THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Technical Memorandum FY24RU1

To:	Jadé Adediwura, RTI Project Manager, TxDOT
From:	CTR RS/Research Team: David Maidment, Matt Bartos, Andy Carter, Harry Evans, Jeil Oh, Paola Passalacqua, Christine Thies, Sujana Timilsina, Tim Whiteaker, (University of Texas at Austin); Kristine Blickenstaff, Jody Avant, Nam Jeong Choi, Scott Grzyb, Jon Thomas, Sam Wallace (US Geological Survey); Matt Ables, Attila Bibok (KISTERS); Dean Djokic, Michelle Johnson (ESRI); Jonathan Nelson (River Mechanics).
Subject:	TxDOT Project 0-7095-01– Tech Memo FY24RU1
Date:	8/30/2024

Flood Assessment System for TxDOT:
Update on Research in FY24

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Acknowledgment

The Project 0-7095-01 team wishes to acknowledge the help of Caitlan Zilligen of the Center for Transportation Research, who helped with formatting, and creating lists of figures and tables for several versions of this report.

1. Project Management

The purpose of this document is to provide a summary for research Project 0-7095-01, Flood Assessment System for TxDOT, of progress made during FY24. This project is an extension of Project 0-7095 "Evaluate Improved Streamflow Measurement at TxDOT Bridges" that was completed in October 2023. The current project was initiated on 26 February 2024, so this report deals with research conducted in the past six months, March to August, 2024. The summary is divided into the progress made for each of the six project tasks, which are themselves divided into 23 Subtasks, as shown in Figure 1.

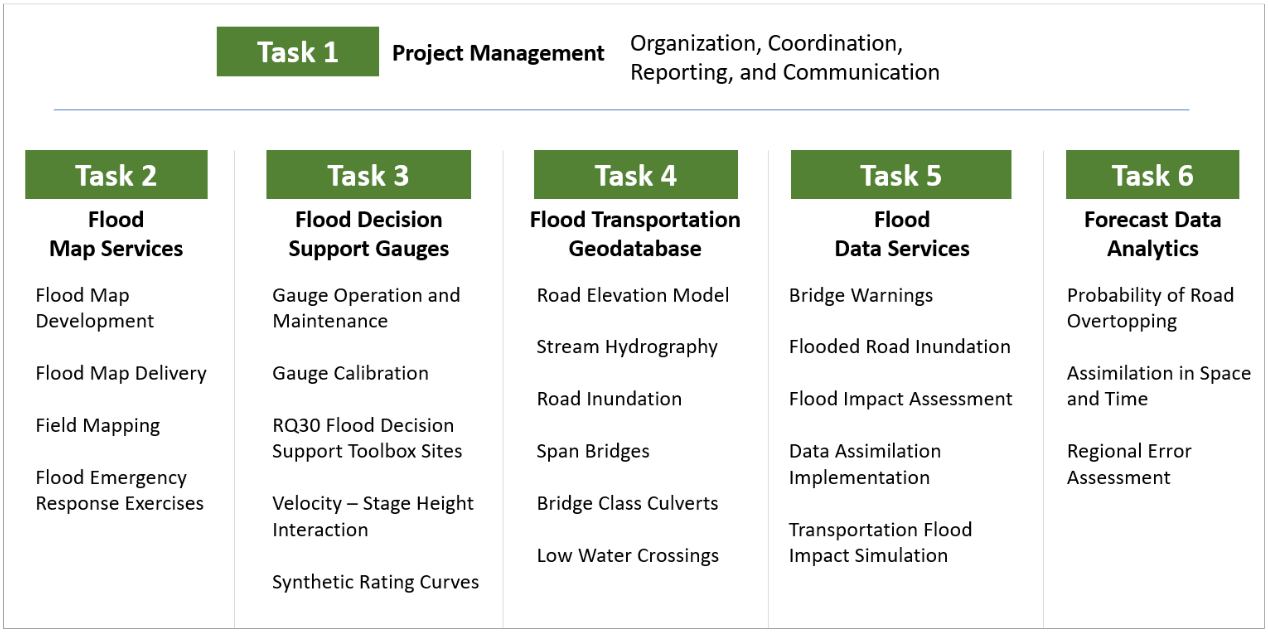


Figure 1 Project Tasks and Subtasks

The timing of this project is extremely important to other USGS projects and the flood science community as a whole. The velocimeter gauge network that was installed and used for this research will result in a lower cost flood alert system through smaller more cost effective velocimeters, fewer visits to establish calibration, and new USGS standard operating procedures. Through these discoveries the velocimeter gauge network will be expanded in the USGS Integrated Water Science Basin 5, the Trinity/San Jacinto. The data coming in from this expanded network will be pulled into the Interagency Flood Risk Management (InFRM) Flood Decision Support Toolbox (FDST) using a new synthetic rating curve that is being developed as an in-kind service for this project. The bridge and road models that are being developed for FAST will also be used in the FDST and will thus continue to be updated and improved by the USGS and fed back into the FAST system. The FDST will continue to grow through investments made by the TWDB and FEMA, along with development of additional Base Level Engineering models, which will help keep these datasets alive and relevant. The StreamStats project that is entering year two with TxDOT and USGS is also investing in datasets that will be used in FAST, including LiDAR developed streamlines and culverts. Each of these projects rely on datasets and tools being developed in this project and will be contributing datasets and tools back into FAST. This is truly a key moment in flood science understanding in the State of Texas and this project is one of the cornerstones.

1.1. Coordination with TxDOT

In April 2024, TxDOT informed the CTR team that it was organizing a TxDOT Project Management Team (TPMT) to interact with the research team on monitoring research progress, and in particular to focus of the delivery of the end products of the Flood Assessment System for TxDOT. In response, the CTR team divided its efforts into two parts: Research and Development. The CTR Development activities are managed by a TACH team which consists of Tim Whiteaker, Andy Carter, Christine Thies and Harry Evans. The TACH team represents CTR in interacting with the TPMT. The Research Team, which comprises all the other CTR staff, supports the TACH team, and reports to TxDOT through the TACH team. The information flow among these various entities is shown in Figure 2.

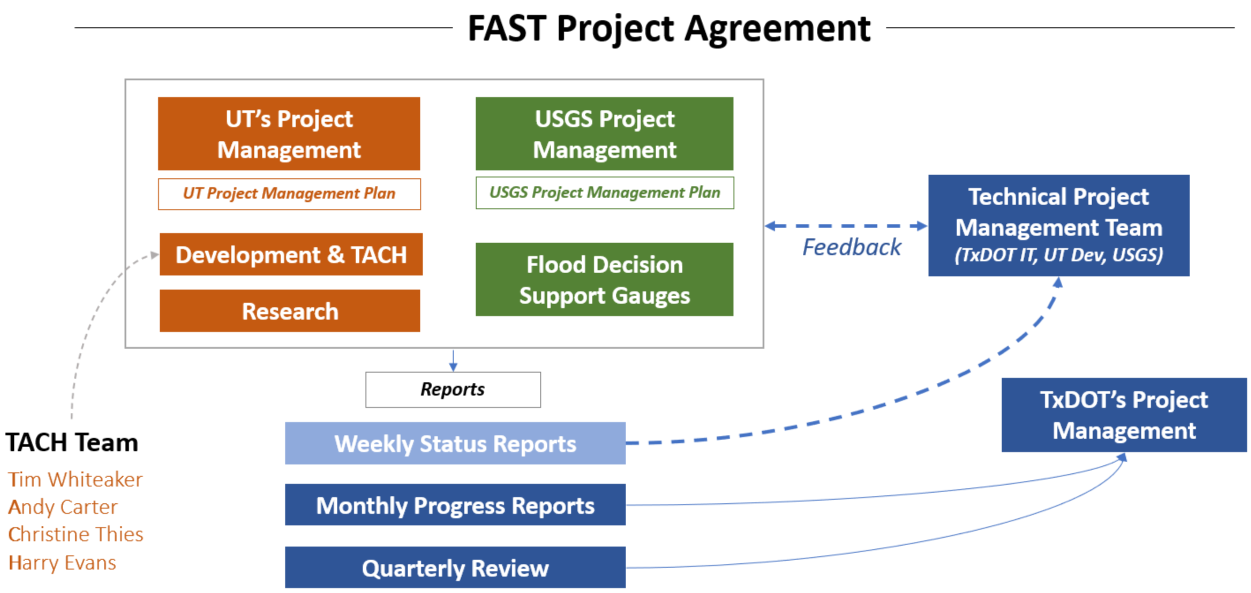
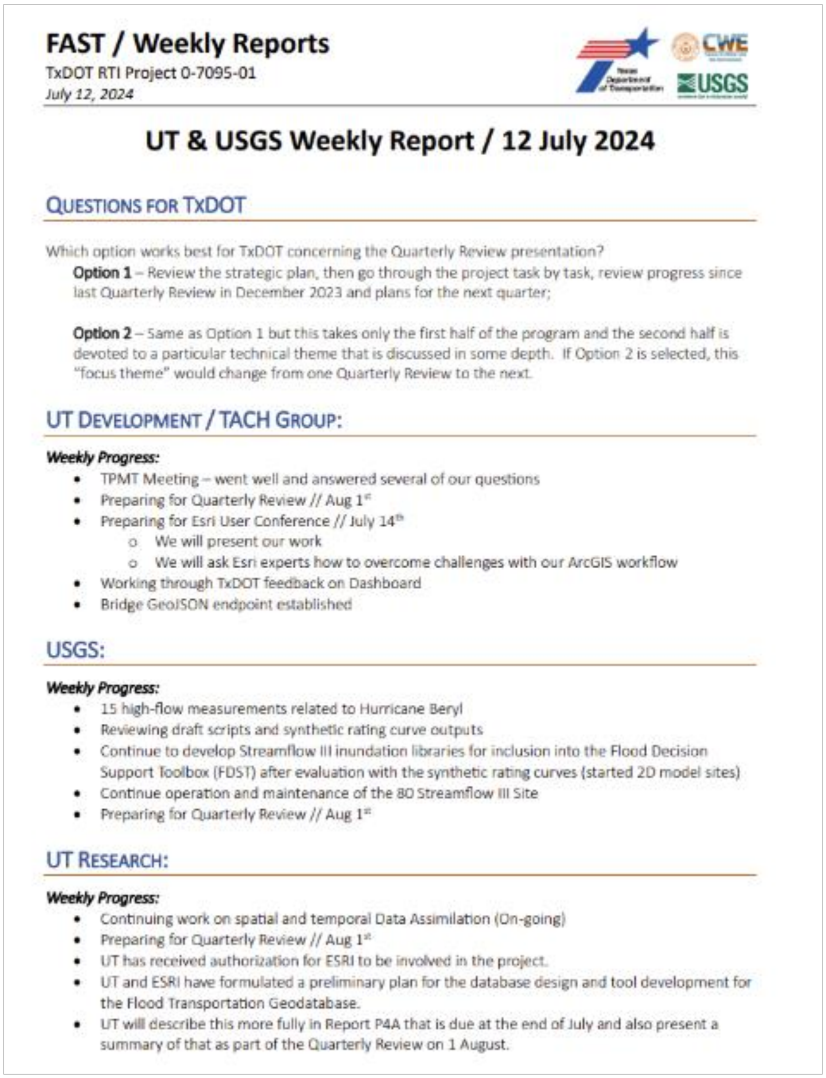


Figure 2 Project Management Structure

The Weekly Report (Figure 3) was initiated as part of the TACH team and enhancement of project management activities. This report is designed as a weekly status and accountability document derived from the research and development teams and sent to the TPMT.



FAST / Weekly Reports
TxDOT RTI Project 0-7095-01
July 12, 2024

UT & USGS Weekly Report / 12 July 2024

Questions for TxDOT

Which option works best for TxDOT concerning the Quarterly Review presentation?

Option 1 – Review the strategic plan, then go through the project task by task, review progress since last Quarterly Review in December 2023 and plans for the next quarter;

Option 2 – Same as Option 1 but this takes only the first half of the program and the second half is devoted to a particular technical theme that is discussed in some depth. If Option 2 is selected, this "focus theme" would change from one Quarterly Review to the next.

UT Development / TACH Group:

Weekly Progress:
- TPMT Meeting – went well and answered several of our questions
- Preparing for Quarterly Review // Aug 1st
- Preparing for Esri User Conference // July 14th
    - We will present our work
    - We will ask Esri experts how to overcome challenges with our ArcGIS workflow
- Working through TxDOT feedback on Dashboard
- Bridge GeoJSON endpoint established

USGS:

Weekly Progress:
- 15 high-flow measurements related to Hurricane Beryl
- Reviewing draft scripts and synthetic rating curve outputs
- Continue to develop Streamflow III inundation libraries for inclusion into the Flood Decision Support Toolbox (FDST) after evaluation with the synthetic rating curves (started 2D model sites)
- Continue operation and maintenance of the 80 Streamflow III Site
- Preparing for Quarterly Review // Aug 1st

UT Research:

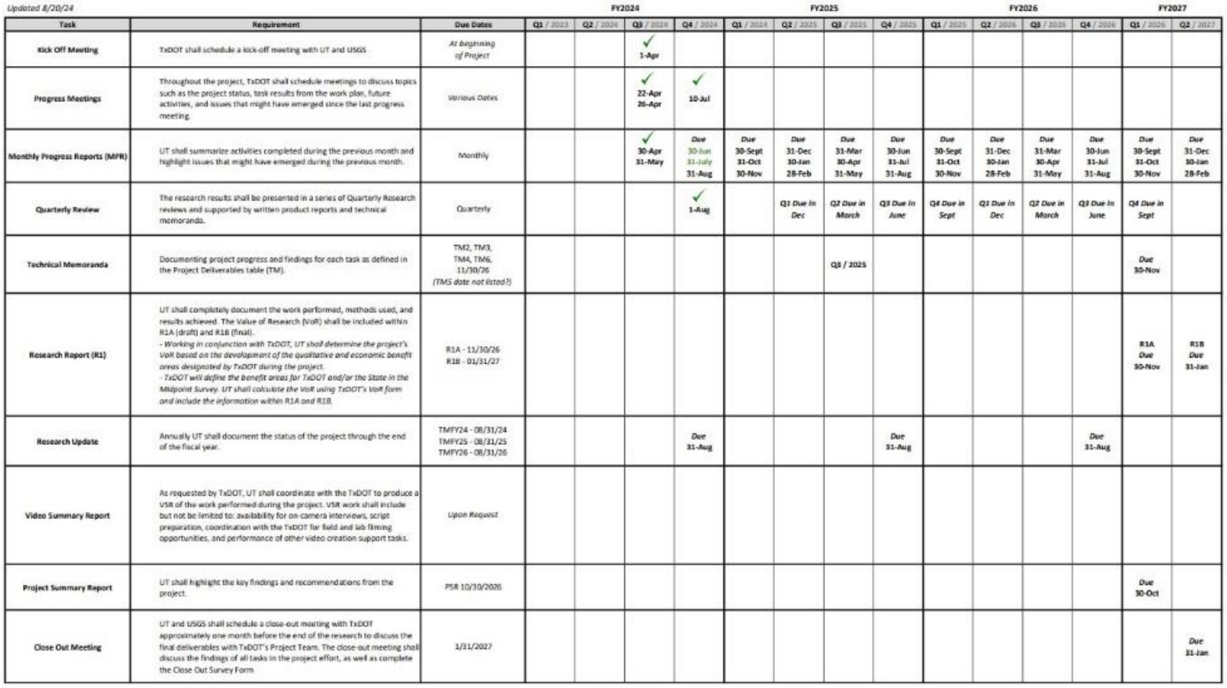
Weekly Progress:
- Continuing work on spatial and temporal Data Assimilation (On-going)
- Preparing for Quarterly Review // Aug 1st
- UT has received authorization for ESRI to be involved in the project.
- UT and ESRI have formulated a preliminary plan for the database design and tool development for the Flood Transportation Geodatabase.
- UT will describe this more fully in Report P4A that is due at the end of July and also present a summary of that as part of the Quarterly Review on 1 August.

Figure 3 Weekly Report to the TPMT

The Project Management Plan (PMP) (Figure 4) was created at the request of the TPMT. The PMP includes documentation of all six Tasks and 23 subtasks, including:

- Documentation of who is responsible for each of the 23 subtasks – both performing and reviewing/approving;
- Detail of the milestones and schedule for those of those subtasks;
- Documentation of any interrelated task dependencies.

This comprehensive project management document is a one stop shop to track this multifaceted project. The PMP is updated and reconciled quarterly, or as often as necessary, based on progress of the project.

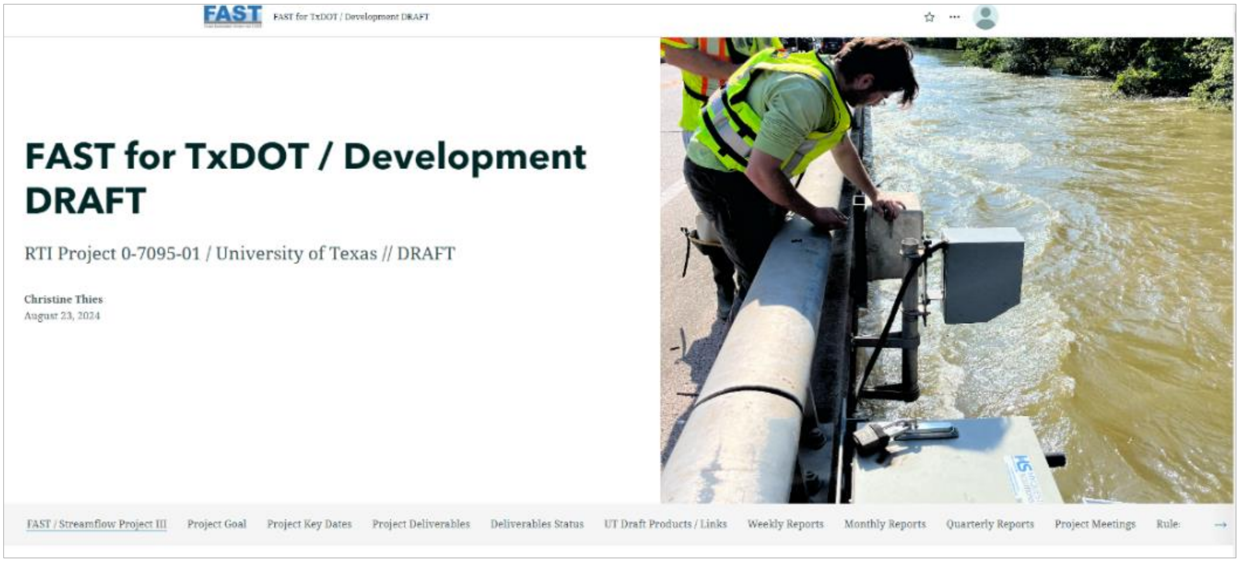


Updated 8/20/24

			FY2024				FY2025				FY2026				FY2027	
Task	**Requirement**	**Due Dates**	**Q1** / 2023	**Q2** / 2024	**Q3** / 2024	**Q4** / 2024	**Q1** / 2024	**Q2** / 2025	**Q3** / 2025	**Q4** / 2025	**Q1** / 2025	**Q2** / 2026	**Q3** / 2026	**Q4** / 2026	**Q1** / 2026	**Q2** / 2027
Kick Off Meeting	TxDOT shall schedule a kick-off meeting with UT and USGS	*At beginning of Project*			✓ 1-Apr											
Progress Meetings	Throughout the project, TxDOT shall schedule meetings to discuss topics such as the project status, task results from the work plan, future activities, and issues that might have emerged since the last progress meeting.	*Various Dates*			✓ 22-Apr 26-Apr	✓ 10-Jul										
Monthly Progress Reports (MPR)	UT shall summarize activities completed during the previous month and highlight issues that might have emerged during the previous month.	Monthly			✓ 30-Apr 31-May	*Due* 30-Jun 31-July 31-Aug	*Due* 30-Sept 31-Oct 30-Nov	*Due* 31-Dec 30-Jan 28-Feb	*Due* 31-Mar 30-Apr 31-May	*Due* 30-Jun 31-Jul 31-Aug	*Due* 30-Sept 31-Oct 30-Nov	*Due* 31-Dec 30-Jan 28-Feb	*Due* 31-Mar 30-Apr 31-May	*Due* 30-Jun 31-Jul 31-Aug	*Due* 30-Sept 31-Oct 30-Nov	*Due* 31-Dec 30-Jan 28-Feb
Quarterly Review	The research results shall be presented in a series of Quarterly Research reviews and supported by written product reports and technical memoranda.	Quarterly				✓ 1-Aug		*Q1 Due in Dec*	*Q2 Due in March*	*Q3 Due in June*	*Q4 Due in Sept*	*Q1 Due in Dec*	*Q2 Due in March*	*Q3 Due in June*	*Q4 Due in Sept*	
Technical Memoranda	Documenting project progress and findings for each task as defined in the Project Deliverables table (TM).	TM2, TM3, TM4, TM6, 11/30/26 *(TM5 date not listed?)*							Q3 / 2025						*Due* 30-Nov	
Research Report (R1)	UT shall completely document the work performed, methods used, and results achieved. The Value of Research (VoR) shall be included within R1A (draft) and R1B (final). *- Working in conjunction with TxDOT, UT shall determine the project's VoR based on the development of the qualitative and economic benefit areas designated by TxDOT during the project.* *- TxDOT will define the benefit areas for TxDOT and/or the State in the Midpoint Survey. UT shall calculate the VoR using TxDOT's VoR form and include the information within R1A and R1B.*	R1A - 11/30/26 R1B - 01/31/27													R1A *Due* 30-Nov	R1B *Due* 31-Jan
Research Update	Annually UT shall document the status of the project through the end of the fiscal year.	TMFY24 - 08/31/24 TMFY25 - 08/31/25 TMFY26 - 08/31/26				*Due* 31-Aug				*Due* 31-Aug				*Due* 31-Aug		
Video Summary Report	As requested by TxDOT, UT shall coordinate with the TxDOT to produce a VSR of the work performed during the project. VSR work shall include but not be limited to: availability for on-camera interviews, script preparation, coordination with the TxDOT for field and lab filming opportunities, and performance of other video creation support tasks.	*Upon Request*														
Project Summary Report	UT shall highlight the key findings and recommendations from the project.	PSR 10/30/2026													*Due* 30-Oct	
Close Out Meeting	UT and USGS shall schedule a close-out meeting with TxDOT approximately one month before the end of the research to discuss the final deliverables with TxDOT's Project Team. The close-out meeting shall discuss the findings of all tasks in the project effort, as well as complete the Close Out Survey Form	1/31/2027														*Due* 31-Jan

Figure 4 Project Management Plan

The Story Map (Figure 5) is an historical log of the entire project. The Story Map archives the numerous meetings, reports, presentations and documents of the project.



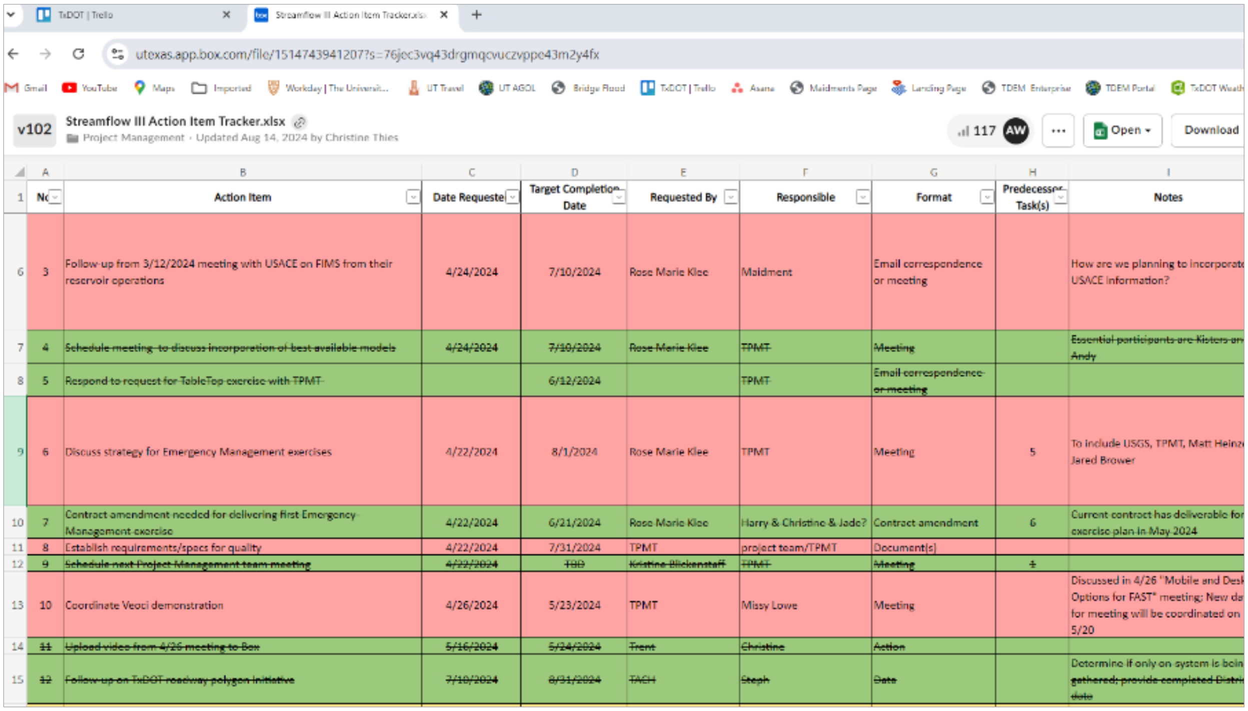
FAST for TxDOT / Development DRAFT

RTI Project 0-7095-01 / University of Texas // DRAFT

Christine Thies
August 23, 2024

Figure 5 The Project Story Map

The Action Item Tracker (Figure 6) documents the status of any action items requested by TxDOT. The Action Item Tracker was created by the TPMT. The TACH team is responsible for continually checking, updating and responding to all action items.



