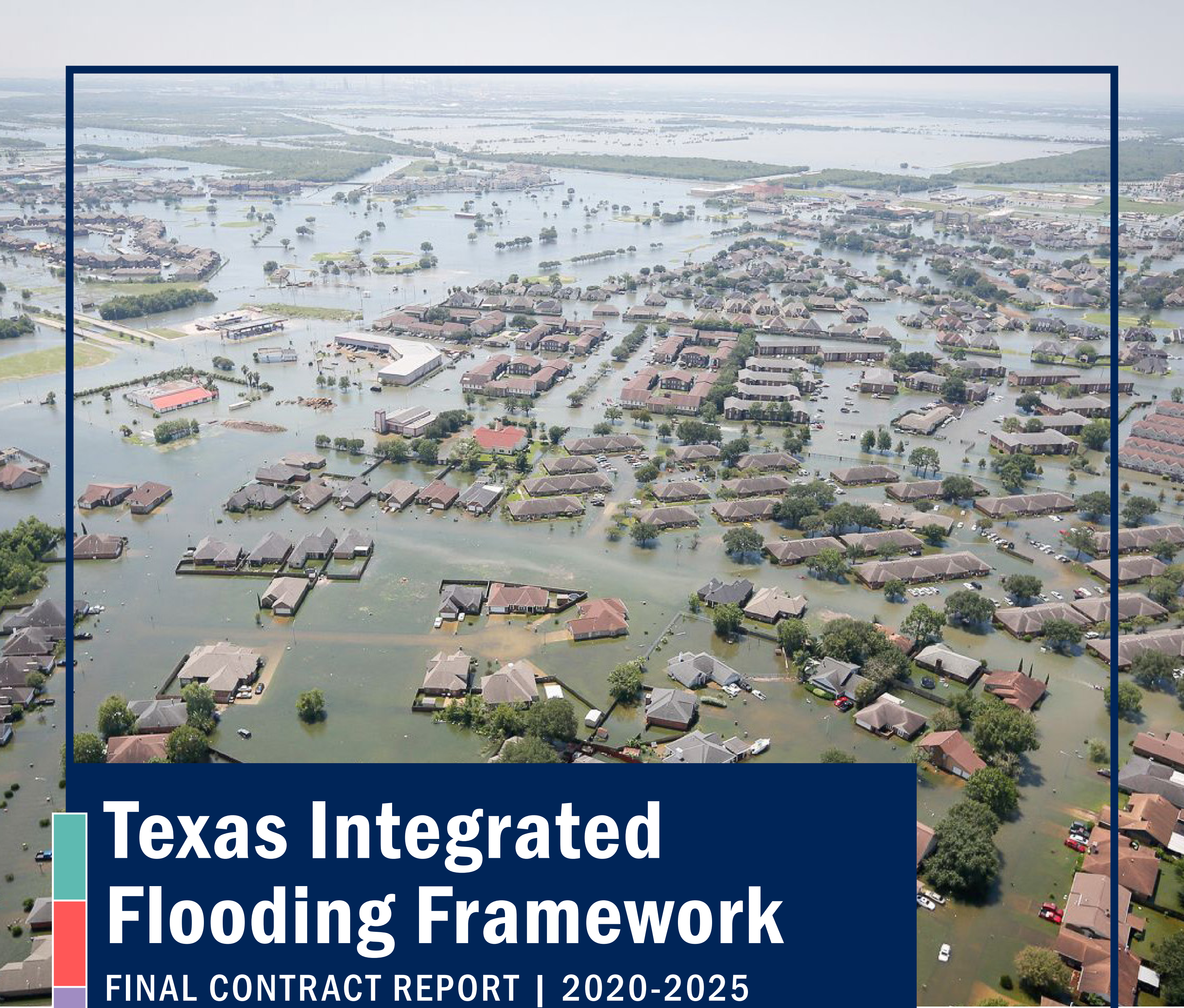

Texas Integrated Flooding Framework

FINAL CONTRACT REPORT | 2020-2025

Texas Integrated Flooding Framework

TEXAS WATER DEVELOPMENT BOARD

USGS science for a changing world

US Army Corps of Engineers.

The Meadows Center for Water and the Environment
TEXAS STATE UNIVERSITY

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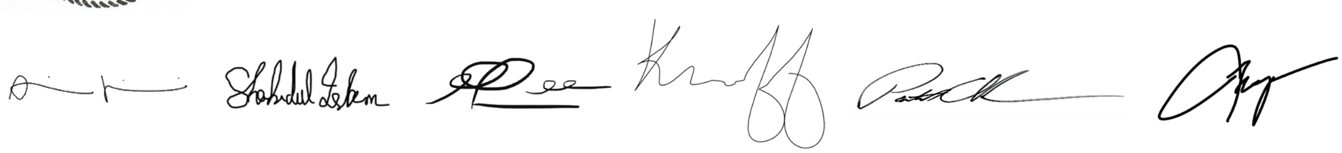

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Cover Photo: Flooding caused by Hurricane Harvey in Southeast Texas © Staff Sgt. Daniel J. Martinez, Air National Guard

Texas Integrated Flooding Framework

FINAL CONTRACT REPORT | 2020-2025

Contract # 21-127-000-C778
Community Development Block Grant
Disaster Recovery Program
Harvey Round 1 Funding

Texas Integrated Flooding Framework

TEXAS WATER DEVELOPMENT BOARD

USGS science for a changing world

US Army Corps of Engineers

The Meadows Center for Water and the Environment
Texas State University

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

Foreword From The TIFF Project Manager

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

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

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

- **Data Needs and Management**: Identifying gaps in existing datasets and establishing protocols for data integration and accessibility
- **Technologies and Modeling**: Evaluating current modeling capabilities and exploring innovative technologies to simulate complex flood scenarios
- **Visualization and Communication**: Developing guidelines and strategies to effectively communicate flood risks to stakeholders and the public
- **Planning and Coordination**: Creating suggestions for coordinated planning across agencies and jurisdictions

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

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

Building directly on the first three years of foundational work, **TIFF will specifically serve the Lower Rio Grande Valley (LRGV)**. Adding LRGV experts to TATs, conducting a regional data inventory and gap analysis, enhancing the new TIFF Coastal Data Surfer with region-specific datasets, creating integrated modeling workflows, and developing targeted communication products in coordination with local and regional stakeholders will help TIFF to tailor research, tools, and recommendations to the unique challenges faced by Starr, Hidalgo, Willacy, and Cameron counties. Work in the year ahead will center on targeted studies, technology investments, and embedding TIFF outputs into flood risk planning and decision-making processes.

Ultimately, TIFF is a foundation for the future of flood science in Texas. TIFF will continue to evolve as a dynamic framework, fostering collaboration among state and federal agencies, academic institutions, local governments, and private sector partners. The TATs will continue to play a vital role in the next phase. Their ongoing involvement will ensure that TIFF remains grounded in the latest science and best practices, while also fostering innovation and cross-sector collaboration.

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

Amin Kiaghadi, Ph.D., P.E.
TIFF Project Manager & Coastal Science Manager, TWDB

Acknowledgements

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

The idea for TIFF was born when colleagues from TWDB, USGS, and USACE began exploring how to better coordinate their work in the wake of Hurricane Harvey to help Texas better understand and manage compound flood risk along the coast.

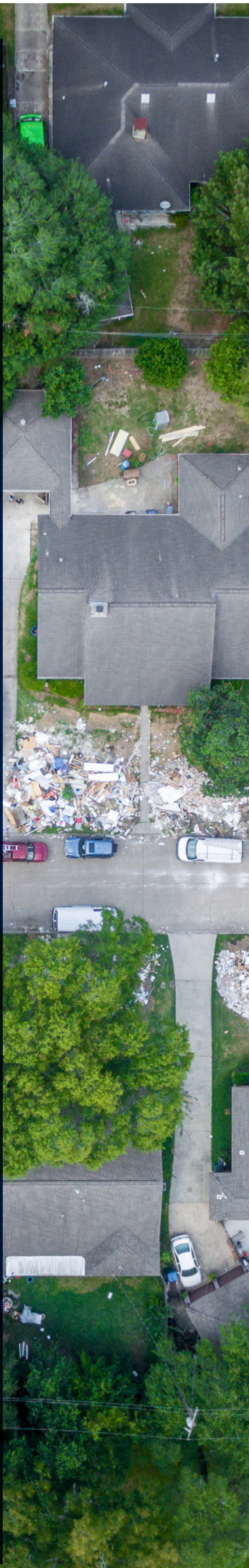
Those early discussions gained momentum when Tyler Payne from GLO recognized that this effort aligned closely with broader state recovery and mitigation goals. With support from GLO through Community Development Block Grant Disaster Recovery funding, TIFF began to take shape. The project officially launched in 2020, with TWDB designated as the lead agency and USGS and USACE serving as core technical partners. Two representatives from each agency were identified to serve as the Steering Committee for TIFF. The Meadows Center for Water and the Environment at Texas State University was selected to join the Leadership Team to guide project implementation, maximize engagement with external experts, and convey the resulting process outcomes to GLO and the public.

Each entity brought its own expertise and perspective to the table, united by a shared vision to develop the tools and knowledge needed to understand and plan for compound flooding along the Texas coast:

- USACE contributed specialized expertise in coastal processes and freshwater and marine systems. Their work focused on hydrologic, hydraulic, and coastal engineering with an emphasis on numerical modeling, in-situ monitoring, and environmental information systems.
- USGS added decades of experience in operating large-scale coastal monitoring and environmental research projects, supporting the project with its capacity for flood warning and prediction, as well as hydraulic and hydrodynamic modeling.
- TWDB ensured that the needs and voices of Texas communities remained at the forefront. They also contributed expertise in geospatial modeling, machine learning, hurricane storm surge simulation, rainfall-induced flooding, and the water-energy nexus.
- The Meadows Center brought its unique blend of technical, science communication, and stakeholder engagement expertise to translate the objectives and goals into an accountable action plan and a structure to guide and support decision-making.

This leadership team is only one component of the TIFF partnership. More than 100 leading experts accepted nominations to volunteer their expertise via four Technical Advisory Teams who guided the development of TIFF's four core components. Additionally, each component was supported by external study providers working behind the scenes to conduct literature reviews and research necessary to meet the TIFF objectives. These study providers included:

- Clint Dawson of the University of Texas (UT)–Austin, Department of Aerospace Engineering & Engineering Mechanics
- Ben Hodges of UT–Austin Maseeh Department of Civil, Architectural, and Environmental Engineering
- Saugata Datta of UT–Austin Department of Earth and Planetary Sciences



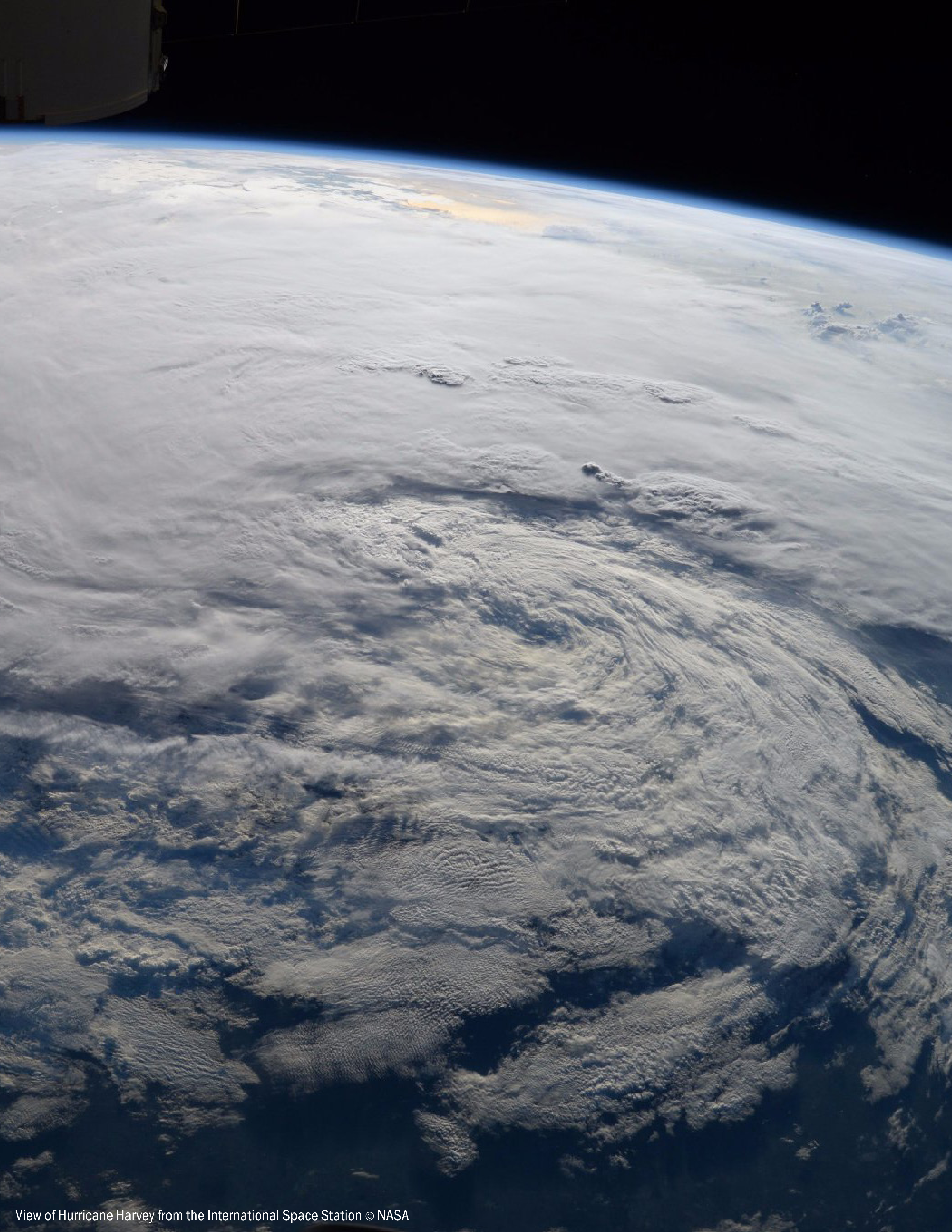
Aerial photograph of Texas coast following landfall of Hurricane Ike in Galveston (2008) © NOAA/NOS/National Geodetic Survey/Remote Sensing Division, NOAA/

- Sina Khani, Mark Loveland, and Erik Valseth of UT–Austin Computational Hydraulics Group at the Oden Institute for Computational Engineering & Sciences
- Keri Stephens, Jovana Andelkovic, Tara Tasuj, and Samanta Varela of UT–Austin from the Department of Communication Studies, Moody College of Communication
- Suzanne A. Pierce of UT–Austin Research Scientist, Texas Advanced Computing Center (TACC)
- Elizabeth Le, UT-Austin School of Information
- Jianhong-Jennifer Ren of Texas A&M University (TAMU)–Kingsville Department of Environmental Engineering
- Gabriele Villarini and Renato Amorim of the Princeton University Department of Civil and Environmental Engineering and the High Meadows Environmental Institute
- Felipe Quintero Duque, Marcela Rojas Oliveros, and Nicolás Velásquez Giron of the University of Iowa, Iowa Institute of Hydraulic Research
- Andrew Kennedy of the University of Notre Dame Department of Civil and Environmental Engineering and Earth Sciences
- David Johnson and Aaron Dewar, Purdue University School of Industrial Engineering
- Meredith Carr, Fatima Bukhari, Ahmad Tavakoly, Chris Massey, Gaurav Savant, and Gregory S. Karlovits of USACE
- Sam Wallace, Glenn Harwell, and Jon Thomas of USGS

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

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

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


View of Hurricane Harvey from the International Space Station © NASA

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Acronyms

ACE	Annual Chance Exceedance
ADCIRC	ADvanced CIRCulation Model
AdH	Adaptive Hydraulics
AEP	Annual Exceedance Probability
AI	Artificial Intelligence
AIC	Aikake Information Criteria
AOI	Areas of Interest
AORC	Analysis of Record for Calibration
API	Application Programming Interface
AWS	Amazon Webservice
BCA	Benefit-Cost Analysis
BLE	Base Level Engineering
CDBG	Community Development Block Grant
CDS	Coastal Data Surfer
CFD	Computational Fluid Dynamics
CFM	Certified Floodplain Manager
CHARM	Community Health And Resource Management
CHART	Coastal Hazards Analysis and Risk Toolkit
CHG	Computational Hydraulics Group
CHL	Coastal and Hydraulics Lab
CHS	Coastal Hazards System
CHS-CF	Coastal Hazards System-Compound Framework
CHS-LA	Coastal Hazards System – Louisiana
CHS-PCHA	Coastal Hazards System - Probabilistic Coastal Hazard Analysis Framework
CHS-TX	Coastal Hazards System – Texas
COOP	Cooperative Observer Network
CPU	Central Processing Unit
CSRM	Coastal Storm Risk Management
CSTORM	Coastal Storm Modeling and Production Systems
CSTORM-MS	Coastal Storm Modeling System
CTXCS	Coastal Texas Protection and Restoration Feasibility Study
CWL	Combined Water Level
DDF	Depth Damage Curve
Delft3D	3D modeling suite to investigate hydrodynamics, sediment transport and morphology and water quality for fluvial, estuarine and coastal environments
DOT	U.S. Department of Transportation

EPA	U.S. Environmental Protection Agency
EQ	Environmental Quality
ERDC	Engineer Research and Development Center
FAIR	Findable, Accessible, Interoperable, and Reusable
FEMA	Federal Emergency Management Agency
FFE	First Floor Elevation
FI-DD	Flood Inundation Data-Driven Model
FI-H	Flood Inundation Hybrid Model
FI-I, FI-II, FI-III, FI-IV	Flood Inundation Models 1-4
FIRM	Flood Insurance Rate Map
FRM	Flood Risk Model
FVCOM	Finite Volume Community Ocean Model
G2CRM	Generation 2 Coastal Risk Model
GCM	Global Climate Model
GCOOS	Gulf of Mexico Coastal Ocean Observing System
GenAI	Generative AI
GIS	Geographic Information System
GLO	Texas General Land Office
GPM	Gaussian Process Metamodeling
GPU	Graphics Processing Unit
GSSHA	Gridded Surface/Subsurface Hydrologic Analysis Model
GUI	Graphical User Interface
H&H	Hydrologic and Hydraulic
HAI	Human-Centered Artificial Intelligence
HCFCD	Harris County Flood Control District
HDF5	Hierarchical Data Format version 5
HEC-FDA	Hydrologic Engineering Center's Flood Damage Reduction Analysis Model
HEC-HMS	USACE Hydrologic Engineering Center Hydrologic Modeling System
HEC-RAS	USACE Hydrologic Engineering Center River Analysis System
HEC-SSP	Hydrologic Engineering Center's Statistical Software Package
HF	High Frequency
HL	Hazard Level
HMGP	Hazard Mitigation Grant Program
HPC	High Performance Computing
HUD	U.S. Department of Housing and Urban Development
HURDAT2	Hurricane Database 2
IBWC	International Boundary and Water Commission

IDRT	Institute for a Disaster Resilient Texas
IIHR	Iowa Institute of Hydraulic Research
InFRM	Interagency Flood Risk Management
InSAR	Interferometric Synthetic Aperture Radar
IWR	Institute for Water Resources
JCBP-TX	Joint Coastal Bivariate Probability Study – Texas
JPM	Joint Probability Model
JPM-AMP	Joint Probability Model with Augmented by Metamodel Prediction
JPM-OS	Joint Probability Model with Optimal Sampling
JSON	JavaScript Object Notation
LEP	Limited English Proficiency
LiDAR	Light detection and ranging
LISFLOOD	Large-scale Inundation Simulation using FLOOD
LRGV	Lower Rio Grande Valley
M3FR	Measuring, Mapping, and Managing Flood Risk in Texas Modeling Catalog
MIKE SHE, MIKE 21 HD, MIKE 11 HD, MIKE+ Rivers	Models developed by DHI for hydrology and hydraulics
ML	Machine Learning
MODFLOW	Modular Finite-Difference Flow Model
MOM	Maximum of the Maximum
MPI	Message Passing Interface
NBS	Nature-Based Solutions
NDBC	National Data Buoy Center
NED	Net Economic Development
NetCDF	Network Common Data Form
NFHL	National Flood Hazard Layer
NNBF	Natural and Nature-Based Feature
NOAA	National Oceanic and Atmospheric Administration
NOPP	National Oceanographic Partnership Program
NSI2	National Structure Inventory 2
NWIS	National Water Information System
NWM	National Water Model
NWS	National Weather Service
OSE	Other Social Effects
OSP	Open Science Platforms
P&G	U.S. Water Resource Council's 1983 Principles and Guidelines for Water and Related Land Implementation Studies

PE	Professional Engineer
POM	Princeton Ocean Model
PRIMo	Parallel Raster Inundation Model
PRISM	Parameter-Elevation Relationships on Independent Slopes Model
PRMS	Precipitation Runoff Modeling System
QA/QC	Quality Control / Quality Assurance
RATES	Research, Applied Technology, Education and Service
RED	Regional Economic Development
Regional Flood Studies	Combined River Basins Studies
RFPG	Regional Flood Planning Group
SC	Steering Committee
SCHISM	Semi-implicit Cross-scale Hydroscience Integrated System Model
SECOORA	Southeast Coastal Ocean Observing Regional Association
SFHA	Special Flood Hazard Area
SFINCS	Super Fast INundation of CoastS
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
SLR	Sea Level Rise
SMART	Specific, Measurable, Attainable, Relevant, and Time-based
STWAVE	Steady-State Spectral Wave Model
SWAN	Simulating Waves Near Shore
SWAT	Soil and Water Assessment Tool
SWL	Still Water Level
SWMM	Storm Water Management Model
TABS	Texas Automated Buoy System
TACC	Texas Advanced Computing Center
TAMU	Texas A&M University
TAT	Technical Advisory Team
TC	Tropical Cyclone
TCEQ	Texas Commission on Environmental Quality
TCOON	Texas Coastal Ocean Observation Network
TCRM	Tropical Cyclone Rainfall Model
TCRMP	Texas Coastal Resiliency Master Plan
TDEM	Texas Division of Emergency Management
TDIS	Texas Disaster Information System
TEA	Texas Education Agency
TEKS	Texas Essential Knowledge and Skills
TFCO	Texas Flood Coordination Office

TFMA	Texas Floodplain Management Association
TGP Test	Target Group Pilot Test
TIFF	Texas Integrated Flooding Framework
TRITON	Two-dimensional Runoff Inundation Toolkit for Operational Needs
TWDB	Texas Water Development Board
TxCFF	Texas Coastal Flood Framework
TxDOT	Texas Department of Transportation
TxGIO	Texas Geographic Information Office
TxRR	Texas Rainfall Runoff Model
UFS	Unified Forecast System
UI	User Interface
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
UT	University of Texas
UX	User Experience
VIC	Variable Infiltration Capacity
WASH123D	Watershed Systems of 1D, 2D, and 3D Models
WRF	Weather Research Forecast
WSE	Water Surface Elevation
WWOD	WaterWorks OnDemand

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

Executive Summary

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

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

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

TIFF was funded by the GLO Community Development and Revitalization Department to improve the modeling, data collection, data management, visualization, planning, and outreach efforts in counties affected by Hurricane Harvey and the Lower Rio Grande Valley (LRGV). TWDB serves as the lead agency coordinating a partnership with USGS and USACE – Galveston District. The Meadows Center for Water served as the process facilitators.

The planning project's ultimate goal is to deliver actionable, science-based recommendations that help Texas meet its pressing flood challenges. By focusing on the four components, TIFF seeks to provide practical solutions to all levels of decisionmakers grappling with the known and potential impacts of coastal flooding in Texas.

TIFF produced 42 detailed recommendations (as well as a multitude of research findings, guidelines, and best practices presented in this report and its supporting materials). Four overarching proposals emerged as central to advancing Texas flood resilience, underscoring the value of expert-driven review:

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

The TIFF Recommendations capture the specific investments needed to advance flood monitoring, modeling, communication, and planning in Texas. Each recommendation is designed to articulate what is needed, what it takes, and ideally what it costs, to provide funders and policymakers with a clear roadmap for strengthening the state's flood resilience, ensuring that communities, infrastructure, and ecosystems along the Texas coast are better protected for the future.

Summarized Component Achievements and Progress

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

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

TIFF Component 1: Data and Monitoring Gap Analysis

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

The literature review covered available flood-related datasets, existing data-model linkages, and critical monitoring technologies and data frameworks needed to support coastal flood analysis in Texas. It considered best practices for building data inventories and creating interactive platforms for data sharing, with an emphasis on the need to improve the accessibility of flood data for decision-makers at all levels. Gap analysis efforts focused on specific "use cases" to identify data needed to improve coastal flood observations, and revealed shortcomings in metadata standards, data compatibility, and coverage of specialized data such as bathymetry, subsidence, and nearshore wave data. Existing monitoring databases have inconsistent data and categorization, existing sensor networks are insufficient to capture meaningful data, and existing data collection efforts are often duplicated.

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

TIFF Component 2: Data Management and Visualization

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

The literature review used systematic and diagnostic approaches, including human-in-the-loop artificial intelligence techniques, to identify communication best practices and effective visualization strategies for flood risk data that meets user needs. Effective communication and interactive visualizations rely on early and ongoing user engagement. The gap analysis revealed shortcomings in communication and visualization tools, particularly in usability, accessibility, and contextual relevance for vulnerable populations. Notable gaps include the need for best practices for menu-driven dashboards and information interfaces that transparently disseminate model uncertainty, as well as clear approaches to integrate model data and outputs into flood planning.

Findings revealed widespread challenges in understanding flood probabilities and map symbology among all audiences (technical, and non-technical). Recommendations call for statewide adoption of communication guidelines, clearer terminology for flood probabilities (especially in bilingual formats), and behavioral studies with target user groups to optimize interface designs and emergency planning.

TIFF Component 3: Integrated Flood Modeling Framework

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

The initial inventory effort was to collect information on current and recent statewide flood-related modeling and data-driven studies and projects (with a focus on coastal flooding and including some local projects). The purpose of the TIFF Statewide Inventory of Flood-Related Modeling and Data-Driven Studies/Projects is to avoid duplicating efforts and to facilitate collaboration and communication among stakeholders. This inventory is intended to serve as a living document for interested stakeholders and contains basic project information, project details, funding sources, and a point of contact information for the various projects with regional importance across the state. The inventory now hosts a total of 140 statewide and 16 local projects and serves all four of TIFF's Components. The statewide inventory of projects, with a brief description, source of funding, and their point of contact information, are provided in Supporting Material 3-12. If you know of any projects that are not currently listed in the inventory, we encourage you to add them here: https://bit.ly/3VcUpsX.

A systematic literature review was conducted with expert teams across hydrology, hydraulics, meteorology, coastal engineering, and probabilistic hazard analysis to analyze the state-of-the-art in flood modeling tools and methods relevant to Texas (coastal, inland, and riverine). The review considered probabilistic modeling approaches along with a variety of models (rainfall and forecasts, river and watershed dynamics, coastal and estuarine surge, wave, and compound flooding processes), identifying strengths, limitations, and application contexts for each modeling type.

The gap analysis highlighted fragmentation caused by limited sharing of coastal flood model metadata and the absence of standardized workflows for coupling diverse models, which currently rely on custom and labor-intensive solutions. Additionally, there were gaps in model coverage for some geographic regions, metadata quality, and quantifying and propagating uncertainties.

The findings highlight the need for a robust, integrated framework (The Texas Coastal Flooding Framework or TxCFF) to link disparate models, facilitate data transfer, and support modular workflows for compound flood risk assessment across the Texas coast. Additional recommendations include prioritizing open-source community models, standardizing and automating data/model sharing, developing model and study databases, improving wave and erosion modeling, and deploying real-time tools for stakeholders.

TIFF Component 4: Planning and Outreach

Component 4 worked to bridge the gap between technical modeling and community priorities, ensuring that flood mitigation strategies are informed by the people and places they are designed to protect.

The targeted literature review and inventory analysis examined planning tools and models from federal, state, and local agencies, with a focus on how these tools support decision-making for compound flooding and risk reduction. It focused on cataloging tools based on their applications, data requirements, and limitations. Component 4 identified key gaps such as outdated databases, inconsistent data standards and reporting formats for planning studies, and missed opportunities to unify ongoing flood risk reduction initiatives.

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

Looking Forward

In 2026, TIFF is conducting additional targeted research specific to the LRGV and engaging the four TATs to identify additional TIFF Recommendations to support the unique conditions and needs of this region. Additional phases of TIFF are envisioned for the future.

Devastation following Hurricane Harvey ©Erin Gay

TIFF Structure and Development

Mission: *TIFF leverages expertise and resources to bring about the best information to enhance coastal flood risk, planning, and mitigation.*

Vision: *TIFF empowers Texans with reliable information to increase flood resiliency.*

Funded by the GLO Community Development and Revitalization Department, TIFF is a collaborative planning project developing recommendations, guidelines, and frameworks to improve the modeling, data collection, data management, visualization, planning, and outreach efforts in counties affected by Hurricane Harvey and the LRGV. GLO, through its CDBG Disaster Recovery Program, funded TWDB to serve as the lead agency to coordinate a comprehensive flood risk reduction planning project in partnership with USGS and USACE – Galveston District. The Meadows Center for Water and the Environment joined the project as process facilitators.

Project Identity

Purpose and Need

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

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

Outcomes

TIFF is not an effort to produce specific models or datasets or to solve a particular problem. Instead, the outcomes of TIFF will be the roadmap to improving the state's modeling, data collection, data management, visualization, planning, and outreach efforts in the future. If existing data, information, products, or models to best meet those needs do not yet exist, TIFF will recommend their creation or development. The science-based recommendations included in this report are intended to guide future state initiatives and strengthen Texas' flood resilience. Their purpose is to provide guidance on building infrastructure and policies that support collecting, sharing, and presenting crucial data for decisionmakers. The intent of TIFF is provide the roadmap and build the partnerships and processes needed for tackling challenges together.

Project Structure

TIFF is an innovative multi-level, multi-agency endeavor whose success belongs to the individuals listed below and the many others housed within the partner agencies who provided their support to this ambitious undertaking.

The TIFF Leadership Team

The TIFF Leadership Team is comprised of the project implementing partners: TWDB, USACE, USGS, and The Meadows Center.

STEERING COMMITTEE AND COMPONENT CHAMPIONS

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

- **Caimee A. Schoenbaechler**, M.E.M., Assistant Director of Surface Water Division – TWDB (Year One)
- **Amin Kiaghadi**, Ph.D., P.E., Coastal Modeling Team Lead – TWDB
- **Coraggio Maglio**, P.E., Hydraulics and Hydrology Branch Chief – USACE-Galveston District (Year One)
- **Mohammad "Shahidul" Islam**, Ph.D., P.E., Subject Matter Expert, Coastal Engineering Section – USACE-Galveston District
- **Michael Lee**, Gulf Coast Branch Chief – USGS, Oklahoma-Texas Water Science Center
- **Samuel Rendon**, Hydrologist – USGS, Oklahoma-Texas Water Science Center (Year One)
- **Patrick Corbitt Kerr**, Ph.D., P.E., D.WRE, Hydrology and Hydraulics Branch Chief – USACE-Galveston District (Years Two-Three)
- **Saul Nuccitelli**, Director of Flood Science and Community Assistance – TWDB (Year Two)
- **Kristine Blickenstaff**, P.E., Integrated Hydrology and Data Science Branch Chief – USGS, Oklahoma-Texas Water Science Center (Years Two-Three)

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

Component 1 – Data and Monitoring Gap Analysis (USGS Champion): Identify available data and data gaps and establish a plan for obtaining data critical for successful coastal flood analysis; Support the expansion and improvement of data observations for inland, coastal, and ocean systems

Component 2 – Data Management and Visualization (TWDB Champion): Ensure that coastal flood-related data and model outcomes can be properly visualized for technical and non-technical end-users; Support the effort led by TDIS regarding coastal flood analysis data management and visualization

Component 3 – Integrated Flood Modeling Framework (USACE Champion): Develop an integrated modeling framework to support inland and coastal flood hazard identification

Component 4 – Planning and Outreach (TWBD Champion): Ensure that data and modeling frameworks incorporate the various end-users' flood planning and mitigation needs; Ensure that the findings from various efforts are well communicated; Closely collaborate with the Community Health and Resource Management (CHARM), Regional Flood Planning Groups (RFPGs), and the Combined River Basins Studies (Regional Flood Studies); Support the expansion and improvement of flood planning in Texas by incorporating the new findings into the existing planning tools or recommending the creation of new tools; Balance and communicate between project-based and regional planning scale solutions

All four Components shared similar overarching objectives:

- establish SMART (Specific, Measurable, Attainable, Relevant, and Time-based) goals for the flood modeling framework
- guide the selection of best technological solutions to ensure a strategic flood modeling framework
- provide technical feedback and professional advice
- review and comment on deliverables

FACILITATION TEAM

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

- **Carrie Thompson**, TIFF Lead Facilitator – Director of Operations, The Meadows Center
- **Anna Jones**, TIFF Facilitator – Science Communications Manager, The Meadows Center
- **Desiree Jackson**, TIFF Facilitator – Science and Stakeholder Engagement Specialist, The Meadows Center
- **Sarah Wingfield**, Digital Media Specialist, The Meadows Center

Key support was provided for several key events early in the project by: Nicolas Terasewicz (Meadows Center) and Sara Omar (Kearns and West).

PROJECT MANAGEMENT

TWDB provides project management and oversaw the multitude of state, federal, and private contracts necessary to execute the project. Several staff played ongoing key roles in the project, including those described in the SC section above, and:

- **Rikki Weaver**, Flood Framework Coordinator
- **Luci Cook-Hildreth**, Grant Specialist

TECHNICAL ADVISORY TEAMS

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

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

The SC identified 172 nominees for the four TAT teams based on the project needs, requirements, and suggestions from GLO. After sending out official invitations (Supporting Material A-1) in March 2021, carefully discussing the expertise and background of the identified nominees, and receiving confirmation from the approached nominees, the SC confirmed membership for 96 people in June 2021. The number of people in each TAT continued to vary and change based on project needs and the availability of experts to continue their participation. In total, 135 experts served as TAT members among the four components (listed below).

The TAT members are well-known experts in various aspects of coastal flooding, including data monitoring, new monitoring technologies, data management and visualization, modeling, planning, and outreach. TAT members serve voluntarily and participate in meetings at the beginning of the project, throughout the project based on specific needs and milestones, and at the end of the project. TAT members receive summary information, data, and project materials before TIFF meetings to ensure well-informed and productive discussions. Members are invited to share information and insights on the best available science, state-of-the-art models, methods, and emerging technologies.

Component 1 (Team Champion: Kristine Blickenstaff, USGS)

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

Component 2 (Team Champion: Amin Kiaghadi, TWDB)

- Alan Zunde, AQUAVEO LLC
- Andrew Juan, TAMU-IDRT
- Bill Kirkey, RATES
- Bridget Scanlon, UT-Austin, Bureau of Economic Geology
- Carlos Sanchez, Cameron County
- Diane Howe, FEMA
- Ibrahim Demir, The University of Iowa
- Jason Fleming, Seahorse Coastal Consulting
- Jeff East, USGS
- Jeff Lindner, HCFCD
- Jeffrey Horshburgh, Utah State University-Utah Water Research Laboratory
- Kay Atoba, IDRT
- Kris Lander, NWS
- Kristine Blickenstaff, USGS
- Laura Stearns, IDRT
- Lee von Gynz-Guethle, West Consultants
- Paul Craig, DSI LLC
- Sam Brody, TAMU-College Station
- Steven Mikulencak, TAMU-AgriLife, CHARM
- Taylor Christian, TWDB
- Velinda Reyes, Office of Hidalgo County Commissioner Ellie Torres
- Federico Antolini, IDRT

Component 3 (Team Champion: Mohammad "Shahidul" Islam, USACE)

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

Component 4 (Team Champion: Amin Kiaghadi, TWDB)

- Andrew Ernest, RATES
- Ataul Hannan, HCFCD
- Augusto Sanchez, Cameron County
- Bridget Scanlon, Bureau of Economic Geology
- Britt Corley, USACE
- Caroline Mccabe, USACE-Fort Worth District
- Christopher Emrich, University of Central Florida
- Daniel Arriaga, IDRT
- Greg Waller, NWS-West Gulf River Forecast Center
- Hanadi Rifai, University of Houston
- Javier Guerrero, RATES
- Jet Hays, GLO
- Jianhong-Jennifer Ren, TAMU-Kingsville
- Jon Thomas, USGS
- Katharine Teleki, IDRT
- Katie Landry-Guyton, National Oceanic and Atmospheric Administration (NOAA)
- Keri Stephens, UT-Austin
- Kiersten Stanzel, Coastal Bend Bays & Estuaries Program
- Lisa Marshall, TCEQ
- Liv Haselbach, Lamar University-Region 5 Flood Planning Group (Neches River)
- Melisa Gonzalez, LRGV Development Council
- Mike Ouimet, Texas Division of Emergency Management
- Reem Zoun, TWDB
- Rick Hallman, NWS-Brownsville
- RoseMarie Klee, TxDOT
- Saji Varghese, USACE
- Siddharth Saksena, Virginia Tech
- Steven Mikulencak, TAMU-AgriLife, CHARM
- Tom Jester, USACE
- Tori Johnson, U.S. Naval Academy
- Wes Birdwell, Texas Floodplain Management Association (TFMA)


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

TIFF Literature Review and Research Partners (Study Providers)

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

UNIVERSITY OF TEXAS-AUSTIN

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

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

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

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

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

TEXAS A&M UNIVERSITY–KINGSVILLE

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

PRINCETON UNIVERSITY

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

UNIVERSITY OF IOWA

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

UNIVERSITY OF NOTRE DAME

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

PURDUE UNIVERSITY

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

USACE

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

USGS

Sam Wallace, Glenn Harwell, and Jon Thomas led the development of a web-based data availability tool to inventory and visualize coastal flood data, laying the groundwork for a statewide framework for ongoing coastal flood data management.

TIFF Community

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

Introduction to Compound Flooding

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

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

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

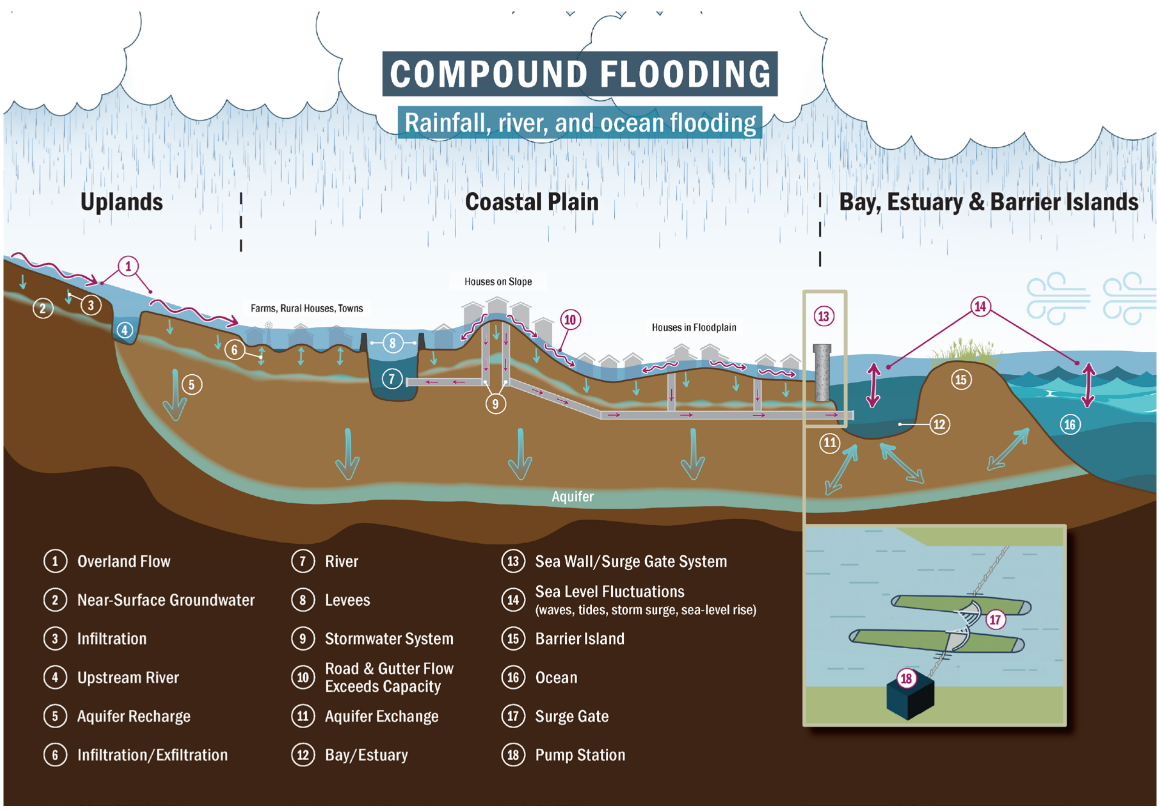


Figure A-1. Compound flooding conditions – multiple and overlapping interactions between flooding types within the design conditions of all infrastructure.

For a more detailed discussion, see Supporting Material 3-9. The overall goal of this section is to provide context for understanding the complexity of compound flooding, and the need for Texas to provide local, regional, and state entities with the compound flood risk information and planning tools necessary for comprehensive regional flood planning and mitigation in the coastal zone.

Flooding Sources

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

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

When two or more of these flooding sources (or drivers) overlap either simultaneously or in sequential combination, a compound flooding event occurs. Instead of addressing challenges related to one source of flooding, communities are faced with evaluating multiple flooding hazards and behaviors.

