Final Report: Review of the Underlying Theory, Technical Methodology and Data Sources in the Cursory Floodplain Dataset-Texas Flood Model and Mapping Processes for the State of Texas

Texas Water Development Board Contract #2201792622

Prepared for:
Texas Water Development Board

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May 2024

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Final Report: Review of the Underlying Theory, Technical Methodology and Data Sources in the Fathom-Texas Flood Model and Mapping Processes for the State of Texas

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Executive Summary

The Texas Water Development Board (TWDB) “floodplain quilt”, which patches together available flood hazard data, uses a flood inundation layer (Cursory Floodplain) created by Fathom (the “Fathom-Texas” data product) as a "rapid assessment" tool to fill in the existing flood quilt for areas where no other flood risk models/data are presently available. The Fathom-Texas product provides flood inundation estimation for pluvial, fluvial, and coastal flood hazards, covering the entire state of Texas at a 10-ft (3-m) resolution for flooding events with the return periods of 5, 10, 100, and 500 years. This document outlines the findings of an independent review project that focused on the fundamental theories and methods of the Fathom flood framework. While the Cursory Floodplain dataset includes pluvial, fluvial, and coastal components of flooding, this review effort focused on the pluvial and fluvial datasets only. This report highlights outcomes of this independent review of the Fathom framework and workflow from four perspectives: (1) terrain (DEM) data and dam/levee profiles, (2) channel and floodplain characterization, (3) hydrology, and (4) hydraulics, along with recommendations for appropriate uses of the data.

The goal of this report is to evaluate whether the Fathom-Texas data product is “fit-for-purpose” with the purpose being providing a rough assessment of flooding susceptibility that is suitable for the TWDB or others to use for flood planning purposes. In general, locations far away from predicted inundation areas can be considered lower priority for future analyses whereas locations within or close to predicted inundation areas should receive higher priority for further flood studies. It should be noted that while the Fathom-Texas results may not be suitable for site-specific engineering analyses (such as levee height assessment), it is appropriate to use them for certain planning purposes like preliminary screening. If the Fathom-Texas data product is made publicly available, a statement should be made to the effect that the data product is not the equivalent to those of conventional engineering flood modeling studies and should not be solely relied on for capital investment or quantified risk assessment projects.

1 Project Introduction

Using the latest statewide LiDAR topographic data, the Fathom team updated their continental scale flood model for Texas to generate a statewide flood hazards dataset (also referred as the “Cursory Floodplain dataset”). This dataset includes fluvial, pluvial, and coastal flood hazards layers covering the state of Texas at a 10-ft spatial resolution for the 20%, 10%, 1%, and 0.2% annual exceedance probability (AEP), i.e., 5, 10, 100, and 500-year events, respectively. The dataset is intended to be used by the Texas Water Development Board (TWDB) as "rapid assessment" flood inundation estimates to fill in the gaps where no other flood hazards layer is available in the statewide floodplain dataset (also called the “floodplain quilt”). To assist in ascertaining the appropriate usage and limitations of the models, a research team led by Dr. Nick Fang (PI, the University of Texas at Arlington) and Dr. Ben R. Hodges (Co-PI, the University of Texas at Austin) was tasked by the TWDB to review the underlying theories, technical methodologies, and data sources used in the Fathom-Texas modeling/mapping framework. A comprehensive review was performed based on available information pertaining to the Fathom-Texas flood hazards data including thirty-eight (38) academic research articles, technical reports, and other documents and materials (e.g., technical memorandums from TWDB) and the discussions with the Fathom team members at the two virtual meetings conducted on June 21, 2022, and June 8, 2023. This document summarizes the main findings and recommendations for the use of the Fathom-Texas flood hazards data.

The review team previously built up a well-grounded understanding of all the components of the framework during **Phase 1** of this project, which laid a solid foundation for further investigations in **Phase 2**. **Section 2** illustrates the background information of the Fathom-Texas Modeling Framework, followed by comprehensive findings and suggestions as summarized in four perspectives with recommendations for appropriate uses of the Fathom-Texas data:

- Perspective 1: Terrain (DEM) data and levee/dam profiles
- Perspective 2: Channel and floodplain characterization
- Perspective 3: Hydrology
- Perspective 4: Hydraulics

Section 3 summarizes recommendations for use of the Fathom Flood Hazards data.

2 Fathom-Texas Flood Modeling Framework

The Fathom modeling framework is a complex hydraulic modeling system consisting of two primary components, namely (I) a model builder that utilizes a number of different data sources to automatically construct hydraulic models of a specified geographic region and (II) a hydraulic model (LISFLOOD-FP) which solves a simplified form of the shallow water equations (SWE) in two dimensions across the model domain. LISFLOOD has a long history in flood modeling beginning with Bates (2000). More recently, LISFLOOD was adapted to create a global fluvial and pluvial flood modeling scheme, first described by Sampson et al. (2015) and updated by Bates et al. (2021). This modeling system was further customized and applied over the State of Texas using the available 10-ft terrain data from the Texas Geographic Information Office (TxGIO) (formerly the Texas Natural Resources Information System or TNRIS) and several regional datasets. The datasets for the model include USGS stream records, NHDPlus hydrography data, United States Army Corps of Engineers (USACE) levee profiles, and National Oceanic and Atmospheric Administration (NOAA) frequency rainfall data including intensity-duration-frequency (IDF) curves called Atlas 14 (Perica et al., 2018). **Figure 2-1** shows a conceptual flowchart of the Fathom modeling framework for Texas with six color-coded steps as described below.