Streamflow III Action Item Tracker.xlsx
Project Management · Updated Aug 14, 2024 by Christine Thies

	A	B	C	D	E	F	G	H	I
1	Nc	Action Item	Date Requeste	Target Completion Date	Requested By	Responsible	Format	Predecessor Task(s)	Notes
6	3	Follow-up from 3/12/2024 meeting with USACE on FIMS from their reservoir operations	4/24/2024	7/10/2024	Rose Marie Klee	Maidment	Email correspondence or meeting		How are we planning to incorporat USACE information?
7	4	~~Schedule meeting to discuss incorporation of best available models~~	~~4/24/2024~~	~~7/10/2024~~	~~Rose Marie Klee~~	~~TPMT~~	~~Meeting~~		~~Essential participants are Kisters an Andy~~
8	5	~~Respond to request for TableTop exercise with TPMT~~		6/12/2024		~~TPMT~~	~~Email correspondence or meeting~~		
9	6	Discuss strategy for Emergency Management exercises	4/22/2024	8/1/2024	Rose Marie Klee	TPMT	Meeting	5	To include USGS, TPMT, Matt Heinz Jared Brower
10	7	~~Contract amendment needed for delivering first Emergency Management exercise~~	4/22/2024	6/21/2024	Rose Marie Klee	Harry & Christine & Jade?	Contract amendment	6	~~Current contract has deliverable for exercise plan in May 2024~~
11	8	Establish requirements/specs for quality	4/22/2024	7/31/2024	TPMT	project team/TPMT	Document(s)		
12	~~9~~	~~Schedule next Project Management team meeting~~	~~4/22/2024~~	~~TBD~~	~~Kristine Blickenstaff~~	~~TPMT~~	~~Meeting~~	~~1~~	
13	10	Coordinate Veoci demonstration	4/26/2024	5/23/2024	TPMT	Missy Lowe	Meeting		Discussed in 4/26 "Mobile and Des Options for FAST" meeting; New da for meeting will be coordinated on 5/20
14	~~11~~	~~Upload video from 4/26 meeting to Box~~	~~5/16/2024~~	~~5/24/2024~~	~~Trent~~	~~Christine~~	~~Action~~		
15	~~12~~	~~Follow-up on TxDOT roadway polygon initiative~~	~~7/10/2024~~	~~8/31/2024~~	~~TACH~~	~~Steph~~	~~Data~~		Determine if only on system is bein ~~gathered; provide completed Distri date~~

Figure 6 The Action Item Tracker

Project 0-7095-01 was initiated with a Kickoff Meeting on 1 April 2024, and overall progress of the research effort was reported in an oral Quarterly Review held on 1 August 2024. Information presented at these meetings can be seen at:
https://www.caee.utexas.edu/prof/maidment/FAST/Presentations/Presentations.htm

Short Reports P2A, P3A, P4A, P5A have been completed for Tasks 2-5 during this project period, which can be seen at:
https://www.caee.utexas.edu/prof/maidment/FAST/Documents/Documents.htm

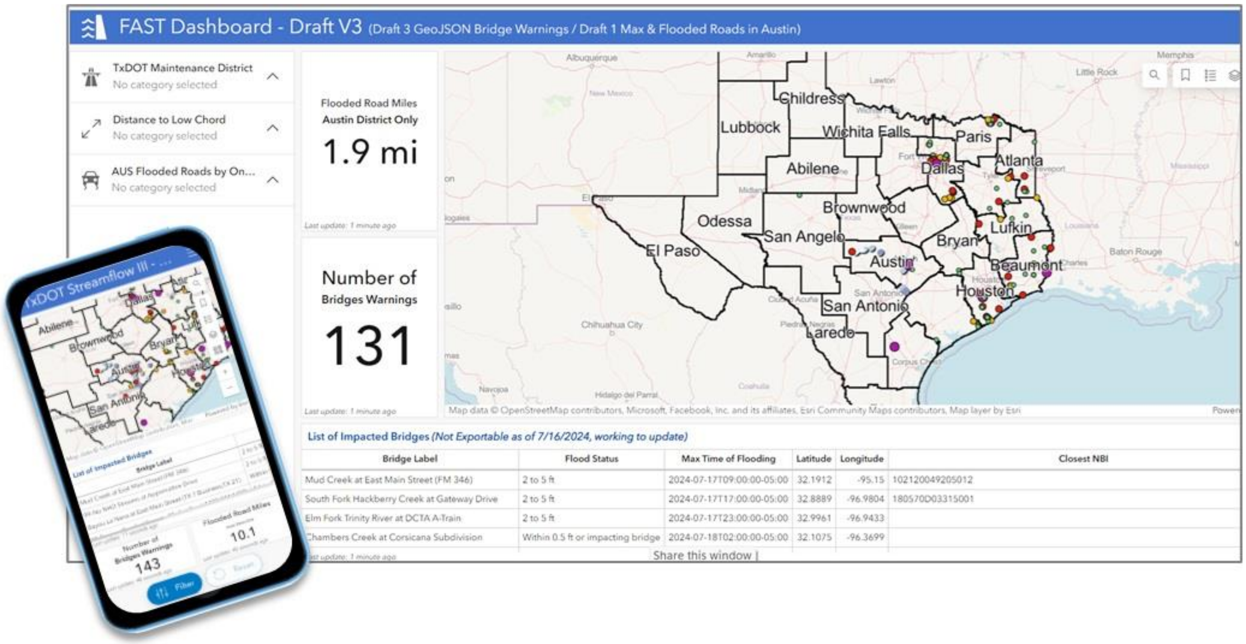
2. Flood Map Services

2.1. FAST Flood Dashboard

The UT/TACH Development team successfully created the initial drafts of both the Bridge Warning layer and the Flooded Roads layer. However, to test the accessibility and functionality of these datasets, we needed a practical testing environment. To address this, we developed a ‘sandbox’ using the ESRI Dashboard environment, called the FAST Flood Dashboard.. We granted TxDOT access to the Dashboard for both desktop and mobile devices, which allowed us to gather valuable feedback from the Technical Project Management Team (TPMT). This feedback was instrumental in guiding the development of the next draft versions of bridge and road layers.

Key features of the Dashboard include:

- An interactive map enabling the selection of specific Bridge Warnings and Flooded Roads
- Filtering capabilities by Maintenance District, Bridge Warnings, “Distance to Low Chord,” and On/Off System Roads.
- An exportable Bridge Warnings table.
- A count of bridges with a water-to-low chord distance of less than 2 feet.
- A count of flooded road miles (Austin District only).


FAST Dashboard - Draft V3 (Draft 3 GeoJSON Bridge Warnings / Draft 1 Max & Flooded Roads in Austin)

TxDOT Maintenance District
No category selected

Distance to Low Chord
No category selected

AUS Flooded Roads by On...
No category selected

Flooded Road Miles
Austin District Only
1.9 mi
Last update: 1 minute ago

Number of
Bridges Warnings
131
Last update: 1 minute ago

List of Impacted Bridges *(Not Exportable as of 7/16/2024, working to update)*

Bridge Label	Flood Status	Max Time of Flooding	Latitude	Longitude	Closest NBI
Mud Creek at East Main Street (FM 346)	2 to 5 ft	2024-07-17T09:00:00-05:00	32.1912	-95.15	102120049205012
South Fork Hackberry Creek at Gateway Drive	2 to 5 ft	2024-07-17T17:00:00-05:00	32.8889	-96.9804	180570D03315001
Elm Fork Trinity River at DCTA A-Train	2 to 5 ft	2024-07-17T23:00:00-05:00	32.9961	-96.9433	
Chambers Creek at Corsicana Subdivision	Within 0.5 ft or impacting bridge	2024-07-18T02:00:00-05:00	32.1075	-96.3699	

Last update: 1 minute ago

Share this window |

Figure 7 FAST Flood Dashboard

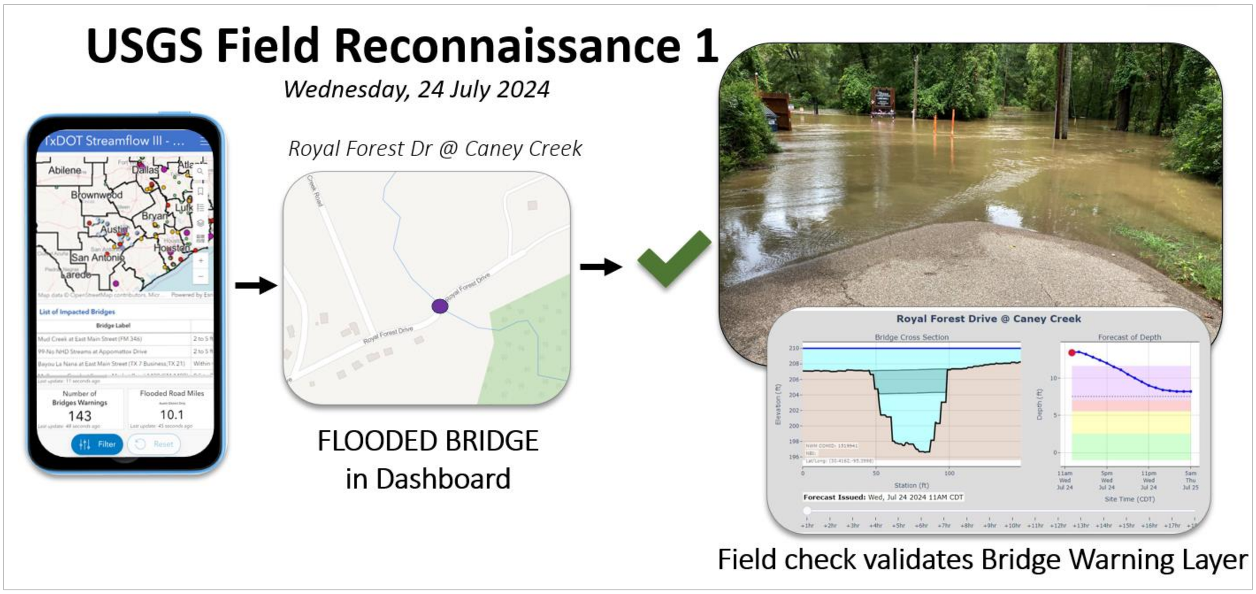
With the feedback received, we were able to make further improvements and obtain additional input from the TPMT. This approach not only facilitated efficient feedback collection but also allowed us to address questions regarding the layer development. Overall, the ‘sandbox’ concept proved to be highly effective in advancing the data development process.

2.2. USGS Field Reconnaissance

The USGS conducted field reconnaissance visits to validate findings from the test version of the FAST Flood Dashboard during flooding on 24-25 July 2024. These checks were carried out at locations on Texas Department of Transportation roadways around Houston that are not currently gauged by USGS equipment but are instead standalone bridge crossings monitored through the FAST Flood Dashboard application. The reconnaissance efforts yielded mixed results. At three locations, shown in Figures 8-10, the application accurately reported flooding, with the roadways being inundated at depths and magnitudes consistent with what was displayed by the FAST Flood Dashboard. In Figure 10, the wire weight measurement indicated a height of 3.9 ft to the bridge deck, while the FAST Flood Dashboard estimated a height of 2-5 ft. However, several other sites turned out to be false alarms, where the application indicated flooding, but the roadways were found to be dry during the field visits.

These findings provided critical feedback on both the application’s successes and areas needing improvement. Specifically, the false flood reports were traced back to inaccuracies in bridge location data within the application. In these cases, the bridge was inaccurately marked in the middle of the open channel flow, either upstream or downstream of the bridge’s actual position.

This error caused the application to incorrectly assume the bridge was submerged whenever water levels in the channel exceeded the bed elevation, as opposed the bridge elevation.



USGS Field Reconnaissance 1

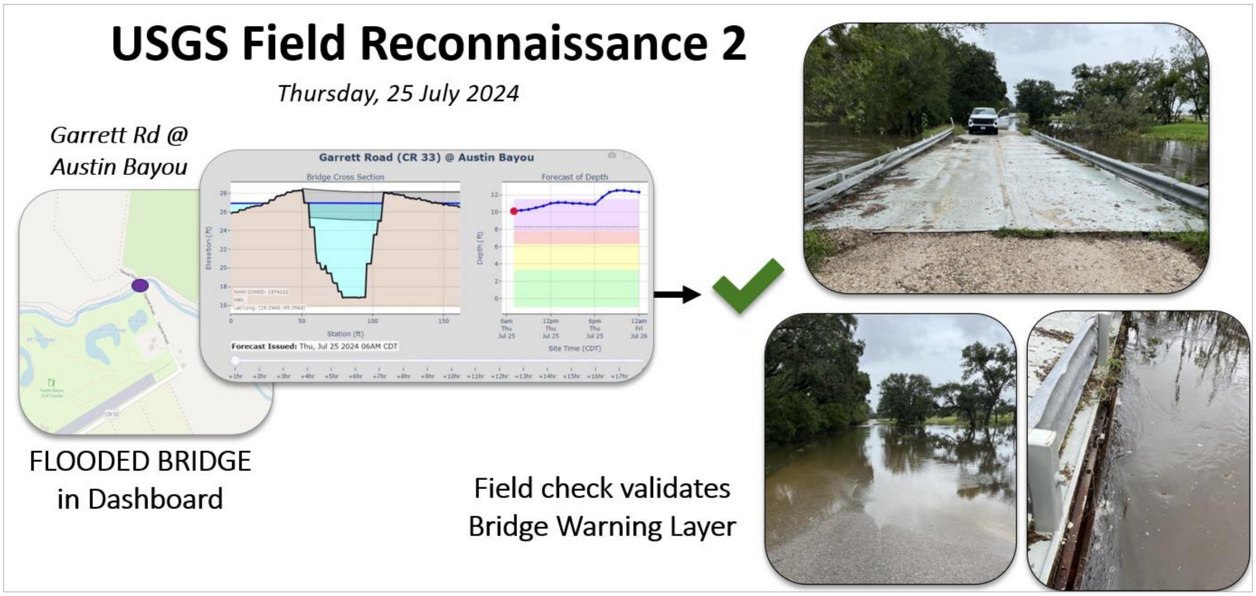
Wednesday, 24 July 2024

Royal Forest Dr @ Caney Creek

FLOODED BRIDGE
in Dashboard

Field check validates Bridge Warning Layer

Figure 8 USGS Field Reconnaissance 1



USGS Field Reconnaissance 2

Thursday, 25 July 2024

*Garrett Rd @
Austin Bayou*

FLOODED BRIDGE
in Dashboard

Field check validates
Bridge Warning Layer

Figure 9 USGS Field Reconnaissance 2

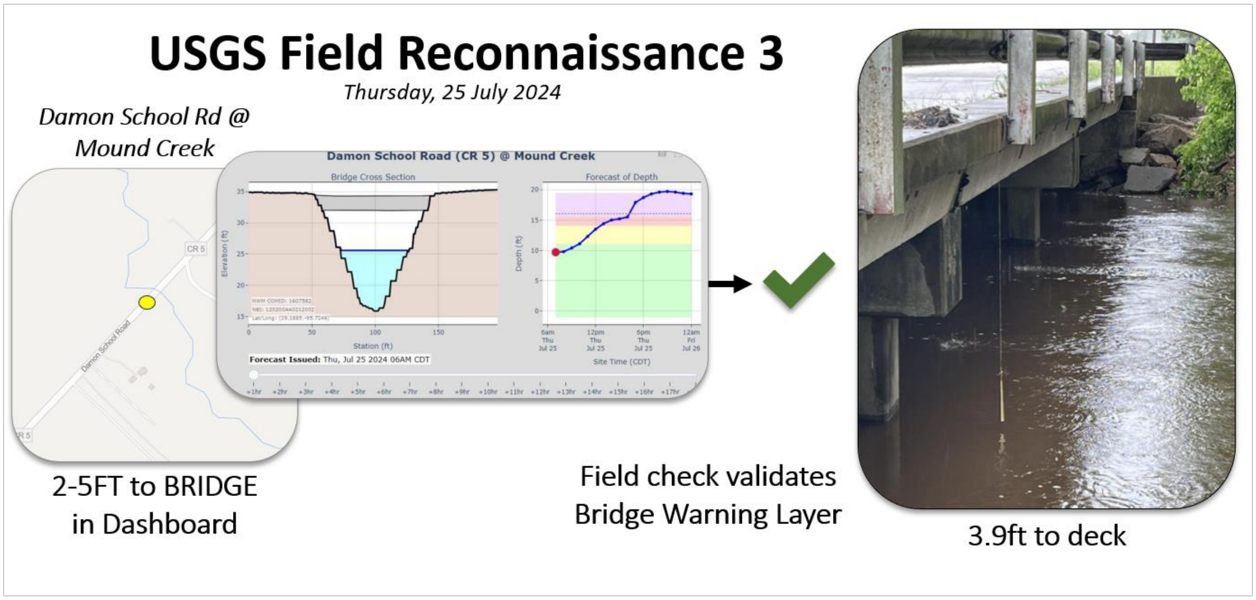


Figure 10 USGS Field Reconnaissance 3.

To address these issues and enhance the application's reliability, the USGS plans to make field reconnaissance during storm events a more routine procedure. This ongoing validation process will help ensure the flooded bridge and roadway application is as accurate as possible. Additionally, the plan includes the possible expansion of these validation efforts by involving USGS personnel from various regions across the state, outside of the core project team, to gather a broader range of validation data and improve the overall effectiveness of the application.

2.3. Flood Response Exercise Planning

The main purpose of an exercise is to involve the TxDOT Maintenance staff in helping to identify and evaluate the functionality, usefulness, usability, accessibility, and efficacy of the layers and applications under development. There are three types of exercises to choose from: Workshops, Tabletop Exercises, and Functional Exercises.

1. **Workshop:** A workshop is an informal discussion in an office or classroom environment. The workshop is designed to gather feedback from TxDOT stakeholders to develop specific products, such as draft layers and mapping applications. Participants provide insights, perspectives, experiences, and guidance on what data and information would be most beneficial.
2. **Tabletop Exercise:** A tabletop exercise involves TxDOT personnel discussing simulated scenarios in an office or classroom environment. Participants engage in scenario discussions before breaking into smaller functional groups to use the applications under

development in response to these scenarios. After the breakout session, the groups reconvene to provide feedback on the applications' usefulness and suggest improvements, which are then used to create an improvement plan.

3. **Functional Exercise:** A functional exercise involves using the prototype applications to test functionality, usability, and usefulness while assessing whether the applications enhance coordination between MNT, EOC, and TxDOT staff. This exercise culminates in a formal feedback session (Hot Wash), which is used to develop an improvement plan.

Recommendation: We recommend conducting a Functional Exercise to test the layers (Bridge Warnings and Flooded Roads) and applications while gathering user feedback. This type of exercise places participants in a realistic setting, replicating their typical work environment, which often leads to more accurate and practical critiques of the applications. It usually draws out a more accurate critique of the applications from the participants.

Overview of Recommended Functional Exercise: The purpose of the Functional Exercise is to test the layers and mapping applications for functionality, usefulness, usability, access and efficacy. All the participants gather at the exercise location, most likely a District office or Maintenance field office. The participants will be divided into two groups, an EOC group and a Field Response group. Everyone is briefed on the purpose of the exercise and trained on how to use the applications. Following that, a scenario is displayed showing flooding on roads and/or bridges in the immediate area.

The Field Response Group is deployed to predetermined locations to observe flooded roads or bridges. They collect field data, such as photos, and make necessary notations within the field application. The EOC Group remains in the office, utilizing the desktop application. They monitor real-time data collected by the field crews and interact with the dashboard and various map layers. After data collection, the Field Response Group returns to the District or Maintenance office. After reassembling, a "Hot Wash" or after-action review is conducted. Each group provides feedback and critiques the applications, highlighting what worked well, what didn’t, and offering recommendations for improvement. This feedback is documented by the exercise facilitators and compiled into a report. The report serves as the foundation for an improvement plan for the UT research and development team to refine the application in alignment with TxDOT’s requirements.

Figure 11 Conducting a Functional Exercise

3. Flood Decision Support Gauges

3.1. Gauge Operation and Calibration

The calibration of RQ-30 velocity sensors is progressing as planned. A total of 20 sensors have been successfully calibrated, helping to ensure the accuracy and reliability of streamflow data across multiple sites. In addition to these calibrations, ongoing verification measurements are being conducted to confirm that the sensors remain properly calibrated over time. This verification process involves cross-referencing the sensor readings with independent measurements, reinforcing the integrity of the data collected by the calibrated RQ-30 gauge.

The calibration process is executed using the targeted approach developed during the Streamflow II project, which focuses on medium and higher flow conditions. Specific cross-section geometries, including the main channel and overbank flow areas, are prioritized to ensure the sensors are calibrated under flood conditions. This method has proven effective in delivering satisfactory results while maintaining adherence to the project timeline.

All calibrations have been completed on time, according to the proposed schedule. The ongoing verification efforts continue to ensure the sensors maintain their accuracy, providing reliable streamflow data for future analysis and decision-making.

Moving forward, we will continue verification measurements at all calibrated sites and prepare for additional calibrations as required by the project scope.

While significant progress has been made, it is important to note that some of the 80 gauge locations have not yet been measured using ADCP. This is primarily due to the flashy nature of the streams, which complicates the timing and conditions under which accurate measurements can be taken. Additionally, efforts have been prioritized in areas that have been more heavily impacted by widespread rainfall. Since most of the flooding in these regions is driven by localized rainfall runoff, focusing on these areas first ensures that we address the most critical sites for calibration and data collection. As conditions allow, we will extend our calibration efforts to the remaining locations.

Figure 12 shows the length of record at the RQ-30 sites as of June 2024. The record lengths range from a low of 1 year at the most recently installed site, 08041945, N Fk Taylors Bayou at IH 10 nr Hamshire, Tx (whose installation was delayed by bridge reconstruction at the chosen location) to 3.67 years at the longest record site (08167000 Guadalupe River at Comfort, Tx, installed during the Streamflow I project). In total about 200 station-years of data have been recorded, an average over the 80 gauges of 2.5 station years per gauge.

Figure 13 shows the number of ADCP measurements through time, and also across the project domain. There is a noticeable increase from west to east, reflecting the fact that the wetter regions in the east have more flood events to sample. Additionally, the summer of 2023 was a particularly dry period which made it difficult to capture flood data. Figure 14 shows the number of ADCP measurements per site. There are 26 sites shown without a measurement as yet and 54 sites at which measurements have been made. The median number of measurements per site is 3. The site with 17 measurements is 08167000 Guadalupe River at Comfort, where the RQ-30 gauge is co-located with a conventional USGS gauge operational since 1939. More than 800 flow measurements have been made at this site over the 85 years since its inception, or about nine measurements per year. The capacity to calibrate an RQ-30 site with just a few ADCP measurements shows the economy of this method compared to conventional rating curve development and maintenance.