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

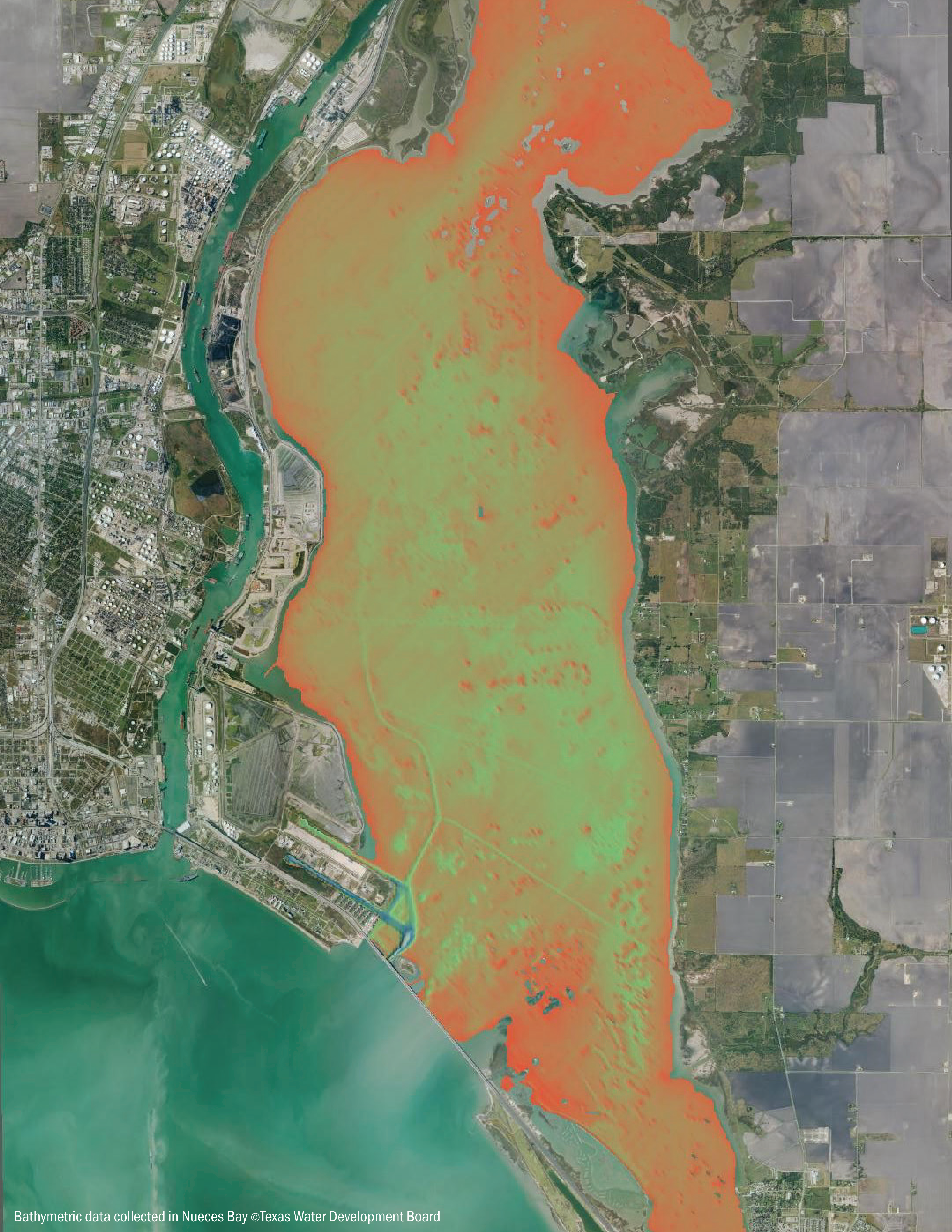
Flooding Behaviors

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

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

The challenge of analyzing and modeling compound floods is that the effects cannot be treated separately and simply added together. In other words, one cannot separately model the flooded volume expected from rainfall, river, and oceanic storm-surge and then add these volumes to predict the flooded areas and depths. This is because each flooding type has interactions with the others, which affects the fate and transport of flood waters. This is why the TIFF project sought to gather the best available information about coastal flooding to improve the current state procedures (e.g., spatially, temporally, technologically, periodically, scientifically, and fundamentally) in data gathering/collection, data management/visualization, modeling, planning, and outreach.

The findings and Recommendations presented in this report uniquely address the complex challenges associated with understanding, predicting, and planning for compound flooding.



Bathymetric data collected in Nueces Bay ©Texas Water Development Board

1 Component 1: Data and Monitoring Gap Analysis

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

1.1 What is Data and Monitoring Gap Analysis?

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

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

Data and monitoring gap analyses inform the suitability and readiness of flood models to address any given decision set, and are crucial steps in developing an integrated framework to help decision-makers understand and plan for coastal flooding.

1.2 Why Data and Monitoring Gap Analysis Matters to Texas

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

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

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

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

1.3 The Guiding Objectives of TIFF Component 1

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

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

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

1.4 Approach to Objectives

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

- identify the leading experts and data practitioners in Texas (23 were selected)
- ask the experts if TIFF is asking the right questions and course-correct as needed
- inventory what data exists for the Texas coast
- conduct gap analyses to identify what data is missing and needed
- initiate coordination with TDIS to begin displaying and integrating data relevant to coastal flood planning and to establish data linkages for priority datasets
- provide structured feedback to GLO on data availability and tool functionality
- implement a data classification system
- create the CDS platform (more below)
- produce recommendations to guide Texas

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

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

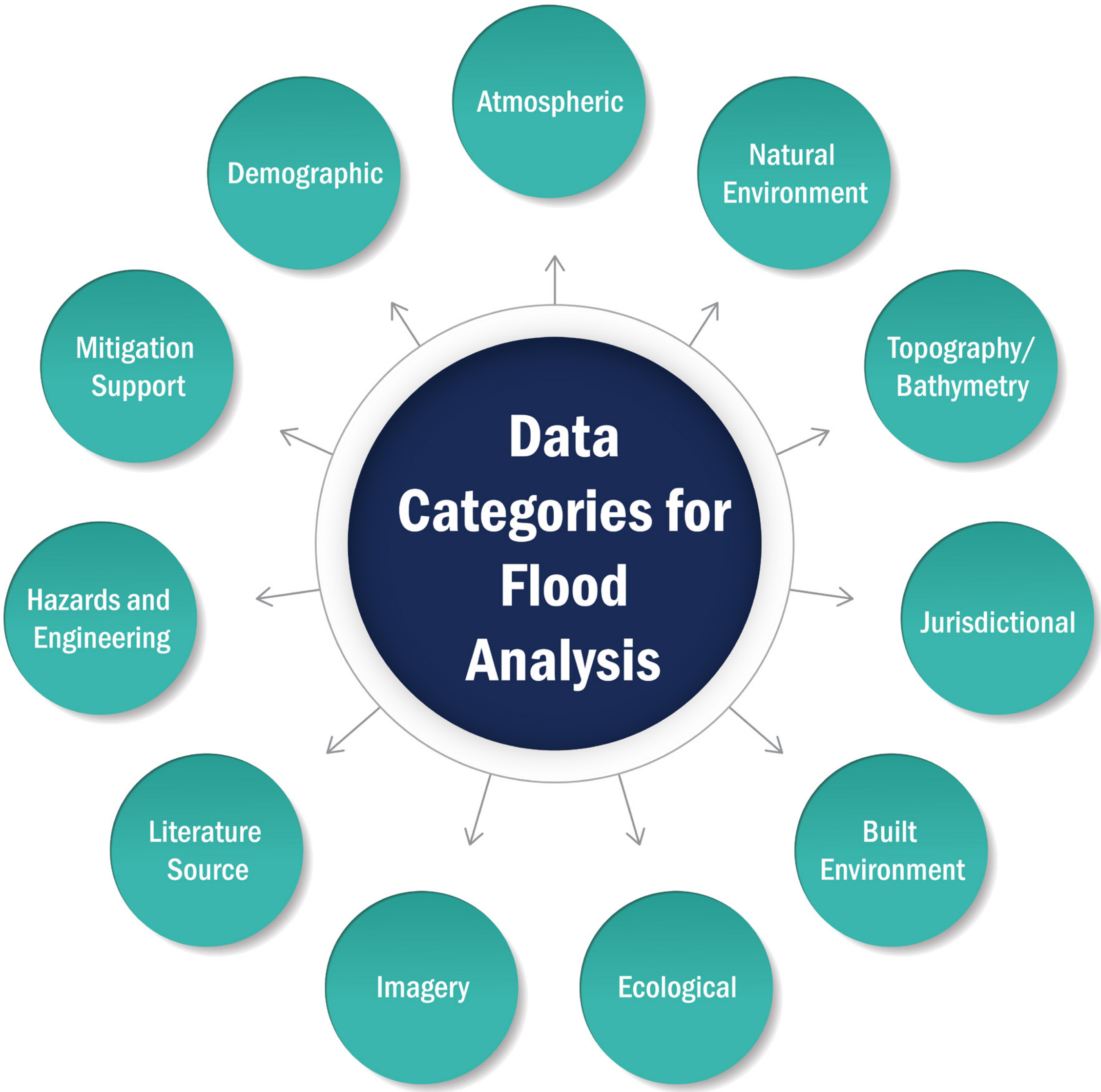


Figure 1-1. Diagram showing the 11 TIFF coastal data classes developed to organize metadata and enable effective filtering of datasets for specific needs.

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

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

Several topic-specific workshops were conducted to further inform data needs and coordination strategies:

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

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

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

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

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

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

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

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

KEY FUNCTIONS OF THE COASTAL DATA SURFER

By integrating interactive mapping, expanded dataset access, and modeling support, the TIFF-informed CDS will directly contribute to better flood preparedness, response, and mitigation efforts across Texas, ultimately reducing risks to communities, infrastructure, and ecosystems. The CDS will serve as 1) an adaptable data and model repository, 2) a coastal data inventory, 3) a tool for performing ongoing data gap analysis, 3) an interactive mapper, and 4) a catalog of model inputs:

1. **Adaptable Data and Model Repository** - The data availability web interface aims to help decision-makers identify future data collection needs to support flood assessments and planning by compiling readily available published flood-related datasets into a single, simplified, categorized, and readily accessible database. The TIFF dataset aggregates a diverse set of contributions from federal, state, local, academic, and nonprofit institutions. Each source provides datasets in various formats, such as GIS layers, tabular data, reports, images, and other digital products, which are essential for flood modeling, hazard analysis, and planning. Major data sources in the CDS include:
   - **USGS**: 26 datasets, including reports, GIS layers, tabular data, and images
   - **TWDB**: 25 datasets, covering reports, GIS layers, tabular data, and images
   - **NOAA**: 15 datasets, including GIS layers, tabular data, images, and other formats
   - **Environmental Information Exchange Network**: 7 tabular datasets relevant to environmental and water quality parameters
   - **FEMA**: 6 datasets, comprising GIS layers, tabular data, reports, and images
   - **Utah Climate Center**: 6 datasets, including GIS layers, tabular data, and images useful for climate and weather analysis

- **Texas A&M AgriLife Extension**: 6 datasets, consisting of GIS layers, tabular data, and images focused on environmental monitoring
- **TxDOT**: 5 GIS datasets, supporting infrastructure and mobility planning
- **TWDB – Texas Geographic Information Service (TxGIO)**: 5 GIS datasets focused on statewide water planning
- **TAMU-Corpus Christi**: Conrad Blucher Institute provided 3 datasets, including tabular data and images relevant to coastal hydrology
- **U.S. Fish & Wildlife Service**: 3 GIS datasets that support ecological and conservation planning
- **U.S. Census Bureau**: 3 datasets, comprising GIS layers and other demographic or economic data formats
- **TxGIO DataHub**: 3 datasets, including GIS layers and imagery
- **Integrated Ocean Observing System**: 3 datasets, including tabular data and oceanographic imagery

Supporting Material 1-1 includes a full list of datasets included in the CDS and their APIs.

2. **Data Inventory** - The public-facing web interface serves a broad audience across various disciplines and flood-related research areas. As a 'one-stop shop' for flood-related data in the study area, the data availability tool should be equally useful to all user groups and dynamic enough to inform the crucial and rapidly evolving climate of flood research along the Texas coast.

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

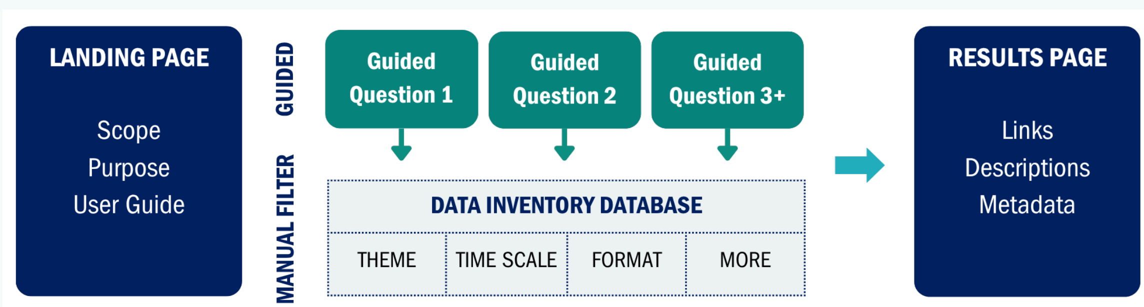


Figure 1-2. A simplified schematic highlighting the web interface's two options for interacting with the data inventory: by a guided questionnaire or through a manual filter of the underlying data inventory database.

The following screenshot (Figure 1-3) captures "Question 6" in the CDS's Guided Search. Users are prompted to specify which modeling software the data will be used in, enabling more tailored filtering of data products. Available options include:

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

See Supporting Material 1-1 for details about the datasets and associated models included in the CDS.

Users may also choose:

- "Select All" to view all relevant data, or
- "I only want the data, I am not building a particular model" for general use cases.

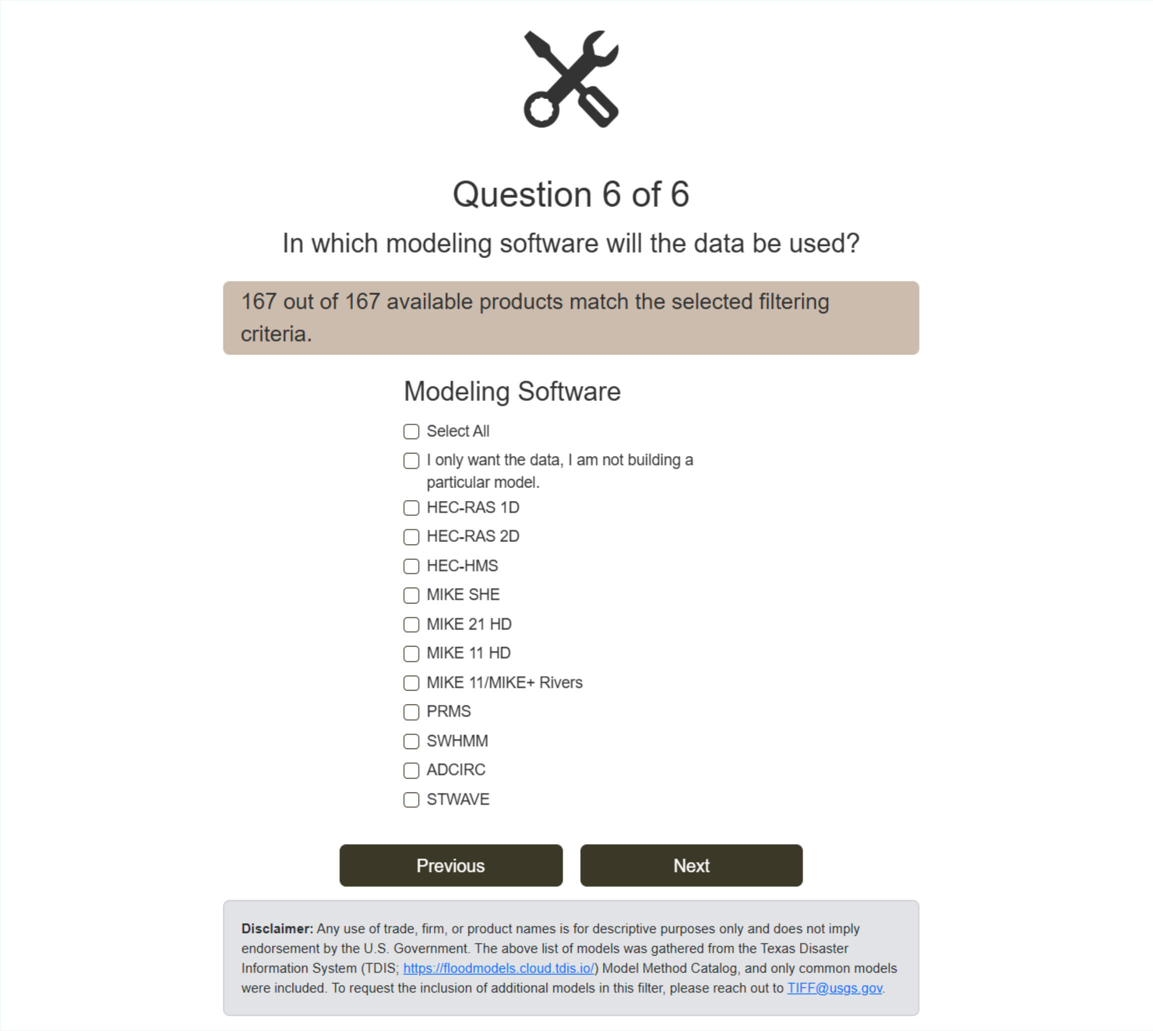


Figure 1-3. A dynamic result count updates based on prior answers and this selection, helping users understand how their criteria refine the dataset. This enhancement supports better discovery and relevance for both technical and non-technical users.

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

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

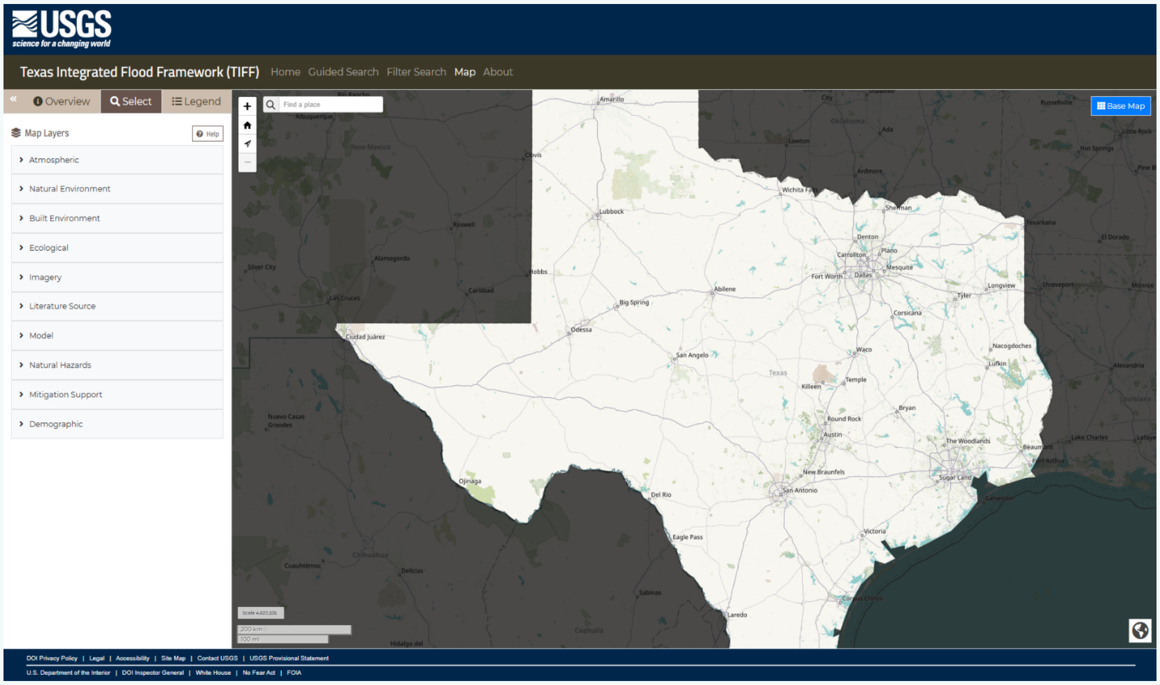


Figure 1-4. Screenshot displaying the interactive map interface where users can explore data layers by thematic category. Users can click on any of the following categories to view and load relevant map layers: Atmospheric, Natural Environment, Built Environment, Ecological, Imagery, Literature Sources, Models, Natural Hazards, Mitigation Support, and Demographics.

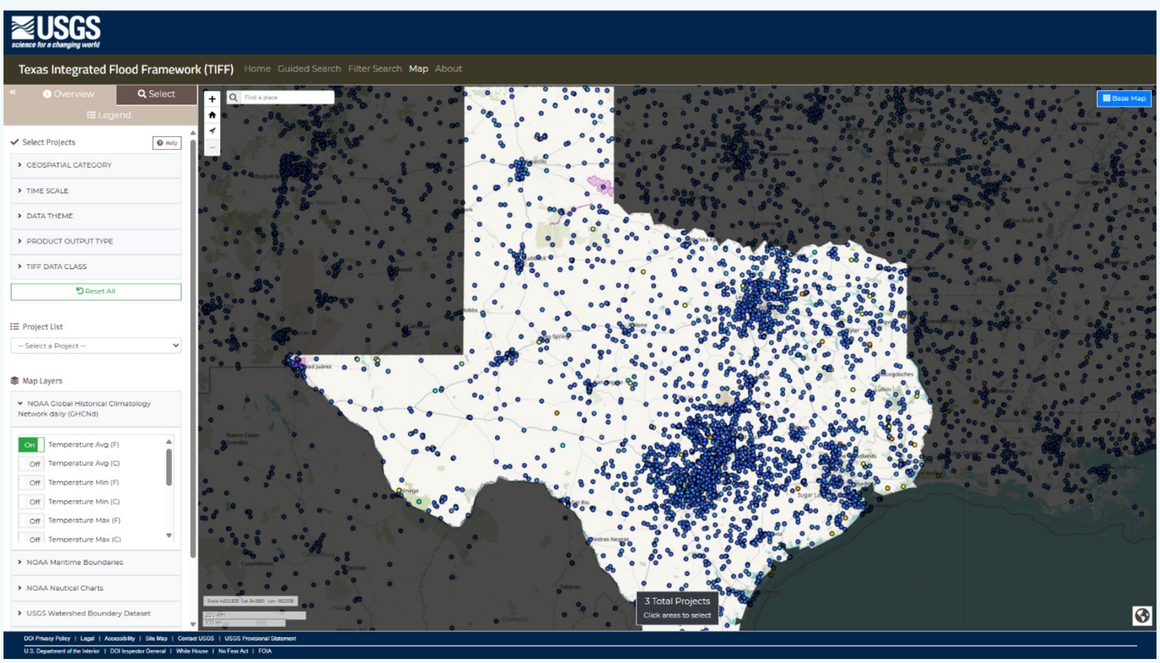


Figure 1-5. Screenshot displaying a visual mask applied around the state of Texas to keep the user's focus strictly on Texas, reducing visual clutter from neighboring states.

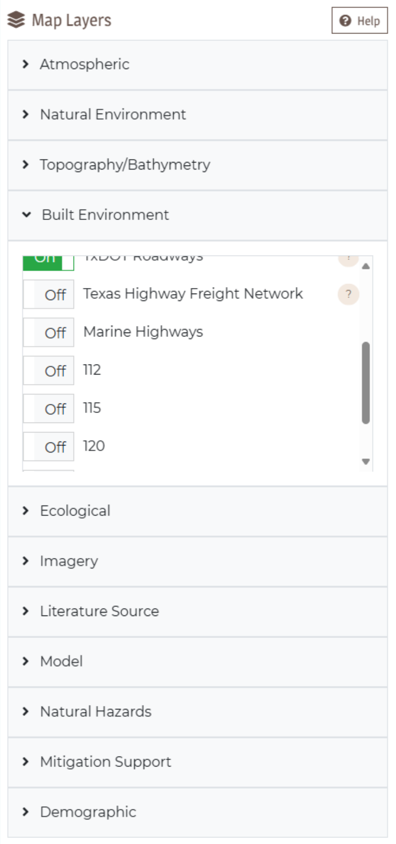


Figure 1-6. Screenshot highlighting map layers that have a "?" icon. When users hover over the icon, a tooltip appears providing helpful information about that specific layer. This improves usability and supports better decision-making.

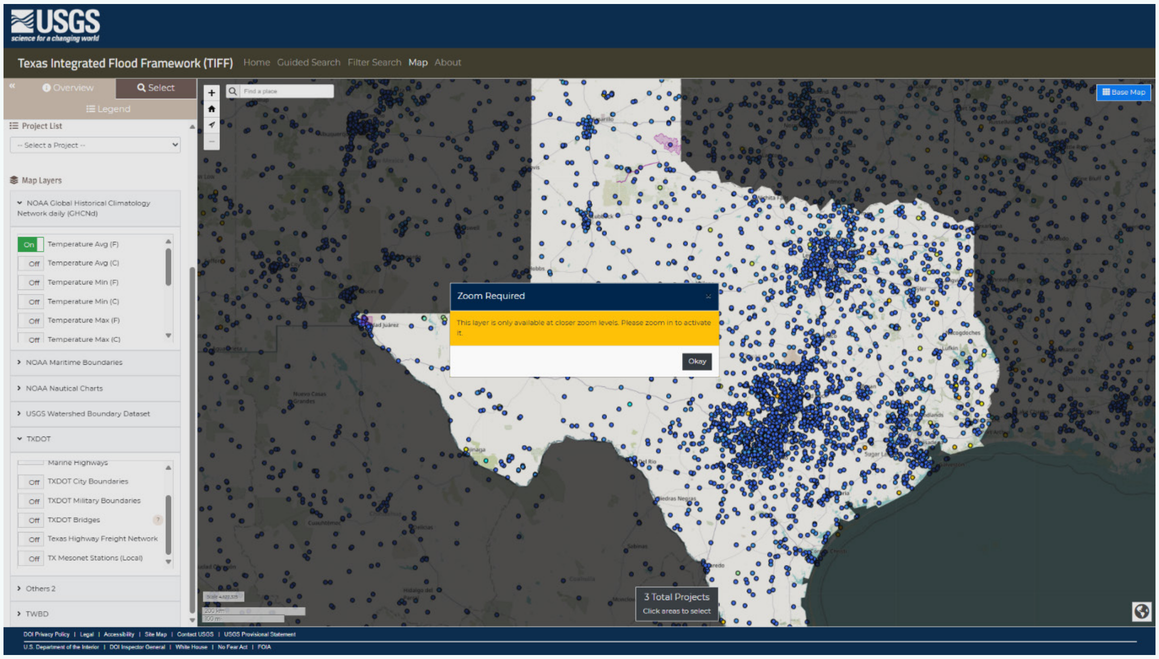


Figure 1-7. Screenshot showing an alert that appears when a user attempts to load layers with high data density without zooming in. The alert advises the user to zoom in closer to avoid long loading times. The final screenshot demonstrates the outcome after zooming in — the relevant data is successfully displayed, improving both performance and user experience.

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

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

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

Flooded residential street © Luis, Adobe Stock

1.5 Implementation of Objectives

Objective 1: Establish a Data and Monitoring TAT

The SC identified USGS hydrologist Samuel H. Rendon to serve as the initial Team Champion for Component 1's TAT. Samuel led the effort from 2021-2023. Kristine Blickenstaff and Jonathan Thomas assumed the Champion role for Component 1 in 2023.

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

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

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

The following advisors were selected to serve as members of the Component 1 TAT based on their expertise in coastal flood data availability, technical data collection requirements, and the interpretation and application of modeling methodologies.

COMPONENT 1 TECHNICAL ADVISORS

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

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

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

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

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

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

As with all inventories, a data inventory should start with an understanding of what is being inventoried and why. Component 1 engaged the TATs by asking for volunteers to join a Data Workgroup to determine what datasets apply to coastal flood analysis. A list of approximately 100 datasets was split into ten major data classes, and the Data Workgroup was asked to review each data class and its associated datasets and add any additional datasets that apply to that data class. As a result, an additional 53 datasets were identified. Next, TIFF curated the results into a list of 143 individual datasets that are shown in column three of Supporting Material 1-2.

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

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

TIFF then created a single RFPGs-TIFF Data Classification Map, relating the curated list of critical datasets created by the Data Workgroup with the lists and categories developed by the RFPGs, while taking care to as closely as possible mirror the initial schema presented by the RFPGs. This Data Classification Map also included a TIFF Data Themes field to relate datasets that may fall into different categories based on the use case or other reasons. TIFF then asked the Data Workgroup to determine any other names that may apply to each dataset and select the appropriate keywords that best described each of the 143 datasets, shown in column three: TIFF Initial Dataset Name (Supporting Material 1-2). Columns 5-12 of Supporting Material 1-2 show the results of these efforts, with a summary of the TIFF Data Classification Workshop provided in Supporting Material 1-3.

Additionally, TDIS and TIFF have determined that a purpose-driven hierarchical structure is the most effective way of organizing the information needed to create the data availability tool by linking the purpose of analysis to each dataset. An initial iteration of the conceptual schematic for a purpose-driven structure is shown in Figure 1-8, with explanations of each term described below:

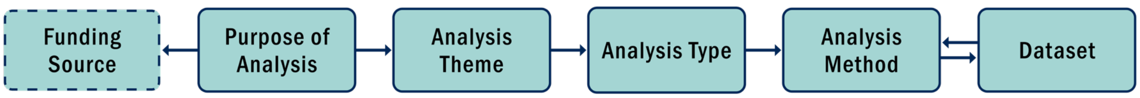


Figure 1-8. Schematic of the purpose-driven inventory structure.

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

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

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

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

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

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

Figure 1-9 shows a possible example of how the "Analysis Method" of HEC-HMS may be used in support of a particular "Purpose of Analysis." This example generally illustrates the connections to be made and the expected branching structure as each "Purpose of Analysis," "Analysis Theme," etc., is filled out to correspond to the "Dataset" inputs and outputs. TIFF then held a workshop with the Data Workgroup to gather feedback on the framework, focusing on the areas of "Purpose of Analysis," "Analysis Type," and "Analysis Method."

The workshop included an interactive, facilitated discussion to solicit feedback on the purpose-driven structure and determine what analysis types and methods are important to workshop participants. TIFF asked participants to answer the questions associated with each framework element and consider whether their contributions are high priority (important in the near term) or low priority (important in the long term). Participants contributed their feedback and responses verbally or by using a virtual and collaborative whiteboarding tool. Supporting Material 1-4 includes a summary of this workshop.

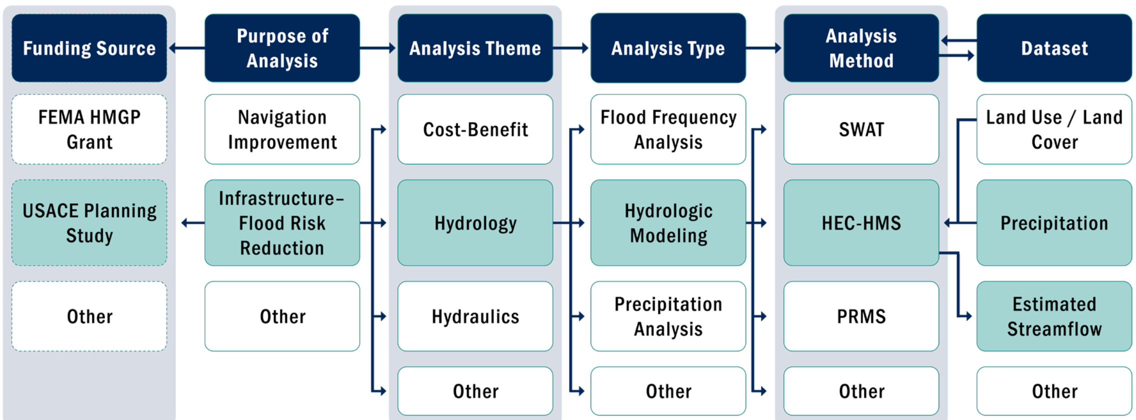


Figure 1-9. Example of hydrologic modeling using the HEC-HMS within the purpose-driven structure.

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

TIFF collaborated directly with TDIS to ensure that all pertinent, readily available datasets were incorporated while avoiding overlapping efforts. Beyond data inclusion, the partnership emphasized collaboration, with TIFF and TDIS while developing data linkages to support critical coastal flood analysis use cases. This included aligning metadata structures, standardizing data formats, and coordinating workflows to ensure robust and consistent integration across platforms. Regular communication, including periodic updates and quarterly meetings, ensured progress, accountability, and sustained alignment between both teams. These data linkages were attributed to the compiled datasets, using 11 TIFF Classes, and subsequently used in the CDS. These classifications were critical to organize metadata guidance and enable the user to filter the entire data inventory to highlight data availability specific to their needs. This framework enabled users to query the full coastal dataset inventory, filter by temporal and format requirements, and directly link to the appropriate data sources.

In its first year, TIFF assisted TDIS in determining the appropriate data structure and conducted an extensive search of flood-related data types available in Texas to inform stakeholders about the available datasets for various model types (TIFF, 2022). Datasets were categorized by data class (atmospheric, natural environment, topography/bathymetry, jurisdictional, built environment, ecological, imagery, literature source, model, hazards and engineering, mitigation support, demographic, and public health) as well as thematic category (hydraulic, hydrologic, risk, water quality) to support the review and classification of datasets. Furthermore, digital repositories and APIs for linkage with an eventual interface were identified to support the creation of the CDS. After data categorization and source cataloging, it was determined whether each dataset had a readily accessible digital format for ingestion into the eventual web interface (see Supporting Material 1-3).

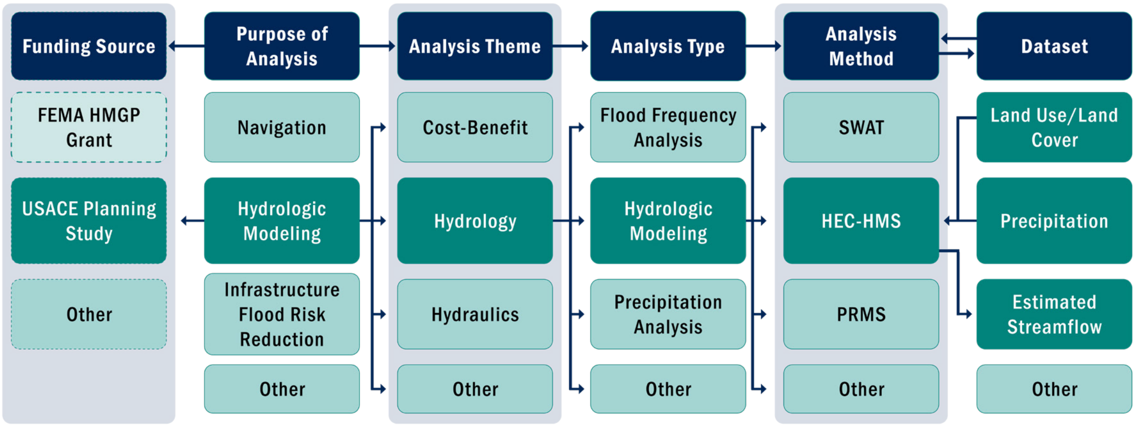


Figure 1-10. A decision tree linking the necessary data for hydrologic analysis using the USACE HEC-HMS. Linkages include FEMA's Hazard Mitigation Grant Program (HMGP), SWAT, and PRMS.

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

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

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

This data inventory may not be comprehensive, but TIFF performed an exhaustive search for a myriad of model input data categories, ranging from meteorological to geographic and socioeconomic. Specifically, TIFF led focused workshops to better understand and assess data classification and linkages along with bathymetric, subsidence, and wave data needs.

DATA CLASSIFICATION WORKSHOP

A data classification workshop was held to review the results of the second TIFF Component 1 Data Monitoring Gap Analysis, specifically the "Data Classification Survey," and determine next steps for advancing data taxonomy and ontology to support a comprehensive coastal flood data inventory. Seven respondents completed the survey, contributing 49 unique keyword tags to the dataset. Survey feedback was generally negative, with respondents finding the survey lengthy and difficult to use. Recommendations included splitting the survey by theme, grouping similar datasets, reducing length, and tailoring questions to field-specific experts. The discussion then shifted to metadata standards for observational datasets. Participants agreed that improvements to the survey process should inform metadata development, specifically in terms of thematic organization, targeted expert input, and group-based refinement. The final topic focused on linking datasets to models and analysis types. The group recommended starting with a few base use cases, specific models and analyses, and performing a literature review to identify existing data-model linkages. These initial linkages would then be refined by the TAT, with additional use cases added iteratively.

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

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

BATHYMETRIC WORKSHOP

Bathymetric data is one of the most important datasets for coastal modeling, but there are obstacles to collecting high-quality data. Bathymetry is highly dynamic, meaning data must be collected regularly. As a result, the datasets are sometimes outdated and inaccurate. TIFF hosted a virtual bathymetry workshop with 90 participants on May 18, 2022, to improve statewide collaboration and advance bathymetry data in Texas. The workshop focused on gathering insight from the TAT members and other bathymetry experts and end-users to develop a statewide priority map for bathymetry acquisition needs and target available resources. TIFF used this information to conduct an inventory and gap analysis for bathymetry data, which resulted in a TIFF recommendation for the areas needing immediate bathymetry data acquisition and the associated costs to complete the work (Supporting Material 1-5).

SUBSIDENCE WORKSHOP

Subsidence is a multi-faceted problem that affects not only land but also groundwater and surface water systems. Many agencies, universities, and organizations across the state are advancing their knowledge and data related to subsidence, but efforts are needed to coordinate these endeavors. TIFF and TWDB cohosted a virtual subsidence workshop with 177 participants on September 7, 2022, to improve statewide coordination for subsidence data collection and sharing. The goal of the workshop was to gather insights from subsidence experts, including the TAT members and faculty from various universities, about acquisition and resource needs for advancing subsidence data in Texas. The workshop concluded with a poll to gather participant feedback and gauge interest in their continued involvement with the collaborative subsidence efforts (Supporting Material 1-6).

WAVE WORKSHOP

One of the more important datasets lacking along the Texas coast, as identified by the TATs, is wave data. TIFF hosted a virtual nearshore wave data workshop on November 2, 2023. The 75 participants explored the opportunities and challenges of wave data collection methods and data measurement needs to support flood mitigation and response efforts. The workshop gathered insights from TAT members and a diverse mix of wave data experts to identify data gaps for various usages and develop strategies to fill these gaps while promoting collaboration among researchers and practitioners working on nearshore wave data. Following the workshop, the TAT and wave workshop participants were asked to complete a Wave Data Mapping Survey (Supporting Material 1-7) to identify priority areas of interest for nearshore wave data collection. This data inventory will supply key information about data coverage, attribute type, and data category for the eventual streamlined access and parsing of the data inventory. This initial data inventory laid the foundation for the development of a data inventory mapping interface (described below).

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

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

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

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

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

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

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

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

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

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

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

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

Objective 8: Evaluate and provide updates on new monitoring technologies

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

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

Recognizing the need for improved coastal monitoring technologies, TIFF evaluated various sensor systems and data collection platforms to determine the most effective solutions for coastal flood monitoring. TIFF developed a recommendation to identify and use a platform to assess various sensors, installation approaches, data transmission options, and power options to identify the most robust options for coastal data collection (Recommendation C1.8A: Operate Testing Sites for Water Monitoring Devices). As water monitoring technologies evolve, the need for robust field testing in challenging environments becomes paramount. TIFF proposes to partner with local, state, and federal agencies to design, install, and operate a testing platform in a coastal environment to evaluate the functionality, environmental resilience, and accuracy of new and existing advanced water monitoring equipment. This platform will provide real-time data and insights into the equipment's performance under varying coastal conditions, helping to ensure that selected monitoring technologies meet both regulatory standards and practical performance criteria. The platform can be used to:

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

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

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

A critical component of the TIFF process was the vetting and finalization of recommendations, ensuring that proposed strategies would have a meaningful impact on Texas' ability to plan for and respond to coastal flooding. Given the complexity of flood risk management and the diverse data, modeling, and monitoring needs involved, it was essential to have a structured, expert-driven approach to refining these recommendations. The TAT members played a key role in this process, leveraging their specialized knowledge and experience to optimize each recommendation before it was finalized.

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

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

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

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

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

- **Potential end users**: Who would benefit from or need to implement the recommendation, e.g., state agencies, researchers, emergency management personnel, policymakers?
- **Time sensitivities**: e.g., urgency and timeframes for successful implementation
- **Implementation entities**: Which organizations or agencies would be responsible for putting the recommendation into action?
- **Associated costs**: e.g., budgetary and funding considerations necessary for execution

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

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

By leveraging expert collaboration, structured evaluation, and comprehensive refinement, the TIFF process successfully produced recommendations that will help Texas enhance its ability to prepare for, respond to, and mitigate coastal flooding in the years to come.

Ultimately, eight TIFF Recommendations resulted from the research and expertise associated with Component 1. See the Recommendations Section for summary handouts that can be used to seek further support for implementation.

Table 1-1. Component 1 objectives and associated recommendations.

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

TIFF RECOMMENDATIONS, DATA MONITORING AND GAP ANALYSIS

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

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

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

Project phases and deliverables should align with other agency flood and hazard mitigation planning cycles, such as the TWDB 2024-2028 Regional Flood Plan. Ongoing maintenance costs vary annually and should be allocated across project phases. Agencies can collaborate on funding different phases or use a cost-sharing formula. Key costs include cloud hosting, data storage, production, User Interface/User Experience (UI/UX) components, security services, and technical debt management.

The CDS is a crucial and ongoing investment.

Key actions when implementing this recommendation include:

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

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

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

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

Potential partners include Texas Councils of Governments for coordinating emergency management and providing inundation photos to enhance observations, TWDB for expertise in socio-economic flood risk factors, and TxGIO as a potential service provider for imagery data storage. Organizations managing local sensor networks, such as the Southeast Coastal Ocean Observing Regional Association (SECOORA), may also contribute to this effort. Key stakeholders include county agencies and non-profits that can serve as community organizers and connectors.

