorda Bay

Austin, B., A. Kennedy, T. Osting, and C. Walker. 2015. Evaluation of freshwater delivery alternatives to East Matagorda Bay. Texas Water Development Board Contract No. 1400011759. 49 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1400011759_TSU.pdf)

Study Objectives

Using existing available data and studies, this project investigated methods to augment freshwater inflows into East Matagorda Bay (EMB). The goal was to determine the timing and delivery rate of freshwater to EMB that could have a positive impact on the health and productivity of the estuary. Additionally, this project examined cost-effective engineering solutions for delivering available water from the Colorado River into EMB. The volume of freshwater inflow was investigated to determine the benefit associated with reducing EMB salinity for a certain time period to an assumed desirable salinity target range between 20 ppt and 30 ppt. The volume of freshwater inflow to EMB was also investigated with respect to time periods where that water can be removed from the Colorado River, minimizing impacts to the new Colorado River delta.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

NA. The study did not validate freshwater inflow standards (none exist for East Matagorda Bay, see 30 TAC 298.310(d)). Rather, this was a strategy study to evaluate options for providing additional freshwater to EMB. The study used the science and freshwater inflow standards developed for Matagorda Bay to help identify freshwater volumes that would be beneficial in EMB.

This study combined existing flow data, modeled estimates of flow (including estimates from the TWDB), and estuarine health information (including the MBHE studies, which primarily focused on

Matagorda Bay, not EMB) to identify periods of ecologically stressed conditions, the freshwater volume that might alleviate some of that stress, and practical considerations for getting freshwater to EMB.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

NA. The study did not collect new data or test cause and effect. The study did use the cause (freshwater inflow) and effect (salinity and habitat quality) relationships developed for Matagorda Bay and adapted them for EMB.

Q3. Did the study evaluate a strategy for achieving environmental flows?

Partially. This study evaluated several possible strategies for providing freshwater inflows to EMB.

The Colorado-Lavaca BBEST concluded that EMB is "is overall a sound environment even though it may have changed community composition since it was cut off from the main bay." (Colorado-Lavaca BBEST Report, 2011). Subsequently, the Colorado-Lavaca BBASC "expressed strong concerns about the reductions of freshwater inflows to East Matagorda Bay" (Colorado-Lavaca BBASC Report, 2011). Given these concerns and despite the lack of a formal standard, the Colorado-Lavaca BBASC identified EMB as being a prime candidate for a strategies evaluation to provide more freshwater inflow. Furthermore, 30 TAC § 298.310 (d) states: "strategies to provide additional freshwater inflows to East Matagorda Bay should be pursued." Accordingly, this study is directly relevant to the broader vision of improving freshwater inflows across the system.

The EMB study explicitly evaluated seven scenarios for providing additional freshwater inflows to EMB. All of these methods were based on routing surface water, via pipeline and/or natural channels, to EMB. Also briefly discussed were four alternative strategies.

The seven scenarios evaluated ranged from relatively elaborate (e.g., Scenario #1: piping water from upstream of Bay City to EMB) to simpler (e.g., Scenario #5: connecting the old Colorado River channel to EMB by a breach or pipeline through the narrow intervening marsh). Feasibility-level cost estimates were provided for each scenario. Ultimately, Scenario #4, which envisions piping water from the Colorado River upstream of the GIWW to EMB, was selected as the best balance between cost and salinity reduction. The larger option under Scenario #4 was estimated to have a capital cost of $15.8M (AS Report Table 6; without engineering design, construction oversight, and permitting, which were estimated and should have been included in the final estimated cost) and an annual operations and maintenance cost of $260,000 (SN10 Report Table 7).

The feasibility of implementing Scenario #4 is based on several factors, including legal and regulatory hurdles, cost, and ecological tradeoffs.

In addition to the seven detailed scenarios, the report briefly discussed four alternatives:

1. Augmented flow pathways between GIWW and north side of EMB
2. Southwest Cut
3. Brackish Groundwater

4. Alternative marsh focus areas and freshwater destinations

Despite these uncertainties, the report represents a strong effort to evaluate the most practicable and cost-effective approaches for providing additional freshwater in an area that frequently exhibits high salinity and low mixing with the gulf (and hence the freshwater could provide benefits for a relatively long period of time).

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

Partially. This study relied on existing models, data, and evaluations. This study did repackage this information into a spreadsheet mass balance calculation to estimate the reduction in EMB salinity caused by various inflow volumes. This spreadsheet calculation is only briefly described (page 25, SN10 Report) and consists of two different approaches, one with an arbitrary bay volume of 25% of EMB and no mixing with the rest of the bay, and one with the same volume but including tidal and dispersive mixing. However, the mixing algorithm is not described. Also, it is unclear which model was used in the remainder of the report.

The spreadsheet tool can likely be used in the future to evaluate the impact of other freshwater delivery options on salinity in EMB, assuming it can be provided from the contractor and is reasonably user-friendly. This tool may also be useful in other estuaries, although it appears to be fairly site-specific.

Q5. Did the study identify additional data or knowledge gaps?

Yes. The study describes areas for future study (Section 6.1, SN10 Report)

As background, the BBASC report identified several strategy options for future consideration for EMB, as follows:

1. Conduct study of the needs of EMB, including the feasibility of directing additional flows to the bay.
2. Redirect flood flows from in Brazoria County to EMB
3. Build small channels without boat access to improve circulation in East Matagorda Bay
4. Evaluate reasonableness of pumping groundwater into EMB
5. Build siphons or pipelines under the intracoastal waterway to ensure that local inflows actually reach the bay.
6. Assure that strategies chosen are not impaired by the intracoastal waterway
7. Explore the feasibility and efficacy of using various cuts to increase freshwater inflows to the bay- e.g., St. Mary's Bayou and Caney Creek

The EMB study mentioned and/or partially addressed options 1, 3, 4, 5, and 7.

The BBASC work plan has a component on EMB in task 12, as follows:

Identify methods to lower salinities in East Matagorda Bay without degrading the *environmental condition of the bay.*

This would be a desk-top study to identify techniques to lower salinity in the bay. Meetings with technical experts and stakeholders would be essential. Proposed alternatives may need to be addressed in an environmental impact statement under the National Environmental Protection Act. Additional monitoring or field studies may be identified.

The SN10 study appears to fit this task, although it did not involve an environmental impact statement or monitoring or field studies.

While the SN10 Study does not reflect implementation of a strategy, it does provide grounds for additional study, with the ultimate goal of selecting and implementing a strategy. The following bullets paraphrase the areas for future study identified in the EMB Study and include their relevance to the work plan and, for monitoring, the environmental flows process in general:

1. Perform additional field work and/or analysis to better establish ecological benefits of freshwater inflows to EMB.
    a. Such benefits could help justify the costs to implement any of the strategies considered. However, quantifying such benefits remains elusive, even in a system that is clearly more saline than its natural condition (defined as Matagorda Bay before the prograding delta split the bay in the 1920s and 1930s). Given the relative lack of studies focused on EMB, such work would be beneficial.
2. Refine the hydrodynamic salinity model to better understand inflows and salinity responses.
    a. This task would be helpful to better understand the extent and duration of salinity reductions as a result of supplemental freshwater inflow. However, EMB has relatively limited exchange with other waterbodies (e.g., the Gulf), particularly in the western end. As a result, even without a more precise model, we have confidence that the freshwater would reside in the system for an extended period of time.
3. Evaluate marshes north of the GIWW for possible addition of freshwater.
    a. Relative to providing freshwater to EMB, providing water to these marshes has several potential advantages, including (1) fewer miles and less complicated pipeline or channel conveyance, (2) longer residence time of freshwater in the ecosystem of interest, (3) higher ecological function of marsh, as compared to open bay bottom, and (4) a potentially clearer ecological endpoint (salinity low enough to sustain spartina) with fewer ecological tradeoffs.
    b. Accordingly, a suitable focus for this evaluation would be to determine if lack of freshwater is inhibiting the productivity of the marshes, or if (1) their productivity is already high, relative to similar areas, or (2) their productivity is limited by other factors, such as lack of sediment and/or subsidence. Only if their productivity is limited, and limited by freshwater

inflow, would subsequent strategy evaluations under the environmental flows program be useful.

4. Evaluate modifying the spoil islands along the south side of the GIWW (north side of EMB).
    a. A conversation with USACE would be critical. Any breaches of these islands would likely increase maintenance dredging obligations (and hence USACE costs) and may also increase erosion of the marshes on the north side of the GIWW. As part of the Coastal Texas Study (sometimes referred to as the "Ike Dike"), one of the proposed ecosystem restoration projects is to rebuild an island between the GIWW and EMB (https://coastalstudy.texas.gov/progress/alternatives/index.html). As such, the USACE proposal is counter to the concept of opening up these islands. For these reasons, this option needs careful thought before investing much time or effort.
5. Explore feasibility of pumping brackish groundwater into EMB
    a. This option has several advantages and may be considered elsewhere along the coast. Coordination with other BBASCs is recommended to evaluate its practicality, cost, and ecological benefits.
6. Perform an evaluation with WAM to determine water availability for any selected scenario (e.g., scenario #4).
    a. Given that the time periods when EMB needs freshwater the most likely correspond to time periods with the least legal availability of water, it is imperative that water be demonstrated to be available before investing much further effort in any of the scenarios that contemplate diverting freshwater from the Colorado River.

SN11: Improve simulation of groundwater/surface water interaction in the Groundwater Management Area 12 groundwater availability model

Young, S., T. Jones, and M. Jigmond. 2017. Field studies and updates to the Central Carrizo-Wilcox, Queen City, and Sparta GAM to improve the quantification of surface water-groundwater interaction in the Colorado River Basin. Texas Water Development Board Contract No. 1548301856. 120 pp + Appendices. [Includes Texas Water Development Board Contract No. 1548304853 as Task 6 to this report].
(No weblink found on TWDB website)

Study Objectives

This study is part of efforts to improve the understanding and management of environmental flows for the Colorado and Lavaca River basins and to improve the ability to properly characterize and model surface water-groundwater interaction using the groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers.

Primary objectives of the work include providing a framework for understanding field studies and computer models related to surface water-groundwater interaction; describing the characteristics of the Colorado River and Colorado River Basin; reviewing previous surface water-groundwater studies for the Colorado River; mapping the Colorado River alluvium in Groundwater Management Area 12; revising the model discretization in the vicinity of the Colorado River and its major tributaries in the update of the groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers currently underway; and developing a work plan for field studies designed to quantify surface water-groundwater interaction at specific locations in the Colorado River Basin for use in guiding modeling of groundwater base-flow contribution to streams.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

NA. This was not an objective of the study.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

Partially. The study provided a comprehensive synthesis of available data and previous studies related to the groundwater system of the Colorado River system. This included estimates of the hydraulic conductivity and estimations for the base elevation and thickness of the alluvium. Water quality assessments provided insights on the impacts of reservoir operations and anthropogenic activities. The study also provided a framework for study site locations, sampling methodologies and recommendations for modifications to the existing groundwater availability model for the central portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers. These recommendations are intended to support a better representation of the Colorado River and its tributaries and the areal and vertical extent of the Colorado River alluvium. Although not directly amendable to testing cause and effect relationships between flow and ecological response, the study results and recommendations if implemented will provide important simulation results of the impact of groundwater pumping on surface water flows necessary to assess cause and effect relationships under existing and future water management scenarios.

Q3. Did the study evaluate a strategy for achieving environmental flows?

No. This was not an objective of the study.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

Partially. The study provided updated information and recommendations to improve the groundwater availability model and therefore a better estimate of groundwater-surface water interactions. We note that updating the groundwater availability model will improve the assessment of projected surface water discharges under existing and future scenarios of groundwater pumping.

Q5. Did the study identify additional data or knowledge gaps?

Yes. The primary purpose and results from this study was identification of key physical properties of the Colorado River aquifer systems and identification of study sites and field methods necessary to improve the groundwater availability model.

SN12: An evaluation of the variability of sediment and nutrient loading into Matagorda Bay from the Colorado River

This is a data only study and SN04, SN12, SN20, and SN33 are combined under the discussion in Section A.6 given that they were methodologically the same.

SN13: Validation or refinement of the adopted TCEQ standards for the Colorado and Lavaca rivers

Bonner, T., J. Duke, and Bio-West, Inc. 2017. Instream flows research and validation methodology framework 2016-2017: Colorado and Lavaca Rivers. Texas Water Development Board Contract No. 1600012010. 73 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600012010.pdf)

The instream flow components of SN07, SN08, SN13, SN15, and SN21 are combined under the discussion in Section A.7 given that they were methodologically and analytically combined by the authors across basins.

SN14: Evaluation of rainfall-runoff patterns in the Upper Colorado River Basin

Kennedy Resource Company, R.J. Brandes Consulting, and Crespo Consulting Services, Inc. 2017. Evaluation of rainfall/runoff patterns in the Upper Colorado River Basin. Bonner, T., J. Duke, G. Guillen, Bio-West, Inc. 2017. Instream flows research and validation methodology framework 2016-2017. Texas Water Development Board Contract No. 1600012011. 71 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600012011_Kennedy.pdf)

Study Objectives

The purpose of this study was to explore whether recent flows in the Colorado River basin upstream of the Highland Lakes are in fact substantially lower than what has been observed historically, and if so, determine the likely reasons for the disparity. The project was tailored to make use of existing relevant information readily available from various sources and to assess the overall rainfall-runoff relationships at a limited number of key locations within a large study area in order to better understand the observed streamflow conditions occurring over time and the activities that are, or could be, impacting these flows.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

NA. This was not an objective of this study.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

Partially. Although this was not a primary focus of the study, it did collate data on factors that likely impact the estimation of the naturalized flow regime not previously considered. These factors (see Q5 below) have the potential to impact estimation of both existing and future flow regimes.

Q3. Did the study evaluate a strategy for achieving environmental flows?

No. This was not an objective of this study.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

No. This was not an objective of this study.

Q5. Did the study identify additional data or knowledge gaps?

Yes. The study documented that observed precipitation has remained steady while flows have declined at all sites. The naturalized flows indicated that for a majority of the study sites, declines in flows can be attributed to permitted water use and construction of large upstream reservoirs. However, at some sites, flow depletions were not associated with upstream consumptive water rights while all sites appear to exhibit a decline in the naturalized flows and attributed to unknown factors not accounted for in the naturalization process. The authors note that high water years (2015 – 2016) will likely translate into an increase in the trend of naturalized flow post drought.

The study identified several factors that are not accounted for in the naturalized flow estimates that are suspected of contributing to the declining naturalized flows:

1. The proliferation of noxious brush.
2. The construction of small reservoirs.
3. Groundwater use and aquifer water level declines.
4. Changes in average temperatures and drought conditions.

We believe this study clearly documents that the Colorado River Basin since 1990 has experienced increased extreme wet/dry events and that air temperatures have been steadily increasing over the period of record analyzed. The long-term implications of these four factors on future flow regimes to meet Senate Bill 3 targets and/or ecological responses remain unknown.

A.4 Guadalupe, San Antonio, Mission, and Aransas Rivers

SN15: Instream flows research and validation methodology framework

San Antonio River Authority, T. Bonner, J. Duke and Bio-West, INC. 2015. Instream flows research and validation methodology framework: Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas and San Antonio Bays Basin. Texas Water Development Board Contract No. 1400011709. 153 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1400011709_instream.pdf)

The instream flow components of SN07, SN08, SN13, SN15, and SN21 are combined under the discussion in Section A.7 given that they were methodologically and analytically combined by the authors across basins.

SN16: Guadalupe Bayou flow and inundation study

Carothers, R., B.R. Hodges, and P. Passalacqua. 2015. Guadalupe Bayou flow and inundation study final report. Texas Water Development Board Contract No. 1400011710. 49 pp +

Appendices.
(https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1400011710%20GuadalupeBayou.pdf)

Study Objectives

The report presents the methods and results of the mapping, field work, and modeling of the Guadalupe bayou system. The study considered inundation mapping using topographical analyses to estimate potential flooded area as a function of water surface elevation, hydrodynamic modeling to estimate the flooded areas as a function of flow rate, and field data collections to support a better understanding of the bayou system and validation of the developed models.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

No. This was not an objective of the study.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

Partially. The study collected LiDAR data to refine the bathymetric characteristics of the Guadalupe delta and bay system. These data were used to inform estimates of the area of inundation and different water surface elevations. The study also collected air and water pressure, water temperature, and conductivity at several locations for use in the hydrodynamic model calibration.

Q3. Did the study evaluate a strategy for achieving environmental flows?

No. This was not an objective of the study.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

Partially. The study also developed the GBHM (Guadalupe Bayou Hydrodynamic Model) from the study bathymetry and water surface elevation data. The model can simulate tidal flooding, rainfall, river flooding, and wind driven flow effects. The study primarily focused on development of the underlying computational mesh for the model but did not actually test the model. The initial modeling effort focused on checking flow paths and blockages necessary to evaluate system connectivity. The actual calibration of the hydrodynamic model was beyond the scope of the project. As such, the authors note that in its present form, it is not a predictive tool for evaluating flow dynamics within the bayou system.

Q5. Did the study identify additional data or knowledge gaps?

Yes. The study recommended additional field data on bayou depths where these data were estimated. The model will also need additional data on the relationship between GBRA gate settings (elevations) and resulting impact on flow routing. At present, only full gate open or closed are approximated. If data on gate settings are available, these should be incorporated into the analysis. The study also identified that the initial field data collected still needed to be analyzed, and additional data is necessary for future model development and calibration.

SN17: Rangia clam investigations

Black, B.A., and M. Heaney. 2015. *Rangia* clam investigations. Texas Water Development Board Contract No. 1400011711. 36 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1400011711_SARA.pdf)

Study Objectives

The purpose of the study was to develop a methodology using side-scan sonar to map *Rangia* clam locations and to use growth-increment analysis to identify environment-growth relationships.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

NA. This was not an objective of the study.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

Yes. this study collected new data and developed a statistical approach to test the relationship between flow and ecological response.

Rangia clams were identified as a focal species for San Antonio Bay by the Guadalupe-San Antonio BBEST. As a result, the BBEST's freshwater inflow recommendations were based, in part, on literature describing the positive effects of low salinity on *Rangia* recruitment. This study collected *Rangia*, measured *Rangia* growth, and correlated growth to environmental variables, including salinity, in an attempt to corroborate the understanding of the BBEST.

The study collected *Rangia* in Mission Bay and Guadalupe Bay, which are in the upper reaches of Copano and San Antonio Bays, respectively. These were combined with *Rangia* from Trinity Bay and Sabine Lake to increase sample sizes. *Rangia* were described as uncommon in these systems and relatively few live *Rangia* were collected. Enough *Rangia* were collected to generate tentative conclusions but not definitive ones. Furthermore, the observation that *Rangia* are uncommon, even in parts of the bay where anecdotal evidence suggested they would be most common, may persuade the BBEST and BBASC to reconsider their decision to rely on *Rangia* as a focal species. It should be also noted that TPWD Coastal Monitoring gear (e.g., bag seines, trawls, oyster dredges) exhibits a negative bias towards detection of Rangia, which are faunal soft-bottom species.

In the laboratory, *Rangia* characteristics were measured, including length, width, weight, age, and the width of each year's growth increment. Collectively, these data allowed the authors to identify years of strong recruitment (or not), and years of strong growth (or not). Environmental variables were then evaluated to try to determine factors that may positively contribute to recruitment and growth. While the results cannot be considered conclusive, due to small sample sizes and other confounding factors, the data suggest that "major recruitment events are generally preceded by high discharge events" and "growth chronologies [were] positively correlated to prior fall and winter salinity" (SN17). In summary, low salinities appear to favor recruitment (as expected by the BBEST) but higher salinities appear to favor growth. These results, if corroborated with additional data, could provide a basis for a stronger understanding of the impacts of freshwater inflow (and hence salinity) on *Rangia*.

Q3. Did the study evaluate a strategy for achieving environmental flows?

NA. This was not an objective of the study.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

NA. This was not an objective of the study.

Q5. Did the study identify additional data or knowledge gaps?

Yes. This study identified several data and knowledge gaps, as follows:

- Additional *Rangia* sampling in these systems and other systems, especially near the mouths of rivers, to increase the statistical power of the data and to better understand how environmental conditions affect recruitment and growth
- Examining the potential influence of short-term events (e.g., floods) on *Rangia*
- Expanding the approach to include freshwater mussels
- Sampling *Rangia* in Native American middens
- Expanding tree-ring chronologies to south Texas

In addition, a weakness of the study identified by the authors was the lack of continuous salinity measurements close to, or within, each sampling area. This required the regression to be based on salinity variability at a regional monitoring station instead of absolute salinity values at the site. It also required the use of TXBLEND model outputs to generate salinity values for Mission Lake. While not expressly identified as a data gap by the authors, these weaknesses could be ameliorated by additional long-term monitoring stations.

SN18: Assessing the effects of freshwater inflows and other key drivers on the population dynamics of blue crab and white shrimp using a multivariate time series modeling framework: Phase I

Buskey, E.J., L.P. Scheef, and J. Xue. 2015. Assessing the effects of freshwater inflows and other key drivers on the population dynamics of blue crab and white shrimp using a multivariate time-series modeling framework. Texas Water Development Board Contract No. 1400011712. 92 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1400011712_BlueCrab.pdf)

SN22: Assessing the effects of freshwater inflows and other key drivers on the population dynamics of blue crab and white shrimp using a multivariate time series modeling framework: Phase II

Scheef, L.P., and E.J. Buskey. 2019. Assessing the effects of freshwater inflows and other key drivers of the population dynamics of blue crab and white shrimp using multivariate time-series modeling framework: Phase 2. Texas Water Development Board Contract No.

1600011966. 43 pp + Appendices.
(https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600011966.pdf)

Study Objectives

Phase I: This study provided 1) reviews of studies related to blue crab and white shrimp abundances in the Mission-Aransas and Guadalupe Estuaries, and 2) describes a multivariate autoregressive analysis framework (MAR) of the TPWD Coastal Monitoring Database of species abundance data to assess the effects of freshwater inflow and other potential drivers on local abundances of blue crab and white shrimp in the Mission-Aransas and Guadalupe estuaries.

Phase II: The goal of Phase II was to refine the models developed during Phase I to improve their utility in informing freshwater inflow recommendations. Specifically:

1. Update the datasets used in the original models with 2014-2015 data and rerun the models to verify the previous results.
2. Reformat the datasets from the seasonal divisions used in the original study to reflect the seasonal divisions used in the TCEQ instream flow standards.
3. Generate MAR models using the new seasonal divisions.
4. Attempt to identify whether conditions during particular seasons are more influential on overall focal species abundances.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

No. The study did not validate any environmental flow standards but did provide analyses that can be utilized to inform evaluation of the standards. However, the study does present an analysis of factors which may contribute to abundance of blue crabs and white shrimp, two potential bioindicators. The BBEST considered the inclusion of these species in the development of flow standards for the Guadalupe-San Antonio and Mission-Aransas systems but ultimately decided not to include them in the salinity zonation analysis that they used to develop the freshwater inflow recommendations. The BBEST developed freshwater inflow standards based on the habitat (salinity) needs of eastern oyster and Atlantic *Rangia*.

These target inflow levels were based on analysis of salinity responses in areas within the bay systems where indicator species (oyster and *Rangia*) are most abundant. The BBEST suggested that while freshwater inflow did not appear to drive blue crab abundance, it may be a factor in blue crab growth. Although the BBEST found that there appeared to be a statistical relationship between freshwater inflow and white shrimp, they elected not to include white shrimp in the salinity zonation analysis because of concerns that this abundance-salinity relationship may be a spurious autocorrelation and not a causal one. The BBEST did however consider “overlay” analyses for white shrimp and for blue crab, vis-a-vis the negative impact caused to them from parasites and disease which apparently increase at higher salinities. Although overlay analysis was not used to make or modify the freshwater inflow recommendations, they generally conclude that higher FWI and lower salinities are preferable for these two species.

Similar to the BBEST report, the current work plan study devotes considerable effort (part 1 of the Phase I study) to a literature review of factors influencing abundance of blue crab and white shrimp. Consistent with the BBEST report, the findings from this study are often complex, contradictory, and ultimately inconclusive. There is some evidence to support a correlation between inflows and white shrimp abundance, though questions regarding the physiological relationship remain (white shrimp tolerate a wide range of salinities). Blue crabs also have wide salinity tolerances though there is data showing that abundance declines during periods of very low inflow and high salinity. For both species, there is a recognition that specific life stages may be more sensitive to salinity ranges and other environmental factors. It is also true that environmental factors driving community responses are not well studied or understood. Their location within the bay was also noted as a potential factor. Responses of different sexes is also identified as an important consideration.

Phase II of the study employs a multi-variate autoregressive analysis framework (MAR) of the long-term TPWD Coastal Monitoring Database containing species abundance data to assess the effects of freshwater inflow and other potential drivers on local abundances of blue crab and white shrimp (discussed in more detail below). The top line conclusion of this analysis is that the relationship between freshwater inflow and both blue crab and white shrimp were only seen in models with lags of one to two years, indicating that freshwater inflow may positively influence these populations at longer time scales. The other main finding was that for blue crab the effect of temperature was more important while for white shrimp inflow was a more important driver. The study conclusions seem to indicate that more freshwater inflows are better for white shrimp but does not provide any interpretation of the study results in the context of the standards.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

Yes. While the study did not include any new data (it relied almost exclusively on the TPWD Coastal Monitoring Database), it did apply a new scientific approach for testing the statistical relationship between flow and ecological response based on a multi-variate autoregressive (MAR) analysis.

MAR is a tool for the analysis of systems in which there are many potentially interacting variables that may have lagged, confounding effects. Given the challenges in developing statistical relationships between freshwater inflow and these two species it seems reasonable that a multivariate approach might be useful in accounting for confounding effects and specifically isolating the effects of freshwater inflow on species response. The variables included in the preliminary models for blue crab and white shrimp included predators, commercial catch, water quality parameters and climate variables. While most, if not all of these factors, were referenced in the preceding literature review as potential drivers and it therefore seems reasonable that they be included in these preliminary models, the models did not include some of the more important factors that were identified in the literature review or which most vexed the BBEST in their analysis. These included different responses based on age class and sex, effects on growth, effects on parasitism and diseases and effects related to spatial factors (e.g., open bay versus wetland areas). The literature review also implies that while white shrimp in particular do not seem to have a physiological response to the range of salinity values produced by different freshwater inflow conditions, there was speculation in this report and in the BBEST work that perhaps other factors associated with freshwater inflow and specifically nutrient loads associated with freshwater inflow, may have an impact on biota.

The report includes numerous types of data and various agencies that produce these data, however in the end, the final models relied almost exclusively on data provided through the TPWD CMD with the exception of river discharge data from USGS. In some cases, variables were dropped because they added little to the model predictions, while other data were not included because of gaps in datasets or lack of overlap with the TPWD time series. The TPWD data covers a long period and includes water quality measurements taken contemporaneously with biological collections. There is a version of MAR called Multivariate Autoregressive State-Space Modeling (MARSS) which is designed to handle missing data which could perhaps allow for incorporation of some of the other data, but a more important issue is that the data relating to the issues identified in the literature survey as the most likely confounding factors are not available. The TPWD data set does not identify the sex of individuals collected. While there are total length measurements for a subset of samples collected, there would likely be significant challenges and issues with how this information could be used, and it seems unlikely that the data would be suitable to address questions of nursery use of fresher wetland areas during early life stages. Unlike oysters, for which there is some data on parasites such as dermo and drill, less is known regarding similar data for species of parasites and diseases that impact blue crab. The TPWD CDM does include spatial location data, and the models did initially include spatial segregation (Copano, Aransas, San Antonio, and Espiritu Santo), but these segregations were very coarse, presumably to ensure that there were a sufficient number of samples, but do not address the concerns related to marsh/edge versus open bay habitat use. Finally, nutrient loads were not specifically addressed. To be fair it should be noted that since Longley (1994) set out the Texas state methodology for assessing freshwater inflow needs these nutrient (and sediment) loads have been recognized as potentially important factors. Longley (1994) also identified temporal lag periods in freshwater inflow effect on commercial fisheries species. The original TxEMP models included placeholders for objectives and constraints related to their quantification though they never were incorporated in the calculations. Likewise, the BBEST report included discussion of these loadings. The challenge of understanding their distributions, circulation, and residence times, all changing as functions of changes in loadings from changing treatment processes or upstream impoundments, makes getting a handle on these factors far beyond the scope of this study. It is not clear that the data exists to address the most important knowledge gaps.

The main goal of the Phase II study was to repeat the MAR analysis with the datasets reformatted to reflect the seasonal divisions used in the instream flow standards January-March (winter), April-June (spring), July-September (summer), and October-December (fall). There are two complications with this goal. The first is that while these seasons reflect the seasonal divisions used to define instream flow standards, these divisions do not apply to the analysis used to develop the freshwater inflow standards nor the standards adopted by the TCEQ. Freshwater inflow standards were only adopted for spring (February-May) and summer (June -September). These seasonal divisions were determined specifically based on *Rangia* survival and recruitment in the spring and the threat of oyster parasitism/disease during the summer. While it may be useful for a study to determine whether flows derived for those particular objectives would be valid to protect blue crab and shrimp, given their very different seasonal life cycles it would likely make sense to use either the instream seasons or the oyster/*Rangia* seasons to evaluate crab and shrimp responses.

The second complication with the goal is that given the TPWD schedule, which only collects gill net datasets in the spring and fall, the data was unsuited for these seasonal divisions and therefore the goal was abandoned. Had the authors considered the two seasonal breakdowns which were included in the freshwater inflow recommendations (Spring and Summer) rather than the four used for the instream standards it is conceivable that the gill net data could have been useful in this analysis. We note that the MAR analysis ultimately collapsed into a simple linear regression.

Q3. Did the study evaluate a strategy for achieving environmental flows?

NA. This was not addressed in the study.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

Yes. The study developed a tool to estimate the relationship between seasonal freshwater inflow and the abundance of blue crabs and white shrimp. This tool was used to predict changes in abundance in response to four modeled flow scenarios and this approach could be used to inform stakeholders in their evaluation of proposed flows as a result of the application of the TCEQ standards for future permits.

Q5. Did the study identify additional data or knowledge gaps?

Yes. The study- did recommend alternative formulations of the flow ecology relationships, for example formulating relationship to test the importance of extreme events as opposed to average conditions. The study also suggested potential expanded applications on other species and in other bays or by incorporating size/age class or sex into the model formulation. Finally, while phase II included a limited application of the model results to long term freshwater inflow estimates derived from WAM runs, the authors suggest that alternative simulations could be used to test effect of other water management scenarios.

SN19: Strategy options for meeting attainment frequencies for the estuaries

San Antonio Bay Partnership, Inc., Trungale Engineering and Science, and ASR Systems, LLC. 2015. Strategy options for meeting attainment frequencies for the estuaries. Texas Water Development Board Contract No. 1400011713. 69 pp. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1400011713_SanAntonio.pdf)

Study Objectives

This report presents strategies to increase the frequency at which the targets for freshwater inflow volumes, which have been determined by a panel of experts to be supportive of a sound ecological environment in San Antonio Bay, are met or exceeded. The study includes estimates of the timing and volumes of additional freshwater inflows necessary to meet Strategy Target Frequencies (STF) defined by the Guadalupe-San Antonio-BBASC. STF define the percent of time various freshwater inflow levels should be met or exceeded over a long-term period of record.

The report quantifies freshwater volumes that could be made available to supplement freshwater inflow for San Antonio Bay with the implementation of a strategy based on the dedication of wastewater return flows and unappropriated water, and the use of Aquifer Storage and Recovery (ASR) to allow managed releases timed to achieve specific STF goals. The strategy has been simulated using the Guadalupe-San Antonio WAM and other appropriate tools to demonstrate how it could be implemented and how the benefits in terms of increases in freshwater inflow during critical periods are demonstrated. Planning level cost estimates and implementation plans comparable to those used in Senate Bill 1 (SB1) regional water planning have been prepared. This work was funded by the TWDB and performed on behalf of the Guadalupe-San Antonio BBASC.

The purpose of this effort is to provide information and guidance to the Guadalupe-San Antonio BBASC and TCEQ regarding potential strategies which, if implemented, might increase the seasonal availability of freshwater inflow, and improve the achievement of STF's for San Antonio Bay.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

NA. This study did not validate the adopted instream flow or freshwater inflow standards. Rather, this was a strategy study that evaluated how an ASR system could be implemented to store unappropriated flows and wastewater return flows during wet periods, and to recover this water (i.e., pump it out of the aquifer and into the Guadalupe River) during dry periods, to increase the achievement frequencies of the freshwater inflow standards.

The study evaluated the frequency of attainment of the freshwater inflow standards under a baseline condition, represented by WAM Run 3 (which assumes full utilization of all water rights with no return flows). Under this condition, certain components of the freshwater inflow standards are not met at the frequencies specified in the TCEQ standards. More specifically, the driest periods (representing the lowest inflows) occur more frequently than the target identified in the standards. To reduce the frequency of these driest periods, return flows and unappropriated flows were assumed to be available to recharge into an ASR system during wetter periods, and then pumped out of the ASR system during the driest periods.

The study did not assume dedication of all return flows; rather 54.1% was used for San Antonio Water System wastewater treatment plants (SAWS WWTPs) and 63.2% was used for all other WWTPs (these percentages are characterized by the authors as "somewhat arbitrary", but they are a reasonable assumption for the evaluation). Similarly, the study did not attempt to eliminate all of the driest periods, but rather targeted reducing the frequency of these periods to that identified in the standards.

With these assumptions, if the ASR project outlined in the study were implemented, the attainment frequencies in the standards would be expected to be met.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

NA. The study did not test for cause and effect between flow and ecological response.

Q3. Did the study evaluate a strategy for achieving environmental flows?

Yes. This study focused on a strategy for achieving freshwater inflow standards. More specifically, if the ASR project outlined in the study were implemented, the attainment frequencies in the standards would be expected to be met.

The study provided significant information and guidance on the existing regulatory framework (as of 2015) and identified several significant hindrances to implementation, including the following:

1. The ASR project would likely require the dedication of certain unappropriated flows to the environment. Such dedication is not currently allowed under TCEQ rules, and it is

unclear if an ASR project built to support environmental flows could confidently access water, and ultimately discharge water to the bay, without it.

   a. The most straightforward solution would be for TCEQ rules to allow for new water rights permits to have the environment as an authorized beneficial use.

2. The ASR project, as envisioned, would rely on bank filtration to provide water treatment, which is not allowed under TCEQ rules.
   a. The most straightforward solution would be for TCEQ rules to allow for bank filtration in circumstances such as this project, i.e., where the water will not be used for drinking water.
3. The study would require the dedication of certain wastewater return flows to the environment. Such dedication is not explicitly authorized under TCEQ rules and it is unclear if it would be permitted.
   a. The most straightforward solution would be for TCEQ rules to allow for a bed and banks permit to protect return flows for the environment.
4. To be eligible for state SWIFT funding, a project must be a recommended water management strategy (WMS) in the regional water plan. However, based on TWDB rules, projects that solely support environmental flows are not eligible to be recommended WMSs. Accordingly, SWIFT funding is not a possibility for the strategy evaluated in the study. One possible workaround mentioned by the authors is if an ASR project were proposed for multiple uses, e.g., municipal consumptive use and environmental flows. In this case, it is possible that a portion of the cost could receive SWIFT assistance, although perhaps only the portion dedicated for municipal use.
   a. The most straightforward solution would be for TWDB rules to allow for projects that are designed to benefit the environment to be eligible for SWIFT funding.

The above bullets are based on observations made during the SN19 study (i.e., prior to 2015). Since completion of the SN19 study, the Texas legislature passed bills to clarify rules and promote ASR projects. HB 721 (86th Legislature) provided funding for a study to better understand the suitability of aquifers for ASR. The 86th legislature also passed HB 720, which clarifies that unappropriated water can be appropriated for ASR, provided the water is subsequently pumped out for beneficial use. Providing water for instream use continues to be an authorized beneficial use but issuing a new permit for that purpose likely would be inconsistent with the current language of Section 11.0237 (a) of the Water Code. The distinction is important in the context of converting water from another use under an existing permit to use for flow protection.

Perhaps greater than the regulatory hurdles are the challenges of funding. The authors prepared a cost estimate, including most of the primary cost elements (costs associated with purchasing a water right or return flows were explicitly not included, but may be necessary). Distilled down, the debt service on the capital costs plus annual operation and maintenance costs were estimated at full build-out of the project (ten well clusters) to be $43 million per year. This results in a unit cost of $2.67 per thousand gallons, which would be relatively high for treated water at the tap, much less for untreated water. Based on note 6 of Table 5-1, this project would be expected to recover water and discharge it to the bay six months out of every four years (on average).

The report helpfully provides costs for a single well cluster, which would be approximately one-tenth the cost of all ten well clusters, but (because of losing the economies of scale) would have a higher unit cost ($2.92 per thousand gallons).

Everyone involved in Texas water supply issues understands that there are no easy solutions and there will be no strategies that are both cheap and effective to supplement environmental flows. This study evaluates a technologically and environmentally attractive solution that has significant regulatory and cost hurdles. It is technologically attractive, because ASR is a proven technology (albeit at a modest number of sites in Texas), it requires little land space, and it eliminates losses due to evaporation. It is environmentally attractive, because storage could occur during wet years followed by recovery and discharge to the bay during dry years. However, this project is expensive.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

Partially. The study did not develop a tool to evaluate environmental flow regimes. Rather, this study adapted the Region L WAM to remove return flows (to develop a baseline scenario). Therefore, the study did develop a variant of the WAM that could possibly be used to understand flows under this condition. The study also developed an aquifer water balance model to identify suitable recharge and recovery rates, storage volumes, and operational guidelines.

Q5. Did the study identify additional data or knowledge gaps?

Yes. In addition to the regulatory concerns discussed above, the study also identified additional technical analyses to be performed, including the following:

1. Use TxBLEND, or another hydrodynamic model, to evaluate the salinity reduction caused by the freshwater flows from the ASR system and wastewater return flows. The current study focused on simply reducing the frequency of occurrence of the lowest freshwater inflow category. A hydrodynamic model would predict the impact on salinity of both the recharge phase of ASR operation (which would increase salinity in the bay) and the recovery phase of ASR operation (which would decrease salinity in the bay). The authors note that these impacts on salinity "will be useful in assessing the relative ecological value provided by the supplemental inflows". Like all strategy studies, identifying, and quantifying, the ecological benefit of the strategy is a worthwhile, but challenging, goal.
2. Hydrogeologic testing and pilot studies to better understand pumping rates, volumes, wellfield locations, and water quality. This recommendation is eminently reasonable, as success, not to mention optimization of the project, is far from guaranteed with the current level of information. Helpfully, certain aspects of this data need are costed in Table 5-1. However, even this is expensive: the ASR demonstration testing, and feasibility assessment is estimated at over $30 million.