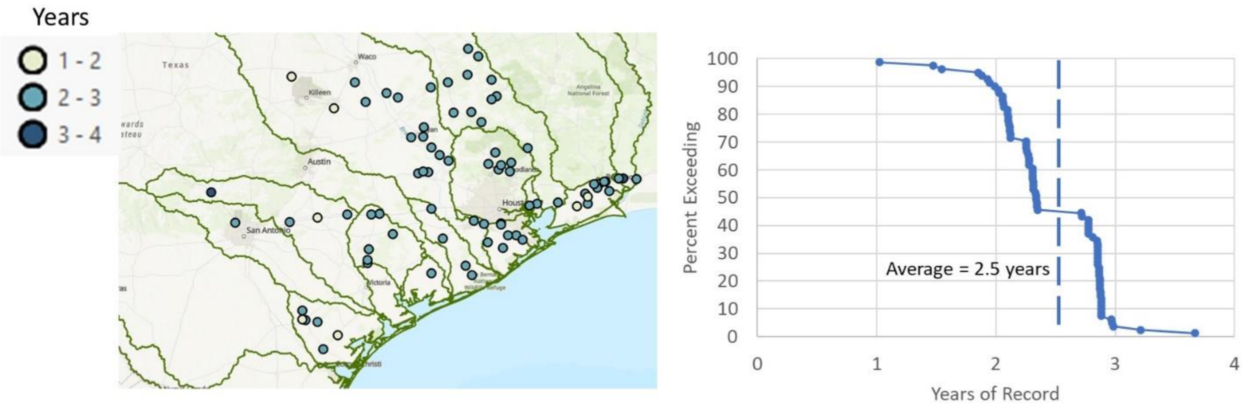


Figure 12 Length of measured record at the RQ-30 sites

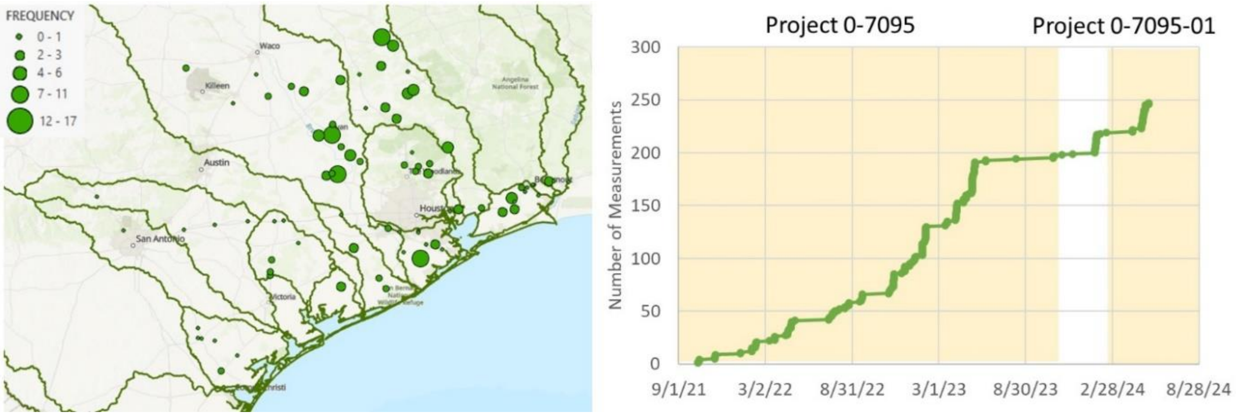


Figure 13 Distribution of ADCP measurements in space and time

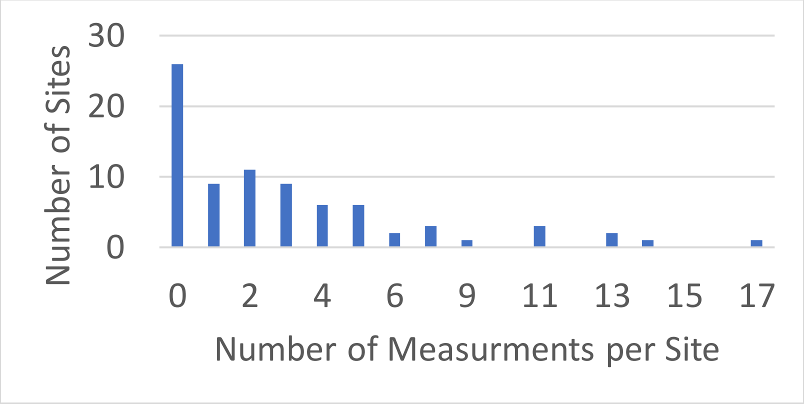


Figure 14 Number of ADCP measurements per site

3.1.1. Hurricane Beryl

A significant highlight of the project to date was the occurrence of Hurricane Beryl on July 7-10, 2024, which provided the first major stress test for the RQ-30 gauge network. The hurricane's impact was widespread, affecting gauges from the coast all the way to northeast Texas, including our furthest gauge installation in Palestine, Texas. Our crews responded to the flooding within six hours after the eye of the hurricane passed. Over a three-day campaign, 15 flood measurements were conducted, despite the considerable challenges posed by widespread flooding, road closures, and the lack of hotel vacancies. Additionally, several USGS team members, particularly those based in Houston, faced significant obstacles such as personal electricity outages, yet they prioritized the critical task of gathering flood data, underscoring their dedication to data collection efforts.

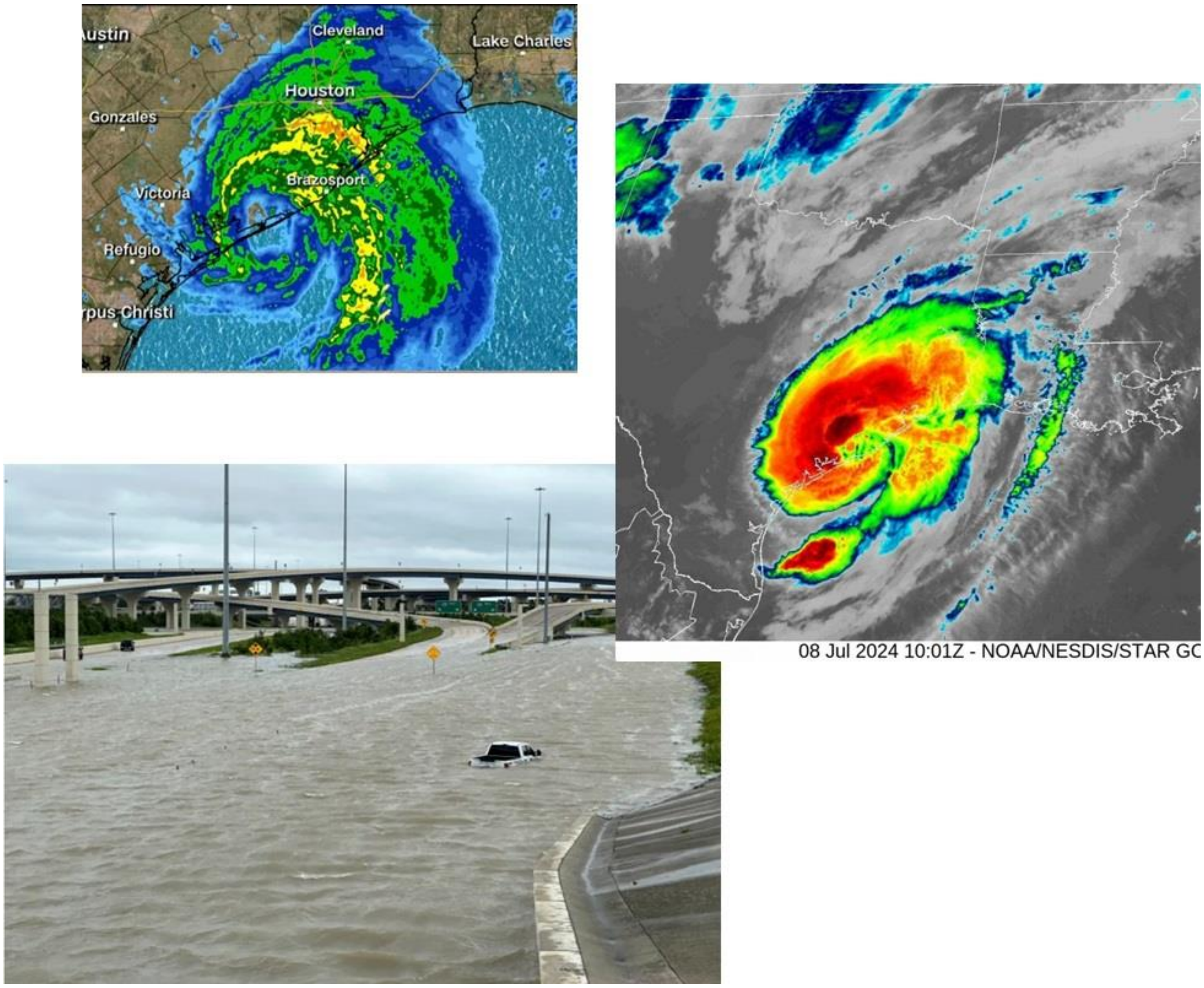


Figure 15 Images from Hurricane Beryl

The data collected during this event has been invaluable, not only for flood analysis but also for identifying potential issues with our current systems. One key challenge observed was related to data collection during windy conditions, which can have a notable impact on velocity sensor data collection. The RQ-30 gauges measure surface point velocities, which are then converted into average velocities for the entire channel using a “k-factor.” This k-factor is sensitive to changes in point velocities, and during the hurricane, strong winds caused temporary spikes or “noise” in the data. These fluctuations can introduce biases in the computed discharge, depending on the direction of the wind relative to the flow. Although these anomalies subsided as the storm passed, they highlighted the need for further analysis and potential adjustments to account for such conditions.

Another significant issue identified was with the telemetry systems in place. As power outages occurred during the hurricane, several cell towers had limited functionality, leading to high congestion on the remaining operational towers. This resulted in slowed data transmission and, in two cases, a complete halt in data reporting from the gauges until normal cell tower operations resumed. This interruption in data flow is particularly concerning during critical events like hurricanes, where real-time data is essential for decision-making. A potential solution to this problem is to switch to a more appropriate cellular service such as the “FirstNet” network offered by AT&T. FirstNet prioritizes signals for first responders during emergencies, which could significantly improve the reliability of data transmission during future disasters. The consideration of this network transition is now a key focus to enhance the resilience of the gauge network in response to similar events in the future.

3.2. Synthetic Rating Curves

The USGS has been developing a statistics-based synthetic rating curve for an ungauged sites using a regional regression equation to estimate direct discharge based on selected predictor variables that can be acquired with a reasonable level of effort. The regional regression equation effort stems from the existing equation developed for Texas by Asquith and others (2013)[1] utilizing USGS field measurement records. The equation is based on a Generalized Additive regression Model (GAM), which allows linear and smoothing functions for non-linear terms. The method is effective for ensuring a good model fit for complex data.

An updated but still preliminary synthetic rating curve equation for FEMA Region 6 is presented in Eq.(3.1):

$$\log(\boldsymbol{Q}) = -0.3509 + 1.281\log(\boldsymbol{A}) - 0.2346\log(\boldsymbol{B}) + f_5(\boldsymbol{X},\boldsymbol{Y}) + f_6(\boldsymbol{P}) + \mathbf{HLRcoeff} \quad (3.1)$$

where log = base-10 logarithm, $\boldsymbol{Q}$ = discharge in m^3/s, $\boldsymbol{A}$ = cross-sectional flow area in m^2, $\boldsymbol{B}$ = top width in m, $\boldsymbol{X}$ and $\boldsymbol{Y}$ = Albers easting and northing distances respectively in m, $\boldsymbol{P}$ = mean annual precipitation in mm, and f_5 and f_6 are smoothing functions of the location and precipitation predictor variables, **HLRcoeff** is a Hydrologic Landscape Region coefficient.

As shown in Figure 16, predictor variables **A** and **B** are the area and top width of the channel cross-section, which are functions of gauge height at each site thus the equation can be used to develop a synthetic stage-discharge rating curve.

---

[1] Asquith, W.H., Herrmann, G.R., and Cleveland, T.G., 2013, Generalized Additive Regression Models of Discharge and Mean Velocity Associated with Direct-Runoff Conditions in Texas: Utility of the U.S. Geological Survey Discharge Measurement Database, Journal of Hydrologic Engineering, Vol. 18, Issue 10, https://doi.org/10.1061/(ASCE)HE.1943-5584.0000635.

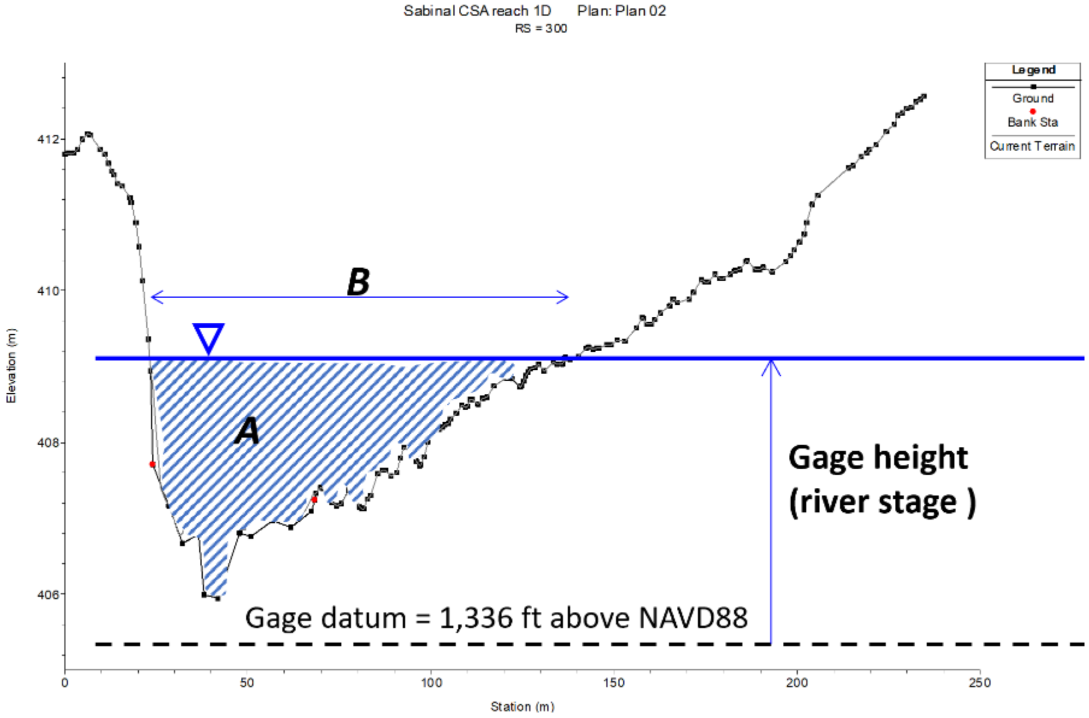
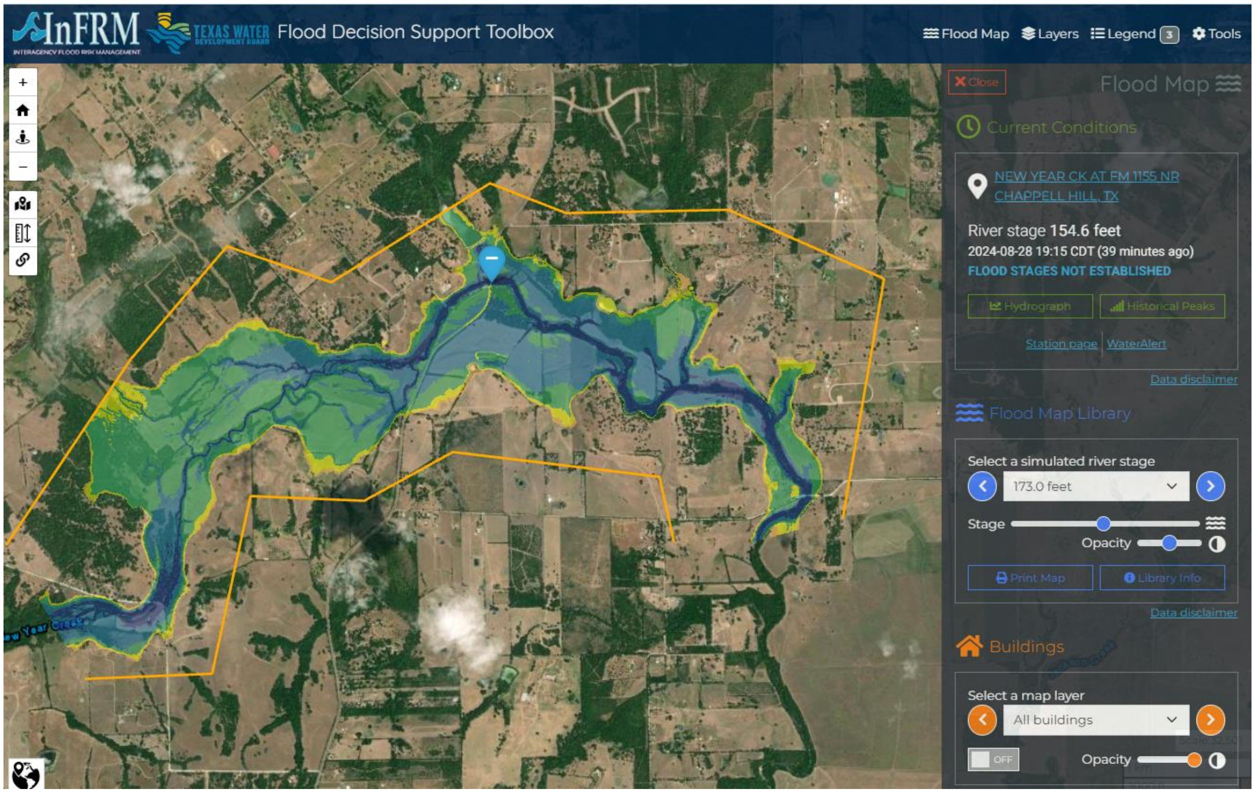


Figure 16 Stream cross-section used in constructing a synthetic rating curve.

Conventional rating curves, a cornerstone of accurate flood modeling and often a calibration target for flood-inundation models, can require years of accumulated discharge measurements for development. The proposed method is a viable alternative to estimate discharge for newly installed stream gauges or ungauged locations along a stream.

3.3. Flood Decision Support Toolbox Sites

The Flood Decision Support Toolbox (FDST) https://webapps.usgs.gov/infrm/fdst/ is a web-based flood information system developed by the US Geological Survey, in collaboration with other federal and state partners in an organization called InFRM (Interagency Flood Risk Management). It provides very detailed forecast flood maps around USGS gauge sites, as illustrated in Figure 17. The extent of inundation is related to the forecast discharge, converted to a water surface elevation using either an existing rating curve at the gauge site, or a synthetic rating curve, developed as described in Section 3.2.



NEW YEAR CK AT FM 1155 NR CHAPPELL HILL, TX

River stage **154.6 feet**

2024-08-28 19:15 CDT (39 minutes ago)

FLOOD STAGES NOT ESTABLISHED

Select a simulated river stage: 173.0 feet

Stage

Opacity

Select a map layer: All buildings

OFF

Opacity

Figure 17 FDST Map for New Year Creek at FM 1155 near Chappell Hill, TX.

The InFRM group also serves as the repository for Base Level Engineering flood models, developed using 1D or 2D versions of HEC-RAS, as shown in Figure 18. There are about 200 HUC8 watersheds in Texas. Of these, about 40 have Base Level Engineering with 1D HEC-RAS models and the remainder with 2D HEC-RAS models. All the new Base Level Engineering studies are being done with 2D HEC-RAS models.

There are 80 RQ-30 gauges in the FAST network. Of these, 41 sites have 1D BLE models and 39 sites have 2D BLE models. Currently, 35 of the 41 sites with 1D BLE models have been evaluated for inclusion into the Flood Decision Support Toolbox (FDST). Of these 41 sites, three have been completed and uploaded to the FDST, 26 have been completed or are in the review process, six are not a good fit for map library creation, and the last six are in progress and expected to be finished by the end of the fiscal year. Of the 39 sites with two-dimensional (2D) models: 14 do not have a Base Level Engineering model (BLE) available for download yet; 11 are coastally influenced and are pending model guidance; three are completed or are in the review process; one is not a good fit for map library creation; the other ten are in progress and expected to be completed by the end of the fiscal year.

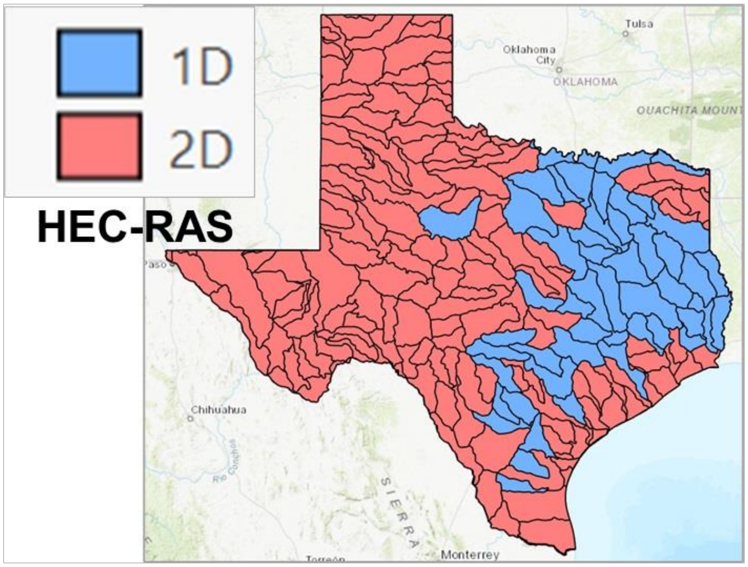


Figure 18 Base Level Engineering coverage of Texas with 1D and 2D HEC-RAS models of HUC8 watersheds

Because the FDST requires rating curves for independent validation and newer sites such as the RQ-30 gauges typically do not have full-range rating curves available for several years, synthetic rating curves are being developed and used to calculate the library Root Mean Square Error (RMSE) for these sites. FDST guidance is that RMSE values are acceptable if they are under 5 feet (ft), with anything less than 3 ft considered ideal. The RMSE ranges from 0.3 feet – 3.6 feet, with an average of 1.8 feet for the sites currently modeled. As shown in Figure 19, Nelson Creek at FM 247 nr Huntsville, TX gauge (08065925) has shown the smallest RMSE so far, with a value of 0.3 ft.

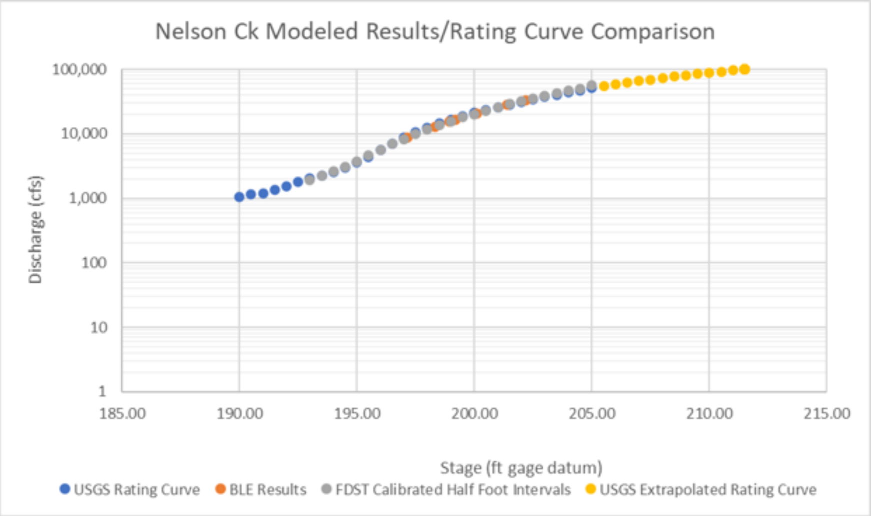


Figure 19 Chart showing discharge (cfs) – stage (ft) relationships of U.S. Geological Survey, Base Level Engineering model, and Flood Decision Support Toolbox streamflow data at the Nelson Creek at FM 247 nr Huntsville, TX gauge (08065925).

The gauge with the largest discrepancy so far is Walnut Creek at FM 46 nr Bremond, TX (08108710), with an RMSE of 3.6 feet (Figure 20)

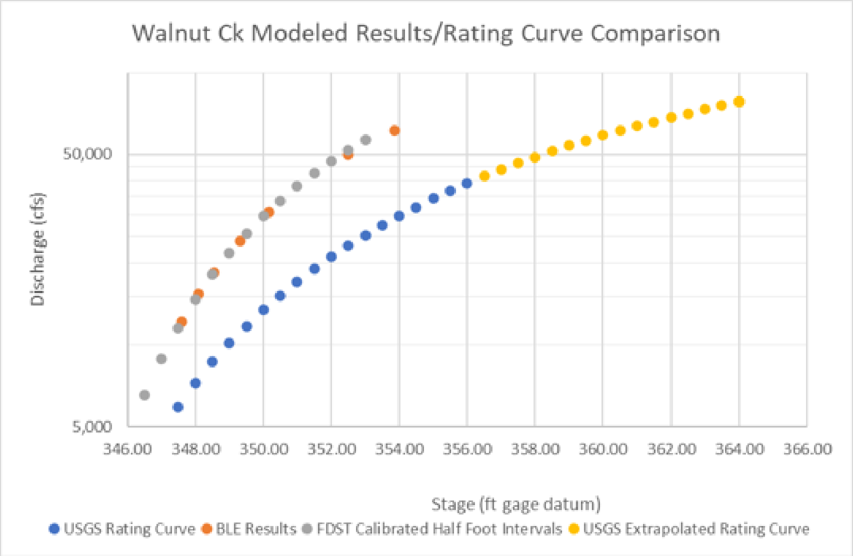


Figure 20 Chart showing discharge (cfs) – stage (ft) relationships of U.S. Geological Survey, Base Level engineering model, and Flood Decision Support Toolbox streamflow data at the Walnut Creek at FM 46 nr Bremond, TX gauge (08108710).

No sites have failed the independent validation checks based on synthetic rating curve comparison. The few sites that have been identified as not good fits for inclusion into the FDST have either been on the edge of the model or in a location that is not conducive to modeling. For example, Cow Bayou at FM 2643 nr Mooreville, TX (08097000) is at the upstream edge of the model boundary, as shown in Figure 21.

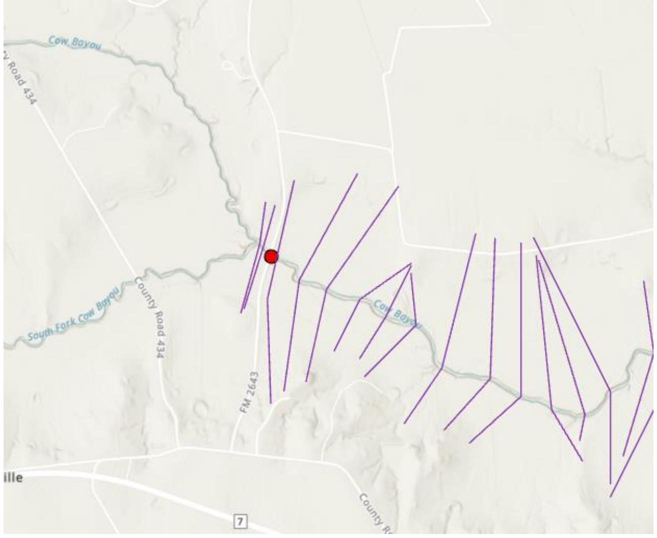


Figure 21 Map showing the location of the Cow Bayou at FM 2643 nr Mooreville, TX gauge (08097000) relative to the Base Level Engineering cross-section extent.

Library creation from 2D models is much more complex than 1D modeling, so these are taking longer to complete. 2D models were recently started and don't have any rating curve comparisons yet, but we plan to have as many sites as possible completed before the end of the fiscal year. Gauges that are coastally influenced are on pause for now as we wait on modeling guidance. These sites are expected to be affected by both riverine flooding and coastal storm surge, so our current modeling practices do not apply to all expected scenarios at these sites.