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

The expansion of measurement networks is a cost-effective investment. Key actions when implementing this recommendation include:

- **Data Gap Analysis**: Identify under-sampled areas based on flood frequency, severity, and proximity to vulnerable infrastructure and populations.
- **Exposure and Damage Assessment**: Evaluate data availability and gaps for assessing exposure and damage, incorporating socio-economic factors to refine flood models.
- **Expand Sensor Networks**: Expand local sensor networks and explore funding opportunities through local jurisdictions.
- **Standardized Data Integration**: Develop best-practice guidelines for verifying and incorporating diverse datasets into flood models, ensuring consistency across studies. One potential resource for this phase is the IDRT pilot community data collection tool, which includes a survey, training process, and web portal for displaying results. This tool could be adapted for other regions.
- **Improve Data Completeness**: Address significant data gaps by integrating anecdotal sources, such as citizen science contributions, local agency data, timestamped inundation photos, and media reports.

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

TIFF recommends the establishment of a nearshore wave data collection network along the Texas coast to address critical data gaps, enhance the understanding of extreme wave events, improve daily flood forecasting, and strengthen coastal risk assessment.

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

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

The Nearshore Wave Data Collection Network is a crucial and ongoing investment. Key actions when implementing this recommendation include:

Inventory and Gap Analysis - Conduct a comprehensive inventory and gap analysis of nearshore wave data along the Texas coast to improve understanding of extreme wave events and flood forecasting. Use existing models and datasets to identify priority regions based on coastal infrastructure, population growth, and risk factors. Experts recommend focusing on areas with inconsistent wave measurements, such as Galveston Bay, Port Arthur's Pleasure Island, Keller Bay, Carancahua Bay, and Port Aransas.

Instrumentation Selection - Deploy three types of wave measurement instruments: offshore buoys with independent power supplies that report data every 30–60 minutes, nearshore sensors transmitting real-time directional and non-directional wave data, and shore-based sensors activated during inundation events. Prioritize cost-effective solutions, such as Spotter buoys, along with GPS integration into existing systems, like TDIS or TAMU's Texas Automated Buoy System (TABS). Consideration should be given to the costs of maintenance, data transmission, storage, analysis, and dissemination, which may exceed the costs of instrumentation.

Deployment of Monitoring Stations - Identify and secure monitoring station locations, ensuring resilience to extreme weather. Assess permitting requirements for buoy deployments and integration with NOAA's National Data Buoy Center (NDBC). Develop nearshore and shore-based monitoring infrastructure (may require specialized platforms).

Model Integration and Forecasting - Integrate real-time data into wave, surge, and inland flood models to enhance forecasting. Hourly forecasts will cover the entire Texas coast, including bays, by combining observational data with model outputs. Existing models will be adapted for seamless integration with new datasets.

Data Management and Sharing - Establish a centralized platform for real-time data sharing and long-term storage. High-resolution (15-minute interval) and high-frequency (6 Hz or higher) wave data, including wave height, period, and direction, will support model calibration and validation. Store raw data in barometric-corrected NetCDF format per climate and forecast metadata standards, ensuring permanent availability for post-event analysis.

Long-Term Maintenance and Partnerships - Build partnerships with federal and state agencies (NOAA, GLO, USACE, USGS, Gulf of Mexico Coastal Ocean Observing System (GCOOS), National Oceanographic Partnership Program (NOPP)) for sustained data collection and funding. Engagement with contractors, private entities, universities (TAMU), and industry will support short-term spot measurements. Estimated costs include $100,000–$1,000,000 per year for measurements, $200,000 per year for modeling (with potential increases for model development), and $500,000 for initial buoy deployment. Assess additional funding needs for network expansion and explore collaborative funding strategies to distribute maintenance costs.

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

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

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

Streamlining access to subsidence information and analyses will empower stakeholders to develop informed, effective strategies for mitigating the risks associated with subsidence in Texas.

Subsidence districts, such as the Houston-Galveston Subsidence District, can play a key role by utilizing their existing monitoring stations. These stations could also help expand monitoring efforts to other subsidence areas across the state.

The Centralized Subsidence Monitoring Dashboard is a crucial and ongoing investment, estimated at $200,000–$400,000. Key actions when implementing this recommendation include:

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

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

This data provides more detailed surface distinctions – such as urban structures, vegetation, and water bodies – compared to traditional 30-meter datasets, which are essential for flood impact prediction and management. This data will:

- improve understanding of water flow dynamics and land cover effects
- enhance flood simulations for infrastructure
- support assessments of sea-level rise and coastal changes
- align flood management with federal standards, fostering better coordination with NOAA, FEMA, USACE, and other agencies

Integrating this high-resolution data into coastal flood models will improve flood resilience by enhancing flood simulations, supporting response efforts, and informing long-term planning.

TIFF recommends partnerships with NOAA, TxGIO, and state and local stakeholders to ensure seamless data accessibility and effective implementation. Key actions when implementing this recommendation include:

- testbed numerical model studies for performance evaluations
- developing guidelines for integrating high-resolution land cover data into existing coastal flood models to improve flood simulation accuracy

The data will support flood resilience planning tools used by TWDB, local governments, and emergency management agencies. The total budget is estimated to be between $1–$3 million for all Texas coastal counties. The project timeline is 1-3 years, with future updates occurring every 5–10 years, based on funding and demand.

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

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

TIFF recommends the collection of critical bathymetric data at priority areas along the Texas coast, as identified by project Technical Advisors, to significantly increase the accuracy of coastal flood modeling and forecasting. Agencies could collaborate to better coordinate bathymetry data acquisitions and leverage limited funding resources.

The cost of bathymetry acquisition depends on the type of water body (shallow, deep, and rivers), size of project, and method of collection. Agencies can collaborate on funding different actions or use a cost-sharing formula. Assess additional funding needs for coastal measurement expansion. Key actions when implementing this recommendation include:

- Identify and secure monitoring locations in priority areas identified by experts such as Nueces Bay, Lower Galveston Bay, Sabine Lake, Laguna Madre, and more
- Integrate data into wave, surge, and inland flood models to enhance forecasting
- Establish a centralized platform for data sharing and long-term storage
- Build partnerships with federal (NOAA, USGS) and state agencies (TWDB, TDIS) for sustained data collection and funding
- Develop QC/QA guidelines for identifying monitoring station locations and integrating data into flood models

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

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

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

By delivering real-time data and critical insights, these testing platforms will enhance flood analysis, strengthen coastal resilience strategies, and equip stakeholders with effective tools and methodologies. Key actions when implementing this recommendation include:

- **Site Selection and Design**: Partner with local experts to identify optimal coastal site(s) and design modular, durable platforms that support multiple devices while meeting permitting requirements
- **Equipment Selection and Installation**: Implement a standardized process to select and install sensors for wave height, water quality, and weather parameters, ensuring proper calibration and accuracy
- **Data Collection and Monitoring**: Develop a real-time data acquisition system with remote access and automated alerts for malfunctions

- **Environmental Resilience Assessment**: Evaluate device performance under dynamic coastal conditions, tracking uptime, recalibration needs, and resistance to salinity and biofouling
- **Data Analysis**: Enable stakeholders to analyze data for accuracy, reliability, and operational resilience, ensuring alignment with agency requirements
- **Long-Term Sustainability**: Establish a self-sustaining model through subscription fees, grants, partnerships, and sponsorships

Partnerships with traditional monitoring agencies (e.g., USGS) and other entities (e.g., universities, flood control districts, and non-profits) should be encouraged where feasible. Leveraging existing monitoring sites for technology evaluations can support new methods while filling spatial monitoring gaps with cost-effective solutions.

One recommended technology for testing is disposable, biodegradable flood level sensors, which provide short-term data collection in communities with limited funding. Designed to last six months, these sensors offer lower data quality and are not a replacement for traditional gages. TIFF recommends a multi-year timeline to evaluate emerging technologies under various weather conditions. Annual costs are estimated to be between $500,000 and $5,000,000, with potential savings from using existing platforms.

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

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

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

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

The assessment of the accuracy of HF radar data is a crucial investment. Key actions when implementing this recommendation include:

Data Collection and Comparative Studies - Identify available in-situ monitoring stations (e.g., TABS and NOAA buoys) for comparative studies. Temporary buoys will be deployed where necessary, particularly in Sabine Lake and Galveston Bay, where in-situ data is limited. Comparative studies will be conducted between HF radar data and buoy/vessel-based observations to evaluate performance across different environmental conditions

Long-Term Evaluation - Conduct extended studies to assess the reliability of HF radar systems over time. Seasonal and extreme weather event impacts on HF radar measurements will also be analyzed

Stakeholder Engagement and Reporting - Leverage collaborations with GLO, GCOOS, NOAA, and other coastal management entities to share findings. Interim and final reports summarizing results, challenges, and recommendations will be published. Guidelines for integrating HF radar data into broader coastal management strategies should be developed

Sunrise over Bob Hall Pier on Padre Island ©Steven Miller

1.6 The Future of Texas Data and Monitoring

The targeted research, interactive workshops, input from subject-matter experts, and recommendations have laid the groundwork to enhance data gap assessments, identify monitoring priorities, and promote best practices for coastal flood data. These findings provide a clear path forward for improving flood resilience across the Texas coast.

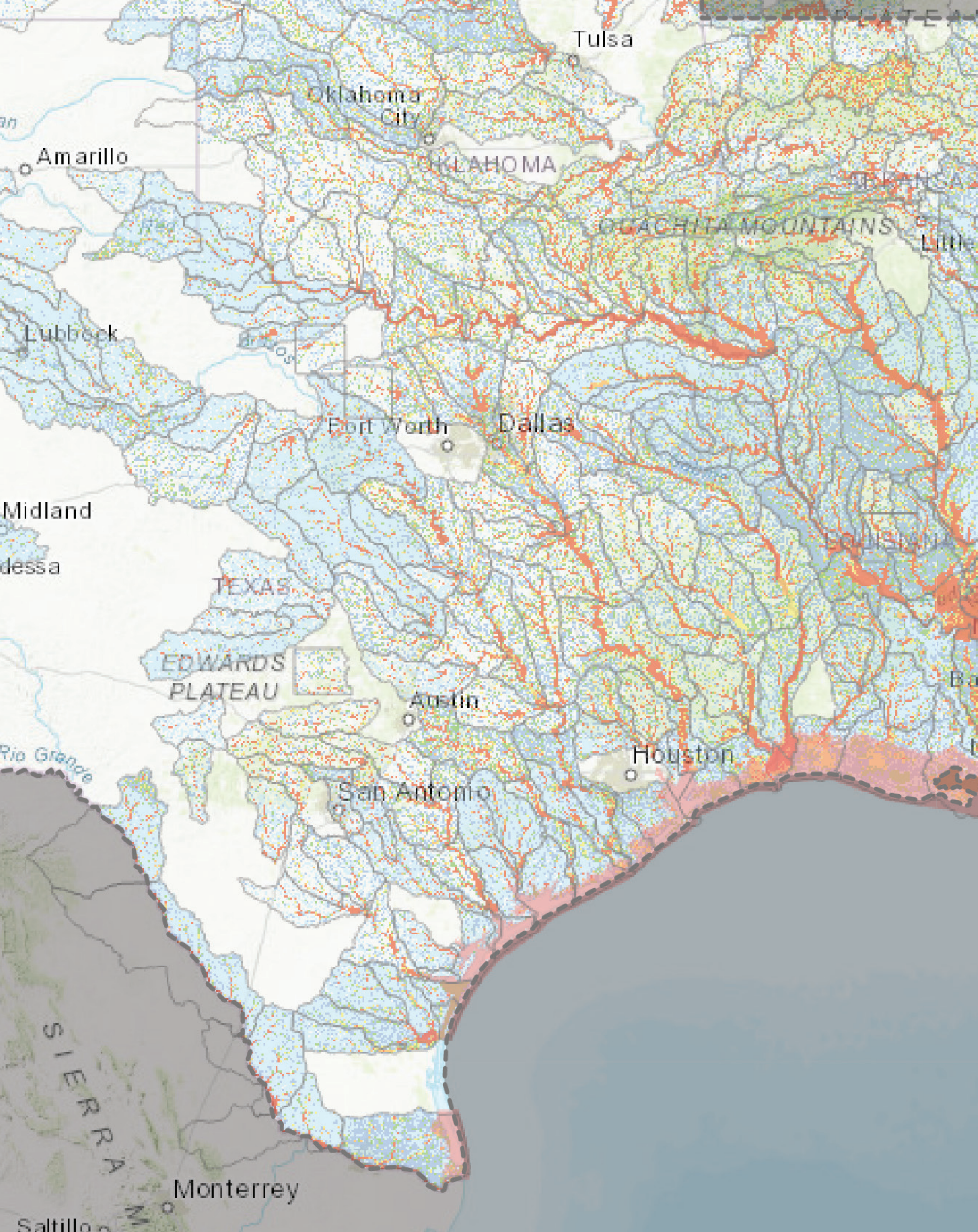
TIFF partners will continue to refine the CDS by incorporating spatial and modeling features that allow users to assess data gaps more precisely and allocate resources more effectively. These enhancements will enable stakeholders to evaluate spatial and technical deficiencies in the existing data landscape. Ongoing collaboration with agencies and partners has helped to ensure that the data and findings generated through Component 1 can be integrated into broader flood planning and mitigation efforts. The continued tool development and incorporation of new monitoring technologies will further strengthen the framework, enhancing both the efficiency and effectiveness of flood mitigation strategies. Although a broad inventory of available coastal flood data and models has been compiled, continued efforts are needed to expand this foundation in the future.

While the CDS provides users with the ability to filter and assess data gaps based on their unique needs, there remains a broader requirement for regular and comprehensive evaluations of critical datasets. It is recommended that an annual assessment of key coastal datasets be conducted using the CDS to identify gaps in spatial, temporal, and formatting coverage. Conducting this assessment prior to the state budget cycle will enable agencies to align funding requests with the most urgent data collection needs, ensuring more strategic investment in flood resilience.

Key recommendations from this study emphasize the importance of improved nearshore wave data, bathymetric data, and subsidence monitoring—all identified as critical by experts, workshop participants, and data gap analyses. Implementation of these recommendations will provide vital information for modeling and decision-making, ultimately helping to safeguard life and property in flood-prone coastal regions.

Throughout the project, TIFF worked closely with partner agencies and stakeholders to ensure that the collected data and findings are not only accessible but also actionable. By improving data integration, accessibility, and monitoring technologies, Component 1 has significantly strengthened Texas' ability to assess and respond to coastal flood risks. The long-term impact of this work ensures that decision-makers have access to accurate, timely, and comprehensive flood-related information to support disaster preparedness, response, and planning in vulnerable coastal areas.

During the course of this project, the LRGV was incorporated into the TIFF study area with region-specific objectives. To support coastal flood analysis in the LRGV, Component 1 will expand the TAT with regional experts, assist TDIS in organizing relevant data, and evaluate existing inventories from the GLO and TWDB. The team will conduct gap analyses, recommend plans for ongoing inventory updates, assess emerging monitoring technologies, and identify potential testbed sites. Leveraging prior research and the development of the CDS, the LRGV assessment will serve as a use case to evaluate dataset completeness and support future enhancements to the CDS.



Snapshot of FEMA's Estimated Base Flood Elevation Viewer

2 Component 2: Data Management and Visualization

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

2.1 What is Data Management and Visualization?

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

In coastal flood planning contexts, data management involves organizing vast datasets (including atmospheric, ecological, demographic, and engineering data) into thematic categories. These datasets must be stored securely, structured consistently, and made digitally accessible for integration into interactive web platforms. Robust data management practices also address challenges in storing, accessing, versioning, and sharing model outputs, ensuring data integrity and interoperability across systems.

Visualization tools should support both technical and nontechnical users by enabling intuitive exploration of risk scenarios. When paired with strong data management, these tools can translate complex flood hazard information into actionable insights for planning and mitigation.

Designing communication strategies with a focus on usability, accessibility, and contextual relevance enhances user understanding. A proactive co-design approach fosters more effective interfaces and user experiences, encouraging broader engagement. Organizing communication strategies around behavioral archetypes and evaluating user decisions helps tailor messages and improve the impact of visualizations.

2.2 Why Data Management and Visualization Matters to Texas

One primary focus of TIFF is to identify techniques and strategies to effectively communicate flood risk through data visualizations or other information-sharing strategies.

Finding effective ways to share collected data from coastal flood models and tools with various audiences is key to decision processes that rely on accurate and reliable information/education. Component 2 focused on understanding the data management and visualization needs of technical and nontechnical user groups in Texas to develop tailored strategies for information tools and communication approaches designed to motivate behavior change. It is key to identify ways that flood model results can be better disseminated (and uncertainties better communicated) to nontechnical audiences.

Extensive research across various fields and input from subject matter experts and stakeholders in Texas have converged on the urgent need for improved communication strategies. *The TIFF Guidelines for Coastal Flood Information Design and Communication* (*The TIFF Communication Guidelines*) presented below convey key highlights and core recommendations that address knowledge gaps and propose innovative approaches to leverage technology and information from data collections and coastal modeling for more effective communication of complex flood risk information. Furthermore, these guidelines outline specific insights that can be seamlessly integrated into design processes, from engaging with community members to implementing functional design practices for UIs. *The TIFF Communication Guidelines* also emphasize the need to deliver information products that are culturally and contextually adapted to the target user group. Ultimately, the goal is to incorporate the best available scientific and engineering information into accessible formats, with a strong focus on enhancing the user experience. By tailoring information to meet the specific needs of target user groups, we can inspire well-informed decisions and empower communities across Texas to navigate flood risks effectively.

2.3 The Guiding Objectives of TIFF Component 2

TIFF Component 2 is an effort to identify opportunities for technical and nontechnical end-users to properly visualize any coastal flood-related data and model outcomes. This effort consisted of six objectives:

1. Establish a TAT to support Component 2
2. Assist TDIS with designing and testing the conceptual framework for managing, visualizing, and disseminating large volumes of coastal flood-related datasets, including data visualization system(s)
3. Conduct an inventory on coastal flood-related UIs
4. Recommend guidelines for coastal flood UIs, including the level of end-user access, analysis capability, visualizations, and included datasets
5. Assist TDIS with identifying and recommending computational hardware/software requirements for flood-related analysis and visualization
6. Make recommendations pertinent to future data management and visualization needs to GLO

2.4 Approach to Objectives

Efforts under this Component involved interacting with TAT members and incorporating their feedback, conducting extensive literature reviews, leading a stakeholder workshop, developing *The TIFF Communication Guidelines*, including tailored visualization guidelines for three prioritized target user groups, and administering a statewide survey to assess portions of the guidelines (Supporting Material 2-1).

After forming the Data Management and Visualization TAT and gathering initial feedback on the envisioned approach, TIFF worked in collaboration with the TIFF partners, the TAT, TDIS, and the Study Providers described below to explore the challenges, goals, and opportunities associated with proper visualization of coastal flood-related data and model outcomes.

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

Building upon the coastal flood UI inventory, TIFF partnered with Components 2 and 4 Study Providers from the UT-Austin's Moody College of Communications and TACC to recommend guidelines for coastal flood UIs. In identifying effective strategies for communicating flood risk to end-users through data visualizations and other outreach techniques, the Study Providers and TATs found that objectives of both Component 2 (Data Management and Visualization) and Component 4 (Planning and Outreach) overlapped, as data visualization is an impactful way to communicate flood risk. Likewise, to improve coastal flood UIs, it is essential to understand the respective end-users.

Through extensive literature reviews, stakeholder collaboration, and surveys with TFMA (Supporting Material 2-2) and TAT members, *The TIFF Communication Guidelines* were developed. Insights from the surveys, along with stakeholder input from the Stakeholder Needs Workshop (see Workshop Findings), informed the development of visualization guidelines to enhance flood risk communication for three prioritized target user groups: property owners, property renters, and people with limited English proficiency (LEP), due to their vulnerability to coastal flooding and the potential benefits of improved risk communication.

The TIFF Communication Guidelines were developed to fulfill the aforementioned needs, functioning as a strategy for entities designing information visualizations and communication tools to effectively convey flood risk to both general audiences and specific groups affected by coastal flooding. These guidelines are best practices for presenting flood risk in a way that is clear, transparent, and user-friendly. Their use will ensure that both general audiences and those directly affected by coastal flooding can accurately interpret and respond to the information.

Subsequent sections detail how Component 2 and 4 efforts also led to a set of recommendations for future work and potential funding.

A Houston-resident holds a sign warning passersby to slow down following Hurricane Harvey © Glenn Fawcett

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

The TIFF Guidelines for Coastal Flood Information Design and Communication (TIFF Recommendation C2.3A)

The TIFF Communication Guidelines (Supporting Material 2-1) are meant to establish clear objectives for the design of information tools and communication approaches that inform flood risk decisions. Designs should strive to motivate behavior change that is based on the best available knowledge and information.

STEP #1: DETERMINE OBJECTIVE OF THE FLOOD PRODUCT DESIGN

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

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

STEP #3: DESIGN PRACTICES THAT LEAD TO MEANINGFUL COMMUNICATION

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

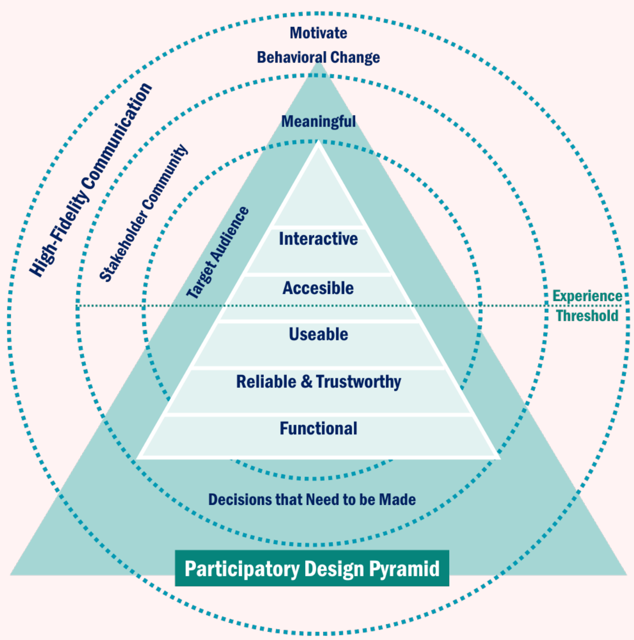


Figure 2-1. Participatory Design Pyramid

STEP #4: ACHIEVE HIGH-FIDELITY COMMUNICATION

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

2.5 Implementation of Objectives

Objective 1: Establish a Data Management and Visualization TAT

In collaboration with other components, Component 2 played a critical role in ensuring that data systems are not only technically sound but also contextually relevant and user-friendly. Through a co-design approach, projects should engage stakeholders early and often to align visualization tools with real-world needs. This inclusive process helps ensure that the final products are accessible, meaningful, and capable of supporting informed decision-making across Texas.

To lead the development of a robust data management and visualization framework, the SC appointed Dr. Amin Kiaghadi as the Component 2 Champion. Dr. Kiaghadi brings a unique blend of technical expertise, leadership, and interdisciplinary experience to this role. As Manager of the Coastal Science Department at TWDB, he oversees a portfolio of projects focused on coastal resilience, flood planning, and water resource management. His academic and professional background, including a Ph.D. in Environmental Engineering and postdoctoral research in computational sciences, positions him to guide the integration of advanced data systems and visualization tools into the TIFF initiative. Under Dr. Kiaghadi's leadership, the Component 2 TAT was assembled to support the strategic organization, accessibility, and usability of complex datasets. The TAT includes experts in geospatial analysis, data architecture, environmental modeling, and user-centered design. Their collective mission is to ensure that data collected across atmospheric, hydrologic, coastal, and human behavior domains are properly curated, stored, and visualized in ways that support both technical and non-technical users.

The following advisors were selected to serve as members of the Component 2 TAT based on their expertise in coastal flood data availability, technical data collection requirements, and the interpretation and application of modeling methodologies.

COMPONENT 2 TECHNICAL ADVISORS

- Alan Zunde, AQUAVEO LLC
- Albert Aldana, City of Weslaco
- Andrew Juan, TAMU-IDRT
- Bill Kirkey, RATES, Inc.
- Brian Barr, January Advisors
- Bridget Scanlon, Bureau of Economic Geology
- Carlos Sanchez, Cameron County
- Carola Kaiser, Coastal Emergency Risks Assessment-Louisiana State University
- Diane Howe, FEMA
- Federico Antolini, TAMU
- Gordon Wells, UT-Austin, Center for Space Research
- Ibrahim Demir, The University of Iowa
- Jason Fleming, Seahorse Coastal Consulting
- Jeff East, USGS
- Jeff Lindner, HCFCD
- Jeff Reichman, January Advisors
- Jeffrey Horshburgh, Utah State University-Utah Water Research Laboratory
- Justin Terry, HCFCD
- Kay Atoba, TAMU-IDRT
- Kris Lander, NWS
- Kristine Blickenstaff, USGS
- Laura Stearns, TAMU-IDRT

- Lee von Gynz-Guethle, West Consultants
- Paul Craig, Dynamic Solutions International, LLC
- Russell Blessing, TAMU-IDRT
- Sam Brody, TAMU-College Station
- Steven Mikulencak, TAMU-AgriLife/CHARM
- Taylor Christian, TWDB
- Velinda Reyes, Office of Hidalgo County Commissioner Ellie Torres

In service to the objectives of Component 2, support was provided to the TDIS team for data storage, access, and management, with an emphasis on interoperability and long-term sustainability. This includes establishing metadata standards, visualization techniques, data management, and archiving strategies that align with best practices in flood-related data management. The team also supported the formation of conceptual frameworks that translate complex flood risk data into actionable insights for planners, decision-makers, and community stakeholders.

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

TIFF examined the literature (see Component 3: Objectives 3 and 4) and worked closely with the TATs (Supporting Materials 3-10) and TDIS to assess the essential components and strategic considerations for designing a conceptual framework for managing, visualizing, and disseminating large volumes of coastal flood-related datasets, including data visualization systems. This section provides an overview of the considerations of such a framework, a collaborative software platform for the advancement of coastal flood modeling in Texas (Supporting Material 3-19). See Component 3: The Case for a Texas Coastal Flood Framework for a detailed discussion recommending the development of a Texas Coastal Flooding Framework (TxCFF).

As noted in Component 1, TIFF assisted TDIS in determining the appropriate data structure and performed an extensive search of the types of flood-related data available in the state of Texas to make stakeholders aware of the available datasets for a variety of model types. Datasets were categorized by data class (atmospheric, natural environment, topography/bathymetry, jurisdictional, built environment, ecological, imagery, literature source, model, hazards and engineering, mitigation support, demographic, and public health) as well as thematic category (hydraulic, hydrologic, risk, water quality) to support the review and classification of datasets. Furthermore, consideration of the needs of an eventual web interface required the identification of digital repositories or APIs for linkage on the eventual web interface. After data categorization and source cataloging, it was determined whether each dataset had a readily accessible digital format for ingestion into the eventual web interface (Supporting Material 1-1).

TIFF also performed an exhaustive search for a myriad of model input data categories ranging from meteorologic to geographic to socioeconomic. This data inventory supplied key information about the data coverage, attribute type, and data category for the eventual streamlined access and parsing of the data inventory. This effort was shared and discussed with TDIS over regular meetings and specific working groups (Supporting Material 1-1). This initial data inventory laid the foundation for the development of the CDS tool, which is described in detail in Component 1: Objective 2.

TIFF also provided support to the TDIS team by providing domain expertise in data management and visualization efforts. TIFF met with TDIS leadership and technical teams several times, on a regular quarterly basis, to offer data collection and flood modeling domain expertise, and began facilitating quarterly meetings to share updates and collaboration opportunities.

DATA MANAGEMENT

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

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

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

It is important to develop workflows and best practices for the data to be archived from a simulation with structured organization including naming conventions, sufficient metadata and other documentation. This effort needs to be closely coordinated among potential users, so that needed data is not thrown away or not needed data is saved unnecessary. An example of a collaborative infrastructure for data storage is the DesignSafe[1] portal, which specializes in data management for natural hazards.

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

1 NSF NHERI Design Safe website: https://www.designsafe-ci.org.

DATA DISSEMINATION

TIFF is proposing a software framework to address the complexities of Texas compound flooding that encapsulates models and their coupling with analysis tools and workflows. See Component 3: The Case for a Texas Coastal Flood Framework for a more detailed discussion, along with (Supporting Material 3-11). Data dissemination and data products provided by such a framework require substantial planning and resources. The input files and results generated by various models involved in compound flood simulations are too large for a typical user and would require huge bandwidths for routine data transfer. Indeed, the challenges of sending large datasets over the internet are one of the reasons that Google's Earth Engine[2] focuses on providing computation using Google servers rather than downloading data to your local machine (costs of in-place data manipulation are much less than the bandwidth costs of data transfer.) Thus, in building a software modeling framework, there needs to be thought given to the data products that need to be routinely available to users and access workflows for more sophisticated and complete archival data sets. In particular, the need of flood hazard modeling for a large number of flood inundation simulations requires a consensus on what time/space resolution needs to be archived for each simulation.

Accessing External Data

The sources and formats for the external data are varied, so a range of data conversion algorithms must be implemented. Thus, a major challenge in any compound flood modeling project is extracting the data from various sources and reformatting it for use within the modeling system. The type and quantity of data required will depend on the models implemented in the framework. A discussion on landscape, meteorological, far-field process, and validation/calibration data is provided below:

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

Meteorological and Climate Data - Flood inundation models are driven by meteorological data (e.g., wind, rain). Although insight can be gained by modeling a single storm, such as Hurricane Harvey, we need to model a wide range of possible/probable storms to provide foundations for improving future flood protection. Thus, there is a need for model forcing data that covers a range of historical storms and future storms. Traditionally, flood modeling for urban engineering design has

2 Google Earth Engine website: https://earthengine.google.com

been done using spatially uniform rainfall for a storm with a simple constant rainfall rate over a time interval based on a “return period” that reflects the probability of the storm occurring (e.g., the 100-year storm has a 1% chance of occurring in any given year). Such an approach is simply untenable for the hurricanes and tropical storms that drive compound flooding along the Texas coast, as the spatial/temporal patterns of both rain and wind are crucial to the flooding behavior. Datasets for historic storms to drive compound flood models need to include the spatial/temporal patterns of both rainfall and wind, which can be obtained from either direct observations or models. These are typically large datasets that require expertise to extract and prepare for modeling.

Creating “what if” rainfall and wind fields for possible storms is even more challenging. Presently, there is exciting research going on in creation of “synthetic storms” that are derived by simulation models that use the statistical behavior of real storms to generate artificial storm data with similar characteristics. Using such tools, wind/rain data sets can be created to consider “what if” conditions for a range of storms applied at a variety of locations along the coast. Such models may also provide a means of examining how storms might behave under climate change, but such work has yet to be proven.

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

The state-of-the-art in developing synthetic tropical cyclones for probabilistic hazard analysis has typically been referred to as Joint Probability Modeling – Optimal Sampling (JPM-OS). These methods have become a standard probabilistic approach for quantifying coastal storm hazards due to tropical cyclones (Nadal-Caraballo et al., 2020). The events, or storms, are developed from combinations of parameters based on historical distributions of meteorological and climate variables recorded during past tropical cyclones. The event parameter sets are used in high fidelity atmospheric and then numerical hydrodynamic and wave models to develop flood water levels. To determine their frequencies curves, they are then integrated with the frequencies and joint probabilities of the inputs to produce the hazard. For instance, ERDC/CHL currently uses a Probabilistic Coastal Hazard Analysis Framework (CHS-PCHA) where a JPM-OS type method is used to quantify coastal hazards. Tropical cyclone atmospheric parameters (e.g., winds, pressure) are determined from Hurricane Database 2 (HURDAT2) climatology, and used to drive numerical atmospheric, hydrodynamic and wave models to produce surge systems responses which have been traditionally integrated to produce hazard curves. CHS hazard probabilities for surge are hosted publicly on the CHS website[3] for regional studies along the Atlantic, the Gulf (including an older Texas Study) and the Great Lakes. More recent detailed study data can be requested there or through USACE.

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

3 ERDC CHS website: https://chs.erdc.dren.mil

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

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

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

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

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

COASTAL USER INTERFACES

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

In addition to the required criteria for coastal flood UI, the TAT members identified some gaps in our understanding of the visualization methods for:

- demonstrating uncertainty in the models in a way that is understandable for both technical and non-technical end-users
- compound flooding risk that accounts for all components (i.e., storm surge, rainfall, relative sea level rise, king tides, etc.) (Supporting Material 2-3 and 2-4)

As a first step to finding the answers to the abovementioned questions and filling the identified gaps, TIFF created an inventory of flood-related UIs. Such an inventory could help future endeavors by TIFF in defining general and specific rules/criteria.

As an initial step of the inventory, TIFF generated an inventory matrix to help create a uniform list (metadata) of comparable attributes among UI sites. The matrix contains 20 attributes, as shown in Table 2-1 below. The attribute includes basic information such as name, interface links, partner agencies, mission and vision statements (if any), as well as other properties and characteristics of interfaces, such as spatial and temporal resolution, and the existence of real-time data and the API. TIFF began the inventory by preparing a list of 44 interfaces with a variety of visualization functionality.

INVENTORY OF COASTAL USER INTERFACES

Out of the 44 interfaces, only 34 were related to the inventory and were still functional at the time of this report on the TexasFlood.org website and Supporting Material 2-5. For the ease of illustration, the original inventory table was paired down into a total of three tables (Supporting Material 2-6).

The inventory revealed the following points and was used as a foundation for the remainder Component 2 tasks:

- The majority of the 34 investigated coastal UIs are only offered in English
- Only two of the 34 UIs let the users upload shapefiles
- None of the UIs let the users conduct new analyses
- There are many overlaps among various UIs with regard to the data type, source, and the visualization method they use to present the data
- Many UIs do not have/provide metadata
- Most UIs do not have/provide a coverage map (preferably as a downloadable shapefile)
- An API is only provided in some of the UIs
- Visualization methods are limited to basic functions such as zoom in/out, turn on/off layers, print/share map, pop-up attribute table, legend, charts, base map options, address search, and transparency. There are a few UIs with more advanced methods, such as sliding maps.
- Downloading the data is not offered by many of the UIs

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

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

Objective 4: Recommend guidelines for coastal flood UIs, including the level of end-user access, analysis capability, visualizations, and included datasets *(Content presented to address this objective also meets the objectives associated with TIFF Component 4's Objective 5: Support the development of flood communications and educational materials.)*

While identifying effective strategies for communicating flood risk to end-users, the Study Providers and TAT members found that objectives of this Component 2 (Data Management and Visualization) and Component 4 (Planning and Outreach) overlap, as data visualization is an impactful way to communicate flood risk. Likewise, to improve coastal flood UIs it is essential to understand the respective end-users. The flood communication recommendations for both Components 2 and 4 work together and build upon each other.

Moreover, the research revealed that the term "end-user" should be replaced with "target user," recognizing that these groups should be involved throughout the design process, not just at the end.

To meet Objective 4, TIFF assembled an inventory of existing coastal flood-related UIs (Supporting Material 2-5), conducted targeted literature reviews to identify best practices, surveyed attendees at a TFMA conference (Supporting Material 2-2), and hosted a stakeholder workshop to analyze target users and their decision-making needs. These efforts culminated in a Stakeholder Decision Map (see Stakeholder Map of Target User Groups) and the identification of three prioritized target user groups (property owners, property renters, and individuals with LEP) for coastal flood model data. Understanding technical and non-technical end-users' specific needs for visualizing data and model outcomes enabled the development of *The TIFF Communication Guidelines* (Supporting Material 2-1) for Texan decision-makers, that include level of end-user access, analysis capability, visualizations, and included datasets. The Study Providers then conducted a statewide survey to test aspects of the Guidelines and developed evaluation metrics to assist in the design and assessment of future visualization and communication tools.

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

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

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

LITERATURE REVIEW OF COASTAL USER INTERFACES, USER EXPERIENCE, VISUALIZATION, COMMUNICATION, AND EDUCATION

To develop *The TIFF Communication Guidelines*, including access levels, analytical capabilities, visualizations, and datasets, a literature review was conducted on a) differences between technical and nontechnical audiences, b) rural and urban populations, c) how uncertainty impacts interpretations of flood risk, d) audiences at particular risk from floods, e) stakeholders who support audiences at particular risks, f) new and innovative visualization approaches to communicate flood risk, and g) user experience and UI best practices.

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

An overview of the findings from the literature review can be found in Supporting Materials 2-7, 2-8, and 2-9, and includes the following topics:

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

Literature Review Methodology

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

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

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

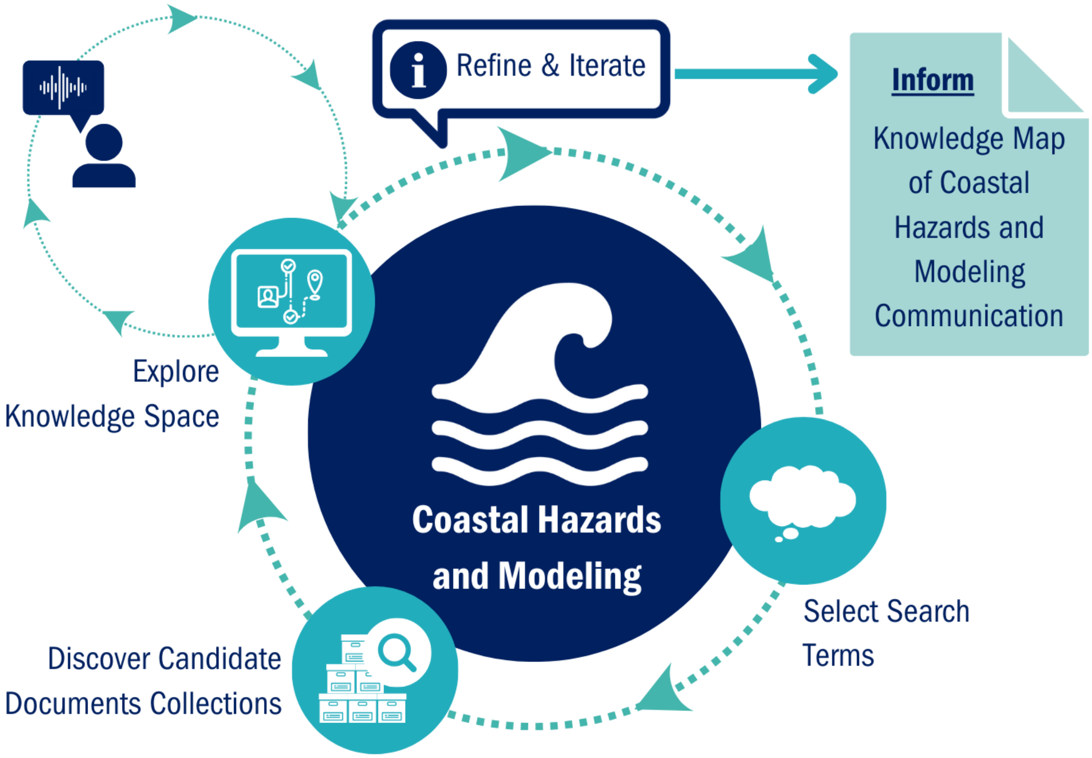


Figure 2-2. Conceptual diagram of a human-in-the-loop process supporting the use of AI applications to accelerate exploration and discovery tasks for systematic and diagnostic literature searches (Pierce, SA 2024).

The remaining steps to identify appropriate literature progressed from discovery tasks to exploratory tasks using the AI-enabled workflow. A total of ten seed articles providing foundational knowledge were closely examined and analyzed using a forward and backward citation process to identify other relevant research. See Supporting Material 2-10 for detailed information on the literature review process.

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

Key Lessons Learned: Disseminating Information to Nontechnical Audiences

- Use multiple formats to reach different audiences. When speaking to an audience with low numeracy, reduce their need to make inferences from numeric data. Numbers must be self-explanatory and explain uncertainty. Denominators and time periods should be consistent (Peters, 2020; Spiegelhalter et al., 2011, 2017).
- The most important information should be shown first, highlighting the meaning of the main messages (Peters, 2020)
- Visual communication benefits from using templates, consistency, single hues, Arial and Helvetica fonts, and little decoration
- For accessibility, a color vision deficiency simulator must be used

- Italics, rainbow-colored maps, red-green or orange-green colored maps must be avoided, as well as using colors that conflict with colors often used to depict risks or hazards. Map designers can use online tools that are useful for deciding which colors to use, whether those would be color blind safe, etcetera. Examples of these tools are Colorbrewer 2.0 (Brewer & Harrower, 2013) and Adobe Color Wheel (Adobe Color, n.d.).Visuals should focus on communicating when the flood will occur, its impacts, and the actions to be taken (Heggli et al., 2023). Avoid overcrowding visuals.
- Be cautious about interactivity and animations – they may introduce unnecessary complexity. Acknowledge the limitations of information quality and relevance, and avoid chart junk, such as three-dimensional bar charts (Spiegelhalter et al., 2011, 2017).

Key Lessons Learned: Nontechnical Audience Needs for Flood Risk Visualizations

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

Key Lessons Learned: Rural/Urban Populations

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

Key Lessons Learned: Flood Communication Technologies

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

Key Lessons Learned: User Experience Principles for Flood Interface Design

- UX design should balance usability and emotional responses to create engaging and effective interfaces
- Integrating machine learning into UX design can create more personalized and adaptive user experiences
- Incorporating feedback mechanisms in design helps refine it and improve user satisfaction

- Apply principles like emergence, closure, and proximity from Gestalt theory to organize content and enhance visual understanding
- Using hierarchy, alignment, and color effectively can improve usability and engagement
- Categorizing information using navigator tabs can display relevant results for different user needs
- Features like zoomable/pannable functions enhance map navigation and information retention

TIFF COMMUNICATION BEST PRACTICES

This section presents best practices guidance developed from research that establishes clear objectives for the design of information tools and communication approaches that inform flood risk decisions.