SN20: An evaluation of the variability of sediment and nutrient loading into San Antonio Bay from the Guadalupe/San Antonio River

This is a data only study and SN04, SN12, SN20, and SN33 are combined under the discussion in Section A.6 given that they were methodologically the same.

SN21: Continuation of instream flows research and validation methodology framework

San Antonio River Authority, T. Bonner, J. Duke, and Bio-West, Inc. 2017. Instream flows research and validation methodology framework 2016-2017. Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays Basin. Texas Water Development Board Contract No. 1600011937. 78 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600011937.pdf)

The instream flow components of SN07, SN08, SN13, SN15, and SN21 are combined under the discussion in Section A.7 given that they were methodologically and analytically combined by the authors across basins.

A.5 Nueces River and Corpus Christi and Baffin Bays

SN23: Re-examination of the 2001 Agreed Order monthly targets and safe yield versus current demand evaluations: Phase I

HDR. 2015. Nueces BBASC Work Plan Study No. 1. Re-examination of the 2001 Agreed Order Monthly Targets and safe yield versus current demand evaluations. Texas Water Development Board Contract No.1400011716. 32 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1400011716_Nueces.pdf)

SN30: Re-examination of the 2001 Agreed Order monthly targets: Phase 2

HDR. 2017. Nueces BBASC Work Plan Study: Re-examination of the 2001 Agreed Order Monthly Targets: Phase 2. Bonner, T., J. Duke, G. Guillen, Bio-West, Inc. 2017. Instream flows research and validation methodology framework 2016-2017. Texas Water Development Board Contract No. 1600012014. 22 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600012014_Nueces_BBASC_Study.pdf)

Study Objectives

Phase I: This research was recommended to examine what modifications to the Agreed Order might be considered for ecological purposes and to quantify the associated impact of any such modifications on the reliable water supply of Corpus Christi and its customers.

The two main goals of the study are:

- Determine if a “shift” has occurred in inflows and what impact this “shift,” if used to modify monthly targets in the Agreed Order, might have on safe yield and freshwater inflow to Nueces Bay (Scope of Work Task 1).
- Compare freshwater inflow to Nueces Bay resulting from a safe yield demand of 192,000 ac-ft/yr to a current demand of 130,000 ac-ft/yr.

Phase II: The Phase II study integrated results from Phase I with input from area stakeholders to identify new alternative scenarios for the Agreed Order on monthly targets for additional evaluation. The primary goals of Phase II are as follows:

- Identify potential alternative monthly target scenarios from stakeholder’s input.
- Evaluate identified scenarios and compare results of system yield and freshwater inflow to Nueces Bay for each scenario.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

NA. This study did not validate the adopted instream flow or freshwater inflow standards. Rather, this study examined recent hydrology to identify a possible shift in seasonal inflow patterns and to evaluate the impacts of alternative monthly targets in the Agreed Order on system yield and freshwater inflows.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

NA. This study did not collect new data or develop an approach for testing flow and ecological responses. The Phase 1 study did perform a new evaluation of hydrologic data, focusing on seasonal patterns. The data were suggestive of some shifts, e.g., a decrease in inflows in April, May, June, August, and December (Table 4-1 and associated text). However, the authors recognize that these shifts may be a random effect of the relatively short period of recent data. Ultimately, the authors conclude: *"this evaluation did not show statistically significant shifts that could be incorporated into a new set of recommended monthly pass-through targets."*

The Phase 2 study had a more focused scope, in that it solely evaluated the effects of variations in monthly inflow targets on firm yield and freshwater inflows.

Overall, the authors observe that the system *"is driven more by the inflows into the reservoir system than by the actual monthly inflow targets."* As a result, the simulated changes to the inflow targets have a modest impact on both firm yield and median annual inflows. Subsequently, the authors note:

> *The results of this study indicate that there could be opportunities to adaptively manage the system in such a way to provide flow when it is potentially more critically needed, but without data indicating a high likelihood of desirable biological response to the modified flows, a pilot study would be based on an incomplete hypothesis lacking an expected outcome…. It seems premature to make a recommendation for a specific modification to the monthly Agreed Order targets for a pilot study without a linkage to indicate how these modifications correlate to a biological response.*

This suggests that an updated understanding of the linkage between monthly inflows and ecological health could be used to guide changes to the target inflows in the Agreed Order, potentially without adversely affecting firm yield.

Q3. Did the study evaluate a strategy for achieving environmental flows?

Partially. The study evaluated a strategy for achieving environmental flows in part. The study focused on simulating variations in monthly inflow targets. These variations are relative to the targets in the Agreed Order. They are not related to the environmental flow standards. The model results provided include summary statistics and frequency plots of annual and monthly inflows. The study did not attempt to compare these modeled inflows to the standards.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

NA. The study did not develop a tool for evaluating environmental flow regimes.

Q5. Did the study identify additional data or knowledge gaps?

Yes. The Phase 2 report has a few suggestions for future work, including the following:

- Combine the model-predicted inflows with harvest-inflow equations developed for the Nueces Estuary to estimate impacts to the ecosystem. This could include updating the harvest-inflow equations with TPWD Coastal Monitoring Database.
- Updating the model to accommodate the potential release of stored water during drought. Such releases are not part of the Agreed Order but could potentially provide ecological benefits and modeling would be needed to understand what impact such releases may have on firm yield.

The Phase 1 and Phase 2 studies are responsive to the fourth priority of the BBASC work plan ("Re-examination of the 2001 Agreed Order monthly targets"). Combined, these studies have evaluated a number of alternative inflow target patterns. In general, different patterns have only a modest impact on firm yield and median annual freshwater inflows. Monthly inflow patterns do change appreciably. As discussed in the Phase 2 report, a reasonable next step would be to understand if the different monthly patterns have a beneficial impact on the ecosystem.

SN24: Using landform and hydraulic modifications to increase the benefit of freshwater inflows to Nueces Bay and Nueces Delta: Phase I

Dodson, J., K. Dunton, E. Hill, B. Hodges, G. Jackson, B. Nicolau, M.K. Skoruppa, D. Sullivan, K. Thompson, and G. Ward. 2016. Using landform and hydraulic modifications to increase the benefit of freshwater inflows to Nueces Bay and Nueces Delta. Texas Water Development Board Contract No. 1400011717. 79 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600012013_hanson_Final.pdf)

SN29: Using landform and hydraulic modifications to increase the benefit of freshwater inflows to Nueces Bay and Nueces Delta: Phase II: Verification and feasibility assessment for landform modifications in the Nueces Delta

Dodson, J., G. Jackson, C. Koester, M. Ellen, K. Thompson, H. McNeil, B. Hodges, C. Jalbert, and A. Gilmer. 2017. Using landform and hydraulic modifications to increase the benefit of freshwater inflows to Nueces Bay and Nueces Delta – Phase II: Verification and feasibility assessment for landform modifications in the Nueces Delta. Bonner, T., J. Duke, G. Guillen, Bio-West, Inc. 2017. Instream flows research and validation methodology framework 2016-2017. Texas Water Development Board Contract No. 1600012013. 81 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600012013_hanson_Final.pdf)

Study Objectives

Phase I: This study explored the potential for providing minimum flows of freshwater to portions the

Nueces Marsh to ameliorate hypersaline conditions. Various options included construction of water control structures and hydraulic modifications, use or reuse of treated wastewater, and changes in pass-through events (see Nueces BBASC "Work Plan for Adaptive Management" [Nueces BBASC, 2012]). The study also summarizes an evaluation of several strategies, recommended by the Nueces BBASC (2012), involving the potential use of hydraulic and landform modifications within the Nueces Delta/Bay system to increase the benefit of the often limited quantities of freshwater inflows by redirecting and delivering those flows into areas of the Nueces Delta where they would help to restore some level of pre-development ecosystem function.

Phase II: The Phase II study extended to evaluation of specific issues and recommendations from the Phase I study, which included: 1) determining how to provide legal and physical access to the proposed diversion channel project sites, 2) collecting data and information to be used to satisfy requirements of future permitting and regulatory efforts, 3) collecting elevation data to help validate the NDHM modeling conducted in Phase I, and 4) developing recommendations for construction techniques applicable to wetland areas.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

No. Strictly speaking the study did not directly address the flow standards. Rather the study proposes a strategy alternative to achieve some of the identified ecological goals, which were part of the basis upon which the freshwater inflow standards were developed. The adopted freshwater inflow standards for the Nueces Estuary were based on recommendations by the BBEST which determined salinities needed to maintain a sound ecological environment based on seasonally distributed inflow volumes from the Nueces River estimated to achieve these salinities at a specific location within the Nueces Bay. The BBEST also recommended an annual overbanking event each year at Calallen Dam. However, the BBASC and ultimately TCEQ, while recognizing the ecological importance of overbank events, declined to include this overbank flow recommendation citing "loss of property and access for individuals inhabiting this stretch of river and should not be recommended as part of a standard or a permit requirement."

The Nueces BBEST concluded that "that all rivers, streams, and bays were sound ecological environments, except the Nueces Bay and Delta, which were determined to be unsound ecological environments." (BBEST, 2011). The BBEST made this determination based on their conclusion that:

> *. . . the substantial alterations in freshwater reaching the bay and delta which have led to a failure to sustain a healthy complement of native species and its associated beneficial physical processes . . . (and that) a modification of flow regime will be required to rebuild these species and processes to sound levels.* (Ibid.)

The flows identified to maintain a sound ecological environment are many times greater than current inflow conditions, due to upstream flow by the two large upstream reservoirs upstream. While the study does not address the adopted flow standards and therefore does not validate them, it does address the most critical issue relating to the health of the estuary by focusing on restoring the ecological health of the Nueces Delta upstream of Nueces Bay. The study reinforces this finding through "Expert Judgment" and an extensive review of the studies and strategies that have been undertaken since the 1980's to provide more water into the delta via Rincon Bayou.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

Partially: These studies collected data but did not test the cause and effect relationship between flow and ecological responses. Phase I was a desktop, primarily GIS/Google Earth, analysis which employed a salinity circulation model NDHM (see Modeling salinity fluxes in the Nueces delta - TWDB#1400011719). The overall approach basically assembled existing data, primarily developed over the last few decades to route water through Rincon Bayou into the Nueces delta, and then to solicit the input of experts as to the most promising alternatives that would maximize wetland areas with suitable inundation and salinity conditions.

The ecological analysis was consistent with the BBEST flow recommendation report and concluded that salinities below 25 ppt would benefit *S. alterniflora* and included a sufficient level of detail of standard and accepted statistical approaches to demonstrate this relationship and also explain the importance of this indicator species. The final selection of three strategies appears to have relied on practical considerations rather than the result of a formal, data driven methodology. The experts concluded that these three selected alternatives are expected to increase the area within the delta with desirable habitat conditions

The Phase II study included additional desktop analyses and field data collection efforts useful for validation of the hydrodynamic model, however we could not find this specific analysis in the report. The site visits did lead to the decision to drop one of the strategies (Project 5) from further considerations due primarily to challenges with site access and impacts from disposal of dredged materials.

Q3. Did the study evaluate a strategy for achieving environmental flows?

Partially: The Phase I study considered nine strategies that either created channels to connect wetland areas, including bladder dams to control these connections, or direct wastewater return flows into specific areas within the Nueces Delta. The study recommended further analysis of two landform modifications and one direct (wastewater return flow) hydrologic augmentation project. The two landform modification proposals do not include additional freshwater to the Nueces Delta but do propose rerouting flow paths within the Delta to move existing freshwater to additional locations. The study provides a thorough and comprehensive review of the implementation challenges such as infrastructure needs and cost as well as the regulatory framework that will need to be navigated in order to develop these alternative strategies to provide freshwater to a system that is currently unsound as a result of being deprived of these inflows. The study provides detailed discussions of the various permitting requirements from federal, state, and local entities including discussion of contingencies if preferred approaches are unavailable. The grant and funding section contains cost estimates that follow the framework established through the SB1 regional planning process including breakdowns of capital cost, annual debt service, and O&M costs that will be familiar to stakeholders with experience in the SB1 regional planning process.

In Phase II of the study, permitting, regulatory and cost evaluations were further refined. Numerous permitting issues including construction and flood control permitting and best management practices are discussed in some detail. The Phase 2 study provided updated detailed cost estimates for each project evaluated arising from challenges relating to access and disposal and ultimately retained two projects for further consideration.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

No. The primary tool applied in this study, the NDHM salinity circulation model was developed as part of another Senate Bill 3 work plan study (Modeling salinity fluxes in the Nueces delta - TWDB#1400011719) and is discussed in further detail in the review of that study.

Consistent with our synthesis review that Senate Bill 3 monitoring and validation efforts should focus on upper bay and estuary systems, these studies focus on a more limited geographic scope, i.e., the delta as opposed to the entire Nueces Estuary. Previous studies relied on TxBLEND for modeling which focuses on larger geographic scopes (full estuaries), and course timesteps (months as opposed to days). This study, and several others (Trinity and San Antonio) have begun to focus on more limited areas (deltas) at finer time steps (days). This shift in spatial and temporal focus acknowledges that the extent of freshwater inflows specific to the Senate Bill 3 adopted standards have limited geographic scope in these bay systems.

We believe this is a germane consideration given the uncertainty of freshwater inflow responses in the delta versus potential benefits to the whole bay (see comments for SN26). We are not necessarily advocating to ignore the full estuary and note that TxBLEND, does an acceptable job of reproducing observed salinities at course geographic and temporal scales but is not able to predict changes at the finer geographic or temporal scales (i.e., delta specific) that we can expect water management decisions to impact. This issue is somewhat addressed in the report:

> *Finally, the salinity transport analysis of the NDHM results by Li and Hodges (2015) showed that the model representation of narrow channels allows excessively high flow rates, which could result in overestimate of freshwater transport into the lower estuary. This effect appears to be caused by the coarser model grid (30 x 30 m) used in the present NDHM, compared to the finer grid (15 x 15 m) used in the earlier version (Ryan and Hodges, 2011). Unfortunately, the coarser grid is necessary to keep the model computational costs low enough to be able to run simulations 15 times faster than real time (e.g. 1 month simulated in 2 days of computer time).*

Q5. Did the study identify additional data or knowledge gaps?

Partially: The Phase I study was primarily a screening study which did not include field studies or generate any new, site-specific information; however, Phase II of the study was primarily a data mining effort from existing sources with a few notable exceptions. This data included LiDAR, USGS topography, USDA soils, FEMA, RRC oil, gas, and railway locations, historic aerial imagery, NWI EMST, and EFH. Desktop reviews included an analysis of federal and state-listed threatened and endangered species that could potentially occur at the project site and a consideration for Birds of Conservation Concern, the MBTA, and nesting birds. A desktop level archeological evaluation was also performed. This study also included site visits to perform wetland delineations, assess habitats to determine potential for threatened and endangered species and evaluate site access. The report also states that data was collected to support validation of the hydrodynamic model, although a validation analysis does not appear in the report.

SN25: Nueces watershed pre- and post-development nutrient budgets

HDR. 2015. Nueces BBASC Work Plan Study No. 3. Nueces watershed pre- and post-development nutrient budgets. Texas Water Development Board Contract No. 1400011718. 159 pp. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1400011718_Nueces.pdf)

Study Objectives

This report relies on data and modeling to provide an approximate average nutrient budget in Nueces Bay during the pre-development and post-development periods. In this study, pre- and post-development refer to the periods before and after the filling of the Choke Canyon Dam reservoir in 1986.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

NA. This was not an objective of the study.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

Partially. New nutrient data was not collected for this study, but the study did synthesize data from a number of disparate sources to provide important insights into the effects of inflows on nutrient loading. The nutrient data for the pre and post development nutrient budgets for Nueces Watershed were collected from a variety of existing data sources, and included water quality (nutrients, chlorophyll a), streamflow, land use, and wastewater treatment plant data. Annual nutrient loadings were calculated for four locations, including the Atascosa River, Whitsett and three locations on the upper, middle, and lower Nueces River Basin (Laguna, Three Rivers, Mathis). Annual nutrient loadings were calculated for wet, dry, and average years before and after the construction and filling of Choke Canyon Reservoir in 1986. Their analysis showed that total phosphorous (TP) and total nitrogen (TN) decreased at Three Rivers after 1986 (post development) while the TP at Mathis showed an increase post-development, while TN decreased in average and wet years, but increased in dry years. Not surprisingly, the study found that nutrient loadings were lower in the upstream, undeveloped portions of the watershed compared to downstream, more developed areas. Changes were found in nutrient loadings from Three Rivers to Mathis with nitrogen loads greater at Three Rivers than at Mathis. This could be due to nutrient enrichment at Three Rivers and/or nutrient uptake between Three Rivers and Mathis, which would most likely be due to uptake and/or transformations within Lake Corpus Christi. The possible role of reservoirs and other impoundments as nitrogen sinks should be considered when evaluating the effects of freshwater inflows on ecosystem productivity and function. Nutrient fate and transport in the watershed are essential to understand biological productivity in estuaries. However, this study did not address the relationship between freshwater inflows, nutrient loadings and ecosystem health or species abundance. That connection needs to be evaluated in future studies.

Q3. Did the study evaluate a strategy for achieving environmental flows?

NA. This was not an objective of this study.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

Partially. This study developed a method for estimating nutrient loading to the Nueces Estuary which incorporated several different potential sources of nutrients to a watershed. This method could be applied to other estuaries, and the study made recommendations for future research to improve and refine estimates of nutrient loading. However, the study did not extend this effort to address the effects of higher or lower nutrient loadings on ecosystem function or productivity. Accurate estimates of nutrient loading to estuaries are an important component of any effort to understand the relationships between freshwater inflows and estuarine productivity and ecosystem function. These methods could be integrated into future research and models to evaluate environmental flow regimes and their effect on estuarine ecology.

Q5. Did the study identify additional data or knowledge gaps?

Yes. In terms of data gaps, it is clear that long term data collected on watershed nutrients would be improved if the data were collected and analyzed using standard procedures and quality controls, at the appropriate spatial and temporal scales, and include all organic and inorganic sources of nutrients. From the perspective of understanding estuarine ecology, sampling throughout the watershed may not be necessary but could be limited to a location near the major river input of freshwater where flow rates and nutrient concentrations could be monitored. New in situ nitrate sensors are being developed and improved that could provide automated measurements of this important nutrient on a more frequent basis to understand how nutrient concentrations change over pulses of freshwater inflows.

In terms of knowledge gaps, the report pointed out that there is a need to better understand the role of reservoirs, such as Lake Corpus Christi and Choke Canyon as sources and sinks of nutrients in watersheds. There is also a need to quantify the effects of reservoirs on sediment transport, which, for example, is important to an understanding of phosphorous transport, which is readily adsorbed to sediment particles. Filling these and other data gaps would provide the data for more accurate modeling of nutrient loads in watersheds, which can then be related to ecological responses.

SN26: Modeling salinity fluxes in the Nueces delta

LI, Z., and B.R. Hodges. 2015. Modeling salinity fluxes in the Nueces Delta. Texas Water Development Board Contract No. 1400011719. 49 pp. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1400011719_Nueces%20Delta.pdf)

Study Objectives

This report documents the work to improve and extend the Nueces Delta Hydrodynamic Model (NDHM). The project goals were (i) model calibration and validation, (ii) analysis of freshwater pumping, and (iii) extending the model to include Nueces Bay. The project further attempted to extend the Nueces Delta model to include all of Nueces Bay.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

NA. This was not an objective of the study.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

Partially. Although this study did not collect new data, it used new data collected by the TWDB for validating the existing NDHM model. Model validation took the form of a qualitative review of time series plots comparing model output and observations at 14 sites within the Nueces Delta which monitor elevation and salinity. When model results diverged from observed data, three primary reasons were given:

1. Lack of simulation of pore water and evaporation in the model,
2. Coarsening of the model grid, which especially affects narrow channels, and
3. To lesser extent, not accounting for Rincon bayou gate opening and closing.

Q3. Did the study evaluate a strategy for achieving environmental flows?

Partially. The evaluation of strategies related to achieving environmental flows was the primary focus of another Nueces work plan study "Using Landform and Hydraulic Modifications to Increase the Benefit of Fresh Water Inflows to Nueces Delta and Nueces Bay – phases I and II." The NDHM model was used in these other work plan studies to evaluate strategies. Within SN26, there is a strategies evaluation discussion which is focused on a single metric: inundation effectiveness. Inundation effectiveness reports the ratio of area inundated to the amount of water provided under different pumping assumptions. The study recognizes that a finer scale, more ecologically relevant metric, would be more appropriate and specifically recommend that the BBASC provide a target inundation. We are uncertain if the recommendation would be inclusive of depth, duration, acreage, or all of these metrics. Ultimately, the landforms studies, which considered the results of the NDHM, selected strategies based on more practical considerations than quantitative model results.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

Yes. The study developed a hydrodynamic and salinity transport model to evaluate the effects of freshwater input on the Nueces Delta. The study explained the process of developing and testing an estuarine circulation model, specifically the relative importance of errors introduced when estimating the initial conditions for elevation, velocity, and salinity. Selection of initial conditions for salinity has a very significant effect, velocity very little, and elevation intermediate.

The study provides a valuable explanation for why it is not always preferable to calibrate a model to match observations. In this case, when errors are likely the result of processes that are either not included in the model (evaporation and pore water exchange), or not related to the calibration parameter being adjusted, or is disconnected from the response (e.g., calibrating bottom surface roughness coefficient when wind drag is the source of the error). Hopefully, future work will be able to develop an approach that can correct for the effect of channel widening that occurs as result of the coarsening of the model grid.

As noted above, the study did not provide a quantitative analysis of model performance that might have provided better justification than the qualitative comparisons used to support validation of the model. Ultimately, the question of "*Does the model perform well enough in the right places (areas where inundation is most sensitive to flow changes) and at the right times (when flow changes can impact inundation and salinity)?*" is difficult for the reader to answer. To the answer this question, ask if the error/uncertainty within the model is less than the change in response due to flow modification. At this time, it appears that the reported error in the model appears to be greater than the effect of putting more water into Rincon Bayou. This outcome makes the model difficult to apply for decision-making.

A reasonable path forward would seem to require addressing the following questions:

1. How can the NDHM be used to inform BBASC deliberations regarding environmental flow standards?
2. What output(s) from the NDHM is most relevant to the BBASC?
3. Is the relevant output(s) accurately enough predicted for the BBASC to use?
    a. If not, what improvements to the NDHM are necessary to make it suitable for use by the BBASC?

Once these questions are answered, a clear path forward for improving the model (if necessary) can be developed.

Q5. Did the study identify additional data or knowledge gaps?

Yes. The study recommends additional work to improve the delta model performance:

1. Deriving a relationship between channel widening and roughness that can be used for slowing the flows in channels that are physically narrower than the model grid resolution, and
2. Developing sub-models for evaporation and porewater salinity release that can be used to improve the model validation results.
3. As a minor point, the operation of the gate at the channel between the upper end of the Rincon Bayou and the main stem of the Nueces River needs to be included in the model.

We believe that these seem wholly appropriate and are high priorities to reduce uncertainty associated with the proposed strategies for restoring the delta.

In addition to calibration, validation, and application of the NDHM (Nueces Delta Hydrodynamic Model), the study also proposed to expand the model to include Nueces Bay. The study failed to achieve this objective due to the increased computing demands of a larger model. The authors recommend several approaches to resolve these issues. However, before moving forward with these recommendations, it is important to reconsider what benefits might be gained from extending the model from the delta to the bay. Is the purpose to model salinity in the bay for ecological purposes, or simply to develop more accurate boundary conditions for the delta portion of the grid? If the former, then there needs to be a consensus on how salinities in the bay might affect the ecosystem and inform environmental flow standards. If the latter, then there needs to be a clear articulation of how the NDHM model would be notably improved by expanding the model grid.

The Nueces BBEST focused its ecological analysis on the delta while the adopted flow standards address flows into the bay, downstream of the delta. A common theme for Nueces work plan studies has been resolving the spatial disconnect between a set of standards aimed at meeting bay salinity targets and the adjacent (and upstream) location most in need of the ecological benefits of these inflows (i.e., delta). Perhaps a single delta/bay model could help resolve this disconnect. However, before expending resources to achieve this goal, it might make more sense to continue focusing on the delta. Meaningful changes to bay inflows, may require significant release from upstream storage and it is not clear that ecological benefits have been demonstrated.

SN27: Nueces Bay circulation assessment project

This study was not provided for review.

SN28: Identify vegetation/marsh changes occurring in the Rincon Bayou Delta and the relationship of those changes to freshwater inflow

Dunton, K.H., T. Whiteaker, and M.K. Rasser. 2019. Patterns in the emergent vegetation of the Rincon Bayou Delta, 2005-2016. Texas Water Development Board Contract No. 1600011971. 44 pp. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600011971.pdf)

Study Objectives

This study assessed the percent cover and species composition of emergent vascular vegetation in the Rincon Bayou Delta (Nueces Delta) to establish a baseline for long-term assessment of this unique ecosystem. This work was initiated in part, to evaluate the combined effects of higher salinities from reduced water inflows and sediment delivery to the Delta, relative sea level rise, and increased erosion from wave action on the delta.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

NA. The study did not attempt to validate the adopted instream flow or freshwater inflow standards. Rather, this study focused on vegetation changes in the Rincon Delta.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

Yes. This study collected new data but did not develop a scientific approach for testing flow and ecological response.

The study collected aerial imagery of the Rincon Delta in November 2016. These data were then combined with existing ancillary data, including vegetation texture, a modified soil vegetation index, distance from water, and a LiDAR-based digital elevation model. Collectively, these data were then computationally related to manual, on-the-ground, measurements of vegetation species and ground cover. Once trained, the algorithm was able to predict vegetation species and ground cover throughout the project area. This approach closely matched a similar effort that was previously performed on a set of aerial imagery collected in 2005.

Vegetative communities are known to shift based on salinity, inundation frequency, and other conditions. Accordingly, reductions in freshwater inflows that lead to higher salinity may cause a change in vegetation communities (e.g., percent cover and species composition) that can be quantified using high resolution aerial imagery. This study compared vegetation communities from 2005 and 2016 and concluded that "long-term shifts in vegetative patterns are not evident in our data that indicate a clear trajectory of ecosystem change." However, while the 2005 and 2016 data evinced only modest shifts in vegetation assemblages, manual measurements collected at selected sites since 1997 do show interannual shifts in vegetation due to short term wet and dry periods (Figure 20, SN20). As a result, the study shows that:

1. Wet and dry periods cause shifts in the vegetative community.
2. No long-term shift from 2005 to 2016 was evident.
3. Repeating this study on a decadal frequency may be useful in identifying future long-term shifts in the system.

The study described, qualitatively, how changes in freshwater inflows lead to relatively predictable changes in community composition (pages 39 to 40, SN20). Such changes would seemingly be amenable to quantification and perhaps incorporation into freshwater inflow standards. While this was beyond the scope of the study, it is an option for the BBASC to consider in the future.

Q3. Did the study evaluate a strategy for achieving environmental flows?

NA. This was not an objective of the study.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

No. The study did not develop a tool for evaluating environmental flow regimes. However, the study further established a consistent method for acquiring and processing aerial imagery to quantify changes in vegetative communities. These results cannot currently be used to explore the impacts of changes in environmental flow regimes, in large part because the 2005 to 2016 datasets did not indicate substantial changes. However, if future inflows undergo long-term, directional shifts, similar data may help to understand the impacts on vegetation. Conceivably, a functional relationship could be developed between freshwater inflows (and/or salinity) and vegetative communities. Ultimately, if combined with goals for vegetative communities, this could lead to a mechanism for evaluating environmental flow regimes.

Q5. Did the study identify additional data or knowledge gaps?

No. The study did not expressly identify data or knowledge gaps. The study did recommend repeating this effort on a decadal frequency, so that future trends in vegetation can be quantified. From an environmental flows adaptive management perspective, such monitoring would only provide value if it could be related back to freshwater inflows. This would require (1) a sustained shift in freshwater inflows enough to produce a quantifiable shift in the vegetative community, (2) an analysis approach that quantifies the linkage between inflows and community, and (3) vegetative community goals set by the BBASC (e.g., desired abundance ranges for each of the key species).

Once the goals are determined, the linkage to inflows could be used to inform possible revisions to the freshwater inflow standards.

The authors indicated that it is difficult to spectrally separate some plant species and some substrate categories. This suggests that some improvements, e.g., in imaging technology or the use of additional ancillary data, would be helpful.

SN29: Using landform and hydraulic modifications to increase the benefit of freshwater inflows to Nueces Bay and Nueces Delta: Phase II: Verification and feasibility assessment for landform modifications in the Nueces Delta

Dodson, J., G. Jackson, C. Koester, M. Ellen, K. Thompson, H. McNeil, B. Hodges, C. Jalbert, and A. Gilmer. 2017. Using landform and hydraulic modifications to increase the benefit of freshwater inflows to Nueces Bay and Nueces Delta – Phase II: Verification and feasibility assessment for landform modifications in the Nueces Delta. Bonner, T., J. Duke, G. Guillen, Bio-West, Inc. 2017. Instream flows research and validation methodology framework 2016-2017. Texas Water Development Board Contract No. 1600012013. 81 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600012013_hanson_Final.pdf)

This is discussed under SN24 above as it was a continuation of that study.

SN30: Re-examination of the 2001 Agreed Order monthly targets: Phase 2

HDR. 2017. Nueces BBASC Work Plan Study: Re-examination of the 2001 Agreed Order Monthly Targets: Phase 2. Bonner, T., J. Duke, G. Guillen, Bio-West, Inc. 2017. Instream flows research and validation methodology framework 2016-2017. Texas Water Development Board Contract No. 1600012014. 22 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600012014_Nueces_BBASC_Study.pdf)

This is discussed under SN23 above as it was a continuation of that study.

SN31: Nutrient Budget for Nueces Bay

Anchor QEA, LLC. 2017. Nutrient budget for Nueces Bay. Bonner, T., J. Duke, G. Guillen, Bio-West, Inc. 2017. Instream flows research and validation methodology framework 2016-2017. Texas Water Development Board Contract No. 1600012015. 47 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600012015_anchor.pdf)

Study Objectives

This report describes the development of a nutrient budget for nitrogen, which was determined to be the limiting nutrient, and includes quantitative estimates of loadings to Nueces Bay under average conditions during historical (i.e., pre-development) and present conditions (i.e., post-development) based on available data, model output, and literature. Budget components evaluated include local watershed inputs, groundwater inputs, municipal and industrial point source discharges, tidal exchanges, wet deposition, dry deposition, burial, and biochemical reactions such as denitrification. For each budget component, estimated changes in total nitrogen from pre- to post-development conditions are highlighted and discussed where possible.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

NA. While the study did not validate the adopted freshwater inflow standards, it did reconfirm that nutrient loading into Nueces Delta and Bay has declined significantly.

The Nueces BBEST spent considerable effort to explain the importance of nutrient loading on the ecological health of this system and declared this to be an unsound ecological environment (Nueces BBEST Environmental Flow Regime Recommendations Report, 2011) and one of the only areas in Texas to be designated as such by a BBEST. The BBEST specifically identified that a reduction in inflows have compromised nutrient elemental cycling which has led to a system that was once productive that is now barren. The BBEST not only identified the problem and its cause, but they also made specific flow recommendations intended to restore the system. The recommendation was to increase the frequency of attainment of specified flows. In order to support nutrient loading, and other ecological responses, the BBEST recommended "one overbanking event each year with a peak flow of 3,600 cfs measured at the USGS streamflow gaging station at Calallen Dam with a central tendency volume of 39,000 acft" (Nueces BBEST Environmental Flow Regime Recommendations Report, 2011).

The study largely confirmed (with significant concerns regarding uncertainties associated with the available data) the BBEST conclusion that nutrient loading into Nueces Bay has been reduced. The study also concluded that a significant part of the deficiency in nutrient loading is likely the result of decreased inflows while the other significant factor is the reduced concentrations of nitrogen in the water entering the bay (an issue which is outside the influence of the environmental flow standards).

Although the study did not address the specific flow magnitudes and volumes recommended by the BBEST, the study acknowledges the more general, theoretical basis in support of restoring a natural, historical condition. However, there may be merit in determining whether the values that the BBEST recommended are sufficient and appropriate to the goal.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

No. The study does not include any new data; it relied on analysis of existing data to perform nutrient balance calculations.

Q3. Did the study evaluate a strategy for achieving environmental flows?

NA. This was not an objective for this study. However, the study acknowledges that since the Nueces Delta is limited in nitrogen, a strategy for diverting wastewater treatment plant effluents toward the Nueces Delta may be considered in order to alleviate the problem.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

Partially. The study applies a standard approach for determining the mass balance of nutrients, specifically nitrogen for the Nueces Delta and Bay system. Given the lack of pre-development data for a number of the components, there is significant uncertainty associated with most of the estimates. However, the framework of the study could likely be applied to other estuarine systems on the Texas coast.

Q5. Did the study identify additional data or knowledge gaps?

Yes. The study identified significant data gaps related to the lack of pre-development data which have led to significant uncertainties related to most of the components of the nitrogen budget for the pre-development, productive system. The study suggests consideration of investigation of paleo-ecological reconstruction for assessing pre-development conditions.

The study reconfirms that nitrogen is the limiting nutrient and that the relationship between freshwater inflow and nitrogen loading as well as the relationship between nitrogen availability and productivity are not quantified. As a result, the authors caution against using this study to recommend increasing freshwater inflow standards. This suggests that additional studies to quantify these relationships should be conducted before the BBACS considers how to change the freshwater inflow standards.

SN32 Alternative methods to add freshwater to the Nueces Delta

Buzan, D., and E. To. 2017. Alternative methods to add freshwater to the Nueces Delta. Bonner, T., J. Duke, G. Guillen, Bio-West, Inc. 2017. Instream flows research and validation methodology framework 2016-2017. Texas Water Development Board Contract No. 1600012016. 67 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600012016_F&N.pdf)

Study Objectives

The objective of this study was to identify ways to add more water to the Delta to protect and enhance its ecological condition. This report identified potential alternatives, some of which have been evaluated in water plans for Region N and provides stakeholders a general idea of factors involved in implementing these alternatives.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

NA. This was not an objective of the study. Rather, this study focused on strategies to increase freshwater inflows to Nueces Delta.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

NA. The study did not collect new data or develop a scientific approach for testing cause and effect relationships. The study summarized information on the ecological effects of adding water to the Delta (SN32, Section 5), noting that maintaining salinities in the Delta below 25 ppt are "important to its ecological health," in part to maintain *Spartina alterniflora* marsh habitat.

Separately, the Nueces BBASC supported a hydrodynamic and salinity model of the Nueces Delta (Li and Hodges 2015). However, this model had significant limitations, resulting in a poor calibration and validation. Buzan and To (2017) did not present any use of the Li and Hodges model or any other estimation of the effects on salinity of the freshwater alternatives examined. Accordingly, there is no quantification of the spatial area, duration, or magnitude of reduced salinity associated with any of the freshwater alternatives.

Q3. Did the study evaluate a strategy for achieving environmental flows?

Partially. No specific environmental flow standards exist for the Nueces Delta. Standards do exist for inflows to "Nueces Bay and Delta" (30 TAC 298.430(a)(3)), but there are no distinct values for the delta, and it is understood that most freshwater stays in the river channel and discharges directly to the bay without going to the delta. Despite the lack of a dedicated standard, it is recognized that the Nueces Delta is an important ecosystem that would benefit by increased freshwater inflows. Accordingly, this study evaluated 18 strategies (referred to as "alternatives" in the report), 14 of which would increase freshwater inflows (these numbers are as per the executive summary, however the summary section says that 15 would increase freshwater inflows, and none of these are clearly demarcated in the text, so it is unclear) and 4 of which would modify the discharge location and/or routing of existing freshwater inflows (or maybe 3 would, again, the report is unclear).

This study combined professional experience, literature reviews, and interviews with regional experts to provide a synopsis of how each of the 18 strategies could be implemented. Factors evaluated include cost, water source, water volume, effects of removing water (from the water source location), effects of adding water (to the Delta), regulations, and expected strategy timeframe. The 18 strategies span a wide range of concepts, including small and large projects, episodic and continuous flow projects, and projects that add sediment as well as water (part of the historical decline of the Nueces Delta is perceived to be due to a lack of sediment input, suggesting that adding sediments would be beneficial).

Upon embarking on this Nueces Delta study, there was clearly no consensus on the best strategy for improving freshwater inflows. The study did an admirable job of considering a range of options, presenting each in a consistent manner, and evaluating relevant strategy characteristics. Because this was essentially a desktop appraisal of 18 strategies, it is limited by approximate calculations (e.g., costs are very preliminary and sometimes based on professional judgment) and largely qualitative discussions of potential ecological impacts. These limitations are reasonable, in that it would not make sense to go to the effort of generating detailed and quantitative information on all 18 strategies. Providing this overview of the strategies, with the expectation that additional details would be developed in the future for the most promising strategies, is an appropriate overall approach. Indeed, this overall approach should be considered by all BBASCs, some of which have invested significant funds into evaluating a single strategy.

The study concluded with a qualitative comparison of 15 of the 18 strategies (SN32, Table 9 , Page 63), across six characteristics (flow [continuous or not], freshwater, volume [≥5 acre-feet/day], sediment added, delivery location, and energy required). The report does not prioritize the 15 strategies, nor does it provide direction to the reader on how the strategies should be prioritized. Rather, the report suggests that "alternatives qualitatively assigned the most checks [i.e., check marks] may provide the most ecological benefit to the Delta."

The report does suggest that diverting discharge from the Allison Wastewater Treatment Plant to the Nueces Delta is worth further effort, in large part due to the low estimated cost. However, the report indicates that even this alternative has drawbacks, including the following:

- The low estimated cost is contingent on reaching an agreement with regulators to not treat the high ammonia concentrations in the effluent.
- There may be some negative ecological consequences in the tidal portion of the Nueces River near the existing Wastewater Treatment Plant outfall. For example, diamondback terrapins have been observed congregating near the outfall during high salinity conditions.
- This strategy would require confidence that the Allison Wastewater Treatment Plant is not going to be decommissioned by the City of Corpus Christi. Decommissioning has been noted in the past.

The contractor provides few recommendations and little direction to the BBASC, leaving the decision as to what is the best strategy up to the BBASC to further evaluate.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

NA. This was not an objective of the study. The study did not develop any identified tools, although presumably there are cost calculations that were developed and could be provided for future use.

Q5. Did the study identify additional data or knowledge gaps?

NA. The study did not explicitly identify any additional data or knowledge gaps but did recognize that the evaluations performed were approximate and/or qualitative. For example, the summary section states, *"A comprehensive analysis of the ecological benefits of each alternative are [sic] beyond the scope of this study."* The implied next step would be for the BBASC to select one or more potential strategies for further evaluation, then to identify important data gaps (e.g., to refine the strategy costs and ecological benefits) to address in subsequent studies.

SN33: An evaluation of the variability of sediment and nutrient loading into Nueces Bay from the Nueces River

This is a data only study and SN04, SN12, SN20, and SN33 are combined under the discussion in Section A.6 given that they were methodologically the same.