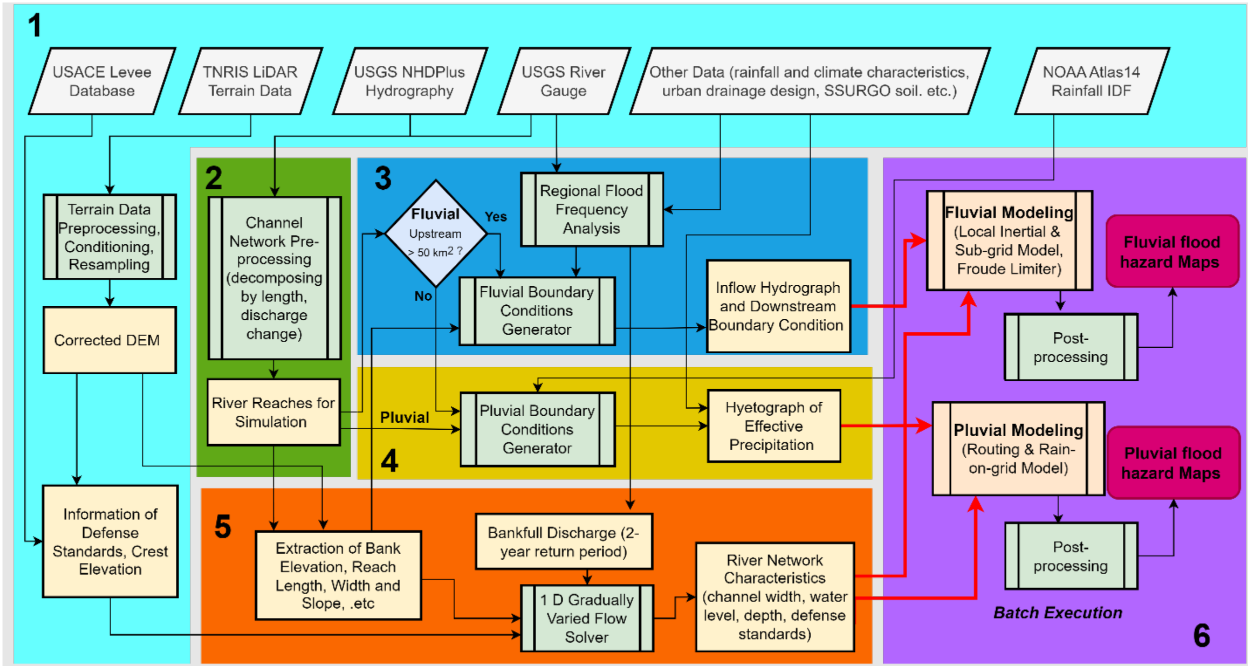

Figure 2-1. **Conceptual flowchart of the Fathom modeling framework for Texas**

Step 1 (Cyan color): Fathom assembles relevant input datasets (e.g., terrain, hydrography, flood defense locations, and standards, rainfall and climate characteristics, soil types, etc.) into a consistent resolution (10 ft). Fathom also preprocesses (e.g., gap filling), conditions, and resamples higher-resolution LiDAR DEM data into a coarser 100 ft x 100 ft raster grid for model input. The USACE levee information is incorporated with corrected DEM data for the later modeling process. **Table 2-1** summarizes the major input data with sources. Note that coastal flooding is not in scope of this review so that Fathom-Texas application of the NOAA coastal gauge data is not evaluated in this study.

Table 2-1. **Model input datasets**

Description	Data Source	Link
River gauge data	USGS	https://waterdata.usgs.gov/nwis/rt
Levee data	USACE	https://levees.sec.usace.army.mil/#/
Rainfall IDF data	NOAA	https://hdsc.nws.noaa.gov/hdsc/pfds/
Hydrography data	USGS	https://www.usgs.gov/national-hydrography/nhdplus-high-resolution
Terrain data	TxGIO (formerly TNRIS)	https://geographic.texas.gov/ (formerly https://tnris.org/)
SSURGO Soil Survey data	USDA	https://www.nrcs.usda.gov/resources/data-and-reports/soil-survey-geographic-database-ssurgo
Köppen-Geiger Climate Classification data	The University of Veterinary Medicine Vienna	https://koeppen-geiger.vu-wien.ac.at/

Annual Average Rainfall data	WorldClim	https://worldclim.org/
River Width data	Global River Width from Landsat (GRWL)	https://zenodo.org/record/1269595

Step 2 (Green color): Fathom decomposes the river network into discrete reaches (range from 10km - 100km) for further simulations based on the catchment-scale analysis, using logic rules with respect to upstream area thresholds, mean annual flood (see definition in Perspective 4: "Boundary Conditions"), or reach length limits. New reaches are defined when the upstream area has changed significantly (e.g., 80% change in upstream drainage area), mean annual flood changes by 20%, or when a maximum reach length condition (100 km) is met. The USGS NHDPlus Hydrography data is used in this step to provide information on river reaches.