Best Practices for the Interface Design Process

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

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

Understanding how the dashboard will add value to an organization aligning the design process with its strategic goals. Knowing the type of dashboard that will be created allows for tailoring the design to meet specific needs, ensuring that the information presented is relevant and actionable. Moreover, focusing on key metrics that highlight actionable information helps users quickly identify important trends and insights, leading to more informed decisions. The format and layout of the dashboard are also critical, as those affect how easily users can navigate and comprehend the data. Finally, incorporating capabilities that enhance user interaction with the information, such as filters and drill-down options, makes any dashboard dynamic and user-friendly.

Best Practices for Communicating Flood Risk with High Fidelity

Extensive research across various fields and input from subject matter experts and stakeholders in Texas have converged on the urgent need for improved communication strategies. The following best practices (adapted from Peters et al. (2022)) present key highlights and core recommendations that address knowledge gaps and propose innovative approaches to leverage technology and information from data collections and coastal modeling for more effective communication of complex flood risk information. Furthermore, these practices outline specific insights that can be seamlessly integrated into the design process, from engaging with community members to implementing functional design practices for user interfaces. They also emphasize the need to deliver information products that are culturally and contextually adapted to the target user group. Ultimately, the goal is to incorporate the best available scientific and engineering information into accessible formats, with a strong focus on enhancing the user experience. By tailoring information to meet the specific needs of target user groups, we can inspire well-informed decisions and empower communities to navigate flood risks effectively.

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

TIFF incorporated all the research conducted, including feedback on communicating and visualizing uncertainty and the specific criteria and UX requirements to produce the recommended *The TIFF Communication Guidelines* (see Approach to Objectives: TIFF Guidelines for Coastal Flood Information Design and Communication for more details, and Recommendation C2.3A).

TFMA CONFERENCE SURVEY TO ASSESS HOW FLOOD RISK IS COMMUNICATED AND VISUALIZED TO STAKEHOLDERS

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

Communication mechanisms with wide broadcast, appealing delivery methods, and a focus on enhancing decision-making for long-term needs can improve the decision-making process for stakeholders (Mostafiz, 2022). The TFMA survey also asked about flood visualizations. Respondents believe that 3D models and detailed maps showing rainfall or water flow direction are most effective for explaining flood risk to primary stakeholders compared to simpler flood maps. Respondents also find web applications with uncertainty ranges and color-coded flood depth helpful. Hence, web-based tools, 3D mapping, serious games, and other innovations are appealing delivery methods and can engage people to create two-way and participatory exchanges. These tools are more precise when they communicate uncertainty and are tailored to individuals with LEP, an important audience in Texas.

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

STAKEHOLDER NEEDS WORKSHOP

TIFF hosted a Best Practices in Identifying Stakeholder Needs around Flooding Workshop with 98 participants on June 28, 2024 (Supporting Material 2-11). The workshop aimed to differentiate between user personas, user profiles, and behavioral archetypes; understand approaches agencies use to identify flood information target users, and their reasoning; and consider ways to inform communication strategies for targeting end-user groups.

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

The workshop gathered insights from the Component 4 TAT members and a mix of agency practitioners experienced in working with different types of potential users of flood information. Its objectives included identifying implementation and evaluation metric needs for target users, highlighting information gaps, and developing strategies to address these challenges. Additionally, the workshop aimed to foster collaboration among practitioners and researchers involved in flood risk planning decisions. (See Supporting Material 2-11 for workshop materials and additional details.)

The discussion sharpened the focus around ways to identify and prioritize flood-related data and information for target users. Specifically, behavioral archetypes – identifying ways to cluster groups of users according to the decisions/behaviors they need to make – appeared most relevant for the current effort. User personas are commonly used in marketing and user experience research. They have also been used in flood-related efforts, such as those conducted by CHARM and from the research conducted in Virginia Tech. Personas are a realistic, but fictional representation of a member of each audience segmented group (Kaplan, 2022). The process of crafting a persona likely helps the product designers better think through what members of that group need and the nuances to consider. Given that the persona's main criticisms are that it cannot be "adequately verified or falsified" or proven to be entirely relevant towards its target users (Chapman & Milham, 2006), this tool should ideally be used in conjunction with other methods that involve actual interactions with the people representing the persona (e.g., focus groups, interviews, and other tests) (Nielsen, 2019).

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

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

IDENTIFYING TARGET USERS FOR COMMUNICATION

Leveraging user-centered and co-design approaches from the beginning and considering behavioral archetypes (grouping people according to the types of decisions they need to make) can lead to more effective and user-friendly interfaces and information visualizations tailored to targeted users. This also often provides useful and usable content to inform broad audiences.

Begin by carefully considering what groups of people should be involved in co-designing communication tools and emphasize efforts to understand how information is meaningful in the contexts where solutions or actions will be implemented. Using a human-centered approach, facilitators should attempt to understand the core contexts and concerns that matter. Define the pain points and key challenges or risks that need to be avoided or overcome. Explore ideas and develop prototypes that can be tested quickly.

The most valuable time will be used to diagnose what is needed to communicate meaningful, data-rich messages with a particular group of people. Effective communication begins with identifying individuals who understand the circumstances and have the lived experience needed to shape technical information, ensuring it's accessible and usable for the communities that rely on it.

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

→ USER GROUP

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

→ STAKEHOLDER

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

→ AUDIENCE

Audiences are groups of people who receive messages.

→ TARGET USER

A target user is a subgroup of people most likely to be interested in and benefit from a product or service. They are a specific segment of the overall population that share common characteristics, such as demographics, interests, or needs.

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

Stakeholder Map of Target User Groups

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

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

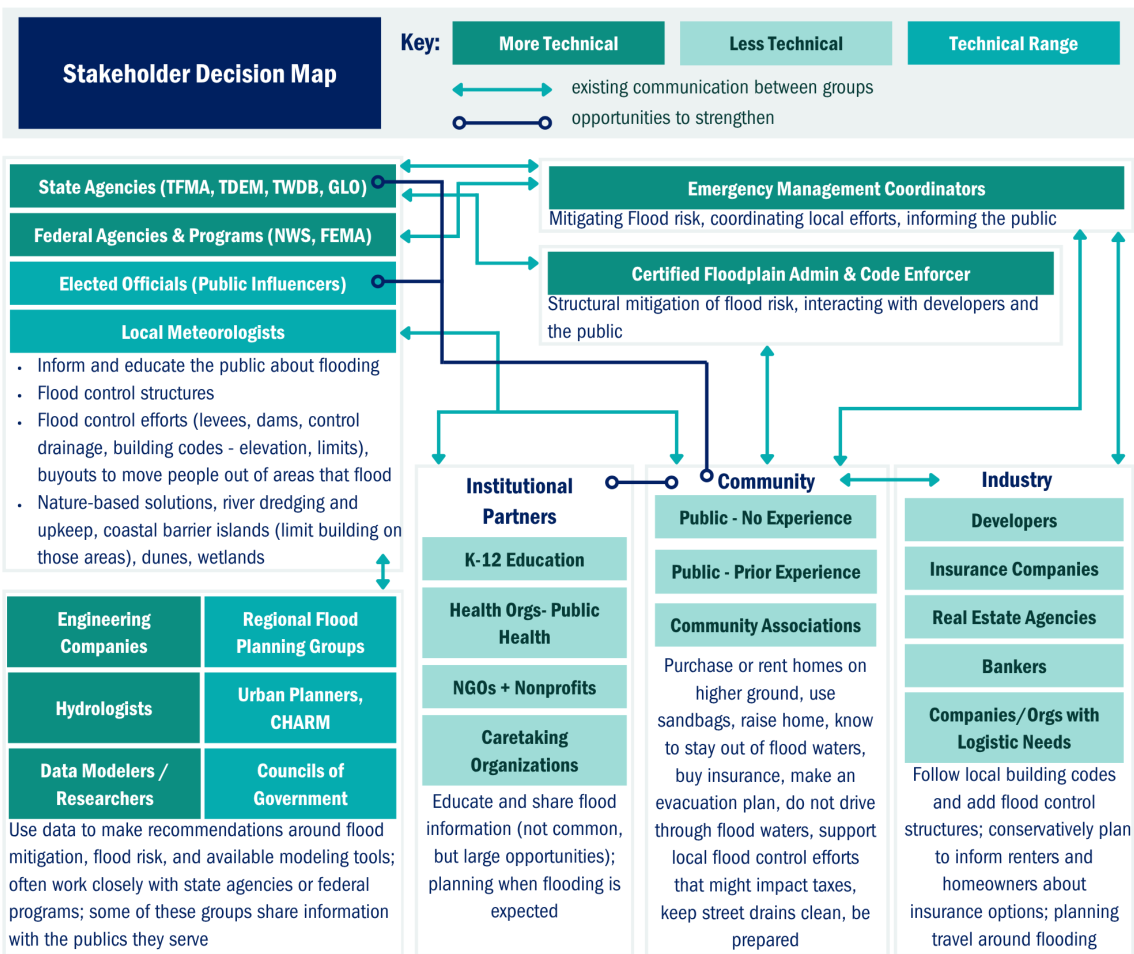


Figure 2-4. The Stakeholder Decision Map summarizes the identified stakeholder groups, their technical user levels, current and future communication paths, and the types of decisions they need to make regarding coastal flooding.

Potential Public Target User Groups

The stakeholder map in Figure 2-4 is further elucidated by Table 2-2 through Table 2-5, which detail the groups and categories of public-related target user groups and the types of decisions they need to make. These decisions revolve around insurance, heightened flood risk, infrastructure-related risk, and responsibility for others. Presenting this information in a clear, organized manner allows state-level stakeholders to better grasp the complex landscape of flood-related decision-making among various public stakeholder groups. This understanding is crucial for developing effective policies and communication strategies to mitigate flood impacts in Texas.

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

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

* per Towncharts, 2022 American Community Survey Census

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

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

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

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

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

Target User Groups	Explanation of How They Are Responsible For Others
Nursing/Assisted Care Homes/Group housing	Have particular needs around helping their residents evacuate when needed, and they need to understand the vulnerability of their location in a given rain/coastal event
Schools	Not only responsible for keeping children safe, but also play a role in educating the population. They need to understand the vulnerability of their location in a given rain/coastal event and if their school will need to be converted into a shelter.
Hospitals	Have dedicated staff who plan for emergencies and likely have needs around evacuation routes, logistics, deliveries, and staffing support
Employers	Often overlooked, but major employers often play a role in helping their employees be prepared for disasters. Employers also have a financial reason to get their employees safely to and from work. This could be an important group to examine because they provide a metachannel (multiple ways) for reaching many individuals.
Food banks	Often involved in the response and recovery effort. They also need information concerning the vulnerability of their location, logistics, and staffing support.
Nonprofits serving the community (including religious organizations)	Often help people in the community recover from flooding, but they can also be involved in sharing preparedness information and in providing temporary shelter during events

Process Used to Select Prioritized Target User Groups

Professionals in the fields of marketing, user-centered design, and user experience have long known that "the public" is not a single entity with definable characteristics. NOAA's hurricane messaging report of 2021 found this to be pivotal in how they approached creating websites for the various audiences that constitute "the public" in the coastal communication space. When the goal is to change behavior, information must be personally relevant or people will not pay attention (Lustria et al., 2013). Therefore, identifying specific needs that a group of people have and designing a flood message or a product to meet those specific needs is common.

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

To focus on audience segmentation, TIFF began by identifying segmentation criteria. Prior work had helped define types of target users of coastal flood data. After that, a literature review was conducted to identify the possible decisions that different target users might make concerning coastal floods. Third, the Stakeholder Workshop helped decide that using a behavioral archetype approach was most appropriate for this project.

Potential target users were grouped by the decisions they might make, forming the Stakeholder Decision Map found in Figure 2-4. Groups were added into this map to better understand, not only the decisions each group makes, but also the relationships between the different groups, including the type of support and communication links between groups.

Additional criteria used to evaluate which target user group to prioritize included:

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

Selected Prioritized Target User Groups

Building from the extensive list of potential target user groups, the Stakeholder Decision Map, and the audience segmentation criteria, TIFF prioritized three target users (property owners, property renters, and individuals with LEP). See Supporting Material 2-7.

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

the person perceives some kind of risk factor. Uncertainty is recognized as part of this information-seeking behavior, and property owners often have these knowledge gaps.

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

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

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

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

The types of information this target user group needs include:

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

The main mitigation decisions these property-owner target users need to make include:

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

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

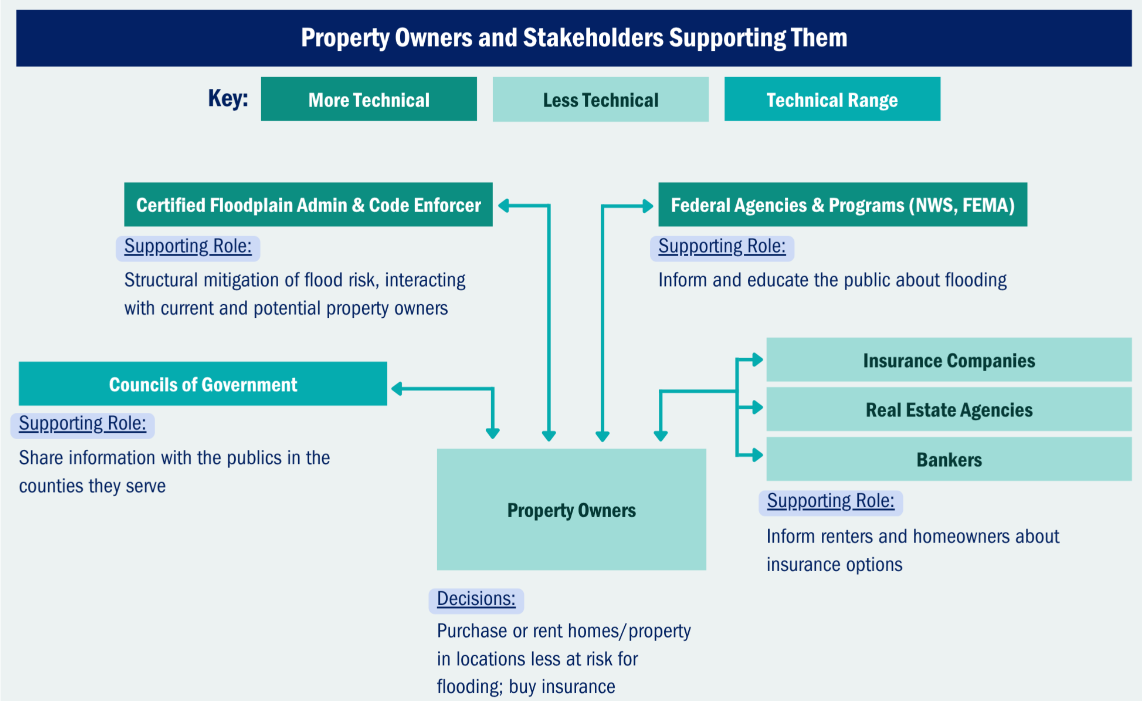


Figure 2-5. Property owners and stakeholders supporting their decisions. This diagram demonstrates the major stakeholder groups that support property owners when they are making flood-related decisions.

The main lessons learned about property owners are:

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

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

and thus, have more difficulty recovering from future disasters (Dundon & Camp, 2021; Lucas & Young; 2022; National Academies of Sciences, Engineering, and Medicine, 2024).

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

The types of information this target user group needs include:

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

The main decisions renters have to make include (some overlap with property owners):

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

The main lessons learned about property renters are:

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

3. **Individuals with Limited English Proficiency in Coastal Areas** - Many ongoing projects in Texas concerning flood knowledge and information-seeking have revealed a lack of information targeted at people with limited English proficiency. For instance, there is a lack of materials in Spanish to help Spanish speakers make informed decisions about coastal flooding. Prior research often identifies groups of people who do not speak English in the U.S. as being especially at-risk to disasters during preparation, response, and recovery (Cutter et al., 2010; Teo et al., 2019). Complex document filing procedures that require extensive time, and resources only exacerbate these challenges (Howell & Elliott, 2019).

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

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

Specifically, Hispanics (the most common group of individuals with LEP along the Texas coast) come from a cultural background that relies heavily on family and friends for their disaster information (Teo et al., 2019). A specific request made by TAT members was to include majority-minority populations. While there is a clear difference between Spanish speakers and people who are Hispanic (they or their family have heritage from Spain or a country in Latin America), better understanding this majority minority population provides a reason for the focus on Spanish speakers.

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

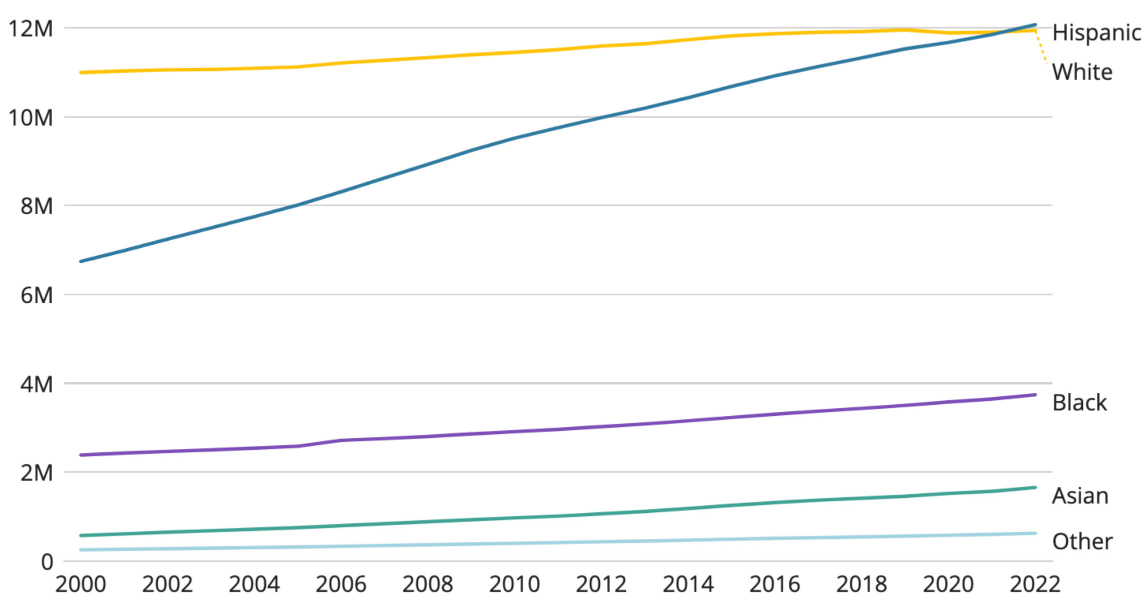


Figure 2-6. Hispanic Texans are the largest demographic group in Texas as of 2022.

In 2022, the population was 12,068,549 for Hispanic/Latino/a/e Texans and 11,939,611 for White Texans. Black/African American and Asian are of one race only. Other includes American Indian and Alaska native (of one race only), Native Hawaiian and Other Pacific Islander (of one race only), or people who identify as two or more races (any combination of White, Black/African American, American Indian/Alaska Native, Asian, Native Hawaiian/Other Pacific Islander, or Some Other Race), and does not include Hispanic/Latino/a/e (Ura, 2023).

Table 2-6 ranks the 18 coastal counties according to the number of people who are five years of age and older. Seven of the 18 counties have at least 30% of their population speaking Spanish at home, including two counties located in the LRGV (Cameron County and Willacy County). While that does not mean people in those households cannot speak English, it often means English is not preferred and they can understand information better in Spanish.

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

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

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

The types of information this target user group needs are very broad and include:

- understanding the probability that a property might flood
- whether the property is in a designated flood hazard area

- whether flood insurance is optional or will be required
- whether a property has a history of flooding
- whether surrounding areas have a history of flooding
- proper evacuation routes, the use of sandbags
- staying out of flood waters
- ways to recover (including finding new places to work) if floods impact them

The main decisions individuals with LEP have to make include (some overlap with property owners and renters):

- the location of property to purchase
- planning evacuation routes
- Additionally, individuals with LEP are often members of communities that focus on extended family and they rely on family for trusted information.

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

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

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

STATEWIDE SURVEY TO TEST ASPECTS OF TIFF COMMUNICATION GUIDELINES

A statewide survey was conducted to test *The TIFF Communication Guidelines* (Supporting Material 2-1) on the identified target user groups: property owners, property renters, and individuals with LEP.

Survey Methodology

The survey was administered online. The sample demographics were specified to meet the project goals, and the sample was invited to participate by the company, Centiment. The specified demographics included appropriate coastal areas and demographic representation of Texas: zip codes of Texas coastal counties, age, gender, and race/ethnicity. Table 2-7 provides the detailed demographics of the full sample.

TIFF collaborated closely with IDRT to determine appropriate types of properties to test and the details to include with each property. The properties tested were not directly beachfront to avoid a bias on property cost, and each home was a 3-bedroom 2-bath on slab foundation. Real locations were used with modified addresses. Google Street View was used for the images. At the end of the study, participants were informed that no deception was involved and were provided a link to IDRT's new Buyer's Aware tool (https://buyersaware.org/) for those interested in learning more about coastal flooding in Texas.

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

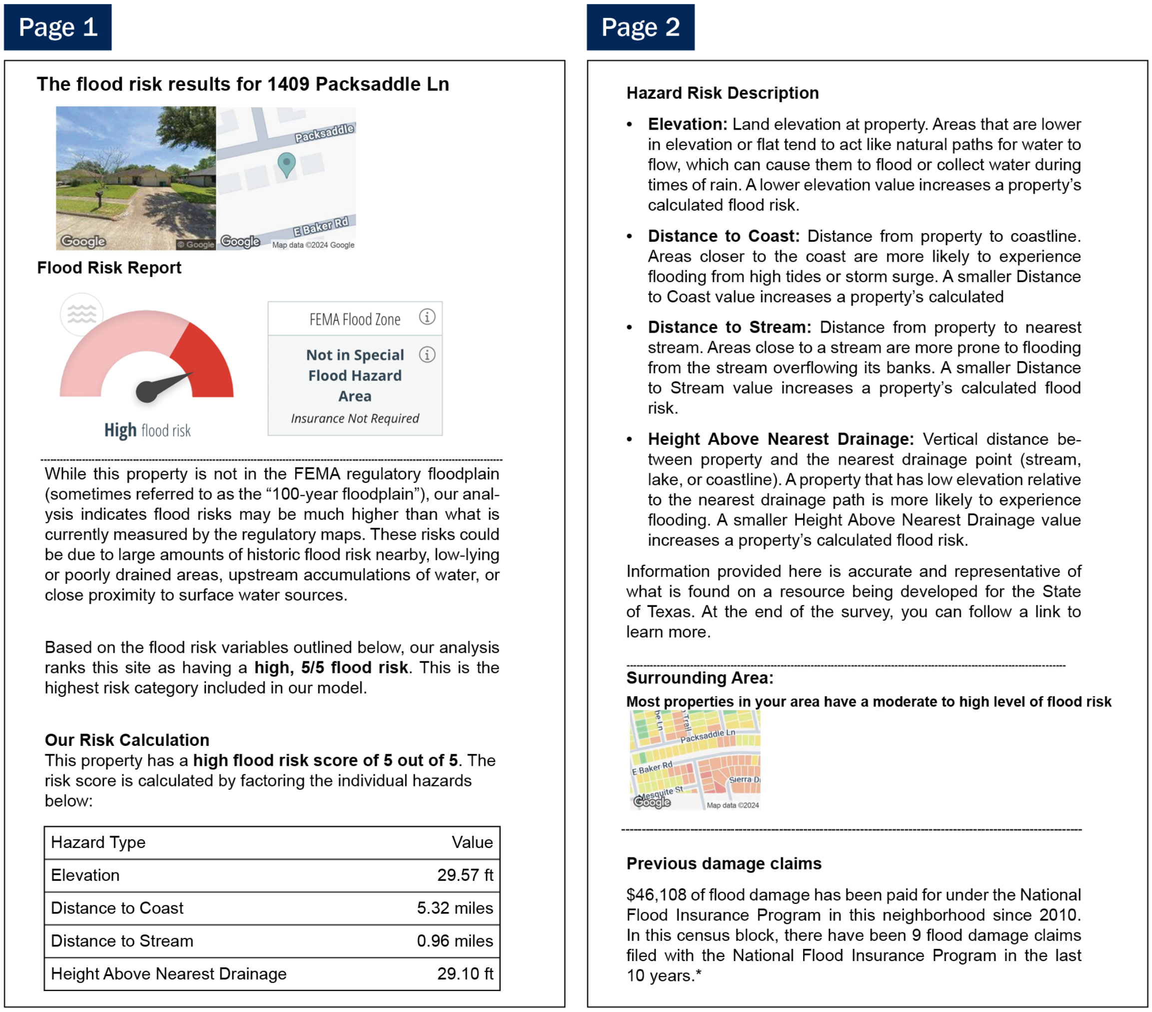
> *Assume you have a family member who is considering RENTING/PURCHASING a home that is a 3-bedroom 2-bath modest home close to the Texas coast. They have shared the following information about this home from a website, and they want your help making a decision about RENTING/PURCHASING this home. Please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

In order to narrow the specific experimental tests, none of the test properties were in a flood hazard area where flood insurance would be required. IDRT provided the graphics and information for this experimental test showing an example of the most elaborate type of condition study participants viewed (Figure 2-7).

Specifically, TIFF tested the following conditions for these two target user groups (property owners and property renters):

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

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



Page 1

The flood risk results for 1409 Packsaddle Ln

Flood Risk Report

High flood risk

FEMA Flood Zone

Not in Special Flood Hazard Area

Insurance Not Required

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

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

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

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

Page 2

Hazard Risk Description

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

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

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

Previous damage claims

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

Figure 2-7. Sample experimental condition.

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

Variable	Category	Number	%
Total Sample		2660	100.0%
Region	Coastal	964	36.2%
	Non-Coastal	1696	63.8%
Gender	Woman	1382	52.0%
	Man	1273	47.9%
	Other	5	0.2%
Hispanic	No	1532	57.6%
	Yes	1128	42.4%
Race	White	2004	75.3%
	African/Black	309	11.6%
	Asian	42	1.6%
	Native Hawaiian/Pacific Islander	7	0.3%
	American Indian/Alaskan Native	54	2.0%
	Other/multiple identities	244	9.2%

Table 2-7. Continued

Variable	Category	Number	%
Household Size	1	519	19.5%
	2	819	30.8%
	3	502	18.9%
	4	463	17.4%
	5	195	7.3%
	6	98	3.7%
English Proficiency	More Than 6	64	2.4%
	Not Very Well	14	0.5%
	Fairly Well	179	6.7%
	Very Well	2467	92.7%
Employment	Full-Time Employment	1086	40.8%
	Part-Time Employment	335	12.6%
	Retired	561	21.1%
	Student Only	107	4.0%
	Student Who Is Also Employed	40	1.5%
	Unemployed and Looking For Work	280	10.5%
	Unemployed and Not Looking For Work	134	5.0%
	Other	117	4.4%
Income	less than $20,000	510	19.2%
	$20,000-39,999	582	21.9%
	$40,000-59,999	522	19.6%
	$60,000-79,999	386	14.5%
	$80,000-99,999	215	8.1%
	$100,000-119,000	156	5.9%
	$120,000-139,999	75	2.8%
	$140,000-159,999	92	3.5%
	$160,000-179,999	44	1.7%
	$180,000 or more	78	2.9%
Major Flood Experience Lifetime	Never	1115	41.9%
	Once	959	36.1%
	More Than Once	586	22.0%
Flood Property Damage	No	1209	45.5%
	Minor	937	35.2%
	Major	392	14.7%
	Lost Everything	122	4.6%
Floodplain Current	No	1630	61.3%
	Floodplain Current	651	24.5%
	I Don't Know	379	14.2%
Neighborhood Flood History	No	1048	39.4%
	Yes	1392	52.3%
	I Don't Know	220	8.3%
Flood Insurance Status	Never Had	1485	55.8%
	Had In the Past but Not Currently	612	23.0%
		563	21.2%

Findings from Survey Testing Portions of *The TIFF Communication Guidelines*

The survey contained experimental tests as well as tests around meaningful variables. This section explains those major findings. Here are some general findings not specified for the TIFF target users:

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

Comparing the Perceptions of Coastal with Non-Coastal Texas Residents

While the focus of TIFF is on coastal target users, the survey was expanded to include a separate comparison group of non-coastal residents who are also property owners and renters. The major findings were:

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

Experimental Tests for the TIFF Prioritized Three Target User Groups

Flood perception differences based on property owners versus renters: As described in the Methodology section, study participants viewed the same exact property, but in one case they were told their family member was considering purchasing the property and in the other, they were told their family member was considering renting the property. Findings included:

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

Findings specific for individuals with LEP: The survey revealed that:

- People who did not speak English very well had lower perceptions of the probability and severity of flood risks than people who spoke English very well. This group had lower intentions to recommend their family buy flood insurance or to advise them to use sandbags to prepare for floods.
- Individuals with LEP were more likely to believe that renting a home has a lower risk than buying it.
- Individuals with LEP thought the map was less helpful and they claimed they needed an interactive map significantly less than people who spoke English very well.

Visualization Guidelines Tailored for TIFF Target Users

As described above, there are many audiences who could use coastal flood model data (in varying forms) to make various decisions. Grouping audiences by the types of decisions they make (e.g., purchasing property) helps craft visualizations, communication approaches, and messages that can effectively reach specific audiences.

Following the TIFF selection of prioritized target user groups, and a statewide survey to test aspects of *The TIFF Communication Guidelines*, TIFF recommends that these **visualization guidelines** within the overarching communication guidelines be adopted by entities sharing coastal flood data:

Visualization Guidelines for Property Owners as a Target User of Coastal Flood Products - Many small business owners rent a storefront; therefore, they do not control the building and rely on property managers/owners. Their biggest concerns are centered around their contents and inventory.

1. Keep the visualization simple: Avoid adding too many details and information to the tool, and keep it uncluttered to maintain readability.
2. Use intuitive symbols and colors: Use symbols and colors that are easy to understand and have clear meanings for the audience. Avoid rainbow colors and check colors with a color vision deficiency simulator to assure accessibility.
3. Provide context: Use labels, annotations, and legends to provide context and help the audience understand the presented data.
4. Use interactive features: Add features like zooming and panning to help the audience explore the map and data.
5. Use responsive design: Ensure visualizations are responsive and can be viewed on different devices (e.g., mobile).
6. Test with the audience: Show the visualization to a sample audience to understand their feedback and refine the visualization based on their feedback. Utilize the user-centered framework when creating visualization tools.
7. Ensure data accuracy and reliability: Ensure that the data being presented is accurate and reliable and provide a source for the data if possible.
8. Include numerical and verbal expressions of uncertainty, prioritizing numerical expression to reduce subjective interpretations (e.g. if adding terms like “slight”, “moderate”, or “high” add quantitative ranges).

Visualization Guidelines for Property Renters as a Target User of Coastal Flood Products - Generally, renters are in more at-risk social situations, especially as they often have low to moderate risk perception. Additionally, property renters are often uninsured, underinsured, and unaware of flood risk. As property renters can be more susceptible to flood risk, they are often less prepared for flood events.

1. Renters should be able to find information and navigate features without confusion, especially regarding risk and insurance data. Renters should have current information of the benefits, requirements, and potential repercussions of flood insurance surrounding property values. Information should help renters understand their protections or lack thereof.
2. Include search features that allow renters to filter properties based on criteria and history of flood information
3. Include features to increase communication between the landlords and renters
4. Ensure that information is accessible on a variety of devices such as desktops, tablets, smartphones, and other mobile devices

Platforms and maps should inform the renter of how the lack of insurance affects their community, and increase knowledge of areas at risk, with interactive features like panning to understand the data and information.

Visualization Guidelines for People with Limited English Proficiency as a Target User of Coastal Flood Products - Some communities perceive flood risk as a greater general problem compared to U.S.–born people. For example, Spanish speakers have high concern for property damage, injuries, and daily disruptions due to floods. They face several vulnerabilities that make them more susceptible to the damaging effects of coastal flooding. These vulnerabilities include:

1. These communities are often of lower socioeconomic status, which limits access to financial resources and state disaster assistance, impacting their ability to afford insurance and recover from disasters.
2. Language barriers prevent access to life-saving information like warnings and educational material.
3. Reduced social networks and community support can impede Spanish-speakers and other individuals with LEP from protecting their lives effectively during emergencies.
4. Disaster preparedness and response among individuals with LEP may be hampered by low trust in governmental organizations.
5. Foreign born individuals with LEP have, in general, lower levels of mitigation actions and insurance coverage compared to U.S.–born or white people.
6. Higher renter status among, for example, foreign-born Hispanics limits their ability to undertake mitigation actions and maintain flood insurance.
7. Individuals with LEP demonstrate less hazard-specific knowledge and face language barriers, limiting their awareness and access to disaster risks and recovery assistance information.

These factors collectively result in less effective preparedness, response, and recovery actions in disaster contexts for communities with LEP, leading to disproportionate impacts during calamities. Addressing these vulnerabilities and incorporating appropriate approaches in emergency systems are crucial for reducing them (Maldonado et al., 2015; Trujillo-Falcón et al., 2024). Before designing a communication tool to address audiences with LEP, ask the following questions:

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

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

Here are some visualization guidelines for individuals with LEP:

1. Present information in both English and other languages. Keeping track of two sets of different materials can create organization pressure and leave some people out.

2. Employ bilingual communicators who can effectively translate and disseminate information before and during emergencies if communicating directly to communities
3. Provide warnings in both visual and oral formats. Visuals can transcend language barriers and are especially helpful for those with limited literacy. Provide demonstrations or simulations of self-protective actions in multimedia formats to enhance understanding.
4. Use different channels: television, radio, digital platforms, Facebook, WhatsApp, or Instagram
5. Establish channels for feedback and questions, such as hotlines or community meetings
6. Use simple and clear language in both English and other languages. Avoid complex jargon to ensure that everyone can understand important updates and instructions during emergencies.
7. Ensure consistency and reliability in preparedness messaging to build credibility over time
8. Clearly outline available resources, such as shelters, insurance options, and emergency assistance in, for example, Spanish. Include information on how to access these resources, and eligibility requirements
9. Be transparent about potential risks and uncertainties and clearly communicate the actions authorities are undertaking to mitigate the risk
10. Collaborate with trusted community organizations and leaders to disseminate information, as individuals with LEP often rely on informal networks. Partner with churches and with local language media outlets.
11. Recognize and respect the diverse cultural backgrounds and disaster experiences of LEP communities. Consider regional dialects and colloquialisms to ensure the message is relatable and easily understood.
12. Do not resort to easy stereotypes as these may convey a limited effort to understand this diverse audience
13. Provide training for community leaders in disaster preparedness and response to enhance their ability to relay accurate and timely information to their communities. Encourage the role of knowledge brokers, such as bilingual community leaders. Invite community members to share their experiences and suggestions, fostering a sense of ownership and involvement.

EVALUATION METRICS AND METHODS TO DESIGN AND ASSESS FUTURE EFFORTS

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

To effectively evaluate the effectiveness of flood communication and visualization approaches and tools, it is essential to consider various categories of interest that also align with the diverse needs and contexts of target users. Table 2-10 provides practical measures to evaluate the design and implementation of visualization and communication tools.

By tracking quantitative evaluation metrics, an agency, program, or project can gain valuable insights into how effectively flood risks and coastal modeling information or visualization tools are performing.

Together with more tailored metrics for specific target users, an organization should be able to assess performance over time and identify areas for improvement. The categories in Table 2-10 provide a set of quantifiable metrics that can be adapted to fit the goals and objectives of a project, program, or information tool. Additionally, a Target Group Pilot Test (TGP Test) methodology was developed for this report and provides a useful approach for designing hypothesis-driven tests for target users. The approach is designed to be reusable and adaptable, leveraging insights from previous research and emerging AI tools to create measurable performance metrics.

As human-AI partnering methodology, the TGP Test approach leverages large language models and structured prompt engineering. The step-by-step workflow begins with 1) creating a user query based on a seed document to ground the search, such as a peer-reviewed article or report about a target audience of interest, 2) preparing and submitting structured prompts iteratively to 3) eliciting a design for evaluating communication and visualization, 4) iterate and revise, and 5) completing an experimental design structure that aligns with a specific user group and topical question of interest. While this approach is conceptual at the time of this report (and AI tools are not yet accessible to all people needing to evaluate flood communication tools/efforts), it represents a workflow to specify testable designs for communication and visualization in the future (Stephens et al., 2023; Trujillo- Falcón et al., 2024; Mobley et al., 2024).

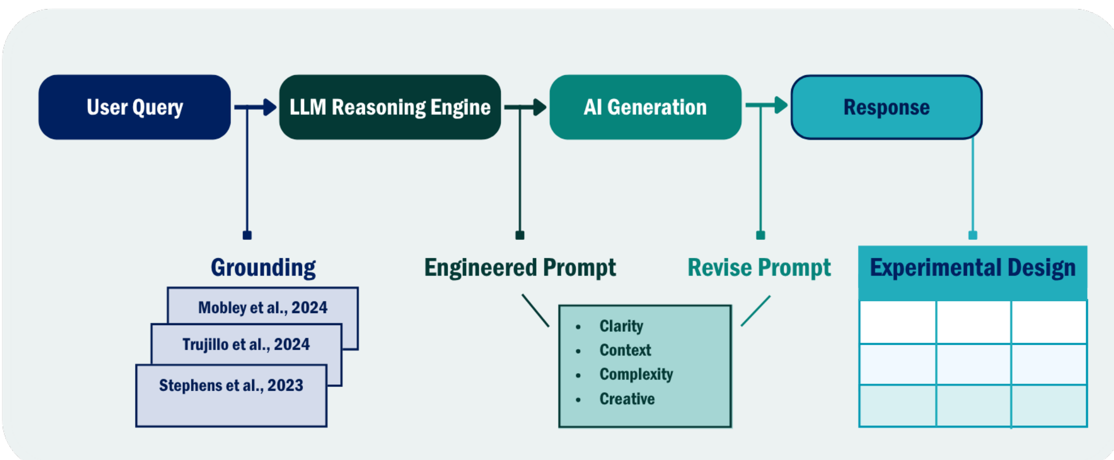


Figure 2-8. Step-by-step TGP Test workflow using artificial intelligence.

Tailored Approach Specifying Testable Hypotheses and Evaluation Metrics

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

In the case of this report, testable hypotheses were evaluated around aspects related to communication about access to tools or information, understanding scientific uncertainty in communication about flooding, and the value of data to inform user groups. An example experimental design is presented in Table 2-9 for a TGP Test Design to Assess Scientific Uncertainty for Flood Visualization and Communication with Property Owners and Property Renters.

The process of designing a prompt and applying it to a problem can enhance the design of communication and visualization experiments. The approach applied for this report uses an iterative methodology to formulate structured queries and interact with a large language model service to generate a customized TGP Test. Table 2-8 presents the prompt design and example phrasings to frame the design outputs.

The development of evaluation metrics should be guided by the specific goals and objectives of flood communication projects. It is crucial to identify and align with the intended target user group to ensure that the information conveyed is relevant and actionable. For reference, an example hypothesis-driven design to evaluate uncertainty communication with property owners and property renters is presented in Table 2-9 below.

Table 2-8. Design prompts for testable hypotheses, experimental tasks, and observable metrics.

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

Table 2-9. TGP Test designs to assess scientific uncertainty for flood risk visualization and communication with property owners and property renters.

Target Groups: Home and Business Property Owners and Renters in Coastal and Non-coastal Areas		
Decision: Property Purchase Decision Support		
Evaluated: Analysis Capabilities and Uncertainty Representations		
Prompt Design	**Example Prompt Phrasing**	**Measurable Observation**
H5 – Scenario-Based Assessment	Present participants with a series of flood maps that include varying levels of uncertainty indicators, such as probability ranges or confidence intervals	Ask participants to interpret these indicators and make decisions based on the perceived risk to help assess their understanding of uncertainty
H6 – Uncertainty Comprehension Quiz	Develop a quiz that includes questions about the meaning of different uncertainty indicators used in the maps	For example, questions could ask participants to explain what a "10% chance of flooding" means in practical terms or to compare the risk levels between different areas based on the map's uncertainty data.
H7 – Decision-Making Tasks	Provide participants with tasks that require them to make decisions under uncertainty, such as choosing a location for a new home or deciding whether to purchase flood insurance	Evaluate how participants incorporate uncertainty information into their decision-making process
H8 – Feedback and Reflection	After completing tasks H5-H7, ask participants to reflect on their decision-making process and the role that uncertainty information played.	This can provide insights into their thought processes and any difficulties encountered in interpreting uncertainty.
H9 – Confidence Rating	Ask participants to rate their confidence in the decisions they made based on uncertainty about flooding	This can help identify whether participants feel certain about the risk of flooding.

Designs based on Stephens et al., 2024 with Co-Pilot assistance in configuring designs.

Key Features to Consider for Evaluation Design

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

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

The proposed best practices, evaluation metrics, and *The TIFF Communication Guidelines* offer a structured approach to assessing the effectiveness of flood risk communication and visualization tools. The general evaluation categories present reliable options to assess user understanding and engagement, effectiveness of communication, usability and accessibility, adaptability and flexibility, visual and aesthetic quality, and impact and reach. For optimal results, design and test tools with specific target users in mind. Tool developers should determine specific target users (e.g., property owners, individuals with LEP) early and define their unique information needs. Finally, implement testable hypotheses as experimental tasks to refine the tools, adapt evaluation strategies, and assess tool access, uncertainty, and data aspects of flood communication tools.

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

Table 2-10. This summary table provides an overview of evaluation metrics, measurement methods, frequency of measurement, and target outcomes across evaluation metric categories for assessing the effectiveness of communication and visualization tools.

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

Table 2-10. Continued

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

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

The approach to identifying and recommending computational hardware and software requirements for flood-related analysis and visualization involves assessing many factors, including the scale and complexity of modeling needs. Building upon the in-depth literature reviews (Supporting Materials 3-1 through 3-7), the model coupling workshop (Supporting Material 3-10), and collaboration with TDIS and the TAT members, the Study Providers (see Objective 2) prepared an overview of considerations including availability and cost of computational resources, evolving computing architecture, and operation and maintenance.