A.6 Multi-System Studies - Estuaries

The following group of studies represent a systematic approach to monitoring the relationship between discharge and turbidity with suspended sediment, total nitrogen, and total phosphorus within Galveston, Matagorda, San Antonio, and Nueces Bays.

SN04: An evaluation of the variability of sediment and nutrient loading into Galveston Bay from the Trinity River watershed

SN12: An evaluation of the variability of sediment and nutrient loading into Matagorda Bay from the Colorado River

SN20: An evaluation of the variability of sediment and nutrient loading into San Antonio Bay from the Guadalupe/San Antonio River

SN33: An evaluation of the variability of sediment and nutrient loading into Nueces Bay from the Nueces River

SN04, SN12, SN20, and SN33 are data only studies and have been combined here given their same basic methodological and analysis approaches.

Study Objectives

The purpose of this project was to add data and information to further the understanding of the variability of sediment and nutrient concentrations and loads entering selected Texas bays and estuaries across a range of hydrologic conditions. In addition, methodologies were developed to advance our ability to monitor freshwater inflow, sediment and nutrients entering these systems through acoustic and/or optical instrumentation and surrogate model development.

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

NA. This was not an objective of the study. Rather, this study collected flow, sediment, and nutrient data to support a better understanding of loads from four rivers (Trinity, Colorado, Guadalupe-San Antonio, and Nueces) into their respective estuaries.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

Yes. This study collected new flow, sediment, and nutrient data, but did not develop a scientific approach for testing flows and ecological responses.

This monitoring study was performed under a data only contract with the TWDB. An undated project summary describing the status of the ongoing effort was provided, but a formal report was not. Accordingly, while the project summary provides some data, it provides limited interpretation or insights as to how the data might be used by the BBASCs. Furthermore, the data collected, and calculations performed differed among the rivers, providing inconsistent information to each BBASC. This is an important observation but should not be interpreted as a criticism; the USGS's efforts are a work in progress, and the TWDB elected not to fund a formal report. Because the USGS's work product was a limited project summary, this review is somewhat abbreviated, relative to other study reviews.

Much of the work focused on sampling suspended sediment and nutrient concentrations. Fundamentally, these parameters are difficult to use in an evaluation of environmental flow standards. For each, there is an optimal concentration that is difficult to define. With too few sediments, coastal marshes deteriorate. With too few nutrients, productivity is depressed. Conversely, too much sediment chokes out vegetation and other biota, while too many nutrients cause eutrophication (characterized by excessive algal blooms, potentially harmful algal blooms, and low dissolved oxygen when the algae decompose). In his comment letter to the SAC, Trinity-San Jacinto BBEST member Robert McFarlane (July 19, 2010) urged the SAC and other environmental flow participants to focus on "what is in the water - the dissolved, suspended and particulate material that support the heterotrophic components of the rivers and estuaries." Subsequently, has an approach for defining optimal concentrations of what is in the water, or how to define environmental flow recommendations to achieve those concentrations, been laid out and had optimal concentrations been defined, then the USGS data could be more directly used.

Another challenge is the observation that suspended sediment and nutrient concentrations do not always correlate to flows. Often, higher flows create higher velocities and shear stresses, which increase suspended sediment concentrations. This may also increase the concentration of sediment-bound nutrients. Quantitative relationships between flows and these constituents frequently show a positive correlation and are typically referred to as rating curves. The USGS project summary provided little information on any such rating curves, although it did note that the Guadalupe River near Tivoli site "showed no statistically significant correlation between nutrient concentrations and streamflow or suspended-sediment concentration." Accordingly, at least for San Antonio Bay, even if the BBASC had identified an optimum concentration for nutrients in the inflows, it would be difficult to define a freshwater inflow recommendation to achieve that desired level.

These challenges are inherent to water quality issues and are likely the reason that none of the BBESTs or BBASCs based their flow recommendations explicitly on suspended sediment or nutrients.

Another component of this study was the evaluation of divergent flow paths near the mouth of the Trinity and Guadalupe Rivers. Because of extensive interconnected channels, measuring flow in this immediate area is challenging and may require multiple flow gauging stations. While the USGS's efforts are interesting, it is difficult to know how the BBASCs could use the information. For example, in the Trinity River, the most downstream instream flow standard is at the "Trinity River near Romayor" USGS gauge, which is well upstream of the complex flow patterns near the mouth of the Trinity River. The freshwater inflow standard for Galveston Bay from the Trinity River does not specify a location, but this standard is typically evaluated using the WAM, which does not include the complex flow patterns near the mouth of the Trinity River. Accordingly, whether or not the water flows through one channel or another on the way to Galveston Bay is immaterial to the BBASC's high-level deliberations. Such scientific information may be useful for hydrodynamic modeling or marsh restoration efforts, for example, but are not directly relevant to the BBASC.

Q3. Did the study evaluate a strategy for achieving environmental flows?

NA. This was not an objective of the study.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

NA. This was not an objective of the study.

Q5. Did the study identify additional data or knowledge gaps?

Yes. These reports include a "future considerations" section that recommends continuation of the monitoring efforts. These sections also identify possible expansions to the monitoring, including environmental isotopes (e.g., δ15N and δ15O of nitrate) to help distinguish nitrogen sources. However, given that estuarine productivity has not been demonstrated to be inadequate to support a sound ecological environment, nitrogen has not been demonstrated to limit productivity, and an optimal concentration or load of nitrogen has not been identified, it is unclear what the BBASC would do with a better understanding of nitrogen sources.

The portion of the Trinity-San Jacinto BBEST report that recommends freshwater inflows and was authored by the "Flow Regime" group states:

> *The committee discussed the weakness of the flow – salinity – ecology relationships when compared to flow – nutrients – ecology relationships, but determined that there is sufficient flow-salinity data and insufficient flow-nutrient data for our purposes. Nutrients in various forms have a more direct impact on the abundance of estuarine species than salinity. More data on the relationship of freshwater and nutrient content of those flows should be collected in the future as part of the adaptive management program.*

Based on this statement, there is clearly a hope that with more data, better relationships can be identified to make freshwater inflow recommendations. The first step would be to establish a relationship between flow and nutrients, which, as discussed above, is not always straightforward. The second step would be to establish a relationship between nutrients and ecology, but this relationship will clearly not be straightforward. As discussed above, both too few, and too many, nutrients can be problematic.

Ideally, the BBESTs and BBASCs will more explicitly identify what relationships they are looking for (in the form of a hypothesis), and then the USGS can explicitly collect data to confirm or refute the hypothesis for each basin.

These studies were identified by the authors as contributing to the following work plan studies (quoted text from the study in italics, perspective of the review team in regular font):

- *Contributes to several priority activities identified by the Trinity, San Jacinto Basin and Bay Area Stakeholder Committee in the Trinity, San Jacinto basin and bay area work plan (TSJ BBASC 2012) including to gather water quality data and sediment characterization data.*
    - Several water quality related efforts were suggested by the BBEST, among the 64 work elements that they identified. The BBASC did not prioritize the water quality efforts, but rather listed them under "Remaining tasks to be considered in future revisions to the Work Plan."
- *Contributes to several priority activities identified by the Colorado, Lavaca Basin and Bay Area Stakeholder Committee in the Colorado, Lavaca basin and bay area work plan (Tasks 11, 12, and 16) to improve estimates of freshwater inflows and quantify sediment and nutrient loading to Matagorda Bay.*

    - Tasks 11 and 12 are expansive but have little mention of mainstem flows, nutrients, or sediments. Task 16 is related to delta formation, which is dependent on sediment loads, but it does not specify how the BBASC would select an optimal delta formation rate and make a freshwater inflow recommendation to promote that delta formation rate.
- *Contributes to a Tier 1 recommendation to improve streamflow gaging and water quality monitoring as well as a Tier 3 recommendation to evaluate sediment transport affecting the Guadalupe Estuary delta as identified by the Guadalupe, San Antonio Basin and Bay Area Stakeholder Committee in the Guadalupe, San Antonio basin and bay area work plan (GSA BBASC 2012).*
    - This USGS study is also related to another Tier 3 recommendation for nutrient load and concentration monitoring.
- *Contributes to Tier 2b recommendation for assessment of transportation and loading of sediment to the Nueces Estuary (Nueces BBASC).*
    - The BBASC work plan identifies a lack of sediment as being a contributor to subsidence and decay of the older delta, suggesting that increased sediment load (which sometimes occurs with increased flows) would provide ecological benefits.

While the USGS study supports these work plan elements, at least in part, it is unclear exactly what each BBASC intends to do and exactly what data they need to accomplish their goals. Accordingly, it is also unclear how the USGS study meets the needs of each BBASC.

A.7 Multi-System Studies – Instream Flows

The following studies essentially follow the same methodological and analytical approaches for aquatic resources in the Brazos, Colorado-Lavaca, and Guadalupe-San Antonio rivers. The estuary component of the study in the Brazos River is discussed under SN07 in Section A.2.

SN07: Instream flows research and validation methodology framework and Brazos Estuary characterization

Bonner, T., J. Duke, G. Guillen, K. Winemiller, Bio-West, Inc. 2015. Instream flows research and validation methodology framework and Brazos Estuary characterization. Texas Water Development Board Contract No. 1400011722. 159 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1400011722%20BIO-WEST.pdf)

SN08: Validation or refinement of the adopted TCEQ environmental flow standards for the Brazos River

Bonner, T., J. Duke, G. Guillen, and Bio-West, Inc. 2017. Instream flows research and validation methodology framework 2016-2017: Brazos River and Associated Bay and Estuary System. Texas Water Development Board Contract No. 1600012009. 120 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600012009.pdf)

SN13: Validation or refinement of the adopted TCEQ standards for the Colorado and Lavaca rivers

Bonner, T., J. Duke, and Bio-West, Inc. 2017. Instream flows research and validation methodology framework 2016-2017: Colorado and Lavaca Rivers. Texas Water Development Board Contract No. 1600012010. 73 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600012010.pdf)

SN15: Instream flows research and validation methodology framework (Guadalupe-San Antonio)

San Antonio River Authority, T. Bonner, J. Duke and Bio-West, INC. 2015. Instream flows research and validation methodology framework: Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas and San Antonio Bays Basin. Texas Water Development Board Contract No. 1400011709. 153 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1400011709_instream.pdf0

SN21: Continuation of instream flows research and validation methodology framework (Guadalupe-San Antonio)

San Antonio River Authority, T. Bonner, J. Duke, and Bio-West, Inc. 2017. Instream flows research and validation methodology framework 2016-2017. Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays Basin. Texas Water Development Board Contract No. 1600011937. 78 pp + Appendices. (https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600011937.pdf)

Study Objectives

This group of studies primarily evaluated pulse flow events of the TCEQ adopted standards in the respective basins relying on responses of the macroinvertebrate, fish, and riparian components of the riverine system. SN15/SN21 also examined elements of floodplain connectivity in the Guadalupe/San Antonio River systems. Specific to the Brazos Estuary system, SN07 described water quality and nekton community patterns and quantified estuary salinity regime, nutrients, suspended solids, and utilization by estuarine dependent nekton. A component of these studies also attempted to develop a validation methodology framework for the instream flow component of the TECQ adopted standards. The reader is directed to detailed independent peer review comments which are replicated in each of the three final reports (SN08, SN13, and SN21).

Q1. Did the study validate the adopted instream flow or freshwater inflow standards?

Riparian - Partially. The authors relied on a simplified estimation of stream discharges necessary to inundate at least 80 percent of three defined ‘Levels’ (i.e., elevation breaks in the channel topography) associated with different zonation of riparian species (and age structure) which were compared to the TCEQ flow standards. The authors provided pragmatic justification for their use of the 80% inundation factor but acknowledged that this threshold criterion was arbitrary and a matter of professional judgment. This metric was assumed to equate with long term maintenance of the riparian community. The field methods and analyses applied to translate flow depth to discharge at a study site from the nearest USGS gage showed limited success, and the authors note that their estimated discharges to inundate a specific level are uncertain and likely overestimated.

They note that the 1/year BBEST recommended flow inundated all the riparian indicator species at all sites. However, the TCEQ 1/spring flow tier discharge only inundated 2 of 13 riparian indicator species distributions 80% or more of the time. They conclude that this could be problematic in terms of long-term recruitment dynamics, given spring is the seed dispersal and germination window for the selected indicator species. This concern is exacerbated by their estimation that only 1 of 13 species were inundated more than 80% of time with the defined 1/summer TCEQ flow standard. Similarly, they estimate only 1 of 13 species were inundated more than 80% of the time during the winter flow standard window, which include the fall seed drop.

Based on their results, they conclude that the TCEQ flow standards generally do not meet the riparian community needs on a seasonal or annual basis. They suggest that maintenance of the existing riparian zones would likely require higher flows with a 1/spring and 1/fall periodicity but do not provide a revised estimate or specific recommendation for discharge magnitudes.

Aquatics - No. First, we note substantive technical issues were identified by the independent peer reviews related to sampling design that impaired the ability of the data to inform validation of the pulse flows in terms of aquatic resource responses. In essence, the study methodology is best characterized as monitoring short-term responses in fish and macroinvertebrate relative abundance and density and is therefore unsuitable to infer long-term population or community dynamics that relate to maintenance of a sound ecological environment. Although a suite of statistical tests was used to compare seasonal, site-specific, and across-site results, the fundamental endpoint was that some taxa and some sites showed statistical differences while others did not. We particularly note that the study design did not link site-specific characterizations (or changes) in the geomorphic properties, such as channel morphology or substrate, that may have allowed inference to mechanisms linking aquatic resource changes to the observed flow regimes.

The aquatics component of the study is best characterized as descriptive in terms of highlighting statistical differences in density and abundance of fish and macroinvertebrates to short term hydrologic pulse flow events. These data could be used to support an evaluation of acceptable ranges in ecological response variables that has been noted as a necessary element to interpret whether a system is maintaining a sound ecological environment. However, the studies do not provide any relevant discussion of their results in terms of the reported ranges of flow-ecology relationships documented in the widely available flow-ecology peer reviewed scientific literature. This was also noted in the independent peer review comments. We believe that these comparisons can still be made and provide important insights toward refinement of the bounds for a sound ecological environment.

We note the importance of understanding the implications of the observed change in required discharge magnitudes necessary to inundate later habitats over the two-year study period, which was attributed to changes due to flooding between the assessment periods. We stress this level of change (> 1000 cfs) underscores the dynamic nature of these riverine environments where changes in channel geomorphology may result in an assessment concluding different outcomes based on the magnitude of these changes (i.e., meets a standard versus not meeting a standard). Ultimately, the validation of any component of the flow standards (subsistence, base flows, pulse flows, overbank flows) will need to address both short- and long-term dynamics of the geomorphic template given that flow-ecology relationships are broadly understood to be controlled by interactions between hydrologic forcing and geomorphic setting.

Q2. Did the study collect new data or develop a scientific approach for testing the cause and effect relationship between flow and ecological response?

Yes. These studies collected characteristics on the fish assemblages in selected mesohabitats (e.g., riffles, runs, pools) as well as macroinvertebrates. The riparian communities were examined using different assessment approaches that focused on the relationship between water surface elevation and flows necessary to provide inundation of target indicator species at various channel elevations. Limited data on three lateral connectivity sites in the Guadalupe/San Antonio River system were also evaluated in terms of estimated discharges (water surface elevations) necessary to maintain connectivity between the main channel and these off-channel habitats.

Q3. Did the study evaluate a strategy for achieving environmental flows?

NA. This was not an objective of these studies.

Q4. Did the study develop a tool (e.g., a hydrodynamic model) that decision-makers can use for evaluating environmental flow regimes?

Partially. The SN07 report recommended a 'validation framework' that was subsequently removed from the remaining studies at the request of the TWDB which was supported by similar recommendations in the peer review comments. We agree with the decision to remove material as the framework was more of a decision tree to guide site-specific studies that incorporated stakeholder perceptions of importance or priorities related to proposed actions. The framework did not provide a scientifically rigorous approach to specifically target the validation of the adopted flow regimes in terms of flow-ecology relationships or validation of the adopted standards.

Q5. Did the study identify additional data or knowledge gaps?

Yes. The reports suggested additional long-term monitoring, including assessments targeting freshwater mussels. 'Post-flood aquatic community shift dynamics' and 'Channel morphology' studies were also recommended. We believe, however, that the purpose of the post-flood and channel morphology studies can be addressed by integrated long-term monitoring programs. The simple establishment of reference cross sections in a riffle, run, and pool mesohabitat at each study site with replicate channel topography, discharge estimates, and substrate characteristics at the onset of these studies would have developed a baseline and trend analysis capability and permitted their integration in the analyses of the target aquatic species collections.

We note in particular the results for estimated discharge thresholds necessary to maintain lateral habitat connectivity that increased by over 1,000 cfs within the two-year study period. The authors attributed this to flooding between the first and second year of sampling. This underscores the variability of the geomorphic responses to flow regimes sufficient to elicit detectable changes in the diversity, relative abundance, and density of aquatic communities. These changes or ranges in the ecological metrics can potentially be mischaracterized as negative trends in a sound ecological environment when in reality these larger scale shifts may be the norm on decadal or longer time frames. Understanding the difference between degradation of a sound ecological environment versus expected ranges in the ecological metrics requires systematic integrated geomorphic, water quality and ecological monitoring programs.

Appendix B – BBASC Work Plan Suggested Priorities

Table B.17. Trinity-San Jacinto Basin/Galveston Bay suggested work plan priorities.

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
1	3-Tier study area development.	H	The integrated monitoring efforts in the Trinity-San Jacinto are effectively addressing this study element.
2	Flow regime component characterization.	H	The integrated monitoring efforts in the Trinity-San Jacinto are effectively addressing this study element.
3	Evaluate interrelationships between environmental flow regimes and proposed water supply projects.	L	A focus on flow-ecology validation and defining ranges of a sound ecological environment are a higher priority.
4	Surveys of long reaches covering TCEQ-adopted flow sites.	L	The integrated monitoring efforts in the Trinity-San Jacinto are effectively addressing this study element.
5	Imagery analyses.	L	The integrated monitoring efforts in the Trinity-San Jacinto are effectively addressing this study element.
6	Prioritization of intensive study sites.	H	The integrated monitoring efforts in the Trinity-San Jacinto are effectively addressing this study element.
7	Intensive site-specific studies of high priority sites.	H	The integrated monitoring efforts in the Trinity-San Jacinto are effectively addressing this study element.
8	Analyses and establishment of baseline ecological conditions.	H	The integrated monitoring efforts in the Trinity-San Jacinto are effectively addressing this study element.
9	Identification of Indicator Metrics & Species.	H	The integrated monitoring efforts in the Trinity-San Jacinto are effectively addressing this study element.

Table B.17 (continued)

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
10	Identification of typical riffle-run sequences, conduct low flow subsistence monitoring, biological surveys.	M	The integrated monitoring efforts in the Trinity-San Jacinto are effectively addressing this study element.
11	Synoptic survey of selected rivers under baseflow conditions.	M	The integrated monitoring efforts in the Trinity-San Jacinto are effectively addressing this study element.
12	Coordinated surveys during high flow pulses.	L	Geomorphic channel monitoring under existing study designs is addressing this work element.
13	Basin-wide baseline surveys of (state listed species) mussels and related studies.	M	This may inform some indication of a sound ecological environment but not directly inform validation efforts for flow-ecology relationships.
14	Coordinate data gathering and special studies with work plan being developed for Senate Bill 2.	L	We believe that this has been effectively completed.
15	Gather water quality data and sediment characteristic data within the segments related to Gages TR near Oakwood (Note: within SB 2 segment for TR), TR at Romayor, SJR near Cleveland, and WFSJR near Conroe.	H	We believe these data provide important input to defining flow-ecology responses.
16	Gather Trinity River channel physical data for segments related to Gages TR near Oakwood (Note: within SB 2 segment for TR), TR at Romayor, SJR near Cleveland, and WFSJR near Conroe.	H	We believe these data provide important input to defining flow-ecology responses.
17	Analyze data and develop findings and conclusions regarding the relationship between water quality data and the proposed flow regimes.	M	Water quality may represent a limiting factor during a drought of record but not likely a factor under normal flow regimes.
18	Evaluate the effect of the appropriate flow recommendations on salinity zones for additional indicators starting with, but perhaps not limited to, those initially identified by the TSJ B&E subcommittee.	M	Data suggests that the use of indicators stratified by salinity zones may be more appropriate, since greater changes in salinity occur near freshwater sources where more sensitive bioindicators exist.

Table B.17 (continued)

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
19	Test the conclusion that these indicators (either the three immobile species or an expanded list) are appropriate for representing the health of Galveston Bay.	H	BBEST primarily relied on TPWD nekton data. But most species exhibited poor correlation with salinity. More sensitive bioindicators were needed.
20	Recognizing that estuarine species have broad tolerances for salinity ranges, if a set of indicators responsive to salinity cannot be identified "as representing a healthy Galveston Bay ecosystem in its entirety" this should be explicitly stated and some attempt to quantify the relative benefit of preferred salinity zones to overall estuarine health might be attempted.	M	This task may become necessary after further analysis and possible adoption of local indicators.
21	Consider the addition of new species which were previously not recognized during the BBEST process.	H	BBEST primarily relied on TPWD nekton data. But most species exhibited poor correlation with salinity. More sensitive bioindicators were needed.
22	Analyze frequencies of occurrence of proposed freshwater inflows.	M	This is an ongoing task that will continue as new data is compiled. Also, continued analysis to determine the appropriate time steps (e.g., monthly, daily, cumulative) needed to provide predictive models relating previous flow regime, salinity and biotic responses are needed.
23	Analyze geographic factors related to flows and salinity zone areas.	M	An analysis of topographic features (e.g., Texas City Dike) and their influence on circulation and salinity is needed. Possible partners would be the USCOE who are evaluating the influence of tide gates on hurricane storm surge.

Table B.17 (continued)

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
24	Expand current analysis to evaluate broader range encompassing a full flow regime or propose alternative or complementary approach to address other components of freshwater inflow regime.	M	This can be deferred as part of reassessing inflow needs based on upper bay and estuary focus.
25	BBEST design and promote studies to obtain the data necessary for statistical modeling.	M	This goal is inherent in any project. The development of models that describe the effect of freshwater inflow including important co-variables (e.g., seasonality, location in estuary) on resulting salinity, nutrients and biota.
26	Nutrient concentration water sampling at frequencies shorter than two weeks.	H	In order to understand the influence of freshwater inflow more information regarding nutrient data are needed to better understand linkages with primary production.
27	BBEST develop recommendations for monitoring projects.	H	Multiple benefits (e.g., fiscal resource leveraging) would be generated if more input were provided to existing programs that support monitoring (e.g., TPWD, GBEP, TWDB, TCEQ).
28	Process for identifying environmental flow regime for the estuary (could include: reevaluation of the process for determining the relationships between salinity and Vallisneria, Rangia reproduction, and/or oyster parasitism.	H	These sessile organisms are located in the upper part of the bay (Trinity Delta) and are sensitive to changes in salinity.
29	Determine how best to evaluate changes from a sound ecological environment.	H	Although a critical task this will likely be an ongoing process as the knowledge base increases from ongoing monitoring.
30	Initiate quantitative data collection for Atlantic *Rangia.*	H	Rangia are located in the upper part of estuaries located along the upper and mid-coast estuaries and are sensitive to changes in salinity.

Table B.17 (continued)

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
31	Initiate or expand monitoring programs designed to assess reproduction of Rangia and parasite and predator impacts on oysters.	M	Rangia are located in the upper portions of estuaries (upper and mid-coast) and are sensitive to changes in salinity. TPWD methods probably under-samples Rangia. Continuous parasite monitoring is lacking.

Table B.18. Brazos Basin/Estuary suggested work plan priorities.

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
1	Continue cooperative funding agreements for stream flow gauging stations into the future, especially for the 20 focal reaches evaluated in this report.	H	We have assumed that this cooperative funding is supported external to SB3.
2	Continue the on-going routine water quality monitoring at all locations that coincide with the focal reaches of the recommended flow regimes.	H	We have assumed that this cooperative funding is supported external to SB3.
3	Continue TSS data collection at routine water quality monitoring locations.	H	We believe that this continued monitoring is vital to establishing flow-ecology relationships to indicator taxa and defining limits to a sound ecological environment.
4	Continue support for reservoir surveys and evaluate the latest reservoir capacity information during the adaptive management review processes.	L	A focus on flow-ecology relationships and defining the expected ranges of indicators of a sound ecological environment takes precedence.
5	Conduct studies to evaluate the benefits of over-bank flows to help maintain a healthy river system, including sediment and nutrient transfer, moving the river channel, maintaining the riparian ecology, and maintenance of oxbows.	M	We believe these studies, results from Winemiller et al., (2021) and literature provided in the Appendix C has demonstrated the importance of these over-bank flows to sustaining a sound ecological environment.
6	Commission a long term study to monitor salinity, nutrient transport, and sediment transport and deposition, and associated estuarine health in order to detect any negative effects as upstream projects are implemented over the next few decades.	H	These two studies are the first efforts to characterize the relationship of inflow, water quality and biota, including larval and juvenile recruitment into the lower Brazos River. Further studies are needed. Nothing currently planned.
7	Analyze the BBASC environmental flow recommendation at the Richmond gage and compare to the results of the BBEST analysis.	M	This is informative but establishment and maintaining long-term monitoring is a higher priority.
8	Continue fish surveys (of all species) on the Middle Brazos Segments 1204 and 1206.	M	We suggest that focusing on integrated monitoring at established monitoring sites is more important.

Table B.18 (continued)

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
9	Conduct additional studies for the area from Possum Kingdom to Whitney, including the golden algae issue.	M	The primary benefit to this is understanding the dynamics of golden algae on impacting a sound ecological environment that may be flow regime related.
10	Conduct ALM assessments with expanded habitat data for the Salt, Double Mountain, and Clear Forks of the Brazos River and the river upstream of Possum Kingdom reservoir.	M	We suggest that focusing on integrated monitoring at established monitoring sites is more important.
11	Historical and current community analyses should include other taxonomic groups as well as fish, especially mussels and aquatic insects.	M	The results from Winemiller et al., (2021) in conjunction with SN07, SN08 clearly indicate that mussels are not likely good indicators and macroinvertebrates have variable responses to flow regime components. However, monitoring the status as indicated in Winemiller et al., is warranted.

Table B.19. Colorado-Lavaca Basin/Matagorda Bay suggested work plan priorities.

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
1	Describe relationships between flow, and physical, chemical, and biological structure and function of the streams and how these relationships support ecological health.	H	This represents a component of our suggested long-term monitoring efforts.
1 sub 1	Identify stream locations and estuaries not included in the BBEST environmental flow regime report that should be analyzed for relationships between flow and environmental health.	L	Better to focus on refining knowledge at existing locations.
1 sub 2	Review best available science for determining environmental flow regimes for streams.	L	Not a region-specific task. TWDB staff should take lead on this.
2 sub 1	Describe ecological services provided by perennial pools.	L	Difficult to establish standards around zero flows.
2 sub 2	Describe relationships between aquatic biota (including riparian and floodplain species) and flow.	H	This is a component of our suggested long-term monitoring effort.
2 sub 3	Describe relationships between physical habitat and flow.	H	This is a component of our suggested long-term monitoring effort.
2 sub 4	Describe upstream-downstream connectivity and lateral connectivity of streams with the floodplain and aquatic features like wetlands, backwaters, sloughs, and oxbows under different flow conditions.	H	This is a component of our suggested long-term monitoring effort.
2 sub 5	Identify ecological effects of overbank flows and flows that reach, or almost reach, flood stage elevation but do not overbank.	M	TCEQ unlikely to incorporate flows near bankfull in standards but we maintain overbank flows are a required element to maintain a sound ecological environment.
3	Describe relationships between groundwater and stream flow.	M	More knowledge regarding the link between groundwater and surface water is important but doesn't directly inform standards.

Table B.19 (continued)

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
3 sub 1	Determine relationships between groundwater withdrawals from the Carrizo-Wilcox and the Gulf Coast aquifers and flows to rivers.	M	More knowledge regarding the link between groundwater and surface water is important but doesn't directly inform standards.
4	Describe relationships between water chemistry and flow regime components.	L	Water chemistry often not a strong function of flow and also difficult to determine targets.
5	Increase understanding of how different factors affect calculation of flow regime components and hydrologic conditions over time.	L	Reevaluating HEFR options unlikely to result in changes to standards.
6	Determine how groundwater development activities, as listed in the then current State and relevant Regional Water Plan, might influence river flows and the physical and hydrologic connections between surface water and groundwater.	M	More knowledge regarding the link between groundwater and surface water is important but doesn't directly inform standards.
7	Research best methods to determine sediment transport and channel maintenance of streams for which environmental flow standards have been set.	M	This is a component of our suggested long-term monitoring effort.
7 sub 1	Describe changes in geomorphology, i.e., trends in channel elevation, longitudinal profile, width, floodplain width, stream form, bed sediment size, and the role the flow regime contributes to those changes.	H	Data would be informative, but difficult to base an environmental flow standard on
8	Evaluate and update the WAM, with particular emphasis on Run 3 and Run 8 for both the Colorado and Lavaca River basins, with a goal of the development of a daily time-step capability that could be employed for environmental flow assessment tasks.	M	It would be helpful to have these models available.
9	Evaluate decline in flows in the upper Colorado Basin with a particular emphasis on understanding the apparent change in relationship between rainfall and river flow.	L	Studies have been performed.

Table B.19 (continued)

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
10	Develop a method for obtaining site-specific commercial fishing harvest data and for maintaining appropriate confidentiality of those data and develop an approach for incorporating reliable commercial fisheries harvest data into the analysis of the relationship between freshwater inflows and species productivity.	L	Data could be very valuable, but may be difficult to obtain, quality control, and use.
11	Refine estimates of freshwater flow to the bays.	L	TWDB has separately funded an ungaged hydrology study.
11 sub 1	Describe flows into Garcitas Creek and their sources with particular emphasis on the reach downstream of the USGS gage.	L	Small scope would provide limited information to benefit to other portions of the basin.
12	Describe relationships between freshwater inflow to bays, and physical, chemical, and biological structure and function of the estuaries and how these relationships support ecological health.	H	This is a component of our suggested long-term monitoring programs.
12 sub 1	Identify improvements made in methods for determining environmental flow regimes for estuaries.	L	Not a region-specific task. TWDB staff should take lead on this.
12 sub 2	Describe relationships between freshwater inflow, marsh, and the threatened diamond-back terrapin populations.	M	This will depend on whether this is considered a key indicator species.
12 sub 3	Describe the relationship between freshwater inflow and Rangia clam abundance in upper Lavaca Bay.	M	This is likely a component of the suggested long-erm monitoring
12 sub 4	Describe the relationship between freshwater inflow, location and size of oyster reefs, and health of oysters in Lavaca Bay and Matagorda Bay.	M	Much work has already been performed, but oysters are very important and likely an indicator for long-term monitoring.

Table B.19 (continued)

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
12 sub 5	Evaluate relationships between freshwater inflow and the distribution, health, and abundance of seagrass in East Matagorda Bay and Matagorda Bay.	L	Seagrasses are strongly affected by other factors and are studied by other groups.
12 sub 6	Describe relationships between salinity and commercially important indicator species (e.g., white and brown shrimp, blue crab, and Gulf menhaden).	M	This should be considered during refinement of indicator species for long-term monitoring. If the focus is upper bay and estuaries, this may not be as important.
12 sub 7	Identify marsh changes occurring in the Lavaca River and the Matagorda River deltas and relationship of those changes to freshwater inflow.	H	Marsh habitat is a good candidate for freshwater inflow strategies and efforts are being made by others to physically protect marshes.
12 sub 8	Evaluate achievement of the BBEST freshwater inflow recommendations in Matagorda Bay (based on the Matagorda Bay Health Evaluation recommendations) and ecological response to those freshwater inflow quantities and distribution.	L	The MBHE flow recommendations aren't occurring and so cannot be directly tested. Other, more general, studies are more appropriate.
12 sub 9	Describe the relationship between freshwater inflow and sound environment in the coastal drainages of East Matagorda Bay.	H	Marshes to the north of East Matagorda Bay could be a good target for supplemental freshwater inflows.
12 sub 10	Identify methods to lower salinities in East Matagorda Bay without degrading the environmental condition of the bay.	L	Lack of stakeholder consensus on salinity targets.
13	Describe the relationships between subsidence and salinity regimes in East Matagorda Bay.	L	Subsidence is not directly related to environmental flows.
14	Improve the existing hydrodynamic model or use other hydrodynamic models to model hydrology, circulation, and salinity patterns for Matagorda, East Matagorda, and Lavaca Bays.	M	Good hydrodynamic models provide a strong foundation for many other studies.
15	Implement a program to review effectiveness of strategies that could be used in areas where there may be inadequate amounts of water for an ecologically sound stream or estuary.	M	This may be better approached as part of Regional Planning processes.
16	Quantify the effects of sediment transport on delta formation in Lavaca and Matagorda Bays.	L	The Colorado River delta is expanding and not directly related to environmental flows.

Table B.20. Guadalupe-San Antonio Basin/San Antonio Bay suggested work plan priorities.

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
1	Instream Flows - SB2 TIFP Guadalupe Study.	H	Top priority of GSA BBASC adaptive management work plan.
2	Instream Flows - Streamflow Gaging and Synoptic Flow Study.	H	High priority of GSA BBASC work plan.
3	USGS Streamflow Gaging and Water Quality Monitoring.	H	Essential to accurately measure instream flows and water quality.
4	Synoptic Flow Measurements to Estimate Freshwater Inflow and Applicability of Lower River Gaging Stations.	H	Important for understanding instream flows.
5	Bays & Estuaries - Rangia Clam Investigations.	L	Demonstrated that *Rangia* not abundant enough in these systems to be a useful focal species.
6	Bays & Estuaries - Life Cycle Habitat & Salinity Studies for Key Faunal Species.	L	Several sources available for life cycle and salinity studies.
7	Bays & Estuaries - Hydrodynamic & Salinity Model Improvements.	H	TWDB priority in house.
8	Instream Flows - Full Accounting of Surface Water.	M	Important for understanding instream flows.
9	Instream Flows - Riparian Assessment and Monitoring.	M	Instream flows affect fauna and flora in riparian habitat.
10	Instream Flows - Biological Sampling and Monitoring.	M	Difficult to assess instream flows without monitoring focal species.
11	Instream Flows - Geomorphic Studies and Monitoring.	M	Instream flows affect geomorphology and species habitats.
12	Bays & Estuaries - The Distribution and Abundance of Marsh Vegetation in Relation to Salinity and Elevation in the Guadalupe Estuary Delta.	M	Vegetation monitoring carried out annually in Mission-Aransas Estuary (NERR).

Table B.20 (continued)

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
13	Bays & Estuaries - Habitat Suitability Models for Eastern Oysters, Blue Crabs & White Shrimp.	M	Oysters not considered in this study – blue crabs and white shrimp show time lags between freshwater inflows, salinity and other environmental variables and TPWD data.
14	Bays & Estuaries - Development of an Inundation and Salinity Model of the Guadalupe Estuary Lower Delta and Adjacent Bays.	M	Important for understanding impacts of FWI and drought on marsh vegetation.
15	Instream Flows - Groundwater Studies.	M	Potentially important source of FW in instream flows and FWI to estuaries but challenging to measure.
16	Instream Flows - Water Quality Monitoring.	H	Need to understand nutrient concentrations instream to understand effect of FWI on estuaries.
17	Instream Flows – Invasives.	M	Invasive species can displace native species and disrupt ecosystem function such as zebra mussels.
18	Bays & Estuaries - Nutrient Load & Concentration Monitoring.	H	Nutrient data critical to understanding harmful algal blooms, hypoxia and other issues affecting ecosystem structure and function.
19	Bays & Estuaries - Role of Cedar Bayou in the Exchange of Water and Meroplankton to the Guadalupe Estuary.	L	Mission-Aransas NERR monitors meroplankton in Mesquite Bay – no clear pattern between periods when CB opened or closed.
20	Bays & Estuaries - Evaluation of Sediment Transport Affecting the Guadalupe Estuary Delta.	H	Sediment dynamics important to understanding coastal subsidence and Sea level rise.
21	Bays & Estuaries - Sea Level Rise Associated with Climate Change.	L	Surface elevation tables (SETs) and water level monitoring ongoing in Mission-Aransas NERR..

Table B.21. Nueces Basin/Nueces Bay suggested work plan priorities.

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
1	Describe relationships between flow and physical, chemical, and biological structure and function of the streams and how these relationships support ecological health.	H	This represents a component of our suggested long-term monitoring efforts.
2	Describe the role of flow in the ecological health of the stream.	L	This is well established in the open literature and the annotated bibliography provides ample evidence.
3	Identify stream locations and estuaries not included in the BBEST environmental flow regime report that should be analyzed for relationships between flow and environmental health.	M	Targeting existing locations already identified should remain a priority.
4	Conduct additional modeling of relationships between in-stream habitat and flow.	M	Monitoring data similar recommended by Winemiller et al., (2021) should be the focus.
5	Describe ecological services provided by perennial pools.	L	This is interesting but not specifically germane to existing standards.
6	Identify flow regime components and quantities necessary to sustain mussels and compare to flow regimes identified necessary to sustain fish communities.	M	Results from Winemiller et al., (2021) suggests that targeting flow regimes for target fish and riparian indicators are likely sufficient to address mussels.
7	Describe how surface flow patterns and quantities are changing compared to the period of record patterns. Include consideration of possible future flows and diversions.	L	A focus on establishing existing relationships for flow-ecology and bounds to a sound ecological environment are more pressing.
8	Describe groundwater flow into streams and how is it changing.	L	Relative to other monitoring needs, this is considered a low priority.
9	Describe relationships between benthic macroinvertebrates and flow.	L	Note synthesis reviews contained in the citations in the annotated bibliography indicated highly variable responses except in drought conditions.

Table B.21 (continued)

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
10	Identify water development activities planned for the future, and how they might influence groundwater, river flows, and physical and hydrologic connections between the two.	M	This represents an interface between Senate Bill 3 and the Regional Planning efforts and can inform strategies for attainment of adopted flow standards.
11	Describe changes in geomorphology, i.e., trends in channel elevation, longitudinal profile, width, floodplain width, stream form, bed sediment size, and the role the flow regime contributes to those changes.	H	This is an identified element of a systematic integrated monitoring program.
12	Identify the best period of record to use in deciding which hydrologic condition and hydrologic triggers should be used.	M	This will provide some insights to understand back-casting analyses as outlined in Winemiller et al., (2021).
13	Identify key flow-dependent ecosystem functional (create ecological structure) processes associated with a sound ecological environment.	H	This can be achieved using the proposed monitoring and analysis framework outlined by Winemiller et al., (2021) and supported by the suggested long-term monitoring.
14	Develop sustainability boundary analysis.	L	Relative to other efforts, this can be deferred.
15	Relationships between Freshwater Inflow and Ecological Health.	M	We have suggested that a focus on upper bay and estuary systems and following the recommendations contained in Montagna et al. (2020, 2021).
16	Relationships between salinity and fish/shellfish abundance.	M	We have suggested that a focus on benthos rather mobile species.
17	Improve methods for determining environmental inflow regimes.	H	We have suggested that this can be accomplished based on long-term monitoring and using the recommendations outlined in Winemiller et al., (2021).
18	Relationship Between Freshwater Inflow and Oysters Reefs.	M	This remains relevant relative to the influence of anticipated flow volumes related to the adapted standards.