Step 3 (Blue color): Fathom determines fluvial boundary conditions for each river reach using the Regionalized Flood Frequency Analysis (RFFA) for inflow discharge and solves the water levels with normal depth as the downstream boundary condition. The RFFA is established for calculating peak flow based on USGS gauge discharge and annual rainfall and climate characteristic datasets (See **Table 2-1**) (Smith et al., 2015). With the calculated peak flow, a simple triangular hydrograph is then determined with a time to concentration estimated based on wave travel time (Manning's roughness) along a river network. The channel information is extracted from **Step 5**. The resulting hydrographs and downstream boundary conditions are then used as the model input for the two-dimensional fluvial modeling, as described in **Step 6**. It is noted that the RFFA approach is only applied to the channels with an upstream drainage area larger than 50 km^2, while the channels with upstream areas smaller than 50 km^2 are modeled explicitly by the pluvial modeling with the rain-on-mesh methods, as described in **Step 4**.

Step 4 (Gold color): Fathom determines pluvial boundary conditions using intensity-duration-frequency (IDF) curves from the NOAA Atlas 14 dataset to calculate rainfall accumulations for each 30-arcsecond grid, where for each cell, a simple triangular hyetograph is generated with a Horton infiltration model. Using soil types from the SSURGO database, effective rainfall information is then generated and used as input for a two-dimensional rain-on-grid pluvial model across the entire domain in **Step 6**. For some urban areas, the infiltration model can be substituted with local drainage design standards (5 or 10 years) along with settlement size and density if available.

Step 5 (Orange color): Fathom estimates the river network characteristics (e.g., river channel depths, defense standards, etc.), including the estimated channel bathymetry using a 1-D gradually varied flow (GVF) model with a bed nudging simplification. A bank-full condition is used by the model to determine the channel bathymetry, which is defined based on the 2-year return period discharge from the RFFA method as described in **Step 3**. The DEM and river reach information from previous steps, including bank elevation, reach length, channel width (GRWL in **Table 2-1**), slope, etc., serves as input to the GVF model. The characteristics of the reaches (e.g., channel width, water level, water depth, and defense standards) are then used as the model input for both fluvial and pluvial models in **Step 6**.

Step 6 (Purple color): Fathom constructs model input files for batch executions allowing simulations of all reaches in both fluvial and pluvial hazards layers across the desired range of return periods, assembles reach simulation results, and post-processes results into 10-ft contiguous hazards layers. The fluvial hazard layers are produced with the fluvial boundary conditions from RFFA and channel characteristics as input from previous **Steps 3** and **5**. The fluvial model is a 1D high-resolution hydraulic model using the local inertial form of the shallow water equations (SWE). The local inertial form of the SVE cannot correctly represent supercritical flow, so a Froude limiter is then applied to maintain the flow regime at or below critical conditions during the modeling process. The pluvial hazard layers are produced from the 2D Rain-On-Grid modeling with effective precipitation time series and channel characteristics as input from **Steps 4** and **5**. The pluvial modeling process varies based on flow conditions: in most cases, it solves the inertial simulations on a 2D grid, similar to the fluvial model, with the source of rain falling on the grid at each timestep; however, for very shallow depths in steep-slope areas, the standard 2D model is replaced with a slope-dependent form of a constant-velocity routing method, causing water to move water downslope at a fixed velocity estimation based on the slope. The post-process of the model outputs as downscaled from 100 ft to 10 ft is also undertaken in this step.

2.1 Perspective 1: Terrain (DEM) data and levee/dam profiles

The Fathom-Texas modeling framework incorporates the latest LiDAR digital elevation model (DEM) data from the TWDB as the underlying terrain data. The LiDAR data is preprocessed by Fathom for consistency and completeness (e.g., DEM gap fillings) for a 10 ft x 10 ft raster grid. Since it is presently impractical to rapidly model all of Texas at the 10-ft scale, Fathom-Texas creates a coarser 100 ft x 100 ft grid for modeling using a bilinear resample method to achieve computational efficiencies. Modeled results at the 100-ft resolution are downscaled back to the original 10-ft resolution, following the approach in (Schuman et al., 2014), which can be summarized as follows:

1. The 100-ft resolution water surface elevations are extracted from the Fathom-Texas model. To allow inundation with proper propagating out from the edge of the coarse resolution data, the simulated water surface elevations at the edge of a simulated inundation footprint are extended by one 100 ft x 100 ft cell.
2. The extended water surface elevations are resampled (bilinear resampling) to the 10-ft x 10-ft resolution as the high-resolution DEM. This method provides a water surface elevation mask and a high-resolution DEM, both on the same grids.
3. The DEM values are then subtracted from the water surface elevation data on the 10 ft x 10 ft grid to determine water depth and negative values are set to zero, yielding a new high-resolution inundation depth layer.
4. The above process can produce positive water depths that do not have any direct connection to a contiguous river floodplain and hence are suspected to be erroneous predictions. These areas typically occur because the 100-ft model resolution removes smaller scale blocking features that exist in the 10-ft DEM. To remedy this issue, Fathom-Texas creates an “isolated depth mask” to

identify cells that are disconnected from the floodplain. A “connection threshold” is used to determine which cells at the 10 ft x 10 ft grid are set to zero depth, using a connected threshold of 36, corresponding to 4 cells in the coarse resolution data, where the rest are set to zero for the inundated depth.

Proper representations of flood defenses like levees and dams remains a key challenge in any flood model. Many of these features are not well-represented in DEMs unless the survey resolution is smaller than 1 or 2 ft. Furthermore, terrain analysis techniques (such as the upscaling of Fathom-Texas, described above) tend to eliminate any narrow levees that are well-represented in the DEM. In theory, geometric knowledge of the missing levees can be used to include the levees on a coarser grid, requiring an extensive code development and validation effort (Hodges, 2015; Kahl et al., 2022). But such methods were not seen to be attempted in the Fathom-Texas model.

The Fathom-Texas approach to levees is to model two types of scenarios: (I) “return period” scenarios using flows at a given exceedance (e.g., 1%, or 100-yr flood); in this case the levees designed at or above the exceedance are assumed to hold, and (II) “overtopping” scenarios where the levees are assumed to have globally overtopped or failed (Bates, 2023). The levees are solely based on information from the 2021 U.S. Army Corps of Engineers (USACE) National Levee Database. These are represented either with known crest elevation information or with extracted maximal pixel values from the terrain dataset (Wing et al., 2019). The levee profiles are used in the “return period” mechanism, where the modeled inundation is excluded within the service areas of levees and “forced” to travel somewhere else when the return period is less than or equal to the standard of protection. For the break or overtopping scenarios (return period higher than levee design standard), the levees are simply assumed to fail completely without performing hydraulic modeling. This latter condition is arguably a worse case condition as it neglects partial blockage and reduced flows during an overtopping event.

Dams are always a problem for large-scale hydrologic-hydraulic modeling as the dam operating procedures are typically not readily available. Indeed, the operating procedures of many dams depend on the judgments of the operators, who incorporate lessons from history and knowledge of predicted rainfall, antecedent soil moisture, and risks associated with overtopping. Since it is presently impractical to include detailed operating information from all dams in Texas into the Fathom-Texas model, Fathom-Texas factors the impacts on dam structures into the downstream flow data with the assumption that the downstream flow data record inherently captures the influence of upstream dams and uses it to estimate extreme flows in regionalized flood frequency analysis (RFFA). A review of the Fathom-Texas model data by Halff Associates Inc. indicates that while the model generates consistent floodplain information as those of the TWDB floodplain quilt and National Flood Hazards Layer (NFHL), it tends to provide different floodplain information in regions surrounding reservoirs, lakes, and major river channels (see **Figures 2-2** and **2-3**). For example, the red areas as shown in **Figure 2-3** exhibit larger inundation from the flood quilt than Fathom layer; green areas show smaller inundation from the flood quilt than the Fathom layer. In particular, the Fathom-

Texas flood depth information downstream of a dam is generally underestimated. The reason for this bias is unclear.

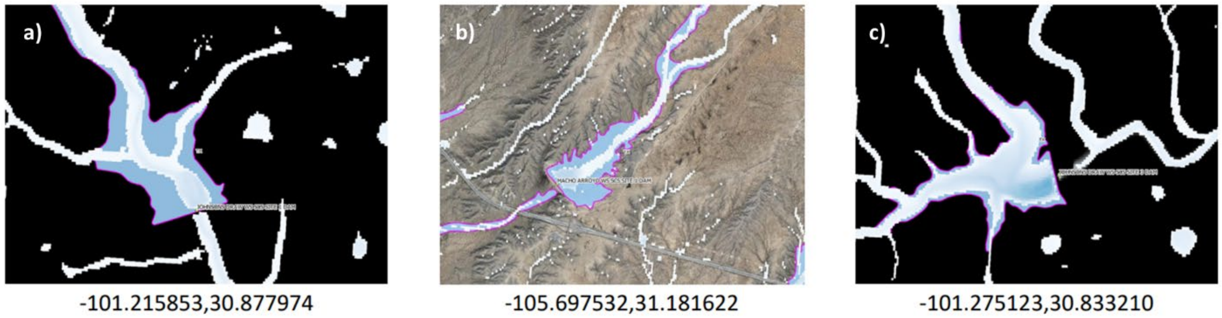

Figure 2-2. National Flood Hazards Layer (NFHL) in blue and outlined in purple vs. Fathom inundation data in white near three Soil Conservation Service (SCS) reservoirs with their coordinate locations. a) Johnsons Draw WS SCS Site 1 Dam; b) Macho Arroyo WS SCS Site 1 Dam; c) Johnsons Draw WS SCS Site 3 Dam (Source: TWDB, 2021a.)