3.4. Hydrodynamic Modeling

Since initiation in June 2024, this subproject has focused on three areas: (1) back and forth communication and data checking to ensure the accuracy and completeness of local surveys to be collected at ten of the 80 RQ30 sites; (2) addressing modeling uncertainty with regard to boundary conditions; and (3) initial modeling to develop workflows and explore the data. The survey data in (1) is intended to complement the existing lidar with detailed information near and underneath bridges at the RQ-30 sites, as required for accurate modeling of the relationships between sensor information and model-predicted water-surface elevation, velocity, discharge and road/floodplain inundation.

As of this writing, one detailed survey has been delivered at the New Year Creek (NYC) site. Early model results and data inspection suggested some or all of that survey had elevation errors, especially in regard to missing or incorrect culvert elevations. Initially, this appeared to be a coordinate system error, which did exist, but did not explain the magnitude of the observed errors. These errors will be fixed; this data checking process is necessary for ensuring the accuracy of the remaining surveys.

Recent work on tasks (2) and (3) relate to the fundamental concept of this subproject, which is to use the sensor data and a 2-dimensional (and, in some cases, three-dimensional) computational flow models to increase the precision of prediction for discharge and inundation (with specific focus on road inundation). Typically, 2D models require accurate ground-surface and channel bathymetry information along with boundary conditions on discharge at the upstream end of the reach and water-surface elevation at the downstream end of the reach, along with roughness estimates. These requirements do not fit our data.

We have (or will have) accurate ground surface and bathymetric data in the sensor reaches, but the only other information is mid-reach sensor data and engineering judgement about potential roughness values for the channel and floodplain. Thinking about uncertainty, the first issue is the downstream boundary condition on elevation. If we set the downstream elevation in the model, the results are strongly altered by that assumption, such that we could easily match the sensor elevation by adjusting the elevation at the downstream end of the reach such that the model prediction at the sensor is perfect. This defeats the purpose of the modeling, as it means the data is being used to predict the data.

The most common treatment for this problem is to set a condition other than elevation at the downstream end of the model reach (such as Froude number equals 1, or uniform flow, etc) and then make the reach long enough that the prediction in the region of interest (in this case, the sensor) is far enough upstream that the downstream assumption has no effect. To investigate this, we ran several models with a free-overflow downstream condition at the New Year Creek site using our best judgement for roughness settings and varying the reach length over a large range. Figure 22 shows the shortest and longest reach lengths considered. For each model run, the time period of the model was set to ensure that the water-surface elevation predicted at the sensor converged. The result is shown in Figure 23, where we have nondimensionalized downstream distance by the width of the active stream channel (30m).

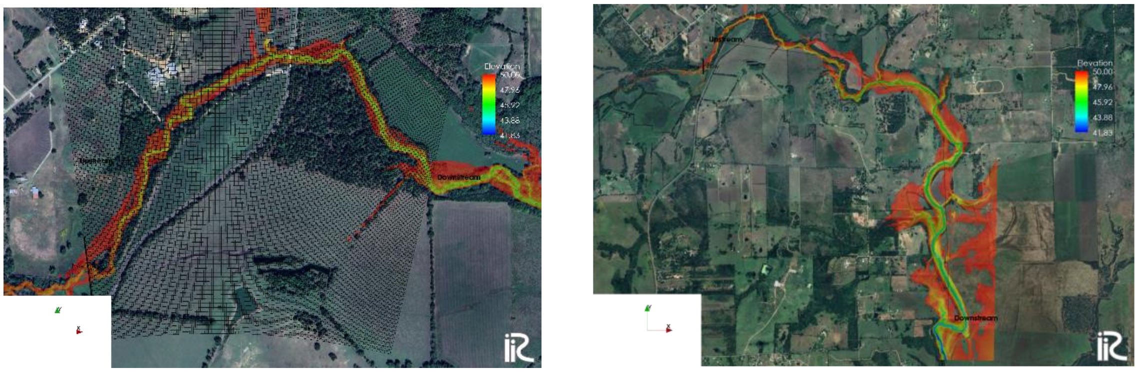


Figure 22 Shortest (left) and longest (right) reach lengths for evaluating boundary condition.

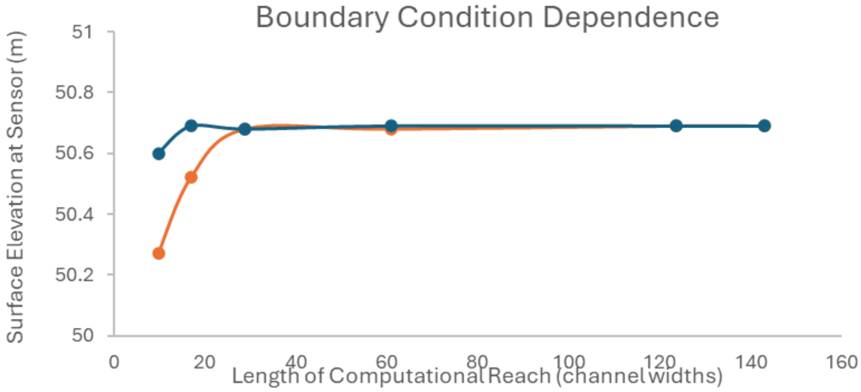


Figure 23 Dependence of Water Surface Elevation prediction at the sensor on the downstream boundary condition. The orange line is standard free overflow, the blue line is uniform flow with specified slope.

The orange line in Figure 23 suggests that accuracy at the sensor requires a downstream length of at least 60 channel widths to preserve a sub-2cm error (consistent with Real Time Kinematic survey data). Adding to that the upstream channel needed to accurately treat the road overtopping suggests reach lengths of 100 channel widths. This is long from a computational standpoint. We programmed several additional lower boundary conditions to circumvent this issue and found that the best choice was a uniform flow condition with user-specified slope. The result is not sensitive to the choice of slope (provided the chosen value is around half to double the actual channel slope) and the domain requirements are shortened to about 30 channel widths as seen in the blue line in Figure 23, representing a huge computational saving as well as predictions at the sensor that are essentially independent of the downstream boundary condition, as desired. This is a good solution and has now been integrated into the iRIC modeling system.

Developing the workflow for this subproject has been time-consuming and required hundreds of model runs and testing of various methods. The method is easiest to explain in terms of the data. Figure 24 shows a raw graph of sensor water-surface elevation and velocity for the 3-day flood of March 22, 2022 – it's quite messy. However, after applying a simple averaging filter, the data looks pretty good, as shown in Figure 24b and 24c. The data shows typical hysteresis associated with unsteadiness, with rapidly increasing velocity followed by an increase in elevation as the flood discharge comes up, producing the well-known counter-clockwise hysteresis (see Figure 25).

Unsteadiness is not the only source of hysteresis, as roughness distribution and changes, sediment transport, bank failure, floodplain storage, and so forth can also produce this effect. The modeling system employed here can handle these other effects, but we start by assuming the simplest approach, which is that unsteadiness is the major source of hysteresis. The workflow for that simplest approach is to run predetermined hydrographs to build a library of instantaneous flows with coupled values of discharge and both surface velocity and elevation at the RQ30 sensor location. Since these realizations are from the model results, they include hysteresis due to unsteadiness, floodplain storage, and spatial (but not temporal) distributions of roughness. Bed mobility, sediment transport, and channel changes are neglected (at least for now).

Although the bathy/topo is incorrect due to the survey issues, Figure 26 shows the results from several triangular hydrographs, with increasing hysteresis corresponding to increased up and down ramp rates. For each value of velocity and water surface elevation in the diagram (taken from the model at the sensor location), the discharge and the road inundation, culvert flow, etc., are given by the model. Turning this around, each velocity – water surface elevation pair from the sensor can be related to discharge, etc., using this library. In the simplest version, this library gives a surface of Q values as a function of the sensor data, but in more complex realizations, the "surface" may be 3- or 4- dimensional, including, for example, velocity and water surface elevation ramping rates rather than just their values, or it could form the database for "teaching" a machine learning predictor with a heavy dose of physics in the mix.

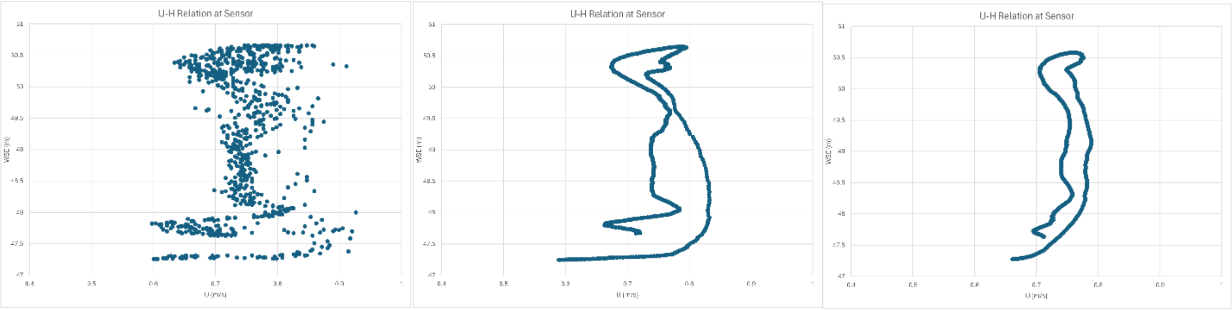
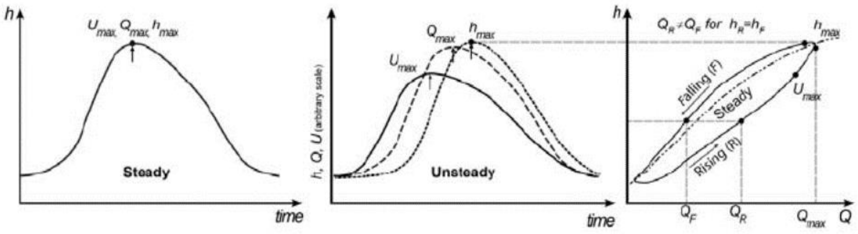


Figure 24 Raw data, lightly smoothed data, and more heavily smoothed RQ-30 data left to right.



(a) (b) (c)

Figure 25 Adapted from Graf and Qu (2004)[2]

Figure 26 Surface velocity and elevation predicted at the NYC RQ-30 sensor for triangular hydrographs with peak discharges of 100m3/s and lengths of 4 days (green), 1 day (blue) and 0.5 day (purple).

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[2] Graf, W. H., and Qu, Z. (2004). Flood hydrographs in open channels. Proceedings of the Institute of Civil Engineers Water Management, 157, 45–52

Thus, as soon as corrected survey data is available at this and other sites, the next step is to rebuild the libraries of u-h-q with model runs, initially using triangular hydrographs, and to use those libraries with time series of sensor data to evaluate discharge, road overtopping, flow patterns, etc. Although simple, this workflow presents huge computational advantages over a predictor-corrector type method, where we feed the sensor data into the model and iterate to find the best choice of discharge at each time step.

4. Flood Transportation Geodatabase

4.1. Flood Geodatabase Design Principles

The Flood Transportation Geodatabase (FTG) is an extension of the Arc Hydro geodatabase design focused on flood forecasting of transportation infrastructure. It is a template (foundational) geodatabase design that is expected to be extended with specific requirements for a project. As such, it does not contain specific project implementation details, but rather only the key elements that provide basic link between categories of data related to flood transportation forecasting:

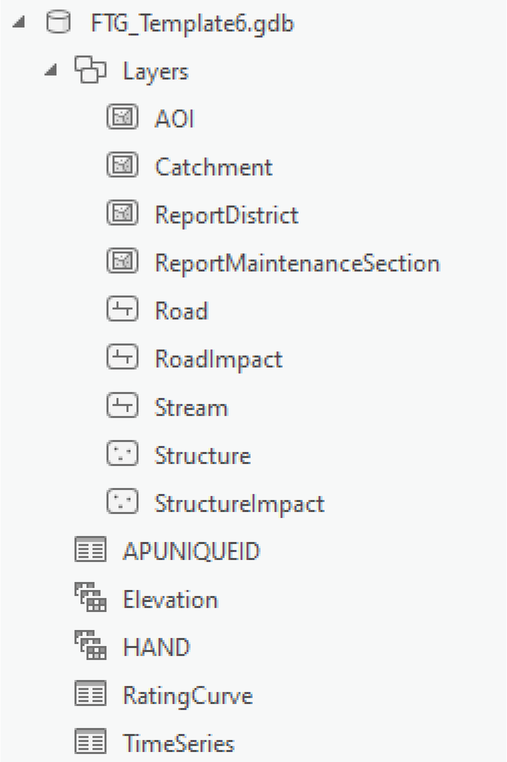
- **Topography and hydrography.** Elevation and stream definitions used to map out streams used in forecasting and their characteristics and establishing elevations at which transportation infrastructure are affected by flooding.
- **Hydrology/hydraulics/forecasting.** Definition of rating curves (stage-discharge curves) that are used to convert flows from flow forecasting into stages that are defining impacted infrastructure.
- **Critical infrastructure.** Transportation infrastructure of interest. Two types are identified:
    - Point features that can include bridges, culverts, low water crossings, or any other infrastructure type that can be represented as a point from flood forecasting point of view.
    - Linear features that can include roads, railroads, or any other infrastructure type that can be represented as a line from flood forecasting point of view.
- **Reporting elements.** Polygonal units used to report flooding for. This can include transportation districts, maintenance district, political boundaries, etc.

As a template, the role of the Flood Transportation Geodatabase is to identify data modeling patterns that can be applied in a consistent way for specific project applications, not to represent all possible data modeling scenarios. The patterns apply to definition of attributes, unique identifiers, layer types, relationships between the layers, and quality control aspects of these elements. Esri’s geodatabases provide rich data modeling capabilities and are the foundation of the Flood Transportation Geodatabase. In addition, the Flood Transportation Geodatabase is an extension of Arc Hydro data model and leverages its key data modeling patterns.

Since the Flood Transportation Geodatabase is fundamentally an analytical geodatabase, it is important that the foundational data are in systematic, projected coordinate system that can support efficient development and quality control of participating data. Ideally, horizontal and vertical units should be the same to avoid any unit conversion problems during data development and quality control. If necessary, explicit units that are different than units of base data can be captured explicitly within data structures.

Once the data are implemented for a specific project, they can then be transformed in other projections to support operational aspect of transportation infrastructure flood forecasting.

Figure 27 presents the template Flood Transportation Geodatabase structure.



- FTG_Template6.gdb
  - Layers
    - AOI
    - Catchment
    - ReportDistrict
    - ReportMaintenanceSection
    - Road
    - RoadImpact
    - Stream
    - Structure
    - StructureImpact
  - APUNIQUEID
  - Elevation
  - HAND
  - RatingCurve
  - TimeSeries

Figure 27 Flood Transportation Geodatabase

4.2. Flood Geodatabase Components

The Flood Transportation Geodatabase has the following components.

1. Topography: Elevation model is represented as a mosaic dataset. In addition, or alternatively, a height above nearest drainage (HAND) surface can be represented as well.

- Elevation mosaic dataset.
- HAND mosaic dataset.

2. Hydrography: Hydrography is represented by the streams and catchments (drainage areas draining to stream segments). Streams are hydrographic features at which flow forecasting is performed, while catchments define the zone of influence for each stream.

- Catchment polygon feature class.
- Stream line feature class.

3. Hydrology/hydraulics/forecasting: Rating curves describe stage-discharge for each stream and tie flow forecast to the stage forecast for each reach. A TimeSeries table contains the time series of flow and stage forecasts for each forecast period and stream reach.

- RatingCurve table.
- TimeSeries table.

4. Critical Infrastructure: Transportation infrastructure consisting of lines and points of interest.

- Road line feature class.
- Structure point feature class.

5. Reporting Elements: There are two types of reporting elements.

- Base elements. Polygonal units defining areas used to report flooding for. These elements are definitional elements and do not change over time. In the Flood Transportation Geodatabase, two of these elements are defined, but there can be more depending on the specific implementation requirements.
    - ReportDistrict.
    - ReportMaintenanceSection.
- Dynamic elements. These elements match infrastructure elements and contain these infrastructure elements that are affected by flooding over the forecast period.
    - RoadImpact.
    - StructureImpact.

4.2.1. Linking the Components

Data elements in the Flood Transportation Geodatabase are related to each other using spatial and attribute relationships. Each feature class has a primary (unique) identifier that can be used to indicate how one feature is related to another. For example, StreamID can be found in several Flood Transportation Geodatabase data elements:

- Stream feature class – unique identifier.

- Time series table – indicates stream rating curve.
- Structure – indicates stream that is affecting the structure.
- Road – indicates stream that affects the road segment.

Structure and road feature classes have several internal and external identifiers:

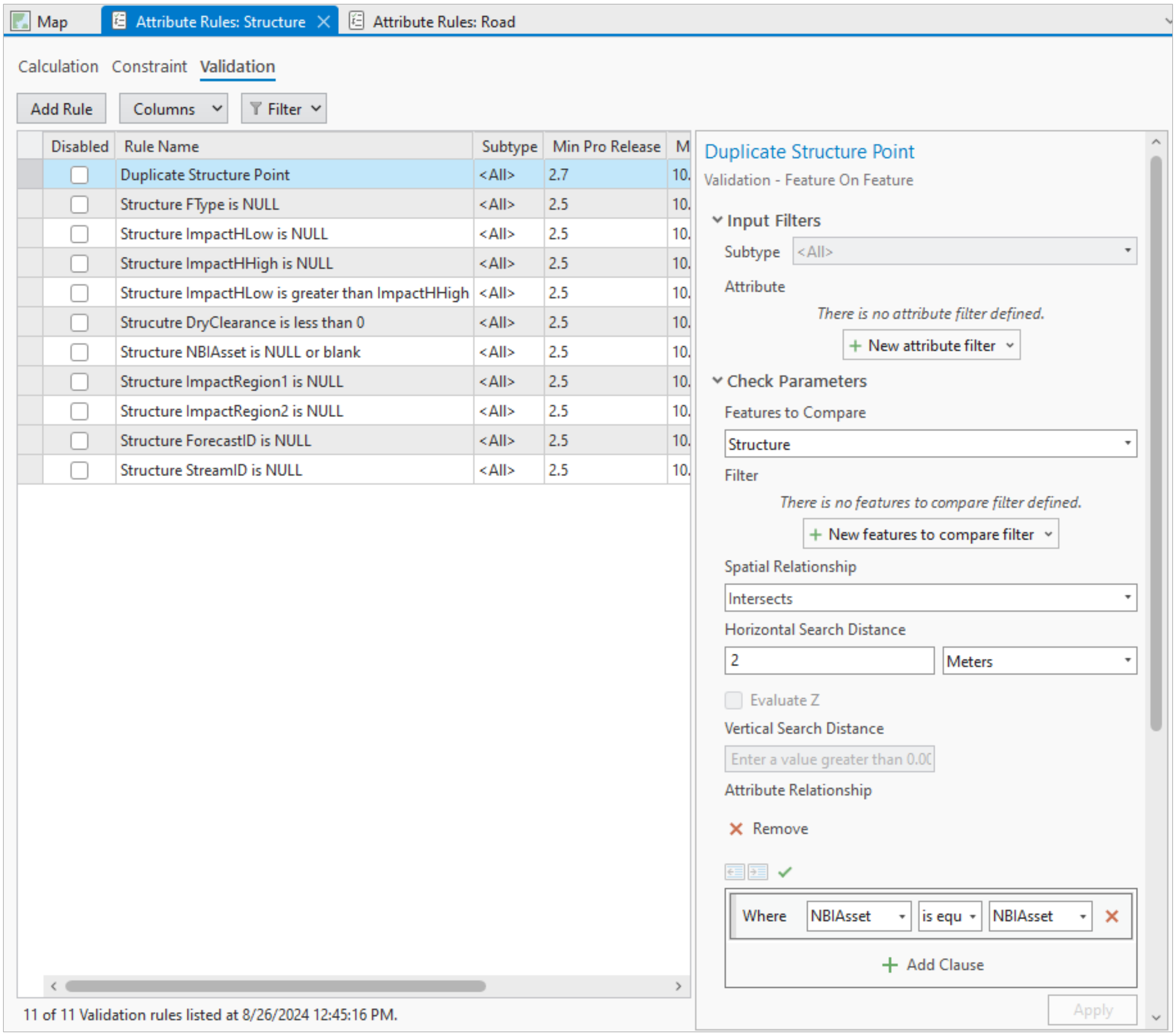
- HydroID (optional) – internal unique identifier.
- HydroCode (optional) – external unique identifier to be used for linking with other databases describing the same feature (e.g. National Bridge Inventory or AssetWise databases).
- StreamID – identifier for the stream feature influencing ("flooding") the structure.
- ForecastID – identifier for the flow forecasting system forecasting the flow at the stream influencing the structure.
- ImpactRegion1 – identifier of the first reporting unit.
- ImpactRegion2 – identifier of the second reporting unit.

4.3. Quality Assurance / Quality Control

To have confidence in the quality of the data, it is best to have quality assurance and quality control in place. One of the places this can be implemented is part of the database design. The ArcGIS geodatabase has features that help build integrity in the data. Besides defining proper field types and assigning domains, additional rules can be configured to automatically populate fields, prevent invalid edits, and perform quality data review of existing features. Attribute Rules are advanced data design capabilities that enhance the editing experience and improve data integrity.

Once the basic geodatabase schema is established, Attribute Rules are configured at the feature or object class level and stored directly in the geodatabase. There are two methods of creating these Attribute Rules, using Arcade and/or ArcGIS Data Reviewer extension. Arcade is a lightweight expression language and does require some scripting knowledge. ArcGIS Data Reviewer provides a library of data validation checks that are GUI-based and easily configurable.

Different types of validation rules are possible, geometry-, attribute-, or spatially-based. Figure 28 depicts Data Reviewer's Ready-To-Use rules that are configured on the Structure feature class. The first rule in the list is looking for duplicate Structure features within a user-defined tolerance that share the same NBIAsset identifier. The remaining rules in the list are validating if the values for those attributes are correctly populated.



Disabled	Rule Name	Subtype	Min Pro Release	M
☐	Duplicate Structure Point	<All>	2.7	10.
☐	Structure FType is NULL	<All>	2.5	10.
☐	Structure ImpactHLow is NULL	<All>	2.5	10.
☐	Structure ImpactHHigh is NULL	<All>	2.5	10.
☐	Structure ImpactHLow is greater than ImpactHHigh	<All>	2.5	10.
☐	Strucutre DryClearance is less than 0	<All>	2.5	10.
☐	Structure NBIAsset is NULL or blank	<All>	2.5	10.
☐	Structure ImpactRegion1 is NULL	<All>	2.5	10.
☐	Structure ImpactRegion2 is NULL	<All>	2.5	10.
☐	Structure ForecastID is NULL	<All>	2.5	10.
☐	Structure StreamID is NULL	<All>	2.5	10.

11 of 11 Validation rules listed at 8/26/2024 12:45:16 PM.

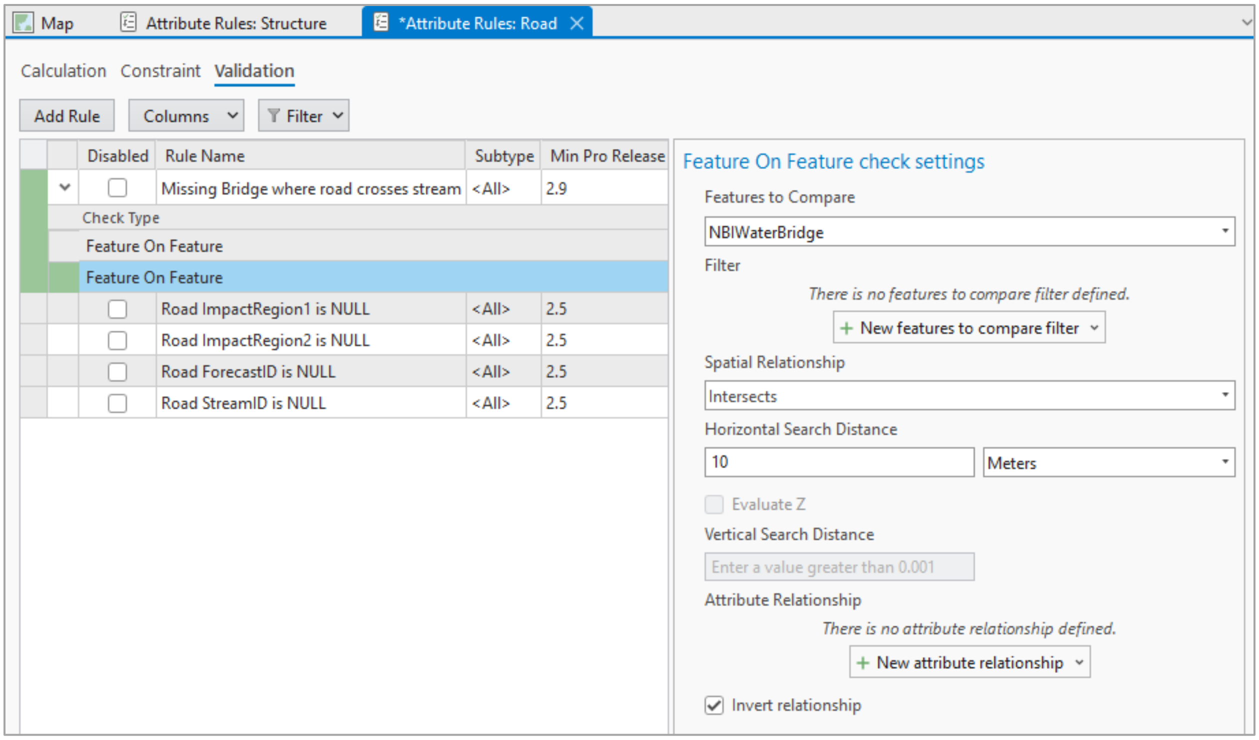
Duplicate Structure Point
Validation - Feature On Feature

Input Filters
Subtype: <All>
Attribute
There is no attribute filter defined.
+ New attribute filter

Check Parameters
Features to Compare: Structure
Filter
There is no features to compare filter defined.
+ New features to compare filter
Spatial Relationship: Intersects
Horizontal Search Distance: 2 Meters
☐ Evaluate Z
Vertical Search Distance: Enter a value greater than 0.0(
Attribute Relationship
✕ Remove
Where NBIAsset is equ NBIAsset ✕
+ Add Clause

Figure 28 Checking rule for the Structure feature class

More complex rules can be set to validate data across multiple feature classes. In Figure 29 for the Road feature class, a rule is set to identify roads that crosses a stream and does not have a structure feature within 10 meters of the road feature.