Table B.21 (continued)

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
19	Evaluate potential for Allison wastewater effluent with its nutrients and other return flows (e.g., Oso Bay returns) to improve environmental health of the Rincon Bayou delta.	H	This remains an important strategy to meet adopted standards that improve the ecological health of the system.
20	Identify vegetation/marsh changes occurring in the Rincon Bayou delta and relationship of those changes to freshwater inflow.	H	This remains an important strategy to meet adopted standards that improve the ecological health of the system.
21	Define ecological effects of zero flow event duration, intervals between periods of zero flow, and long-term frequency of zero flow occurrences.	L	We suggest this has little pragmatic utility given the adopted flow standards and not likely that TCEQ would incorporate a zero flow element into a standard.
22	Continued monitoring of vegetative indicators.	H	This is an element of our suggested long-term monitoring.
23	Salinity Monitoring and Real Time (SMART) Inflow Management Study.	H	This is an element of our suggested long-term monitoring although the pragmatic use of the real time data to effect flow regime changes remains unknown.
24	Re-examination of the 2001 Agreed Order Monthly Targets.	H	This is basically addressed by the existing studies to inform potential recommendations to the adopted standards.
25	Safe yield demand vs. current demand evaluation.	L	We suggest this has little utility in meeting Senate Bill 3 adaptive management objectives.
26	Explore Landform Modifications to Nueces Bay and Nueces Delta.	H	This can inform landscape scale factors affecting trends in a sound ecological environment and inform expected ranges that maintain a sound ecological environment.
27	Ecologically Sound Environment Strategy Effectiveness Program.	L	We suggest that this be deferred until a sound ecological environment attributes and ranges of expected variability are established.

Table B.21 (continued)

BBASC Study Number	Study Title	Statewide Synthesis Project Team Priority	Statewide Synthesis Rationale
28	Evaluate probable effects of climate change (a greenhouse warmed future) on water resources including supply, demand, and the ecological condition of rivers and streams and associated bays in the Nueces Basin.	M	We believe that this should be deferred until a sound ecological environment attributes and ranges of expected variability are established under existing conditions.
29	Nueces Watershed Pre- and Post-Development Nutrient Budgets.	H	This can inform the expected variation in a sound ecological environment and relates to interpretation of system response in light of long-term monitoring.
30	Assessment of Sediment Transport and Loadings into the Nueces Delta and Estuary.	H	This represents an element of our suggested long-term monitoring effort support a statewide view of the systems.

Appendix C – Annotated Bibliography

This annotated bibliography provides citations targeting:

1. Adaptive Management
2. Instream Flows, Flow-Ecology Responses, Life Histories, Instream flow Validation
3. Estuaries
4. Geomorphology, Fluvial Processes and Hydrology
5. Riparian

Literature targeted Texas basin and bay systems but germane literature nationally and internationally is also included. Both peer reviewed and gray literature sources are provided. A number of review articles and databases on flow-ecology relationships covering hundreds of studies have been included. These references are provided to help inform the BBASC/BBEST in the adaptive management process and support ongoing research efforts under Senate Bill 3 and related research efforts.

Adaptive Management

The following citations contain resources that explain the adaptive management process, key elements, implementation strategies, pitfalls, and in particular stressing the importance of establishment long-term monitoring programs and stakeholder engagement necessary to inform the adaptive management process.

Higgins, J. V., C. P. Konrad, A. Warner, and J. T. Hickey. 2011. A framework for monitoring, reporting and managing dam operations for environmental flows. Version 1.0. SRP measures working group.

Developing and implementing environmental flows and evaluating ecosystem changes in response involve: 1) defining an environmental flow prescription; 2) assessing the degree to which the prescription is implemented; 3) short-term monitoring of ecosystem responses to environmental flows; and 4) long-term monitoring of ecosystem status and trends that relate to flow. The primary purpose of this document is to assist practitioners in selecting a few well-considered indicators to monitor, as opposed to an exhaustive list that is expensive to implement and not necessarily more informative.

National Research Council 2004. Adaptive Management for Water Resources Project Planning. Washington, DC: The National Academies Press. https://doi.org/10.17226/10972.

There are multiple views and definitions regarding adaptive management, but elements that have been identified in theory and in practice are: management objectives that are regularly revisited and accordingly revised, a model(s) of the system being managed, a range of management options, monitoring and evaluating outcomes of management actions, mechanisms for incorporating learning into future decisions, and a collaborative structure for stakeholder participation and learning.

Souchon, Y., C. Sabaton, R. Deibel, D. Reiser, J. Kershner, M. Gard, C. Katapodis, P. Leonard, N.L. Poff, W.J. Miller, and B.L. Lamb. 2008. Detecting biological responses to flow management: Missed opportunities; future directions. River. Res. Applic. 24: 506–518 (2008)

The conclusions of numerous stream restoration assessments all around the world are extremely clear and convergent: there has been insufficient appropriate monitoring to improve general knowledge and expertise. In the specialized field of instream flow alterations, we consider that there are several opportunities comparable to full-size experiments. Hundreds of water management decisions related to instream flow releases have been made by government agencies, native peoples, and non-

governmental organizations around the world. These decisions are based on different methods and assumptions and many flow regimes have been adopted by formal or informal rules and regulations. Although, there have been significant advances in analytical capabilities, there has been very little validation monitoring of actual outcomes or research related to the response of aquatic dependent species to new flow regimes. In order to be able to detect these kinds of responses and to better guide decision, a general design template is proposed. The main steps of this template are described and discussed, in terms of objectives, hypotheses, variables, time scale, data management, and information, in the spirit of adaptive management. The adoption of such a framework is not always easy, due to differing interests of actors for the results, regarding the duration of monitoring, nature of funding and differential timetables between facilities managers and technicians. Nevertheless, implementation of such a framework could help researchers and practitioners to coordinate and federate their efforts to improve the general knowledge of the links between the habitat dynamics and biological aquatic responses.

Stankey, G.H., R.N. Clark, and B.T. Bormann. 2005. Adaptive management of natural resources: Theory, concepts, and management institutions. USDA General Technical Report, PNW-GTR-654, August 2005. 73 pp.

This report reviews the extensive and growing literature on the concept and application of adaptive management. Literature from a diverse range of fields including social learning, risk and uncertainty, and institutional analysis was reviewed, particularly as it related to application in an adaptive management context. The review identifies opportunities as well as barriers that adaptive management faces. It concludes by describing steps that must be taken to implement adaptive management.

Summers, M.F., L.P. Holman, and R.C. Grabowski. 2015. Adaptive management of river flows in Europe: A transferable framework for implementation. Journal of Hydrology 531 (2015) 696-706.

Planned adaptive management studies on multiple rivers under the European Water Framework Directive represent an opportunity to learn about ecological flow requirements and improve the quantitative evidence base. However, identifying clear ecological responses to flow alteration can be a significant challenge, because of the complexity of river systems and the other factors which may confound the response. This paper describes the Adaptive River Management (ARM) framework, a flexible framework for implementing adaptive management of river flows that is transferable to other regions of the world.

Webb, J.A., R.J. Watts, C. Allan, and A.T. Warner. 2017. Chapter 25. Principles for monitoring, evaluation, and adaptive management of environmental water regimes. In: Water for the Environment from policy and science to implementation and management. Eds. A.C. Horne, J.A. Webb, M.J. Stewardson, B. Richter, and M. Acreman. Elsevier Press. ISBN: 978-0-12-803907-6

Provides a comprehensive overview of the history of adaptive management, the key role of monitoring to inform knowledge acquisition, measures of adaptive management success, the role of long-term monitoring for evaluation of ecosystem responses to environmental flows, and the role of stakeholders in the process.

Webb, J.A., R.J. Watts, C. Allan., and J. C. Conallin. 2018. Adaptive management of environmental flows. Environmental management (2018) 61:339-346. DOI 10.1007/s00267-017-0981-6

Reviews a number of adaptive management related publications and highlights both success and failures and specifically note the lack of equal contributions by researchers, managers, and local stakeholders to the adaptive management process.

Williams, B. K., R. C. Szaro, and C. D. Shapiro. 2009. Adaptive Management: The U.S. Department of the Interior Technical Guide. Adaptive Management Working Group, U.S. Department of the Interior, Washington, DC.

Provides a clear elucidation of what adaptive management is, when it should be utilized, how it should be implemented, how to assess when it is successful and related operational issues.

Instream Flows, Flow-Ecology Responses, Life Histories, Instream flow Validation

A key finding in our synthesis review of the instream flow validation studies (see Appendix A Section A.7) was the lack of discussing study results in light of the broader scientific literature on flow-ecology relationships or in the context of expected ranges or variation in measured indicator metrics. The citations below are provided to better inform the context of study results in light of expected ranges in responses for multiple taxa related to alterations in the hydrologic regime (magnitude, frequency, duration, rate of change and timing) as well as other natural and anthropogenic induced changes. These resources also provide an expanded context to establishing expected characteristics and variability or ranges of indicators of a sound ecological environment.

Anderson, A.A., C. Hubbs, K.O. Winemiller, and R.J. Edwards. 1995. Texas Freshwater Fish Assemblages following Three Decades of Environmental Change. The Southwestern Naturalist, Sep., 1995, Vol. 40, No. 3 (Sep., 1995), pp. 314-321

In 1953, C. Hubbs and colleagues surveyed fishes from a large number and variety of freshwater habitats throughout the state of Texas. Thirty-three years later, he replicated sampling at 129 of these sites within the Red, Sabine, Neches, Trinity, Brazos, Colorado, Guadalupe, San Antonio, Nueces, and Rio Grande drainages. Care was taken to match original sampling effort, times, and dates at each location. Relative proportional abundances of families showed numerous changes from 1953 to 1986 within the ten basins. Mantel tests comparing family abundances in 1953 and 1986 datasets showed little overall change statewide. Sites in the eastern half of the state that did not contain marine species showed less significant positive covariation between early and recent datasets than those in western Texas. Rank plots of species diversity (H') for the two regions of the state showed a consistent trend of decreased diversity over time in eastern Texas. A similar plot for west Texas showed decreased diversity with time, but only within species-poor assemblages. The analyses reveal reductions in biological diversity on a local scale, but also reveal relative stability in statewide and regional ichthyofaunas. Despite the encouraging large-scale trends, several Texas fishes went extinct and others are threatened as a result of local habitat disturbances, including alteration of instream flow, eutrophication, and exotic species introductions.

Apse, C., M. DePhilip, J. Zimmerman, and M.P. Smith. 2008. Developing Instream Flow Criteria to Support Ecologically Sustainable Water Resource Planning and Management. The Nature Conservancy. 196 pp.

This report was produced to support efforts to develop and implement an instream flow protection system through a collaborative process with the public agencies that make up the Pennsylvania Instream Flow Technical Advisory Committee (TAC). The scope assessed “available data, tools and approaches that can be used to meet the overall goal of statewide instream flow protection criteria.” The scope also included a “pilot watershed study effort using existing data to develop general stressor-response relationships between flow alteration and ecological health.” In accordance with the project scope, this report includes an evaluation of the primary options for statewide instream flow (i.e., environmental flow) criteria development, estimates of related costs, and evaluation of pilot studies classifying Pennsylvania rivers statewide and linking flow alteration to biological response in the Susquehanna watershed.

Armanini, D. G., N. Horrigan, W. A. Monk, D. L. Peters, and D. J. Baird. 2010. Development of a benthic macroinvertebrate flow sensitivity index for Canadian rivers. *River Research and Applications.*

Developed an index for assessing ecological impacts of hydrologic alteration, based on the sensitivity of macroinvertebrates to river flow. Intended as a tool for improving river management and restoration efforts, the Canadian Ecological Flow Index (CEFI) is an easily calculated metric that can be applied in many places across Canada without requiring collection of new data.

Armstrong, D. S., Richards, T. A., and Brandt, S. L. 2010. Preliminary assessment of factors influencing riverine fish communities in Massachusetts. U.S. Geological Survey Open-File Report 2010-1139.

Determined relations between fish-community characteristics and anthropogenic alteration, including flow alteration and impervious cover, relative to the effects of physical basin and land-cover (environmental) characteristics. Fish data were obtained for 756 fish-sampling sites from the Massachusetts Division of Fisheries and Wildlife fish-community database.

Armstrong, D. S., T. A. Richards, and S.B. Levin. 2011. Factors influencing riverine fish assemblages in Massachusetts. U.S. Geological Survey Scientific-Investigations Report 2011-5193.

Assessed factors that influence riverine fish assemblages in Massachusetts, including land use and flow alteration.

Bonner, T., and D.T. Runyan. 2007. Fish assemblage changes in three western Gulf Slope drainages. Final Report to TWDB Contract No. 2 005-483-033. 46 pp.

The purpose of this study was to quantify fish assemblage changes in three riverine environments in Texas (lower Brazos River, lower Sabine River, and lower San Antonio River). These rivers represent gulf slope drainages west of the Mississippi River drainage that collectively share similar geological histories and ichthyofauna (Conner and Suttkus 1987) but differ along precipitation and anthropogenic impact gradients. Additionally, we analyzed stream flow records in these watersheds to describe relationships among hydrologic alterations, fish assemblage changes, and specific fish population changes.

Bruckerhoff, L.A., D.R. Leasure, and D.D. Magoulick. 2018. Flow–ecology relationships are spatially structured and differ among flow regimes. J Appl Ecol. 2019; 56:398–412.

We used a trait- based approach to quantify flow–ecology relationships in classified flow regimes and assessed the influence of spatial autocorrelation on our inferences. Our main objective was to compare relationships between stream hydrology and fish traits among flow regimes. For comparison, we also assessed these relationships for all streams combined, ignoring flow regime classifications. Several studies have documented strong relation-ships between fish traits and hydrology at broad spatial scales, but these studies did not account for differences among flow regimes (McManamay, Bevelhimer, and Frimpong, 2015; McManamay and Frimpong, 2015; Mims and Olden, 2012, 2013; Poff and Allan, 1995; Poff et al., 2010). We contribute to this body of work by testing these relationships in specific flow regimes at a regional, management level spatial scale.

Caiola, N. C. Ibanez, J. Verdu, and A. Munne. 2014. Effects of flow regulation on the establishment of alien fish species: A community structure approach to biological validation of environmental flows. Ecological Indicators 45 (2014) 598–604.

The lower Ebro River (Catalonia, Spain) has a fish community dominated by alien species in both richness (55%) and abundance (78%). This river stretch is regulated by many dams and its flow was severely reduced by increasing water uses. We found strong evidence that the success of establishment and dispersal of alien fish species in this Mediterranean large river is enhanced by flow reduction through decreased water flow velocity in the littoral zone. Results show that when water flow is below 0.40 m/s, the probability that a fish community is dominated by alien species is higher than 50%, according to a logistic regression model that achieved 91% of well classified cases when predicting alien species dominance over natives. This relationship was used to perform an ecologically-based validation (biological validation) of 12 environmental flows proposed by several authors using different hydrologically-based methods.

Carlisle, D.M., D.M. Wolcok, and M.R. Meador. 2010. Alteration of streamflow magnitudes and potential ecological consequences: a multiregional assessment. Front Ecol Environ 2010; doi:10.1890/100053

Human impacts on watershed hydrology are widespread in the US, but the prevalence and severity of streamflow alteration and its potential ecological consequences have not been quantified on a national scale. We assessed streamflow alteration at 2888 streamflow monitoring sites throughout the conterminous US. The magnitudes of mean annual (1980–2007) minimum and maximum stream flows were found to have been altered in 86% of assessed streams. The occurrence, type, and severity of streamflow alteration differed markedly between arid and wet climates. Biological assessments conducted on a subset of these streams showed that, relative to eight chemical and physical covariates, diminished flow magnitudes were the primary predictors of biological integrity for fish and macroinvertebrate communities. In addition, the likelihood of biological impairment doubled with increasing severity of diminished stream flows. Among streams with diminished flow magnitudes, increasingly common fish and macroinvertebrate taxa possessed traits characteristic of lake or pond habitats, including a preference for fine-grained substrates and slow-moving currents, as well as the ability to temporarily leave the aquatic environment.

Chem. W., and J.D. Olden. 2017. Evaluating transferability of flow–ecology relationships across space, time and taxonomy.

To evaluate the merit of using environmental guilds to transfer knowledge of flow responses across taxonomy, we compared flow–ecology relationships of species within the same flow guild (fluvial specialists that are more dependent on rapidly flowing water versus habitat generalists that can persist in more lentic flow conditions) and of species exhibiting similar life-history strategies (equilibrium, opportunistic, or periodic as defined by Olden et al., 2006).

Davis, M. M., and S.K. Brewer (eds.). 2014. Gulf Coast Prairie Landscape Conservation Cooperative Regional Hypotheses of Ecological Responses to Flow Alteration. A report by the GCP LCC Flow-Ecology Hypotheses Committee to the Southeast Aquatic Resources Partnership (SARP) for the GCP LCC Instream Flow Project. Wildlife Management Institute Grant Number GCP LCC 2012-003

Identified the distribution of flow-sensitive species and developed 27 regional flow-ecology hypotheses targeting fish, mussels, birds, and woody riparian species related to hydrologic parameters (magnitude, duration, frequency, rate of change, and timing) based on published studies.

DePhilip, M. and Moberg, T. 2010. Ecosystem flow recommendations for the Susquehanna River basin. Report to the Susquehanna River Commission and U.S. Army Corps of Engineers. The Nature Conservancy. 96 p

Systematically compile qualitative flow-ecology relationships for all ecosystem components of all river types in the Pennsylvania's Susquehanna River basin. This approach has also been applied to Pennsylvania's Delaware and Ohio River basins and New York's Great Lakes basin, resulting in precautionary environmental flow criteria to protect inter-annual and intra-annual flow regimes throughout these large watersheds.

European Commission. 2015. Ecological flows in the implementation of the Water Framework Directive. Guidance Document No. 31. Technical Report - 2015 – 086. 108 pp.

Building on an assessment of progress in Water Framework Directive (WFD) implementation in its 1st cycle, the Blueprint1 to safeguard Europe's water resources stressed the urgent need to better address over-abstraction of water, the second most common pressure on EU ecological status, and to recognize that water quality and quantity are intimately related within the concept of 'good status'. This would require an EU-wide acknowledgement of the ecological flows, i.e., the "amount of water required for the aquatic ecosystem to continue to thrive and provide the services we rely upon". To achieve this, the Blueprint proposed the development of a guidance document in the framework of the WFD common implementation strategy (CIS) that would provide an EU definition of ecological flows and a common understanding of how it should be calculated, so that ecological flows may be applied in the next cycle of river basin management plans (RBMPs) due for adoption by the end of 2015. This document is intended to support a shared understanding of ecological flows (Eflows) and ways to use them in the RBMPs. To that end, it covers a working definition in the context of the WFD. Secondly, it provides an overview of the steps in the WFD cycle where Eflows play a role. Thirdly, this document draws upon lessons learned from practices that Member States already carry out in this field and provides information on methodologies, monitoring, measures and evaluation concerning Eflows.

Freeman, M. C. and Marcinek, P. A. 2006. Fish assemblage responses to water withdrawals and water supply reservoirs in Piedmont streams. *Environmental Management,* **38** (3): 435-450.

Investigated fish assemblage responses to water withdrawals and water supply reservoirs in Piedmont streams in Georgia, USA. Although never intended for this purpose, the state of Connecticut used these research results as the basis for its streamflow standard.

George, R., R. McManamay, D. Perry, J. Sabo, and B.L. Ruddell. 2021. Indicators of hydro-ecological alteration for the rivers of the United States. Ecological Indicators 120 (2021) 106908

Recent decades have produced a river of field data linking hydrologic alteration to fish populations in hundreds of U.S. River systems. Adverse impact thresholds and relationships between flow alteration and fish populations are key for advancing environmental flow conservation and environmental flow regulations in U.S. waterways. Prior work has established relationships in individual rivers and fine scale basins, but not for large basins or at national scale. As a first step toward establishing consistent fish-flow relationships and adverse impact thresholds in every US waterway, we analyze a nation-wide aggregated dataset from McManamay et al., 2017 containing co-located estimates of altered hydrologic metrics (HMs) for flow and native fish richness. In each medium sized river system (HUC4) we (1) identify the hydrologic metrics that most powerfully explain observed impacts on native fish richness, (2) estimate an adverse resource impact threshold defining excessive flow alteration, and (3) attribute the main causes of observed flow alteration. Strong empirical relationships between hydrologic metrics and native fish richness are thus established for most HUC4 basins in the continental U.S. and can be used as guidelines for science-based management. However, the findings underline a major aquatic ecology data gap in the western U.S. where a lack of statistically adequate field observations currently prevent clear results, and this gap will hinder science-based management of those river basins until it is filled.

Hammontree, S.E., J.A. Mabe, and J.H. Kennedy. 2012. Habitat Requirements of the Golden Orb (Quadrula aurea), Final Report for Texas Water Development Board and Texas Parks and Wildlife Department TWDB Contract No. 0904830970 and TPWD Contract No. 404304. 46 pp.

This study is focused on the determination of habitat parameters influencing distributions of Golden Orb (*Q. aurea*) mussels in the Guadalupe-San Antonio River basin. The objectives were to identify four sample sites with sufficient populations of *Q. aurea* to evaluate habitat parameters, evaluate the distribution of *Q. aurea* at selected sample sites in relation to habitat parameters and monitor flow conditions at these locations, calculate the shear stress ratio (RSS) for multiple flow conditions and the relationship with mussel density at selected sites, and compile and summarize life history information for *Q. aurea* and related species.

Kanno, Y., and Vokoun, J. C. 2010. Evaluating effects of water withdrawals and impoundments on fish assemblages in southern New England streams, USA. *Fisheries and Management Ecology* 17:272-283.

Evaluated the ecological effects of water withdrawals and impoundments on fish assemblage structure using electric fishing data collected at 33 wadeable streams in Connecticut, USA.

Karatayev, A.Y., and L.E. Burlakova. 2008. Distributional Survey and Habitat Utilization of Freshwater Mussels. Final Report to TWDB Grant No. 434135. 47 pp.

Provides data on mussel distribution, habitat utilization and other related data in the Brazos, San Antonio, and Sabine River Basins.

Kendy, E., C. Apse, and K. Blann. 2012. A practical guide to environmental flows for policy and planning, with nine case studies from the United States. The Nature Conservancy.

Explains how scientists in 5 states and river basins (Michigan, Massachusetts, Colorado, Ohio, and the middle Potomac River basin) quantified flow-ecology relationships for water withdrawal permitting and planning.

Kennard, M.J. 2005. A Quantitative Basis for the Use of Fish as Indicators of River Health in Eastern Australia. A thesis submitted in fulfilment of the requirements of the degree of Doctor of Philosophy, Centre for Riverine Landscapes, Faculty of Environmental Sciences, Griffith University, Brisbane, Australia. 236 pp.

Identify five key requirements of a quantitative and defensible river health assessment program that needs to be evaluated before indicators based on fish can be validly applied for river health assessment in the region. The five requirements are: 1) quantification of error associated with sampling fish; 2) assessment of natural ranges of spatial and temporal variation in fish assemblage attributes; 3) accurate definition of the reference condition expected for these attributes in the absence of human disturbance; 4) demonstrated relationships of the indicators with disturbance; and 5) evaluation of potentially important confounding environmental and biological factors. These are critical considerations for minimizing the frequency of Type I errors (incorrectly classifying a site as impaired) and Type II errors (incorrectly classifying a site as unimpaired) and accurately assessing river health.

Kennen, J. G., Kauffman, L. J., Ayers, M. A., Wolock, D. M. and Caolarullo, S. J. 2007. Use of an integrated flow model to estimate ecologically relevant hydrologic characteristics at stream biomonitoring sites. *Ecological Modeling*: 20 p.

Used non-metric multidimensional scaling (NMS) to evaluate variation in aquatic-invertebrate assemblage structure and built a series of multiple linear regression (MLR) models that identify the most important environmental and hydrologic variables driving the differences in aquatic-invertebrate assemblages across a disturbance gradient.

Kennen, J. G., and Riskin, M. L. 2010. Evaluating effects of potential changes in streamflow regime on fish and aquatic-invertebrate assemblages in the New Jersey Pinelands. U.S. Geological Survey Scientific Investigations Report 2010-5079, 34 p

Evaluated structural and functional responses of fish and aquatic invertebrate assemblages to increased water extraction from aquatic ecosystems of the New Jersey (USA) Pinelands, using basin size as a surrogate for water availability. Forty-three 100-meter-long stream reaches were sampled during high- and low-flow periods across a designed hydrologic gradient.

Kennen, J. G., K. Riva-Murray, and K. M. Beaulieu. 2010. Determining hydrologic factors that influence stream macroinvertebrate assemblages in the northeastern US. *Journal of Ecohydrology*, 3(1), 88–106.

Related streamflow patterns to aquatic macroinvertebrate assemblages in 67 small-to-medium upland streams in the northeastern United States and found negative effects of hydrologic alteration on biotic integrity. Mean April flow and duration of high flows were particularly indicative of assemblage variability.

King, A.J., B. Gawne, L. Beesley, J.D. Koehn, D.L. Nielson, and A. Price. 2015. Improving ecological response monitoring of environmental flows. Environmental Management 55, 991-1005 (2015). https://doi.org/10.1007/s00267-015-0456-6

Environmental flows are now an important restoration technique in flow-degraded rivers, and with the increasing public scrutiny of their effectiveness and value, the importance of undertaking scientifically robust monitoring is now even more critical. Many existing environmental flow monitoring programs have poorly defined objectives, nonjustified indicator choices, weak experimental designs, poor statistical strength, and often focus on outcomes from a single event. These negative attributes make them difficult to learn from. We provide practical recommendations that aim to improve the performance, scientific robustness, and defensibility of environmental flow monitoring programs. We draw on the literature and knowledge gained from working with stakeholders and managers to design, implement, and monitor a range of environmental flow types. We recommend that (1) environmental flow monitoring programs should be implemented within an adaptive management framework; (2) objectives of environmental flow programs should be well defined, attainable, and based on an agreed conceptual understanding of the system; (3) program and intervention targets should be attainable, measurable, and inform program objectives; (4) intervention monitoring programs should improve our understanding of flow-ecological responses and related conceptual models; (5) indicator selection should be based on conceptual models, objectives, and prioritization approaches; (6) appropriate monitoring designs and statistical tools should be used to measure and determine ecological response; (7) responses should be measured within timeframes that are relevant to the indicator(s); (8) watering events should be treated as replicates of a larger experiment; (9) environmental flow outcomes should be reported using a standard suite of metadata. Incorporating these attributes into future monitoring programs should ensure their outcomes are transferable and measured with high scientific credibility.

Konrad, C. P., Brasher, A. M. D. and May, J. T. 2008. Assessing streamflow characteristics as limiting factors on benthic invertebrate assemblages in streams across the western United States. *Freshwater Biology*.

Used a nonparametric screening procedure to identify different forms of streamflow-invertebrate associations for streams across the western United States. Selected ceiling and floors that represent conditional responses of invertebrates to streamflow were analyzed using quantile regression. "Although this approach cannot distinguish the effects of streamflow on invertebrates from those of confounding factors that are correlated with streamflow ... [it] is an assessment of the potential for a particular type of streamflow pattern, such as frequency of high flows, to limit a characteristic of benthic invertebrate assemblages."

Le, C.T.U., W.L. Paul, B. Gawne, and P.J. Suter. 2019. Quantitative Flow-Ecology Relationships Using Distributed Lag Nonlinear Models: Large Floods in the Murray River Could Have Delayed Effects on Aquatic Macroinvertebrates Lasting More Than Three Decades. Water Resources Research, 56, e2019WR025896. https://doi.org/10.1029/2019WR025896

Research is being done around the world to understand how much water is required to sustain river ecosystems, and therefore, how much can be extracted for consumptive uses such as irrigated agriculture. We used long-term monitoring data (1980–2012) on aquatic macroinvertebrates—which includes insects, crustaceans, mussels, snails, and worms that spend all or part of their life in water—collected along 2,300 km of the Murray River, Australia, to investigate the relationship between river flow and the health of aquatic ecosystems. These data indicate that small to medium flows might have an immediate effect through improvements in water quality, but large floods may have sizeable, delayed impacts on macroinvertebrates lasting more than three decades. The number of species and overall abundance of macroinvertebrates initially decreased, due to washout, but then increased for a period of about 25 years after the historic flood of 1993, persisting throughout the Millennium drought (1996–2010). The positive legacy of floods might be due to an influx of woody debris during the event, which can provide habitat and food for macroinvertebrates until decomposition of the woody material is complete.

Li, R.Y., and F.P. Gelwick. 2005. The relationship of environmental factors to spatial and temporal variation of fish assemblages in a floodplain river in Texas, USA. Ecology of Freshwater Fish 2005: 14: 319–330.

To extend our understanding of temperate, large river assemblages, we assessed the distribution of fishes in a downstream unregulated portion of the Brazos River in Texas, USA. Our objectives were to: (1) quantify and compare spatial and temporal variation among assemblages in shallow-margin versus deep-water habitats, (2) identify species–environment relationships that are likely to explain the structure of assemblages within these habitats and (3) quantify and compare assemblage structure that is related to seasonal versus nonseasonal components of environmental variation.

Lynch, D.T., D.R. Leasure, and D.D. Magoulick. 2019. Flow alteration-ecology relationships in Ozark Highland streams: Consequences for fish, crayfish and macroinvertebrate assemblages. Science of the Total Environment 672 (2019) 680–697

We examined flow alteration-ecology relationships in benthic macroinvertebrate, fish, and crayfish assemblages in Ozark Highland streams, USA, over two years with contrasting environmental conditions, a drought year (2012) and a flood year (2013). We hypothesized that: 1) there would be temporal variation in flow alteration-ecology relationships between the two years, 2) flow alteration-ecology relationships would be stronger during the drought year vs the flood year, and 3) fish assemblages would show the strongest relationships with flow alteration. We used a quantitative richest-targeted habitat (RTH) method and a qualitative multi-habitat (QMH) method to collect macroinvertebrates at 16 USGS gaged sites during both years. We used back-pack electrofishing to sample fish and crayfish at 17 sites in 2012 and 11 sites in 2013. We used redundancy analysis to relate biological response metrics, including richness, diversity, density, and community-based metrics, to flow alteration. We found temporal variation in flow alteration-ecology relationships for all taxa, and that relationships differed greatly between assemblages. We found relationships were stronger for macroinvertebrates during the drought year but not for other assemblages, and that fish assemblage relationships were not stronger than the invertebrate taxa. Magnitude of average flow, frequency of high flow, magnitude of high flow, and du-ration of high flow were the most important categories of flow alteration metrics across taxa. Alteration of high and average flows was more important than alteration of low flows. Of 32 important flow alteration metrics across years and assemblages, 19 were significantly altered relative to expected values. Ecological responses differed substantially between drought and flood years, and this is likely to be exacerbated with predicted climate.

Mcgregor, G.B., J.C. Marshall, J.S. Lobegeiger, D. Holloway, N. Menke, and J. Coysh. 2018. A Risk-Based Ecohydrological Approach to Assessing Environmental Flow Regimes. Environmental Management (2018) 61:358–374 DOI 10.1007/s00267-017-0850-3

For several decades there has been recognition that water resource development alters river flow regimes and impacts ecosystem values. Determining strategies to protect or restore flow regimes to achieve ecological out-comes is a focus of water policy and legislation in many parts of the world. However, consideration of existing environmental flow assessment approaches for application in Queensland identified deficiencies precluding their adoption. Firstly, in managing flows and using ecosystem condition as an indicator of effectiveness, many approaches ignore the fact that river ecosystems are subjected to threatening processes other than flow regime alteration. Secondly, many focus on providing flows for responses without considering how often they are necessary to sustain ecological values in the long-term. Finally, few consider requirements at spatial-scales relevant to the desired out-comes, with frequent focus on individual places rather than the regions supporting sustainability. Consequently, we developed a risk-based ecohydrological approach that identifies ecosystem values linked to desired ecological outcomes, is sensitive to flow alteration and uses indicators of broader ecosystem requirements. Monitoring and research is undertaken to quantify flow-dependencies and ecological modelling is used to quantify flow-related eco-logical responses over an historical flow period. The relative risk from different flow management scenarios can be valuated at relevant spatial-scales. This overcomes the deficiencies identified above and provides a robust and useful foundation upon which to build the information needed to support water planning decisions. Application of the risk assessment approach is illustrated here by two case studies.

McManamay, R.A., D.J. Orth, J. Kauffman, and M.M. Davis. 2013. A database and meta-analysis of ecological responses to stream flow in the South Atlantic Region. Southeastern Naturalist, Vol. 12, Monograph 5: pp. 1-36.

McManamay, R.A., D.J. Orth, and J. Kauffman. 2011. Ecological Responses to Flow Alteration in the South Atlantic Region: A Literature Review and Meta-Analysis. Final report to the Southeastern Aquatic Resource Partnership. 62 pp.

These are two companion studies compiled 186 studies related to either empirical and theoretical relationships between flow and ecology in the South Atlantic region (SAR) of the United States. A total of 109 of the 186 sources had sufficient information to support quantitative analyses. Ecological responses to natural changes in flow magnitude, frequency, and duration were highly variable regardless of the direction and magnitude of changes in flow while the majority of ecological responses to anthropogenic-induced flow alterations were negative. Fish abundance, diversity, reproduction, and habitat consistently showed negative responses to anthropogenic flow alterations, whereas other ecological categories (e.g., macroinvertebrates and riparian vegetation) showed somewhat variable responses and even positive responses (e.g., algal abundance). Several flow-ecology relationships were developed related to changes in hydrology (magnitude, duration, frequency, rate of change, and timing) for algae, birds, ecosystem gross primary productivity, macrophytes, mammals, organic content, fish, macroinvertebrates, and riparian species.

Michel Leclerc, André Saint-Hilaire and José Bechara. 2003 State-of-the-Art and Perspectives of Habitat Modelling for Determining Conservation Flows, Canadian Water Resources Journal, 28:2, 135-151, DOI: 10.4296/cwrj2802135

The objective of this paper is to review current knowledge and techniques presently being used and developed to estimate or simulate aquatic habitat availability and quality, in order to determine the most appropriate flow regime. These methods were reviewed at a recent workshop held in Quebec City on March 4 and 5, 2003. Papers in this special issue of the Journal were written by the keynote speakers invited to the workshop. Our paper provides a broad overview of their findings, as well as a survey of the state-of-the-art.

Mims, Meryl C., and Julian D. Olden. 2012. Life history theory predicts fish assemblage response to hydrologic regimes. *Ecology*, 93:35-45.

Tested ecological theory predicting directional relationships between major dimensions of the flow regime and life history composition of fish assemblages in perennial free-flowing rivers throughout the continental United States. Their results provide empirical evidence illustrating the value of using life history theory to understand both the patterns and processes by which fish assemblage structure is shaped by adaptation to natural regimes of variability, predictability, and seasonality of critical flow events over broad biogeographic scales.

Mueller, M., and J. Geist. 2016. Conceptual guidelines for the implementation of the ecosystem approach in biodiversity monitoring. Ecosphere 7(5):e01305. 10.1002/ecs2.1305

The theoretical concept of the ecosystem approach (EA) aims at assessing ecosystem function based on integrative assessments of multiple levels of biological organization. Since the United Nations Convention on Biological Diversity in 1992, the EA has been increasingly integrated into environmental policy and legislation, but to date, its practical implementation remains vague with a lack of universal guidelines and concrete recommendations for its use across ecosystem boundaries. On the basis of a re-view of scientific literature, worldwide environmental legislation and existing monitoring approaches, we identified the most important factors which hamper the feasibility of the EA. We propose a generally applicable methodology for implementing the EA in ecological and environmental monitoring across different ecosystems and habitat types. Successful application of the EA largely depends on adequately standardized and synchronized sampling designs for all abiotic and biotic components, appropriate depth of taxonomic identification, and sufficient spatial and temporal replication. The proposed step- by- step guidelines for using the EA are valid across ecosystem types, geographic regions, and for a variety of data types, making them promising tools for ecological monitoring.

Osting, T., R. Mathews, and B. Austin. 2004. Analysis of Instream Flows for the Lower Brazos River - Hydrology, Hydraulics, and Fish Habitat Utilization. Final Report, Volume I – Main Report. Submitted to the US Army Corps of Engineers in fulfillment of Obligation No. W45XMA11296580 and TWDB Contract No. 2001-REC-015

This report addresses the impact of the proposed Allens Creek Reservoir project on the hydrology and aquatic habitat in the lower Brazos River, and on the migration of saline water in the Brazos River estuary. Regional characteristics of the lower Brazos River basin are presented along with historical stream flow records that are analyzed for changes in flow regime over time. A preliminary investigation of the impact of the Allens Creek project on sediment transport is also included.

Pease, A.A., J.M. Taylor, K.O. Winemiller, and R.S. King. 2011. Multiscale Environmental Influences on Fish Assemblage Structure in Central Texas Streams. Transactions of the American Fisheries Society 140:1409–1427, 2011.

We investigated the influences of local and landscape-scale environmental variables on fish

assemblage structure among 64 stream reaches in two large river basins in central Texas. The broad spatial extent of this study region pro-vided an opportunity to examine fish assemblage–environment relationships at multiple scales across a range of stream types in landscapes exposed to varying degrees of anthropogenic alteration. We used nonmetric multidimensional scaling (NMS) combined with permutational analysis of variance, k-means cluster analysis, and indicator species analysis to evaluate broad-scale influences of ecoregional and large river basin boundaries on fish assemblage structure. We also estimated relationships between fish assemblage structure and environmental factors with NMS and rotational vector fitting across all ecoregions and within ecoregions. Ordinations of sites based on species composition grouped stream reaches together according to ecoregion, and k-means clustering identified three groups that corresponded with ecoregional membership. Several species had high affinities with specific ecoregions, a pattern that tracked broad-scale physiographic differences in climate, topography, terrestrial vegetation, and instream habitat. Within ecoregions, we observed that local-scale stream habitat variables as well as larger-scale landscape features were significantly related to fish assemblage composition. Substrate composition was a key local-scale habitat factor, and a gradient of rocky substrate to predominance of mud and silt correlated strongly with assemblage structure within all three ecoregions. The abundance of instream woody debris was also an important local-scale correlate for fish assemblage structure. At the landscape scale, patterns of agricultural and urban land development in the surrounding watersheds were consistently associated with fish assemblage structure in each ecoregion. This study adds important information toward a better understanding of how environmental factors structure fish assemblages across scales, which should facilitate refinement of existing habitat and biological indices for conservation of stream habitats and their biota.