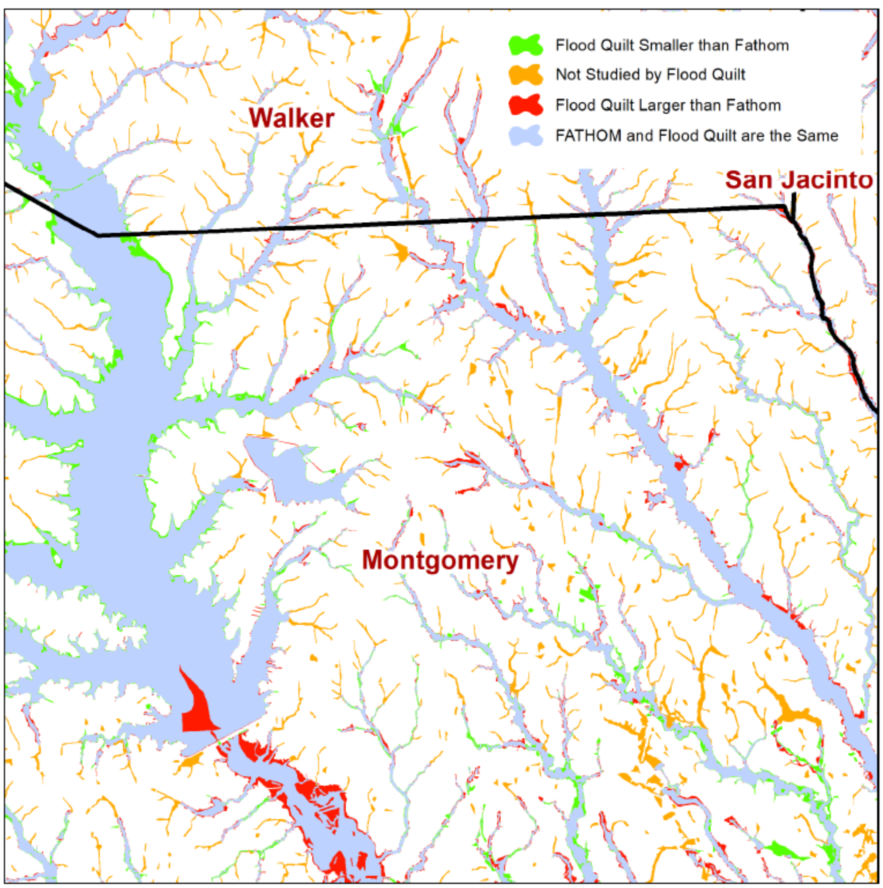

Figure 2-3. Fathom fluvial and pluvial data extent compared to the Floodplain Quilt (Sources: TWDB, 2021b)

Overall, the approach to handling terrain, levees, and dams in Fathom-Texas is reasonable and fit-for-purpose of rapid assessment. However, the results can be easily misunderstood or misinterpreted by future users simply because the output is presented on the high-resolution (10 ft) grid. Users will tend to presume that the model is providing high-resolution results, which leads to a misunderstanding of the error, bias, and uncertainty in the model. **We recommend that all results from the Fathom-Texas model be tagged with a caveat such as "These results were computed on a grid 10 times coarser than the display grid, which means the model uncertainty is much larger than implied by the high-resolution representation." Furthermore, while we understand that uncertainties could come from Fathom-Texas and engineering models, we recommend that TWDB conduct comparison studies between both results across many different "typical" Texas landscapes to understand the differences between both results and include them as part of the Fathom-Texas data. Ideally, such differences in measurements can be used to create inundation maps of possible larger and smaller inundation areas so that users can immediately see the likely range of uncertainty.**