Disabled	Rule Name	Subtype	Min Pro Release
☐	Missing Bridge where road crosses stream	<All>	2.9
Check Type			
Feature On Feature			
Feature On Feature			
☐	Road ImpactRegion1 is NULL	<All>	2.5
☐	Road ImpactRegion2 is NULL	<All>	2.5
☐	Road ForecastID is NULL	<All>	2.5
☐	Road StreamID is NULL	<All>	2.5

Feature On Feature check settings

Features to Compare: NBIWaterBridge

Filter: *There is no features to compare filter defined.*

Spatial Relationship: Intersects

Horizontal Search Distance: 10 Meters

☐ Evaluate Z

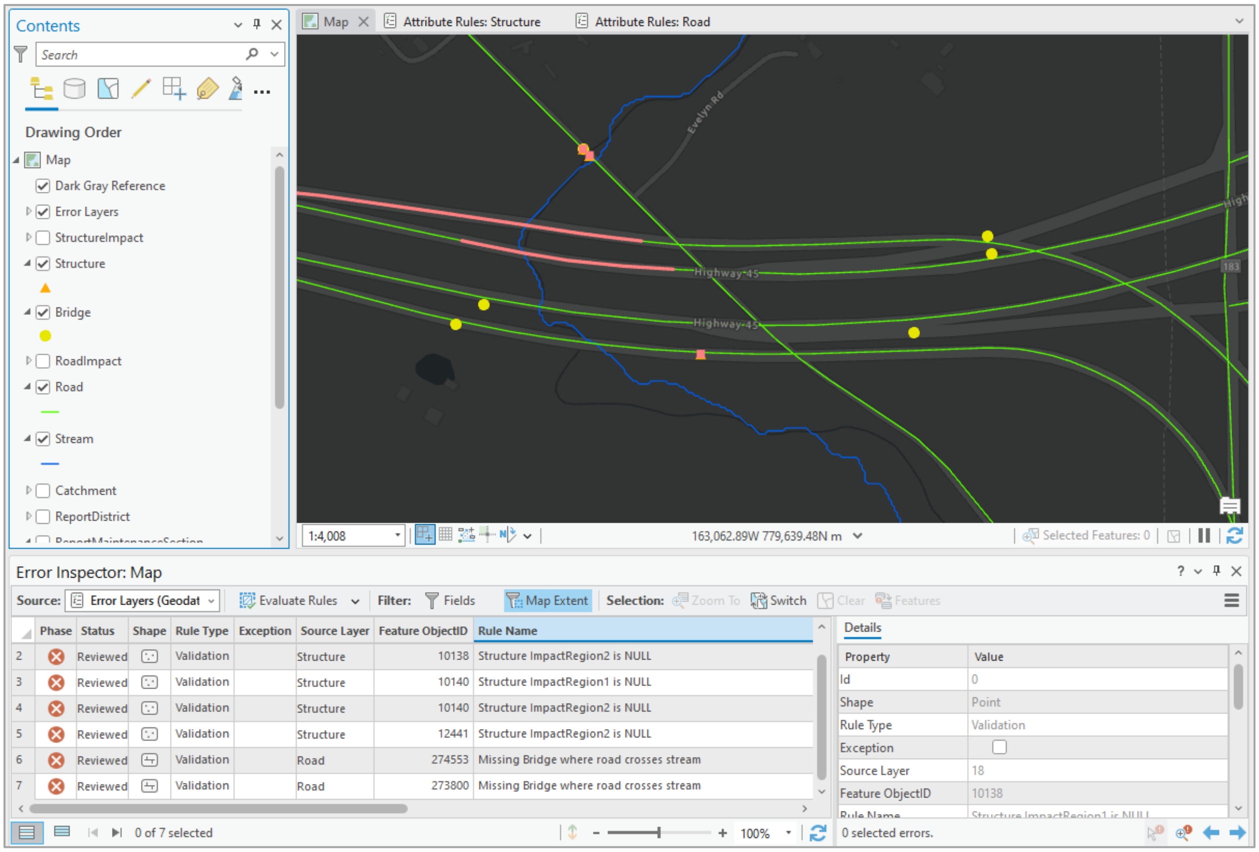
Vertical Search Distance: Enter a value greater than 0.001

Attribute Relationship: *There is no attribute relationship defined.*

☑ Invert relationship

Figure 29 Checking rule for the Road feature class

Once the validation rules are set, they can be evaluated at the map's visible extent or data's full extent level. The results are accessible using the Error Inspector and can be used to navigate to the feature in error and track the error. Note that each error is stored as an error feature in the error layers.



	Phase	Status	Shape	Rule Type	Exception	Source Layer	Feature ObjectID	Rule Name
2	☒	Reviewed		Validation		Structure	10138	Structure ImpactRegion2 is NULL
3	☒	Reviewed		Validation		Structure	10140	Structure ImpactRegion1 is NULL
4	☒	Reviewed		Validation		Structure	10140	Structure ImpactRegion2 is NULL
5	☒	Reviewed		Validation		Structure	12441	Structure ImpactRegion2 is NULL
6	☒	Reviewed		Validation		Road	274553	Missing Bridge where road crosses stream
7	☒	Reviewed		Validation		Road	273800	Missing Bridge where road crosses stream

0 of 7 selected

Details

Property	Value
Id	0
Shape	Point
Rule Type	Validation
Exception	☐
Source Layer	18
Feature ObjectID	10138
Rule Name	Structure ImpactRegion1 is NULL

0 selected errors.

Figure 30 The Data Inspector locates errors in the input data

4.4. Flood Transportation Geodatabase for the Austin District

The Flood Transportation Geodatabase template data model was used as a base for importing data developed for the TxDOT Austin District. Data were developed and provided by the CTR research team from sources shown in Table 1.

A step-by-step process including additional geoprocessing, field calculation, and data loading will be presented in a separate document. The resulting geodatabase is a good starting point for assessing provided flood transportation data consolidated into a standardized data model. This database can be used to review data quality issues that will improve implementation of the system state-wide.

It is expected that the Flood Transportation Geodatabase and its implementation to TxDOT data will evolve as the project progresses and additional reporting and data requirements are identified. The Flood Transportation Geodatabase data modeling foundations provide the flexibility and extensibility required for the model evolution.

Table 1 Flood Transportation Geodatabase for the Austin District

Data type	Source	FTG target layer	Comment
Hydrology	ORNL\Pin2Flood (UTFAST_Austin.gdb)	Catchment	
Reference	AGOL	HUC08AOI	Optional
Reference	FloodTransportGeodatabaseVer2.gdb\ Bridges\NBIBridges	NBIWaterBridge	Optional
Reporting unit	FloodTransportGeodatabaseVer2.gdb\ AdminBoundaries\Districts	ReportDistrict	
Reporting unit	FloodTransportGeodatabaseVer2.gdb\ AdminBoundaries\MaintenanceSections	ReportMaintenanceSection	
Static infrastructure	(RoadService) Library.gdb\Road	Road	
Forecast infrastructure	(RoadService) RoadFloodingHAND.gdb\Road	RoadImpact	
Hydrology	ORNL\Pin2Flood (UTFAST_Austin.gdb)	Stream	
Static infrastructure	(BridgeService) tx-bridge-geom.sqlite\ main.merged_output_3857	Structure	Bridges
Static infrastructure	FloodTransportGeodatabaseVer2.gdb\ Bridges\NBIBridges	Structure	Culverts
Static infrastructure	FloodTransportGeodatabaseVer3.gdb\ Bridges\LowWaterCrossings	Structure	Low water crossings
Forecast infrastructure	(BridgeService) BridgeMaxWarnings.gdb \Bridge	StructureImpact	
Reference	FloodTransportGeodatabaseVer2.gdb \AdminBoundaries\Texas	Texas	Optional
Hydrology	ORNL\Pin2Flood (UTFAST_Austin.gdb)	RatingCurve	
Forecast	AGOL	TimeSeries	NWM download

4.5. Flood Inundation Mapping

Flood inundation mapping (FIM) is essential for real-time flood prediction. At its core, FIM involves creating a series of maps that depict potential flood extents for various flow rates in a stream.

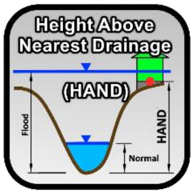
By performing hydraulic calculations for a range of flow rates in a stream, the elevation and depth of floodwaters can be determined. The flood boundaries for these scenarios can be precomputed and stored as maps before any flooding occurs. For each river, a series of these maps, corresponding to different flow rates, is organized into a "**flood raster stack**." This stack allows for the creation of a rating curve, which establishes the relationship between flow rate and flood elevation. Since this flow-elevation relationship is derived from simulated models rather than in-field observations, it is commonly referred to as a "**synthetic rating curve**."

Flood inundation maps (FIMs) are typically generated using hydraulic floodplain modeling software. There is a wide range of hydraulic calculation methodologies available to develop these maps, each with its own strengths and limitations. Some models are quicker and easier to deploy consistently across large areas, such as an entire state, but they may raise concerns about accuracy. On the other hand, more advanced methods may involve engineer-prepared models that offer greater accuracy but require a more significant investment of time and resources to extract FIMs.

For this project, there are three hydraulic methods that are being evaluated for the creation of FIMs. They are Height Above Nearest Drainage (HAND), RAS2FIM-1D and RAS2FIM-2D.

Figure 31 Hydraulic Methods for Flood Inundation Map (FIM) creation.

4.5.1. Height Above Nearest Drainage (HAND)



Height Above Nearest Drainage (HAND) is a FIM method used to estimate the elevation difference between a specific point on the landscape and the point where its drainage enters the nearest stream. HAND is calculated by determining the vertical distance from a location to the nearest point where water would naturally drain. HAND is quick and cheap to produce and is currently employed by the National Weather Service (NWS) for flood inundation mapping across the continental United States.

For Texas, FIM products including maps and synthetic rating curves were determined for every stream within the NWS network. The Texas data was determined from 3-meter resolution terrain. The 3-meter HAND flood maps and synthetic rating curves are the current (FY 2024) basis for the prediction of road and bridge flooding in FAST.

4.5.2. RAS2FIM-1D

Based on geospatially attributed one-dimensional HEC-RAS floodplain models, RAS2FIM-1D is designed to generate a FIM library. For a stream, a synthetic rating curve is generated based on ‘reach-averaged’ flood depths derived from the HEC-RAS simulations. The goal is to create a library of flood depth inundation grids paired with a corresponding rating curve, which can be integrated with the National Water Model’s discharge data and forecasts to produce real-time and predictive floodplain mapping using detailed HEC-RAS 1-D models.

As of August of 2024, the National Water Center of the NWS has used Base Level Engineering (BLE) submittals to convert 1D HEC-RAS models for twelve (12) HUC-8 watershed in Texas.

4.5.3. RAS2FIM-2D

The CTR team is developing software that allows for the creation of FIMs from available HEC-RAS 2D models. Many tens of millions of dollars have been spent by the Texas Water Development Board (TWDB) and FEMA with consulting engineers to create 2D models for over half of the State of Texas.

In Fiscal Year (FY) 2024, the University of Texas's contributions included the establishment of an open-source GitHub repository [https://github.com/andycarter-pe/ras2fim-2d] that generates flood depth and water surface elevation (WSEL) raster files for streams within a given 2D HEC-RAS model's limits. The code produces products keyed to the reference version of the NextGen National Hydrofabic.

The goal of RAS2FIM-2D is to utilize open-source technology to compute Flood Inundation Maps (FIMs) from 2D HEC-RAS models. Relative to both HAND and RAS2FIM 1D, this is a computationally more arduous process. Current code is written to leverage high-performance computing (HPC) resources. Without supercomputing facilities, like the Texas Advanced Computing Center (TACC), creating FIMs would be difficult to scale across the state in a timely manner.

For brevity, the current workflow of RAS2FIM-2D is provided in the flowing steps:

- Identify the streams within a provided 2D HEC-RAS model.
- Determine the upstream point for each stream and compute the peak flow rate.
- In the unsteady simulated model, emit a constant flow rate from each upstream point until the model stabilizes. Stability is defined as minimal change in the WSEL for the computational cells that become wet due to the constant flow.
- For each "stable" run for a given stream and constant flow rate, create flood depth and WSEL raster files in compliance with federal Interagency Flood Risk Management (InFRM) guidance.
- Simulate multiple flows, up to the peak flow rate, down a given reach to a "stable" condition. Pair the resulting raster products with these known flows to create a library of flood inundation maps and corresponding synthetic rating curves.

For example, as shown in Figure 32, a constant flow of 14,100 cubic feet per second (cfs) was simulated down the NextGen mainstem "1884413" for 29 hours. Flow path "wb-2410254" is one of many streams in the hydrofabric along this mainstem. Once the model stabilized, the wet cells closest to this flow path were identified. The water surface elevations for these computational cells were used to create depth and water surface elevation raster files based on detailed terrain data.

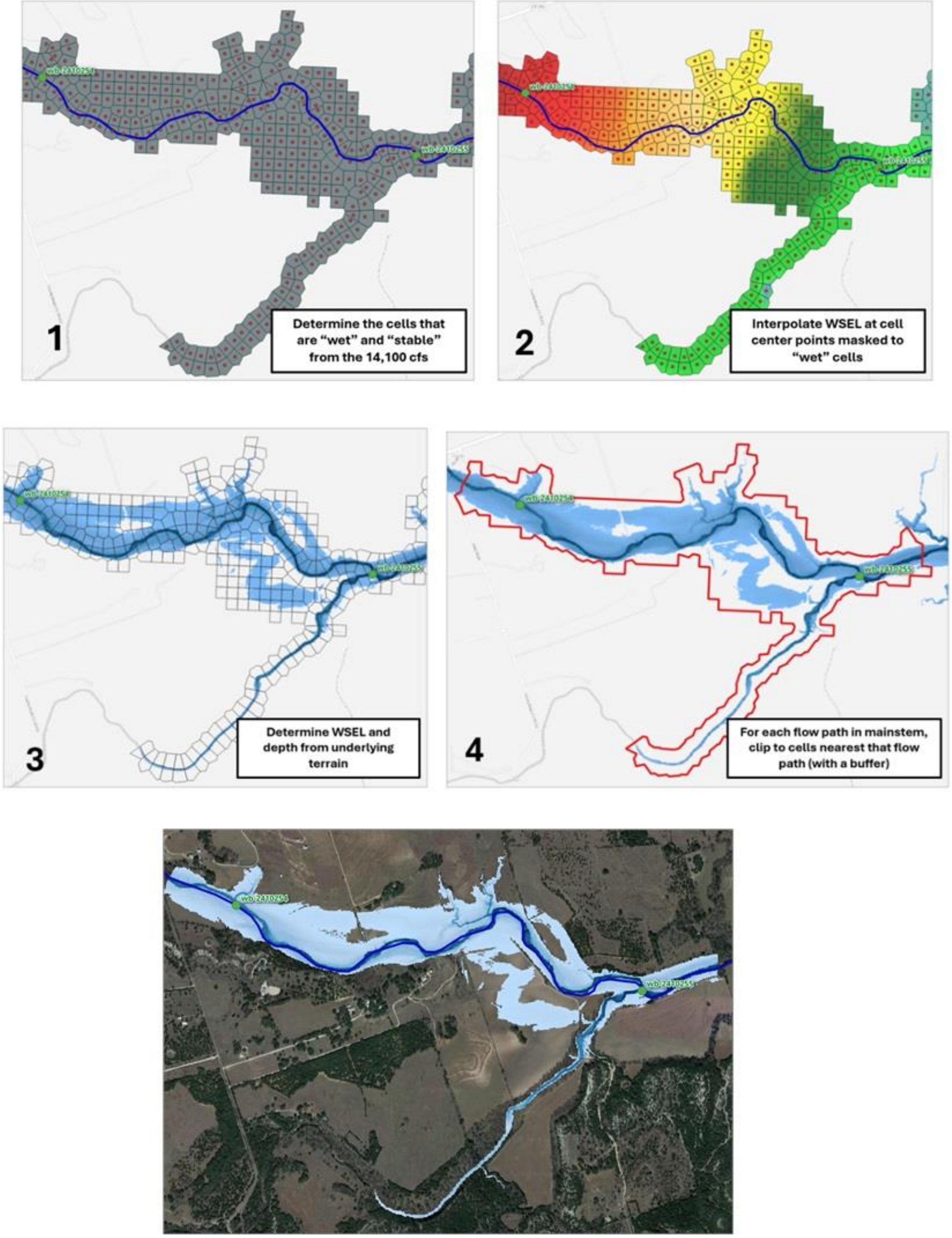


Figure 32 Creating a Flood Inundation Map using RAS2FIM-2D

The 2D simulations are believed to provide more accurate flood inundation mapping compared to both "height above nearest drainage" (HAND) and 1D HEC-RAS workflows. As illustrated in

Figure 32, the 2D simulations effectively quantify backwater effects of mainstem flows into incoming tributaries, which are typically missed by previous methodologies.

4.5.4. Work Planned for FY25

Planned work for FY25 includes containerizing and deploying the developed code on a High-Performance Computer (HPC) for scaling and load testing. The goal is to harness supercomputing resources to generate 2D-derived synthetic rating curves and flood inundation raster libraries, replacing HAND methodologies where 2D HEC-RAS models are available. It is anticipated that these models will yield more accurate hydraulic predictions for road and bridge flooding than HAND or 1D HEC-RAS.

Due to the current limitations of HEC-RAS, a portion of the workflow will require a Windows virtual machine. In such cases, the team plans to build and provide a publicly accessible cloud-based distribution, such as an Amazon Machine Image (AMI) or a similar platform.

Most of the computational workflow for running RAS2FIM-2D will rely on free and open-source software available on GitHub. For components utilizing open-source technology, Docker files will be provided, offering both documentation and instructions on creating the appropriate computational environment to run the RAS2FIM-2D code.

4.6. Culverts and Low Water Crossings

Across Texas, there are about 45,000 drainage structures documented in the National Bridge Inventory. Of these, about 25,000 are span bridges over water and about 20,000 are “bridge-class” culverts, which are culverts that are more than 20 feet in length along the road. Typically these “bridge-class” culverts are multiple concrete box culvert structures that are strong enough to support the road above them. There are an unknown number of smaller culverts that are built through road embankments and are less than 20 feet in length along the road. TxDOT maintains a database called “AssetWise” that includes pictures and key dimensions of bridge-class culverts, including their length, width, height, and orientation with respect to the road direction. Local authorities collect survey information to similarly describe their culverts.

A low water crossing is a portion of a road whose surface is sufficiently close to the stream elevation that it is expected that water will overflow the road even in moderate rainfall events. These often have culvert pipes to convey low flows during normal weather conditions. Figure 33 shows a low water crossing on FM 150 at Onion Creek in Hays County, Texas. The CTR Project team developed a Rapid Culvert Assessment procedure to gather field data on such structures during Project 0-7095:
https://www.caee.utexas.edu/prof/maidment/StreamflowII/Documents/ProjectP6B2Project07095.pdf

Figure 33 Low water crossing on FM 150 at Onion Creek

There are two critical elevations associated with a culvert. The first is the invert or low elevation of the culvert pipes, which is generally close to the bottom of the stream. The second is the elevation of the road surface. If this information is substituted into the FHWA HY-8 culvert hydraulics program, a rating curve for the culvert can be calculated. An example of these methods is shown in Figure 34 for a concrete box culvert with two barrels, each 6' feet wide and 5' high. The culvert is 293' long. The flat part of the rating curve is where water starts flowing over IH-10. A particularly useful feature of HY-8 is that the discharge at which the road is first overtopped is a result of the computation. The methods used to create the 3D culvert model and the rating curve are described at:

https://www.caee.utexas.edu/prof/maidment/RoadElevationModel/Culvert/IH10Culvert.pdf

https://www.caee.utexas.edu/prof/maidment/RoadElevationModel/Culvert/IH10CulvertHY8.pdf

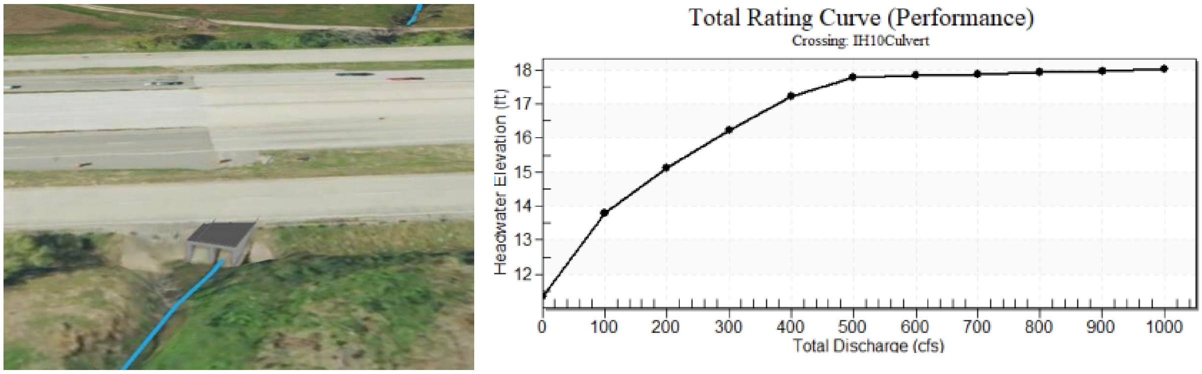


Figure 34 3D culvert model and rating curve for a culvert under IH-10 southwest of Beaumont, Texas.

The 3D culvert model uses a rule set created in ArcGIS City Engine based on the length, width, height and orientation of the culvert boxes. So far, there is no comparable rule set for circular culverts. Figure 35 shows a Bridge-Class Culvert under a Road Elevation Model on for Shoal

Creek at Anderson Lane in Austin, Texas. The five barrels are 10' wide, 6' high and 72' in length. Hence, this bridge-class culvert has a length that is not much larger than its overall width, whereas the smaller culvert, below bridge-class in Figure 34, has a length that is much greater than its width.

Figure 35 3D culvert model for a bridge-class culvert on Anderson Lane at Shoal Creek in Austin, Texas.

The HY-8 program is maintained for FHWA by Aquaveo, located in Provo, Utah, which is associated with Brigham Young University (BYU). https://www.aquaveo.com/software/wms-hy-8 The CTR research team has a collaborative project with BYU supported by the Cooperative Institute for Research to Operations in Hydrology (CIROH), under which a "headless" version of HY-8 has been programmed that can be called from an external source, such as ArcGIS Pro. If a 3D representation of culverts stored in the Flood Transportation Geodatabase has the appropriate attributes needed to operate the HY-8 culvert calculator, and if the headless version of that calculator is programmed to operate under Arc Hydro, then it follows that culvert rating curves could be generated for all three kinds of drainage structures shown in Figures 33-35. Accomplishing all this will require significant engineering effort, but it is achievable.

5. Flood Data Services

5.1. KISTERS Data Services Infrastructure

The University of Texas has created methodologies and developed computer code to predict flooding on Texas' transportation network. This work includes advancements in (1) hydrologic modeling corrected by additional stream gauging and (2) the mapping of warnings for bridges and roads likely to flood. KISTERS' role in this project is to operationalize the research team's innovations. The aim is to deliver continuously operating computer services that provide TxDOT with actionable flooding information and data services.

KISTERS' responsibility is to take the researchers' software and deploy it in a manner that allows it to run efficiently and reliably in a real-world environment (like Amazon Web Services). This involves ensuring the code's compatibility with scalable infrastructure and integrating it into a system that can handle large volumes of data. The end goal is to ensure that TxDOT receives timely, accurate flooding predictions and warnings that can be used for decision-making and emergency response.

The research team is creating a geodatabase for road transportation that includes details like road geometry and stream hydrography (rating curves). To use this data for real-time flood warnings, it needs to be connected to and calculated with real-time stream flow data. This process is managed by a backend service hosted by KISTERS, which updates the data every hour to support bridge warnings and flood assessments for roads. The service incorporates short-range forecasts from the National Water Model (NWM) to perform the necessary calculations for the road and bridge warning services.

KISTERS supplies real-time flood prediction data, updated hourly. This raw data is processed into geospatial layers for bridge warnings (points). TxDOT has requested that these layers be accessible through a 'data agnostic API,' which should provide a consistent interface for interacting with different spatial data sources, such as GIS, spatial databases, and web services. The team is considering options like ArcGIS Online (AGOL), GeoServer, and GeoJSON to serve these layers. The immediate goal is to integrate these layers into a web map and dashboard, as shown in Chapter 2 of this report.