Persinger, J.W., D.J. Orth, and A.W. Averett. 2010. Using habitat guilds to develop habitat suitability criteria for a warmwater stream fish assemblage. River. Res. Applic. (2010), DOI: 10.1002/rra.1400. 11 pp.

The diversity of fish species found in warmwater stream systems provides a perplexing challenge when selecting species for assessment of instream flow needs from physical habitat analyses. In this paper we examined the feasibility of developing habitat suitability criteria (HSC) for the entire fish community of a warmwater stream using habitat guilds. Each species was placed a priori into a guild structure and habitat data were collected for depth, velocity, Froude number, distance to cover, embeddedness and dominant and subdominant substrate. Correct guild classification was tested with linear discriminant analysis for each species. Correct classification based on habitat-use data was highest for riffle and pool-cover guilds, whereas the fast-generalist and pool-run classes, the broader niche guilds, were more frequently misclassified. Variables most important for discriminating guilds were Froude number, velocity and depth in that order. Nonparametric tolerance limits were used to develop guild suitability criteria for continuous variables and the Strauss linear index was used for categorical variables. We recommend the use of a wide array of variables to establish more accurate habitat analysis. Additionally, guild HSC can be developed with similar effort to that needed to develop HSC for a small number of individual species. Results indicate that a habitat guild structure can be successfully transferred to another river basin and that habitats for a diverse fish assemblage can be adequately described by a small number of habitat guilds. This approach represents an alternative for incorporating entire fish assemblages into habitat analyses of warmwater stream systems.

Poff, N., and J. Zimmerman. 2010. Ecological Responses to Altered Flow Regimes: A Literature Review to Inform the Science and Management of Environmental Flows. Freshwater Biology. 55. 194 - 205. 10.1111/j.1365-2427.2009.02272.x.

A total of 165 papers published over the last four decades were categorized in light of flow alteration in terms of magnitude, frequency, duration, timing and rate of change as reported by the individual studies and were utilized to examine the ecological responses according to taxonomic identity (macroinvertebrates, fish, riparian vegetation) and type of response (abundance, diversity, demographic parameters). Macroinvertebrates showed mixed responses to changes in flow magnitude, with abundance and diversity both increasing and decreasing in response to elevated flows and to reduced flows. Fish abundance, diversity and demographic rates consistently declined in response to both elevated and reduced flow magnitude. Riparian vegetation metrics both increased and decreased in response to reduced peak flows, with increases reflecting mostly enhanced non-woody vegetative cover or encroachment into the stream channel. They conclude that flow alteration is associated with ecological change and that the risk of ecological change increases with increasing magnitude of flow alteration.

Praskievicz, S., and C. Luo. 2020. Assessment of flow–ecology relationships for environmental flow standards: a synthesis focused on the southeast USA, Hydrological Sciences Journal, 65:4, 571-582, DOI: 10.1080/02626667.2020.1714051

Environmental flow standards are a management tool that can help to protect the ecosystem services sustained by rivers. Although environmental flow requirements can be assessed using a variety of methods, most of these methods require establishing relationships between flow and habitat of species of concern. Here, we conducted a synthesis of past flow–ecology studies in the southeast USA. For each state or interstate river basin, we used the published data to determine the flow metrics that resulted in the greatest changes in ecological metrics, and the ecological metrics that were most sensitive to hydrologic alteration. The flow metrics that were most important in preserving ecological metrics were high-flow duration and frequency, 3-day maximum and minimum, and number of reversals. The ecological metrics most sensitive to hydrologic alteration were mostly related to presence or absence of key indicator species.

Rodger, A.W., K.B. Mayes, and K.O. Winemiller. 2016. Preliminary Findings for a Relationship between Instream Flow and Shoal Chub Recruitment in the Lower Brazos River, Texas. Transactions of the American Fisheries Society 145:943–950, 2016

Seasonal flow pulses in rivers facilitate spawning, dispersal, and early life stage survival of many fish species. To evaluate the effectiveness of current flow standards to sustain threatened fish populations, we investigated the relationship between hydrology and recruitment of the Shoal Chub *Macrhybopsis hyostoma*, a broad-cast-spawning minnow in the Brazos River, Texas. From March 2013 to March 2014, we collected metalarval and juvenile Shoal Chub bimonthly at night using arrays of stationary drift nets. Otoliths were examined to estimate age, and the relationship between hatch date and discharge was analyzed. Shoal Chub recruited under both base-flow and pulse-flow conditions, including intervals of increasing, decreasing, and stable discharge. However, hatch dates of surviving fish indicated greater levels of recruitment during flow pulses, particularly on the rising limb. Greatest recruitment occurred during flow pulses of a magnitude defined as two per season according to the method of hydrological analysis adopted by the state's environmental flow program. Our findings imply that the state's current environmental flow standards for the lower Brazos River may be insufficient to sustain Shoal Chub populations and additional research on this issue is warranted

Rolls, R.J., C. Leigh, and F. Sheldon. 2012. Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration. Freshwater Science, 2012, 31(4):1163–1186

Alterations to the natural flow regime affect the structure and function of rivers and wetlands and contribute to loss of biodiversity worldwide. Although the effects of flow regulation have been relatively well studied, a lack of synthesis of the ecological consequences of low flows and droughts impedes research progress and our grasp of the mechanistic effects of human-induced water reductions on riverine ecosystems. We identified 6 ecologically relevant hydrological attributes of low

flow (antecedent conditions, duration, magnitude, timing and seasonality, rate of change, and frequency) that act within the temporal hierarchy of the flow regime and a spatial context. We synthesized the literature to propose 4 principles that outline the mechanistic links between these low-flow attributes and the processes and patterns within riverine ecosystems. First, low flows control the extent of physical aquatic habitat, thereby affecting the composition of biota, trophic structure, and carrying capacity. Second, low flows mediate changes in habitat conditions and water quality, which in turn, drive patterns of distribution and recruitment of biota. Third, low flows affect sources and exchange of material and energy in riverine ecosystems, thereby affecting ecosystem production and biotic composition. Last, low flows restrict connectivity and diversity of habitat, thereby increasing the importance of refugia and driving multiscale patterns in biotic diversity. These principles do not operate in isolation, and many of the ecological pathways that are affected by low flows are likely to overlap or occur simultaneously, potentially resulting in synergistic and complex effects. Last, we outlined major human-induced threats to low-flow hydrology and how they act upon the ecologically relevant hydrological attributes of low flow to affect potential changes in riverine ecosystem integrity. The mechanistic links described in this synthesis can be used to develop and test hypotheses of low-flow hydrological–ecological response relationships in a cause–effect framework that will have value for both research and river flow management. Continued experimental research and ongoing consolidation of ecological information will improve our understanding and ability to predict consequences of low-flow alteration on river, floodplain, and estuarine ecosystems.

Rosenfeld, J.S. 2017. Developing flow–ecology relationships: Implications of nonlinear biological responses for water management. Freshwater Biology. 2017; 62:1305–1324.

Specific goals of the study were (1) to provide a more explicit framework for interpreting flow–ecology relationships; (2) to identify which general categories of ecological attributes are most likely to show linear versus nonlinear responses to flow, and how this may affect flow management decisions; and (3) to consider how ecologists can work towards synthesizing locally derived relationships from disparate sources into more general flow–ecology relationships with greater potential transferability among sites. The emphasis of this review is on flow–ecology relationships at low-magnitude flows when competition between instream- and out-of-stream uses is typically most intense, but general insights should be relevant to flow–ecology relationships operating at higher flows (e.g., channel-forming, fish passage and spawning flows).

Rytwinski, T., M. Harper, J.J. Taylor, J.R. Bennett, L.A. Donaldson, K.E. Smokorowski, K. Clarke, M.J. Bradford, H. Ghamry, J.D. Olden, D. Boisclair, and S.J. Cooke. 2020. What are the effects of flow-regime changes on fish productivity in temperate regions? A systematic map. Environ Evid (2020) 9:7 https://doi.org/10.1186/s13750-020-00190-z

To identify relevant articles for inclusion in this systematic map, we searched six bibliographic databases, 29 organizational websites, one search engine, and 297 reviews, and solicited grey literature through relevant sources. We screened articles at title and abstract, then by full-text using predefined inclusion criteria. Included studies were coded for key variables of interest, along with a very basic critical appraisal for internal validity (i.e., susceptibility to bias). The quantity and characteristics of the available evidence, knowledge gaps and subtopics with sufficient cover-age for full systematic reviewing are reported in a narrative synthesis. The distribution and frequency of examined effects of flow-regime changes on fish productivity outcomes are presented in visual heatmaps. total of 1368 studies from 1199 articles were included in the systematic map database and used to identify a number of interesting themes in the evidence base: (1) large evidence bases were found in temperate regions of United States of America (USA), Canada, and Australia; (2) most studies either used a temporal or spatial trend design i.e., lacking a ‘true’ before intervention time period, or no intervention control sites; (3) the most studied causes of altered flow regime were natural (e.g., floods, droughts, climate change), hydroelectric facilities (hydro), and dams with no hydro; and

(4) there were clear clusters of studies evaluating effects of changes in magnitude and surrogate measures (e.g., velocity, water depth) on fish productivity outcomes, in particular abundance and diversity metrics. A number of potential knowledge gaps were identified: including geographic (Northern Africa, and possibly parts of Asia), causes of altered flow regime (restoration, land-use change, and water abstraction/extraction/diversion), interventions (flow duration, frequency, rate of change, or timing), outcomes (population viability) and specific intervention/cause/outcome groups (e.g., changes in flow magnitude due to hydro or natural causes and fish survival, performance, and reproduction). A few aspects in methodology were also identified across studies, primarily a lack of true comparators (e.g., temporal or spatial trend designs).

Sabine River Authority of Texas, Texas Commission on Environmental Quality, Texas Parks and Wildlife Department and Texas Water Development Board. 2007. Baseline Fish Collections Lower Sabine River Priority Instream Flow Study. Final Report under TWDB Research and Planning Fund Research Grant, Contract No. 0604830567. 29 pp.

Biological data compiled during reconnaissance included benthic macro-invertebrate and fish data sets from rapid bio-assessments of many of the main tributary streams of the Sabine River in Texas through a basin-wide effort that began in 1993 to characterize the biological community of the priority subwatersheds of the Sabine River Basin. Biological data has also been collected from the main stem of the river for specific studies but not as a basin-wide effort. Most main stem biological data is from a benthic macro-invertebrate monitoring contract with a local industry from 1989-1992 and from some Texas Commission on Environmental Quality (TCEQ) fish collection work near Anacoco Bayou in 2003. An analysis of the bibliography compiled during reconnaissance revealed a lack of recent biological data for the main stem of the lower Sabine River. Collections and habitat assessments were made at eight sites beginning May 2006 through September 2006 by staff from Texas Parks and Wildlife Department, TCEQ, TWDB, and SRATX. The magnitude of the effect of Hurricane Rita and the drought of early spring 2006 on the diversity and population of species collected has not yet been assessed. Additional sampling is proposed to mitigate any seasonal or equipment bias as well as to further assess the effects of the hurricane and the drought.

San Antonio River Authority. 2006. Lower San Antonio River Watershed Instream Flows Study Biological Collection Summary Report. Final Report to TWDB Contract No. 2005-483-562. 27 pp.

The goal of this study is to conduct new biological collections, which will attempt to fill in information gaps concerning fish assemblages. Further, these collections are aimed at improving baseline data as part of scoping potential instream flow studies, supplementing information needed for understanding trends in fish assemblage dynamics and allowing preparation of a conceptual model of fish assemblage dynamics in the study area.

Senay, C., Z.E. Taranu, G. Bourque, C.J. Macnaughton, G. Lanthier, S. Harvey-Lavoie, and D. Boisclair. 2017. Effects of river scale flow regimes and local scale habitat properties on fish community attributes. Aquat Sci (2017) 79:13–26 DOI 10.1007/s00027-016-0476-1

The general goal of this study was to investigate how river flow regime and local habitat properties explain and predict fish community attributes in unregulated and regulated rivers. Our objectives were to identify the hydrological indices that best describe the flow regimes of river segments subjected to different regulation types (unregulated, run-of-the-river, storage, and peaking), and to estimate the relative importance of hydrological indices (river scale), and water depth, water velocity, and substrate composition (local scale) in explaining and predicting local fish community attributes (species richness, total density, and total biomass). We surveyed 880 sites (~300 m2) in 25 rivers (14 unregulated and 11 regulated) located in six physiographic regions of Canada.

Stanley, C.E., J.M. Taylor, and R.S. King. 2012. Coupling Fish Community Structure with Instream Flow and Habitat Connectivity between Two Hydrologically Extreme Years. Transactions of the American Fisheries Society 141:1000–1015, 2012

Hydrologic variability and instream habitat connectivity play fundamental roles in structuring fish communities in lotic ecosystems. We collected fish assemblage and physical habitat data from 28 central Texas streams during the summers of 2006 (a drought year with minimal summer precipitation and low stream flow) and 2007 (an exceptionally wet year with periodic flooding in spring and sustained high flows throughout summer). We evaluated the correspondence between the magnitude of physical habitat and fish community composition change in stream reaches sampled in these two contrasting years using ordination, successional vector analysis, and indicator species analysis. In 2006, streams characterized by disconnected pools had different fish community structure and habitat characteristics than streams that had habitats connected by flowing water. The amount of interannual change in both fish community structure and habitat characteristics was greatest between streams that had disconnected pools in 2006 and their paired samples in 2007. Indicator species analysis identified species that had affinities to disconnected habitats during 2006, which included opportunistic life history strategists typical of temporary waters (western mosquitofish *Gambusia affinis* and blackstripe topminnow *Fundulus notatus*) and equilibrium strategists that rely on stable pool habitats for nesting (longear sunfish *Lepomis megalotis* and largemouth bass *Micropterus salmoides*). Conversely, indicator species of connected riffle–pool habitat included fluvial specialists (central stoneroller *Campostoma anomalum*, spotted bass *Micropterus punctulatus,* and bullhead minnow *Pimephales vigilax*). In summer 2007, the numbers of most species of fish declined markedly compared with 2006. Community structure between previously disconnected and connected stream types was also highly variable in 2007. However, strong recruitment of juveniles following spring flooding and sustained high summer flow significantly increased the frequency and abundance of two periodical strategists, channel catfish *Ictalurus punctatus* and flathead catfish Pylodictus olivaris in both types of streams in 2007. These findings provide important insights into how individual species' life history strategies influence the response of fish community structure to extreme hydrologic events, which are likely to increase in frequency in many parts of the world due to climate change.

Visser, A., L. Beevers, and S. Patidar. 2017. Macro-invertebrate community response to multi-annual hydrological indicators. River Res. Applic. 33: 707–717 (2017)

In order to better model flow variability, and hence im-prove current understanding of hydroecological relation-ships for groundwater rivers, this paper aims to examine the presence of lag in the hydroecological relationship (using LIFE scores as a proxy). These relationships are assessed using a long-term (21-year, 1993–2014) paired hydrological and ecological data set for a groundwater dominated system (River Nar, Norfolk, UK). Multi-annual and multi-seasonal flow variables are intended to account for both the cumulative (inter-annual) and seasonal (intra-annual) flow effects. The multi-annual aspect of the hydroecological relation-ship (lag) is systematically explored within the proposed statistical modelling framework through the addition of time-offset hydrological variables. Thus, the key objectives are the following: (1) To identify and develop a suitable statistical modelling framework exploring the multi-annual and multi-seasonal aspect of the hydroecological relationship (a lag in response); (2) To examine the influence of seasonal low/high flows within the relationship; and (3) To explore practical channels for wider implementation of the framework.

Webb, J. A., M. J. Stewardson, et al., 2010. Detecting ecological responses to flow variation using Bayesian hierarchical models. *Freshwater Biology*.

Demonstrate the use of Bayesian hierarchical models to detect ecological responses to flow variation in data-poor situations such as large-scale, disperse environmental flow monitoring programs.

Webb, J.A., S.R. Wealands, P. Lea, S.J. Nichols, S.C. de Little, M.J. Stewardson, and R. H. Norris. 2011. Eco Evidence: using the scientific literature to inform evidence-based decision making in environmental management. Conference: Proceedings of MODSIM 2011 - International Congress on Modelling and Simulation At: Perth, Australia 2472-2478.

Developed a database that contains over 1000 evidence items from over 400 papers related to flow-ecology relationships for multiple taxa with an associated free analysis toolbox accessible via the web (https://toolkit.ewater.org.au/Tools/Eco-Evidence) using causal inference techniques.

Webb, J.A., S.J. Nichols, R. H. Norris, M.J. Stewardson, S.R. Wealands, and P. Lea. 2012. Ecological responses to flow alteration: Assessing causal relationships with Eco Evidence. Wetlands (2012) 32:203-213. DOI 10.1007/s13157-011-0249-5

Provides a case study on the application of the Eco Evidence database and analysis toolbox based on an eight step framework that applies causal inference techniques. Demonstrated flow-ecology relationships for wetland species responses.

Webb, J.A., K.A. Miller, E.L. King, S.C. de Little, M.J. Stewardson, J.K.H. Zimmerman, and N.L. Poff. 2013. Squeezing the most out of existing literature: a systematic re-analysis of published evidence on ecological responses to altered flows. Freshwater Biology, 58, 2439–2451

Utilized the Eco Evidence method and software to synthesize literature on ecological responses to human altered river flow regimes, demonstrating its ability to synthesize the literature on a management issue of global significance (Dudgeon et al., 2006; Arthington et al., 2010). More specifically, we compare the Eco Evidence results to those of Poff and Zimmerman (2010; hereafter PZ2010) demonstrating the particular benefits and promise of this standardized approach compared to a more traditional literature review. We were able to test hypotheses at scales directly relevant to management (i.e., effects of directional changes in flow components on specific taxa) and to identify where evidence was consistent, conflicting, or insufficient to reach a conclusion. We use this reanalysis not only as a synthesis of current knowledge in freshwater ecology, but as a case study to demonstrate the utility of the Eco Evidence approach to inform a range of complex environmental management issues.

Wilding T. K. and Poff N. L. 2008. Flow-ecology relationships for the watershed flow evaluation tool. Colorado Water Conservation Board, 49 p

Mined diverse data from 149 sources, including journal articles, technical reports and theses, to quantify relationships between streamflow conditions and riparian vegetation, fish, and aquatic macroinvertebrates for the three types of streams that exist in Colorado, USA. Comparison of measured ecosystem parameters across a range of flow conditions (varying levels of modification) allowed patterns to emerge that provided a basis for quantifying ecosystem response. Where ecosystem complexities precluded a simple monotonic response to flow change, the best-available flow-ecology relationship was inferred as the ceiling of the scattered data, as defined by quantile regression (Cade and Noon 2003).

Winemiller, K.O., F.P. Gelwick, T. Bonner, S. Zeug, and C. Williams. 2004. Response of Oxbow Lake Biota to Hydrologic Exchanges with the Brazos River Channel. Final Project Report to TWDB Contract No. (2003-483-493, 2003-483-006). 232 pp.

This report provides findings from a research project that examined responses of fish assemblages and individual species to hydrologic variability in channel and floodplain habitats of the lower Brazos River. The project was funded by the Texas Water Development Board in consultation with the Texas

Commission for Environmental Quality and the Texas Parks and Wildlife Department. The project was designed to supplement existing environmental information (Winemiller et al., 2000; Gelwick and Li 2002), particularly with regard to ecological responses to instream flow variation and was motivated by pending water development plans in the lower Brazos River Basin. Our goals were to identify fish taxa that may benefit from, or otherwise respond to, floodplain connectivity, to explore how fish biodiversity (species assemblages) in oxbow lakes with variable connection frequencies are influenced by periodic flood events, and to document fish assemblages in the main channel, with emphasis on flow-sensitive species.

Zeug, S., and K.O. Winemiller. 2007. Ecological correlates of fish reproductive activity in floodplain rivers: a life-history-based approach. Can. J. Fish. Aquat. Sci. 64: 1291–1301 (2007). doi:10.1139/F07-094.

Reproductive activity of seven species representing three divergent life history strategies was monitored monthly for 2 years in channel and floodplain habitats of the Brazos River, Texas, USA, to evaluate associations between reproductive activity and biotic and abiotic factors predicted by conceptual models to influence reproduction. An information-theoretic approach was used to select best approximating models for each species, and model-averaged estimates of regression coefficients were calculated. Model selection indicated that monthly flow based on the 30-year hydrograph and temperature was strongly supported as factors associated with reproductive activity of all three life history strategies. The timing of reproduction in relation to the long-term hydrograph was related to life history traits. Reproductive activity of species with large adult size and high fecundity was greatest in spring just prior to increasing flows, whereas species with small adult size and extended breeding seasons exhibited greater activity in late spring and summer when mean flow was greatest. Nest-building species with parental care were more abundant in off-channel habitats where floods were less common. Instream flow management would benefit from consideration of flow and habitat requirements needed to support the diverse life history strategies displayed by fishes in river–floodplain systems.

Estuaries

Adams, J.B. 2014. A review of methods and frameworks used to determine water requirements of estuaries. Hydrological Science Journal 59:451-465.
This reviews the methods developed for determining environmental water requirements for estuaries in Australia, South Africa and the USA, including monitoring needs, risk assessment and adaptive management.

Ajemian, M.J., K.S. Mendenhall, J.B. Pollack, M.S. Wetz, and G.W. Stunz. 2018. Moving Forward in a Reverse Estuary: Habitat Use and Movement Patterns of Black Drum (Pogonias cromis) Under Distinct Hydrological Regimes. Estuaries and Coasts (2018) 41:1410–1421. https://doi.org/10.1007/s12237-017-0363-6

Understanding the effects of freshwater inflow on estuarine fish habitat use is critical to the sustainable management of many coastal fisheries. The Baffin Bay Complex (BBC) of south Texas is typically a reverse estuary (i.e., salinity increases upstream) that has supported many recreational and commercial fisheries. In 2012, a large proportion of black drum (*Pogonias cromis*) landed by fishers were emaciated, leading to concerns about the health of this estuary. In response to this event and lacking data on black drum spatial dynamics, a 2-year acoustic telemetry study was implemented to monitor individual-based movement and seasonal distribution patterns. Coupled with simultaneous water quality monitoring, the relationship between environmental variables and fish movement was assessed under reverse and classical estuary conditions. Acoustic monitoring data suggested that the BBC represents an important habitat for black drum; individuals exhibited site fidelity to the system and were present for much of the year. However, under reverse estuary conditions, fish summertime

distribution was constrained to the interior of the BBC, where food resources are limited (based on recent benthic sampling), with little evidence of movement across the system. Out of eight environmental variables used to model fish movement using multiple linear regression, the only significant variable was salinity, which exhibited a negative relationship with movement rate. These findings suggest that prolonged periods of hypersalinity, which are detrimental to other euryhaline species due to increased osmoregulatory costs, reduce black drum distribution patterns and can limit the species' access to benthic habitats supporting abundant prey resources.

Arismendez, S.S, H.-C. Kim, J. Brenner and P.A. Montagna. 2009. Application of watershed analyses and ecosystem modeling to investigate land–water nutrient coupling processes in the Guadalupe Estuary, Texas. *Ecological Informatics* 4: 243-253.

This paper analyzed ecosystem response to watershed-derived nutrient loads from the two main watershed to San Antonio Bay and found different drivers of nitrogen loading, point sources in the San Antonio River Basin and nonpoint sources in the Guadalupe River Basin, and therefore, differing estuarine ecosystem responses.

Arthington, A., J. Kennen, E.D. Stein, J.A. Webb. 2018. Recent advances in environmental flows science and water management – innovation in the Anthropocene, Freshwater Biology. 63: 1022-1034.

This is a summary of the major findings from the special issue of Freshwater Biology on "Evaluating and Managing Environmental Water Regimes in a Water-Scarce and Uncertain Future".

Beck, M.W., K.L. Heck Jr., K.W. Able, D.L. Childers, D.B. Eggleston, B.M. Gillanders, B. Halpern, C.G. Hays, K. Hoshino, T.J. Minello, R.J. Orth, P.F. Sheridan, and M.P. Weinstein. 2001. The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates. *BioScience* 51: 633-641.

This paper reviews the history of the concept that nearshore ecosystems provide an important function as nurseries and proposes testable hypothesis to focus efforts in research, conservation, restoration, and management related to this issue.

Batchelor, M.E., and C.G. Guthrie. 2008. Galveston Bay freshwater inflow re-study. Final Report Texas Water Development Boardy Contract No. 0704830673. 45 pp.

This report addresses two tasks assigned to the Texas Water Development Board, which are related to the development of productivity-inflow regression equations for commercial fisheries harvest data and for Texas Parks and Wildlife Department fisheries-independent data. The first task was to extend the existing statistical analyses for the Galveston Bay Freshwater Inflow Study to include the most recent harvest and inflow data. It was also part of this task to relate freshwater inflows to Texas Parks and Wildlife's fisheries-independent dataset for Galveston Bay using existing methodologies. These analyses were conducted, compared, and evaluated. The second task was to explore new methodologies in relating freshwater inflows to the health of estuarine ecosystems along the Texas Coast. Several different approaches at multiple temporal and spatial scales were explored and evaluated. The results from these analyses can be used to determine which data sets and which approaches are helpful for making recommendations for freshwater inflows into Galveston Bay.

Brock, D.A., R.S. Solis, and W.L. Longley. 1996. Guidelines for water resource permitting: Nutrient requirements for maintenance of Galveston Bay productivity. Final Report to USEPA, Texas Water Development Board, Assistance Agreement No. X-996024-01-2. 130 pp.

Nutrient modeling targeting development of primary productivity requirements and permitting guidelines to maintain ecological conditions within Galveston Bay.

Brown, C., J. King, L. Van Niekerk, S. Taljaard. 2020. Status and trends in EFlows in South Africa. Natural Resources Forum 44: 66-88.

A review that explores progress made in environmental flow assessments and implementing their outcomes in Southern Africa.

Bugica, K., B. Sterba-Boatwright, and M.S. Wetz. 2020. Water quality trends in Texas estuaries. Marine Pollution Bulletin 152: 110903. https://doi.org/10.1016/j.marpolbul.2020.110903.

Spatial and temporal water quality trends in Texas estuaries including effects of freshwater inflows.

Cardoso, P.G., D. Raffaelli, A.I. Lillebo, T. Verdelhos, and M.A. Pardal. 2008. The impact of extreme flooding events and anthropogenic stressors on macrobenthic communities' dynamics. *Estuarine, Coastal, and Shelf Science* 75:553-565.

This paper explores the interactions between extreme weather events (e.g., intense floods) and anthropogenic stressors (e.g., eutrophication) on the dynamics of the macrobenthic assemblages and the socio-economic implications that follow. The study argues that impacts longer term anthropogenic impacts reduced system stability and the resilience of the macrobenthic assemblages, so that its ability to cope with other stressors was compromised.

Dittmann, S., R. Baring, S. Baggalley, A. Cantin, J. Earl, R. Gannon, J. Keuning, A. Mayo, N. Navong, M. Nelson, W. Noble, and T. Ramsdale. 2015. Drought and flood effects on macrobenthic communities in the estuary of Australia's largest river system. *Estuarine, Coastal, and Shelf Science* 165: 36-51.

This paper developed a flow index to assess the biological response subject to the duration of the preceding drought and flow volumes. The analysis identified ecological benefits of intermediate and continuous flow and that resilience of estuarine macrobenthos to drought and flood events was affected by flow history.

Du, J. and Park, K. and Shen, J. and Zhang, Y. J. and Yu, X. and Ye, F. and Wang, Z. and Rabalais, N. N., A hydrodynamic model for Galveston Bay and the shelf in\hack{\break} the northern Gulf of Mexico, 2019, Ocean Science, v15, n4, pp 951--966, https://os.copernicus.org/articles/15/951/2019/

A SCHISM hydrodynamic model of the northern Gulf of Mexico including calibration to Galveston Bay.

Duarte, C.M., A. Borja, J. Carstensen, M. Elliot, D. Krause-Jensen, N. Marba. 2015. Paradigms in the recovery of estuarine and coastal ecosystems. Estuaries and Coasts 38: 1202-1212.

This review identifies six paradigms of recovery of estuarine ecosystems and using case studies discusses the differing pathways of degradation and partial recovery and presents a conceptual model indicating how restoration efforts may accelerate recovery.

Elliot, M., L. Mander, K. Mazik, C. Simenstad, F. Valesini, A. Whitfield, E. Wolanski. 2016. Ecoengineering and Ecohydrology: Successes and failures in estuarine restoration. Estuarine, Coastal and Shelf Science 176: 12-35.

Discusses estuarine restoration as Type A ecoengineering where the physico-chemical structure is modified assuming that ecological structure and function will follow, and Type B where the biota are

engineered directly through restocking or replanting and provide case studies.

Estevez, E.D. 2002. Review and Assessment of Biotic Variables and Analytical Methods Used in Estuarine Inflow Studies. Estuaries, Dec., 2002, Vol. 25, No. 6, Part B: Dedicated Issue: Freshwater Inflow: Science, Policy, Management: Symposium Papers from the 16th Biennial Estuarine Research Federation Conference (Dec., 2002), pp. 1291-1303

This paper provides an overview of the work of estuarine ecologists to develop empirical foundations for coastal river regulation, giving attention to models taken from river management, insights from success in basic estuarine ecology, documentation of estuaries harmed by inflow change, and past and ongoing efforts to develop useful scientific tools. Approximately 300 citations were retrieved in literature searches. The median year of publication was 1992, signifying that half of the citations are relatively recent (produced in the last 10 years). The majority of the literature originated from North America and Europe although there is an important South African literature. Few citations concerned individual species; most literature dealt with living resources concerning habitats, communities, and ecosystems. Readers interested in the core literature on freshwater inflows to estuaries, prior to 1992, may consult Copeland (1966), Aleem (1972), Hopkins (1973), Gunter et al., (1974), Snedaker et al., (1977), Benson (1981), Cross and Williams (1981), Mahmud (1985), Skreslet (1986), Rozengurt and Hedgpeth (1989), and Halim (1990a,b).

Froeschke, B.F., and G.W. Stunz. 2012. Hierarchical and interactive habitat selection in response to abiotic and biotic factors: The effect of hypoxia on habitat selection of juvenile estuarine fishes. Environ Biol Fish (2012) 93:31–41 DOI 10.1007/s10641-011-9887-y

Habitat selection is a shared process among animals where individuals choose areas that differ in biotic and abiotic characteristics to maximize individual fitness. We used manipulative laboratory mesocosm choice experiments to examine hierarchical and interactive relationships influencing this habitat selection process of estuarine fishes. We assessed selection among substrate, dissolved oxygen (DO) concentration, food availability, and predation risk using two common juvenile estuarine fish species, pinfish (*Lagodon rhomboides*) and Atlantic croaker (*Micropogonias undulatus*). For both species oxygen concentration greatly influenced selection patterns; fishes strongly avoided low DO conditions, while in higher levels of DO factors such as substrate or food influenced selection patterns. However, both species strongly avoided predators even when alternative habitat was severely oxygen limited. These results suggest that predation risk may be the greatest determinant of habitat selection of the factors considered. Expansion of low DO areas in the world's oceans is a major anthropogenic disturbance and is rapidly increasing. Assessing impacts of hypoxia on habitat usage of mobile organisms is critical as changes in environmental metrics including predator distribution and DO levels may alter habitat selection patterns disrupting critical ecosystem processes and trophic interactions. Our results indicate that juvenile fishes may forgo emigration from hypoxia due to predation risk. If similar patterns occur for juvenile fishes in estuaries they may potentially suffer from reduced growth, reproductive output, and survivorship.

Froeschke, B.F., G.W. Stunz, M.M. Rees Robillard, J. Williams, and J.T. Froeschke. 2013. A modeling and field approach to identify essential fish habitat for juvenile bay whiff (*Citharichthys spilopterus*) and Southern Flounder (*Paralichthys lethostigma*) Within the Aransas Bay Complex, TX. Estuaries and Coasts (2013) 36:881–892. DOI 10.1007/s12237-013-9600-9.

The goal of this study was to use an ecosystem based approach to consider the effect of environmental conditions on the distribution and abundance of juvenile bay whiff and southern flounder within the Aransas Bay Complex, TX, USA. Species habitat models for both species were developed using boosted regression trees. Juvenile bay whiff were associated with low temperatures (<15 °C, 20–23 °C), moderate percent dry weight of sediments (25–60 %), salinity >10, and moderate to high dissolved oxygen (6–9mgO2/l, 10–14 mg/l). Juvenile southern flounder were associated with low temperatures (<15 °C), low percent dry weight of sediment (<25 %), seagrass habitat, shallow depths (<1.2 m), and high dissolved oxygen (>8 mg O2/l). Our results indicate that conservation measures should focus along the eastern side of Aransas Bay and the north corner of Copano Bay to protect essential fish habitat. These findings provide a valuable new tool for fisheries managers to aid in the sustainable management of bay whiff and southern flounder and provide crucial information needed to prioritize areas for habitat conservation.

Froeschke, B.F., P. Tissot, G.W. Stunz, and J.T. Froeschke. 2013. Spatiotemporal Predictive Models for Juvenile Southern Flounder in Texas Estuaries, North American Journal of Fisheries Management, 33:4, 817-828, DOI: 10.1080/02755947.2013.811129

Southern Flounder *Paralichthys lethostigma* supports a multimillion dollar commercial and recreational fishery in the Gulf of Mexico. Despite its economic importance, the Southern Flounder population has been declining for decades. To improve the management of this fishery, both population trends and changes in environmental conditions need to be considered. Using two different statistical modeling techniques, boosted regression tree (BRT) and artificial neural network (ANN), a 29-year fisheries-independent record of juvenile Southern Flounder abundance in Texas was examined to illustrate how environmental factors influence the temporal and spatial distribution of juvenile Southern Flounder. Boosted regression trees show the presence of juvenile Southern Flounder is closely associated with relatively low temperatures, low salinity levels, and high dissolved oxygen concentrations. Both ANN and BRT models resulted in high predictive performance with slight spatial differences in predicted distribution. Both models suggested high probability of occurrence in Galveston Bay and East Matagorda Bay. The ANN accurately predicted higher probability of occurrence in Sabine Lake compared with the BRT model. Our results will provide tools for fisheries managers to enhance management and sustainability of the Southern Flounder population. Moreover, these results also identify a predictive framework for proactive approaches to ecosystem management by providing more data to identify essential habitat features and understanding relationships between abiotic and biotic factors within those habitats.

Froeschke, B.F., M.M. Reese Robillard, and G.W. Stunz. 2016. Spatial biodiversity patterns of fish within the Aransas Bay complex, Texas. Gulf and Caribbean Research Vol 27, 21-32, 2016 DOI: 10.18785/gcr.2701.03

The goal of this study was to consider the effects of habitat type and environmental conditions on the biodiversity of fishes within the Aransas Bay Complex, Texas and provide a management framework and an ecosystem examination of Essential Fish Habitat (EFH). A stratified, randomized experimental design was used to collect fishes from seagrass, oyster, and non—vegetated habitats within the Aransas Bay Complex from February through May 2010 over large spatial scales at the “bay—complex” level. We developed a biodiversity habitat model using Boosted Regression Trees (BRT). Fitted functions from the “best” fit BRT habitat model indicated that fish biodiversity was greatest in seagrass areas closest to the inlet (< 80 cost—distance units) during early spring, with temperatures < 18°C and dissolved oxygen levels between 7—8 mg O2/L in shallow depths (< 0.5 m). Results from community assemblage analyses showed significant differences among habitats with highest abundance of fishes found in seagrass, followed by non—vegetated substrate, and oyster reef. The relatively high abundance of fishes at non—vegetated bottom compared to the low abundance found at the oyster reef was most likely due to the spatial location of the habitats sampled. Our results indicate that future conservation measures should focus along the eastern and southern areas of Aransas Bay to protect EFH with highest levels of biodiversity. The modeling approach developed in this study provides a framework for natural resource managers to identify habitats supporting the greatest biodiversity of juvenile fishes.

Gillson, J. 2011. Freshwater inflow and fisheries production in estuarine and coastal systems: where a drop of rain is not lost. Reviews in Fisheries Science 19: 168-186.

A synopsis of the impacts of freshwater inflows on fisheries production with examples from eastern Australia and southern Africa.

González-Ortegoń, E., P. Drake. 2012. Effects of freshwater inputs on the lower trophic levels of a temperate estuary: physical, physiological or trophic forcing? *Aquatic Science* 74:455–469.

This paper found that freshwater inputs appeared to effect estuarine lower trophic levels via a combination of different forcing (physical, physiological or trophic) mechanisms. Although several general patterns can be derived, the response of the system to freshwater inputs was not always univocal.

González-Ortegoń, E., M.D. Subida, A.M. Arias, F. Baldó, J.A. Cuesta, C. Fernández-Delgado, C. Vilas, and P. Drake. 2012. Nekton response to freshwater inputs in a temperate European Estuary with regulated riverine inflow. *Science of The Total Environment* 440:261-271.

The paper found that while natural and human-controlled freshwater inputs play a significant role in determining the physicochemical conditions and the biota of the Guadalquivir estuary these effects seemed to have only transitorily affect the estuarine nekton, either directly (flushing out) or indirectly (through changes in salinity, turbidity and prey availability) and a quick reestablishment of the estuarine nekton (strong resilience) was observed following freshwater inputs together with the recovery of environmental conditions within the estuary.

Guthrie, C.G. 2010a. TxBLEND Model Calibration and Validation for the Guadalupe and Mission-Aransas Estuaries. TWDB Technical Memo. 46 pp.

This report focuses on the calibration and validation of TxBLEND for the Guadalupe and Mission-Aransas estuaries but is not limited to the San Antonio-Aransas-Copano bays system. Instead, the model includes Matagorda Bay to the northeast and Corpus Christi Bay to the southwest in order to better simulate water circulation and salinity transport within the estuary. TxBLEND was calibrated for velocity, discharge, surface elevation, and salinity for the period 1987-1997. The model subsequently was validated for salinity for the period 1999-2009. Model validation focused on model performance near established long-term monitoring locations.

Guthrie, C.G. 2010b. TxBLEND Model Validation for the Upper Guadalupe Estuary Using Recently Updated Inflow Data. TWDB Technical Memo. 25 pp.

This technical memo documents the TxBLEND hydrodynamic and salinity transport simulations conducted for the Guadalupe Estuary at the request of the Guadalupe-San Antonio Bay and Basin Expert Science Team (G-SA BBEST) to aid their effort in fulfilling the mandates of the Senate Bill 3 process for developing environmental flow recommendations for the Guadalupe and Mission-Aransas estuaries. This document focuses on the validation of salinity at sites in the upper Guadalupe Estuary.

Guthrie, C.G., and C. Schoenbaechler. 2011a. Comparison of Two Hydrology Datasets, as Applied to the TxBLEND Model, on Salinity Condition in Nueces Bay. TWDB Alternate Hydrology Technical Memo. 13 pp.