2.2 Perspective 2: Channel and floodplain characterization

The Fathom-Texas modeling framework uses the USGS NHDplus hydrography dataset to represent river and stream channels. This dataset is linked to and conditions the LiDAR DEM of floodplains for channel processing. A channel solver based on the gradually varied flow (GVF) approximation creates the channel geometries required for hydraulic (flow) models for computing water depths and floodplain areas. Since measured datasets of channel geometries are not available for all rivers in Texas, a channel geometric model is required for the process. In general, using a mixture of measured and model-approximated cross-sections leads to data consistency problems, so the GVF approach is utilized by Fathom for a unified channel dataset. An initial approximation of riverbed elevations is made by subtracting water depth from the bank height profile, where pixel-wise river depths are estimated by using Manning's equation. Due to backwater effects, these initial bed elevations often result in an overprediction of the water surface elevation at bank full discharge for all river reaches where diffusion of shallow water wave properties are important, as this is the case for most lowland rivers and deltas. The GVF solver seeks channel bed elevations by minimizing the least squares difference between the observed water surface profiles (from DEM and at the bank full discharge condition for 2-year flow) and the simulated by the GVF to eliminate overprediction scenarios. Fathom further utilized a simplified version of GVF (nudging step as described in **Step 3** and as shown in **Figure 2-4** for the GVF method adaptation) to achieve computational efficiencies (Neal et al., 2021). For reaches shorter than 10 km, a unique regression model is used to generate the river bathymetry for both the cross sections and widths. This approach is an advancement compared to prior models using uniform flow assumptions and is regarded as more accurate by the Fathom team (Neal et al., 2021). The review team thinks that while the GVF approximation is a simple and efficient approach to generating channel geometries (and is certainly better than uniform flow), it has the potential to generate undesirable outcomes in bed geometry, which can cause sharp changes in water surface elevations in the hydraulic (flow) solver, which could lead to inaccurate solutions of water depths. The Neal et al. (2021) study provides valuable insights into model accuracy through evaluations conducted at UK sites. However, it is important to note that the paper does not specifically address how these findings translate to the Texas context, where regional characteristics and hydrological conditions may differ significantly. At one of the conducted meetings, the Fathom team stated that this challenge had been addressed by adding regularization terms to the optimizer for generating physically plausible solutions in the channel solver. To date, no published technical reports that adequately outline the regularization process could be found during the project period.

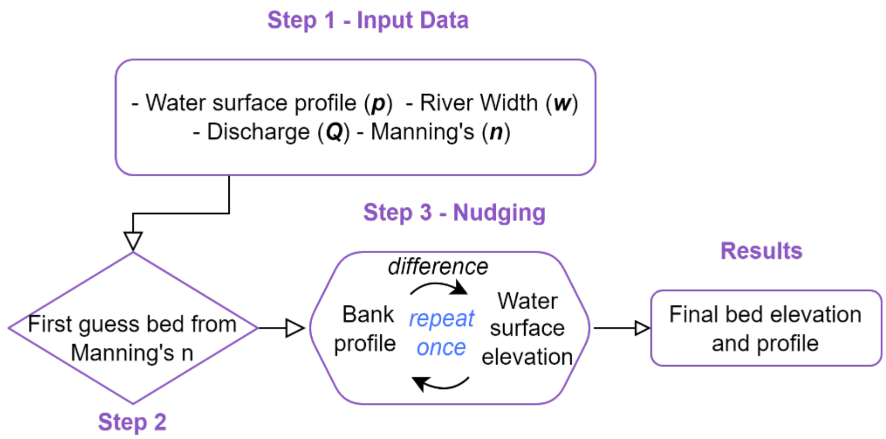

Figure 2-4 Workflow of the GVF method and the simplified nudging method (step 3) adapted based on Neal et al. 2021.

Overall, the approach to approximating the unknown channel geometry in Fathom-Texas is reasonable and state-of-the-art. However, the need to approximate river geometry leads to a source of error and uncertainty in the model results that cannot be quantified. This issue is a principal limitation of the Fathom-Texas model that can (with present knowledge) only be fixed by implementation of engineering-level models with adequate channel surveys. **The review team recommends that TWDB develop a centralized database of channel surveys and all future flooding studies must contribute to the database.**

2.3 Perspective 3: Hydrology

The computation of both rainfall (pluvial) flooding and riverbank overflow (fluvial) flooding in the Fathom-Texas modeling framework heavily depends on boundary conditions such as the forcing information (rainfall and river inflows) to drive the model. For the Fathom-Texas approach only small catchments (< 50 km^2) use the computationally intensive “rain-on-grid” approach, which is a 2D overland flow model that provides inflows to the river network. For large catchments, a Regionalized Flood Frequency Analysis (RFFA) is used to estimate the flowrates from the catchment based on historical gauge data (Zhao, et al., 2020).

The rain-on-grid model for small catchments (< 50 km^2) uses the NOAA Atlas 14 (Perica et al., 2018) precipitation intensity-duration frequency (IDF) estimates for any design storms with a 1-hour duration. The Fathom team believes a 1-hour storm is adequate for modeling pluvial catchments less than 50 km^2 as the time of concentration should be less than 1 hour. The rain-on-grid model uses a 1 km x 1 km (i.e., ~ 3,300 ft x 3,300 ft) 2D grid to represent the spatial variability of rainfall and the local overland flows. For each event, a simple triangular hyetograph is generated as input into a Horton infiltration model based on soil types from the USGS grided Soil Survey Geographic Database (gSSURGO). For urban areas, the infiltration model can be substituted with local drainage design standards (5 or 10 years) with respect to settlement size and density if available (TWDB, 2021c). The “rain-on-grid” approach provides the net addition of water volume to each cell of the model at each timestep from the design rainfall hyetographs.