KISTERS Datasphere is a data management platform designed for managing environmental data. It allows organizations to collect, store, and share large volumes of data effectively. The platform supports real-time data processing, integrates with various systems, and offers tools for data visualization and reporting, as shown in Figure 36.

For this project, KISTERS provides a computing cluster that operates continuously to support TxDOT's flood forecasting services. This cluster plays a key role in extracting, transforming, and loading (ETL) external federal datasets.

In summary, KISTERS provides a computing cluster that supports TxDOT's flood forecasting by processing data and offering real-time information on flooded roads and bridges.

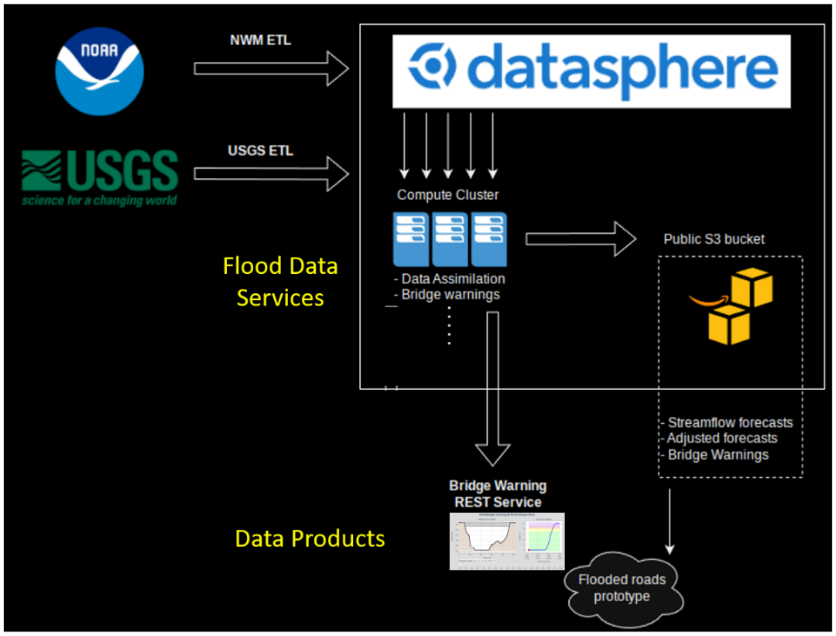


Figure 36 KISTERS Datasphere cloud Infrastructure for TxDOT project

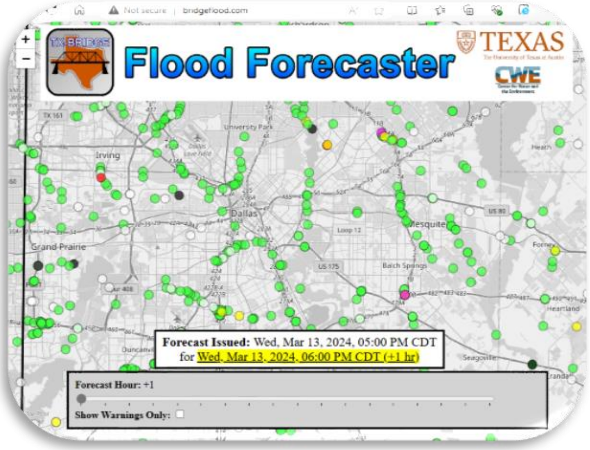
5.2. Flooded Bridge Services

5.2.1. Initial Bridge Cross Section Service

The University of Texas at Austin has created a system to flag bridges at risk of flooding. It combines 18-hour flow rate forecasts from the National Water Model with 3-meter HAND rating curves. The system uses simplified bridge shapes, which are programmatically extracted from LiDAR data and digital elevation models. The software to extract the simplified geometry, called TX-bridge ("Texas Bridge"), is open-source and available on GitHub: https://github.com/andycarter-pe/tx-bridge .

A bridge database encompassing a total of 37,488 bridges was extracted. The database can be accessed at: https://web.corral.tacc.utexas.edu/nfiedata/acarter/tx-bridge-db-20230919/ . A data dictionary of the bridge database is detailed in Appendix A of Technical Memorandum 5B, Road and Bridge Flooding from Project 0-7095: https://www.caee.utexas.edu/prof/maidment/StreamflowII/ReferenceDocs/0-7095-TM5B-Final.pdf

A prototype website was created to provide flood warnings for bridges. Launched in November 2023 at http://bridgeflood.com/ this web server was designed to assess the effectiveness of communicating flood risks to TxDOT personnel. The "bridgeflood" prototype website showed a map with dots representing bridges, color-coded by flood risk, Figure 37. The risks were grouped based on how close the water is to the bottom of each bridge.



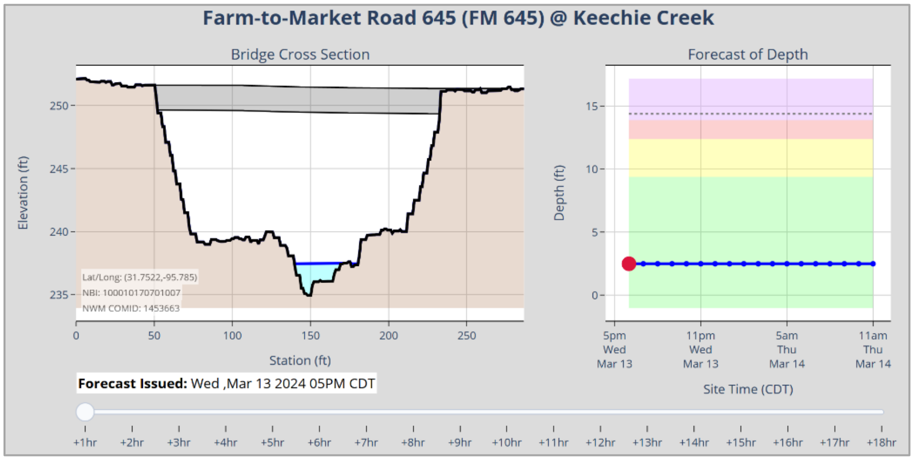
Forecast Issued: Wed, Mar 13, 2024, 05:00 PM CDT
for Wed, Mar 13, 2024, 06:00 PM CDT (+1 hr)

Forecast Hour: +1

Show Warnings Only: ☐

Figure 37 Bridgeflood.com – Texas Bridge Warning Prototype Webserver

When a point is clicked, an interactive graphic would be rendered showing the predicted water level at the bridge, Figure 38.



Forecast Issued: Wed ,Mar 13 2024 05PM CDT

Figure 38 Bridgeflood.com: Cross Section Plot

The Bridgeflood.com web server showed its potential to TxDOT with a successful proof of concept. However, it was a standalone system, making it difficult to integrate with other TxDOT web mapping services like ArcGIS Online (AGOL). This lack of flexibility meant it couldn't be easily used within TxDOT's existing infrastructure.

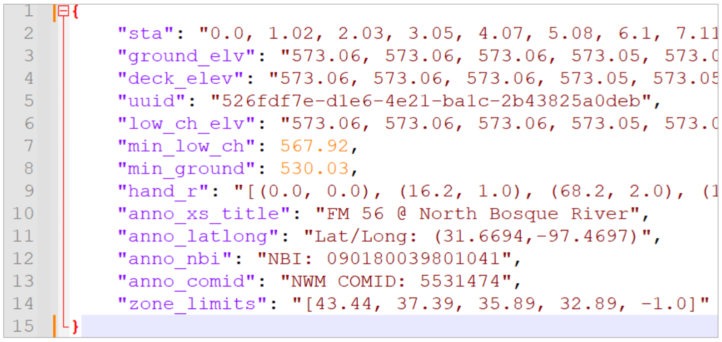
5.2.2. Enhanced Bridge Cross Section Service

To enhance modularity and integration with existing TxDOT web services, it was proposed in February 2024 to split the Bridgeflood prototype into two separate services. The first service would run hourly, evaluating and rendering a color-coded geospatial point layer for approximately 19,000 bridge warnings in the Texas database. The second service would act as an engine that generates a cross-section plot with the flood profile at a specific bridge whenever a user requests it.

To help create a service for plotting bridge cross-sections, an open-source project called “tx-bridge-xs” was developed https://github.com/andycarter-pe/tx-bridge-xs . This project includes items needed to set up a “Flood Warning Cross Section Web Server,” including instructions.

The project uses special tools called Docker containers and a web server called Flask to run the service. It displays interactive graphics using Plotly, showing a visual representation called a ‘bridge envelope.’ For each bridge, there’s a chart that illustrates how water depth changes over the next 18 hours. Each bridge is linked to a specific stream from the National Water Model that it crosses generating flood warnings.

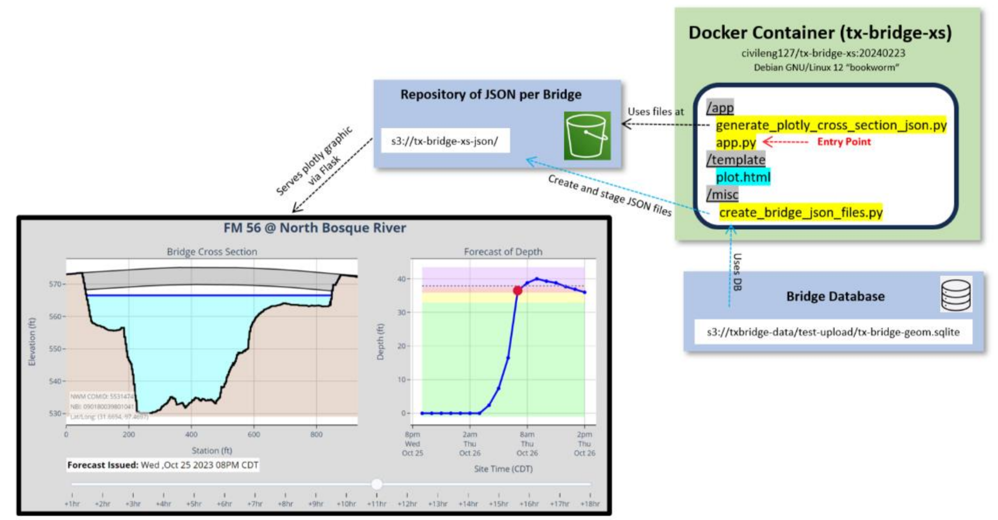
For this service, each bridge in the TX-Bridge database was converted to an individual JSON file. This JSON file contains the geometry of the bridge and the synthetic rating curve. The JSON file in Figure 39 is located at http://s3.amazonaws.com/tx-bridge-xs-json/526fdf7e-d1e6-4e21-ba1c-2b43825a0deb.json



```
{
    "sta": "0.0, 1.02, 2.03, 3.05, 4.07, 5.08, 6.1, 7.11
    "ground_elv": "573.06, 573.06, 573.06, 573.05, 573.0
    "deck_elev": "573.06, 573.06, 573.06, 573.05, 573.05
    "uuid": "526fdf7e-d1e6-4e21-ba1c-2b43825a0deb",
    "low_ch_elv": "573.06, 573.06, 573.06, 573.05, 573.0
    "min_low_ch": 567.92,
    "min_ground": 530.03,
    "hand_r": "[(0.0, 0.0), (16.2, 1.0), (68.2, 2.0), (1
    "anno_xs_title": "FM 56 @ North Bosque River",
    "anno_latlong": "Lat/Long: (31.6694,-97.4697)",
    "anno_nbi": "NBI: 090180039801041",
    "anno_comid": "NWM COMID: 5531474",
    "zone_limits": "[43.44, 37.39, 35.89, 32.89, -1.0]"
}
```

Figure 39 Individual Bridge JSON file

Combining the Docker Container with a repository of bridge JSON files, a documented and replicateable web microservice was created allowing for the realtime rendering of bridge warning cross sections, as shown in Figure 40.



Sample URL

`http://127.0.0.1:5000/xs/?uuid=526fdf7e-d1e6-4e21-ba1c-2b43825a0deb&list_flows=0,0,0,0,0,0,0,100,1000,5000,28000,42000,50000,45000,42000,35000,30000,25000&first_utc_time=2023-10-26T02:00:00`

Figure 40 'TX-Bridge-XS' deployed web microservice

5.2.3. KISTERS Bridge Warning Service

Part of KISTERS Datasphere is a service that continuously monitors and aggregates predicted streamflow data across Texas from NOAA's National Water Prediction Service. To use the 'TX-Bridge-XS' microservice, it is essential to connect the bridge cross sections to a streamflow aggregation service like Datasphere. As shown in Figure 41, KISTERS has established this connection and deployed a "Bridge Warning Service" within their Amazon Web Services (AWS) Virtual Private Cloud (VPC), which operates continuously and in real-time allowing for rendering the cross-section information "on-demand."

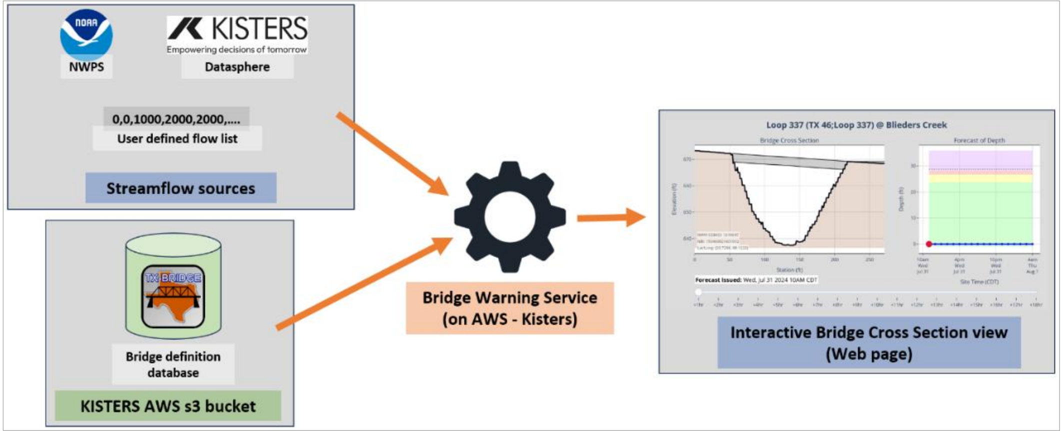
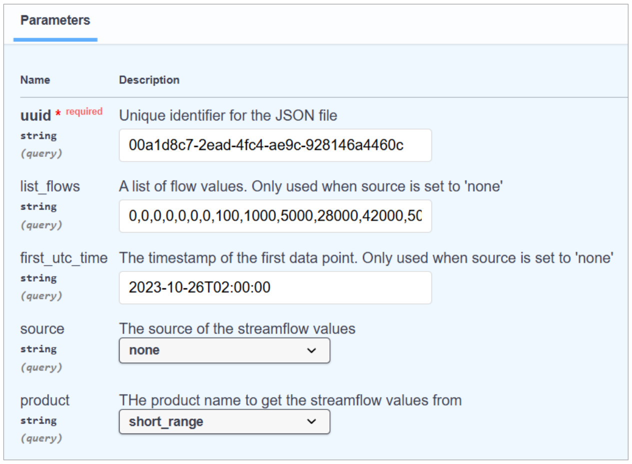


Figure 41 Schematic of the functionality of KISTERS' Bridge Cross Section Web Service

Example URL: https://bridges.txdot.kisters.cloud/xs/?uuid=00a1d8c7-2ead-4fc4-ae9c-928146a4460c&source=datasphere&product=short_range

5.2.4. Bridge Cross Section API

The KISTERS Bridge Warning Service is a RESTful API which was built in Python using the FastAPI framework and Plotly for graphic generation. FastAPI integrates with Swagger by default. Swagger is a framework for API design and documentation that helps future developers understand and consume RESTful web services. This service's documentation is currently exposed through https://bridges.txdot.kisters.cloud/docs#/default/get_cross_section_plot_xs__get This interface documents how to build URLs to retrieve bridge cross sections, Figure 42.



Name	Description
uuid * required string *(query)*	Unique identifier for the JSON file 00a1d8c7-2ead-4fc4-ae9c-928146a4460c
list_flows string *(query)*	A list of flow values. Only used when source is set to 'none' 0,0,0,0,0,0,0,100,1000,5000,28000,42000,5
first_utc_time string *(query)*	The timestamp of the first data point. Only used when source is set to 'none' 2023-10-26T02:00:00
source string *(query)*	The source of the streamflow values none
product string *(query)*	THe product name to get the streamflow values from short_range

Figure 42 KISTERS Bridge Warning – Swagger User Interface

The URL generated from Swagger in Figure 42 is shown below and generates the graphic shown in Figure 43.

https://bridges.txdot.kisters.cloud/xs/?uuid=00a1d8c7-2ead-4fc4-ae9c-928146a4460c&list_flows=0%2C0%2C0%2C0%2C0%2C0%2C0%2C100%2C1000%2C5000%2C28000%2C42000%2C50000%2C45000%2C42000%2C35000%2C30000%2C25000&first_utc_time=2023-10-26T02%3A00%3A00&source=none&product=short_range

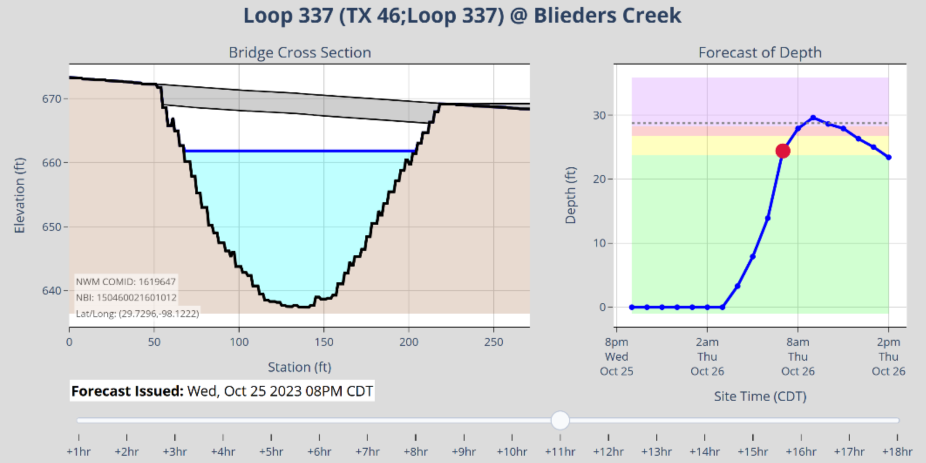


Figure 43 KISTERS Bridge Warning Graphic

5.2.5. Radar Gauge Data Assimilation

In the National Water Model (NWM), data assimilation involves incorporating real-time observational data into the hydrologic model to enhance the accuracy of streamflow predictions. This process adjusts the model using data from radar stream gauges, ensuring that its simulations more closely reflect actual conditions.

When more stream gauges are included, they provide additional data that can be integrated into the NWM, further improving the model's ability to predict streamflow, flooding, and hydrological timing with greater accuracy. By regularly updating the model with real-world observations, data assimilation reduces forecast uncertainty and supports more effective water management and emergency response efforts.

Data assimilation relies on two key components: (1) sensor data and (2) a computational method to incorporate these sensor data into the base model. This requires an Extract, Transform & Load (ETL) process. KISTERS has developed an ETL workflow on their cloud servers to continuously pull, format and archive a continuous data stream of the needed data from both the National Water Model (NWM) and USGS' stream gauges.

These data are ingested into a computational engine developed by the University of Texas which is planned to be deployed on KISTERS servers. Once this has been completed, these services will perform data assimilation and broadcast corrected results hourly for the National Water model streams within the State of Texas, as shown in Figure 44.

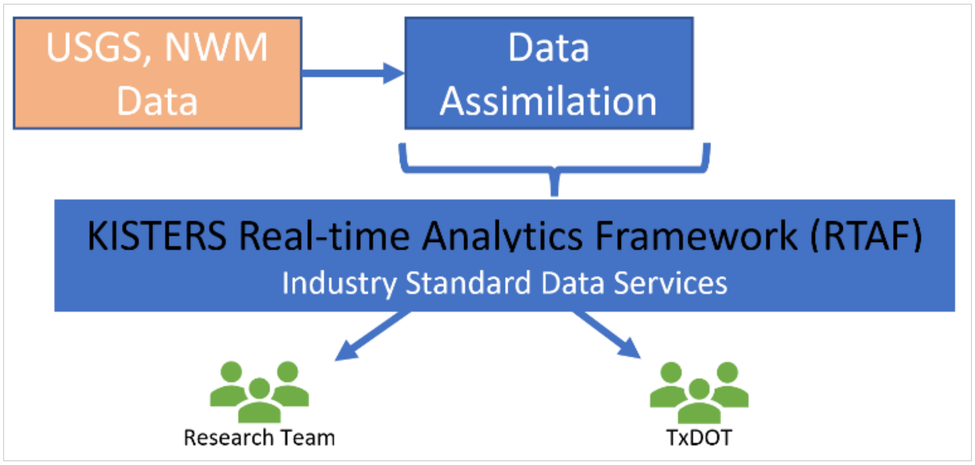


Figure 44 Data Assimilation Schematic

5.3. Flooded Roads Service

The University of Texas has published a forecasted flooded roads service for the Austin District. The static data used to build the service include TxDOT Roadway Inventory lines, rating curves and catchments from the 3-meter HAND data built for Texas, and a road elevation model for the Austin District computed at Oak Ridge National Laboratory. This previous research was done in collaboration with the Texas Division of Emergency Management.

The service is updated at UT-Austin by a scheduled task approximately hourly with the latest short range forecast from the National Water Model, which is produced by KISTERS Datasphere. When the task sees a new forecast, it downloads the forecast data, converts streamflow to water depth using rating curves, and finds all road lines with a minimum HAND value less than the water depth. These flooded roads are then used to update a service which is hosted in The University of Texas's ArcGIS Online instance as a hosted feature service.

Users interact with a view built from the service. The view is associated with two services, only one of which is active at a given time. When a forecast is processed, the inactive service is updated, and only when the update is complete does the scheduled task switch the view so that it points to the newly updated service, leaving the previously active service as an inactive service ready for the next update. This minimizes downtime during services updates, and guards against the user seeing no data if an update did not complete successfully. The scheduled task tracks the update process, and if an update fails, it can self-recover and attempt to complete the update, leaving the view intact (albeit with slightly stale data based on the previous forecast that was successfully processed) for the end user.

The flooded roads forecast includes On-System and Off-System roads, and it has an attribute indicating flooded depth. This was done to test the methodology. However, for exercise purposes, The University of Texas may filter the view to show only On-System roads, and to show only whether the road is flooded or not.

Figure 45 Flooded road line shown in orange on the Llano River

6. Forecast Data Analytics

6.1. Regional Error Assessment

The project researchers Sujana Timilsina and Paola Passalacqua have developed a draft manuscript, which has been reviewed and approved by TxDOT for submission for journal publication. This paper concerns the error assessment of the National Water Model (NWM).

The abstract of this paper includes the following summary: “We assess the performance of NWM versions 2.1 and 3.0, focusing on both retrospective data and short-range forecasts. The analysis reveals significant improvements in version 3.0, particularly in reducing Root Mean Square Error (RMSE) during major flooding events such as Hurricane Harvey. Short-range forecasts with data assimilation outperform retrospective analyses, highlighting the importance of updated data assimilation methods. Despite these advancements, we identify ongoing challenges in predicting both the magnitude and timing of peak flow events and underscore the need for further improvements in the model to enhance its reliability.” This section of the present report provides some technical detail behind these conclusions.

In order to create a baseline for the evaluation of the Data Assimilation approaches, we evaluated the streamflow forecasts from the National Water Model (NWM) version 2.1 and 3.0 at the river network scale, utilizing data from over 600 USGS gauges distributed across Texas. This extensive dataset allowed us to quantify the errors associated with the NWM and to compare the performance of its previous versions against the current version. We used multiple metrics like Root Mean Squared Error (RMSE), Kling-Gupta Efficiency (KGE), Percent Bias (PBIAS) and Normalized Nash-Sutcliffe Efficiency (NNSE) to quantify the performance of the NWM streamflow predictions for the retrospective data and the short-range data. Table 2 compares the forecast errors using the retrospective data for the period 2018 to 2023. Except for TS Imelda the NWM version 3.0 is consistently more accurate than NWM version 2.1. Table 3 makes a similar comparison looking instead at the short-range forecasts from the NWM version 2.1. The errors are much less because the USGS gauge observations are used to initiate the forecast values.

Table 2: Median value of error metrics for NWM retrospective data version 2.1 and 3.0 for storm events, and for the whole data period (2018-2023)

Metrics	Harvey		Hanna		Imelda		Whole Period	
	NWM 2.1	NWM 3.0	NWM 2.1	NWM 3.0	NWM 2.1	NWM 3.0	NWM 2.1	NWM 3.0
RMSE	58.87	24.07	4.33	1.87	12.73	14.07	43.20	26.73
KGE	-0.28	-0.24	-0.24	-0.32	-0.35	-0.17	0.16	0.30
PBIAS	-640	-0.45	-17.12	-34.92	14.43	-27.54	1.90	-13.03
NNSE	0.25	0.25	0.13	0.22	0.17	0.28	0.47	0.52

Table 3: Mean and Median values of error metrics for short-range data for NWM 2.1 for storm events and for the whole data period (2018-2023)

Metrics	Harvey		Imelda		2018-2023	
	Mean	Median	Mean	Median	Mean	Median
RMSE	5.20	0.28	7.68	1.50	22.51	9.99
KGE	-155.74	0.30	-509.81	-0.66	0.20	0.86
PBIAS	13112.67	6.39	16937.17	13.45	19.07	-1.51
NNSE	0.31	0.11	0.32	0.11	0.73	0.86

A NNSE value of 1 indicates a perfect model, whereas values below 0.5 indicate that the model performs worse than the mean of the observed data. The spatial maps (Figure 46) show that, for NWM 2.1, 300 locations have NNSE less than 0.5 and 223 locations have NNSE greater than 0.5. For NWM 3.0, 251 locations have NNSE less than 0.5 and 313 locations have NNSE greater than 0.5. The NWM performs worse than the mean of the observed data in more than 44% locations for both NWM 2.1 and 3.0.