CHS-TX STUDY: AN EXAMPLE

An example of the typical data management and computational resource needs for a large regional compound flooding study is provided by the 2023 study using the USACE-ERDC Coastal Hazard Systems for Texas, referred to as CHS-TX. This study conducted flood inundation models for results that were integrated into flood hazard analysis and could be hosted in CHS, to make a large amount of the data available to the public. The required computational resource and storage needs are provided in Table 2-11. The numerical modeling involved a dynamically linked storm surge (ADCIRC) and nearshore wave model (STWAVE) that allowed each model to share solution results during the coupled run time steps. A total of 660 synthetic tropical cyclones and 47 non-tropical events were simulated over three different starting water levels, a base sea level plus two sea level rise scenarios. The synthetic storm events ranged from a 4-day duration up to 13 days, with a typical or average duration being six days. For each storm event, a deep-water wave model known as WAM, was used to simulate wave conditions for the entire Texas Coast using each of the storm events. The storms were only simulated once and were used to generate boundary conditions for the nearshore wave model domains. The surge model was run for the entire length of the storm wind and pressure conditions, and the nearshore wave were computed for a duration of time that coincided with when the storm forcing winds reached the model domains and lasted until the storm force winds exited the domains. The CHS-TX modeling was performed during the 2016-2018 timeframe using HPC computational resources at USACE-ERDC. A typical run time for the coupled ADCIRC+STWAVE was six hours using approximately 1800 HPC cores, which translates into about 10,000 CPU hours per simulation. Performing the same simulation using current HPC computing resources at USACE-ERDC would take approximately 3.5 hours with the same number of cores for a total of about 6000 CPU hours. The original study used approximately 40 million CPU hours to complete all the simulations, 660 synthetic tropical cyclones, 47 non-tropical events, and seven historical tropical cyclones repeated for three different sea level conditions, plus time required for calibration and stabilization. The model outputs for storm surge, velocities, winds, pressure, and wave conditions included both peak values for each quantity, along with time series data at every ADCIRC node and every STWAVE grid cell, in addition to values stored at the 18,322 save points. The data storage requirements for this example simulation are discussed in Supporting Material 3-7.

Table 2-11. Examples of computational and data resources for CHS-TX.

Description	Computational or Data Need
Models	ADCIRC coupled with nearshore wave model STWAVE, and deep-water wave model WAM
Number of Nodes / Number of Elements	4.53 million nodes / 8.98 million elements
Elements Sizing (maximum, minimum, average coastal)	62 km maximum, 24 meters minimum, 150 meters average coastal zone
Number of Save Points	18,332 save points
Number of Tropical Cyclones	660 synthetic tropical cyclones
Number Nontropical Storms	47 non-tropical events
Number of Validation Storms	7 validation storms
Number of Augmented Tropical Cyclone Suite Storms	765,600 synthetic TCs
Computational Cost	6000 to 12000 CPU Hours per simulation
Model Data Storage	Average of 200 GB not compressed per simulation
Archived Model Data	50 TB compressed for 660 simulations
Data Stored in CHS for Public Access (earlier version)	~ 600 GB (tropical cyclones only)

Availability and Cost of Computational Resources

Substantial computational and storage resources are required to effectively build/use any regional-scale compound flood inundation model and provide the extensive scenario (ensemble) data needed for flood hazard analysis. HPC systems, medium sized local computing clusters or cloud computing infrastructure will be critical for handling the complex and large-scale simulations. Note that few groups in Texas (outside of some universities and federal agencies) have on-premise large-scale computing resources, particularly HPC resources that are necessary for compound flood inundation modeling and the GPU resources that might be needed for future versions of advanced flood hazard modeling. Access is available via cloud-based resources, but they also require significant expertise in selecting the hardware configurations to use and in installing the computational software. Furthermore, the cost of cloud-based such systems may be prohibitive, particularly when compared to shared on-premises HPC resources. Compound flood modeling of large spatial regions that includes all physical components is beyond the capabilities of desktop computers at present. Furthermore, the complexity of the models, how to integrate them, and the required expertise in setting up and executing the models is beyond the reach of most users in industry and those involved in policy, emergency response, and planning for the Texas coastal zone.

Potential Computational Resources for Developing a Compound Flooding Software Framework (See TxCFF in Component 3)

WaterWorks OnDemand (WWOD) - A potential path for developing a compound flooding software framework is using USACE HPCs and cloud-based resources, such as WWOD. USACE HPC systems could perform the simulations and archive the data. However, access would be restricted to Department of Defense personnel. Thus, the data would need to be transferred to another platform yet to be identified. The USACE WWOD system is being developed with an open-access community usage paradigm to help streamline complex computational workflows such as those required by compound flooding assessments. WWOD uses code as an infrastructure to configure the cloud computing requirements and dockerized containers, to allow (for example) easy install and setup of the operating system environments and flood modeling computational software. Predefined semi-automated workflows are being developed that guide users through setup and execution of the modeling processes. The WWOD platform is a major delivery mechanism for an overall numerical model modernization effort being led by USACE-ERDC. The goals of that effort are to guide investments in numerical technologies and data management while improving and integrating the modeling and data products as well as improving the accessibility of the data and lowering the entry level threshold for applying the complex numerical models without negatively impacting solution accuracy. Existing workflow within WWOD could serve as the foundations for building even more complex workflows for compound flooding hazards analysis for Texas. Furthermore, this system and its workflows would be able to be deployed in such a way as to make the data access and further computing resources available to community partners.

University HPC resources - As another option, design and development of such a system can be conducted using university HPC resources (e.g., TACC), which can be contracted under Texas interagency agreements. However, for long-term access of industry users as well as state, county, and city employees, it will be necessary to consider long-term hosting requirements for the tool. Commercial products such as AWS, Microsoft Azure, or Google Cloud offer hosting flexibility, but cost analyses must include data transfer fees, processing expenses, and long-term data retention strategies (see Data Management).

TxGIO or TDIS - As a third alternative, the TWDB and GLO might find it more cost-effective to develop suitable HPC capabilities within TxGIO or TDIS (which generates a different cost structure for equipment and maintenance). A hybrid computational approach using on-premises HPC clusters for real-time computation and cloud storage for archival purposes may optimize both cost and operational efficiency. These infrastructure needs must be balanced against project budgets, requiring continuous assessment as the model evolves and computational demands grow. Discussions of possible hosting approaches should be proceeded in parallel with building the software framework so that the code developers can consider long-term hosting issues in the framework design.

Evolving Computing Architecture

Computing architectures are always changing in response to new ideas and technology. Graphics Processing Unit (GPU) computing is becoming more prominent, especially at modern supercomputer centers and federal agencies where a focus is on AI/ML models that efficiently use GPU systems. This trend may continue but using parallel CPU architecture will likely dominate physics-based models for the next decade. The challenge is that the underlying structure of GPU architecture creates non-trivial coding challenges for physics-based models due to the inherent connectivity within the solutions. Consequently, rewriting physics-based models for GPUs is time-consuming and may not provide sufficient speed-up to justify the costs. However, some components of the compound flooding software system may be better suited for GPU. In particular, both flood hazard analysis and new Flood Inundation Data-Driven (FI-DD) data-driven models for flood inundation that are trained on conventional physics-based inundation models may be more efficient when designed on GPU. Thus, there is a need to consider designing for access to both CPU and GPU architectures.

Another option may be to adopt or develop new models at are GPU-optimized and still maintain the required levels of physics to accurately represent the hydrodynamics processes. Cloud storage can also facilitate reuse of the modeling data by making it more accessible and having it alongside computing resources suitable for data manipulation and analysis, which can often be GPU based. There is a possibility that the wider applicability of the GPU architecture particularly for AI/ML will eventually drive parallel CPU architectures out of the market so that they cannot be cost-effectively maintained and operated. In such a case, it would be necessary at a future date to either adopt new physics-based models or to rewrite the existing physics-based flood inundation models for GPU machines. As mentioned previously, this is a non-trivial task, given the complexity of physics-based flood inundation models that have typically been developed over a decade or more. As a conservative estimate, it would take 3 to 5 years to rewrite a single complex physics-based flood model with an additional 1 to 2 years for full testing, validation, and development of updated graphical UIs as well as supporting software for pre- and post-processing.

Resources for Different Objectives

Computational resource needs for compound flood analysis depend on the overall objective. A comprehensive compound modeling/analysis framework (such as the proposed TxCFF described under Component 3) can support a wide range of uses, including building an inundation database, screening level analysis, operational strategy evaluation, planning strategy evaluation, and detailed infrastructure design. Each of these has different computational resource requirements.

Building a flood inundation database - In general, flood inundation models are too computationally expensive to run in response to custom "what if" scenarios that stakeholders might want to examine. Thus, a key aspect of the software should be running a set of extensive flooding scenarios that can be later accessed for various user purposes and conducting flood hazard analyses. Running these scenarios will be the most computationally intensive part of the framework. Once these have been built for a particular testbed location, updates for additional "what if" cases can be conducted as needed using the full models or surrogate models trained on the full database could be used instead.

Screening level analysis - Agencies often look toward "screening" analyses that require rapid computation of a variety of high-level options. In such analyses a relatively high level of uncertainty is typically tolerated. The ideal framework would include an extensive database of flood inundation scenarios, previously run with high levels of accuracy using full-physics models, that can be used as part of a screening analysis (as discussed above). Where new "what if" scenarios are required, the tool could provide rapid-response reduced-physics modeling (with increased uncertainty) to allow managers to rapidly assess different options and decide whether the additional efforts of full-physics modeling are warranted for a given application.

Operational Strategy Evaluation - The effectiveness of real-time operational strategies can be evaluated using performance metrics such as response times, the accuracy of forecasts, and the efficiency of stakeholder communication during events. Post-event analysis provides critical feedback for improving model accuracy and updating protocols based on lessons learned. Tools to meet such objectives can be built using flood inundation and hazard analysis models within the framework or as stand-alone desktop or web applications that access the framework's databases. Such tools typically do not have extensive computational resource requirements, although their database access speed can be a critical limitation. Web applications that are executed within the same resources where the database is located, like in a cloud-computing environment, can greatly reduce latency.

Planning Strategy Evaluation - Long-term planning strategies should be evaluated through scenario-based, risk-based, models that incorporate climate projections, land-use changes, and infrastructure developments. Key metrics include cost-benefit analyses, risk management in flood-prone areas, and the impact of planned projects on overall flood resilience. Similar to operational strategy evaluation, the tools to evaluate planning strategies often do not require extensive computational resources, but the speed of their database access to previously run scenarios will control their efficiency. Where such analyses need to create new "what if" conditions, or situations where the project designs are expected to significantly alter flood conditions, then new simulations will be required, and their computational resource requirements will scale on the size of the testbed domain.

Detailed Infrastructure Design - Creating a system that can be used for detailed infrastructure design is the most challenging use-case for computational resources. Inherently, proposed infrastructure will change compound flooding in ways that are not likely included in the existing "what if" scenarios used to build the framework's inundation database. Furthermore, designers typically seek to evaluate a range of design options, each of which might have a different impact and require a different flood inundation model. To make the system useful for design, there needs to be straightforward ways for model users to address a smaller subset of the testbed (e.g., a neighborhood) and setup/run a range of "what if" models for their design vision. Systems such as the USACE's WWOD workflows and USACE's Coastal Storm Modeling and Production Systems (CSTORM) serve as examples that can be expanded to include compound flooding and not just coastal surge and waves. Whether such model of smaller areas can be run on local (non-HPC) workstations or will require access to HPC, or cloud computing remains uncertain and is likely to change over the next 5 to 10 years as computing hardware changes and software and methods evolve.

Texas Stakeholder Involvement

Effective flood resilience efforts require an operational framework that ensures collaboration among key stakeholders, including TWDB, GLO, and other state, local agencies and for-profit and non-profit organizations. Each of these entities brings unique expertise, and their roles in building, maintaining, and using an operational framework should be clearly defined. TIFF could be tasked with overseeing the technical aspects of model implementation and maintenance, ensuring its continuous improvement. TDIS can work with TIFF and other Texas agencies for supporting data management and dissemination effort. Coordinating efforts between these entities will be key to ensuring the flood modeling framework remains operationally sound, continuously updated, and relevant. The involvement of local municipalities and communities, which may provide qualitative insights into flood risk and resilience needs, should also be strongly considered. This integrated stakeholder approach ensures that the flood model supports comprehensive flood management across Texas, meeting both technical and community needs, now and into the future.

Collaboration with Federal Entities

Close collaboration with federal agencies such as NOAA, USGS, FEMA, the U.S. Department of Transportation (DOT), and USACE is imperative. NOAA's involvement, especially through its local weather offices, is critical to gaining a localized understanding of watershed dynamics, improving forecast accuracy, and ensuring the models reflect real-world environmental conditions. USGS's efforts, such as the Federal 3D National Elevation Program and other geospatial data acquisition initiatives, are vital to establishing a comprehensive and high-resolution database. USACE contributes critical expertise in hydraulic modeling, flood risk management, and access to detailed datasets from their flood control infrastructure and navigation projects (e.g., levee, dam, reservoir, floodgates). DOT's input is essential for incorporating transportation infrastructure data and understanding the impacts of flooding on evacuation routes, roadways, and critical transportation assets. These federal collaborations will provide essential datasets, including topographic, bathymetric, infrastructure, and transportation network details, needed to support both inland and coastal flood modeling across the state of Texas. Furthermore, the involvement of these federal entities should extend to continuous model updates and enhancements, ensuring that the latest scientific data and flood risk trends are incorporated into state-wide modeling efforts. Coordination with these agencies can also facilitate the sharing of best practices and avoid duplication of efforts, ensuring that resources are used efficiently.

Operations and Maintenance Support

Long-term support and code maintenance of model coupling software framework and database management is out of reach for most universities and can only be undertaken or coordinated by agencies or research centers with stable and experienced workforces. Universities can provide crucial manpower for developing and testing new code and algorithms, but there needs to be some means to make the software framework available and ensure integration of updates. We can think of these tasks as operational control and maintenance control. The former is the task of making a software system available online as a functioning user application. The latter is to make sure the code works as desired and is routinely updated for advances in research.

There are three basic paradigms that can be applied to operation and maintenance: 1) centralized, 2) community-based, and 3) hybrid:

1. **Centralized control** - The traditional paradigm where a centralized organization (government, corporation, or individual) controls the software. A good example is the USACE's suite of models built and maintained by HEC without providing open-source code for the community to research and adapt.
2. **Community-based** - Over the past three decades, we have seen the emergence of communities that organize around open-source software to provide code updates and/or operational implementations. True community-based software systems tend to be smaller software applications, simply because as they grow larger, they tend to become fractured into a myriad number of "forked" applications and the project loses coherence. The varying quality of maintenance and code validation over variety of forked applications has led to the development of hybrid control, as described below. The plethora of Linux kernels that are available provides a good example of the natural diffusion of community-based models and the subsequent development of a range of hybrid control organizations. Another example is the Princeton Ocean Model (POM) from the late 1980s, which was open-source but predated the GitHub versioning controls that are now standard practice; by the 1990s there were dozens of versions of POM available throughout academia. Today, POM is still somewhat community-based, but is arguably hybrid controlled through the POM user group.[4]
3. **Hybrid** - Most successful "community-based" applications are actually a hybrid organization, with some central entity (often, but not necessarily, a non-profit foundation) providing control over the "accepted" code updates provided by a broader community. This can be thought of as a "gate keeper." The "R" computing software, run by R Foundation[5] is an example of a non-profit that has good, centralized control for maintaining and validating code while allowing substantial

4 Princeton Ocean Model User Group: https://www.pomusers.org/codes

5 R Foundation: https://www.r-project.org/foundation

scope for community involvement. The MODFLOW groundwater modeling program[6] is an example of hybrid organization where a strong central control is exerted by the USGS, but the code is developed in an open-source repository so that outside model developers/researchers can easily make adaptions and advances to the model. USGS retains absolute control over which outside adaptions are incorporated into the model.

The key problem for long-term maintenance and operation of the model coupling software framework is likely to be maintaining a consistent funding scheme that supports four pillars:

1. Operational availability of the codes
2. Maintenance of the codes and incorporating the latest research
3. Developing and testing algorithm advances for the codes
4. Training users and the next generation of modelers

Operation and maintenance for a comprehensive compound modeling system needs to be either within a government agency or with a long-term contractor (which could be commercial, non-profit, or academic such as TDIS. Key to the success will be guarantees of funding that ensure stability of the workforce and continued access to models and data. Keeping a flood modeling system operating and available to a wide range of users requires specialized skills that can be difficult to obtain, hence rapid turnover in either agency or contractor personnel due to variability in funding can create problems. Furthermore, there needs to be dedicated funding streams to university programs for developing and testing algorithms that advance the modeling system and keep it update with the latest research and technology advancements, and training modelers and users that the state, federal agencies, and contractors will need.

6 USGS MODFLOW github website for code: https://github.com/MODFLOW-ORG/modflow6

Road cones blocking flooded road

Objective 6: Make recommendations pertinent to future data management and visualization needs to GLO

As TIFF's ultimate legacy will be the set of recommendations, guidelines, and frameworks to improve the performance, understanding, and communication of flood science, it was imperative that the final recommendations made by TIFF be vetted and optimized by coordinated peer review so that they can be made actionable without hesitation by implementing entities. This coordinated peer review was structured around the component Objectives, in that the Objectives were used to query whether the existing list of potential recommendations completely addressed the goals of TIFF (Supporting Material 2-13).

Ultimately, eight TIFF Recommendations resulted from the research and expertise associated with Component 2. See the Recommendations Section for summary handouts that can be used to seek further support for implementation.

Table 2-12. Component 2 objectives and associated recommendations.

TIFF Component Objective	Resulting Recommendation(s)
Establish a Data Management and Visualization TAT	Objective met by TIFF. No further recommendations.
Assist TDIS with designing and testing the conceptual framework for managing, visualizing, and disseminating large volumes of coastal flood-related datasets, including data visualization system(s)	C2.2A: Study User Interactions with Flood Risk Visualizations C2.2B: Assess Public Evacuation Decision-Making C2.2C: Replace the "Frequency-Based Terminology", i.e., "100-year Flood" by Identifying More Effective Language to Communicate Flood Risk
Conduct an inventory on coastal flood-related UIs and recommend guidelines for a coastal flood UI for Texan decision-makers	C2.3A: Implement TIFF Guidelines for Coastal Flood Information Design and Communication C2.3B: Create Flood Risk Reduction Planning Cards
Make recommendations for UIs, including the level of end-user access, analysis capability, visualizations, and included datasets	C2.4A: Share Lessons of Texas' Flood History C2.4B: Standardize Grantee Shapefiles
Assist TDIS with identifying and recommending computational hardware/software requirements for flood-related analysis and visualization	C2.5A: Study and Develop Alternatives to Menu-Driven Dashboards to Better Reach Target Users
Make recommendations pertinent to future data management and visualization needs to GLO	Objective met by TIFF. No further recommendations.

TIFF RECOMMENDATIONS, DATA MANAGEMENT AND VISUALIZATION

C2.2A: Study how user understanding and gaze patterns change when interacting with different flood risk visualizations and communication tools

To improve flood risk communication, TIFF recommends conducting research that examines how individuals' gaze patterns shift when interacting with various modes of flood risk visualizations. This study will bring people into a visualization lab to evaluate the effectiveness of different visualization modes in enhancing flood risk awareness, and test how different modes of interaction influence user engagement and comprehension. This includes in situ testing, mobile device testing, and using eye-tracking with visualizations, potentially gamifying the process. Results from this study could accelerate understanding of what works for communication and complements efforts to assess emerging technology.

By analyzing gaze patterns, researchers can gain insights into how people engage with visual tools, where they focus their attention, and how well they absorb the risk-related content. This research should focus on testing existing and developing flood risk visualization tools used in Texas, such as the Buyers Aware platform, the CHARM online tool, and dashboards being developed by IDRT and UT-Austin. This research should also consider the usefulness of technologies for communicating model outputs. By studying how users interact with these tools, we can refine their design to enhance user comprehension and decision-making, ultimately improving flood preparedness and response efforts.

The estimated cost for this research is $225,000, covering eye tracking software and hardware, virtual and augmented reality equipment, immersive software, and research design and execution. Costs may be reduced if access to existing eye tracking and keystroke tracking equipment is obtained.

Key actions when implementing this recommendation include:

- **Literature Review** - Conduct a full review of interactive and active learning technologies, including user studies and data/analytics workflows. This includes the development of serious games and the exploration of how to engage adults in playing these games.
- **Eye Tracking and Virtual Reality Studies** - Conduct eye tracking and/or virtual reality studies to observe how gaze behavior changes when different visual representations of flood risk are shown to participants.
- **Key-Logging Study** - Combine the previous studies with a key-logging study, where participants interact with flood risk information on the web. This will help capture and analyze their search behavior and physical actions while seeking out flood risk data.
- **Misinformation Response Studies** - Conduct additional studies to understand how people respond to misinformation about flood risk. These studies will compare reactions to a continuum of flood risk levels, ranging from low to high risk, to gauge how misinformation influences decision-making.

C2.2B: Assess public evacuation decision-making to discover what influences evacuation decisions during a flood event to improve emergency planning and response

TIFF recommends that experiments, surveys, and focus groups be conducted along the Texas Coast to explore how local knowledge influences evacuation decisions. This research should assess public perceptions of media reports, trust in local authorities, and confidence in sources like meteorologists and emergency managers. It should also use a mixed methods approach to identify barriers to evacuation and common assumptions, while incorporating insights from local emergency managers and meteorologists.

Evacuation decisions are complex, influenced by both the probability of events and the potential consequences. Local knowledge, media coverage, and personal experiences shape how communities process this information. A critical question is how past disasters, local media, and community knowledge affect residents' decisions to evacuate or stay.

Hurricanes have a particularly dramatic impact on life-or-death decisions for coastal communities. While flood maps can aid decision-making, many residents do not follow local emergency managers' advice and instead rely on their own judgment. Understanding this decision-making process is essential for improving evacuation strategies and can help guide improvements in effective communication and messaging during a disaster.

The estimated cost for implementation is $450,000. Participants should be compensated to ensure representative data. Key actions when implementing this recommendation include:

- **Review of State Operations Center Practices** - Interview Texas Division of Emergency Management (TDEM) experts with multi-event experience to identify areas for improvement in evacuation processes using better information aids. This information will be used to provide guidance on messaging strategies for informing the public on evacuation decisions.

- **Qualitative Study of Coastal Communities** - Interview evacuees to understand their decision-making, including reasons for evacuating, evacuation costs, and whether flood models or navigation apps influenced their choices. These findings will be used to compare public perceptions of flood risk information with technical data used by experts.
- **Experimental Testing of Tools** - Use the findings from qualitative study to design experiments testing the effectiveness of flood maps and navigation apps in aiding evacuation decisions.

C2.2C: Replace the "frequency-based terminology" (i.e., "100-year Flood") by identifying more effective language to communicate flood risk

A significant challenge in flood risk communication is the language used to describe the probability of experiencing a flood. Research has shown that longer timeframes, such as 100 or 500 years, are difficult for people to grasp, making it harder for them to accurately assess their risk.

TIFF recommends research to explore how numerical reasoning and confidence in using probability estimates influence the public's understanding of uncertainty in flood communication. This research should also focus on developing alternative language to replace frequency-based terms such as "100-year flood" and "1% chance per year," which often confuse and mislead the public.

The estimated cost for implementation is $175,000. To ensure representative data, participants should be compensated. Designing the study to compare findings in both English and Spanish is crucial, as many residents in Texas prefer speaking Spanish.

Key actions when implementing this recommendation include:

- **Interviews with Target User Groups** - Conduct a systematically designed set of interviews with specific target user groups to identify alternative language and timeframe communication options.
- **Online Experimental Survey** - Design and execute an online experimental survey of Texans in these target groups to identify which language options best influence decision making, attitudes, confidence, response efficacy and related factors that influence flood decision making. Project researchers should consider using the Subjective Numeracy Scale and common probability frames used to communicate flooding.
- **Training Language Models** - Use the results from the interviews and online survey to train small language models on the specific language used in different coastal and compound flood scenarios. This includes mapping preferred terms in coastal areas and considering multilingual aspects.
- **Flood Literacy Evaluation** - Determine if the developed alternative language to replace frequency-based terminology increased flood literacy in target user groups, improving their capacity to respond effectively and appropriately to given flood risk information.

C2.3A: Implement The TIFF Guidelines for Coastal Flood Information Design and Communication (*The TIFF Communication Guidelines*)

To improve the clarity and accessibility of flood risk information, TIFF developed Guidelines for Coastal Flood Information Design and Communication (*The TIFF Communication Guidelines*), which should be followed when developing flood risk maps, visualizations, and communication tools. These guidelines are best practices for presenting flood risk in a way that is clear, transparent, and user-friendly. Their use will ensure that both general audiences and those directly affected by coastal flooding can accurately interpret and respond to the information.

TIFF recommends that TWDB lead this effort, because it serves as the designated State Coordinating Agency for the National Flood Insurance Program in Texas and provides both flood mitigation and protection planning and assistance. TWDB can coordinate partnerships between government organizations, Texas legislators, state funding agencies, flood tool developers, business owners, non-profits, and universities, to promote the adoption of these guidelines.

To ensure widespread adoption of the Guidelines and improvements in how flood risk is communicated to the public and decision-makers, key actions when implementing this recommendation include:

- **Promotional Campaign** - Develop an asynchronous video walkthrough explaining *The TIFF Communication Guidelines.* Host the publicly available video on the TIFF website. Secure expert consensus; then, seek endorsement from state-level decision-makers.
- **Training and Application** - Provide training on how to apply *The TIFF Communication Guidelines* effectively. Use the Texas Water Data Hub and TDIS as a case study to illustrate best practices.
- **Flood Literacy Evaluation** - Determine if The TIFF Communication Guidelines increase flood literacy in general audiences and specific groups affected by coastal flooding, improving their capacity to respond effectively and appropriately to given flood risk information.

C2.3B: Create Flood Risk Reduction Planning Cards

Flood risk maps, visualization tools, and coastal management information portals are essential for raising public awareness and driving action at individual, local, and national levels. These tools help residents, policymakers, and emergency responders understand flood risks, prepare for disasters, and make informed decisions about mitigation and adaptation. However, despite their potential, they often fail to effectively communicate flood risk to general audiences. When flood risk information is not clearly presented, non-technical users may misinterpret the data, either overestimating or underestimating the actual risk. Miscommunication can lead to poor decision-making, reducing the effectiveness of flood preparedness and response efforts.

To address this issue, a more structured approach is needed to ensure that flood risk information is presented clearly and accessibly. TIFF recommends the creation of Flood Risk Reduction Planning Cards based on the TIFF Communication Guidelines for Coastal Flood Information Design and Communication. These cards would serve as a toolkit for planners to better organize and prioritize flood risk reduction activities, providing a structured framework for developing and implementing effective strategies to target and reach their specific audiences.

The cards would also encourage data-driven discussions during the flood risk planning process and offer a visually appealing, user-friendly design to improve engagement and usability. By integrating these planning cards into flood communication efforts, communities can enhance their ability to interpret flood risk data, plan for future events, and build greater resilience against flooding.

TIFF recommends partnerships between academic institutions, planning organizations, state funding agencies, cities and towns, flood control districts, and regional flood planning groups to develop and implement Flood Risk Reduction Planning Cards.

Key actions when implementing this recommendation include:

- **Competitive Analysis & Market Research for Card Deck Development ($50,000-$100,000)** - Conduct a review of existing card decks (e.g., augmented reality 32-card deck), platforms where card decks are marketed (e.g., game crafters), typical costs, and the target audiences that purchase such cards.

- **Card Deck Development ($50,000-$100,000)** - Design and create the Flood Risk Reduction Planning Cards based on insights from the competitive analysis and market research, using the TIFF Communication Guidelines for Coastal Flood Information Design and Communication.
- **User Testing and Evaluation ($50,000-$100,000)** - Evaluate the effectiveness of the cards and gather feedback from users to refine and update the cards for continued improvement.

C2.4A: Share lessons of Texas' flood history to help residents understand past events and make informed decisions

Effectively visualizing and disseminating flood-related information is essential for improving public understanding of flood risks. Accurate and accessible flood data can help communities, decision-makers, and emergency responders interpret complex models and datasets, leading to better preparedness, response, and long-term resilience. However, flood information is often scattered across multiple sources, making it difficult for residents to access and use in decision-making.

To address this gap, TIFF recommends the development of a public resource documenting historical floods in Texas hosted by TDIS. This resource would serve as a centralized platform for residents to explore past flood events and understand their potential future risks. An interactive map interface would allow users to visualize flood events by location, making it easier to see where and when major floods have occurred. Each recorded flood event would include key details such as dates, impacted areas, and the extent of flooding, offering a comprehensive historical record.

The resource should also incorporate predictive insights by integrating flood forecasts and return period data. This would provide users with a clearer picture of potential future flood risks based on historical patterns. By combining historical data with predictive modeling, this tool would enhance public awareness and support more effective flood risk management across Texas.

Key actions when implementing this recommendation include:

- **Clearly define a "major flood"** based on indicators such as loss of life, property damage, rainfall amount, etc.
- **Generate summary tables for each recorded flood** event to include dates, impacted areas, and the extent of flooding.
- **Incorporate predictive insights** by integrating flood forecasts and return period data.
- **Evaluate the effectiveness of the interactive map** interface and gather feedback from users to refine and update the interface for continued improvement.

C2.4B: Standardize grantee shapefiles for all funded flood-related projects to include three critical shapefiles to the funding agency.

Flood-related projects in Texas involve various stakeholders, such as local governments, state agencies, and non-profits, working to improve flood management and response. However, a lack of coordination can lead to overlapping efforts, inefficient use of resources, and missed collaboration opportunities.

TIFF recommends a standardized requirement for all funded flood-related projects to submit three critical shapefiles to the funding agency and other relevant recipients. These shapefiles will provide spatial data on the project's location, scope, and impact area. This standardized approach will allow agencies to quickly identify overlaps between projects, assess geographic synergies, and reduce redundancy.

By incorporating these shapefiles into project planning and evaluation processes, stakeholders can better understand the spatial relationships between ongoing and proposed projects, ensuring that funding is directed toward projects that complement each other. This will not only streamline the allocation of resources but also foster comprehensive planning and clarity in project objectives, ultimately enhancing flood preparedness, mitigation, and response across Texas.

Key actions when implementing this recommendation include:

- Develop guidelines for shapefile format, metadata standards, and submission protocols
- Secure agreement from relevant agencies to adopt these guidelines and standards
- Designate an office or database to manage and analyze shapefile submissions
- Integrate shapefile submission requirements into project scopes and funding application processes

C2.5A: Study and develop alternatives to menu-driven dashboards to better help target users find the flood risk information they need to make flood-related decisions

Generative AI (GenAI), including prompt engineering and large and small language models, presents an opportunity to modernize flood risk visualization and communication. Human-AI teaming enables more intuitive information retrieval and organization, making critical data more accessible.

TIFF recommends a study to assess how GenAI can better help target users find the flood risk information they need for decision-making. Following the study, a Texas-specific GenAI Flood Risk Tool can be developed for broader implementation. This "Texas GenAI Flood Risk Tool" will feature a prompt coaching system to guide users in writing effective prompts, ensuring they receive accurate and actionable responses. It will also define the necessary datasets for the tool and test how different target users interact with it.

If the resources are not available to implement the entirety of this recommendation at once, the following describes how it could be made a multi-phase approach:

- **GenAI Flood Tool Proof of Concept (Two Focus Groups *$225,000)** - Identify at least five public target users and two official target users for the study. Conduct background research to assess these users' flood information needs, leveraging existing research funded by Texas agencies. Carry out initial focus groups of 30-50 participants and in-person lab experiments to analyze how users search for flood information, utilizing methods such as eye-tracking, virtual reality-based eye-tracking, and think-aloud protocols. Consider online experiments. Conduct a follow-up focus group of 18-36 participants to help participants learn prompt-writing techniques and refine their queries to obtain more effective flood-related information.
- **GenAI Flood Tool Development (One Focus Group *$700,000)** - Build on the proof-of-concept findings, applying the insights gained to the same target users. Identify necessary datasets, visual information, and flood-specific small language model requirements. Conduct usability testing of the designed system using the same research methods from the proof-of-concept study, with a sample size of 30-50 participants per group.
- **Flood Literacy Evaluation** - Determine if the alternatives to menu-driven dashboards increased flood literacy in target users, improving their capacity to respond effectively and appropriately to given flood risk information.

C4.9A: Adopt specialized graphics for use across state and local agencies to reach Target Users

Many local communities in Texas still rely on outdated FEMA brochures when conducting flood outreach, which often lack the necessary updates to effectively communicate with today's audiences. Recent research by UT Austin identified three key target user groups and a unified statewide message that resonates with Texas culture. The next step is to bring these findings to life through impactful, localized graphics.

To address this, TIFF recommends updating and finalizing graphics for the TWDB's outreach materials. These graphics will target three key audiences identified by TIFF: property owners, property renters, and people with limited English proficiency. By modernizing these visuals, TWDB can ensure that flood risk communication is more effective and culturally relevant and encourage their use across both state and local agencies.

Key actions when updating graphics used for TWDB messages for specific target user groups include:

- **Design and Finalization of Graphics** - Create visuals targeting the four three audiences, adhering to accessibility standards, and using simple colors and fonts compatible with basic programs like PowerPoint. This standardization ensures that local officials, regardless of technical expertise, can easily edit and customize the visuals to meet their community's needs.
- **Review and Approval Process** - Conduct focus groups with representatives from the three prioritized audiences to evaluate how effectively the graphics communicate key messages. Additionally, the graphics will be reviewed to ensure consistency with the state's flood risk messaging.
- **Production and Distribution** - Make the graphics available in both digital formats (e.g., PDFs, PowerPoint slides) and print formats. Host the graphics on the TDIS to make them easily accessible for local agencies, along with instructions for downloading and customizing the materials for their specific communities.
- **Flood Literacy Evaluation** - Determine if the updated and specialized graphics increased flood literacy in the three target user groups, improving their capacity to respond effectively and appropriately to given flood risk information.
- **Evaluate Priority Groups at Risk to Define Target Users** - The number of priority groups that can benefit from improved TWDB communications about flooding risks is vast. Each group tends to include heterogeneous sub-groups that need to be carefully evaluated to define clear, specific target users of interest for future work.

2.6 The Future of Texas Data Management and Visualization

TIFF's work in collaboration with TDIS, the TAT members, and multiple academic and agency partners established a comprehensive foundation for advancing coastal flood data management, visualization, and communication in Texas. Through extensive literature reviews, targeted workshops, and systematic data inventories, TIFF identified the essential components of a conceptual framework for managing, visualizing, and disseminating large volumes of coastal flood-related datasets, and outlined the critical hardware and software considerations for effectively computing, storing, analyzing, and visualizing flood-related data and model outputs.

Recognizing that effective visualization is central to bridging the gap between complex scientific outputs and actionable decision-making, TIFF conducted a statewide review of existing coastal flood UIs, identified opportunities for improvement, and developed research-based visualization guidelines tailored to three prioritized target user groups: property owners, property renters, and individuals with LEP. By replacing the term "end-user" with "target user," the project emphasized the importance of involving these groups throughout the design process to ensure that visualization tools are relevant, accessible, and impactful. The resulting *TIFF Communication Guidelines*, supported by evaluation metrics and stakeholder feedback, provide a roadmap for creating visualization tools that foster collaboration among agencies, emergency responders, and diverse audiences in Texas coastal communities.

These coordinated efforts spanning data infrastructure, visualization guidelines, and user-focused design, culminated in a set of vetted recommendations and frameworks intended to guide future flood science initiatives. Implementing the resulting findings, best practices, *The TIFF Communication Guidelines*, and recommendations will enhance the accessibility, accuracy, and effectiveness of coastal flood risk communication across Texas.

Future Research

In addition to producing findings, guidelines, and recommendations, TIFF also identified key areas for further research to advance coastal flood communication and decision support. As part of this effort, TIFF explored innovative visualization techniques from other states and countries—such as extended reality technology, digital twins, story maps, and serious games—that hold promise for enhancing engagement but require targeted testing with specific audiences before broad implementation. The project's best practices for the interface design process stress the importance of integrating UX considerations throughout the design process, including collecting and structuring interaction data, processing it to improve usability, adapting interfaces based on feedback, and balancing functionality with aesthetics, as research shows that appealing design can improve comprehension and engagement. These insights, combined with stakeholder input, informed the identification of additional research priorities described in the following section.

EXPANDING TARGET USER GROUPS

Identify additional vulnerable populations beyond the three prioritized target groups, including:

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

ENHANCING ENGAGEMENT, COMMUNICATION, AND INFORMATION MANAGEMENT

Advance tools and methods that improve how users interact with flood risk data and make decisions:

- **Community Stress Baseline** - Develop methods to establish a baseline and assess and report community stress levels after hazard events using biophysical indicators (e.g. galvanic sensors, cortisol levels).
- **'Double Duty' Audiences** - Design support tools for individuals managing multiple roles during disasters (e.g. responders who also communicate with the public), aiming to reduce cognitive and emotional strain.

INCENTIVIZING PREPAREDNESS AND BRIDGING IDENTIFIED GAPS

Investigate opportunities to address gaps in current communication strategies and promote proactive planning through policy and education:

- **Business Continuity Incentives** - Consider programs that reward businesses for developing robust continuity plans, such as insurance discounts or tax incentives
- **Educational Outreach** - Create and disseminate materials that guide businesses and other stakeholders in effective continuity plans in the context of flood preparation.

Sun rising over the Gulf on Padre Island © Tim Malek

Implementation in the Lower Rio Grande Valley

As part of TIFF's continued evolution, the project expanded into the LRGV to address region-specific needs in coastal flood risk communication. Efforts are focused on improving the delivery of flood risk information to diverse audiences, including Spanish-speaking communities. Engagement activities encompass structured interviews with local stakeholders, facilitated workshops, and a community learning exchange event. These activities include testing culturally tailored communication strategies—such as hands-on demonstrations and the use of localized flood maps—to enhance comprehension of flood hazards and promote protective actions. Preliminary findings indicate that experiential learning approaches, particularly those addressing sandbag use and drainage system awareness, measurably increased participant confidence and intent to implement mitigation measures. A comprehensive report detailing the LRGV expansion, methodology, and outcomes will be provided in a forthcoming publication.

Navigation buoy washed up on the beach after a storm on the Texas coast © Michelle, Adobe Stock

3 Component 3: Integrated Flood Modeling Framework

The goal of Component 3 is to develop an integrated modeling framework to support inland and coastal flood hazard identification for the Texas coast.

3.1 What is an Integrated Flood Modeling Framework?

Current flood modeling practices are siloed, fragmented by discipline (e.g., hydrology, hydraulics, meteorology, coastal ocean dynamics), and inaccessible to many state and local agencies due to the high level of technical expertise required. Texas urgently needs a unified, scalable, and reusable integrated framework to evaluate compound flood hazards and inform flood mitigation and resilience planning at the local, regional, and state levels.

Hydrologic, meteorologic, hydraulic, estuarine, and surge models serve as both valuable tools to provide information on flooding hazards and guides in planning and implementing structural and non-structural flood risk mitigation solutions for minimizing flood risk. Various flood process models exist, but each are tailored to address specific challenges related to dominant flooding mechanisms (e.g., pluvial, fluvial, storm surges). While these models have grown in complexity, with many simulating increasingly detailed processes occurring within natural and built systems, an integrated flood modeling framework is needed to better couple different process models (e.g., surge and rainfall-runoff) and accurately resolve total water levels, particularly in the low-lying coastal zones. While FEMA, USACE, NOAA, and other federal agencies have some guidance on this topic, more in-depth guidance and tools are needed for practitioners.

Understanding Flood Modeling

Flood modeling, whether for understanding hazards or to predict inundation, requires a complex set of workflows, data, and models that are created and run by expert modelers. The type of models, their data requirements, and their outputs depend on the user's goals when the model is constructed. Traditionally, such models have been based on what the world looks like right now. However, given the increasing frequency and severity of flood events driven by natural and anthropogenic change, future flood models should integrate changing conditions into data workflows so as to anticipate more frequent and extreme flooding scenarios. Thus, there is a need for workflows that produce standardized "future scenarios" based on climate models that consider both inland and coastal impacts (e.g., rising sea levels, higher storm surge hazards, changes in rainfall patterns). These models should also account for probable land-use changes driven by population growth and urbanization that can exacerbate flood hazards and risks, particularly in areas where natural drainage is disrupted or where flood-prone areas become more heavily developed. It is crucial to include such projections into flood models to ensure resilience in future infrastructure development, flood mitigation, and adaptive planning/preparedness strategies.

HOW MODELS ENHANCE UNDERSTANDING OF FLOOD RISK

Engineers, scientists, policymakers, and managers use a layered modeling and analysis approach to evaluate and predict flood impacts, or "flood risk." The term "flood risk" is an overarching idea that takes into account the flood hazard (the probability of an event), the resilience of the affected systems, and the severity of consequences (including people, property, infrastructure, etc.). We can think of this as a bottom-up cascade from specific to general:

FLOOD INUNDATION → FLOOD HAZARDS → HAZARDS + RESILIENCY + CONSEQUENCES → RISK

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

Flood inundation triggers a flood response from the system; the integration of that flood response across probabilities (or return intervals) is the flood hazard; hazards with resiliency and consequences provide quantification of risk.