This technical memo documents salinity output from the TxBLEND model using this alternate hydrology dataset as applied to the Nueces River Inflow Point. Additionally, this memo documents the comparison between TxBLEND model output using two different hydrology datasets (1) that which was used in the calibration and validation of the TxBLEND model and also (2) the proposed alternate hydrology described herein.

Guthrie, C.G., and C. Schoenbaechler. 2011b. TxBLEND Model Calibration and Validation for the Nueces Estuary. TWDB Technical Memo. 59 pp.

This report focuses on the calibration and validation of TxBLEND for the Nueces Estuary and Upper Laguna Madre, including Baffin Bay, but is not limited to these bay systems. Instead, the model includes Copano and Aransas Bays to the north in order to better simulate water circulation and salinity transport within the estuary. TxBLEND was calibrated for velocity, discharge, surface elevation, and salinity. The model subsequently was validated for salinity. Model validation focused on model performance near established long-term monitoring locations.

Guthrie, C.G., and C. Schoenbaechler. 2011c. TxBLEND Model Calibration and Validation for the Laguna Madre Estuary. TWDB Technical Memo. 60 pp.

This report focuses on the calibration and validation of TxBLEND for the Laguna Madre Estuary including Baffin Bay but is not limited to this system. Instead, the model also includes Copano, Aransas, and Corpus Christi Bays to the north in order to better simulate water circulation and salinity transport within the estuary. TxBLEND was calibrated for velocity, discharge, surface elevation, and salinity. The model subsequently was validated for salinity. Model validation focused on model performance near established long-term monitoring locations.

Guthrie, C.G., and C. Schoenbaechler. 2011d. TxBLEND Model Calibration and Validation for the Lavaca-Colorado Estuary and East Matagorda Bay. TWDB Technical Memo. 72 pp.

This report focuses on the calibration and validation of TxBLEND for the Lavaca-Colorado Estuary and East Matagorda Bay but is not limited to these bay systems. Instead, the model includes Espiritu Santo Bay and San Antonio Bay to the west in order to better simulate water circulation and salinity transport within the estuary. TxBLEND was calibrated for velocity, discharge, surface elevation, and salinity. The model subsequently was validated for salinity. Model validation focused on model performance near established long-term monitoring locations.

Guthrie, C.G., and C. Schoenbaechler. 2012. TxBLEND Model Calibration and Validation for the Trinity-San Jacinto Estuary. TWDB Galveston TxBLEND Technical Memo. 56 pp.

This report focuses on the calibration and validation of TxBLEND for the Trinity-San Jacinto Estuary, or Galveston Bay system. The Galveston Bay TxBLEND model was calibrated for velocity, surface elevation, and salinity for the period 1987 - 1996. The model subsequently was validated for salinity for the period 1997 - 2005. Model validation focused on model performance near established long-term monitoring locations. However, additional sites may be validated upon request or as data becomes available.

Guthrie, C.G., Matsumoto, J., and Solis, R.S. 2012. Analysis of the Influence of Water Plan Strategies on Inflows and Salinity in Galveston Bay. Final report to the United States Army Corps of Engineers, Contract #R0100010015. Texas Water Development Board, Austin, Texas. pp 71.

This study investigates the influence of water plan strategies for the Trinity River Basin on the volume of freshwater inflow reaching Galveston Bay and subsequent effects on salinity conditions within the bay. The Texas Commission on Environmental Quality (TCEQ) regional water availability model (WAM) for the Trinity River basin was modified to reflect future conditions, considering both increased reservoir sedimentation and planned water supply strategies for the region (based on the

2007 Regional/State Water Plan). The WAM then was used to develop water-plan-strategy inflows to Galveston Bay under two management scenarios. The first scenario, designated as a modified WAM Run3 reflects a future condition in which all existing water rights are fully utilized, no return flows are provided, and no term rights occur. The second scenario, designated WAM Run9 (based on a modified WAM Run8), reflects a future condition with anticipated demands and strategies as outlined in the 2007 State Water Plan. These scenarios then were compared to an existing condition and to two recommended target inflow conditions that were developed jointly by the Texas Parks and Wildlife Department (TPWD) and Texas Water Development Board (TWDB) to achieve ecological productivity targets for Galveston Bay.

Guthrie, C.G., and L. Qingguang. 2010. Coastal Hydrology for the Guadalupe Estuary: Updated Hydrology with Emphasis on Diversion and Return Flow Data for 2000-2009. Technical Memo - TWDB Galveston Bay Hydrology. 28 pp.

This technical memo documents the Texas Water Development Board's (TWDB) procedure for estimating combined freshwater inflow data for the Guadalupe Estuary and the specifics related to producing hydrology datasets version #TWDB201002, version #TWDB201004, and alternative version #HDR201001. Additionally, this technical memo reports on the findings of a review and comparison of TWDB diversion and return flows data, obtained from the Texas Commission on Environmental Quality and the South Texas Water Master, with similar data compiled by HDR based on individual reports from water right holders in the Guadalupe and San Antonio River basins below USGS stream gages #8177500 (Coleto Creek near Victoria), #8176500 (Guadalupe River at Victoria), #81888500 (San Antonio River at Goliad). This comparison focuses on the period from 2000-2009, but includes an alternative version containing HDR diversion and return flow data from 1977-2009. The data provided by HDR was beneficial to developing a more accurate representation of combined inflows to the estuary.

Hall, Q.A., M.M. Reese Robillard, J.A. Williams, M.J. Ajemian, and G.W. Stunz. 2016. Reopening of a Remote Tidal Inlet Increases Recruitment of Estuarine-Dependent Nekton. Estuaries and Coasts DOI 10.1007/s12237-016-0111-3

Cedar Bayou, a natural tidal inlet, was recently dredged to allow for direct water exchange between the Gulf of Mexico and Mesquite Bay, TX, USA.We quantified changes in densities of juvenile nekton (fish, shrimps, and crabs) and community structure in Mesquite Bay after Cedar Bayou was reopened by collecting samples at both control and impact sites using an epibenthic sled 1 year before (October 2013–April 2014) and after (October 2014–April 2015) opening. Significantly higher densities of total nekton were observed at the impact sites after opening using a before-after control impact design. Red Drum (Sciaenops ocellatus), Atlantic Croaker (*Micropogonias undulatus*), post-larval penaeid shrimps (*Farfantepenaeus aztecus*, *F. duorarum*, and *Litopenaeus setiferus*), and Blue Crabs (*Callinectes sapidus*) were significantly more abundant at impact sites after Cedar Bayou was opened. Multivariate analysis showed a significant change in impact site communities after opening and was driven by an increased presence of estuarine-dependent species. Overall, this study demonstrates that opening tidal inlets, such as Cedar Bayou, and reconnecting Mesquite Bay to the Gulf of Mexico increased the presence of numerous estuarine dependent species, many of which were not present or occurred at very low densities prior to reopening. Thus, reestablishing the historical connectivity between a productive estuary and the open Gulf of Mexico via Cedar Bayou should reinstitute natural nekton recruitment processes important to the Aransas, Mesquite, and San Antonio Bay regions.

Hall, Q.A., J.M. Curtis, J. Williams, and G.W. Stunz. 2019. The importance of newly-opened tidal inlets as spawning corridors for adult Red Drum (*Sciaenops ocellatus*). Fisheries Research 212 (2019) 48–55

The ability to emigrate from estuarine nursery areas to spawning grounds is essential for the persistence of estuarine dependent species such as Red Drum, (*Sciaenops ocellatus*). Typically, in this region, tidal inlets are the only mechanism for this transfer. Cedar Bayou, a natural tidal inlet, was deliberately closed in 1979 but was recently dredged and reopened. The inlet allows for direct water exchange between the Gulf of Mexico and Mesquite Bay, Texas, USA, and represents a unique opportunity to study estuarine dependent species' migration processes. Adult Red Drum were implanted with acoustic transmitters that allowed us to track their movement patterns before and after the reopening of Cedar Bayou. The goals of this study were to: 1) determine if Red Drum choose migration routes opportunistically in Texas waters; and 2) elucidate general movement patterns and residency estimates for Red Drum in Texas bays. Red Drum showed relatively little movement during the pre-opening period and summer, even after the inlet was restored. Once open, fish actively traversed through Cedar Bayou during the months commonly associated with spawning migrations and coincident with a drop in water temperature. These results demonstrate that Red Drum choose migration corridors opportunistically, thus opening tidal inlets such as Cedar Bayou can provide maturing Red Drum with greater connectivity between estuaries and spawning grounds in the open Gulf of Mexico.

Hu, X., J. Beseres-Pollack, M.R. McCutcheon, P.A. Montagna and Z. Ouyang. 2015. Long-term alkalinity decrease and acidification of estuaries in Northwestern Gulf of Mexico. *Environmental Science and Technology* 49: 3401-3409.

This paper documents a long-term decrease in alkalinity inventory and accompanying acidification of GOM estuaries.

Huggett, R.D., D.A. Purdie, and I.D. Haigh. 2021. Modelling the Influence of Riverine Inputs on the Circulation and Flushing Times of Small Shallow Estuaries. Estuaries and Coasts 44, no. 1 (2021): 54–69. https://doi.org/10.1007/s12237-020-00776-3.

This paper used flushing time calculations based on hydrodynamic modeling and particle tracing used as proxies for eutrophication susceptibility.

James, N.C., J.B. Adams, A.D. Connell, S.J. Lamberth, C.F. MacKay, G.C. Snow, L. van Niekerk, and A.K. Whitfield. 2020. High flow variability and storm events shape the ecology of the Mbhashe Estuary, South Africa, African Journal of Aquatic Science, 45:1-2, 131-151, DOI:10.2989/16085914.2020.1733472

The possible impacts of extreme events on the ecology of selected aquatic biota within the Mbhashe Estuary were investigated during a four year (2010–2013) spring sampling program. During periods of low to average flow conditions the estuary is shallow, turbid and characterized by the presence of fluid mud and the build-up of mud and clay deposits. During these conditions, extremely high biomasses of intertidal microalgae and zooplankton are present. Fish and macroinvertebrate abundance and diversity are also highest during low-flow conditions. Flood events can reset, or partially disrupt, the sediment erosion/depositional cycle and decrease the biomass and diversity of plankton, fish and macroinvertebrate species. The Mbhashe Estuary's unique fluid mud habitat is therefore subjected to regular resetting, which potentially contributes to the fluid nature of the muds. A storm surge in 2011 resulted in the temporary dieback of an area of mangroves, as a result of the deposition of marine sediment. Although extreme events seem to play an important role in the deposition and erosion cycle of the estuary, an increased frequency of both types of extreme events may ultimately result in estuarine habitat loss, which will adversely affect the biota of the estuary.

Jiabi Du, J., K. Park, C. Jensen, T.M. Dellapenna, W.G. Zhang, and Y. Shi. 2021. Massive oyster kill in Galveston Bay caused by prolonged low-salinity exposure after Hurricane Harvey, Science of The Total Environment, Volume 774, 2021 https://doi.org/10.1016/j.scitotenv.2021.145132.

Exceptionally high freshwater inflows from Hurricane Harvey contributed to high mortality of oysters in Galveston Bay.

Johns, N.D. and Heger, N.A. 2018, Characterizing estuarine salinity patterns with event duration and frequency of reoccurrence approaches. Limnol. Oceanogr. Methods, 16: 180-198. https://doi.org/10.1002/lom3.10236

This study presents an innovative approach to characterizing spatial and temporal patterns in salinity representing events of specific magnitude and duration.

Killebrew, F.C., W.J. Rogers, and J.B. Babitzke. 2002. Assessment of Instream Flow and Habitat Requirements for Cagle's Map Turtle (*Graptemys caglei*). Final Report to Edwards Aquifer Authority Contract No. #00-52-AS. 61 pp.

Provides an assessment of the instream flow and habitat requirements for the Cagle's Map Turtle (*Graptemys caglei*) in the Guadalupe River. This included an estimate relative abundance of *Graptemys caglei*, correlate occurrences of *Graptemys caglei* with detailed physical morphometric maps of stream reaches within the main stream of the Guadalupe River, develop field based habitat association of *Graptemys caglei* using instream flow methodologies and other techniques, determine instream flow requirements of *Graptemys caglei*, and address water quality parameters and predict attenuation or degradation of water quality in stream segments.

Kim, H.C. and P.A. Montagna. 2012. Effects of climate-driven freshwater inflow variability on macrobenthic secondary production in Texas lagoonal estuaries: A modeling study. *Ecological Modelling* 235– 236: 67– 80.

This paper employed a bio-energetic model to demonstrate the important of freshwater inflow on secondary productivity.

Kurr, E., 2019. Focused flows to natural nurseries in Texas estuaries. M.S. Thesis. Texas A&M University-Corpus Christi.

Analysis of infauna and epifauna to identify relationship to freshwater inflows and identify nursery areas in upper reaches of bay systems.

Little, S., P.J. Wood, and M. Elliott. 2016. Quantifying salinity-induced changes on estuarine benthic fauna: The potential implications of climate change. *Estuarine, Coastal, and Shelf Science* 198: 610-625.

This paper showed how estuarine responses to changes salinity acts within a hierarchy of factors including substratum type and biotic competition and predator- prey relationships.

Longley, W.L., ed. 1994. Freshwater inflows to Texas bays and estuaries: ecological relationships and methods for determination of needs. Texas Water Development Board and Texas Parks and Wildlife Department, Austin, 1X 386 pp.

This report integrates the results of recent studies with earlier information to provide a comprehensive overview of the importance of freshwater inflows to Texas estuaries. The report emphasizes the relationship of inflows with the chemical composition and physical nature of estuarine ecosystems, bay habitat distribution, physiological processes, biological productivity, and abundance of fish and shellfish populations. In addition, the report presents a methodology for determining the amount and timing of beneficial inflows needed to maintain the productivity of economically important fishery species, and the estuarine life on which they depend. This procedure deals effectively with competing inflow requirements among organisms and includes provisions for achieving management goals for specific estuarine habitats and species. The report provides data and example analyses of inflow needs for San Antonio Bay and the Guadalupe Estuary using several state management objectives.

Lower Colorado River Authority, Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, and Texas Water Development Board. 2006. Matagorda Bay freshwater inflow needs study. 280 pp.

The primary purpose of this study is to reassess the freshwater inflow needs for Matagorda Bay based on more than eight years of new data collected since the completion of the 1997 Freshwater Inflow Needs Study. The earlier study was based on five years of data collected after the U.S. Army Corps of Engineers (USACE) opened a diversion channel in 1991 from the Colorado River into Matagorda Bay to increase freshwater inflows entering into the bay. The current study also reviews and modifies some of the 1997 study methodologies and assumptions. The results of this study indicate that higher freshwater inflows are needed to achieve the Target and Critical inflow needs than indicated in the 1997 study. This is largely due to the availability of additional, more variable data collected over a longer period of time.

Martin, Q. D. Mosier, J. Patek, C. Gorham-Test. 1997. Freshwater inflow needs of the Matagorda Bay System. Lower Colorado River Authority. 229 pp.

Developed a methodology based on the synthesis of three components: (1) development of statistical relationships between freshwater inflows and key indicators of estuarine conditions, (2) computation of monthly and seasonal freshwater inflows to optimize estuarine conditions subject to specific constraints at key estuarine locations and (3) evaluation of estuarine-wide salinity conditions to ensure conditions remain within desired limits.

Matsumoto, J., G.L. Powell, D.A. Brock, and C. Paternostro. 2005. Effects of Structures and Practices on the Circulation and Salinity Patterns of Galveston Bay, Texas. TWDB Technical Memo. 131 pp.

The purpose of the Galveston Bay Modeling Project was to study the effect of structures and practices on the circulation and salinity in Galveston Bay. Five cases were studied: the no diversion case examined the effect of diverting flow from the Trinity River to the San Jacinto River; the no power case examined the effect of power plant withdrawal and discharge of bay water; the Texas City Dike removal case examined the effect of the Texas City Dike; the Houston Ship Channel (HSC) removal case examined the effect of the Houston Ship Channel; and the natural case examined a condition in which all these practices and structures were removed.

McFarlane, R., A. Leskovskaya, J. Lester, and L. Gonzalez. 2015. The effect of four environmental parameters on the structure of estuarine shoreline communities in Texas, USA. Ecosphere 6(12):258. http://dx.doi.org/10.1890/ES15-00326.1

Statistical modeling of TPWD coastal fisheries monitoring data against the water quality parameters of temperature, salinity, dissolved oxygen, and turbidity.

Montagna, P.A., E.D. Estevez, T.A. Palmer and M.S. Flannery. 2008. Meta-analysis of the relationship between salinity and molluscs in tidal river estuaries of southwest Florida, U.S.A. *American Malacological Bulletin* 24: 101-115.

This paper used a meta-analysis approach to develop salinity ranges to predict changes in mollusk assemblages in response to alterations in salinity that result from changes in freshwater inflow.

Montagna, P.A., R.D. Kalke and C. Ritter. 2002. Effect of restored freshwater inflow on macrofauna and meiofauna in upper Rincon Bayou, Texas, USA. *Estuaries* 25:1436-1447.

This paper document the ecological benefits on macrofauna and meiofauna observed by the opening of Rincon Bayou.

Moulton, D.L., M.A. Dance, J.A. Williams, M.Z. Sluis, G.W. Stunz, and J.R. Rooker. 2017. Habitat Partitioning and Seasonal Movement of Red Drum and Spotted Seatrout. Estuaries and Coasts (2017) 40:905–916 DOI 10.1007/s12237-016-0189-7

Acoustic telemetry was used to examine habitat use and movement of two sympatric gamefishes, red drum (*Sciaenops ocellatus*) and spotted seatrout (*Cynoscion nebulosus*), at two spatial scales (habitat and bay) within an estuarine complex. Habitat-scale tracking (~ 1 m–1km) based on an acoustic positioning system revealed that seagrass was used extensively by both species. Red drum also commonly associated with oyster reef and boundaries between habitat types. Spatial overlap between the two species was limited and indicative of habitat partitioning; red drum were commonly observed in the shallow, inner lagoon and spotted seatrout in the deeper, open bay portion of the array. Conspicuous diel shifts were also observed for spotted seatrout; fish transitioned from seagrass to bare substrate and displayed greater rates of movement at night than day. Bay-scale (1–50+ km) tracking over a two-year period primarily showed limited movement within bays; however, directed bay-scale movements by both species were observed during winter and spring, when a small contingent of individuals moved up to 70 km from original tagging locations. Habitat use and movement were species specific and subject to temporal variation, both diel and seasonal. Habitat-scale connectivity was influenced by seascape structure and water depth, and bay-scale connectivity was generally limited, suggesting the sustainability of these fisheries is likely influenced by local conditions.

Neahr, T.A., G.W. Stunz, and T.J. Minello. 2010. Habitat use patterns of newly settled spotted seatrout in estuaries of the north-western Gulf of Mexico. Fisheries Management and Ecology, 2010, 17, 404–413.

This study examined habitat use patterns of newly settled spotted seatrout *Cynoscion nebulosus* (Cuvier) across several Gulf of Mexico estuaries. Intensive sampling using an epibenthic sled was conducted in three Texas bays and among three potential habitat types. A long-term data set (1982 to 1997) from the National Marine Fisheries Service was also used to examine C. nebulosus habitat use patterns in both marsh and seagrass-dominated bay systems for broad regional comparisons along the north-western Gulf of Mexico. Vegetated habitat types such as seagrass and marsh supported the highest densities and use was dependent upon availability of particular vegetated habitat types. In laboratory mesocosm experiments, both wild-caught and hatchery-reared C. nebulosus, showed strong selection for structured and vegetated habitat types. These field and laboratory results suggest that seagrass meadows and marshes may be functioning as important habitat for C. nebulosus in Gulf of Mexico, and other habitat types such as oyster reef need further evaluation.

Nevins, J.A., J. Beseres Pollack, and G.W. Stunz. 2014. Characterizing Nekton use of the Largest Unfished Oyster Reef in the United States Compared with Adjacent Estuarine Habitats. Journal of Shellfish Research, Vol. 33, No. 1, 227–238, 2014. DOI: http://dx.doi.org/10.2983/035.033.0122. URL: http://www.bioone.org/doi/full/10.2983/035.033.0122

Characterizing density patterns of fish and crustaceans across estuarine habitat types can provide useful information regarding their relative value. The oyster reef complex within Sabine Lake Estuary is the largest known in the United States with no record of commercial harvest, and it presents a unique opportunity to understand the habitat value of an unfished reef system in comparison with adjacent estuarine habitats. High abundances of relatively large oysters with complex formations were observed throughout the 2-y study period. Average densities of fish and crustaceans were 6 times greater at the marsh edge than the nonvegetated shallow habitats, and 40 times greater than both the oyster reef and nonvegetated deep habitats. Low faunal densities observed in the oyster reef habitat may be the result of spatial configuration and connectivity to surrounding habitats, collection limitation resulting from its large vertical relief (>1 m) and complex 3-dimensional structure, or habitat selection resulting from water depth. Because the majority of crustaceans and resident and transient fish were observed within the marsh edge and nonvegetated shallow habitats, it is difficult to determine whether oyster reefs within Sabine Lake Estuary provide essential habitats for these species. Although low densities of organisms were observed in the oyster reef habitat, multivariate analysis indicates that the unfished reef supports a unique community of fish and crustaceans. Results provide a valuable baseline for future conservation, restoration, and management actions as we seek to understand more completely and to protect important habitat types.

Oakley, J.W., J. Simons, and G.W. Stunz. 2014. Spatial and habitat-mediated food web dynamics in an oyster-dominated estuary. Journal of Shellfish Research, Vol. 33, No. 3, 841–855, 2014.

Understanding spatial dynamics and creating spatial boundaries of marine food webs is an important topic that resource managers are beginning to understand. Food web structure, mediated by spatial and habitat differences, was examined in a subtropical estuary using stomach content and stable isotope analyses. The goal of this study was to characterize the trophic structure in subtidal oyster reef, intertidal marsh edge, and nonvegetated bottom habitats. Fish and macroinvertebrates were sampled seasonally from July 2006 to April 2007. Spatially, the lower region of the bay supported a more robust food web, with more species and links (72 and 130, respectively) than the upper bay (63 and 87, respectively). Trophic levels (determined by 15N) and carbon sources (determined by 13C) were combined with dietary links (determined by stomach contents), relative population levels, and linkage strength (determined by food volume) to construct 5 dimensional food web diagrams for the 2 regions and 3 habitats studied. The 15N isotope indicated differences in trophic levels and probable nitrogen sources among regions whereas the 13C isotope inferred differences in carbon sources among regions in the Lavaca Bay ecosystem. This evidence suggests that lower Lavaca Bay is providing an environment conducive to robust food webs, and that locations in relatively close proximities within the same estuary can have very different food web interactions. Our data suggest there are significant differences in food web structure at the spatial scales examined in Lavaca Bay, which supports the idea that food webs are compartmentalized. As resource managers move toward ecosystem-based management, they must consider the distinct communities and accompanying food webs associated with the varying habitat types and spatial scales observed in this coastal ecosystem.

Palmer, T.A. and P.A. Montagna. 2015. Impacts of droughts and low flows on estuarine water quality and benthic fauna. *Hydrobiologia* 753:111–129.

This paper analyzed effects of droughts on benthic infaunal communities and three epifaunal species in three semi-arid central Texas estuaries with different inflow dynamics and consequent salinity regimes and found that in drought did not appear to be important drivers of infaunal communities in estuarine regions with normally high salinities (25–32) but did cause decreases in *Litopenaeus setiferus* (white shrimp) and *Callinectes sapidis* (blue crab) abundances and spatial extents.

Palmer, T.A., P.A. Montagna, J.B. Pollack, R.D. Kalke and H.R. DeYoe. 2011. The role of freshwater inflow in lagoons, rivers and bays. *Hydrobiologia* 667: 49-67.

This paper analyzed Macrofaunal community structure to classify Texas estuaries as polyhaline com-munities and contained lagoons (East Matagorda, Matagorda, Christmas, and South Bays) or oligo-mesohaline com-munities and contained the secondary bays (Lavaca Bay and Cedar Lakes) and rivers

(San Bernard River, Brazos River, and the Rio Grande).

Paudel, B. and P.A. Montagna. 2014. Modeling inorganic nutrient distributions among hydrologic gradients using multivariate approaches. *Ecological Informatics* 24:35-46.

This paper used long term data from the Guadalupe, Lavaca, and Nueces estuaries to test whether different inflow regimes result in different nutrient transport and different structural and functional balance of nutrient dynamics.

Paudel, B., P.A. Montagna, and L. Adams. 2019. The relationship between suspended solids and nutrients with variable hydrologic flow regimes, Regional Studies in Marine Science, Volume 29, 2019, https://www.sciencedirect.com/science/article/pii/S2352485518306479

A study of effects of freshwater inflows on salinity, suspended solids, and nutrient concentrations in three Texas estuaries.

Pollack, J. B., D. Yoskowitz, H.C. Kim, and P.A. Montagna. 2013. Role and Value of Nitrogen Regulation Provided by Oysters (Crassostrea Virginica) in the Mission-Aransas Estuary, Texas, USA. PLoS ONE 8, no. 6 (2013): 6–13. https://doi.org/10.1371/journal.pone.0065314.

This paper estimated the ecosystem services value of nitrogen removal by Oysters in the Mission-Aransas Estuary to be $293,993 per year.

Pothina, D., and C.G. Guthrie. 2009. Evaluating Inverted Siphons as a Means of Mitigating Salinity Intrusion in the Keith Lake/Salt Bayou System, Jefferson County, Texas. Final Report to USEPA, Grant No. MX-96401704. TWDB.

As part of this study, data was collected at 11 locations in and around the Keith Lake/Salt Bayou system from December 2005 to April 2007. These included water quality, water level, and velocity measurements, as well as a bathymetric survey; additional data was obtained from other sources. This data then was used to develop and calibrate a high resolution, three-dimensional baroclinic hydrodynamic and salinity transport simulation model of the region using the SELFE modeling software. The model domain encompassed the open water features of Salt Bayou, including the Fish Pass, and other external drivers such as the Sabine-Neches Waterway, the Gulf Intracoastal Waterway, Sabine Lake, and the Gulf of Mexico. The model then was used to evaluate the effectiveness three siphon-flow rate scenarios (constant flow: 1.42m3/s and 2.48m3/s, and a linearly decreasing flow: 1.42m3/s decreasing to 0m3/s) at each of three locations (Star Lake, Willow Lake, or the Salt Bayou Outfall) for the target year of 2003. Model results showed that all siphon locations were able to reduce salinity within a local area, but the extent of salinity reduction varied throughout the year.

Powell, G.L., J. Matsumoto, and D.A. Brock. 2002. Estuaries Vol. 25, No. 6B, p. 1262–1274.

In response to legislative directives beginning in 1975, the Texas Water Development Board (TWDB) and the Texas Parks and Wildlife Department (TPWD) jointly established and currently maintain a data collection and analytical study program focused on determining the effects of and needs for freshwater inflows into the state's 10 bay and estuary systems. Study elements include hydrographic surveys, hydrodynamic modeling of circulation and salinity patterns, sediment analyses, nutrient analyses, fisheries analyses, freshwater inflow optimization modeling, and verification of needs. For determining the needs, statistical regression models are developed among freshwater inflows, salinities, and coastal fisheries. Results from the models and analyses are placed into the Texas Estuarine Mathematical Programming (TxEMP) model, along with information on salinity viability limits, nutrient budgets, fishery biomass ratios, and inflow bounds. The numerical relationships are solved within the constraints and limits and optimized to meet state management objectives for maintenance of biological productivity and overall ecological health. Solution curves from the TxEMP model are verified by TWDB's hydrodynamic simulation of estuarine circulation and salinity structure, which is evaluated against TPWD's analysis of species abundance and distribution patterns in each bay and estuary system. An adequate system-wide match initially verifies the inflow solution. Long-term monitoring is recommended in order to verify that implementation of future water management strategies maintain ecological health of the estuaries and to provide an early warning of needs for adaptive management strategies.

Puckett B.J, S.J. Theuerkauf, D.B. Eggleston, R. Guajardo, C. Hardy, J. Gao, R.A. Luettich. 2018. Integrating Larval Dispersal, Permitting, and Logistical Factors Within a Validated Habitat Suitability Index for Oyster Restoration. Front. Mar. Sci. 5:76. doi: 10.3389/fmars.2018.00076

A habitat suitability index model for oyster restoration including salinity, dissolved oxygen, substrate and various biological and permitting factors.

Reese, M.M., and G.W. Stunz. 2008. Recruitment of Estuarine-Dependent Nekton Through a New Tidal Inlet: The opening of Packery Channel in Corpus Christi, TX, USA. Estuaries and Coasts (2008) 31:1143–1157 DOI 10.1007/s12237-008-9096-x

The US Army Corps of Engineers recently dredged and permanently reopened Packery Channel, historically a natural tidal inlet, to allow water exchange between the Gulf of Mexico and the Laguna Madre, TX, USA. The main objective of this study was to characterize estuarine-dependent recruitment and community structure in seagrass habitats adjacent to Packery Channel pre- and post-channel opening. We sampled fish and crustacean abundance using an epibenthic sled in *Halodule wrightii* seagrass meadows in both control and impact locations over 2 years, 1 year before the opening of Packery Channel (October 2004–May 2005) and 1 year after (July 2005–April 2006). Using the before–after control–impact design, we found significantly fewer nekton post-channel opening. However, we found significantly higher mean densities of newly settled estuarine-dependent species (*Sciaenops ocellatus*, *Micropogonias undulatus*, *Lagodon rhomboides*, *Callinectes sapidus*, and penaeid shrimp) post-opening. Multivariate analyses showed significant community assemblage changes post-opening with increased contribution of estuarine-dependent species post-opening. Our results show that estuarine-dependent nekton are using Packery Channel as a means of ingress into areas of the upper Laguna Madre's seagrass meadows that were previously inaccessible, which may lead to higher fisheries productivity for some of these economically and ecologically important fishery species.

Russell, M.J. and P.A. Montagna. 2007. Spatial and temporal variability and drivers of net ecosystem metabolism in western Gulf of Mexico estuaries. *Estuaries and Coasts* 30: 137-153.
This paper evaluated correlative relationships between temperature, salinity, and freshwater inflow and net ecosystem metabolism (NEM). The relationships were significant but variably across time and space.

Schoenbaechler, C., C.G. Guthrie, and L. Qingguang. 2012. Coastal Hydrology for the Trinity-San Jacinto Estuary. Technical Memo - TWDB Galveston Bay Hydrology. 29 pp.

This technical memo documents the procedure for estimating combined freshwater inflow data and freshwater inflow balance for the Trinity-San Jacinto Estuary and the specifics related to producing TWDB hydrology dataset version #TWDB201101 for this estuary.

Schoenbaechler, C., C.G. Guthrie, and L. Qingguang. 2011. Coastal Hydrology for the Nueces Estuary:

Hydrology for Version #TWDB201101 with Updates to Diversion and Return Data for 2000-2009. Technical Memo - TWDB Galveston Bay Hydrology. 20 pp.

This technical memo documents the Texas Water Development Board's (TWDB) procedure for estimating combined freshwater inflow data and the specifics related to producing hydrology dataset versions #TWDB201001, #TWDB201004, and #TWDB201101 for the Nueces Estuary. The most recent update, version #TWDB201101, includes newly acquired diversion and return data obtained from the Nueces River Authority (NRA), but compiled by HDR, Inc.

Schoenbaechler, C., C.G. Guthrie, and L. Qingguang. 2011. Coastal Hydrology for the Laguna Madre Estuary, With Emphasis on the Lower Laguna Madre. Technical Memo - TWDB Galveston Bay Hydrology. 29 pp.

This technical memo documents the procedure for estimating combined freshwater inflow data and the freshwater inflow balance for the Laguna Madre Estuary and the specifics related to producing TWDB hydrology datasets version #TWDB201101 for the Laguna Madre and #TWDB201101-L for the Lower Laguna Madre only.

Schoenbaechler, C., C.G. Guthrie, and L. Qingguang. 2011. Coastal Hydrology for the Laguna Madre Estuary, With Emphasis on the Upper Laguna Madre. Technical Memo - TWDB Galveston Bay Hydrology. 28 pp.

This technical memo documents the procedure for estimating combined freshwater inflow data and the freshwater inflow balance for the Laguna Madre Estuary and the specifics related to producing TWDB hydrology datasets version #TWDB201101 for the Laguna Madre, both upper and lower portions, and version #TWDB201101-U for the Upper Laguna Madre only.

Schoenbaechler, C., C.G. Guthrie, and L. Qingguang. 2011. Coastal Hydrology for the Mission-Aransas Estuary. Technical Memo - TWDB Galveston Bay Hydrology. 29 pp.

This technical memo documents the procedure for estimating combined freshwater inflow data for the Mission-Aransas Estuary and the specifics related to producing hydrology dataset versions #TWDB201001 and #TWDB201004 for this estuary.

Schoenbaechler, C., C.G. Guthrie, and L. Qingguang. 2011. Coastal Hydrology for the Brazos River Estuary. Technical Memo - TWDB Galveston Bay Hydrology. 13 pp.

This technical memo documents the Texas Water Development Board's (TWDB) procedure for estimating combined freshwater inflow and the specifics related to producing hydrology dataset version #TWDB201004 for the Brazos River Estuary.

Schoenbaechler, C., C.G. Guthrie, and L. Qingguang. 2011. Coastal Hydrology for East Matagorda Bay. Technical Memo - TWDB Galveston Bay Hydrology. 13 pp.

This technical memo documents the procedure for estimating combined freshwater inflow data for East Matagorda Bay and the specifics related to producing hydrology dataset versions #TWDB201001 and #TWDB201004 for this estuary.

Stunz, G.W., T.L. Linton, and R.L. Colura. 2000. Age and Growth of Southern Flounder in Texas Waters, with Emphasis on Matagorda Bay. Transactions of the American Fisheries Society 129:119–125. Estimates of age and growth of southern flounder *Paralichthys lethostigma* from Matagorda Bay, Texas, were made by analyzing thin sections of sagittal otoliths from 892 specimens collected along the Texas coast from May 1992 to January 1995. Marginal increment analysis showed that a single annulus completed formation between January and March. The maximum age differed by bay systems, but it ranged from 0 to 4 years for both males and females. Males were generally smaller than females and exhibited asymptotic growth at an earlier age.

Stunz, G.W., T.J. Minello, and P.S. Levin. 2002a. A comparison of early juvenile red drum densities among various habitat types in Galveston Bay, Texas. Estuaries Vol. 25, No. 1, p. 76–85.

Seagrass meadows are often cited as important nursery areas for newly settled red drum even though many estuaries, such as Galveston Bay, Texas, support large numbers of red drum and have limited seagrass cover, suggesting the use of alternate nursery areas. We examined patterns of habitat use for newly settled red drum at six sampling areas in Galveston Bay; two areas had seagrass beds and four areas had no seagrass. We measured densities in different habitat types using epibenthic sleds and enclosure samplers. Peak recruitment of young red drum to the estuary occurred during September through December. Highest densities of new settlers were found in seagrass meadows (primarily *Halodule wrightii*), but when seagrass was absent, the highest densities of red drum occurred along the *Spartina alterniflora* marsh edge interface. Densities were relatively low on nonvegetated bottom away from the marsh edge. We also examined density patterns in other habitat types at selected sampling areas and found no red drum within marsh vegetation away from the marsh edge interface (5 and 10 m into the marsh interior). Oyster reef *Crassostrea virginica* was sampled using lift nets, and we found no red drum using this habitat, although adjacent seagrass and marsh interface habitats were used. Even though red drum densities in marsh edge were low relative to seagrass, the large areal extent of marshes in the bay complex probably makes marsh edge the most important nursery habitat for red drum in Galveston Bay.

Stunz, G.W., T.J. Minello, and P.S. Levin. 2002b. Growth of newly settled red drum Sciaenops ocellatus in different estuarine habitat types. Mar Ecol Prog Ser 238: 227–236, 2002.

We examined growth of recently settled juvenile red drum in salt marsh, seagrass, oyster reef, and on nonvegetated bottom areas in the Galveston Bay system of Texas (USA). We estimated growth using otolith microstructure from free-ranging fish collected in different habitat types and also measured growth of red drum in experimental enclosures where fish movement was restricted. Otolith growth was closely related to somatic growth in fish of 13 to 33 mm SL, and we used daily otolith increments from the last 10 d before capture as an indicator of growth following settlement into estuarine habitats. Growth rates of red drum captured at marsh, nonvegetated, and seagrass sites were not significantly different; no fish were collected on oyster reef. While reducing potential problems of a lagged response between otolith growth and somatic growth, the use of a 10 d growth period may have increased the likelihood of fish movement among habitats affecting our comparisons. The overall post-settlement growth rate of 0.45 mm d–1 was similar to rates reported in the literature. Movement among habitat types was eliminated in experiments employing 24 solid walled enclosures (60 cm diameter). Growth rates in enclosures over the 7 d experiment were 0.12 mm d–1 in oyster reef, 0.21 mm d–1 on nonvegetated bottom, 0.40 mm d–1 in salt marsh, and 0.42 mm d–1 in seagrass; rates in vegetated enclosures approximated natural growth rates. Significantly higher growth in marsh and seagrass enclosures suggests that growth potential for red drum may be highest in these vegetated areas. However, growth results in enclosures need to be evaluated carefully, because fish movement among habitat types may be important in these shallow estuarine systems.

Stunz, G.W., T.J. Minello, and L.P. Rozas. 2010. Relative value of oyster reef as habitat for estuarine nekton in Galveston Bay, Texas. Mar Ecol Prog Ser Vol. 406: 147–159, 2010 doi: 10.3354/meps08556

Biogenic reefs formed by dense aggregations of the eastern oyster *Crassostrea virginica* are a dominant feature in most estuarine systems along the Atlantic and Gulf of Mexico. Oyster reefs are complex in their structural nature and have long been recognized for their potential habitat value. However, relatively few studies have characterized nekton abundance in this complex habitat type, and live high-relief oyster beds have been particularly difficult to sample with conventional gear. We used a quantitative sampling device to compare nekton use among high-relief live oyster reef, vegetated marsh edge Spartina alterniflora, and nonvegetated bottom habitat types. During 1 yr of seasonal sampling we collected 3791 fishes and 12 386 crustaceans representing 38 and 21 different species, respectively. Density and biomass of most fishes and crustaceans were significantly higher in oyster reef than over nonvegetated bottom. For benthic crustaceans, oyster reef supported a higher density and biomass than vegetated marsh edge. Nektonic crustaceans were generally more abundant in marsh edge than on oyster reef. Species composition and richness varied among habitat types and season; however, richness was highest in oyster reef, followed by marsh edge, and lowest on nonvegetated bottom, except during seasonal low densities during winter. Species composition and size differences were observed among habitat types. Our results show that oyster reef supports a high density, biomass, and richness of estuarine nekton in relation to typically examined estuarine habitat types and has the potential to be an essential habitat. Identifying and quantifying the role of oyster reefs will be critical to implementing effective management for essential fish habitat.