During the major storm events, (Figure 47) higher RMSE values are observed in areas with higher precipitation. The NNSE values are also generally below 0.5 (Figure 48) for all the storm events (> 70% of the locations have NNSE less than 0.5 for Hurricane Harvey) which suggests that the NWM 3.0 struggles with accuracy during higher rainfall scenarios. Most importantly this spatial error analysis showed that the performance of the NWM is not affected by geographic location, meaning that there is no spatial pattern in the performance of the NWM.

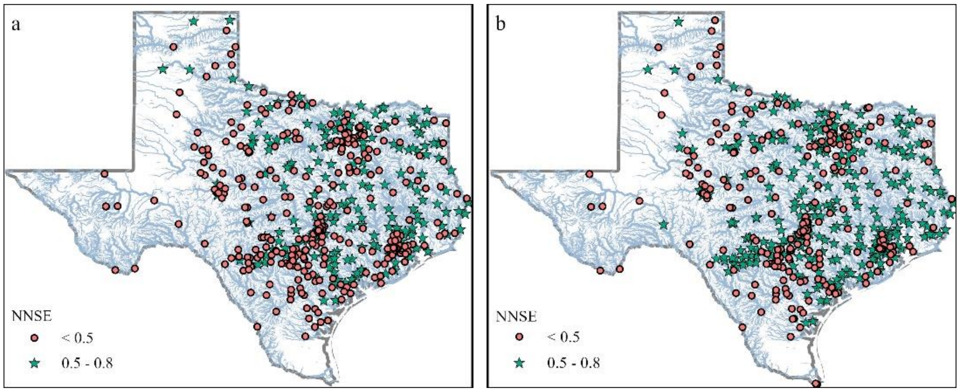


Figure 46 Spatial distribution of NNSE for (a) NWM 2.1 and (b) NWM 3.0. The dots represent the locations where the NNSE values are less than 0.5, whereas the stars represent the location where the NNSE values are greater than 0.5.

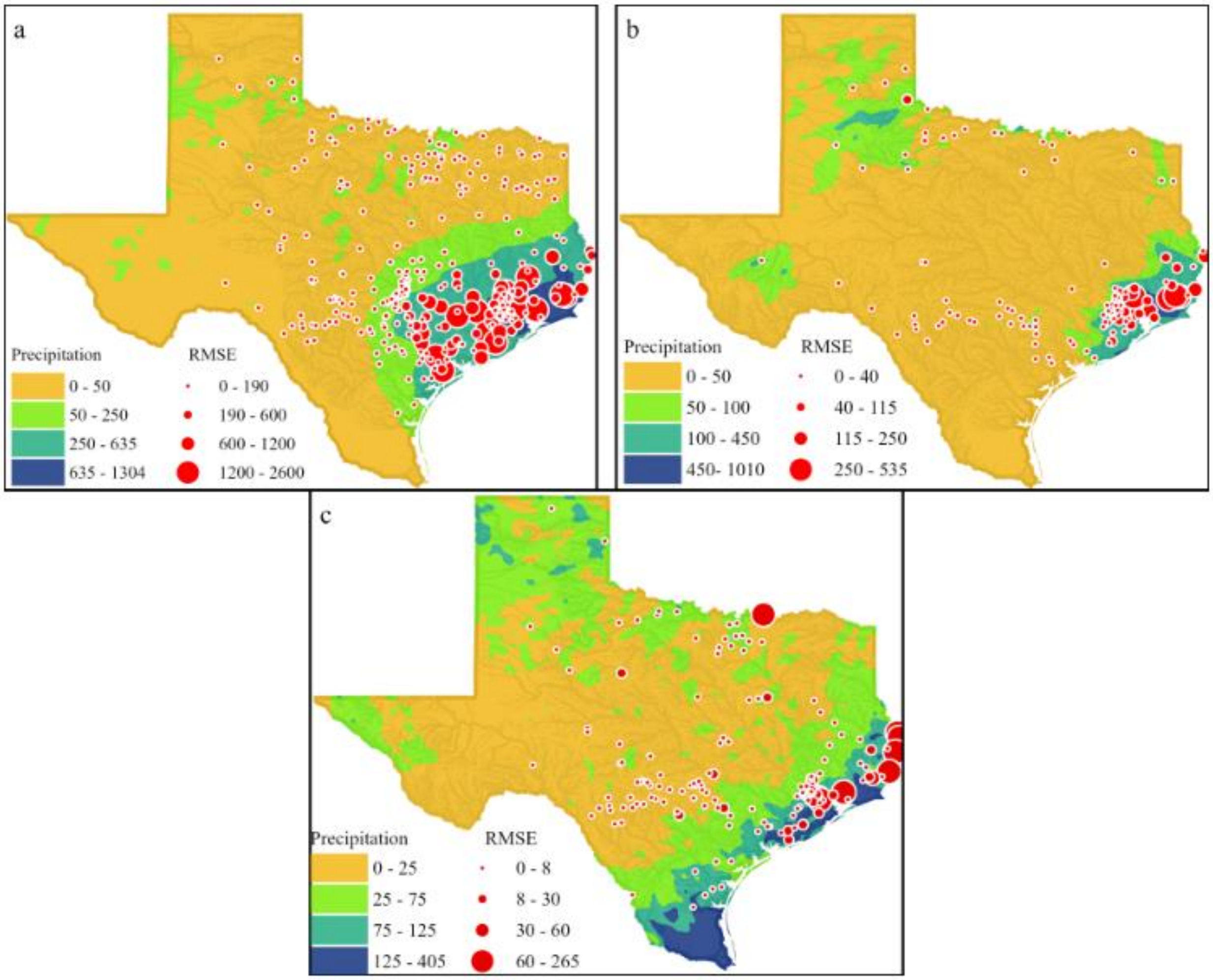


Figure 47 Spatial Distribution of RMSE for NWM 3.0 during (a) Hurricane Harvey, (b) TS Imelda, and (c) Hurricane Hanna overlaid on top of total precipitation (in mm) maps for the events. The size of the dots is proportional to error magnitude.

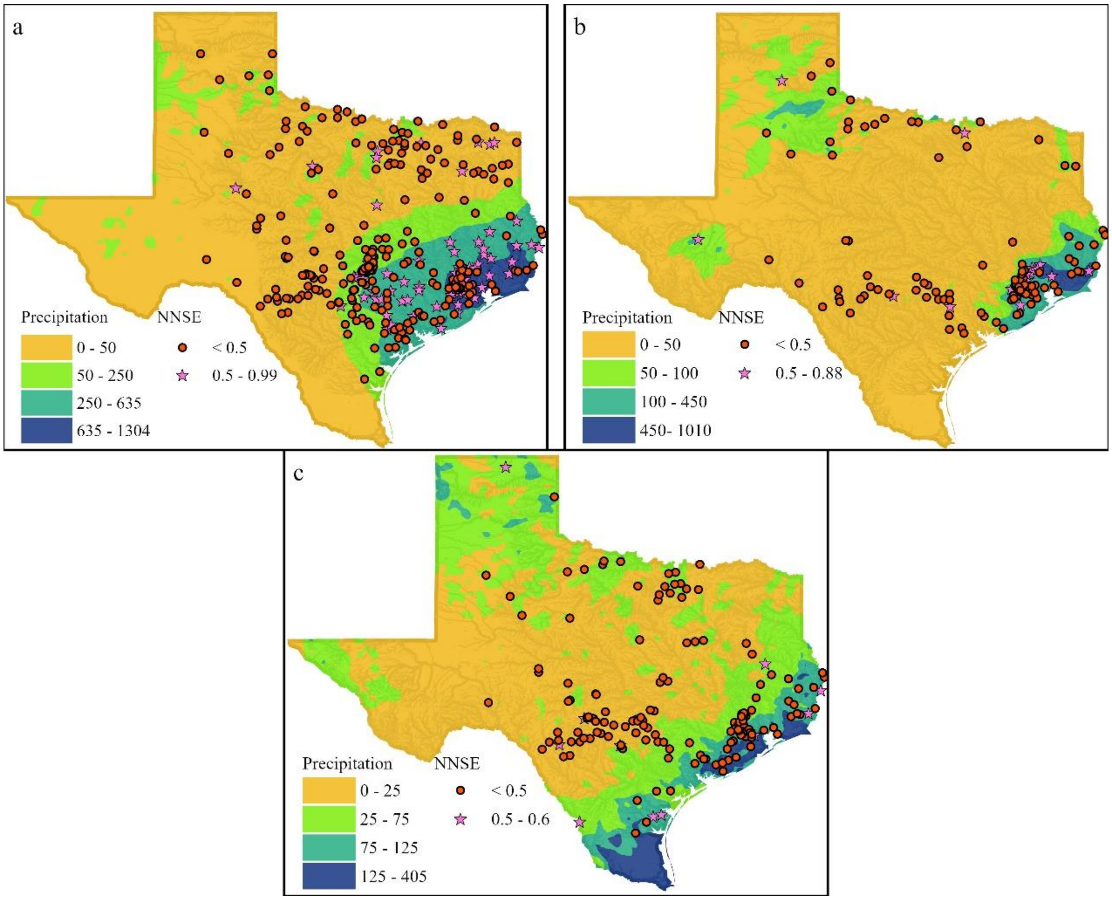


Figure 48 Spatial Distribution of NNSE for NWM 3.0 during (a) Hurricane Harvey, (b) TS Imelda, and (c) Hurricane Hanna overlaid on top of total precipitation (in mm) maps for the events.

6.1.1. Conceptual Functional Equivalent (CFE) Model

In order to be able to correct the National Water Model forecasts for errors in the precipitation forecast, a simplified hydrologic model is needed which converts rainfall into streamflow. The Conceptual Functional Equivalent (CFE) model, a simplified conceptual hydrological model designed to function equivalently to the National Water Model (NWM), is one of the models under consideration for implementation within the NextGen Framework at the National Water Center. Unlike the current Data Assimilation approach being used in this project and described later in this chapter, which utilizes lateral flows from the NWM as input, the CFE model allows for the direct ingestion of forcing data such as precipitation and potential evapotranspiration to simulate runoff within catchments. This flexibility enables the incorporation of locally measured real-time rainfall data into the model.

To evaluate the effectiveness of integrating the existing Data Assimilation (DA) method with the CFE model in Texas, we conducted a simulation of the 2018 Llano flood using precipitation data from the NWM's retrospective forcing dataset. The Data Assimilation process leverages observed streamflow data from four USGS gauges for assimilation, while a fifth gauge located downstream is used for validation purposes.

Figure 49 illustrates the locations of the assimilation and validation gauges, while Figure 50 presents the streamflow predictions at the validation site. The results indicate that the incorporation of Data Assimilation significantly improves the accuracy of streamflow predictions at the validation site, as compared to predictions from simulations without Data Assimilation (labeled as ‘Simulation’ in the plot). These results suggest that the Data Assimilation approach is effective when applied to the CFE model as well.

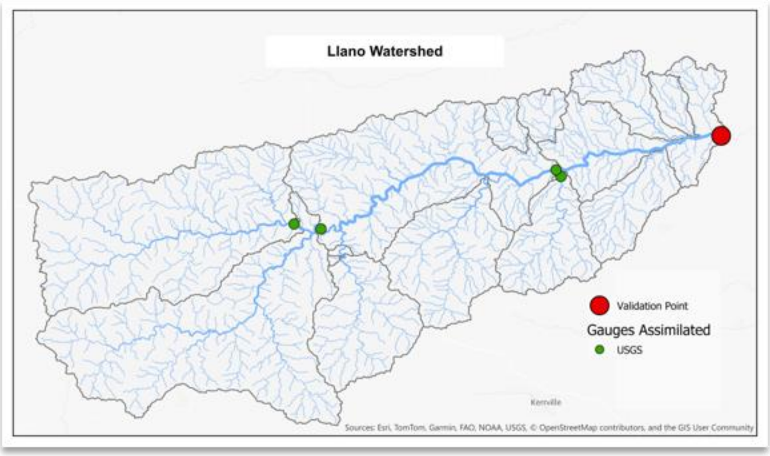


Figure 49 Location of the assimilation and validation gauges in the Llano Watershed.

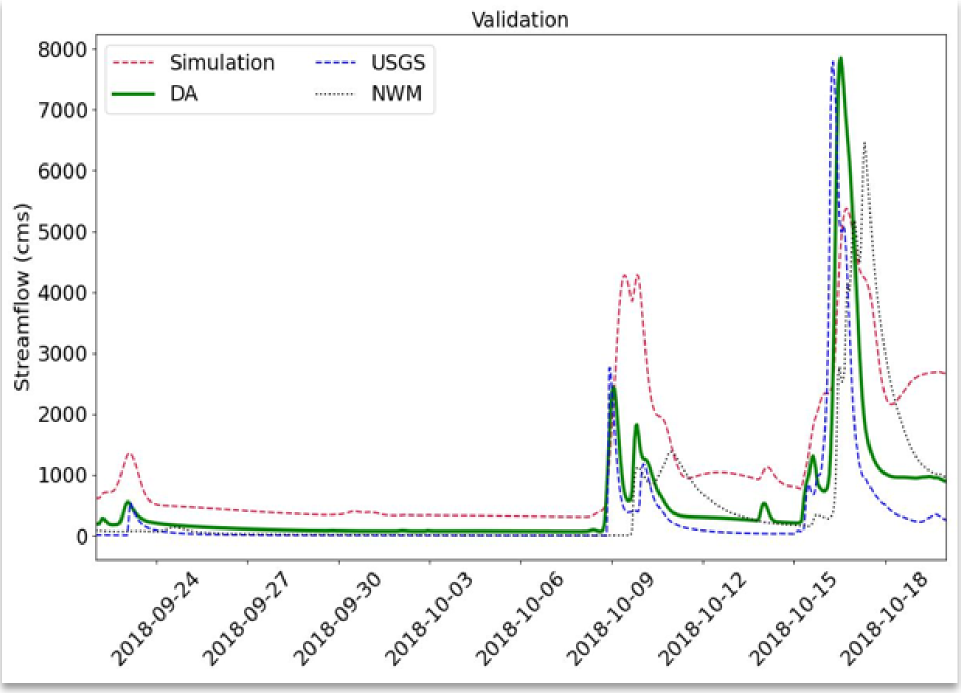


Figure 50 Streamflow predictions from the current NWM retrospective data, simulation (without CFE-based Data Assimilation), after CFE-based Data Assimilation compared to the observed USGS streamflow.

6.2. Forecast Improvement through Streamflow Data Assimilation

6.2.1. Muskingum Routing Model

When using the well-known Muskingum model for routing flows through a river network, the volume of water stored in a reach is computed as the sum of a wedge storage and a prism storage, as shown in Figure 51. The time rate of change of this storage is equal to the difference between the reach inflow and outflow according to the continuity equation. If the storage function describing the prism and wedge storage in relation to the inflow and outflow of the reach is substituted into the continuity equation, resulting flow routing equation is shown in (6.1)

$$Q_{j+1}^{t+\Delta t} = \alpha_j Q_j^{t+\Delta t} + \beta Q_j^t + \chi Q_{j+1}^t + \gamma q_j^t \tag{6.1}$$

where Q is discharge, j and j+1 are location indices along the river reach, t and t+Δt are steps in time, q_j is the lateral inflow into reach j, and the parameters are given by

$$\alpha = \frac{KX + \Delta t/2}{K(1-X) + \Delta t/2} \qquad \beta = \frac{KX - \Delta t/2}{K(1-X) + \Delta t/2}$$

$$\chi = \frac{K(1-X) - \Delta t/2}{K(1-X) + \Delta t/2} \qquad \gamma = \frac{\Delta t}{K(1-X) + \Delta t/2}$$

in which K is the flood wave travel time in the reach (s), and X is the wave attenuation parameter (from 0 to 0.5).

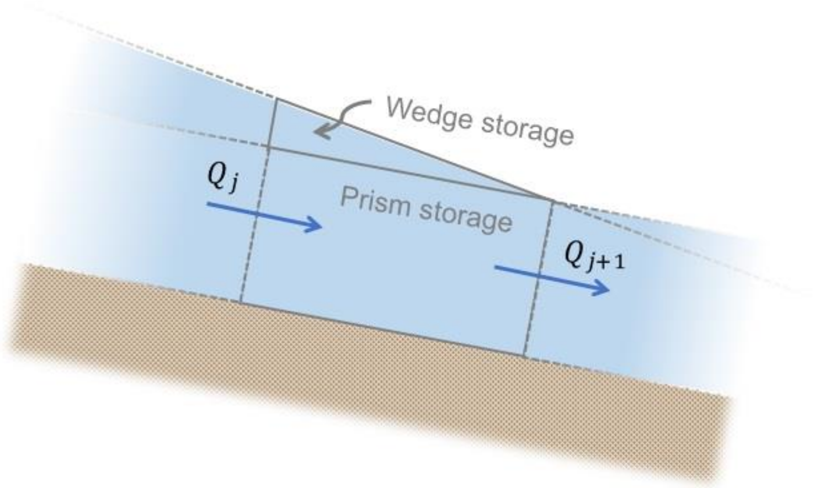


Figure 51 Prism and wedge storage in the Muskingum method

6.2.2. State-Space Representation

If for a particular river reach, the volume of storage is designated as its “state”, x, its inflow is given by u, and its outflow by y, then Equation (6.1) can be rewritten in “state-space” format as follows in which Equation (6.2) is the “state equation” and Equation (6.3) is the “output equation”, and the state, input and output are all in boldface type to indicate that they are now vector quantities defined for all reaches in the network, rather than for a single reach. The routing parameters are contained in matrices as shown Figure 52.

$$\boldsymbol{x}^{t+\Delta t} = A\boldsymbol{x}^{t} + B\boldsymbol{u}^{t} \tag{6.2}$$

$$\boldsymbol{y}^{t+\Delta t} = C\boldsymbol{x}^{t+\Delta t} \tag{6.3}$$

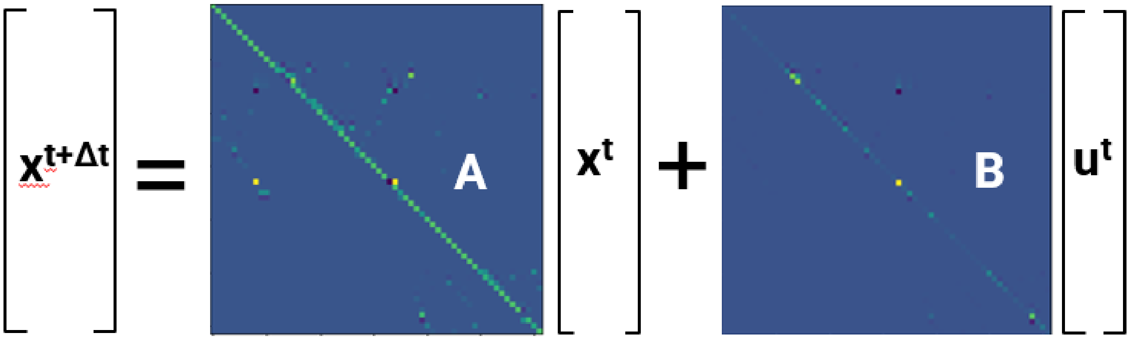


Figure 52 State-space format for Muskingum river routing

6.2.3. Ensemble Forecasting

Suppose now that instead of having a single discharge forecast, there are several such forecasts, and there is a corresponding set of values of **x**, **u**, **y** for each forecast, indexed by i, then Equations (6.2) and (6.3) can be rewritten as:

$$\boldsymbol{x}_i^{t+\Delta t} = A\boldsymbol{x}_i^t + B\boldsymbol{u}_i^t \qquad (6.4)$$

$$\boldsymbol{y}_i^{t+\Delta t} = C\boldsymbol{x}_i^{t+\Delta t} \qquad (6.5)$$

In the 10-day ahead Medium Range version of the National Water Model, there are seven forecasts, or ensemble members, at each six hour time step. However, for the 18-hour ahead Short Range version of the National Water Model, which operates on hourly time steps, there is only enough time within each update cycle to compute a single forecast, so an ensemble of forecast members has to be created by including the forecasts from previous time intervals. The result is a time-lagged ensemble, as shown in Figure 53.

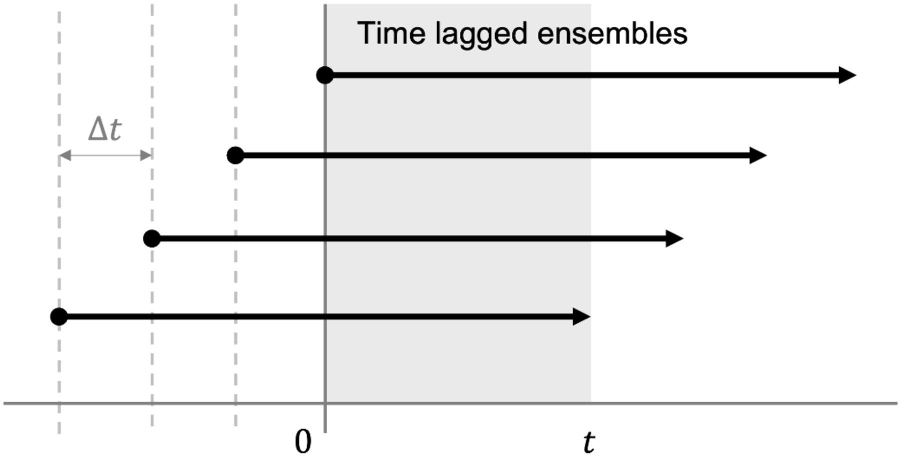


Figure 53 Time-lagged ensemble

To achieve a seven-member time-lagged ensemble, this means including the current forecast and those from the previous six hours, so the ensemble forecast horizon is reduced from 18 hours ahead to 12 hours ahead. The National Water Model short-range forecast can vary significantly from one forecast to the next because of random variations in weather patterns and precipitation. Using a lagged ensemble short-range forecast smooths out this random variation and makes for more stable forecast results from one hour to the next.

6.2.4. Data Assimilation using Kalman Filter

Suppose further, that random uncertainty is introduced into the inputs, designed by w, and into the output measurements, designed by v. The state and output equations can then be written as:

$$\boldsymbol{x}_i^{t+\Delta t} = A\boldsymbol{x}_i^t + B\boldsymbol{u}_i^t + \boldsymbol{w}_i^t \qquad (6.6)$$

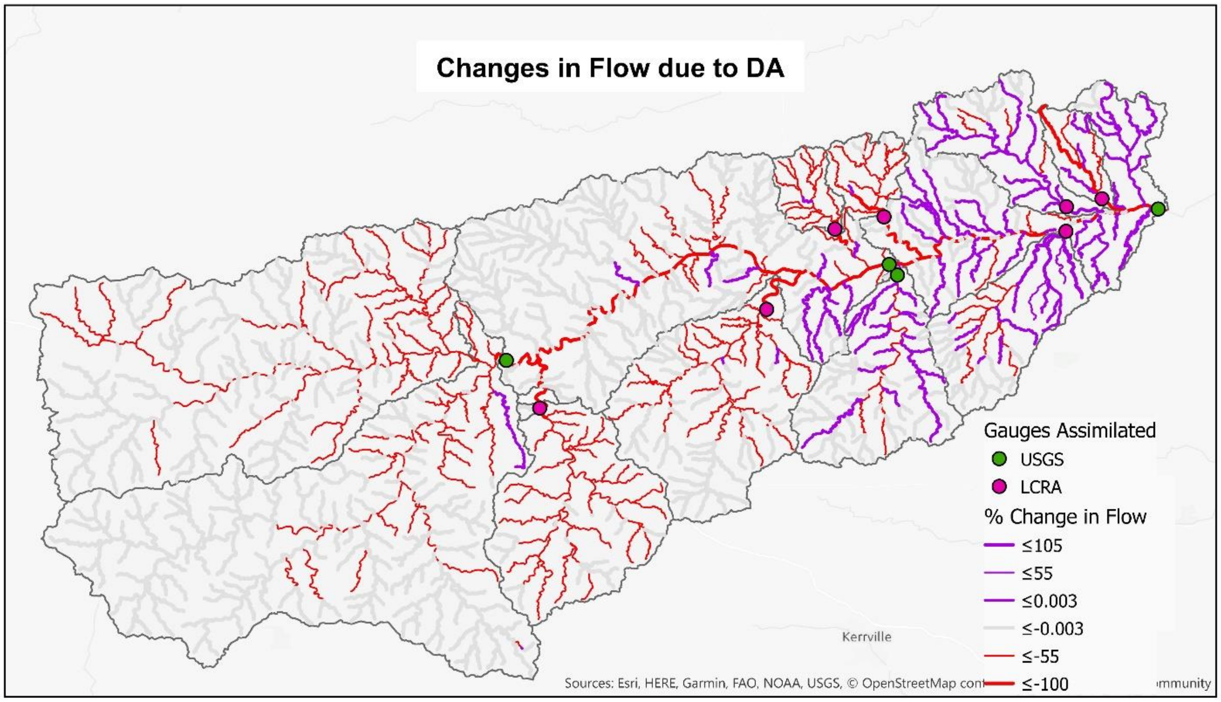
$$\boldsymbol{y}_i^{t+\Delta t} = C\boldsymbol{x}_i^{t+\Delta t} + \boldsymbol{v}_i^{t+\Delta t} \qquad (6.7)$$

As a consequence, the model states and output become random variables, having a mean and covariance, which enables their uncertainty to be quantified and visualized.