Flood risk assessments provide the foundations for decision-making in flood protection design, resiliency/recovery analysis, and emergency planning. Flood hazard analysis provides the statistical (or probabilistic) approach to assessing the magnitude and likelihood of flood events. In general, flood hazard analysis can use flood inundation observations and/or inundation modeling to evaluate the flood hazards associated with a range of prior or possible storms. However, large storm events (hurricanes, tropical storms) along the Texas coast are relatively infrequent, and the available observations are insufficient for an observation-only approach. Therefore, flood hazard analysis is based on the modeling of synthetic events built on the science of flood inundation modeling. Hazard analysis provides a range of storm conditions based on statistical/probabilistic analyses, and then an inundation model predicts the flood water elevation and extents for each storm. The inundation results from the modeled storms are integrated with their probabilities to provide either 1) a map of flood hazard, which is often defined based on the probability of occurrence in a given year that is typically (and misleadingly) expressed as a return interval in years[1], or 2) a single location hazard curve (e.g., a flood frequency curve) that relates specific water levels to their probability of exceedance.

TYPES OF FLOOD MODELING

A review of flood risk analysis and planning tools using flood hazards, system resilience, and event consequences is provided in the TIFF Planning & Outreach component (i.e., TIFF Component 4). Here, under the umbrella of Component 3, a narrower focus on two of the key aspects for quantifying flood risk is provided. These two of flood modeling/analysis are: 1) determining the probability, risk, and hazards of multiple flood events, and 2) given a single event, determine the resulting flooded areas, depths and durations.

The first, ***flood hazard analysis*** (or "probabilistic flood modeling"), characterizes flood frequency (how often floods occur in the area of interest), magnitude (size or severity of an event, such as water level and inundated area), duration (how long an event lasts), and the location (including the existing conditions at the start of an event). Flood hazard analysis seeks to quantify the likelihood that a flood will initiate a "hazard", which could be a damaging water elevation, a wave height, or an erosive force. This analysis provides the foundation of *flood risk assessment*[2] used by policymakers and managers throughout the Texas coastal region.

The second, flood inundation modeling, is event-based modeling representing the time-space evolution of flood physics from a single storm occurring in a region of interest. This analysis provides visualization of the flood depths across the landscape for a particular flood event. Flood inundation modeling seeks to represent extent and depth of flooding caused by a specific single storm or event. In the most sophisticated models, the time-evolution of flooding across the landscape is simulated and can be used to create a movie of how flooding occurs (i.e., how the depth and extent over the land surface changes over time).

These two types of analysis are closely related and incorporate information from each other, as results from flood inundation models often (but not exclusively) provide the water surface elevation data used for flood

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1 The flood with 1% chance of occurring in any given year is known as a "100-year flood," which is misleading to those not well-versed in probabilities. To be somewhat less misleading: a 1% or 100-year flood has roughly a 1% chance of occurring at least once in a 1-year period, a 10% chance of occurring at least once in a 10-year period, and a 26% chance of occurring at least once over the course of a 30-year house mortgage. An important concept is that the occurrence of a storm in any given year (or decade) does not affect the probability of a similar storm occurring in following years.

2 Flood risk assessment integrates data from a range of models and observations to estimate the likelihood of an event (with the exposure and vulnerability). Such risk assessments provide the means to evaluate and discuss the cost/benefits of flood protection strategies, decide on flood protection design and emergency management strategies, and communicate to the public of flood risks particular to their location.

hazard analysis. Flood hazard analysis is typically conducted with a combination of observed data and a suite of flood inundation models.

Both flood hazard analysis and flood inundation models are mathematical representations of flooding that typically require extensive computational resources and scientific expertise to create, test, and apply. These tools are complementary and closely coupled in the process of quantifying the flood hazards that determine flood risk. Flood hazard analysis begins with a statistical analysis of the flood levels and/or the driving forces (meteorological, oceanographic), which are used to drive simulated events using a flood inundation model. Probabilistic models may be used to represent possible future events and statistical models to represent the likelihood of those events, often referred to as synthetic events. Inundation models provide flooding extent, depths, and durations of flooding for a set of individual events. Through flood hazard analysis, the inundation model results are integrated (or aggregated) to develop hazard analysis curves (or flood frequency analysis curves), or maps of flood elevation at different hazard levels (i.e., flood inundation maps).

Flood inundation modeling is a useful tool to evaluate (in detail) what happened in the past and flood scenarios that might occur in the present and future, with and without flood risk management project conditions. Such models are typically (although not exclusively) based on the mathematics of fundamental physical processes (conservation of mass and momentum). These models typically provide a "top-down" view that divides the landscape and ocean into a horizontal grid mesh where the physics equations are modeled at small scales. The model begins with known "initial conditions" of landscape elevation, water levels, winds, etc., and future changes in the winds, tides, sea level (etc.) are enforced in a step-by-step manner. In effect, the physics equations are "marched" step-by-step through time to predict how flood inundation in the next time step changes based on the state in the previous time step and the forcing (e.g., rain, wind, tide) that occurs during that time step. Thus, flood inundation models can provide a detailed space-time history of flooding, e.g., a movie of flood depths across the landscape, which is usually called a "simulation". Alternatively, the time-space data set can be used for analyses such as maximum flood depths or durations. To understand compound floods, inundation models can be used to isolate different flooding drivers and the effects of multiple drivers in combination. As an example, we can evaluate the impact of rainfall and river overbank flooding by modeling storm impacts both with and without river inflow effects (Figure 3-2). The significant increase in water surface elevations with river flooding caused dramatic changes in the flood inundation area.

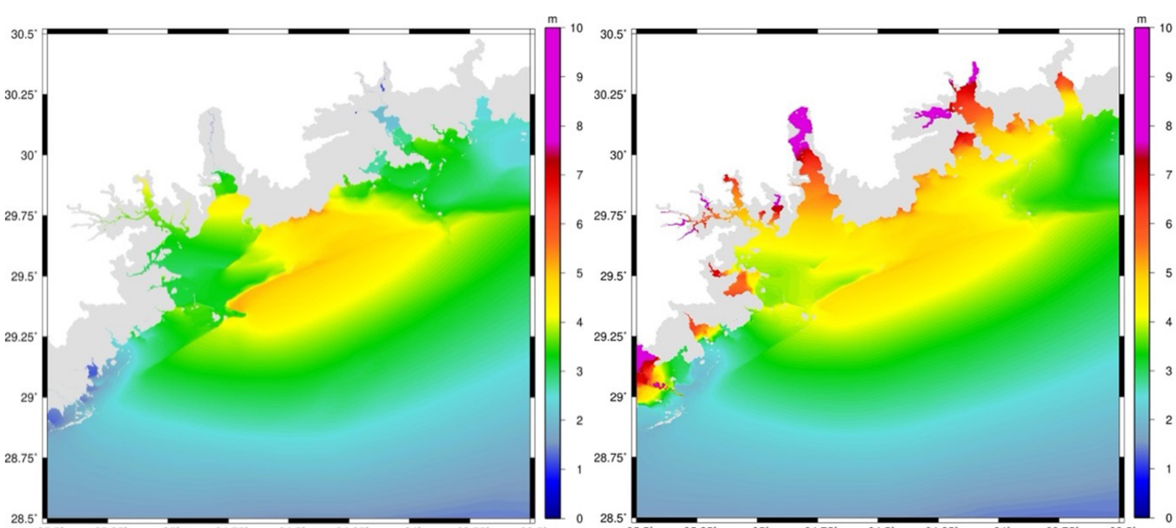


Figure 3-2. Modeled water surface elevation (feet) in the Houston area without river inflow (left), and with synthetic extreme river inflows (right), using winds and oceanic storm surge from Hurricane Ike. Results are from the coastal flood model (ADCIRC).

Each approach is discussed in more detail below. For key characteristics and computational requirements of the different model types, see Supporting Materials 3-1 through 3-7 in the Component 3 Appendix. Further details of these models are summarized in the Model Literature section and in Dawson et al. (2024).

1. **Flood Hazard Analysis** - Typically, in a hazard analysis, a long record of flood levels at a location would be ranked and fit to a distribution, from which the probability of occurrence or exceedance could be calculated to define a hazard curve. However, at a specific location, coastal storms (hurricanes, or tropical cyclones, and non-tropical events) do not occur with the same high frequency that inland flood events occur. Compound coastal storm events, where two drivers, such as storm surge and rainfall runoff, raise water levels to flood elevations, are even more under-represented spatially and temporally in the observational record than those for coastal storm surge and wave hazards. To overcome the paucity of coastal storm flood elevations, the state of practice for storm surge/wave is to conduct the hazard analysis on a set of representative synthetic storms numerically modeled in a JPM framework. JPM samples regional atmospheric parameter distributions (as opposed to local site water elevations), to develop a set of representative parameters for each synthetic storm and identifies its probability. As compound events can have even less observations, their joint probability is difficult to assess (Gori 2023). Thus, frameworks developed for compound flood hazard analysis can be tiered into different degrees of application difficulty, and the selection of that technical complexity of analysis can be based on a project's data availability, numerical modeling capabilities, details of model realizations, and uncertainty or precision required for a specific application (Gutenson et al. 2021). An example of a tiered probabilistic compound hazard framework, developed by USACE as part of the CHS (Nadal-Caraballo et al. 2020), recommends a set of tiers of increasing complexity: from screening efforts that rely heavily on statistical analysis of paired compound observations, to enhanced JPM-based tiers, which use JPM to quantify coastal hazards induced by storm surge and waves linked to inland drives by increasingly sophisticated joint probability schemes between the compound mechanisms. For example, increasingly complex tiers might link coastal and inland mechanisms based on seasonality at a low tier, while a higher tier might couple coastal and inland models forced by synthetic storm driven, Tropical Cyclone (TC) rainfall models.

   Two main approaches have been advanced in recent years: bivariate copula statistical analysis (e.g., Jane et al. 2022) and enhanced JPMs. Bivariate statistical analyses are direct statistical approaches that are conducted directly on the measurements of the hazard, or response variable, being quantified (e.g., gage height, flow, rainfall, water surface elevation). They are typically based on extreme value analyses (Coles, 2001) and can be challenged by limited observations, made more severe by the need for overlapping records (e.g., paired sets) of compound event data. Analyzed using bivariate statistics and representing the relationship between two parameters as a copula, these methods are often used to select joint input pairs for design events to use in numerical models (e.g., hydrologic, hydraulic, and coastal storm surge models). Recent efforts in Texas have included the GLO's River Basin Flood Study, Regional Bivariate Copula Studies, and the Joint Coastal Bivariate Probability Study – Texas (JCBP-TX, Carr et al. 2022) (See Supporting Material 3-8 for more regional examples). The regional studies were conducted by local practitioners following bivariate copula guidelines for several basins in a given region. The JCBP-TX was a coast-wide study across eight large river basins conducted to describe and develop a bivariate copula analysis of the joint probability of compound coincident inland and coastal hazards from recorded observations to assess the interaction of coupled storm surge and rainfall hazards. The reasoning, approaches, and steps for conducting a joint probability bivariate analysis were discussed, and the approach was considered useful for screening level analysis, but sensitive to data availability and assessment choices.

   In enhanced JPMs, synthetic storm parameters are used to drive coupled process-based numerical models for the compound mechanisms (e.g., storm surge, waves, rainfall, and rainfall-runoff)

(Bass and Bedient 2018; Bartlett et al. 2023; Gori 2023), explicitly accounting for the probabilistic relationship between the driving parameters and the joint probability of the compound response (Abbaszadeh 2022). Application of enhanced JPMs can leverage existing numerical process models, such as hydrological, hydraulic, surge and wave models, as well as results from existing JPM analyses for coastal storm hazards, which can provide large sets of synthetic storm parameters, ocean circulation and wave models, and corresponding storm responses and probability densities (Nadal-Caraballo et al. 2015; Nadal-Caraballo et al. 2022a; Nadal-Caraballo et al. 2022b; Gori and Lin 2022). Recent compound flooding JPM analyses include driving a parametric TC rainfall model with JPM synthetic storms and applying that rainfall to hydrologic, hydraulic, and direct flow models (e.g., Bass and Bedient 2018; Gonzalez et al. 2024; Bartlett et al. 2023; Gori and Lin 2022; Liu et al. 2024). These studies demonstrate some of the methods, models, and enhanced JPM applications used for compound flood hazard modeling.

2. **Flood Inundation Modeling for Historical Storms** - Traditional engineering flood inundation models are based on physics equations that are well understood and have more than a century of study. We often call these "mechanistic" models, as they are driven by equations of mechanics rather than by correlations in a data set (The Emergence of Artificial Intelligence and Machine Learning in Flood Modeling section below). These mechanistic models require extensive data for "boundary conditions" (the time-space variation of forcing that creates the flood (rainfall, wind, offshore sea level)) along with the "initial conditions" of the modeled area at the start (e.g., soil saturation, river and lake water levels) and detailed maps of the landscape that describe elevation, soil type, obstructions, and flow pathways. Combining these data in a mathematical model allows us to create a series of "time-marching" pictures of the flood extent and depth during an event. The model itself divides the landscape into a grid of boxes (or "cells") where mathematics for the physics of forces and water transport are used to compute how much floodwater accumulates and how much moves in/out of each cell in a single time step. We can use the model results to create movies of the flood across the landscape, to evaluate the flood behavior at a particular point, and to create maps of flood statistics (e.g., maximum flood depth, length of time flooded). Inundation models of past storms are used to calibrate and validate models (as discussed below) and to build effective inundation models of "what if" conditions, discussed in the "What If" Flood Modeling section.

   Mechanistic flood inundation models are subject to errors and uncertainties in the forcing data (boundary conditions), the initial conditions, and the underlying landscape data. Furthermore, choices in the model's mathematical design and coding will affect the underlying error behavior. As the model is marched through time from its starting point, it will slowly accumulate error. In general, every mechanistic model has a "time horizon" beyond which we cannot trust its predictions (even when predicting the past). Modelers use "calibration" to adjust models to better match observations of a historic event. For example, the flow of flood water over the landscape depends on the "roughness" of the landscape. Through past studies, we can relate the roughness to the type of landscape (e.g., open farmland, buildings, and roadways will all have different values for roughness). Unfortunately, the precise coefficient that correctly represents the real world would require detailed study and data for each grid cell in a model, which is impractical for any large flood model. Thus, we use calibration to adjust roughness coefficients *within the accepted bounds of uncertainty* to get better agreement between the model and observations. To understand a model's uncertainty and likely error, a model is calibrated with data from one or more storms and then is "validated" by representing a storm that was not in the calibration data set. This approach allows the modeler to compare the validation model's results to observed data and quantify the error. This validation error represents the uncertainty in the model results for any storm that is similar to those in the validation and calibration data set. This validation error can be used to communicate the uncertainty associated with the model results, e.g., by providing plus/minus values to predicted flood inundation depths.

"What If" Flood Inundation Modeling - Arguably, the most valuable use of the mechanistic models developed for flood inundation modeling is to predict the likely flooding effects of future storms and/or different scenario analysis. For example, "What if Hurricane Harvey had stalled over Corpus Christi rather than Houston?". Another example is: "What if Houston built a system of deep storage tunnels, would that protect against Hurricane Harvey flooding?". These forms of "what if" modeling poses several significant challenges. First, a modeled future (or alternative) storm is a complex variation of rainfall and wind over time and space that is similar to a real-world storm. This issue has been addressed through research over the past decade in development of "synthetic storms" that mimic the time-space characteristics of real-world storms. A second, more intractable challenge is predicting what the landscape will look like in the future for a "what if" model: how roads will be developed; what areas of farm/ranch land will be converted to housing; how stormwater drainage systems will change; and whether new levees will be built. Finally, "what if" modeling will often use conditions that are outside the formal calibration and validation bounds of the mechanistic model. Such models may be the "best possible" but will have unknown uncertainty (see footnote 2). In general, "what if" modeling must be done with care and with attention to the uncertainty as to how the landscape will change and the extent to which the models exceed calibration and validation conditions.

Table 3-1. Numerical model types of compound flood inundation modeling systems.

Type of Model	Characteristics	Purposes	Computing Requirements	Examples
Flood Inundation Model I (FI-I)	Full physics equations in a single code base	Validation of Water Elevations Engineering Design Sensitivity Studies	High	None
Flood Inundation Model II (FI-II)	Combination of full physics and reduced physics equations in one or more areas in a single code base	Same as Flood Inundation Model I	Medium to High	SCHISM DELFT3D HEC-RAS ADCIRC AdH COASWT
Flood Inundation Model III (FI-III)	Full physics and/or reduced physics in a software framework for coupling codes	Same as Flood Inundation Model I	High	CSTORM-MS NOAA UFS
Flood Inundation Model IV (FI-IV)	Reduced physics and/or low resolution in a single code base	Real-time Forecasting Sensitivity Studies	Low	SFINCS
Flood Inundation Hybrid Models (FI-H)	Combination of physics-based components, surrogate models and/or AI/ML components	Real-time Forecasting Sensitivity Studies Uncertainty Quantification	Variable	Research Codes
Flood Inundation Data-Driven Models (FI-DD)	Surrogate models, probabilistic models, and AI/ML	Forecasting Sensitivity Studies Uncertainty Quantification	GPU capability desirable for AI/ML	Research Codes

Table 3-2. Evaluation matrix of current and potential use cases for different types of inundation modeling. For model selection for different scenarios, "x" indicates that the model is currently in use for this purpose, while "o" indicates that it may be applicable depending on engineering judgment. Note that FI-I models do not currently exist but are arguably suitable for all purposes.

Scenario	Operational Forecasting	Hindcasting and Validation	Planning and Design	Uncertainty Quantification
FI-I	-	-	-	-
FI-II	xx	o	xx	o
Fi-III	o	xx	xx	xx
FI-IV	o	o	xx	xx
FI-H	o	o	xx	xx
FI-DD	o	o	o	xx

THE EMERGENCE OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN FLOOD MODELING

In contrast to the mechanistic approach of flood inundation modeling (Sec. How Models Enhance Understanding of Flood Risk), flood hazard analysis (Sec. I. Flood Hazard Analysis) can be thought of as a type of "data-driven" modeling (where the data may be a combination of observations and results from flood inundation models). That is, the model only "understands" flooding based on the data (observations, model results) rather than through the fundamental physics of water motion. Over the past 15 years, there have been dramatic advances in AI and its sibling ML, which began as pure "data-driven" models but have recently advanced into quasi-mechanistic models. Managers and policymakers should recognize that AI/ML models are presently a research-level tools that do not yet have a strong basis for understanding the uncertainty and likely error associated with its predictions. In particular, AI/ML models used for conditions outside of their "training" range (i.e., their calibration) are of questionable value. The beauty of AI/ML is that you always get an answer, no matter how complicated the question — the ugly is that you cannot (with today's models) be sure the answer is correct, and you typically cannot estimate the uncertainty of its predictions.

AI/ML models are arguably an outgrowth of statistical modeling: a large data set is ingested into a model that uses mathematics to correlate observed input behaviors and make predictions about likely output behaviors. The difference between AI/ML and traditional statistical modeling is in the mathematics that underly the treatment of the data. The key point of AI/ML is that it uses its "training data" to learn the correlations within the data (note that it cannot correlate for conditions that do not appear within the data set itself). Once the model is trained it can rapidly produce predictions for other data sets (which are assumed to be similar!). The biggest drawback to AI/ML is that model training can be a long process requiring extensive computer time as well as careful manual cleaning of the input data set. ChatGPT provides a good example—the rapidity with which ChatGPT can respond to a user's prompt is phenomenal, but it does not reflect the enormous computational time that it took to train the underlying large language model.

AI/ML has the potential to improve flood hazard analysis in several ways being applied in academic and pilot settings, as well as in application. The JPM-AMP method in used by USACE at CHL for regional coastal studies expands the probability and parameter space of the hundreds of regional JPM synthetic storms to many hundreds of thousands of storms and their parameter sets by estimating the model results (i.e. response) through the application of Gaussian process metamodeling (GPM), a machine learning technique developed in collaboration with the University of Notre Dame. The GPM builds on the high-fidelity storm surge and wave models results expanding them to cover more possible storms using the lower cost, lower fidelity technique. This method was applied for compound flooding due to Mississippi River flows and hurricane storm surge, expanding both the JPM parameters and seasonal flow through the GPM (Nadal-Caraballo et al., 2022). Pilot studies, such as the Neches River study conducted by CHL also depended on GPM methods (Carr et al., 2024) while academic efforts have used surrogate modeling in a Bayesian framework to improve storm parameter selection and demonstrate multiple tiers of a Compound Framework in the New Orleans area (Liu et al., 2025 [unpublished manuscript]).

There are reasons to expect that AI/ML will someday take over for mechanistic models for flood inundation modeling, but not today or even in the next several years (the models simply are not sufficiently mature or trustworthy). The key advantage of AI/ML over mechanistic flood inundation models is that AI/ML, when trained, can run much faster than mechanistic models. However, there are two disadvantages to AI/ML modeling for flood inundation that must be overcome before they can supplant mechanistic models: 1) the AI/ML model training is inherently place-specific, that is, a model trained for Houston cannot be applied to Corpus Christi without repeating the entire training process (in contrast, a mechanistic model built for Houston can be readily adapted to other locations), 2) an AI/ML cannot be used for "what if" analyses if the "what if" conditions are outside its training data set. For example, "What if Houston had a set of deep stormwater storage tunnels?" cannot be answered by present AI/ML models. The data set for flood inundation for all storms in Houston does not contain the effects of stormwater storage so an AI/ML has no way to predict the consequences.

The above should not be taken as a blanket condemnation of the future potential for AI/ML. Much as with any modeling technique, AI/ML can be useful as long as we understand and apply the models within their limits. To continue the "what if" example from above, although present AI/ML cannot use historic data to analyze "what if" for proposed Houston stormwater tunnels, such tunnels could be represented in mechanistic flood models and the resulting data used to train AI/ML. Once the AI/ML is trained with the tunnel data it can be used to quickly model a broader array of storms than is practical for a mechanistic model alone. Such a combined modeling approach can be used to "bootstrap" our way to fast predictions that retain the underlying accuracy of mechanistic models. Furthermore, development of hybrid AI/ML that incorporate physics constraints directly within their algorithms may provide foundations for better "what if" capabilities.

An important point is that developing, testing, and proving the trustworthiness of future AI/ML models requires extensive data that can only be provided through the existing, well-proven methods for flood hazard analysis and flood inundation modeling.

3.2 Why An Integrated Flooding Framework Matters To Texas

Currently, some of the most common project-based uses for flood modeling cannot incorporate the effects of compound flooding. There is a need for integration of natural and anthropogenic changing conditions into the modeling workflows to evaluate project impacts.

Projects, such as these described below, provide the impetus and perhaps the avenue to build a reusable computational framework for Texas compound flood modeling (see TxCFF below):

- **Planning Strategy Evaluation** - Federal, state, and local agencies perform site-specific feasibility studies to evaluate proposed projects, identify potential solutions, and recommend suitable solutions for flood hazard reduction. Such feasibility studies may consider either short-term or long-term planning horizons based on the project objectives or goals. The challenge for such studies is that they are inherently "what if" studies that change the conditions under which flooding has been evaluated. Thus, such studies need scenario-based flood inundation models to evaluate impacts of changes. To synthesize inundation model results effectively, a streamlined process is needed to update flood hazard models using outputs from multiple "what-if" scenarios. This will enable systematic cost-benefit analyses, quantification of hazard reduction in flood-prone areas, and assessment of the impact of planned projects on overall flood resilience. Furthermore, long-term planning strategies should be evaluated through models that incorporate climate projections, land-use changes, and infrastructure developments. The scale and scope of the required analyses are challenging for any single project to consider. Presently, such feasibility projects do not have the resources or time to build, run, and analyze high-quality compound flooding inundation models (to make the task tractable they resort to simpler "reduced-physics" models that have relatively wide margins of uncertainty). A reusable computational framework for Texas compound flood modeling could make high-quality modeling more tractable and allow agencies to analyze a broader set of alternatives with greater confidence and reduced uncertainty.

- **Engineering Design** - Communities expend significant funds for engineering consulting firms in developing preliminary designs, cost estimates, and feasibility of flood protection features and/or flood impacts of proposed developments. Much of these funds are spent in setting up and running river flood inundation models or analyzing storm surge models, which cannot (in isolation) represent the complexities of compound flood modeling. Providing engineering firms with stricter guidance and criteria for including compound flooding would, in the present world, simply increase the costs of such studies and substantially slow development projects. There is a need for an effective compound flood modeling system for Texas that provides engineering firms with the tools and the training to more rapidly evaluate possible designs and compound flood impacts. Building such a framework could allow engineering firms to provide direct feedback to the feasibility and planning strategies discussed above.
- **Operational Strategy Evaluation** - Emergency managers use "what if" scenarios to plan operational strategies for flooding response. The present complexity of flood modeling (in particular for compound flooding) makes it impractical for emergency managers to run a wide range of possible storms and test/evaluate/improve their response strategies against the predicted time/space evolution of flooding. To support emergency planning, a flood modeling system could be used in several ways. First, a modeling system can be used prior to events to evaluate the effectiveness of emergency operational strategies, estimate equipment and personnel required for different conditions, and conduct flooding logistics drills where the flood information from the model is provided in a filtered form for managers to practice making decisions with limited information. Second, during a storm event a modeling system could be used to quickly consider "what if" possibilities with flooding details that are not available in the predictive storm modeling of NOAA. Finally, after an event the flood modeling system could be used as a framework for post-event analysis of emergency response performance metrics such as response times, forecast accuracy, and the efficiency of stakeholder communication during events. In addition to improving future emergency response, such post-event analysis can also provide critical feedback for improving model accuracy and updating protocols based on lessons learned.

Much of our baseline flood protection infrastructure is designed/built in a piecemeal fashion, as land is developed. Although this approach is informed by overlapping regulations from the city/town, county, state, and federal agencies that set standards and design guidance based on input from professional societies and the latest research, unfortunately there is no guarantee that ensuring that these individual projects meet drainage and flood protection regulations does not provide the larger community an adequate level of protection. For example, flood protection for an inland river using levees to protect one community may result in shifting the flooding problem to a nearby community. To address this issue, engineers use flood inundation models to predict flood water levels and other impacts (e.g., forces on structure, erosion) across towns, cities, and along the coast for large-scale flood events. When combined with flood hazard analysis, the flood inundation models can be used to identify cost-effective strategies for increasing flood protection across multiple communities, delineate floodplains where development should be discouraged, assist in development of emergency management plans for flood disasters, and provide hazard-based information for stakeholders to decide on design of flood control measures. In common use, probabilistic flood hazard analysis quantifies the known hazards for the existing infrastructure, (i.e., identifying where flooding and damage are deemed more likely) and are used by insurance companies and FEMA to set rates and estimate potential liabilities.

The Challenge of Compound Flooding in Flood Protection Design

Traditionally, flood protection features have been designed for a single flooding source[3]. We protect against commonly expected conditions through flood inundation modeling with 1) a "design" rainfall rate, 2) a "design" river elevation, and 3) a "design" storm-surge height. As a practical matter of costs, time, and resources, we typically cannot build the "design" level of flood protection infrastructure to protect against an estimate of the maximum expected conditions from any flood source. For example, many cities use a "25-year" storm for sizing road gutters – this is a storm that has a 4% chance of occurring in any given year and a 1-in-3 chance of occurring *at least* once in any decade. Thus, overflowing road gutters should not be an everyday occurrence but can be expected with many extreme rainfall events. This standard design approach links flood hazard and flood inundation modeling – flood modeling is used to set the probabilistic storm conditions for the design standard and then flood inundation models are used to evaluate whether a proposed project meets this standard. The key takeaway is that 1) design standards have been traditionally focused on a single type of flooding, and 2) flooding is expected whenever nature exceeds that design standard.

Compound flooding has created a challenge for both flood hazard analysis and flood inundation modeling engineers. PCHA is the standard of practice for storm surge hazards and applies a method wherein historical information about driving parameters (e.g., central pressure deficit, radius to maximum winds) is used in a JPM to develop synthetic tropical storms and drive storm surge models (Carr et al., 2022). Compound flood hazard analysis is challenging for the same key reason that storm surge hazard analysis is challenging: a limited data record of events (which is even more limited when we seek paired events to characterize the joint probability between the two hazards, e.g., rainfall and surge). Therefore, in seeking to represent the likelihood of a compound event composed of storm surge and rainfall, it would be helpful to have a tropical cyclone rainfall model that is driven by the same parameters of the surge model (i.e., JPM parameters). The Tropical Cyclone Rainfall Model (TCRM) described by Lu et al. (2018), and being applied in research and pilot settings, provides such a method, which is computationally efficient and has the same probability of occurrence as the synthetic TC's storm surge. For flood inundation modeling, engineers traditionally use models designed specifically for one of the major flood sources: rainfall, river, or storm surge. Becoming an expert flood inundation modeler in any one area requires years of practice under the guidance of an expert who has a decade or more of experience. However, the term compound flooding[4] first appears in the science/engineering literature in Wahl et al (2015). This rather recent focus is reflected in lagging development of integrative expertise and compound flood inundation models across disciplines. Although researchers in academia and government agencies have been actively pursuing better models for both hazard analysis and inundation from compound flooding over the last decade, this area still lacks consensus models that are accepted as state-of-the-science. Furthermore, effective compound flood modeling requires expert modelers to be spread throughout academia, industry, and government. We lack both this broad modeling community and the cadre of experts needed train and supervise the development of such expertise in both flood hazard analysis and flood inundation modeling.

For additional details, see Compound Flooding in Supporting Material 3-9.

3 Note that rainfall, rivers, and oceans are the "big three" sources of flooding that are typically considered in engineering design. Groundwater flooding in the Texas coastal region is often neglected as it is usually a small contribution to the events that control the design conditions. Nevertheless, groundwater does play an important role in the effectiveness of urban stormwater systems and is a major contributor in some areas beyond the Texas coast.

4 The fundamental ideas of hazard and probability associated "compound flooding" can be found in articles on "joint" and "coincident" flooding in the flood risk/hazard literature prior to 2015, but the popularization of the term "compound flooding" and its prominence over the last decade are arguably associated with the Wahl et al (2015) letter to the journal *Nature Climate Change*.

3.3 The Guiding Objectives of TIFF Component 3

The aim of TIFF Component 3 was to tackle the challenges of developing an integrated modeling framework to support inland and coastal flood hazard identification. This effort consisted of 5 stated objectives, which are described in detail below:

1. Establish a TAT to support Component 3
2. Evaluate and provide feedback on initial inventory of existing and proposed meteorologic, hydrologic, hydraulic, estuarine and surge models to support inland and coastal hazard identification
3. Perform a literature review to identify potential meteorological, hydrologic, hydraulic, and hydrodynamic models for evaluating and mitigating flood risk for Texas
4. Perform a literature review on probabilistic methods for flood hazard estimation
5. Make recommendations for conceptual model-coupling workflow(s) for assessment of compound flooding hazard in coastal Texas

To achieve the objectives of TIFF Component 3, a collaborative and systematic approach was adopted in coordination with the Integrated Flood Modeling TAT. The first step involved establishing the TAT to provide subject matter expertise and guidance throughout the component's execution. After reviewing and providing feedback on the proposed approach of TIFF, the TAT worked closely with Study Providers to evaluate the inventory of existing and proposed meteorological, hydrologic, hydraulic, estuarine, and surge models, ensuring they were suitable for integrated inland and coastal flood hazard identification. A comprehensive literature review was conducted to identify additional modeling tools capable of capturing complex flood dynamics and informing mitigation strategies specific to the Texas context. Parallelly, a focused review on probabilistic methods was carried out to enhance the understanding and estimation of flood hazard uncertainty. Based on these efforts, the TAT developed recommendations for conceptual model-coupling workflows to support assessment of compound flooding risks in the coastal Texas region, with the goal of enabling a robust and integrated framework (the TxCFF) for flood risk evaluation and decision-making. The TxCFF is a software framework that encapsulates models and their coupling with analysis tools and workflows. TIFF recommends the TxCFF as an overarching answer to the goals and the objectives nested under Component 3.


Storm surge damage caused by Hurricane Ike ©NOAA

ZOOMING IN: TIFF'S PRIORITY RECOMMENDATION FOR ONGOING COASTAL INTEGRATED FLOOD MODELING

The Texas Coastal Flooding Framework (TIFF Recommendation C3.5A)

TIFF recommends the development of a collaborative software platform for compound flood assessment to facilitate planning, design, development, flood recovery, and supporting emergency response efforts along the Texas coast.

The state-of-the-art and the underlying context of models for coastal and compound flood inundation modeling and hazard analysis (see Understanding Flood Modeling above and the Model Coupling Workflow Workshop described in Supporting Material 3-10) leads to some observations on the paths forward for Texas. These ideas and considerations are generally applicable to any coastal flood modeling/analysis effort but are specifically address the complexities of Texas compound flooding. A critical need is for a software framework that encapsulates models and their coupling with analysis tools and workflows.

The TxCFF should be a data and modeling system that provides 1) data linkages to existing databases, 2) data transfer between models, 3) a user interface to setup and execute the models as a coupled system, and 4) integration of the output data from component models into a coherent data set for further analysis and visualization. The TxCFF would streamline model coupling workflows, enhance data integration from federal, state, and local sources, and support widespread application through testbeds across the Texas coastal plain.

The path forward is ambitious and will require sustained investment, interagency cooperation, and technical innovation. However, the anticipated benefits are profound. A fully realized TxCFF will enable local and state entities to better quantify and manage flood risks, reduce redundancy in engineering efforts, and dramatically lower the costs associated with flood hazard assessments and infrastructure planning. By transforming the current fragmented landscape into a reusable and extensible framework, the TxCFF will not only advance the state-of-the-science—it will redefine the future of flood resilience across the Texas coastal plain.

The TxCFF would consist of:

- wind and pressure model
- ocean circulation model
- wind/wave model (far field and near field)
- flood inundation (hydraulics) model for river flow and landscape flooding
- upland runoff model (hydrology)
- stormwater drainage model
- groundwater model
- code for input/output
- code for user customization
- code for coupling the various flood inundation component models
- coupling to external meteorological (storm) models/data sets for historic and synthetic storms
- code for calibration, validation, and testing of inundation models
- code for ingesting flood inundation model results into flood hazard analysis
- flood hazard analysis tools
- code for visualizing inundation and hazard analysis results

At the simplest level, the TxCFF could begin as documented workflows for coupling models and data along with codes developed for pre-processing, post-processing and analysis. Over time, the workflows can be codified into a software framework that addresses the key issues of re-usability, access, training, simplification/complexity, and uncertainty. Developing the TxCFF would require a long-term commitment of funds to a consistent project development team that collaborates with agency-sponsored modeling projects to ensure their work can be integrated into the framework. The benefits of integrating hydrologic, hydraulic, meteorologic, estuarine, and coastal models into a single, interoperable system and making advanced compound flood analysis accessible to a broader user base, including planners, engineers, and policymakers far outweigh the costs.

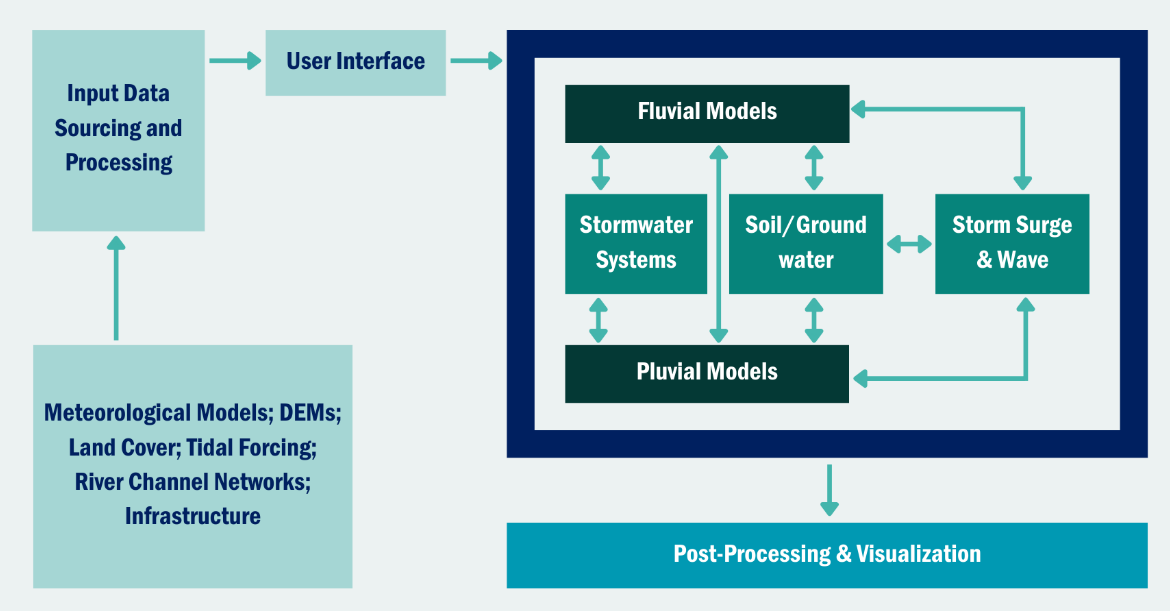


Figure 3-3. Conceptual diagram of model and data couplings within a TxCFF.

For compound flood modeling to become a standard tool in engineering, science, and policy practice, several key points need to be addressed:

1. **Models used within the framework must be validated for Texas, computationally efficient, supported by an active development team and user community, and equipped with graphical user interfaces (GUI) and training documentation** - Community based open-source models are preferred to allow for maximum development options within the software, which is likely to be required when integrating with other models. Open access models do not allow for the same flexibility for code changes but still allow for no-cost usage of the model by a wide range of users. The framework must include coastal surge/circulation and wave models that can be coupled, with the capability to use different hydrodynamic models in the coastal zone for various applications, including three-dimensional baroclinic models and full phase-resolving non-hydrostatic models for wave runup and overtopping. The framework should also include linked H&H models for coastal Texas, building on ongoing initiatives by TWDB, USACE, and others, with options to include wind, pressure, and wave forcing data where these factors are significant (e.g., over large inland lakes).

2. **Models must be re-usable (i.e., the efforts to develop and apply a model to one location should be transferable to another so that each effort is not "reinventing the wheel")** - Currently, flood modeling efforts in the Texas coastal region are custom implementations requiring significant development time, model validation, and specialized skills. A standardized suite of models with coupling software would streamline these projects and allow for consistent engineering decisions based on statistical analysis rather than varying judgments across different basins.

3. **Models need to be widely accessible** - This means flood inundation models and hazard analysis tools within the framework must be accessible to engineers, scientists, and managers across various government levels, academia, and industry. Efficient coastal development requires rapid computation models that meet regulatory standards, supported by user-friendly GUIs and safeguards to prevent misuse. This broad access necessitates robust software and model development. Accessibility is also dependent upon flexibility as well as the availability of training to a broad spectrum of users. The framework should be flexible enough so that individual components can be turned off (e.g., stormwater or groundwater might be unneeded in some scenarios; users might want to evaluate the magnitude of some single forcing, such as storm surge). A user query process or documentation that guides users in best practices for deciding which components to use for their particular application is needed. Comprehensive training is essential for the broad spectrum of users to set up,

run, analyze, and communicate model results. Current fragmented approaches make training impractical. Developing standardized workflows and a common computational framework will enable effective training programs for various user levels. The framework's structure should be portable, extensible, and built with plug-and-play application programming interfaces, leveraging existing coupling frameworks and adhering to community standards for data curation.

4. **Users should have access to models of varying complexity that fit their particular needs** - The challenge in compound flood modeling lies in the undefined scientific basis for simplification and weak interdisciplinary communication. Simplified models, while faster and useful for feasibility assessments, increase uncertainty. Systematic comparisons between full-physics and reduced-physics models are needed to determine acceptable simplification levels. Future workflows should support full-physics approaches and quantify uncertainties from simplified models. The framework should facilitate inter-model and inter-level hazard analysis approach comparisons, allowing users to evaluate which models and hazard analysis approaches are most useful in different situations.

5. **Model results should be provided with quantification of their uncertainty so that users understand the limits of any prediction/analysis** - Quantifying model uncertainty involves understanding the range of possible results due to various types of uncertainty and their distributions. Flood inundation model uncertainty differs from flood hazard analysis uncertainty, requiring systematic evaluation methods in standard workflows. Better knowledge of uncertainty helps modelers make informed choices about model complexity and simplifications, and effectively communicate uncertainties to managers and policymakers. Flood hazard analysis includes aleatory (irreducible) and epistemic (reducible) uncertainties, while flood inundation model uncertainty arises from multiple sources like forcing data, boundary data, and numerical approaches. Accurate quantification and communication of these uncertainties are essential for reliable modeling. The framework should provide the capabilities to build and test methods for uncertainty quantification, sensitive analysis, hazard analysis, and parameter estimation.

6. **Workflows and computational framework need to be created to support model users, developers, model maintenance, and ongoing modeling improvements with ongoing advances in the state-of-the-art of flood modeling -** Continuous coastal development necessitates ongoing compound flood modeling and analysis. A sustainable approach should systematically incorporate knowledge from each project into future efforts, making subsequent projects cheaper, easier to design, and more robust. Projects used within the framework must document model meshes, tools, and lessons learned to streamline future projects. This includes an assessment of available and develop tools and software for both pre-processing (e.g., mesh generation from Digital Elevation Models, probabilistic driving inputs, and other data) and post-processing (e.g., visualization, interactive graphs, and communication of results to stakeholders). These secondary software tools should be readily available, shareable, and validated just as the full models are. Additionally, coupling models using existing software packages requires transparent and well-documented code and documentation. Commitment from project managers and funding agencies is essential for maintaining a standardized compound flood modeling framework.

More detailed information on each of these issues can be found in Supporting Material 3-11.

3.4 Implementation of Objectives

Objective 1: Establish an Integrated Flood Modeling TAT

To support the development of an integrated modeling framework for inland and coastal flood hazard identification, the SC appointed Dr. Mohammad “Shahidul” Islam of USACE as the Component 3 Champion. Dr. Islam was selected based on his extensive technical background and leadership in hydrologic, hydraulic, and coastal engineering, as well as his national-level experience in flood modeling, risk management, and interagency coordination. His deep expertise and contributions to major federal and state flood mitigation initiatives made him an ideal candidate to lead this effort.