The frequency precipitation estimates from Atlas 14 are directly incorporated in the Fathom pluvial rain-on-grid model in a spatially continuous raster format for multiple return periods and durations to generate the 1-hour rainfall intensity/depth for the locations of interest. The approach aims to consider spatial variability of rainfall while simplifying temporal variability by lumping values into a singular rainfall input from 1 hour. **Considering that catchments less than 50 km^2 are often at risk of receiving heavy rainfall with a long duration, this approach may lead to underestimated flood risk for areas less than 50km^2. Therefore we recommend that the TWDB evaluate the frequency precipitation estimates from Atlas 14 utilized in the Fathom model in conjunction with catchment characteristics (sizes, shapes, etc.) to verify the validity of using 1-hour rainfall duration for areas less than (50 km^2) but with a time of concentration longer than 1-hour.**

For large catchments (> 50 sq. km), Fathom-Texas applies the RFFA approach to estimate catchment peak flows to a river. The specific RFFA is a hybrid-clustering approach with a flood-index method (Bates et al., 2021). The methodology consists of two steps: 1) the estimation of an index flood as mean annual flood (MAF), which is the mean of the annual maximum series, followed by 2) the scaling of this index flood using growth curves (the index flood vs. extreme flow magnitudes) based on Generalized Extreme Value (GEV) distribution. The frequency flow values were mainly determined based on the historical data from the available UGSG gauges (444) in Texas via the RFFA method (**Figure 2-5**). It is noted that the HUC-level watersheds as shown in **Figure 2-5** cover less gauges than any other areas of Texas. The underlying theory behind RFFA is that gauge locations are sufficiently “regional” such that ungauged flowrates can be statistically estimated from gauged data. That is, homogeneity across the physics of the system implies homogeneity in the statistics. The method is understood to fail when (i) significant gaps occur in the data sets, (ii) insufficient gauges are available, and/or (iii) the available gauges do not sufficiently span the region. **As**

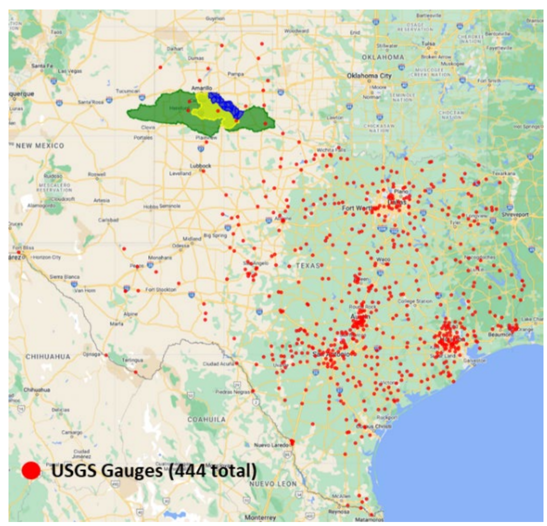

Figure 2-5 USGS River Gauges in Texas and HUC-level watersheds in North Texas.

obvious from Figure 5, both West Texas and the panhandle (Northwest) region have sparse gauges that do not span the region and are unlikely to establish a homogeneous region or sufficient gauges for a valid RFFA model. While the RFFA approach exhibits uncertainties across a large swath of Texas, there does not appear to be any computationally efficient approach that could replace RFFA within the Fathom-Texas model at this moment.

2.4 Perspective 4: Hydraulics

The hydraulic modeling core for the Fathom modeling framework is the LISFLOOD-FP model developed at the University of Bristol, where key members of the Fathom team originate from. This model uses a simplified version of the shallow water equations (SWEs), as discussed below. Formally, the SWEs are derived from the three-dimensional Navier-Stokes equations that govern all fluid flow. The SWEs approximations are: (1) the flow is depth-averaged, (2) the non-hydrostatic pressure is neglected, and (3) a turbulence model is applied. To these well-accepted approximations, LISFLOOD-FP utilizes a local inertial simplification of SWEs significantly reducing computational costs by eliminating the nonlinear advective terms in the SWE. Publications from the Fathom team suggest that the local inertial approximation generates results that are indistinguishable from those from the full SWEs under many conditions (Bates et al., 2010; de Almeida and Bates, 2013). However, the Fathom team also notes that the local inertial approximation is stable only under gradually varied and subcritical flow conditions, i.e., relatively slow and steady flow dominated by free-surface (backwater) pressure gradients. This limitation is not surprising as supercritical flow occurs when the nonlinear advection dominates the free-surface pressure gradients; thus, a local inertial scheme neglecting nonlinear advection cannot correctly present supercritical flow. To stabilize the model for local extremes that are rapidly varied and/or near supercritical flow conditions, the LISFLOOD-FP model uses three methods:

1. A modified numerical scheme (de Almeida et al., 2012) that adds additional dissipation to stabilize the solutions under low-friction conditions that would cause a high-velocity supercritical flow.
2. At very shallow water depth, dropping the SWE entity and substituting a slope-dependent form of a constant-velocity routing method (Sampson et al., 2013) for flows in steep-slope areas where supercritical conditions are likely.
3. A Froude limiter (Coulthard et al., 2013) that applies an *ad hoc* reduction to the local velocity when the model attempts to exceed a criticality threshold.