At those locations where the discharge is actually measured, the error between the observed and modeled discharge can be used as a correction for the measured reach and also for nearby reaches whose discharge is correlated with the measured reach. This is done using a Kalman filter, which applies a correction shown in red in Equation (6.8) to the flow in each reach of the network, where L is the Kalman gain or weighting factor which applies to the difference between the observed value $\boldsymbol{y}$, and the estimated value $\widehat{\boldsymbol{y}}$ and the index k refers to time steps.

$$\widehat{\boldsymbol{x}}_{k+1} = A_k \widehat{\boldsymbol{x}}_k + B_k\, \boldsymbol{u}_k + L_{k+1}(\boldsymbol{y}_{k+1} - \widehat{\boldsymbol{y}}_{k+1}) \tag{6.8}$$

The end result is that flows are adjusted up or down across significant portions of the flow network, as illustrated in Figure 51, which shows the effect of discharge measurements at 11 gauges in the Llano basin of central Texas. The gauges shown with the green dots on the main Llano river are operated by the USGS and they are already used in the National Water Model to adjust the flows passing down the main river itself, employing the “nudging” method, where for each forecast, the initial forecast discharge is set equal to the measured discharge at the USGS gauge site. The red dots show gauges operated by the Lower Colorado River Authority, which are not presently used in the National Water Model.   These correct the tributary inflows coming into the main river. In Figure 54, the red lines are those reaches whose flows are adjusted downwards, and the purple lines those reaches whose flows are adjusted upwards.



Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap con

mmunity

Figure 54 Flows adjusted by data assimilation (DA) in the Llano basin using Kalman filtering

6.2.5. Probability of Bridge Impacts

For a given bridge, the discharge level at which water starts impacting the low chord of the bridge is denoted as z. The forecast discharge for a time-lagged ensemble is given by y_i for each ensemble member. The probability that the discharge at the bridge will exceed the impacting value can be expressed mathematically as:

$$P(Y > z) \ = \frac{1}{N}\sum_{i=1}^{N} H(y_i \ - z) \qquad (6.9)$$

where $H(y_i \ - z)$ is the Heaviside step function, which is 1 if y_i > z and 0 otherwise. N is the total number of time-lagged ensembles.

Figure 55 shows a map of these probabilities computed for 1 April to 1 July 2023 on 2177 bridges in the San Antonio and Guadalupe basins. The small yellow dots in this map indicate bridges functioning under normal conditions, while the large orange dots are frequently impacted, most likely because the bridge thickness is incorrectly specified in the bridge data. For example, the KISTERS URL linkage for Hootowl Hollow West at Johnson Creek https://bridges.txdot.kisters.cloud/xs/?uuid=b5a0d7e3-a9c3-4977-b321-3bbad02b47e8&source=datasphere&product=short_range yields, when queried, the bridge cross-section and forecast shown in Figure 56.

There are about 10 bridges of the 2177 bridges in these two basins that are similarly identified as having incorrect geometries. This approach of computing bridges with high probability of being flooded is a good way of identifying errors in the bridge geometry data.

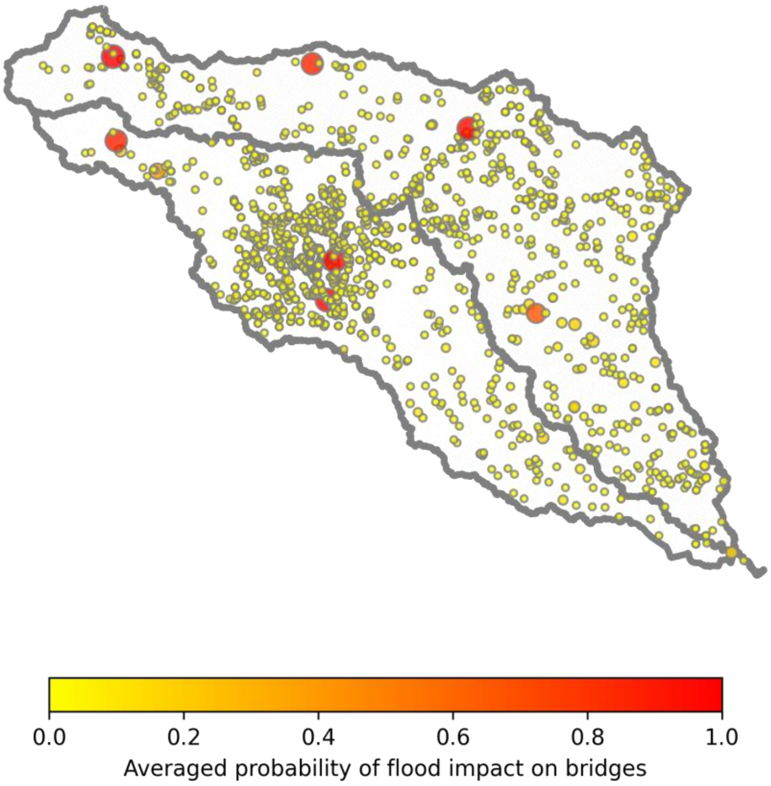


Figure 55 Probability of flood impact on bridges in the San Antonio and Guadalupe basins

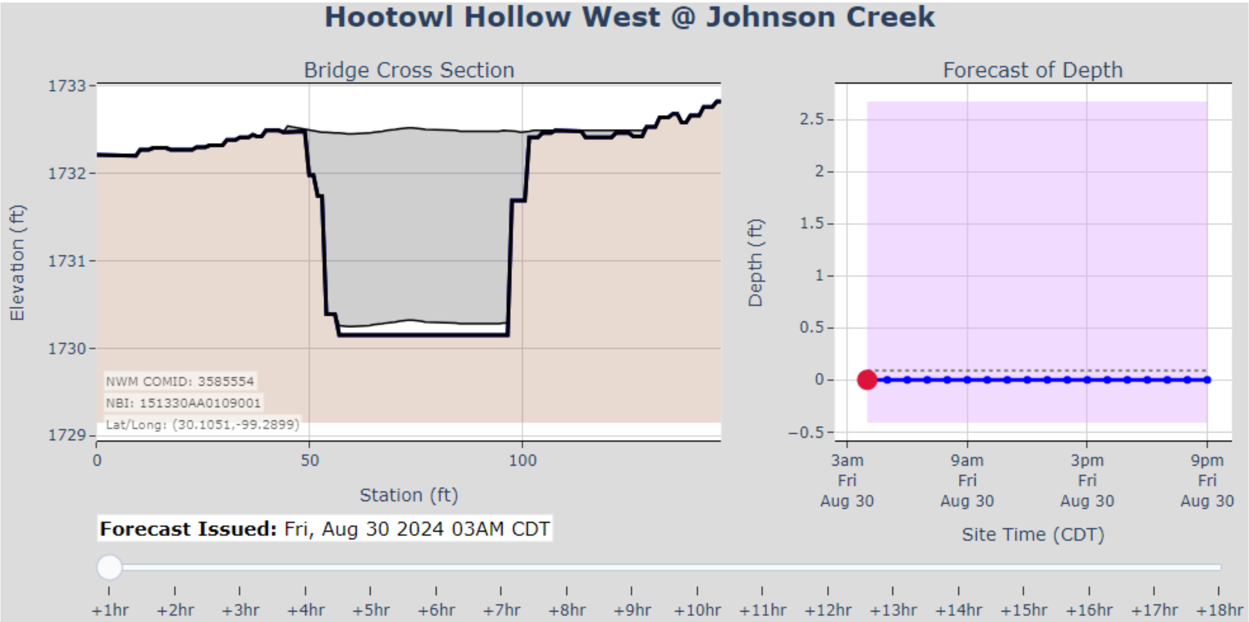


Figure 56 Bridge at Hootowl Hollow West at Johnson Creek

6.2.6. Evaluation of Data Assimilation on two River Basins

To evaluate the forecasting accuracy of our proposed approach at scale, we run a series of tests on two river basins. We focus on the San Antonio and Guadalupe river basins over the period spanning April to July of 2023, in which several large storms occurred.

Testing our approach on forecasts produced over this period, we find that our approach significantly improves forecasting skill in terms of the Continuous Ranked Probability Skill score (CRPSS) and Brier Skill Score (BSS). For both metrics, 1.0 represents perfect forecasting skill. As seen in Figure 57, our approach (blue) shows a higher average CRPSS and BSS at all lead times compared to the National Water Model with nudging (orange).

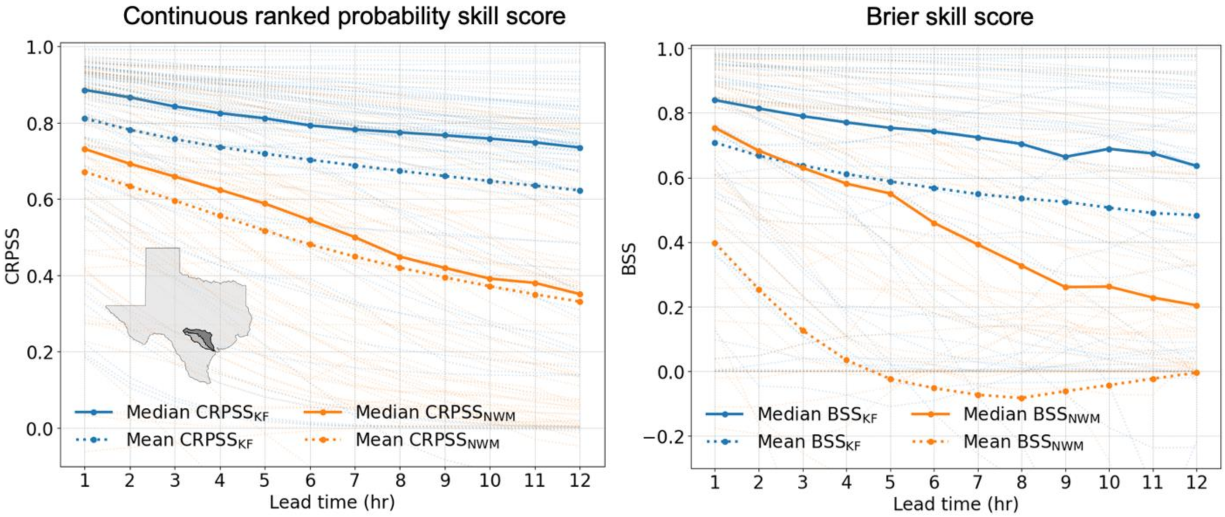


Figure 57 Comparison of Continuous Ranked Probability Skill Score for Kalman Filtering vs. NWM nudging. Our approach outperforms NWM.

6.2.7. Scaling of Muskingum routing and Data Assimilation

A watershed partitioning approach was implemented to allow our proposed modelling and data assimilation framework to scale to larger hydrologic regions. Large river basins in Texas may contain tens of thousands of individual river reaches. Executing the Muskingum routing method synchronously on watersheds of this size can cause issues with memory consumption, slow execution, and numerical instability. Especially when executing data assimilation with Kalman Filtering, large watersheds can be computationally prohibitive due to the need to compute the error covariance matrix, which is $O(n^3)$ in computational complexity (i.e. scales with the cube of the number of reaches).

As illustrated in Figure 58, Co-PI Bartos implemented a method to split large watersheds into smaller watersheds at a series of user-specified breakpoints, execute the Muskingum model simulation for each small watershed in parallel with its execution order depending on its hierarchy in the drainage network, and then collate all discharges together to reconstruct the full response of the watershed. This procedure produces results that are the same as executing the full drainage network model all at once, but with smaller computational expense, reduced memory usage, and greater potential for parallel execution.

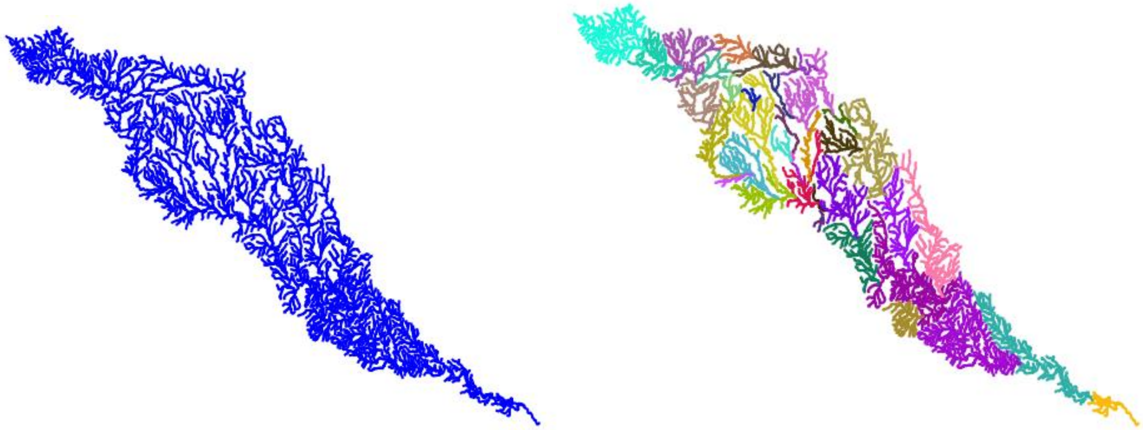


Figure 58 Demonstration of watershed splitting approach on San Antonio coastal river basin.

This new computational approach was initially tested on the San Antonio watershed, which includes 2330 unique river reaches. The watershed was split into 38 subwatersheds, with the split points being the locations of USGS gauge sites. Figure 58 shows the San Antonio watershed as represented in the original unpartitioned Muskingum model (left) and the partitioned model. The model was subjected to a constant lateral runoff input of 1 cms at each reach.

For this case, the partitioned model results in faster execution time, even without parallel processing. For the original model, the simulation takes roughly 0.56 seconds to simulate 100 timesteps, while the partitioned models require only 0.16 seconds to finish the same simulation (2022 M1 MacBook Pro). When implemented on parallel processors, this speed improvement is expected to increase further. The proposed watershed splitting approach provides a scalable way to execute our proposed modeling and data assimilation methodology at the coastal river basin scale without sacrificing computational performance.

To further test the scalability of our proposed approach, the watershed parallelization scheme described above is tested on the USGS Water Resources Region 12, which comprises most of Texas (roughly 78,000 stream reaches). The Muskingum routing model for this hydrologic region is split into roughly 350 HUC 8 regions, as shown in Figure 59 below:

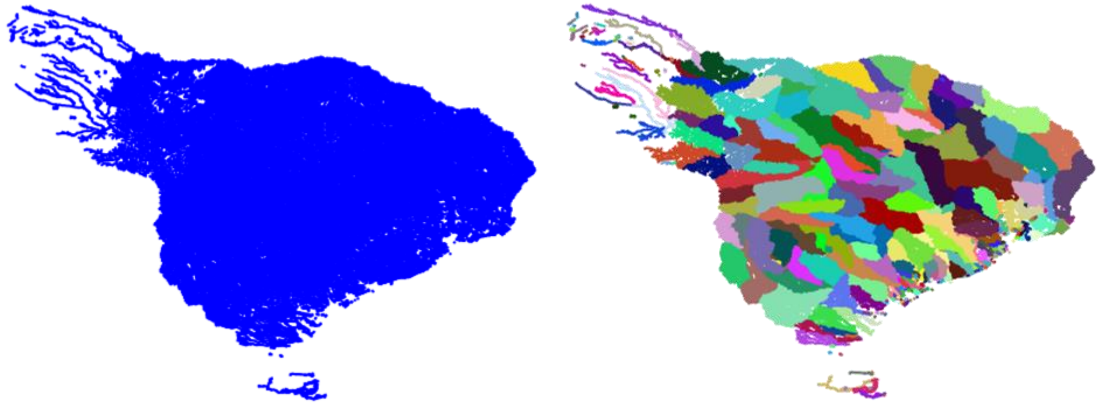


Figure 59 Watershed splitting approach applied to USGS Water Resources Region 12.

For an 18-hour forecast period, the entire USGS Water Resources Region 12 takes roughly 3 seconds to simulate (2022 MacBook Pro), which makes real-time operation easily obtainable. Data Assimilation using Kalman Filtering was also tested on USGS Water Resources Region 12. This operation takes roughly 6 seconds per hour-long simulation timestep (2022 MacBook Pro), which makes real-time operation feasible. Figure 60 shows the correction applied by the Kalman Filter for the period from April 1 to April 11, 2023 (with blue indicating added streamflow and red indicating reduced streamflow).

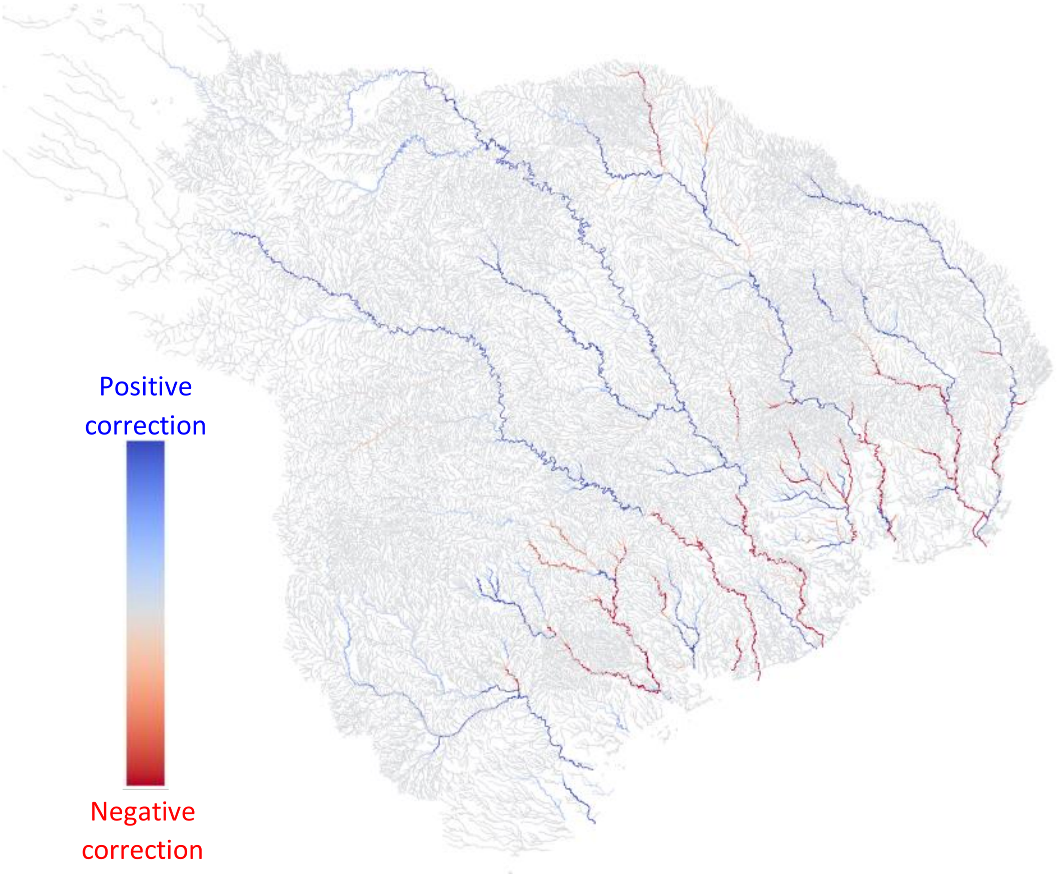


Figure 60 Kalman Filter correction applied to USGS Water Resources Region 12 from April 1 to April 11, 2023.

7. Conclusions

The Flood Assessment System for TxDOT (FAST), Project extension 0-7095-01, was initiated on 26 February 2024. In the six months until August 2024, the following advances were made in the research and in the FAST application.

(1) Project Management: TxDOT formed a 4-person TxDOT Project Management Team (TPMT) to focus its assessment and communications for the project. On the CTR side, a 4-person TACH team was formed to interact with the TPMT so as to focus on FAST development, considered separately from FAST research. The TACH prepares a weekly written report to TPMT and responds to questions received from the TPMT. A detailed Project Management Plan has been developed which identifies the six Tasks and 23 Subtasks in the Project Agreement, notes who is responsible for each, and what cross-dependencies exist between them. A Story Map is maintained to log and link all the project documents. An Action Item Tracker was created by the TPMT, and is maintained by the TACH so as to record what requests for information or action have been completed or are still pending.

(2) Flood Map Services: A FAST Flood Dashboard was developed, which summarizes the number of bridge warnings and length of flooded roads, and permits viewing of the forecast water level at a bridge. This application has both a regular computer screen view, and a mobile-phone screen view. The FAST Flood Dashboard was tested successfully by USGS field reconnaissance at several flooded roads and bridges during a flood event in July 2024. There were, however, other locations where inaccuracy in the underlying road line locations suggested a bridge is continually flooded when it is not. These errors can be corrected by more formal design and execution of a new Flood Transportation Geodatabase. Planning has begun for flood emergency response exercise of the Functional type during FY25.

(3) Flood Decision Support Gauges: All 80 RQ-30 gauges are operational and providing observed streamflow data. About 250 ADCP field measurements have been made at 54 of the RQ-30 sites, and sufficient ADCP measurements and data analysis have been done at 20 sites to calibrate the RQ-30 gauges for correct discharge estimation. About 200 station-years of data have been collected, an average of 2.5 station-years per gauge site. The USGS has developed a preliminary equation for calculating synthetic rating curves at gauge sites without formal rating curves. Using synthetic rating curves where necessary, Base Level Engineering hydraulic models have been used to create flood inundation map libraries at 32 of the RQ-30 sites. At six of these sites, the maps are now operational in the Flood Decision Support Toolbox (FDST). Hydrodynamic modeling has been initiated at site 08111110, New Year Creek at FM 1155 near Chappell Hill, Tx, to establish the workflow for later application at nine other RQ-30 sites. Hydrodynamic simulations conducted at this site show that the more rapid is the rise and fall of the flood discharge hydrograph, the more looped is the hysteresis effect between water velocity and water surface elevation, with higher velocity on the rising limb of the hydrograph and lower velocity on the falling limb. Conversely, the slower is the rise and fall of the flood hydrograph, the smaller is this looped hysteresis effect, close to the conventional stage – discharge rating curve, which assumes that hysteresis is insignificant.

(4) Flood Transportation Geodatabase: An initial Flood Transportation Geodatabase design was prepared which contains four themes – (1) topography and hydrography, (2) hydrology, hydraulics and flood forecasting; (3) critical infrastructure (roads, bridges, culverts, low water crossings); (4) Reporting units (TxDOT Districts and Maintenance Sections). An example Flood Transportation Geodatabase for the Austin District was populated with geospatial data for these four themes drawn from TxDOT and other sources. Application of Quality Control / Quality Assurance rules to this geodatabase was initiated. Because the 3D road lines and 3D bridge lines presently being used in FAST were developed independently of one another during previous research, it is anticipated that QA/QC checking will reveal some discrepancies between them. Going forward, it is anticipated that the QA/QC process applied to this initial Flood Transportation Geodatabase, will inform the design and development of an improved road and bridge line elevation model where the source of the lines is the same for roads and bridges. A software stack called RAS2FIM-2D was developed for computing flood water surface elevation and flood water depth grids from 2D HEC-RAS models developed under the TWDB Base Level Engineering program that now covers much of Texas.

(5) Flood Data Services: At the beginning of this six month project period, the CTR team had developed a demonstration version of a state-wide Bridge Warning Service, published from UT-Austin, but had no Flooded Roads Service. After this six-month project period, the demonstration Bridge Warning Service has been transferred into an operating prototype system that now operates from KISTERS Datasphere, and is automatically being updated as new National Water Model flood forecasts become available. It is the output from this system, incorporated into the FAST Flood Dashboard, that enabled the successful testing of the FAST Bridge Warning services by the USGS during flooding near Houston in July 2024. The CTR team has now developed a demonstration Flooded Roads Service, based on NWM forecast updates from KISTERS, and published through UT-Austin. This service shows the extent of road flooding within the Austin District only. This data service has also been included in the FAST Flood Dashboard. Consideration has begun of how to incorporate Data Assimilation into the KISTERS Datasphere to combine NWS forecasting and RQ-30 stream gauging and create improved flood forecasts.

(6) Forecast Data Analytics: A paper has been prepared and approved by TxDOT for journal submission that examines the performance of the National Water Model in accurately forecasting floods. The paper shows that for Texas there is no spatial pattern to the forecast errors with location in the state, that Version 3.0 of the National Water Model is more accurate than its predecessor, Version 2.1, and that significant challenges still exist when forecasting major floods, such as Hurricane Harvey, because of uncertainty in forecasting very heavy rainfall. A Streamflow Data Assimilation scheme has been developed to combine NWS forecasting and

RQ-30 gauge measurements that corrects the error in the flood discharge forecast across the stream network, not just downstream of the gauges, is able to incorporate an ensemble or lagged ensemble of seven forecast variants, and creates a probability framework for the output discharge and allows for the computation of the probability of impact on the low chord of a bridge or over topping of a road surface. This Streamflow Data Assimilation scheme has been applied successfully to 70,000 stream reaches in USGS Water Resources Region 12, comprising all rivers that flow to the Texas Gulf Coast, except for the Rio Grande.

Planning Activities for FY25

This research update report for FY24, has been prepared using contributions from 20 authors representing five organizations (UT-Austin, USGS, ESRI, KISTERS, River Mechanics), with contributors located geographically in many places in Texas and elsewhere. The report provides a common knowledge base to inform the project team and TxDOT of what has been achieved so far in the FAST project. It is intended to use this knowledge as a baseline from which to plan project activities during FY25, beginning on 1 September 2024.