Complementing his leadership, a multidisciplinary TAT was strategically assembled by the SC. Members were chosen for their demonstrated technical excellence and institutional knowledge in areas critical to flood risk modeling and mitigation in Texas and beyond. The TAT includes experts across a range of specialties—including hydrology, hydraulics, meteorology, estuarine and coastal hydrodynamics, and flood hazard analysis. This inclusive and collaborative approach ensures that the Component 3 framework is informed by the latest science, practical experience, and the diverse perspectives of stakeholders from governmental agencies, academia, and regional institutions.

COMPONENT 3 TECHNICAL ADVISORS

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

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

Numerical models are essential tools for conducting flood analysis studies. Engineers and scientists invest considerable time and resources in data collection, input preparation, and the calibration and validation of model parameters. Many of these models require complex pre-processing steps, often involving manual and time-consuming workflows. These steps must be repeated each time a new model is developed to simulate a particular system. To address this challenge, TIFF prioritized the creation of an initial model inventory aimed at minimizing redundant model development efforts and promoting model sharing and reuse among stakeholders. This effort also supports the identification of geographic areas in Texas where improved model coverage is needed to inform future flood planning initiatives. As part of this effort, TIFF focused on evaluating the model inventories from several ongoing large-scale studies that support flood planning, modeling, and mapping across the state, including:

- USACE's Flood Risk Management, Coastal Storm Risk Management, and Navigational program for Texas region (Supporting Material 3-12)
- GLO's Combined Flood Studies
- TWDB's RFPG
- TWDB's Base Level Engineering (BLE) Studies

The intent of this model inventory development/evaluation is also to create an existing model catalog with key contextual details for users to leverage when searching for existing information in a particular study area. Key metadata and coverage area shapefiles associated with models were collected. This information also provides insight into the geographic distribution of information, that is, where pluvial, fluvial, and/or coastal risk information is abundant and where it is lacking. This initial model inventory and associated model metadata are laying the foundation for the future development of a detailed model metadata catalog, along with the system for model archiving and sharing with diverse stakeholders. For more in-depth technical discussions on the model inventory, see Supporting Material 3-13.

APPROACH TO THE MODEL INVENTORY

The first step to creating and populating the model inventory was to determine what metadata is key to providing sufficient context for the end-user to determine the usefulness and/or appropriateness of the existing model for their intended purpose. In some geographic areas, multiple models have been developed over the years that vary in input and output depending upon when they were developed and what type of analyses were deemed necessary for specific efforts. For instance, there are models that have been developed to inform the design of a specific flood risk management infrastructure solution or for watershed planning purposes that do not relate to a specific infrastructure action, which include analysis of historical events or predictive frequency events, or oftentimes both. On the other hand, some models may have been developed to provide flow and stage information, or to inform sedimentation or water quality studies. These factors were considered when selecting which metadata to include in the inventory.

The model inventory metadata requirements were selected by taking into consideration the minimum information needed to characterize flood models with the relevant context to understand their purpose and provide context for use in hazard identification where appropriate. The description of each model inventory metadata field is listed in Table 3-3. Once the model metadata was collected and categorized, TIFF coordinated with TDIS to compile and disseminate the inventoried information. Geodatabases containing shapefiles that were paired with their respective metadata were shared with TDIS.

Although this model inventory matrix can be used for compiling relevant metadata for any flood planning and risk assessment models, the focus of this inventory matrix was to compile metadata for meteorologic, hydrologic, hydraulic, and coastal models, including estuarine, surge, and wave models, which are applied for estimating flooding hazard extent and depth estimations. However, this model inventory matrix was not designed for comprehensive cataloging of model-related metadata sets. Rather, this simple inventory matrix will provide relevant high-level model metadata. Stakeholders/modelers can use this high-level metadata and follow up with the model developer(s) for the appropriate level of detailed information based on their project needs. Links to documentation (e.g., reports, publications, web pages) associated with each model are included to provide details related to each modeling effort where applicable and/or available. In addition to the metadata, shapefile coverage areas were obtained where available and are indicated in the metadata table in Supporting Material 3-12 and in an online Excel file.

Table 3-3. Inventory matrix metadata fields and their descriptions

Metadata Field	Description
Study Area	Geographic location where model is based
Software	Type of modeling software used (e.g., Hydrologic Engineering Center Hydrologic Modeling System, Hydrologic Engineering Center River Analysis System, Adaptive Hydraulics, Soil Water Assessment Tool, etc.)
Study Title	Title of study associated with model development
Version	Software version the model is currently compatible with (e.g., Hydrologic Engineering Center River Analysis System 6.0)
Focus	The purpose of model development (i.e., what type of analysis or problem the model is expected to inform and/or be leveraged to solve). Categories include: Flood Risk Management; Coastal Storm Risk Management, Water Management, Water Resources, Groundwater, Ecosystem Restoration
Objectives	Summary of study objectives for associated model
Year Developed	Year in which the model was developed
Flow Condition	Specify flow condition of subject model (e.g., Steady-modeled variable does not change with time; Unsteady-modeled variable changes with time
Dimension	Dimension(s) of model geometry and associated results
Status	Status of model development (e.g., planning, ongoing, complete)
Model Point of Contact	Point of contact for the model developer
Geo-Referenced?	Specify if the model is spatially referenced through a projection system [Yes/No]
Shp_ID	Shapefile identifier
Report	Specify if a report is available that accompanies the model and includes pertinent details (e.g., modeling methodology and results.) [Yes/No]
Location	Location of report and/or model
Calibration Events	Summary of storm events leveraged to calibrate the model
Validation Events	Summary of storm events leveraged to validate the model
Analysis Summary	Summary of what type of analysis the model was used for (e.g., alternatives—with and without—project analysis, sensitivity analysis, scenario analysis)
History	Summary of model update history (e.g., if model was adapted from an existing model)
Additional Comments	Any additional pertinent information related to model

THE MODEL INVENTORY

The completed inventory shapefiles of hydrologic, hydraulic, hydrodynamic, meteorological, and coastal models are available on the TIFF website.

The inventory was populated by a combination of outreach, literature review, and existing database integration. Numerous models have been developed to support the USACE-Galveston District's diverse Civil Works program and were catalogued through surveys and collaboration with respective modeling points of contact. In addition to models developed within or for the USACE-Galveston District, several models have been developed by local drainage districts, state agencies, universities, and consultants. These models were identified through meetings and discussions with engineers/scientists and leveraging existing model and/or publication databases. Other cooperators provided model databases that had previously been catalogued (e.g., BLE models), and that information was integrated into the TIFF model inventory format. TWDB provided metadata and coverage areas, as available, for BLE studies, Texas Rainfall-Runoff (TxRR) models, and what was collected as part of the RFPG efforts. GLO's Combined Flood Study stakeholders provided planned model extents for each region and existing models when available. Other sources, such as HCFCD's M3 system, allowed for direct referencing and downloading of relevant modeling information. The intent of this model inventory development/evaluation is to create an existing model catalogue with key contextual details for users to leverage when searching for existing information in a particular study area. This information also provides insight into the geographic distribution of information, that is, where pluvial, fluvial, and/or coastal risk information is abundant and where it is lacking. The modeling software and respective number of each catalogued model are summarized in Table 3-4.

The TIFF Model Inventory was categorized by "model type": Inland, Coastal, Meteorological. Table 3-4 lists the software identified for the Inland and Coastal model types.

1. **Inland Hydrologic and Hydraulic Models** - Numerical models are valuable tools for flood analysis studies. When engineers use models, significant effort is devoted to collecting data, constructing model inputs, and calibrating and validating model parameters. Many models also require sophisticated data pre-processing routines, often with many manual steps. These data pre-processing steps must be repeated each time a new model is created to simulate a system. The limited availability of the model metadata prohibits their sharing and reusing among different stakeholders. The limited metadata availability causes duplication efforts in model development in addition to inducing budget increases and delays in project implementation schedule. While many of these flooding models utilize similar methodology, limited information on the model metadata for the study region of interest often forces modelers to develop a new model from scratch. This causes duplication effort in model development and prevents modelers improving the limitations of previously developed models. From a pragmatic perspective, it is an inefficient use of the modeler's time as a significant amount of time is spent reproducing similar model input files that have been developed previously. One way to begin to address these challenges is through the development of a basic model metadata template for sharing and referencing or reusing models, where appropriate, built by others. With the objectives of making Texas stakeholders aware of the available models, TIFF developed a basic model metadata template which was then applied for compiling available model in the study regions. This model metadata template was not comprehensive, rather, it was made to be straightforward with taking into considerations of minimizing efforts of the interested parties who will provide this model information. This simple model metadata will provide key information about the model coverage and the model developer points of contact so that further detailed model metadata information can be gathered on as needed basis during the model development effort. This initial model inventory will lay the foundation for future development of detailed model metadata catalogue along with the system for model archiving and sharing with diverse stakeholders.

The model inventory evaluation identifies available models within the TIFF study region for facilitating model sharing/reusing among stakeholders and supporting modeling gap analysis for the identification of regions where improved models are needed for future flood planning analysis. This evaluation focused on the ongoing studies for supporting flood planning, modeling, and mapping in Texas:

1. USACE's Flood Risk Management, Coastal Storm Risk Management and Navigational Program (Texas region)
2. GLO's Regional Flood Studies
3. TWDB's RFPGs
4. TWDB's BLE Studies

Further details of these programs and associated large-scale studies, which were/are being implemented as part of this effort, are described in the Supporting Material 3-14. The efforts also include limited evaluation/compilation of other models' metadata, which were readily available to the TIFF partners from their collaboration with local stakeholders, including Harris County and university partners.

Table 3-4. TIFF Model inventory count by software.

Model Type	Modeling Software	Number of Models
Inland	HEC-HMS	130
	HEC-RAS	305
	SWAT	176
	Riverware	1
	Gridded Surface Subsurface Hydrologic Analysis	5
	TxRR Model	129
	Storm Water Management Model	7
	XP Storm Water Management Model	7
	InfoWorks	8
	Interconnected Channel and Pond Routing Model	1
Coastal	Advanced Circulation Model	3
	Adaptive Hydraulics (Coastal)	7
	Beach-FX	1
	Coastal Modeling System-FLOW and Coastal Modeling System-WAVE	8
	Cornell University Long and Intermediate Wave Modeling	2
	Delft3D	5
	DFLOW-FM/ Delft3D-FM	6
	Fully Nonlinear Phase-Resolving Boussinesq-Type Wave Model	2
	Finite Volume Community Ocean Model	1
	Semi-implicit Cross-scale Hydroscience Integrated System Model	1
	Semi-Implicit Eulerian–Lagrangian Finite-Element Model	2
	Super-Fast Inundation of Coasts Model	1
	TxBLEND	7
	Xbeach	1
	Steady State Spectral Wave	2
	Wind Wave Model	1

2. **Coastal Models** - Coastal modeling leverages physical attributes and numerical methods to demonstrate and quantify coastal forcings and their consequences. These models simulate hydrodynamics, waves, and sediment transport along coasts and estuaries. Quantifying these forcings provides insight into their impacts associated with coastal inundation (i.e., storm surge), wave action, and/or geomorphological changes (e.g., beach erosion). These models can range in size from targeted locations along a shoreline to entire oceans, depending on the modeling effort needs. Brief descriptions of coastal hydrodynamic modeling software applied for coastal hydrodynamic modeling on the Texas coast is noted in Supporting Material 3-15.

   The coastal model coverage, shown in Figure 3-4 spans the major Texas bays but varies in complexity and purpose largely based on project needs at the time. Many coastal models are limited to an inland extent since the detail within inland hydrologic/hydraulic models tends to lessen as the riverine environments approach the coast.

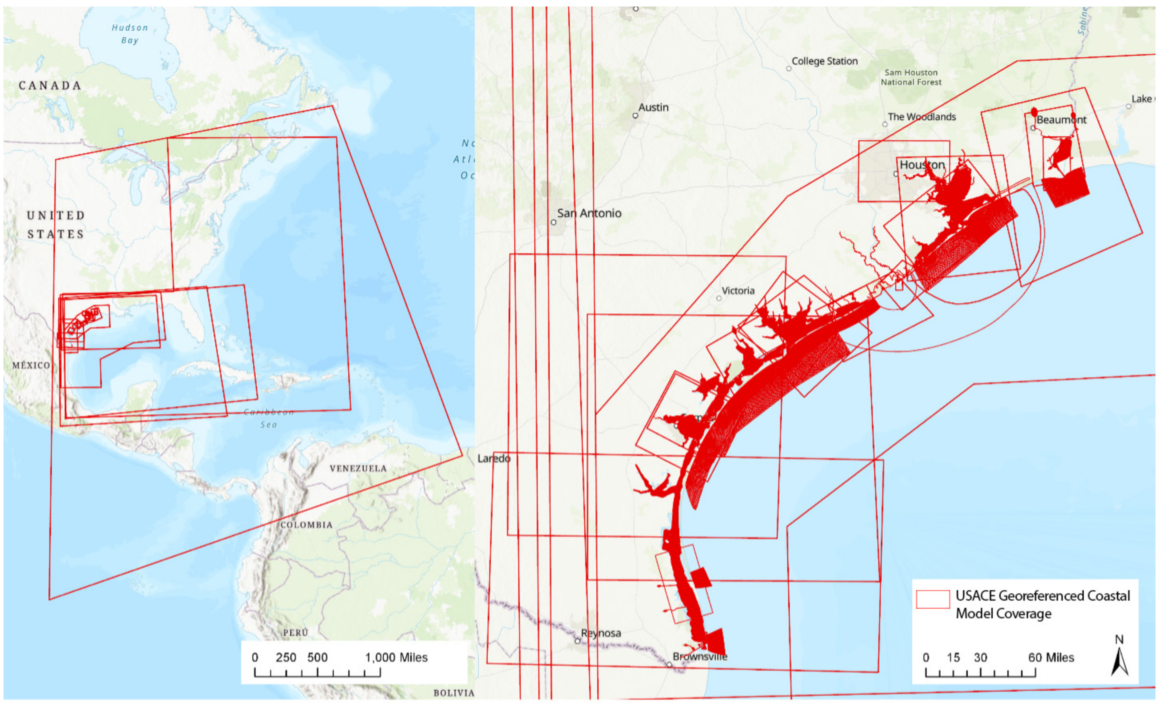


Figure 3-4. Area covered by USACE Georeferenced Coastal Model.

3. **Meteorological Model Products/ Datasets** - TIFF collected meteorological information with a slightly different format than other hydrologic, hydraulic, and coastal information (see Supporting Material 3-1). The meteorological information consists of models used to develop forecasts as well as datasets that have been modified and/or translated into a format digestible for hydrologic, hydraulic, and coastal modeling purposes. The models and datasets include forecast and/or historical information and range from statewide to global in coverage area (see Supporting Material 3-16).

Metadata Findings Across Model Types

The extent of the completeness of each line of metadata was dependent upon what information existed and/or was made available at the time of collection. Some existing models were more robustly catalogued than others, and some did not have all relevant metadata available. It is important to note that the catalogued models are included for reference purposes, and care should be taken when leveraging the existing information. This is particularly true when it comes to models developed for specific infrastructure implementation scenarios (i.e., not widely applicable) or those that were created years ago and leverage outdated data inputs (e.g., outdated precipitation inputs, terrain, land cover data). This model metadata catalogue may be considered as a preliminary base level model information, which can pave the way for future development of a model repository for sharing with diverse stakeholders.

Although a significant number of model metadata sets were compiled for inland hydrologic, hydraulic, and meteorological models as part of this effort, metadata sets were compiled for a limited number of coastal models. Most of the compiled coastal models were developed to support different USACE projects in Texas. However, a significant number of coastal models were developed or are being developed by different universities for improving understanding of processes controlling coastal flood hazards. Other federal (e.g., NOAA and FEMA), state, county, and local agencies also developed or are developing diverse coastal models for coastal flood hazard estimation in support of their respective program needs. Vendors of GLO's River Basin Flood Studies and TWDB's RFPGs also compiled a very limited number of coastal models through their stakeholder engagement surveys.

TIFF suggests the creation of a comprehensive database of coastal models to facilitate model access and sharing among Texas stakeholders, and support improved understanding of coastal flood hazard estimation through leveraging existing models and datasets (Recommendation C3.3D: Develop Database of Flood Modeling Studies).

This database should use the TIFF Model Inventory (shapefiles of hydrologic, hydraulic, hydrodynamic, meteorological, and coastal models) as the test-case for development. The TIFF Model Inventory should be periodically updated as more models become available. The living inventory will prevent duplication of model development efforts, as huge amounts of flooding analysis are being or will be performed to support a wide range of flood resiliency projects.

The key purpose of the database should be facilitating the archiving and sharing of metadata collections, as well as mode input and output files, and providing opportunities for model developers to upload new models for wide dissemination. Further work should consider how the developed models (which vary in resolutions, accuracy, and other factors) can be leveraged and integrated for improved understanding of flood risk along the Texas coast.

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

Hydrologic, meteorologic, hydraulic, estuarine, and surge models serve as both valuable tools to provide information on flooding hazards and guides in planning and implementing structural and non-structural flood risk mitigation solutions for minimizing flood risk. Various flood process models exist, each tailored to address specific challenges related to dominant flooding mechanisms (e.g., pluvial, fluvial, storm surges). These models have grown in complexity, with many simulating increasingly detailed processes occurring within natural and built systems.

TIFF performed a literature review on the state-of-practice of modeling and probabilistic analysis for flood hazard characterization for coastal Texas. The literature review was conducted in collaboration with a team of experts in hydrology, hydraulics, and meteorology from the University of Iowa and Princeton University; a team of hydraulics, estuarine, and coastal modelers from UT-Austin; a team of experts in probabilistic compound flood hazard modeling form Purdue University; and a team of wave experts from the University of Notre Dame. An additional grey literature review (especially focused on the latest findings, results, methods of probabilistic hazard, and flood modeling analysis relevant to the USACE studies which may or may not be publicly available) was conducted in collaboration with the ERDC-CHL of the USACE. TIFF also organized and hosted a monthly TIFF flood modeling brown bag seminar series (Supporting Material 3-17) to share knowledge among TIFF stakeholders, explore state-of-the-art flood modeling and analysis tools, and discuss the future advancements needed in these tools and/or analysis for Texas coastal flood hazard assessment.

THE LITERATURE REVIEW APPROACH

Theme I of this literature review covered five topics: 1) meteorology, 2) hydrology/hydraulics, 3) storm surge, 4) waves, and 5) compound flooding. Theme II of this literature review covered probabilistic modeling of compound flooding.

The summary findings of these literature reviews are provided in the following section. Refer to Supporting Materials 3-1 through 3-7 for detailed information on these literature reviews. The findings provided the foundation for the development of conceptual model coupling workflows and assisted in identifying key knowledge gaps in advancing modeling and probabilistic analysis, and development of several future study recommendations to advance flood hazard characterization in coastal Texas.

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

Literature Review Theme I
(Models for meteorology, hydrology/hydraulics, storm surge, waves, compound flooding)

To comprehend the impacts of compound flooding, a profound understanding of hydrologic, hydraulic, meteorologic, estuarine, and oceanic processes governing rainfall-runoff flooding, storm surge, and wave action along the Texas coast is essential. Hence, the TIFF literature review focused on scrutinizing crucial flooding processes and the state-of-the-art modeling requirements for estimating flood hazards across the Texas coastal study region.

This TIFF literature review encompasses:

- analysis of data sources for topography, bathymetry, land use, and land cover
- integration of data sources for consistent modeling
- examination of upland hydrologic/hydraulic processes and models for rainfall runoff and river flooding
- exploration of processes and models for storm surge and wave action along the coast and their evolution in Texas' bays and estuaries
- investigation into compound flooding processes/models, where waves and storm surge intersect with rainfall and river-induced flooding across the Texas coastal plain and its communities

The summarized findings of this literature review are presented in five sections below (see Supporting Materials 3-1, 3-2, 3-3, 3-4, and 3-5 for detailed information):

A. **Meteorology Modeling** - Rainfall extent and rates during a tropical cyclone event are critical inputs to any compound flood model. Currently, rainfall is one of the most difficult aspects to model due to its highly localized nature, high variability both spatially and temporally, and other factors. Current deterministic weather models, such as the Weather Research Forecast (WRF) model, simply do not operate at the resolution required to accurately model rainfall. In particular, the clouds that drive rainfall must be modeled as a sub-grid scale effect, and cloud physics are difficult to capture. This section focuses primarily on precipitation models that have been or are being developed to improve precipitation models and discusses both deterministic and probabilistic models. In forecast mode, deterministic weather models may be used, or alternative probabilistic models could be employed. For validation and design studies, datasets such as the Analysis of Record for Calibration (AORC) hold promise as input for hydrologic models. Recommendations include further research into probabilistic models for both forecasting and design, and the use of AI/ML. Deterministic models also have shown continued improvement due to continued development of codes such as NOAA's Global Forecast System.

B. **Hydrology and Hydraulics Modeling** - This section provides details on the characteristics and challenges associated with hydrology and hydraulic modeling in Texas. These include the presence of several complex river systems, tributaries, and watersheds along the Texas coast; complexities due to urbanization, rural versus urban flood modeling, the presence of over 600 dams and river obstructions, uncertainties in channel configurations, width, and depth, soil and groundwater interactions, among others. The section outlines several models currently used in Texas, including:

    - HEC-HMS
    - HEC-RAS
    - SWAT
    - Variable Infiltration Capacity (VIC)

- National Water Model (NWM), which is based on the WRF-Hydro model
- U.S. Environmental Protection Agency (EPA) SWMM
- Texas Rainfall Runoff (TxRR) model
- Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) model
- Watershed Systems of 1D, 2D, and 3D models (WASH123D)

(Note: AI/ML models are being investigated for hydrology models and this research will continue into the near future.)

Any, or all, of the above models could be incorporated into workflows or a computational framework for compound flood modeling with consideration of their advantages and disadvantages with respect to the modeling objectives in addition to the other factors. Important considerations for incorporating a particular model include: 1) modeled and/or missing physics, 2) compatibility of programming languages, 3) computing architectures, and 4) the ability to obtain/modify the model source code or access "hooks" in the compiled model application to access relevant data structures and exchange data with other models

A summary of various hydrologic models is presented by comparing their features in Table 3-5. The comparison includes the complexity of the hydrologic processes, the representation of urban structures, the representation of hydraulic structures, the comparison between planning and operational setups, the ease of use, the available support, and the scale range. Each table category is explained below:

- **Complexity** - the level of detail and sophistication that the model uses to simulate the generation and movement of runoff in the watershed (higher complexity models usually require more input data and parameters, but can capture more hydrologic processes and interactions)

Aerial view of damage caused by Hurricane Ike in Galveston © Jocelyn Augustino

- **Scale Range** - the range of spatial scales that the model can be applied to, from small catchments to large basins, depending on the model assumptions, structure, and data requirements
- **Hydraulics** - the model's ability to simulate hydraulic processes at the channel scale using 1 or 2 dimensions
- **Urban** - the ability of the model to account for the effects of urbanization on hydrology, such as impervious surfaces, stormwater drainage systems, and best management practices
- **Structures** - the ability of the model to represent the effects of hydraulic structures, such as dams, reservoirs, weirs, culverts, and bridges, on the flow and water level in the channels
- **Use** - the suitability of the model for different types of applications, such as long-term versus screening-level planning analysis, scenario analysis, impact assessment, or short-term forecasting, warning, and management
- **Ease of Use** - the user-friendliness of the model, such as the availability of graphical user interface, data entry utilities, documentation, and tutorials
- **Support** - the level of support and feedback that the model users can get from the developers, researchers, and other users, such as through forums, websites, publications, and workshops (at the date this report was written)
- **Active** - the current development of the model (Yes: developers are still working on improvements or new versions; No: there is no current development of the model.)

Table 3-5 and Table 3-6, which are related to the hydrologic models, are complemented with Table 3-7 and Table 3-8, which are related to some of the most widely used hydraulic models.

Table 3-5. A comparison of the process complexity represented in the considered hydrologic models.

Model	Complexity	Scale range	Hydraulics	Urban	Structures	Use	Ease of use	Support	Active	Wide Applicability
HEC-HMS	Moderate	Small to Large	No	Good	Good	Planning	High	High	Yes	Yes, suitable for a variety of hydrologic problems, such as flood forecasting, reservoir operations, water quality, and climate change
SWAT	High	Medium to Large	No	Fair	Fair	Planning	Moderate	High	Yes	Yes, suitable for a variety of hydrologic problems, such as watershed management, water quality, erosion, and nutrient cycling
VIC	High	Large	No	Poor	Poor	Planning	Low	Moderate	Yes	Yes, suitable for a variety of hydrologic problems, such as drought monitoring, streamflow prediction, and land-atmosphere interactions
WRF-Hydro	High	Large	Yes	Good	Good	Operational	Low	High	Yes	Yes, suitable for a variety of hydrologic problems, such as flood forecasting, water resources management, and coupled weather prediction
TxRR	Low	Small	No	Poor	Poor	Planning	High	Low	No	No, mainly designed for Texas watersheds and reservoirs
EPA-SWMM	Moderate	Small to Medium	Yes	Excellent	Excellent	Operational	High	High	Yes	No, mainly designed for urban stormwater runoff and sewer systems
GSSHA	High	Small to Medium	Yes	Fair	Fair	Planning	Low	Low	Yes	No, mainly designed for integrated surface-subsurface flow and transport
WASH123D	High	Small to Medium	Yes	Fair	Fair	Planning	Low	Low	No	No, mainly designed for integrated surface-subsurface flow and transport

Table 3-6. A description of the hydrologic processes represented by the models. The colors indicate different degrees of complexity of the different processes (green=low complexity, orange=medium complexity, red=high complexity, and gray=not applicable/forced data).

Process	HEC-HMS	SWAT	VIC	WRF-Hydro	NWM	TxRR	EPA-SWMM	GSSHA	WASH123D
ET Pot	Computed	Computed	Computed	Penman	Penman	None	Constant	Penman	Forcing
ET vegetation	Crop Coefficient	Uses LAI	Uses LAI	Penman	Penman	None	None	Penman	Forcing
ET Surface	After Canopy	None	f(Sat Area)	Penman	Penman	None	None	Penman	Forcing
ET Soil	After Surface	After Canopy	f(Sat Area)	Soil moisture	Soil moisture	None	None	Soil moisture	Forcing
Vegetation	Yes	Yes	Yes	Yes	Yes	None	None	Yes	Yes
Infiltration	Constant	SCS/Green	Linear	Richards eq	Richards eq	SCS mod	Green & Ampt	Green & Ampt	Green & Ampt
Percolation	Constant	Linear	None	Richards eq	Richards eq	Linear	Linear	Richards eq	Richards eq
Subsurface	None	Linear	None	Linear	Linear	None	None	Kinematic	Richards eq
Baseflow	Linear	Linear	Linear	Exponential	Exponential	Linear	Linear	Linear	Topmodel
Tiles	None	Yes	None	None	None	None	None	Yes	Yes
Runoff	Unit Hydrograph	Lag	None	Diffusive	Diffusive	Unit Hydrograph	Linear	Kinematic	Diffusive
Routing	Modified Puls	Muskingum	None	Muskingum	Muskingum	None	Kinematic	Diffusive	Dynamic
Sewers	None	None	None	None	None	None	Yes	Yes	Yes

Table 3-7. A comparison of the process complexity represented in the considered hydraulic models.

Model	Complexity	Scale Range	Urban	Structures	Use	Ease of Use	Support	Active	Wide Applicability
HEC -RAS	Moderate	Small to Large	Good	Good	Planning	High	High	Yes	Yes, suitable for modeling full network of natural and constructed channels, over-bank/floodplain areas, levee protected areas
HEC-2	Low	Small to Medium	Good	Good	Planning	Moderate	Low	No	Yes, suitable for river hydraulics, steady gradually varied flow, natural and man-made channels, bridges, culvers, weirs structures
WASH 123D	High	Small to Medium	Fair	Fair	Planning	Low	Low	Yes	Yes, mainly designed for density-dependent water flow, thermal transport, and salinity transport and sediment and water quality transport in watershed systems
GSSHA	High	Small to Medium	Fair	Fair	Planning	Low	Low	Yes	Yes, mainly designed for simulate surface water flows in watersheds with diverse runoff production mechanisms
TUFLOW	Moderate	Small to Large	Excellent	Excellent	Planning	Moderate	High	Yes	Yes, suitable for modeling of rivers and floodplains, wide range of structures with dynamically adjusted energy losses, sediment transport, lake, and coastal hydraulics
MIKE	Moderate	Small to Large	Excellent	Excellent	Planning	Moderate	High	Yes	Yes, suitable for modeling urban or offshore infrastructure, coastal developments, groundwater, water distribution, wastewater

Table 3-8. A description of the hydraulic processes represented by the considered models.

Process	HEC-RAS	HEC-2	WASH 123D	GSSHA	TUFLOW	MIKE +
Model Type	1D - 2D	1D	1D (Stream River Network)- 2D (Overland Regime) - 3D (Subsurface Media) -Coupled	1D (Stream Flow and Soil Moisture) - 2D (Overland Flow and Groundwater)-Coupled	1D-2D-3D -Coupled	1D-2D (Overland)-3D-Coupled
Geometry	Cross Sections (1D), Terrain Model (2D)	Cross Sections	Cross Sections (1D)	Cross Sections (1D)	Cross Sections (1D)	Cross Sections (Mike 1D River)
Roughness Coefficients	Manning's Roughness	Manning's Roughness	Manning's Roughness	Manning's Roughness	Manning's n, Relative Resistance, Sample Values	Manning's Roughness
Boundary Conditions	Unsteady state: Upstream and Downstream BC (Stage and Flow Hydrograph - Normal Depth) - Internal BC (Stage/Flow Hydrograph, Lateral and Uniform Lateral Inflow Hydrograph-Rating Curve, Groundwater Interflow, Time Series Gate Openings, Navigation Dam, Elevation Controlled Gate)	-	Global Boundaries (Flows, Thermal, Salinity and Sediment transport) - Internal Sources (Junctions, Control Structures) - Media Interfaces	Upstream BC: No-Flow Condition, Downstream BC: Normal Depth, Head, Depth	Upstream and Downstream Boundaries, 1D/2D and 2D/2D Links: Outflow, Inflow, Rainfall, Dambreak Hydrograph, Pumps, Infiltration	Open BC, Closed BC, Inflow and Lateral Inflow, Water Level Boundary (Outlet), QH (Inflow/ Water Level) Boundary
Type of Flow	Steady (1D-2D) and Unsteady (2D)-state	Steady-state	Steady-state	Steady (1D-2D) and Unsteady (2D)-state	Steady (1D-2D) and Unsteady (2D)-state	Steady-state
Flow Equations	Backwater Equation (Steady-state), St Venant Equations (Unsteady state) - Diffusive Wave Model	Backwater Equation	St Venant Equations, Kinematic, Diffusive, and Fully Dynamic (MOC) Waves (1D And 2D) - Richards' Equation For Subsurface Media (Vadose and Saturated Zones) (3D)	Saturated Richards' Flow Equations	St Venant Fluid Flow Equations	St Venant Equations-Diffusive Wave Model
Control Structures	Overall Head Losses (Simplified 1D/2D Bridge Modeling And Detailed Bridge Modeling) - Lateral Structures Modeling	Head Losses (Bridge / Culvert) Calculations (Normal Bridge-Special Bridge, and Special Culvert Methods)	Control Structures (Weirs, Gates, Culverts, Levees, Mass, Or Energy Balance) Is Explicitly Enforced by Solving Flux Continuity and State Variable Continuity (or Flux) Equations	Present Version of GSSHA Channel Routing Includes Support for Weirs. Future Versions Will Include Bridge Crossings, Culverts, Reservoirs, and Lakes.	Rectangular, Circular, and Irregular Shaped Culverts, Bridges Pressure Flow and Vary Losses With Height. Spillways, Pumps and User Defined Height-Flow Curve or Matrix For Downstream Controlled Condition (1D)	Modeling Of Culverts, Weirs, Bridges, Pumps, Gates, Direct Discharges, Dambreak, Energy Losses, Tabulated Structures
Water Properties	Sediment Transport Capacity Functions (Steady–Unsteady-state): Ackers- White, Engelund-Hansen, Laursen, Meyer-Peter Müller, Toffaleti, Yang	-	Bed and Suspended Sediment Transport Methods (1D And 2D)	Soil Erosion and Sediment Routing (Kilinc and Richardson Equations)	Sediment Transport (2D/3D)	Single-Fraction and Multi-Fraction Sediment Transport and Bed Layer Modeling (MIKE 1D)

C. **Storm Surge Modeling** - Storm surge could be the dominant process in any compound flood workflow. Storm surge models have reached a mature state and have been routinely applied to forecasting, hindcasting, planning, and design studies for the last two decades. This section of the Theme I Literature Review discussed the basic physics of storm surge and the characteristics of some of the primary codes in this field, including ADCIRC, Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM), Delft3D, Finite Volume Community Ocean Model (FVCOM), and Adaptive Hydraulics (AdH). These codes are written in either Fortran or C programming language and have been parallelized for HPC environments. ADCIRC and SCHISM have been widely applied for large-scale Texas coastal modeling. SCHISM has the advantage of including a 3D component, while ADCIRC has been more thoroughly validated for Texas storms and is being used currently for design studies for USACE, FEMA's coastal flood risk assessment effort, and other groups developing storm mitigation systems. Storm surge models have also been coupled with wave models to simulate wave-circulation interaction. In recent years, surge models have begun to include inland river inflows in a first attempt to account for compound flooding. Some have also added rain-on-mesh to include direct rainfall effects. In the context of workflows for compound flooding, the storm surge model will be of primary importance, since it is the conduit between oceans, coasts, bays and estuaries, and rivers. The interplay between storm surge and river flows will affect the flood inundation both along the conventional coastal region and well upstream along rivers.

Findings of strength, weakness, opportunities, and threats (SWOT Analysis) of different storm surge models are included in Supporting Material 3-3 and presented in Table 3-9.

Table 3-9. A SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis for storm surge models.

Model	Strengths	Weaknesses	Opportunities	Threats
ADCIRC	Validated for Texas storms Large and diverse user base Parallelized for HPC Tightly coupled with SWAN and STWAVE Inputs from many wind products Open source Runs in forecast mode Community GUI available via SurfaceWater Modeling System	Mostly 2D 3D not well developed Limited stabilization for advection Local mass balance issues	Growing user and developer base New global model widely adopted by NOAA, USACE, FEMA, and internationally	Software optimized for traditional HPC CPUs and not GPUs Unstructured meshing can be time consuming (true for all unstructured models)
SCHISM	Validated for recent storms Open source Numerous integrated modules for waves Parallelized for HPC Seamless transition from creeks to deep ocean (2D to 3D) Conserves mass locally and globally	Not as tested for storm surge or large storms Older code version could be overly diffusive, particularly for large scale domains with limited bathymetry resolving; newer versions have better discretization methods to overcome	Ongoing Active development Adopted by NOAA and international community User group is growing	Steep learning curve Limited built-in graphic User interface support for model set-up and visualization User base is small compared to other models Unstructured meshing can be time consuming (true for all unstructured models)

Table 3-9. Continued

Model	Strengths	Weaknesses	Opportunities	Threats
FVCOM	Solves 3D primitive equations with hydrostatic and non-hydrostatic approximations Coupled with wave model Comparable in accuracy with ADCIRC for storm surge Large user base and well-established model Conserves mass locally and globally	Relatively strict stability constraints Did not show good parallel performance compared to ADCIRC in intercomparison tests Can be overly diffusive due to lower order discretization	Can be employed to study storm surge, internal waves and biogeochemical processes Can include nested spatial domains	Mostly employed for the U.S. East Coast Has not been used for Texas except in intermodel comparison project
DELFT3D/ DFLOW-FM	Very large user base Very flexible code with many modeling options including State-of-the-art for morphodynamics/ sediment Development supported by a large organization Capable of 2D and 3D modes Relatively easy learning curve Conserves mass locally and globally	There is no large-scale calibration and validations studies performed for Texas coastal regions Parallelization efficiency is not as good as other models	Sustainable over the long haul Possibility to do beach erosion and 3D	Code development is outside the U.S. Training is expensive Source code is not fully open source
ADH	Validated for storms across U.S. Capable of multiphysics simulations Advanced numerical scheme, robust to advective problems Includes groundwater transport Conserves mass locally and globally GUI available in community version of SurfaceWater Modeling System	Not fully open source Requires sophisticated linear and nonlinear solvers Can be over diffusive	Under active development with effort focused towards multiphysics coupling Still actively used by USACE districts	User base is small compared to other models Development controlled by USACE
ROMS	Sophisticated numerics Open Source 2D and 3D Conserves mass locally and globally	There is no large-scale calibration and validations studies performed for Texas coastal regions Not validated for storm surge or tides Uses structured grids	Mature model Large user base Stable in 3D	Mostly used for 3D Baroclinic models Not known for storm surge
SLOSH	Efficient Probabilistic framework Conserves mass locally and globally	Simplified model No waves, no advection Tends to overpredict	Wide user base Still used by NHC and NOAA	Old technology User support unknown Future development uncertain

D. **Waves Modeling** - Wind-induced waves tightly interact with surge models in tropical storms. Water velocity and water elevation feeds into wave models and waves increase surface stresses in the coastal ocean. Wave cresting, wave runup, and wave overtopping can impact structures and cause flooding in addition to surge. Wave setup can increase storm surge by up to 1 meter in some cases. For these reasons, most surge models are coupled in some form to wave models. Common wave models are Simulating Waves Near Shore (SWAN), developed at the Delft University of Technology, the STWAVE, developed by the USACE, and WaveWatchIII, developed by NOAA. Waves should be included as an essential part of a compound flood modeling framework because of the tight interaction between waves and surge. Findings of SWOT analysis of different storm WAVE models is presented in the following table. Refer to Supporting Material 3-4 for additional findings of wave modeling literature review efforts.

E. **Compound Flood Inundation Modeling** - The key challenge in compound flood inundation modeling is determining an effective way of quantifying the combined impact of two or more physical flood forcing processes on the short and long-term inundation of coastal zones. This section of Theme I provides a detailed account of the various physical principles and numerical strategies adopted to either 1) couple models representing different physical processes or 2) to develop a fully integrated computational framework. The discussion considers a range of academic and production-level compound flood modeling codes that comprise state-of-the-science. Most compound flood models can be categorized based on either the type of numerical methods (process-based, reduced physics, and data-driven) and coupling strategies (one-way coupled, two-way coupled, integrated, etc.) or by the intended use cases (real-time simulation, probabilistic hazard evaluation, high-resolution spatiotemporal modeling).

Physics-based (mechanistic/deterministic) models are well-established in their respective domains as discussed in the preceding sections. Such models are arguably the primary targets for inclusion in a compound flood modeling framework. Using separate domain models requires “model coupling” (i.e., the exchange of data between mechanistic models as they are marched through time). (See Coupling Flood Inundation Models for Compound Flooding, below, for more information.) The complexity of compound flood inundation modeling is driven by the underlying physics that requires high-resolution space and time discretization, high-quality empirical representation of sub-grid scale processes, and extensive computational time for each simulation. Nevertheless, physics-based mechanistic models have been shown to be well-equipped to capture the interaction effects between competing physical processes and can be used to evaluate flood inundation impacts for various engineering “what if” scenarios.

Researchers are attempting to address the issues of high computational cost of mechanistic modeling through “reduced-physics” models and data-driven AI/ML models. Reduced physics models are those which intentionally simplify some portion of the governing physics equations. The goal for reduced-physics models is to achieve a lower computational cost and/or simplified user operability by (hopefully) only marginally sacrificing flood inundation accuracy. Ideally the results from a reduced-physics model should be within the uncertainty envelope of a process-based model. Some notable examples include static flood models such as the Height Above Nearest Drainage (Nobre et al., 2011) methods, simplified momentum models such as LISFLOOD (Large-scale Inundation Simulation using FLOOD) (Van der Knijff et al., 2010), and SFINCS (Super Fast INundation of CoastS) (Leijnse et al., 2021), and downscaled flood models such as PRIMo (Parallel Raster Inundation Model) (Sanders & Schubert, 2019).

In theory, data-driven AI/ML models, could be trained to provide rapid flood inundation predictions for specific storm conditions that would be faster than traditional mechanistic flood inundation models. However, such models presently require prohibitive amounts of data and computational time for their training. Furthermore, AI/ML methods have yet to be proven effective in correctly capturing events that are outside their training data. Nevertheless, this is a highly active field of research that is rapidly evolving to overcome these challenges through the development of new physics-informed, hybrid-data, graph-based, operator learning, and generative modeling architectures.