The primary effect of the modifications to stabilize supercritical and near-supercritical flows is that some steeply sloping regions are likely to have inundation areas overestimated; i.e., where model provisions (Method 1) and (Method 3) above are active, the model will tend to increase the water depth to reduce flow velocity and maintain subcritical flows. However, where model provision (Method 2) is active, the resultant error, bias, or uncertainty are difficult to quantify due to violating the supercritical assumption (Note: Per a follow-up communication with the Fathom team, flows at very shallow water depth (thin film flows) as described in Method 2 were not considered as shallow water flows so that the full SWEs were not applied to this flow circumstances due to large and unjustifiable computational costs. There is a balance when conducting large scale modeling among computational costs and model details). The second effect of the modifications may lead to reduced inundation areas downstream of steep reaches due to the retention of water upstream. Unfortunately, we do not know the impact of poorly representing supercritical flows with the local inertial approximation over some of the steep areas such as the Texas hill country. Supercritical flows make up a small portion of flows throughout Texas, but it remains to be proven that converting them to subcritical flows does not have significant impacts on the predicted inundation.

Overall, the numerical approach used in Fathom-Texas is reasonable for the general purposes of rapid assessment, with the caveat that it is likely to be significantly wrong on steep slopes and in areas immediately downstream of steep slopes (Adams et al., 2017). **We recommend the TWDB consider producing a "steepness" layer that identifies areas where the slope steepness at the modeled flowrates would have a Froude number greater than one-half.** Furthermore, flood inundation information for such regions should be used with caution until further work has been done to validate the local-inertia method for catchments like the Texas hill country.

3 Recommendations for Use of the Fathom-Texas Flood Hazards Data

This document illustrates the framework and workflow of Fathom-Texas flood hazards data with providing findings and recommendations through four perspectives: 1) terrain (DEM) data processing and dam/levee profiles, 2) channel and floodplain characterization, 3) hydrology, and 4) hydraulics.

1. Terrain Data and Dam/Levee Profiles: The DEM data is initially upscaled to a 100-ft resolution from 10-ft and then downscaled to 10-ft again. The bilinear resample method used for this process assumes the relative heights between lower and higher-resolution DEM data are consistent, which may not always be the case where the terrain elevation changes rapidly. While this is a standard method for handling terrain resampling, users should be aware that this could potentially introduce some degree of error in the model output. Since no detailed dam operation data is included for dams represented in the Fathom model, the model cannot simulate full dynamics of reservoir operations and simulated flood depths tend to be underestimated for areas downstream of dams. For break or overtopping scenarios (simulated inundation levels higher than levee design standard), the levees are simply assumed to fail completely without detailed hydraulic modeling. Users need to be aware of these limitations and use the Fathom-Texas data with caution especially for areas downstream of dams and/or protected by levees and areas surrounding reservoirs, lakes, and major river channels.
2. Channel and Floodplain Characterization: The estimation of river channel bathymetry is vital for accurate flood modeling. Fathom applies a Gradually Varied Flow (GVF) method with a simplified bed nudging approach for

achieving computational efficiencies. While the GVF approximation is a simple and efficient approach to generating channel geometries (and is certainly better than uniform flow), it has the potential to generate undesirable outcomes in bed geometry, which can be further translated to sharp changes in water surface elevations in the hydraulic (flow) solver and inaccurate solutions of water depths. At one of the conducted meetings, the Fathom team stated that this challenge was addressed by adding regularization terms to the optimizer for generating physically plausible solutions in the channel solver.

3. Hydrology: The boundary conditions (Regionalized Flood Frequency Analysis (RFFA)) heavily depend on adequate observed data and dense gauge network. The Fathom inundation information for areas like West Texas and Northwest Texas with sparse data and few gauges, may be subject to uncertainties. Users need to be aware of this when applying the model output for these regions. Users also need to be aware that frequency precipitation information from Atlas14 is utilized in the pluvial rain-on-grid model but not in the fluvial model.
4. Hydraulics: The LISFLOOD-FP model works best under gradually varied and subcritical flow conditions, meaning that it may not simulate accurately under rapidly varied or near-supercritical flow conditions. While the Froude limiter is intended to stabilize the model, it can generate higher water depths (conservative) to keep the critical to subcritical flow regime. Users should be aware of the overestimated water depths, particularly for areas that experience rapid changes in water flow.

In summary, the Fathom flood inundation layer is regarded as a "rapid assessment" tool to supplement the existing flood quilt for areas where no other flood risk data is currently available in Texas. Users should be aware of the limitations for appropriate uses of the data.

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