Texas Comptroller's Natural Resources Program. 2020. Matagorda Bay Economic and Ecological Resources Report. Chapter 1. Introduction to the Matagorda Bay Ecosystem Assessment. https://storymaps.arcgis.com/stories/00496c9f1dbc48f48ef9997977112418

The Matagorda Bay Economic and Ecological Resource Report, produced by the Natural Resources program, synthesizes economic significance, research findings and community involvement in the Matagorda Bay Ecosystem Assessment (MBEA). The Resource Report is available by chapter, themed around focal habitats within the MBEA. Chapters follow a three-tiered approach: (1) ecological background informed by research, (2) economic trends, and (3) project updates including notes from the field and stakeholder feedback. Each chapter is presented as a StoryMap, an ESRI ArcGIS platform, to integrate data, photographs and maps in one website. Use the links below to access each chapter (chapter topics are subject to change).

Texas Department of Water Resources. 1980. Lavaca-Tres Palacios Estuary: A study of the influence of freshwater inflows. LP-106. 350 pp.

Texas Department of Water Resources. 1980. Guadalupe Estuary: A study of the influence of freshwater inflows. LP-107. 339 pp.

Texas Department of Water Resources. 1981. Nueces and Mission Aransas Estuary: A study of the influence of freshwater inflows. LP-108. 380 pp.

Texas Department of Water Resources. 1981. Sabine-Neches Estuary: A study of the influence of freshwater inflows. LP-116. 322 pp.

Texas Department of Water Resources. 1981. Trinity-San Jacinto Estuary: A study of the influence of freshwater inflows. LP-113. 413 pp.

Texas Department of Water Resources. 1982. The influence of freshwater inflows upon the major bays and estuaries of the Texas Gulf Coast: Executive Summary. 2nd Edition. LP-115. 123 pp.

Texas Department of Water Resources. 1983. Laguna Madre Estuary: A study of the influence of freshwater inflows. LP-182. 284 pp.

This series of reports were published as a part of the effort to address the relationship of freshwater inflow to the health of living estuarine resources (e.g., fish, shrimp, etc.) and to present methods of providing and maintaining a suitable ecological environment. The technical analyses were to characterize the relationships which have maintained the estuarine environments historically and which have provided for the production of living resources at observed historic levels.

Texas Parks and Wildlife Department and Texas Water Development Board. 2001. Freshwater inflow recommendations for the Trinity-San Jacinto Estuary of Texas. Final Report to U.S. Fish and Wildlife Service, Federal Aid Project F-37-TA. 66 pp.

This report summarizes the protocol and analyses used to determine the target freshwater inflow (FWI) needed to support the biological productivity of the Trinity - San Jacinto Estuary. Each Texas estuary requires FWI in order to maintain the proper salinity gradients, nutrient concentrations and sediment loading, which in tum support the abundance and distribution of fauna and flora in these systems. Freshwater inflow from rivers and the local ungaged runoff thus acts as a critical mechanism to regulate the coastal factors and processes that produce an "ecologically sound and healthy estuary".

Texas Parks and Wildlife Department and Texas Water Development Board. 2004. Freshwater inflow recommendation for the Laguna Madre Estuary System. Final Report. 115 pp.

This report summarizes the studies conducted by Texas Parks and Wildlife Department (TPWD) studies in order to determine the freshwater inflow amounts needed to sustain the unique biological communities and ecosystems characteristic of a "healthy" Laguna Madre estuary system.

Texas Parks and Wildlife Department and Texas Water Development Board. 2002. Freshwater inflow recommendation for the Nueces Estuary. Final Report to U.S. Fish and Wildlife Service, Federal Aid Project F-37-TA. 99 pp.

This report summarizes studies performed by Texas Parks and Wildlife Department (TPWD) in accordance with Texas Water Code 11.1491 to recommend freshwater inflow targets which sustain the unique biological ecosystems characteristic of an "ecologically sound and healthy" Nueces Estuary.

Texas Parks and Wildlife Department and Texas Water Development Board. 2005. Freshwater inflow recommendation for the Sabine Lake Estuary of Texas and Louisiana. Final Report to U.S. Fish and Wildlife Service, Federal Aid Project F-37-TA. 75 pp.

Texas Parks and Wildlife Department (TPWD) and the Texas Water Development Board (TWDB) have been charged by the Texas Legislature with determining the freshwater inflows that provide suitable salinity, nutrient and sediment loading regimes (i.e., support a sound estuarine environment) for Texas bays. This report presents the results of the freshwater inflow analysis for the Sabine Lake system.

Texas Parks and Wildlife Department and Texas Water Development Board. 1998. Freshwater inflow recommendation for the Guadalupe Estuary of Texas. Final Report to U.S. Fish and Wildlife Service, Federal Aid Project F-37-TA. 102 pp.

Freshwater inflows (FWI) from rivers, streams, and local runoff maintain the proper salinity gradients, nutrient loadings, and sediment inputs that in combination produce an "ecologically sound and healthy Estuary." This report summarizes studies which form the basis for TPWD's recommendation of target freshwater inflows needed to maintain the unique biological communities and ecosystems characteristic of a healthy Guadalupe Estuary in Texas.

Texas Parks and Wildlife Department and Texas Water Development Board. 2010. Freshwater inflow recommendations for the Mission-Aransas Estuarine System. Final Report to U.S. Fish and Wildlife Service, Federal Aid Project F-37-TA. 131 pp.

As a result of severe droughts in the 1950s, the Texas legislature tasked the Texas Water Development Board (TWDB) and the Texas Parks and Wildlife Department (TPWD) "to determine the bay conditions (i.e., sediments, nutrients, and salinity gradients) necessary to support a sound ecological environment." Since freshwater inflows (FWI) are a main driver of bay conditions in Texas, TPWD and TWDB sought to determine the amount of FWI that was needed to maintain the ecological integrity of the estuary. This report summarizes studies that were used to formulate TPWD's freshwater inflow recommendation for the Mission-Aransas system.

Tolan, J.M. 2007. El Niño-Southern Oscillation impacts translated to the watershed scale: estuarine salinity patterns along the Texas Gulf Coast, 1982 to 2004. *Estuarine Coastal and Shelf Science* 72: 247-260

This paper analyzes the relationship between ENSO signal and salinities in Texas Bays and find a strong relationship to low frequencies signal suggesting the management strategies focused on monthly/seasonal time steps may not adequately address the important ENSO-driven periodicities governing coastal estuarine salinity patterns.

Turner, E.L., D.A. Bruesewitz, R.F. Mooney, P.A. Montagna, J.W. McClelland, A. Sadovski, E.J. Buskey. 2014. Comparing performance of five nutrient phytoplankton zooplankton (NPZ) models in coastal lagoons. *Ecological Modelling* 277: 13–26.

This study compared the performance of multiple NPZ models and found that a new one which incorporated benthic consumption dynamics performed slightly better, increased model complexity did not significantly improve performance.

Van Diggelen, A.D. and P.A. Montagna. 2016. Is salinity variability a benthic disturbance in estuaries? *Estuaries and Coasts* 39:967-980.

This paper evaluated the importance of salinity variance, in contrast to average salinity as a drive of benthic diversity.

Van Niekerk, L., S. Taljaard, J. Adams,S. Lamberth, P. Huizinga, J. Turpie and T. Wooldrige. 2019. An environmental flow determination method for integrating multiple scale ecohydrological and complex ecosystem processes in estuaries. Science of the Total Environment. 656:482-494.

This paper presents an environmental flow methodology suitable for highly dynamic microtidal estuaries, focusing on estuaries that are not always connected to the sea.

Wilber, D.H., and R. Bass 1998. Effect of the Colorado River diversion on Matagorda Bay epifauna. *Estuarine, Coastal and Shelf Science* 47:309-318.

This paper found little or no benefit to species abundance of common epifauna following restoration of flows to the west Matagorda Bay thought did suggest that oyster response may be lagged based on historical relationships.

Williams, J.A., G.J. Holt, M.M. Reese Robillard, S.A. Holt, G. Hensgen, and G.W. Stunz. 2016. Seagrass fragmentation impacts recruitment dynamics of estuarine-dependent fish. Journal of Experimental Marine Biology and Ecology 479 (2016) 97–105

Seagrass beds are a key component of the estuarine landscape supporting high productivity, abundant marine life, and serve as nursery areas for many estuarine-dependent species. With increasing anthropogenic activity, there is concern about overall habitat loss via fragmentation and what effects this may have on local biotas relying on seagrasses for persistence. To examine these effects, fragmented seagrass beds (*Halodule wrightii*, Ascherson 1868) in two different bay systems, Corpus

Christi and Aransas Bay, Texas, were delineated, quantified, and mapped, and red drum (*Sciaenops ocellatus*, Linnaeus 1766) was used as a model species to test for impacts of fragmentation on this common estuarine-dependent species. Red drum density, growth, and movement were measured in response to varying levels of fragmentation (i.e., High, Medium, and Low). No difference in initial recruitment of red drum density was observed among fragmentation levels for newly settled arrivals. However, there was a significant size effect; larger fish were found in non-fragmented areas. Growth rates were also com-pared among fragmented habitats using both RNA:DNA ratios and otolith microstructure, and no significant effect of growth among fragmentation levels was found. Migration potential was measured at the landscape-level within and among fragmented seagrass meadows by tagging and releasing 200 juvenile red drum into three separate replicated fragmented networks. Within 24 h, only one fish was recaptured within the original fragmented network. The vast majority of recaptured fish were found in the nearest continuous non-fragmented seagrass bed over 50 m from their release point. These results suggest a temporal transition of small newly recruited red drum, where individuals settle ubiquitously among varying levels of fragmentation but over time migrate toward more continuous beds. This study provides evidence that there may be a fragmentation "threshold" for red drum, whereby once a habitat becomes too fragmented; individuals either suffer higher mortality or more likely move to more continuous landscapes. Overall, this study suggests that habitat fragmentation and loss of more continuous seagrass meadows may have negative impacts on estuarine-dependent species using these areas as their primary recruitment habitat.

Yarnell, Y., E.D. Stein, J.A. Webb, T. Grantham, R.A. Lusardi, J. Zimmerman, R.A. Peek, B.A. Lane, J. Howard, S. Sandoal-Solis. 2020. A functional flows approach to selecting ecologically relevant flow metrics for environmental flow applications. River Research and Applications 36:318-324.

This paper proposes a functional flows approach to understand the relationships between hydrologic change and biologic response that focuses on element of natural flow know to sustain ecosystem processes.

Geomorphology, Fluvial Processes and Hydrology

The literature in this section represents key geomorphic process and baseline conditions in Texas rivers that provide key data to inform interpretation of long-term monitoring of aquatic and riparian resources related to the processes of channel changes driven my hydrology and/or anthropogenic influences at the watershed level.

Cawthon, T. 2007. Channel change on the San Antonio River. Final Report to TWDB Contract No. 0604830638. 52 pp.

Evaluated channel changes in response to hydrology and anthropogenic factors at the watershed scale using imagery and channel cross section data from 1950, 1975, 1995, and 2003.

Coffman, D.K., Malstaff, Greg, and Heitmuller, F.T., 2011, Characterization of geomorphic units in the alluvial valleys and channels of Gulf Coastal Plain rivers in Texas, with examples from the Brazos, Sabine, and Trinity Rivers, 2010: U.S. Geological Survey Scientific Investigations Report 2011–5067, 31 p.

The U.S. Geological Survey, in cooperation with the Texas Water Development Board, described and characterized examples of geomorphic units within the channels and alluvial valleys of Texas Gulf Coastal Plain rivers using a geomorphic unit classification scale that differentiates geomorphic units on the basis of their location either outside or inside the river channel. The geomorphic properties of a river system determine the distribution and type of potential habitat both within and adjacent to the channel. This report characterizes the geomorphic units contained in the river channels and alluvial valleys of Texas Gulf Coastal Plain rivers in the context of the River Styles framework. This report is intended to help Texas Instream Flow Program practitioners, river managers, ecologists and biologists, and others interested in the geomorphology and the physical processes of the rivers of the Texas Gulf Coastal Plain (1) gain insights into how geomorphic units develop and adjust spatially and temporally, and (2) be able to recognize common geomorphic units from the examples cataloged in this report.

Engel, F.L., and J.C. Curran. 2008. Geomorphic Classification of the Lower San Antonio River, Texas. Final Report to TWDB Contract No. 0604830637. 49 pp.

A detailed geomorphic classification of the Lower San Antonio River provides a useful tool to understand differences in physical processes and habitats along the river. In this study, the river was segmented into 25 reaches based on channel and valley characteristics, as shown in the figure below. A description of each reach was provided, including characteristic channel and floodplain features such as point bars, large woody debris dams, cobble riffles, oxbow lakes, and backwater swamps. When investigating the river, some of these reaches may be combined, depending on the processes or features of interest.

Giardino, J.R., and A.A. Lee. 2011. Rates of Channel Migration on the Brazos River. Final Report to TWDB Contract No. 0904830898. 128 pp.

The project calculated rates of channel migration along selected reaches, categorize channel banks for erosion occurrence/potential, develop estimated sediment budget for selected reaches and determined and classified the behavior of channel movement.

Giardino, J.R., and A.A. Lee. 2012. Evolution of Oxbow Lakes along the Brazos River. Final Report to TWDB Contract No. 0904830969. 33 pp.

This work investigated the relationship between oxbow lake geometry and sedimentation for numerous oxbows along the middle and lower reaches of the Brazos River. Specific attributes investigated include: A) the angle of diversion; B) cutoff ratio; C) main channel-lake connections, and D) flood-connections. As is common in geomorphic systems at this scale, (i.e., channel scale) there is non-linearity in the various characteristics of oxbows.

Haschenburger, J.K. 2012a. Sediment transport modeling of channel scale geomorphic processes. Final Report to TWDB Contract No. 1004831127. 27 pp.

This study investigated the use of a two-dimensional (2D) modeling strategy to predict channel adjustment in the lower San Antonio River in response to a range of flood magnitudes. The modeling strategy was employed in one study reach near Goliad and validated with empirical observations where possible. The 2D model permits a more detailed examination of the morphological response of the streambed compared to a one-dimensional (1D) model.

Haschenburger, J.K. 2012b. Sediment transport modeling of reach scale geomorphic processes. Final Report to TWDB Contract No. 0904830899. 48 pp.

This study investigated the use of a modeling strategy to predict channel adjustment and floodplain accretion in the lower San Antonio River. The modeling strategy was employed in three subreaches with different channel characteristics to capture a range of possible geomorphic responses in the river and validated with empirical observations where possible. Using the modeling strategy, flow simulations of prescribed in-stream flows can provide initial insights into the response of the river.

Heitmuller, F.T., and N. Raphelt. 2012. The role of sediment-transport evaluations for development of modeled instream flows: Policy and approach in Texas. Journal of Environmental Management 102 (2012) 37-49.

Instream-flow scientists embrace streamflow as the master variable driving aquatic and riparian ecosystems, and that natural flow variability is imperative for river conservation and restoration efforts. Sediment transport, which is critical for maintenance of physical habitats in rivers and floodplains, has received less direct attention from instream-flow practitioners. This article serves to highlight the roles of sediment-transport evaluations in modifying or verifying instream-flow prescriptions based on hydrology alone. Two examples of sediment-transport evaluations are discussed in relation to the Texas Senate Bill 3 Environmental Flows allocation process, a mandate to “develop environmental flow analyses and a recommended flow regime” that “maintain(s) the viability of the state’s streams, rivers, and bay and estuary systems” using “reasonably available science”. The first example provides an evaluation of effective discharge of suspended-sediment load of the lower Brazos River. The magnitude and frequency of effective discharge occurs between typical high-flow pulses and overbank flows, indicating that hydrologic and physical processes are not optimally coupled in some flow-regime models. The second example utilizes the Hydrology-Based Environmental Flow Regime (HEFR) model to prescribe instream flows for the lower Sabine River and compares modeled bed-material loads for observed and HEFR-prescribed flow regimes. Results indicate that annual water and sediment yields are greatly reduced for the modeled flow regime. It should be noted, however, that different input variables to the HEFR model would have resulted in different computations of water and sediment yields, reinforcing that instream-flow practitioners should exercise great caution when applying rule-of-thumb procedures to generate flow prescriptions.

Hodges, B.R. 2005. Hydrodynamic modeling in rivers with submerged large woody debris. Final Report to TWDB Research and Planning Fund Research Grant 2004-483-010. 14 pp.

The project provided a literature review of existing modeling techniques, and development of a new hydrodynamic modeling theory that included large woody debris.

Hydrographic Consultants, Inc. 2009. Single Beam Bathymetric Survey of Brazos River from East Columbia to the Gulf of Mexico. Final Report to TWDB. 65 pp.

A Single Beam, Hydrographic Survey of the Lower Brazos River covering 35 miles of river below the SH-35 Bridge in East Columbia to the Gulf of Mexico to generate channel topographies suitable for use in channel change monitoring and hydrodynamic model development.

Newson, M.D., and C.L. Newson. 2000. Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. Progress in Physical Geography 24,2 (2000) pp. 195–217.

This article describes the challenges faced by a need (in both theoretical and practical areas) to understand the detail of physical habitat conditions in stream channels. A number of mesoscale approaches are emerging, both from ecology and geomorphology. We outline the field validation of a ‘habitat hydraulics’ approach to the interaction between river discharge and channel form. Qualitative ‘flow types’ are shown to be representative of discrete hydraulic conditions within mesoscale units of the channel bed described as ‘physical biotopes’. The approach is compared with parallel ecological research on ‘mesohabitats’ and ‘functional habitats’. The extent, pattern and discharge–variability of physical biotopes can be surveyed in the field and used as a spatial guide to biological sampling (in this case for benthic invertebrates). Biological patterns (at the scale sampled here) appear to respond first to the river continuum concept’s longitudinal zonation of the channel, but there is a marked secondary signal in statistical analyses from the pattern of biotopes.

Phillips, J.D. 2006a. Geomorphic Context, Constraints, and Change in the lower Brazos and Navasota Rivers, Texas. Final Report to TWDB Contract No. 2005-483-564. 79 pp.

The purpose of this paper is to review the geomorphological basis of classification and characterization schemes, and to evaluate them with respect to two criteria-relevance to instream flow assessment and management programs, and appropriateness for application in the Texas coastal plain.

Phillips, J.D. 2006b. Field Data Collection in Support of Geomorphic Classification of the lower Brazos and Navasota Rivers. Final Report to TWDB Contract No. 0604830639. 100 pp.

The study area is the lower Brazos River (Bryan to Gulf of Mexico) and Navasota River (Lake Limestone to confluence with the Brazos). The objectives were to refine the river styles-based geomorphic assessment to characterize the character, behavior, and current geomorphic condition of the rivers; and determine trends of river evolution and future trajectories of change.

Phillips, J.D. 2007a. Geomorphic Equilibrium in Southeast Texas Rivers. Final Report to TWDB Contract No. 0605830636. 116 pp.

This report is based on a study of the geomorphic equilibrium of the coastal plain portions of the Brazos, Trinity, and Sabine Rivers, and of river systems of southeast Texas more generally. River and stream management, assessment, engineering, and classification is often based on concepts of geomorphic equilibrium, and implicit or explicit assumptions that fluvial systems are in, or develop towards, some form of equilibrium. The purpose of this study is to determine the extent to which that is indeed the case in the study area.

Phillips, J.D., and M.C. Slattery. 2007. Geomorphic Processes, Controls, and Transition Zones in the Lower Sabine River. Final Report to TWDB Contract No. 0600010595. 57 pp.

This report is based on a cooperative research study of the geomorphology of the Lower Sabine River, Texas (and Louisiana). The study focused on delineating major geomorphic process zones, identification of major geomorphic controls, and determination the location and primary controls over key “hinge points” or transition zones.

Phillips, J.D. 2008a. Geomorphic Units of the Lower Sabine River. Final Report to TWDB Contract No. 0704830782. 64 pp.

This report addresses the subreach-scale landforms of the lower Sabine River, Texas/Louisiana from Toledo Bend Dam to Sabine Lake. Building on previous work delineating geomorphic zones or reaches (river styles) and associated environmental controls and hydrologic and geomorphic processes (Phillips, 2008a; Phillips and Slattery, 2007a), this study addresses the characteristic landforms within those zones. The goals were to identify and describe the dominant (in terms of size, frequency of occurrence, and influence on hydrologic and ecological conditions) geomorphic units, to relate these to hydrologic and geomorphic processes and controls, and to link the geomorphic units (GUs) to the river styles zonation. A particular emphasis was placed on transverse bars. These (more-or-less cross-channel) sand bars are important bedforms and aquatic habitat elements in rivers.

Phillips, J.D. 2008b. Geomorphic Processes, Controls, and Transition Zones in the Middle and Lower Trinity River. Final Report to TWDB Contract No. 0704830781. 63 pp.

This report conveys the results of a study of the geomorphology of the Trinity River, Texas, from the confluence with the Elm Fork near Dallas to Trinity Bay. The study was designed to delineate major geomorphic process zones, with an emphasis on stream energetics as indicated by stream power; to identify major geomorphic controls (including sea level and climate change and antecedent topography); and determine the location and primary controls over key "hinge points" or transition zones.

Phillips, J.D. 2011a. Geomorphic Processes, Controls, and Transition Zones in the Guadalupe River. Final Report to TWDB Contract No. 0904831034. 79 pp.

This report conveys the results of a study of the geomorphology of the Guadalupe River, Texas, from its upper reaches in Kerr County to the Guadalupe River delta. The study was designed to delineate major geomorphic process zones; to identify major geomorphic controls; and determine the location and primary controls over key "hinge points" or transition zones.

Phillips, J.D. 2011b. Hydraulic units of the lower Sabine River. Final Report to TWDB Contract No. 1000011022. 82 pp.

This report identifies the hydraulic units of the lower Sabine River, Texas/Louisiana, from Toledo Bend Dam to Sabine Lake, from the perspective of instream flow management. Building on previous work delineating geomorphic zones or reaches (river styles) and geomorphic units, this study addresses the characteristic hydraulic units within those zones. Hydraulic units are ecohydrologic elements shaped by (and influencing) flow-sediment interactions and providing the physical context for specific aquatic habitats and patch dynamics. The dominant (in terms of size, frequency of occurrence, and influence on hydrologic and ecological conditions) hydraulic units (HU) were identified, described, and related to hydrologic and geomorphic processes.

Phillips, J. 2011c. Channel Change Caused by Water and Sediment Distribution in the San Antonio River Deltaic Plain. Final Report TWDB Contract No. 1004831024. 77 pp.

The purpose of this project is to understand historical changes in channel patterns and water and sediment distribution in the lowermost San Antonio River associated with major channel changes (avulsions). The project also seeks to identify areas of high risk or probability for future avulsions, and to develop recommendations for incorporating channel change and avulsion regimes into water resource management. The study area corresponds with the deltaic plain of the river. The San Antonio delta merges with the delta of the Guadalupe River, which the San Antonio River joins near Tivoli.

Phillips, J.D. 2012. Geomorphic Responses to Changes in Flow Regimes in Texas Rivers. Final Report to TWDB Contract No. 1104831147. 85 pp.

The purpose of this study is to develop a model to predict the geomorphic response of alluvial rivers in Texas to changes in flow regimes. The adjustments of alluvial river channels to changes in water and sediment inputs are related to changes in transport capacity, sediment availability, and modes of adjustment, but are characterized by complex responses, nonlinear dynamics, and path-dependent development. Potential modes of adjustment include various combinations of channel widening, narrowing, deepening, and shallowing at the cross-section scale, and changes in planform, slope, and roughness at the reach scale. The dominant mode of adjustment is dependent on the resistance or erodibility of the bed and banks relative to hydraulic forces, how the slope of the channel has been modified, and the relationship between sediment supply and transport capacity. The model is based on a combination of theoretical modeling and empirical data from observations of the effects of dams, water withdrawals-additions, and wet-dry climate cycles.

Phillips, J.D. 2013. Geomorphic responses to changes in instream flows: the flow-channel fitness model. River Res. Applic. 29: 1175–1194 (2013)

The flow-channel fitness model is a conceptual and practical model for predicting the qualitative response of alluvial channels to modifications of flow regimes. 'Fitness' refers to the size of channels compared with the flows they convey, with the terminology derived from traditional geomorphic concepts of overfit and underfit streams. The qualitative predictions refer to whether channels experience aggradation, degradation or relative stability, and whether aggradation or degradation is dominated by width or depth. The model is based on transitions among seven possible fitness states, triggered by key thresholds of sediment supply versus transport capacity and shear stress versus shear strength, and requires that potential changes in sediment supply and water surface or energy-grade slope also be accounted for. The fitness approach can be used where only relative values and changes are known, as is illustrated in three example applications from Texas. The flow-channel fitness model synthesizes key elements from several existing approaches to predicting geomorphic responses to changes in flow and is intended to augment rather than replace quantitative approaches, providing a predictive tool where the data requirements and assumptions for quantitative models cannot be fully met.

Raphelt, N., K. Mayes, and T. Hardy. 2018. Integrating geomorphic assessments in ecological flow regimes: Case study in the San Antonio River, Texas, USA. 12th ISE 2018, Tokyo, Japan. 9 pp.

The Texas Instream Flow Program has embraced this paradigm shift and integrates subsistence flows, base flows, pulse and overbank flows that address flow and water level requirements for aquatic biota, such as freshwater unionid mussels, fish, and riparian systems. These recommendations specifically incorporate inter- and intra-annual flow variability based on multi-disciplinary assessments. In this study, we explore several instream flow regime scenarios and their implications in terms of sediment transport dynamics to maintain the channel structure based on two hydrologic time periods. The first hydrologic period represents minimal flow alteration while the second period reflects substantial flow alteration. Flow regimes based only on studied ecological components varied in their sediment transport dynamics and generally were not sufficient to produce volumes of water necessary to maintain the underlying physical habitat characteristics of the river. Study results are utilized to recommend a geomorphic flow regime component necessary to maintain dynamic channel equilibrium and therefore the associated physical habitats as part of the overall ecological flow regime.

Slattery, M.C. 2007. Sediment budgeting in the upper and middle basins of the Brazos and Trinity Rivers, TX: An assessment of methods and directions for future work. Final Report to TWDB Contract No. 0600010585. 24 pp.

The report documents various approaches to sediment budgeting in the upper and middle Brazos and Trinity River basin in Texas and focused on methods used to construct individual components of a sediment budget and the types of data that can be generated using fairly rapid and straightforward estimation techniques.

Turco, M.J., East, J.W., and Milburn, M.S. 2007. Base flow (1966–2005) and streamflow gain and loss (2006) of the Brazos River, McLennan County to Fort Bend County, Texas: U.S. Geological Survey Scientific Investigations Report 2007–5286, 27 p.

The purpose of this report is to document the results of base-flow analysis (hydrograph separation) of historical (water years 1966–2005 [October 1965 through September 2005]) streamflow and two synoptic streamflow gain and loss surveys of the Brazos River from McLennan County to Fort Bend County, Texas, in March and August 2006. Methods of data collection and analysis are described. Results of hydrograph separation based on available historical data for three sites on the Brazos River and seven sites on tributaries to the Brazos River are presented. Streamflow gains and losses based on flow data collected from 55 sites on the Brazos River and selected tributaries during the two synoptic surveys are presented, and the respective gaining and losing reaches are identified. Water-quality properties (temperature and specific conductance) were collected as a part of the March 2006 survey and are included in the report, but those data were not used in the analysis of gains and losses.

World Meteorological Organization. 2019. Guidance on environmental flows: Integrating E-flow science with fluvial geomorphology to maintain ecosystem services. WMO-No 1235. 52 pp.

It is well established that e-flows refer to the typical seasonal and interannual variability of the natural flow regime, and not only to the minimum amount of water (low flows) to be maintained in a river. In addition to this pure hydrological assessment of natural flow variability, there is also the necessity to link e-flow definition to the related hydromorphological processes and local ecological objectives of a river. This guidance therefore presents a methodology (based on knowledge and literature on river system processes) to consider hydrological and morphological aspects in defining e-flows for environmental river management. The report has been produced within the context of an agreement between the WMO Commission for Hydrology and the Italian National Institute for Environmental Protection and Research (ISPRA), to cooperate in the implementation of activities related to managing river flows and maintaining services offered to human society and ecosystems. The research can be contextualized inside the implementation of the WMO Hydrology and Water Resources program.

Riparian

The citations below provide key life history metrics for riparian species, applied methodologies, responses to flow regime components as well as providing baseline conditions at study sites.

Cooper, D.J. and Merritt, D.M. 2012. Assessing the water needs of riparian and wetland vegetation in the western United States.

Discuss wetland and riparian classification, characteristics and ecology; surface and groundwater hydrology; plant physiology and population and community ecology; and techniques for linking attributes of vegetation to patterns of surface and groundwater and soil moisture. Several case studies are also presented. This USDA-Forest Service report is intended to assist water managers in determining environmental flow needs

Duke, J.R. 2011. Riparian Productivity in Relation to Stream Dynamics Along Two Rivers: San Antonio and Brazos, in Central/ South Texas. Final Report TWDB Contract 1000011020. Center for Reservoir and Aquatic Systems Research, Baylor University. 116 pp.

This study characterized historic river flow along two central Texas rivers (San Antonio and Brazos River), and riparian vigor (measured as tree productivity) as a response to that flow. Black willow, green ash and box elder emerged as key indicator species for describing healthy riparian zones, while hackberry emerged as an indicator of degrading riparian zones. Results indicated that because channel slopes were between 5 and 13m below surrounding landscape on these two rivers, loss of connectivity to saturated soils occurred rapidly with distance to stream. Key species examination showed that while excessively high flows on each river suppress basal increment (BI) for green ash, box elder and black willow thrive at those same flows. Analysis of select floods indicate several events whose flows were large enough to be seen at the monthly as well as the yearly scale and even in tree records, indicating that changes in timing of flood pulses have the potential to influence annual BI for that year's growth so strongly tree rings reflect that event. Currently along the San Antonio River seed dispersal appears to be adequately maintained. Total tree counts, biodiversity and seed dispersal along the Brazos River are lower than the San Antonio, but generally productivity is higher. Flow regimes necessary to maintain vigor in the riparian zones of both these rivers need to include measures to ensure that early life stages of the key indicators are met by ensuring a flooding frequency that a) encompasses their spatial locations, b) provides proper soil saturation to both disperse seedlings and maintain saplings, c) recharges groundwater in the near-bank regions to support a healthy root mass, and d) allows for optimal productivity of mature trees so that resiliency of episodic events allows for rapid recovery.

Green, R.T., F.P. Bertetti, R. McGinnis, and J. Prikryl. 2012. Measuring floodplain hydraulics of Seco Creek and Medina River where they overlie the Edwards Aquifer. Final Report to Edwards Aquifer Authority, SwRI Project No. 20-16488. 69 pp.

This report summarizes the investigation of the hydraulic relationship between Seco Creek and Medina River and the subsurface as it affects the recharge and discharge of the Edwards Aquifer. The project considered similar studies of the hydrogeology of Uvalde County performed in the last several years, with particular emphasis on investigations of the hydraulic significance of the Leona, Nueces, Frio, and Dry Frio Rivers and Elm and Turkey Creeks with regard to regional and local aquifers (Green et al., 2006, 2008a,b, 2009a,b). These recent studies were of interest because they provide direct evidence of the hydraulics and the hyporheic exchange of rivers, floodplain sediments, and subsurface flows of these rivers and streams as they cross the Edwards Aquifer. The Edwards Aquifer Authority chose to investigate the Seco Creek and Medina River to better understand the water budget (i.e., sources of recharge and quantities of discharge) in Medina County.

Hardy, T.B., K. Kollaus, K. Tollman, T. Heard, and J. Tennant. 2012. Aerial Assessment of Aquatic and Riparian Habitat in the Brazos River and Blanco River, Texas. Final Report, Texas Water Development Board. River Systems Institute, Texas State University. 10 pp.

Application of Unmanned Aerial Systems to evaluate high resolution imagery for classification of aquatic and riparian habitats within selected stream reaches of the Brazos and Blanco Rivers.

Lytle, D.A., D.M. Merritt, J.D. Tonkin, J.D. Olden, and L.V. Reynolds. Linking river flow regimes to riparian plant guilds: a community-wide modeling approach. Ecological Applications, 27(4), 2017, pp. 1338–1350

In this paper, we first develop a general model that can be extended to any number of riparian plant species or guilds occurring on a river floodplain. We then parameterize the model for five guilds that represent a wide range of functional vegetation types present throughout western North American dryland rivers and arid land streams worldwide (Aguiar et al., 2013, Stromberg and Merritt 2015): hydroriparian tree, xeroriparian shrub, hydroriparian shrub, mesoriparian meadow, and desert shrub. We use this framework to explore flow scenarios relevant to conservation and management of riparian ecosystems. We then develop new network- based tools derived from sensitivity and elasticity analysis that can be used to identify keystone species (high number of network connections) and important interactions (strong pairwise connectivity) under a variety of environmental contexts.

Manning, A., and K. Meitzen. 2019. Blanco River riparian forest regeneration following a record flood in Central Texas. The Southwestern Naturalist 64(3/4): 195–202.

A record flood in 2015 resulted in widespread disturbance of the Blanco River riparian corridor with extensive loss of vegetation through floodplain stripping. The riparian forest along the Blanco River is slowly recovering via two primary pathways—natural regeneration from the seedbank and through resprouting of damaged trees. We conducted a study of woody riparian vegetation along the Blanco River to quantify the composition of the recovering forest community and the proportion of trees that are regenerating by resprouting vs. seedbank colonizers. The study captured overall compositional and density patterns as well as comparisons among three geomorphic settings including instream channel bars, the riverbank and near channel lower elevation floodplain, and the higher-elevation floodplain to upland terraces. Seedlings represented 90% of the density and only 2% of the biomass; in contrast, resprouted trees represented 10% of the density and 98% of the biomass. Fast-growing pioneer species such as sycamore (*Platanus occidentalis*) and black willow (*Salix nigra*) were dominant nearest the river channel while facultative and upland species such as pecan (*Carya illinoiensis*) and hackberry (*Celtis spp*.) dominated plots higher on the floodplain. Seedlings were far more numerous than resprouts, and seedling density was highest in plots along the riverbank and closest to the channel.

Mauldin, R.P. 2003. Exploring Drought in the San Antonio Area Between 1700 and 1979. Final Report to Edwards Aquifer Authority. 23 pp.

Relying on tree-ring derived estimates of the summer Palmer Drought Severity Index (PDSI) presented by Cook et al., (1999), this document investigates drought frequency, intensity, and duration in the San Antonio area for a 280-year period between A.D. 1700 and 1979. The PDSI is a widely used index that is based on several variables and is designed to monitor soil moisture conditions. In most circumstances, the PDSI varies between 4.0 and -4.0, with an average year falling between 0.5 and -0.5. Here, I define drought as a value of -1.0 or less on the tree-ring derived PDSI. Using this definition, there were 40 droughts reflected in this 280-year stretch, with the average drought lasting 1.8 years. Long-term droughts, defined as droughts exceeding three years in duration, occurred four times in the available data, with three of these four being in the 1700s, and the fourth occurring in the early 1950s. This 1950s drought, covering a six-year period, was both the longest drought reflected in the available records as well as the most intensive of the four long-term droughts.

McBroom, M., M. Ringer, and Y. Zhang. 2014. Instream Woody Debris and Riparian Forest Characteristics in the Sabine River, Texas. Southeastern Naturalist 13(Special Issue 5):1–14.

We examined instream large woody debris (LWD) dynamics on the Sabine River, TX. All wood >10 cm in diameter and >2 m long was measured on four river meanders (meander wavelengths) below the dam on Toledo Bend Reservoir. We determined LWD species, degree of decay, bank orientation, jam association, and stage contact. We also measured riparian vegetation characteristics on each meander. LWD volumes were significantly greater at the site immediately below Toledo Bend Dam, due to the relatively steeper channel gradient and higher rates of channel erosion. Based on mass balance estimates, between 11 and 21% of total annual recruitment came from upstream fluvial transport, and the remainder resulted from bank erosion and tree mortality. We estimated average LWD residence time to be 12–14 years. The lower Sabine River is transport-limited for sediment, and the same is true for LWD. Based on these measurements, it is unlikely that Toledo Bend Reservoir is having a significant impact on LWD dynamics at the measurement reaches due to lacustrine wood storage. Of greater concern in the study system are riparian forest degradation and invasive species spread, which may dramatically affect future LWD loadings and residence times, and thus, riverine biota.

Merritt, D. M., and H. L. Bateman. 2012. Linking stream flow and groundwater to avian habitat in a desert riparian system. *Ecological Applications*, 22(7): 1973-88.

Linked streamflow and groundwater hydrology to avian habitat in a desert riparian system in the Sonoran Desert, USA.

Miller, A.J., R.S. McNamee, H.M., Williams, M.W. McBroom, and M.B. Brown. 2010. The Sabine River Riparian Area: A Definition and GIS Based Methodology for Delineation. Final Report TWDB Contract 0704830783. Stephen F. Austin University. 205 pp.

This literature review identifies components obtained from different wetland delineation and functional assessment methodologies which were employed together as a tool in delineating the

defined riparian area both in the field and through GIS analysis. By combining definition, concepts, and methodologies, a technique was established for delineation in the field and through GIS modeling which utilized together gain rigor in accuracy which greatly adds to future management goals. The literature review and delineation consist mainly of descriptions and concepts applicable to the Southeastern U.S. with sections discussing west Texas when applicable to highlight differences between east and west Texas riparian areas. Three GIS based techniques were investigated for delineating the riparian area.

Moore, G., and B. Alldredge. 2011. Sabine River Riparian Vegetation Assessment Related to Flow Modifications. Final Report TWDB Contract 1004831021. Texas A&M University. 47 pp.

Assessed changes in the hydrologic regime in the Sabine River related to construction and operation of Toledo Bend Reservoir. Established baseline riparian characteristics and topographic community composition and recommendations for future research could be focused on two objectives: inundation mapping and vegetation-flow response guilds. Inundation mapping would reveal what areas of the floodplain are flooded at certain river discharges which could be linked back to elevation differences and vegetation composition within the floodplain.

Peake, P., J. Fitzsimons, D. Frood, M. Mel, N. Withers, M. White, and R. Webster. 2011. A new approach to determining environmental flow requirements: Sustaining the natural values of floodplains of the southern Murray-Darling Basin. *Ecological Management and Restoration* 12(2): 128-137

Cataloged flooding requirements for a long list of flood-dependent plant species in Australia's Murray River floodplain.

Stromberg, J. C., Beauchamp, V. B., Dixon, M. D., Lite, S. J. and Paradzick, C. 2007. Importance of low-flow and high-flow characteristics to restoration of riparian vegetation along rivers in arid south-western United States. *Freshwater Biology,* **52** (4): 651-679

Examined the influence of high and low streamflow durations; flood frequency; depth, magnitude, and rate of ground-water decline; and other hydrologic conditions on phreatic vegetation along rivers in the arid southwestern United States.

Unannotated References

The following unannotated references are provided to document the material originally considered to be included and include links to either the abstract and/or full paper. In some cases, references listed here may have been included in the annotated section above.

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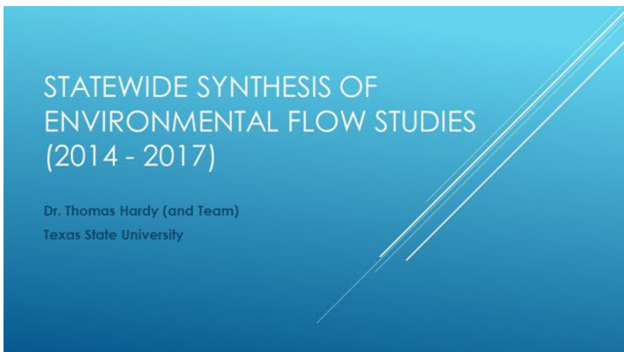
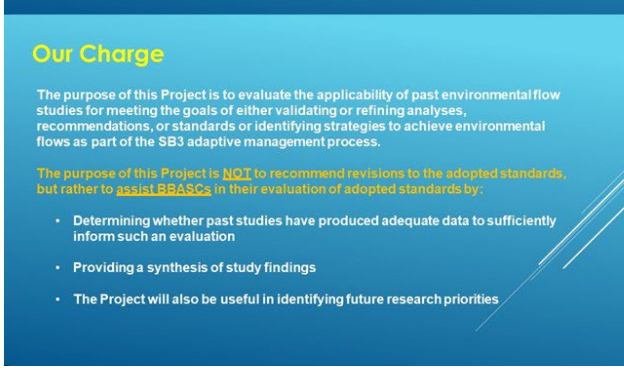
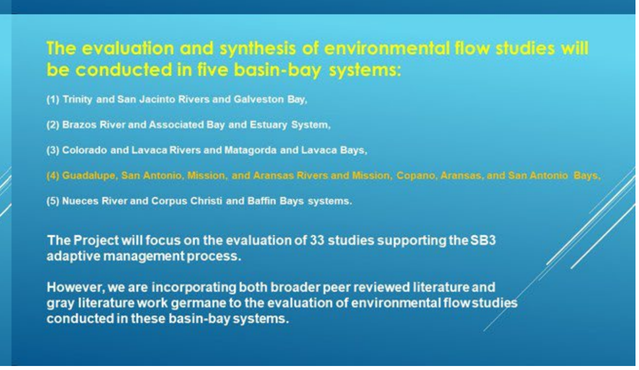
Appendix D – Stakeholder Presentations

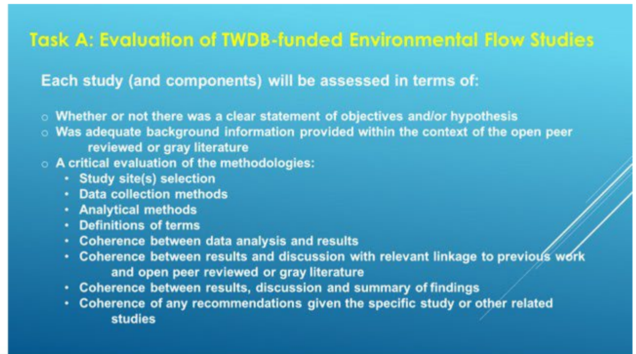
Stakeholder presentations were made in person to the Colorado-Lavaca and Guadalupe-San Antonio BBASCs and via webinars to the Brazos, Nueces, and Trinity BBASCs. In addition, a state-wide webinar was also held on July 27th, 2020. These presentations were utilized to inform the BBASCs of the scope and direction of the project, status, and solicit their input. The presentation to the Colorado-Lava BBASC included a handout that was provided to the attendees and served as the basis to outline the overall goal and objectives for the project which was followed by answering questions posed by attendees. The remaining presentations to BBASCs in person or via a Webinar utilizing the following PowerPoint presentation. As noted, BBASC specific slides were incorporated into the presentations and are provided under each BBASC heading.

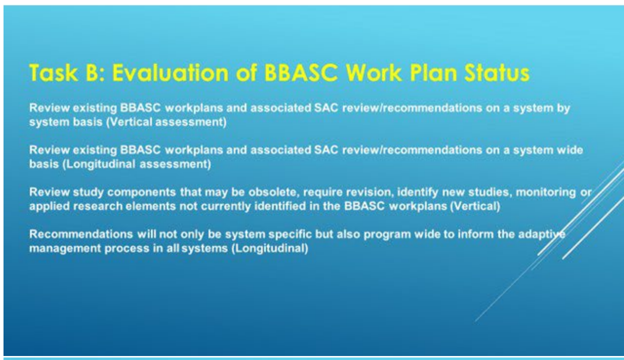


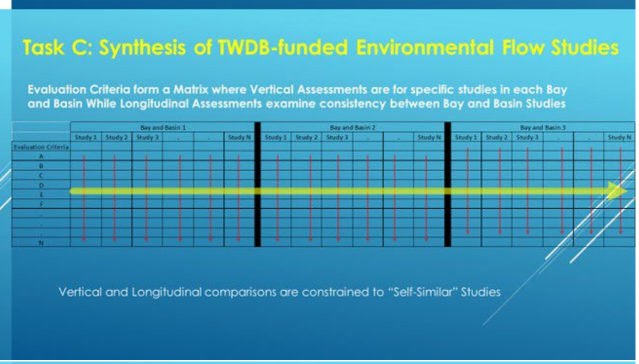


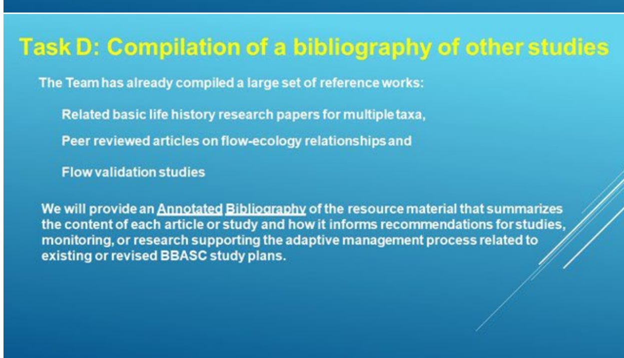


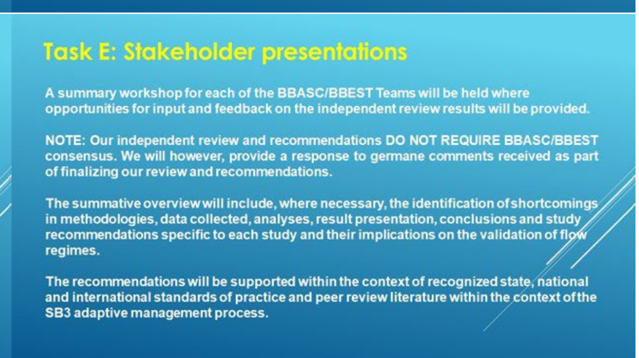
See Below for BBASC Specific Slides used at this location of the presentation











Colorado-Lavaca Bay and Basin Stakeholder Committee

LCRA Eastern Maintenance Facility,
104 East State Highway 71 Bypass, La Grange, TX.
March 1st, 10:00 a.m. – 2:30 p.m.

MEETING AGENDA

1. Introductions
2. Public Comments
3. Approval of Minutes from Most Recent Meeting
4. Presentations by Study Groups
    a. Jordan Furnans, Ph.D., P.E., P.G.
    b. Paul Montagna, Ph.D., Harte Research Institute
    c. <u>Thom Hardy, Ph.D., Texas State University</u>

Note that additional items are contained in the original meeting agenda but have been removed. The following handout was provided specific to this BBASC meeting:

Evaluation of TWDB-funded environmental flow studies - Handout
Each study (and components) will be assessed in terms of:

- *Whether there was a clear statement of objectives and/or hypothesis*
- *Whether adequate background information was provided within the context of the open peer reviewed or gray literature*
- *A critical evaluation of the methodologies, including:*
    - *Study site(s) selection*
    - *Data collection methods*
    - *Analytical methods*
    - *Definitions of terms*
    - *Coherence between data analysis and results*
    - *Coherence between results and discussion with relevant linkage to previous work and open peer reviewed or gray literature*
    - *Coherence between results, discussion and summary of findings*
    - *Coherence of any recommendations given the specific study or other related studies*
    - *Whether the study provided an assessment of estimated attainment frequencies under existing or full water-right allocations*

2. *This process will also entail the identification of any specific recommendations for remedial data needs, reanalysis of data, or applied research to address data/information gaps. The project will also suggest a*

manageable list of short and long-term indicators, and data collection requirements, that can be used to assess ecological form and function of affected resources.

Evaluation of BBASC work plan status

The review, which encompasses the results from Tasks C and D, will specifically address proposed study components that may be obsolete, require revision necessary to address data or knowledge gaps, or identify studies, monitoring or applied research elements not currently identified in the BBASC workplans or priority framework on a system-by-system basis.

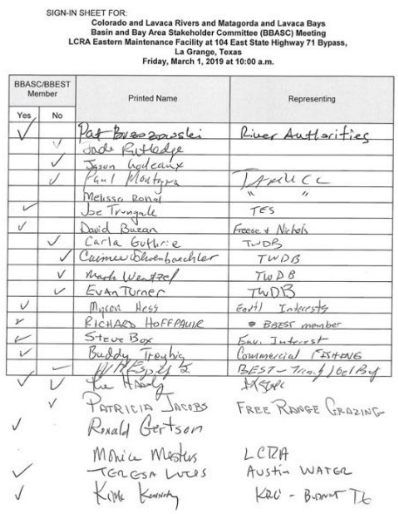
Synthesis of TWDB-funded environmental flow studies

This develops a framework (or matrix) to systematically compare study components across systems in terms of methods, data, analytical approaches and interpretation of results to meet study objectives. This comparison across systems for in-stream, bay/estuary and integrated assessments provides the basis within the context of the broader national and international literature and assessment frameworks identified in Task D to elucidate underlying strategies or in their absence, a methodological framework to achieve a coherent strategy.

Compilation of a bibliography of other studies

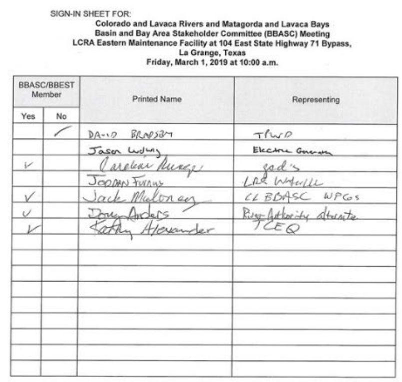
An initial coordination meeting will be held with TWDB and individual BBASC representatives at the outset of the project. We expect these will be in the form of a webinar and/or one day workshop to solicit their understanding of their existing studies, and their workplan study selection and prioritization process. These meetings will also be used to outline our philosophical and methodological approaches to the study. This will pragmatically entail additional Webinars in which we will be asking for clarification and responding to your questions.

The following documents those in attendance based on the meeting sign-in sheet.



SIGN-IN SHEET FOR:
Colorado and Lavaca Rivers and Matagorda and Lavaca Bays
Basin and Bay Area Stakeholder Committee (BBASC) Meeting
LCRA Eastern Maintenance Facility at 104 East State Highway 71 Bypass,
La Grange, Texas
Friday, March 1, 2019 at 10:00 a.m.

BBASC/BBEST Member Yes	BBASC/BBEST Member No	Printed Name	Representing
✓		Pat Brzozowski	River Authorities
	✓	Jade Rutledge	
	✓	Jason Godeaux	
	✓	Paul Montagna	TAMUCC
		Melissa Ronal	" "
✓		Joe Trungale	TES
✓		David Buzan	Freese + Nichols
	✓	Carla Guthrie	TWDB
	✓	Caimee Schoenbaechler	TWDB
	✓	Mark Wentzel	TWDB
	✓	Evan Turner	TWDB
✓		Myron Hess	Envtl Interests
✓		Richard Hoffpauir	BBEST member
✓		Steve Box	Env. Interest
✓		Buddy Treybig	Commercial Fishing
	✓	[illegible]	BEST – Trinity/Gal Bay
✓	✓	[illegible]	[illegible]
	✓	Patricia Jacobs	Free Range Grazing
✓		Ronald Gertson	
		Monica Masters	LCRA
✓		Teresa Lucas	Austin Water
✓		Kirk Kennedy	KRC - Bryant TX



SIGN-IN SHEET FOR:
Colorado and Lavaca Rivers and Matagorda and Lavaca Bays
Basin and Bay Area Stakeholder Committee (BBASC) Meeting
LCRA Eastern Maintenance Facility at 104 East State Highway 71 Bypass,
La Grange, Texas
Friday, March 1, 2019 at 10:00 a.m.

BBASC/BBEST Member Yes	BBASC/BBEST Member No	Printed Name	Representing
	✓	David Bradsby	TPWD
		Jason Ludwig	Electric Generation
✓		Caroline Runge	[illegible]
		Jordan Furnans	LRE Water
✓		Jack Maloney	CL BBASC WPGs
✓		Doug Anders	River Authority alternate
✓		Kathy Alexander	TCEQ

We could find no meeting minutes on the TCEQ website that documented any questions or responses. (https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/colorado-lavaca-bbasc).

Guadalupe, San Antonio, Mission, and Aransas River and Mission, Copano, Aransas, and San Antonio Bays and Basin and Bay Area Stakeholder Committee (GSA BBASC)

GBRA River Annex, Seguin, TX
Monday, March 25, 2019; 2:00 p.m.

The following documents those in attendance based on the meeting minutes.

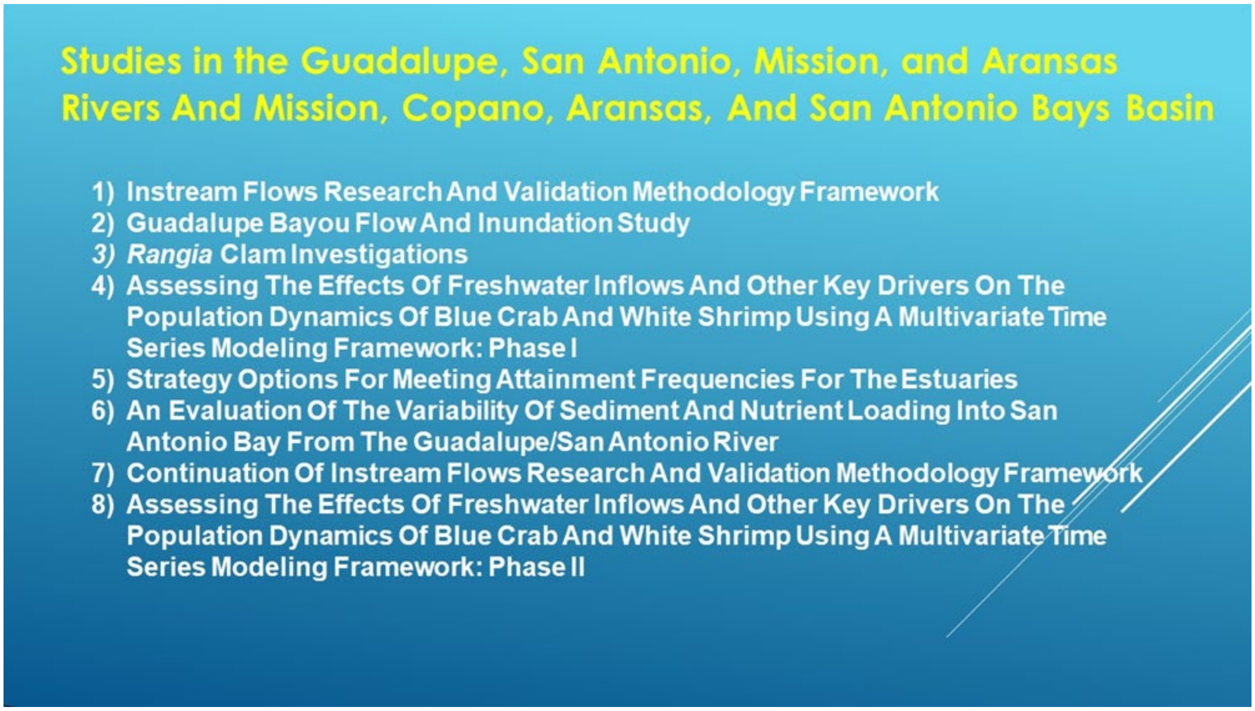
Suzanne Scott, Chair; Dianne Wassenich, Vice-Chair; Jim Bower; Terry Dudley; James Dodson for Ken Dunton; Jennifer Ellis; Charlie Flatten; Colin McDonald; Micah Voulgaris for Milan Michalec; Doris Cooksey; Steve Raabe for Con Mims; Tommy Hill; Jace Tunnell; Thurman Clements, Jr.; Gregg Eckhardt for Robert Puente; Julia Carrillo for Roland Ruiz via teleconference; David Mauk via teleconference.

Meeting Agenda

I. Introductions
II. Public Comment
III. Discussion and Agreement on Agenda
IV. Approval of Minutes from September 15, 2017
V. Briefing of Ongoing GSA BBASC Studies (10-15 min per briefing)
   a. ***Statewide Synthesis of Environmental Flow Studies from 2014 - 2017*, Dr. Thom Hardy**

Note that additional items are contained in the original meeting agenda but have been removed.

Guadalupe-San Antonio BBASC specific PowerPoint Slide:



Meeting Minutes
Briefing of Ongoing GSA BBASC Studies

1) Statewide Synthesis of Environmental Flow Studies from 2014-2017

    a. Dr. Thom Hardy gave an update on the statewide synthesis project that is being conducted in several basins throughout the state. He introduced the team working on the project and gave a brief overview of their backgrounds. The goal of the project is to evaluate the applicability of past environmental flow studies for meeting the goals to refine or validate the analysis, as part of the Senate Bill 3 (SB3) process. The team will investigate whether the studies have produced adequate data to inform the evaluation needed going forward. They will perform a synthesis of study findings within basins and longitudinally across five basins. The team will review 33 studies that supported the SB3 adaptive management process and will synthesize peer-reviewed publications on instream flow assessment validation projects. The study will evaluate international literature into the process. The team has instream flow and estuary specialists to balance the review. The team will be checking for clear objectives and hypotheses, background information sufficient for methods, and will evaluate study sites, data collection, analysis, and coherence in results and recommendations. The team will also evaluate existing work plans, with suggestions for refinement. Each study will be assessed internally within the basin and then will be compared to similar studies across basins. The project will feature a two-level review process because individuals on the team are authors on some reports. The authors will be recused from peer-review, but they may be interviewed for insights into their studies. The team will also have three out-of-state experts review material and assess the peer-review comments for bias. The team will create a bibliography with local and international studies. They will hold stakeholder presentations via webinar and will present findings at the end of the study. The team aims to finish the project by April 2020, but the project will be finalized by August 2020 at the latest.

b. Mr. Terry Dudley asked when the webinars would occur. Dr. Hardy responded that webinars will be held as needed throughout the project and will include a Q&A exchange between the study team and groups.

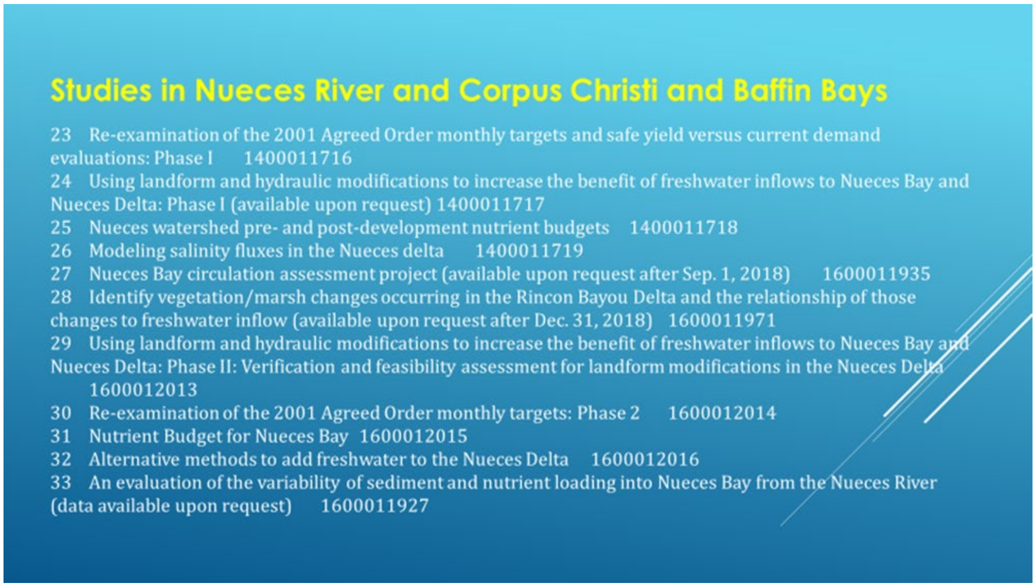
Nueces River and Corpus Christi and Baffin Bays Area Stakeholder Committee

Webinar held April 10th, 2019

The TWDB sent an invitation to this webinar on April 3rd, 2019, via email to 50 individuals. A total of 16 individuals registered while the following 14 attended.

Kathy Alexander	Rae Mooney
Ray Allen	Jade Rutledge
Edward Buskey	Ryan Smith
Paul Carangelo	Evan Turner
James Dodson	Samuel Vaugh
Rocky Freund	Kirk Winemiller
Erin Hill	Cindy Loeffler

Nueces River and Corpus Christi and Baffin Bays Area BBASC specific PowerPoint Slide.



There were no clarifying questions reflected in the summary Webinar report.

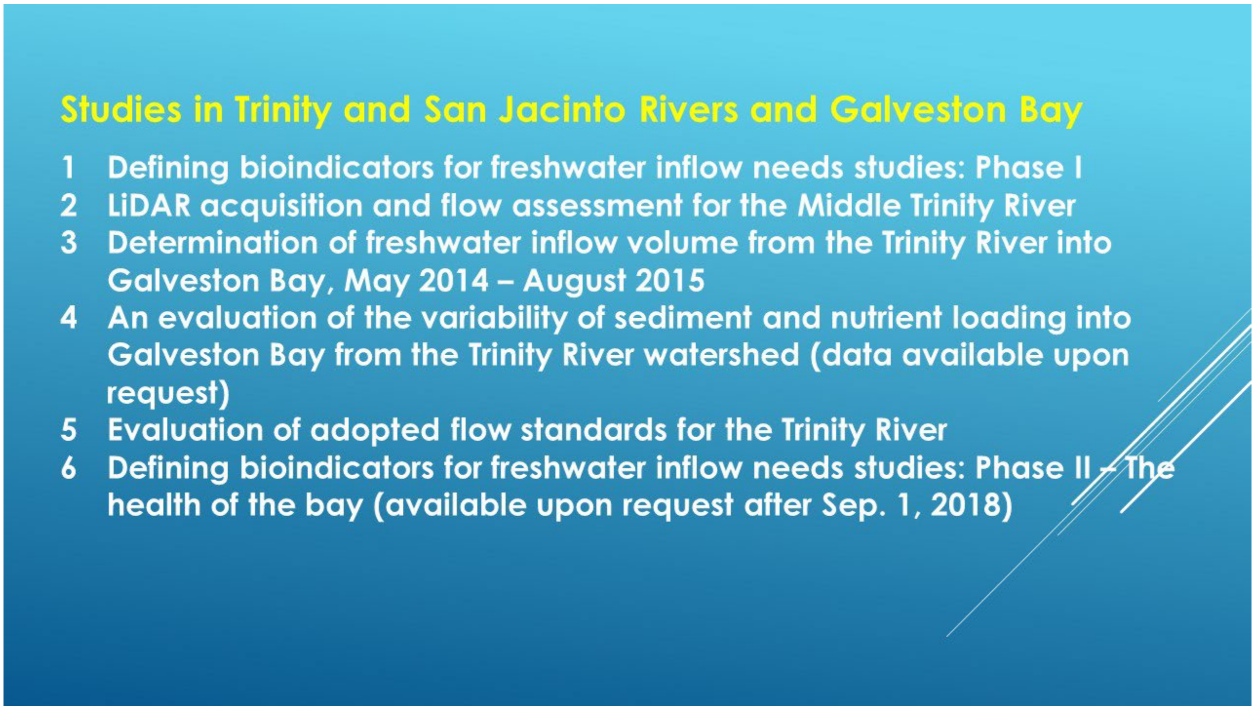
Trinity and San Jacinto Rivers and Galveston Bay Basin and Bay Area Stakeholder Committee

Webinar held April 15th, 2019

The TWDB sent an invitation to this webinar on April 3rd, 2019, via email to 50 individuals. A total of 16 individuals registered while the following 14 attended.

Kathy Alexander	Webster Mangham
John Bartos	Shane Porter
John Dupnik	Antonietta Quigg
William Espey	Jade Rutledge
Woody Frossard	Tony Smith
Jace Houston	Evan Turner
Jim Lester	Kirk Winemiller

Trinity and San Jacinto Rivers and Galveston Bay Basin and Bay Area BBASC specific PowerPoint Slide.



The only question asked if the project would consider on-going work and if there would be a cutoff for the submittal of data or analyses. It was clarified that under the contract, only the studies identified in the RFQ would be reviewed. However, as noted in the report, studies funded up to an including the 2020 – 2021 Biennium were considered when making recommendations related to all existing BBASC workplans.

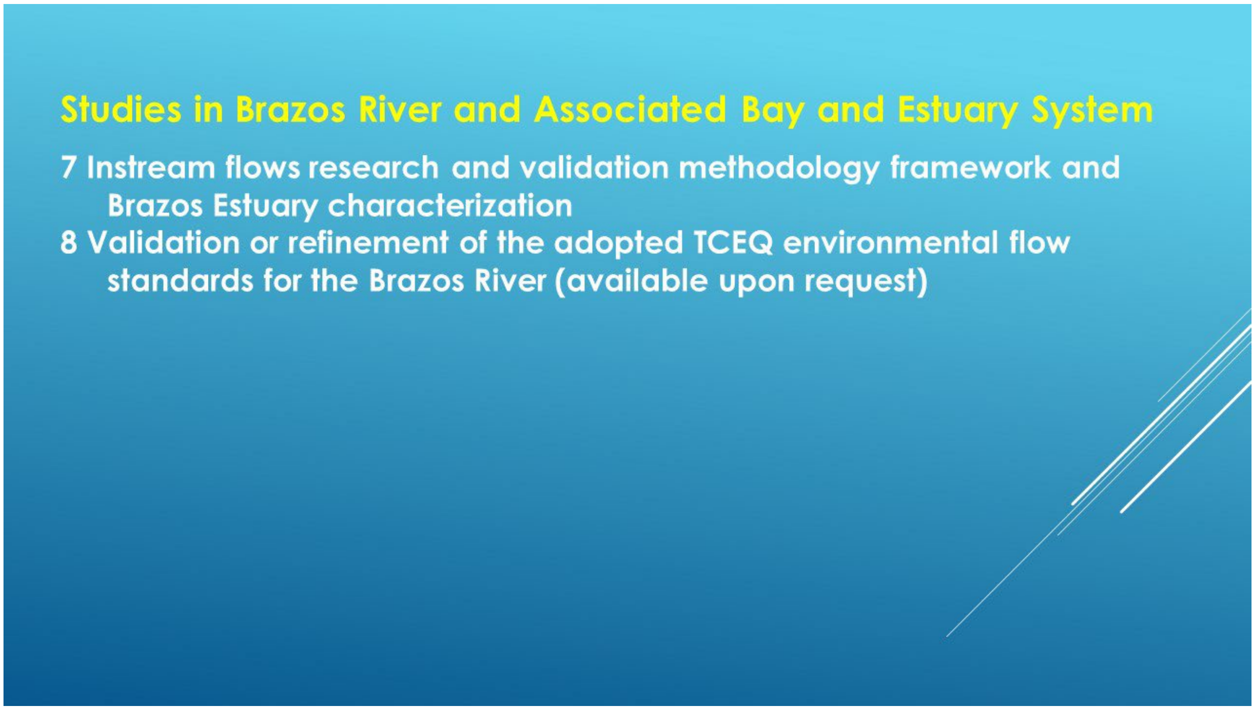
Brazos River and Associated Bay and Estuary System Stakeholder Committee

Webinar held April 16th, 2019

The TWDB sent an invitation to this webinar on April 3rd, 2019, via email to 37 individuals. A total of 15 individuals registered while the following 12 attended.

Kathy Alexander	Zachary Stein
David Dunn	Joe Trungale
Christopher Estes	Evan Turner
Cindy Loeffler	Kirk Winemiller
Tom Michel	Tom Gooch
Tiffany Morgan	Sam Hermitte
Jade Rutledge	Nolan Raphelt

Brazos River and Associated Bay and Estuary System BBASC specific PowerPoint Slide.



There were no clarifying questions reflected in the summary Webinar report.

Statewide Review Project Update – July 27, 2020

Meeting Agenda

Update on Statewide Synthesis of Environmental Flow Studies

GoToMeeting, July 27, 2020, 2:00 PM – 3:30 PM

Purpose

The purpose of this meeting is to provide interested stakeholders with a status update and opportunity for discussion on the Statewide Synthesis of Environmental Flow Studies, TWDB Contract #1900012284 with Texas State University.

Agenda Items

2:00 PM Welcome, Texas Water Development Board

2:05 PM Project Status Overview, Texas State University Project Team

- Instream Flow Study Review Status for Basin-Bay Areas
- Freshwater Inflow Study Review Status for Basin-Bay Areas
- System Wide Review (Synthesis) Status
- Next Steps and Schedule

2:35 PM Q&A/Discussion

3:00 PM Closing, Texas Water Development Board

*Note: We have reserved the meeting room for an hour and a half if more time is needed for discussion. Otherwise, we will adjourn at 3:00 PM.

Submit Questions in Advance

To help the project team prepare for the meeting, we invite you to submit your questions in advance using the following link:
https://forms.office.com/Pages/ResponsePage.aspx?id=jE7QevWSIEuB1hD9iDJYmayLLQYPRIJHmm6wdq2A3RRUQTBKNIZVRIVRQkdWRUk4SDdMRkZaMINMMi4u

Meeting Information

Please join my meeting from your computer, tablet or smartphone.
https://global.gotomeeting.com/join/213550373

You can also dial in using your phone.
United States: +1 (872) 240-3412

Access Code: 213-550-373

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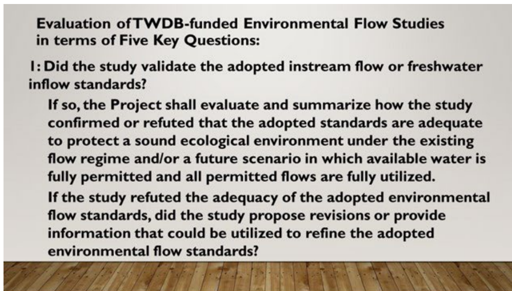
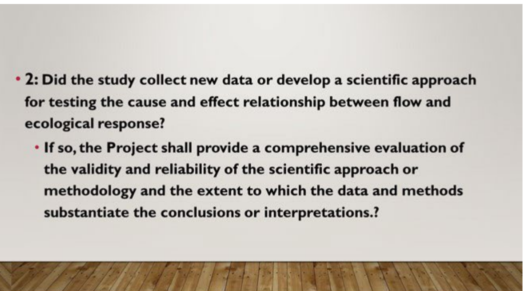
https://global.gotomeeting.com/install/213550373

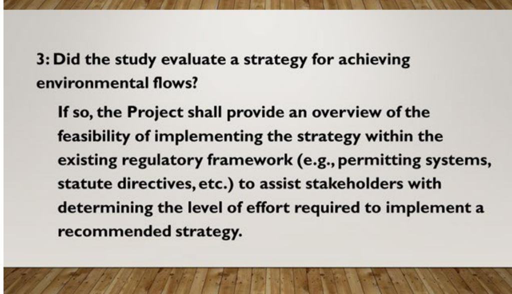
The TWDB sent an invitation to this webinar on April 3rd, 2020, via email to chairs and co-chairs of all five basin the BBASC and BBEST groups, resource agencies and the project team. The following 37 individuals attended.

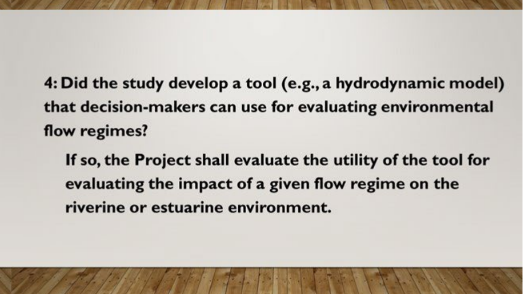
Kathy Alexander	Thomas Hill	Suzanne Scott
John Bartos	Jim Lester	Tony Smith
Patrick Brzozowski	Melissa Lupher	Dale Spurgin
Edward Buskey	Webster Mangham	Zach Stein
Glenn Clingenpeel	Brian Mast	Joseph Trungale
Bryan Cook	Dan Opdyke	Joe Trungale
James Dodson	Nathan Pence	Evan Turner
William Espey	Unknown phone	Kevin Urbanczyk
Tom Gooch	Unknown phone	Dianne Wassenich
George Guillen	Unknown phone	Mark Wentzel
Carla Guthrie	Nolan Raphelt	Kirk Winemiller
Scott Hall	Jade Rutledge	
Myron Hess	Rachel Sanborn	

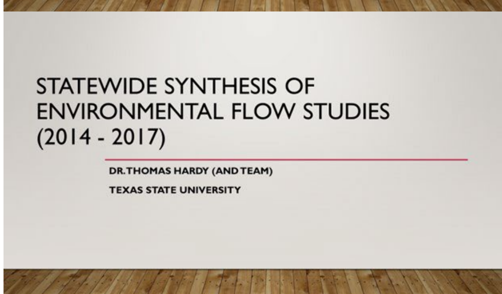
Statewide Review Project Update Power Point

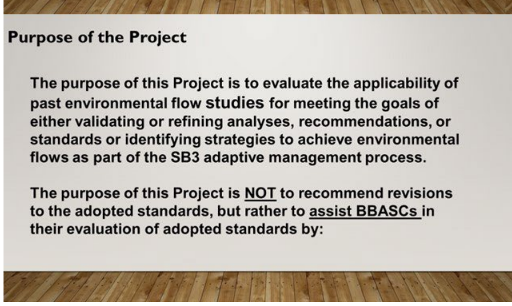


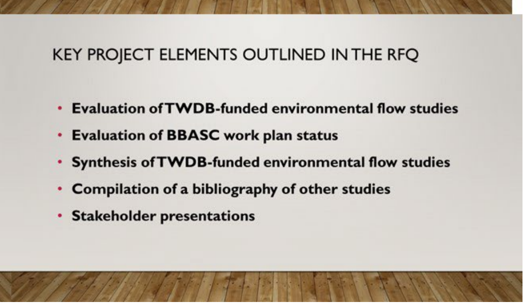


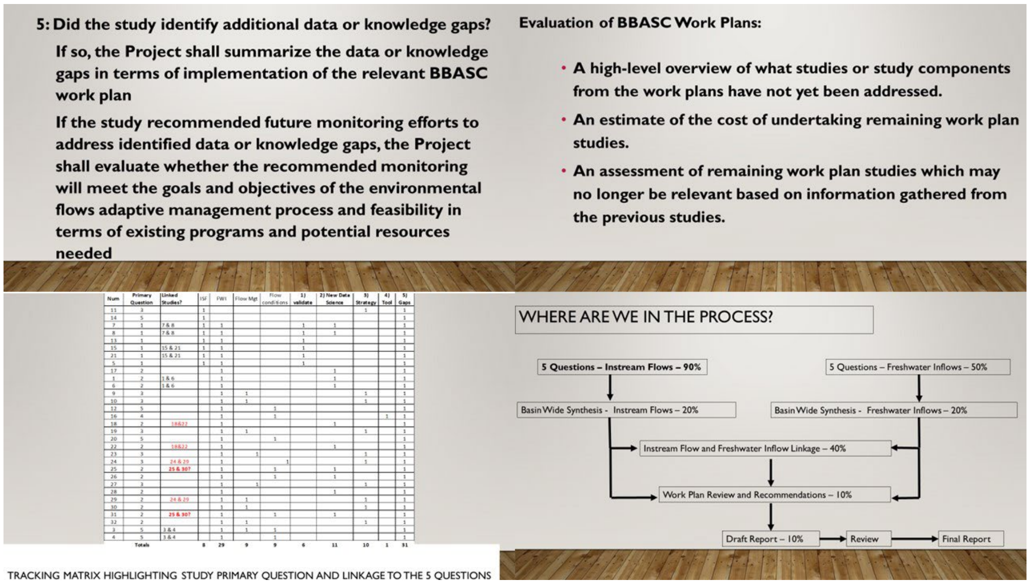


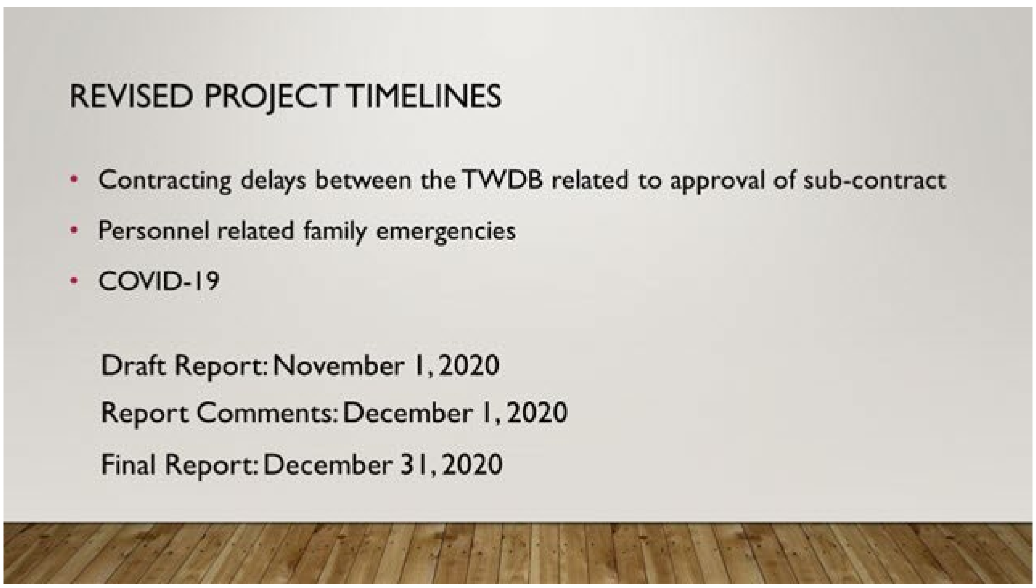












Although there was a link provided in the invitation to submit questions ahead of time, no questions were submitted. General questions during the Webinar were on timelines for review and opportunities to provide comments on the report.