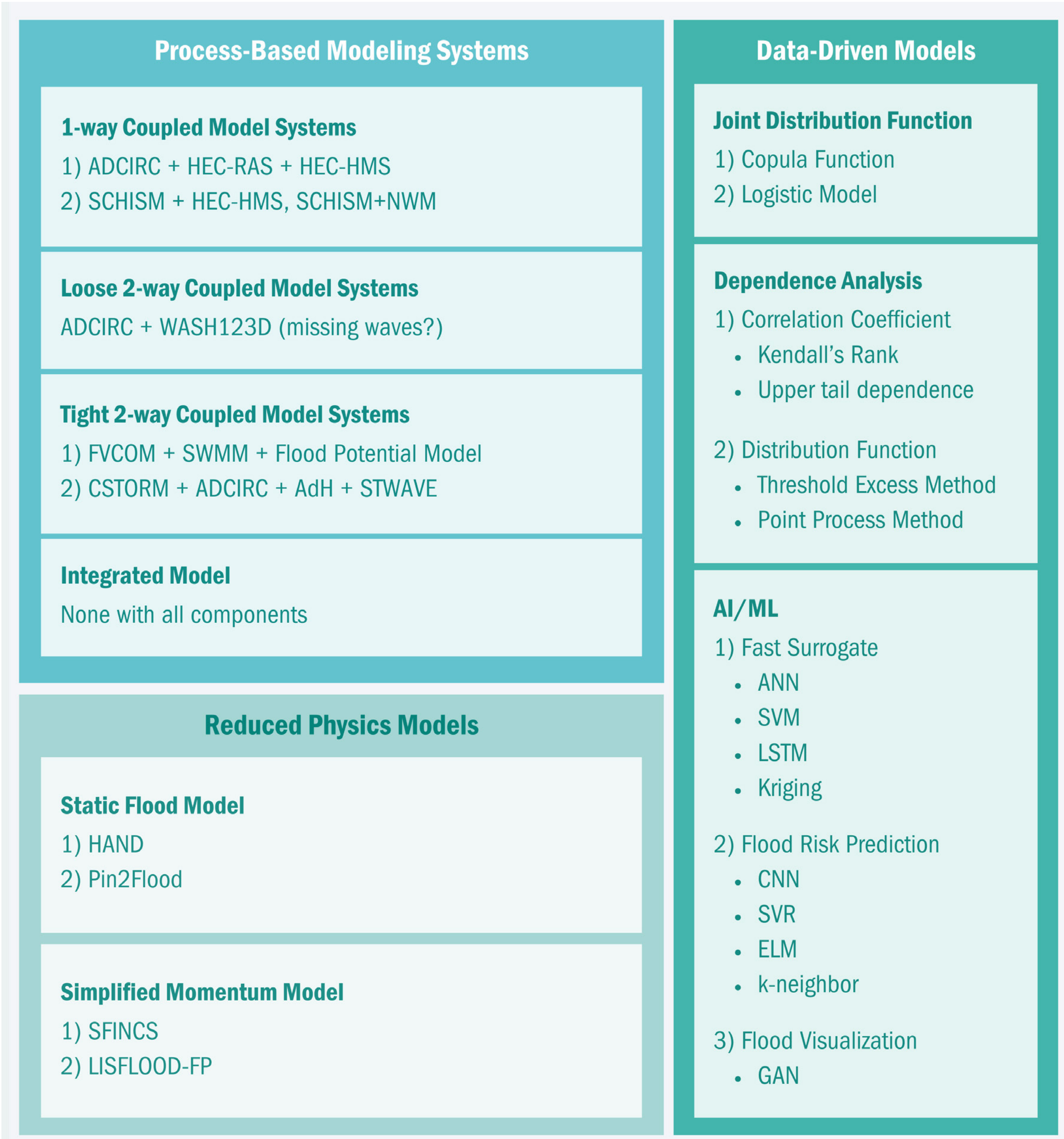


Figure 3-6. Examples of compound flood models found in the literature. Process-based modeling systems include all flood processes (hydrology, hydraulics, ocean, and waves), while reduced-physics models are simplified and may not represent all components. (Couplings between process-based models, reduced-physics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

Literature Review Theme II (Probabilistic Methods for Flood Hazard Estimation)

TIFF also conducted a literature review of techniques for probabilistic compound flood hazard modeling and analysis specific to the coastal Texas region, aiming to create a comprehensive field guide. This analysis is crucial for estimating inundation extents and depths at different frequency events, providing insights for evaluating project benefit computations.

Probabilistic models are an essential component to any compound flood modeling workflow for a variety of reasons. Such models can be used to build Probability Density Functions of inputs into compound flood models that can be sampled, fed into models, and the results used to build probabilistic flood hazard analysis caused by different factors. An example is the use of the JPM-OS to generate synthetic storms for modeling flood hazards due to storm surge. Similar approaches are recommended to be used to generate synthetic storm/rainfall events for probabilistic compound flood hazard analysis. Such methods can also be used in combination with data from measurements or from physics-based models to generate surrogate models for compound flooding. These models are extremely efficient computationally and can be used to estimate impacts from a variety of factors, such as sea-level rise, climate change, etc., over wide ranges of parameter space, which would be computationally prohibitive using high-resolution physics-based models.

The highlighted findings of this probabilistic analysis literature review are reported with detailed information in Supporting Material 3-6.

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

Building on the findings of the model literature review described above, TIFF focused on the development of conceptual model-coupling workflows for assessment of compound flooding hazards in coastal Texas. The goals were to investigate appropriate software, model-coupling frameworks, and conceptual workflows for various simulations with different levels of complexities that may include different types of forces and processes within the GLO's RBFS regions that lead to compound flooding. The major efforts of this work include developing:

a) a conceptual model coupling strategy/workflows (both source code level coupling and using coupling interfaces), including coupling of state-of-the-art meteorologic, hydrologic-hydraulic, wave, and estuarine-surge models for each of the use cases and level of complexities by considering the involved processes/drivers/forces that are present along the Texas coast

b) scenarios and an evaluation matrix to test effectiveness of the conceptual model integration strategy

c) criteria and recommendations for testbed(s) for workflow evaluation (Supporting Material 3-18)

A. COUPLING FLOOD INUNDATION MODELS FOR COMPOUND FLOODING

The coupling among several, if not all, of the physical processes involved in compound flooding is needed in flood modeling as these processes interact during a compound flood event.

Existing coupled systems[5] are typically centered around a keystone model, e.g., a coastal ocean model (Supporting Material 3-5), a H&H model (Supporting Material 3-2), or a meteorology model (Supporting Material 3-1). To date, none of these models individually provides a complete physics representation of all the compound flooding processes (i.e., meteorology, hydrology and runoff, river hydraulics, flood inundation, groundwater, stormwater infrastructure, storm surge, and waves). The physics-based flood inundation models that incorporate coupled physical processes can be characterized into four categories of increasing level of coupling complexity (Santiago-Collazo et al., 2019): 1) one-way, 2) loose two-way coupled, 3) tightly two-way coupled, and 4) fully coupled (Supporting Material 3-5):

One-way coupling is the simplest coupling method from a donor to a recipient model. One-way coupling generally involves coupling two or more models, where one model functions as the receiver of information, whereas the others act as secondary models that provide their outputs to the primary model (Santiago-Collazo et al., 2019). This approach is commonly used for coupling domain models in coastal processes. An example of such coupling is the transfer of upstream or downstream boundary data to or from a HEC-RAS model (Brunner 1994) to or from an ADCIRC model (e.g., Loveland et al., 2021). Such models lack the feedback of physical processes that is provided with two-way coupling.

5 Existing coupling methods associated with specific models are discussed in Supporting Material 3-5.

Two-way coupling (tight or loose) involves the independent execution of two or more models, which sequentially exchange information, such as boundary condition data. In two-way couplings, the fundamental characteristic is that the models operate independently and do not share algorithms or solution variables. The objective of two-way coupling is to enable each model to receive feedback from the others in an iterative fashion, thereby overcoming the primary drawback of one-way coupling without necessitating the creation of an integrated model. Loose two-way coupling and tight two-way coupling represent essentially the same basic processes and differ primarily by their software design (Santiago-Collazo et al., 2019).

Fully coupled (aka monolithic, integrated) models are those that resolve all physical processes within the same computational framework inherently sharing all necessary solution variables without the need for communication to other models. These represent the closest connection between the physical processes of these coupling methods and thus are less likely to induce numerical issues that can occur in one- and two-way coupling.

The State-of-the-Art in Model Coupling

Presently, "one-way" coupling (donor to receiver) is the simplest and most commonly used approach for coastal processes. One-way coupling is a valid approach when changes in the donor caused by the receiver are considered small and such feedback do not substantially change the area of interest (e.g., the flood inundation is presumed[6] to have minimal effect on the storm surge). The assumptions required for one-way coupling can be eliminated by allowing the different models to communicate their results to each other during the time-marching simulation, which is known as "two-way" coupling. Loose and tight two-way coupled models, distinguished primarily by software implementation, allow for feedback between two or more independent models, but may suffer from numerical inconsistency and convergence issues. ADCIRC coupled with WASH123D and the Coastal Storm Monitoring System (CSTORM) are two successful examples of loose and tightly two-way coupled models, respectively (Tritinger & Dillon, 2025; Tanaka & Westerink, 2011). In contrast to coupled models, it is theoretically possible to build a single model that incorporates all the physical processes (i.e., a fully-integrated compound flood inundation model). However, there are currently no examples such models in either commercial applications or research. Progress is being made in this direction and there are notable examples of partially integrated frameworks that cover different subsets of physical driving processes (e.g., SCHISM, AdH, WASH123D, and SFINCS).

Arguably, flood inundation model coupling has been primarily driven by the coastal ocean modeling community, whose models are the most computationally intensive and whose storm surge results are strongly affected by the area available for inundation. The Coupled Systems Centered on Coastal Ocean Modeling section in Supporting Material 3-19 provides a detailed discussion on a number of coupled systems that have been centered around coastal ocean models. Coupled systems centered on hydraulic inundation models are less common than those centered around coastal ocean models. The two most prominent examples (HEC-RAS and AdH) are discussed in the Coupled Systems Centered on Inundation (Hydraulics) Models section in Supporting Material 3-19. The biggest challenge for these models is the two-way coupling with a coastal ocean model such that river flows and river-driven flood inundation interact with storm surge with the correct nonlinear interactions. For compound flood modeling, meteorology is generally treated as a one-way donor model as the feedback from saturated soils to meteorology are arguably on time scales much longer than flood events. Within the meteorological community, modeling systems relevant to compound flooding have been developed, most notably a system for creating spatio-temporal distribution of rainfall from a tropical cyclone and the CSTORM-MS that provides two-way coupling and is already integrated with coastal ocean models ADCIRC and AdH. (See the Coupled Systems Centered on Meteorology section in Supporting Material 3-19 for more details.)

6 The entire point of compound flooding is that one-way interactions cannot be presumed for extreme events but must be shown to be valid. The use of one-way coupling requires modelers to demonstrate that the uncertainties associated with neglecting two-way effects are understood, quantified, and acceptable for the purposes of the model.

Coupling in compound flood hazard analysis (and subsequent risk assessment) increases computational burdens due to the need for many flood inundation model runs and are therefore also affected by the choice of coupling, though somewhat differently. In the case of one-way coupling, if the more computationally intensive model needs only to be run once, this can make the approach much more computationally feasible. However, fully coupled models, which are complex in terms of the physical modeling itself, may have the same number of runs as one-way coupling. Two-way coupling, however, can require immense numbers of model runs for hazard analysis, a fact that should be considered when executing coupling approaches for a project where hazard analysis and risk assessment are needed for planning or design (Supporting Material 3-19).

Flood Hazard Analysis Category for Compound Flood

Hazard analysis for compound flooding can be categorized by "levels" of increasing complexity, similar to the USACE CHS-CF tiers (Supporting Material 3-9). These levels reflect statistically consistent and increasingly robust probabilistic workflows for quantifying compound coastal hazards. The hazard analysis levels of Table 3-10 and Figure 3-7 are discussed in detail in the Flood Hazard Analysis Framework and Workflows section in Supporting Material 3-11.

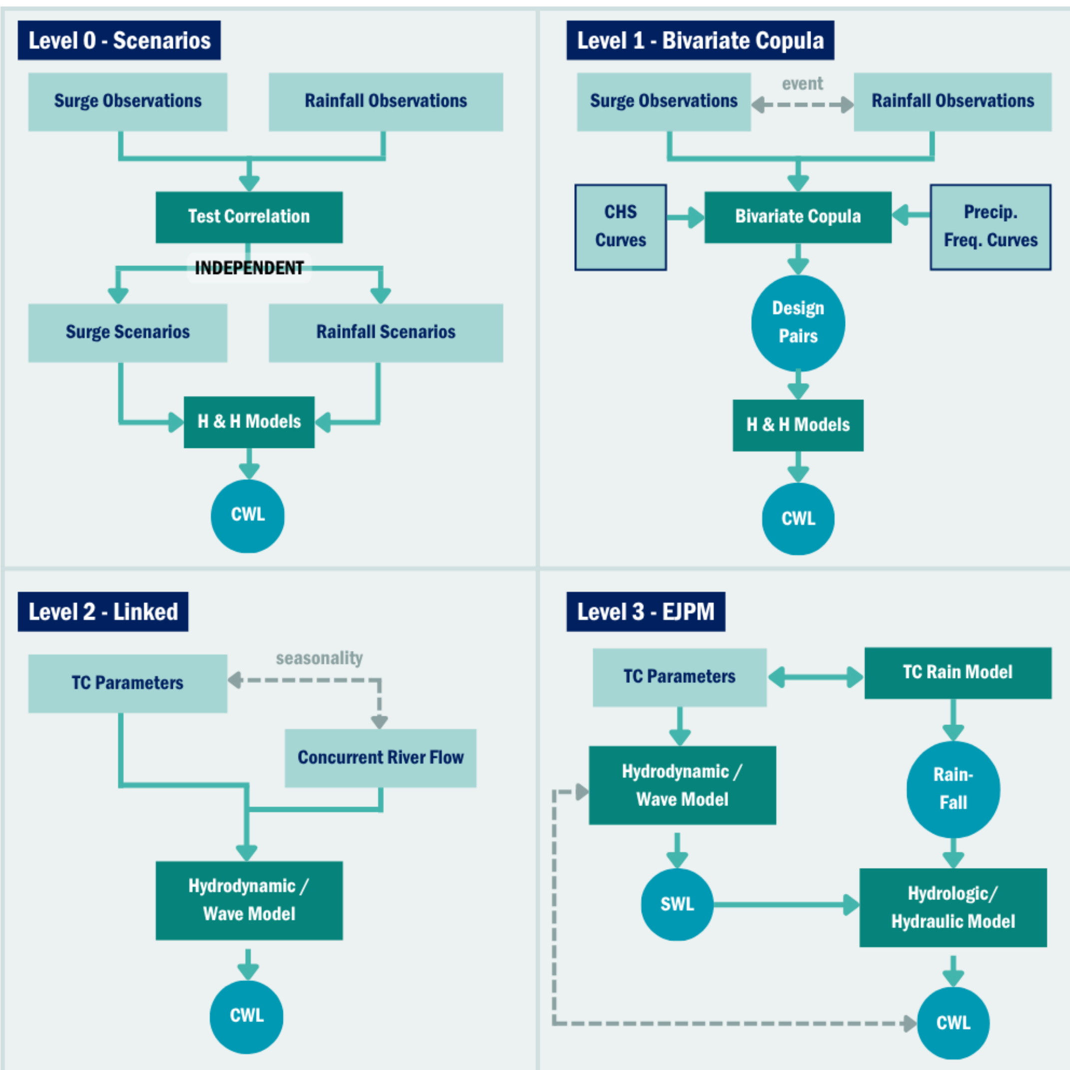


Figure 3-7. Examples of conceptual workflows for a TxCFF (adapted from Liu et al, 2024, unpublished). Variables SWL and CWL represent surge and compound water elevation, respectively.

Table 3-10. Compound flood hazard framework levels.

Hazard Analysis Level	Characteristics	Purposes	Computing Requirements; Uncertainty	Examples
Hazards Level 0 (HL-0): Independent Scenarios Screening	Combined scenario frequency analysis assuming independence between coincident flood drivers Response matrix used to develop inputs and boundary conditions for flood models	Screening for early feasibility Locations with clear evidence of no correlation between coincident events	Low to medium computing requirements High uncertainty strongly dependent correlation being small and representative of any joint probability	"Response Matrix" HEC-SSP
Hazards Level 1 (HL-1): Screening Statistical Approaches	Data Driven statistical approach based on available paired event records Typically statistically represented by a bivariate copula Resulting joint probability curves used to drive flood models	Screening for early feasibility Locations with extensive historical record Projects with limited financial resources or acceptable of high uncertainty	Low to medium computing requirements based on data availability Medium to high uncertainty strongly dependent on number of paired events in historic record	Multivariate analyses Multivariate copula analyses HEC-SSP Bulletin 17C AI/ML approaches
Hazards Level 2 (HL-2): JPM-Hybrid Probabilistic Linking	Synthetic storm driven coastal model linked to simplified inland analysis, such as by correlated parameters and/or random sampling	Areas with highly correlated compound parameters (e.g. seasonality) Independent compound hazards (e.g. river flow and storm surge) Feasibility studies	Medium Uncertainty related to coastal model, correlation and sampling	JPM-OS with Hybrid Monte Carlo JPM hybrid CSTORM-MS
Hazards Level 3 (HL-3): Extended JPM	flood model driven by synthetic TC parameters Can be linked by TC rainfall driven by same parameters One- or two-way model coupling, AI/ML used to expand limited TC parameter space Can include additional complexity such as variable antecedent conditions, TC rainfall with stochasticity; more complex model coupling; additional hazards (e.g. groundwater)	Feasibility Risk-based design of low to medium to high complexity projects Design or studies for critical infrastructure	Medium to High: Lower uncertainty due to improved modeling and probabilistic rigor May have increase in uncertainty due to additional parameters and models	Extended JPM with CSTORM-MS NOAA UFS Hydrodynamic/ Wave models HEC-HMS, RAS AdH Local H&H models Groundwater models

Flood Inundation Modeling Category for Compound Flood

In Table 3-1, TIFF categorized six types of flood inundation models FI-I, FI-II, FI-III, FI-IV, FI-H, and FI-DD. The model types FI-I through FI-IV are conventional physics-based models (i.e., solving mechanistic equations) whereas FI-HM and FI-DD are hybrid and data-driven models focused on flood inundation although they use some of the same underpinnings as probabilistic analysis of flood hazards.

TIFF does not provide specific recommendations for the flood inundation models to be used in particular instances. With the present state-of-the-art, modeler's engineering judgment (backed up by analyses of physical processes, model behaviors and modeling objectives or user needs) must be used to decide on the appropriate models and couplings for various conditions and scenarios. For instance, if soil/groundwater interaction in a given area is known to be a small effect, it may not be worth the added expense and uncertainty to include such a model/module in a particular workflow scenario model coupling.

The Case for a Texas Coastal Flood Framework

The goals of a TxCFF are to provide flexibility for projects, re-usability of workflows and code, and the ability for project manager to determine the "size" that best fits their project. The conceptual organization of flood inundation modeling with the proposed TxCFF is provided in Figure 3-7. Based on the user's modeling objectives, in some cases, prototype codes already exist or are under development to address simplified versions of the conceptual workflow outlined in Figure 3-7. In other cases, extensive research and development would be required to develop and maintain models. There are positive and negative aspects for all of the options (i.e., there is no "one-size-fits-all" solution).

TIFF proposes a variation to be applied as both tiered hazard and flood inundation modeling framework for the TxCFF which is discussed in previous paragraphs (see Table 3-10 and illustrated in Figure 3-7 for tiered hazard analysis and Table 3-1 for flood inundation model).

The workflows for flood hazard analysis tools should be built into the TxCFF framework to couple directly to the output of flood inundation models. The level of complexity for analyzing hazards of a specific project can be chosen to support user needs, such as for coastal risk analysis, design, and mitigation. A critical feature is that the hazard analysis levels should be model agnostic to work with different components of the flood inundation model, as described in (Types of Flood Modeling), depending on which model components are critical to a specific project's focus. Furthermore, the hazard analysis tools must use a basin-agnostic approach that allows location-specific parameters to be defined across the varying geographies in Texas. Implementing hazard analysis within the TxCFF will provide consistency and rigor for site-specific engineering and policy decisions. Increasing complexity of levels within the hazard framework allow for execution to meet different project needs such as speed of execution, data availability/historical record lengths, and computational resource limitations.

Key Considerations for Selecting a Compound Flood Modeling Framework

There are three criteria to be considered before selecting a modeling framework for compound flooding analysis of the Texas coastal region based on project needs:

1. Should flood inundation models use a) the most detailed possible physical equations (FI-I, FI-III), or b) simplified physical equations that allow more rapid solutions (FI-II, FI-IV), or c) data-driven AI/ML models (FI-H, FI-DD) or d) some combination of the above? How do we consider different needs in this choice?

2. Should the model framework be created using a) a monolithic, single model (FI-I, FI-II), or b) as a compound flooding model coupling framework (FI-III)?

3. What hazard analysis level (HL-0, HL-1, HL-2, HL-3) should be used given the data availability and project needs?

To provide background for the following discussions, it is useful to consider the hierarchy of inundation models as presented previously in Table 3-2 and of compound hazard analysis levels in Table 3-1. There are positive and negative aspects for all of the options. There are four different options for physics-based models based on level of complexity and code structure:

1. The Flood Inundation (FI) models of types FI-II and FI-III are those that engineers typically turn to for planning and design analyses.

2. The key difference between FI-I (which do not exist) and FI-II (which exist) is that FI-II models are designed primarily for a particular purpose so they have the full physics equations accepted by the discipline (e.g., ADCIRC, designed for coastal ocean circulation) whereas the addition of other compound flooding components use some reduced physics (relative to those generally accepted by the adjacent discipline).

3. In contrast, a FI-I or FI-III system could be designed from the ground up to include all physics-based processes with their accepted equations.

4. The FI-IV models are different from FI-II in that the former are designed for fast run times by using simplified physical equations (relative to those accepted by the discipline) across all processes.

The FI-H and FI-DD models are presently undergoing research, but hold promise for eventually providing faster inundation models. However, it is difficult to envision how FI-H and FI-DD models can be trained and validated without first building an FI-I/III system that provides sufficient data.

There are four different compound hazard analysis levels of increasingly complexity (and typically decreasing uncertainty) meant to meet different projects needs such as speed of executions, and computational resources within the data available and historic record lengths:

HL-0 - assumes interdependence between compound drivers (e.g., rainfall, surge) based on a simple correlation. To develop joint probabilities of the compound water levels, a response matrix is population by the compound drivers for different paired scenarios with assumed probabilities from existing univariate analyses (e.g., Atlas 14 Precipitation Frequency Analysis). The response matrix is solved for water level using a near-shore flood inundation model, proving the probabilities and water level responses to develop a compound hazard curve. HL-0 is often applied for screening and fast-paced early feasibility assessments of design.

HL-1 - is often applied for similar uses and even for design application, though HL-1 assumes dependence between the compound flood drivers, with their joint probability often represented by a copula (a statistical tool). HL-1 captures more of the joint probability and can reduce uncertainties. However, the method is highly sensitive to the available of a large number of paired historical event with data on both hazards, as well as engineering judgment required for analysis decisions with the statistical method.

HL-2 - differs from HL-1 and HL-0 in that synthetic JPM-type hurricane and non-tropical coastal storms are used for the coastal part of the compound hazard analysis. The inland hazard is linked to at least one of the JPM parameters and sample based on the joint probability between them. An example would be a JPM-Monte Carlo hybrid linking storm intensity (as central pressure deficit) to river flow by seasonality. HL-2 is best applied in case where compound drivers can be simply linked and are otherwise nearly independent.

HL-3 - build on the state-of-the-art probabilistic coastal JPM-type hazard analysis, extending it to include compound drivers (i.e., TC Rainfall) using the same synthetic TC parameters to drive flood models and rainfall models with JPM parameter sets and their known probabilities. This approach can be used for complex use cases, as more elements can be incorporated, and uncertainties are reduced by incorporating machine learning type metamodels and a copula to better define the joint probabilities. Computational costs can be reduced by leveraging existing regional models.

The Question of Simplified or Non-Simplified Flood Inundation Modeling

The question of flood inundation model equations is really a question of what approach should be taken for a baseline model. Neither data-driven (FI-DD) nor hybrid (FI-H) models are appropriate as a baseline because we simply do not have enough data to create and apply such models for accurate predictions of flooding on the coastal plain. That is, any data-driven or hybrid model presupposes the existence of an accurate data set describing flood inundation over a wide range of events and locations, but compound flood events do not happen often enough to provide sufficient data. However, such models remain a useful part of a flood modeling framework.

Type FI-II and FI-IV models (Table 3-2) are inappropriate as baseline approaches models for compound flood inundation modeling. Each flooding discipline (storm surge, rainfall, river overbanking, groundwater) has a cadre of experts that have reached general consensus on the physical equations required to model flooding processes within their specialty. It is inappropriate for compound flood modelers to ignore the decades of work in these areas and implement reduced physics equations simply for faster computational times. If full physics proves too computationally costly for a large storm over large area, then the target should be narrowed until it can be definitively proven that simplified methods are justified. As a matter of science, reduced physics models should only be used in compound flood modeling once comparisons with full-physics models have proven that a discipline's consensus on needed model equations is faulty.

An outcome of building a full-physics modeling system will be the ability to explore this issue and, perhaps, develop well-founded reduced-physics approaches that are appropriate for compound flood modeling. Unfortunately, the present state-of-the-science in compound flood modeling does not support rejecting the existing science of any flood discipline. The need to ensure that the physics equations of the disparate flooding disciplines are included in a baseline model leads us to recommend a compound flooding modeling framework rather than a monolithic model.

A range of flood inundation modeling and hazard analysis approaches are possible for compound flooding, as outlined in Tables 3-1 and 3-2 and discussed in greater detail in Dawson et al (2024). Different types of models have a range of capabilities, computational costs, and examples in the state-of-the-art. In general, a compound flood model framework can be constructed in one of two basic ways:

1. Begin developing a monolithic model that incorporates all important physics (i.e., FI-I) and couples with newly designed flood hazard analysis tools. Although we have the knowledge and capability to build a monolithic compound flood inundation model, the advances in single-discipline inundation models will continue and new advances may be difficult to continually adapt into the monolithic model. The main advantage of a monolithic model is that it provides the best coupling between the different flooding processes. The primary disadvantage is the overall complexity of the code base makes it a challenge to build and maintain unless a dedicated funding stream can guarantee long-term cadre of coders.

2. Building a compound flood modeling "framework," requires software development to couple existing (or future) model codes so that they can talk to one another and provide consistent predictions with flooding interactions. A framework is inherently easier to maintain than a monolithic code base, as the individual codes in a framework are maintained within their discipline. The key disadvantages of a coupling framework are that 1) the computations will be less efficient (slower) than the independent models, 2) the coupling algorithms requires methods that are still in research and development in government and academia, and 3) coupling between open-source and closed-source models can be challenging and will require cooperation of the organizations/agencies maintaining the component models.

Comparing the advantages and disadvantages of the two approaches, our recommendation is to build a software framework (type FI-III) that we can use to integrate both existing and future flood inundation models with hazard analysis tools in a consistent, supported, and replicable manner. The proposed TxCFF allows model developers in discipline areas (river, rainfall, ocean, groundwater) to keep their focus on building/improving their discipline while model integration experts develop the tools and software for coupling models with a TxCFF, simplifying their use, and providing accessible output data. A goal of the FI-III modeling framework should be to provide foundations for future development of FI-H and FI-DD models that can more rapidly compute inundation and thus be more useful for many coastal feasibility, design, and planning purposes.

Building Complex Models Today for Simple Models Tomorrow

Building the flood inundation part of the framework around FI-III models (full physics) puts us in a position to comprehensively evaluate the effectiveness of newly developed approaches in FI-IV, FI-H, and FI-DD models. The number of scenario models that are needed to effectively model flood hazards for long-term planning and impact studies simply cannot be done with full-physics models. However, there does not seem to be any scientifically rigorous path to effective reduced-physics or data-driven inundation models without first developing the full physics models that are needed for training and validation. The way forward is in four steps:

1. selection of synthetic storm parameters or historical storms and identification of their probabilistic and wind and pressure modeling for input to full-physics modeling
2. full-physics modeling
3. training/validation of reduced physics or data-driven models running hundreds to thousands of reduced physics or data-driven models for flood hazard analysis (expanding on high fidelity full-physics results using meta-modeling (machine learning) and copula analysis of hazards)
4. running hundreds to thousands of reduced physics or data-driven models for flood hazard analysis (expanding on high fidelity full-physics results using meta-modeling (machine learning) and copula analysis of hazards)

Beyond the fourth step, which has incorporated AI/ML into the probabilistic model runs to shortcut the need for more high-fidelity runs, there does not appear to be any shortcut to this stepping-stone path in current model application.

Linking Flood Inundation Modeling and Hazard Analysis

Coupling between flood hazard analysis and flood inundation modeling is inherently a different problem than coupling between different physics models within a flood inundation model. The purpose of coupling hazards and inundation is to provide the ability to integrate the results from many inundation scenarios into a unified analysis (Supporting Material 3-11). The proposed TxCFF provides the capability to link inundation and hazard analysis. For each of the framework hazard levels, probabilistic inputs for flood inundation models are developed in slightly different ways and then hazard curves should be developed from the resulting compound water levels (also called the response) of the flood inundation models. The described hazard framework levels allow for a selection of approaches based on 1) compound hazard characteristics (dependence, importance of compound effects over univariate hazard); 2) project needs; 3) complexity and resources; 4) data availability and quality; and 5) robustness and level of uncertainty of results.

HL-0 - links among compound driving hazards are independent scenario pairs over the range of expected univariate hazards. Automation of linking the selected input scenarios to flood inundation models would involve running those models at the specific scenarios, scripting to determine the joint probabilities, and establishing a hazard curve from the probabilities and the outputs of the FI models.

HL-1 - results in a set of isolines expressing the likelihood of the joint probability of different paired compound hazards and allowing selection of 'design storm' inputs of known probability and likelihood established from that joint probability isoline chart. HL-1 follows a bivariate copula approach, for which several possible workflows can be found in the literature (e.g. Santos et al., 2021; Jane et al., 2022; Carr et al., 2022) and simple tools exist or are in development. Flood inundation models can be run for various design cases of the joint probability isoline chart to develop flood inundation maps or hazard curves at various locations.

HL-2 - links inland hazards to coastal hazards using simple single parameter sampling, such as seasonality of hurricane intensity and river flow. For each JPM selected storm parameter set, a river flow is linked by random sampling of the seasonality joint probability to storm intensity. The resulting compound water level responses, once these inputs are passed to the flood inundation model, can then be integrated to produce a hazard curve. For HL-2 and HL-3, automation of linking the hazard analysis inputs would include converting wind and pressure model outputs from the JPM-type synthetic storm development as inputs into the coastal and/or inland flood inundation models. This data may also need to be converted into other input models, such as TC Rainfall models, scripts to link seasonality of parameters and randomly sample from that correlation. This often involves conversion between file types, interpolation between different model grids, and temporal frequency of data for large spatial areas with high temporal resolution.

HL-3 - has the most complex links, linking the inland drivers (e.g., TC rainfall) to the coastal drivers (e.g., storm surge) by driving each model using the same synthetic storm (and its parameters) of known probability. HL-3 can be expanded to include other drivers (e.g., groundwater) if they can be linked to the synthetic storm parameters or applied as model realizations. As with HL-2, automation of linking the hazard analysis inputs would include converting wind and pressure model outputs from the JPM-type synthetic storm development.

Synthetic storm selection can be improved using statistical methods and AI/ML surrogate modeling, such as Bayesian methods, to better represent the range of compound hazards of interests for a specific application. As in HL-2, for HL-3, the flood inundation model compound water level responses, or the augmented AI/ML responses built from the FI models, can then be integrated to produce a hazard curve. Outputs of FI models may require conversion to scripts supporting low-fidelity GPM and meta-gaussian copulas, as well as integration of the results into hazard curves. Hazard curves can be used for design, or in development of inundation maps.

B. TESTBED MODEL PERFORMANCE EVALUATION MATRIX

Modeling compound flooding at large coastal scales is an open problem. However, the research area is rapidly advancing with new models and methods being regularly published. Developing a TxCFF would require a long-term commitment of funds to a consistent project development team that collaborates with agency-sponsored modeling projects to ensure their work can be integrated into the framework.

The TxCFF should provide flood inundation modeling validation against historical data for Texas storms from NOAA, USACE, USGS, NDBC, TWDB, and other data sources. Model performance should be evaluated through quantitative validation metrics, which could include Root Mean Square Error, Pearson's Correlation Coefficient, Mean Absolute Error, and Refined Correlation Coefficient. Inter-model comparisons should also be made to assess accuracy and computational efficiency. Systematic performance studies and computing requirements for various models should be made and reported on for decision-making purposes on which models to use as part of the TxCFF.

Flood hazard analysis uncertainty uses many of the same datasets for validation and assessment of bias and uncertainty. Confidence limits are often based on the assumption of a normal distribution with the number of standard deviations used to assign the limits. For statistical approaches, such as the bivariate copula, correlations are sometimes characterized by a p-value, though this is controversial since it represents the likelihood of the null hypothesis. Different types of correlation coefficients-Pearson's correlation coefficient r, and Spearman's rank correlation coefficient ρ and Kendall's τ represent linear relationships or ranked relationships, respectively. Various fitting measures for probability distributions and copula are available to characterize the certainty of those fits. The model performance and evaluation metrics for flood hazard analysis depend on the specific approach and tools used (e.g., hydrological models, hydraulic models, or machine learning-based models). The matrix below in Table 3-3 lists key important model output parameters, what their performance is assessed against, and metrics that can be used to assess the model's skill and performance. However, the detailed information on each type of component flood inundation models (e.g., hydrologic, hydraulic, storm surge) is listed in the Supporting Material 3-11. Other performance considerations should be on the amount of time and data required to fully set up a model, the computational demands of executing the model to include any parallel computing scaling efficiencies.

Table 3-11. Model skill and performance evaluation matrix

Model/Analysis	Key Model Outputs for Performance	Validation Data	Metrics
		Flood Analysis	
Atmospheric Wind and Pressure Model (i.e. Planetary boundary layer model)	Time series of surface winds velocities and atmospheric pressure	Historic storm event gauge measurements	Average absolute and relative uncertainty, non-exceedance confidence levels based on unbiased uncertainty
Hydrodynamic Model	Peak still water level, Peak storm surge, time series water levels and depth averaged velocities	Historic storm event water level and current gauge measurements and high-water marks	Average absolute and relative uncertainty, non-exceedance confidence levels based on unbiased uncertainty
Combined Wind and Pressure Driven Hydrodynamic Model	Absolute and relative uncertainty of atmospheric and hydrodynamic models	Historic storm event collocated gauge measurements	Aggregated error statistics for absolute and relative uncertainty
Wave Model	Hmo = significant wave height, peak period, mean period, and direction	Buoy recorded wave heights	Absolute and relative uncertainty, non-exceedance confidence levels based on unbiased uncertainty
TC Rainfall Model	Event total precipitation; frequency analysis	Precipitation observations (e.g. Stage IV); Existing precipitation frequency analyses (e.g. Atlas 14)	Mean absolute error, average absolute uncertainty
Hydrologic (Rainfall Runoff) and Hydraulic (River System) Models	Flow and stage hydrograph peak magnitude, time of arrival and duration	Historic storm event flow and/or water level gauges	$\overline{R^2}$ = coefficient of determination; RMS = root mean square error; mean absolute error, average absolute or relative uncertainty
		Hazard Analysis	
Gaussian Process Metamodel (GPM)	Water level	High fidelity hydrodynamic water levels	$\overline{cc}$ = correlation coefficient; $\overline{R^2}$; $\sqrt{\overline{se}}$ = square root of the squared error (where bar indicates averaged over all storms)
Compound Multi-level GPM (HL-3 and 4)	Water level; peak flow	High fidelity hydrodynamic and flow water level, peak inflow from hydrologic model	$\overline{cc}$, $\overline{R^2}$, $\sqrt{\overline{se}}$
Parameter Independence (HL-0)	Paired event data		Correlation coefficients: Pearson's r, and Spearman's rank correlation coefficient ρ and Kendall's τ
Peaks-Over Threshold Extreme Value Analysis (HL-2)	Water level quantiles	Water level quantiles for different distribution thresholds	WMSE = weighted mean square error; mean excess
Distribution Fits (non-extreme events; HL-2)	Distribution parameters	Water level observations, number of distribution parameters	Aikake Information Criteria (AIC), log-likelihood of the model, Cramer-von-mises distance.
Copula Fitting (HL-2)	Copula type and parameters		AIC, alpha (Pearson's correlation coefficient converted from Kendall's τ

C. CRITERIA AND RECOMMENDATIONS FOR TESTBED SELECTION

Steps toward this prioritization include:

- select initial sites based on stakeholder engagement, available resources, storm and flooding scale, data availability, dominant flood hazards (coastal and inland), and geographic characteristics
- consider a diverse range of regions that include single or multiple watersheds with at least one substantial river system connected to the coast (e.g., may or may not have records of historical data useful for statistical and model calibration/validation purposes; are urban or rural; may contain coastal bays and barrier islands to provide additional complexity and variety; may contain multiple watersheds that converge into other watersheds and coastal area; are important for economic purposes such as shipping, fisheries, and tourism; have been historically understudied due to compound flooding)
- ensure a balanced mix of hazard types, while allowing flexibility to apply and compare different compound hazard analyses and flood inundation models

Seven regions are considered priority locations for building TxCFF capabilities. See Figures 3-9 through 3-15 for more details on each location:

1. **Houston/Galveston Region** - TIFF recommends prioritizing this region in the deployment of the TxCFF because it includes several different types of inlet flows into an irregularly shaped bay with complex hydrodynamics, supports a large population with community involvement, has a long history of hurricane impacts, and also has one of the longest tidal gages in the country.
2. **Freeport Region** - TIFF recommends prioritizing this region in the deployment of the TxCFF because the Brazos River empties directly to the Gulf, so it experiences a different kind of compound inundation than the other regions considered. Drainage areas upstream are largely industrial with little infiltration and irregular flood control measures.
3. **Rio Grande/Laguna Madre** - TIFF recommends prioritizing this region in the deployment of the TxCFF because it is a long shoreline bay with several tributaries as well as a large river outlet. The contributing rivers are heavily regulated and international agreements and impacts could be a controlling factor in considering coastal storm risk management. This region is also an excellent example of a data and model-poor watershed of international importance.
4. **Beaumont/Port Arthur Region**
5. **Corpus Christi Region**
6. **Matagorda Bay Region**
7. **Brownsville/South Padre Island Region**

(Justification on these selections is provided in Figures 3-9 through 3-15 and Supporting Material 3-10.)

These testbeds will expand the geographical and ecological diversity of compound coastal flood modeling studies in Texas. Each region presents unique challenges, from industrial infrastructure and environmental conservation to cross-border considerations and riverine-coastal flood interactions. These areas have distinct characteristics and vulnerabilities, thus offering a comprehensive range of conditions for testing and improving compound flood models and assessing flood hazards. By incorporating both natural and anthropogenic factors (such as urbanization, riverine systems, and coastal features) these testbeds will provide a robust foundation for evaluating and mitigating flood hazards across the Texas coast. Note that these descriptions do not include details such as existing measurements, gages, dominant processes or existing models, but instead focus on the region, its hydro-climatic and coastal characteristics, as well as environmental and economic needs and drivers.

RECOMMENDATIONS FOR CONCEPTUAL MODEL-COUPLING WORKFLOW(S) FOR ASSESSMENT OF COMPOUND FLOODING HAZARD IN COASTAL TEXAS

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

Ultimately, sixteen TIFF Recommendations resulted from the research and expertise associated with Component 3. See the TIFF Recommendations Section for summary handouts that can be used to seek further support for implementation.

Table 3-12. Component 3 objectives and associated recommendations.

TIFF Component Objective	Resulting Recommendation(s)
Establish an Integrated Flood Modeling TAT	Objective met by TIFF. No further recommendations.
Evaluate and provide feedback on initial inventory of existing and proposed meteorologic, hydrologic, hydraulic, estuarine and surge models by the Study Providers to support inland and coastal hazard identification	Objective met by TIFF. No further recommendations.
Perform a literature review to identify potential meteorological, hydrologic, hydraulic, and hydrodynamic models for evaluating and mitigating flood risk for Texas	C3.3A: Advance Hydraulic Modeling Simulations with HEC-RAS Distributed-Memory Parallelization C3.3B: Establish Guidelines for Nature-based Features to Reduce Flood Risk C3.3C: Develop Rapid Predictions of Flooding Hazards C3.3D: Develop Database of Flood Modeling Studies C3.3E: Enhance Wave Models and Data to Improve Accuracy in Populated Areas C3.3F: Automate Topography and Bathymetry Data Processing C3.3G: Evaluate the AORC C3.3H: Advance AI/ML Techniques for Flood Modeling C3.3I: Integrate Model Applications Currently Used for Urban Stormwater and Flood Hazard Hydrodynamics C3.3J: Quantify the Impacts of Erosion on Storm Surge C3.3K: Quantify Wind-driven Inland Flows to Enhance Flooding Models
Perform a literature review on probabilistic methods for flood hazard estimation	C3.4A: Advance the Use of the Joint Probability Method in Compound Hazard Assessment C3.4B: Develop a Tropical Cyclone Rainfall Generator C3.4C: Quantify Sensitivities of Existing Models C3.4D: Retrospective Modeling of Historic Landfalling Hurricanes
Develop recommendations for conceptual model-coupling workflow(s) for assessment of compound flooding hazard in the coastal Texas region	C3.5A: TxCFF Development

TIFF RECOMMENDATIONS, INTEGRATED FLOOD MODELING

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

The HEC-RAS model is widely used for flood hazard characterization in Texas coastal watersheds but faces computational limitations, especially in flat terrain where inter-basin flow transfers affect flood extent and depth. Current modeling requires breaking very large watersheds into smaller sections, creating edge-matching issues and making real-time flood response impractical.

TIFF recommends a distributed-memory parallelization approach to enable HEC-RAS to run across multiple nodes in a High-Performance Computing (HPC) environment, significantly reducing simulation times from days to minutes. Faster computations will improve flood planning, emergency response, and the ability to incorporate high-resolution (1m) Texas LiDAR data for more accurate topographic representation in the model.

Enhancing HEC-RAS with HPC capabilities would also support integration with coastal surge models, improving compound flood hazard assessments critical for the Texas coast, enabling more efficient and accurate result comparisons across modeling scales and platforms for performance benchmarking.

Key actions when implementing this recommendation include:

- Analyze and identify performance bottlenecks in the 2D HEC-RAS computational engine source code
- Develop and validate a small model domain test case for ongoing testing
- Implement MPI-based parallelization using a single program–multiple data approach
- Ensure physical structures remain local to individual subdomains during decomposition
- Map local arrays to global arrays and manage inter-CPU data communication
- Perform GUI integration and iterative testing for usability and functionality
- Verify code accuracy and scalability with increasing processor counts
- Provide guidance on optimal subdomain sizing for performance and load balancing
- Perform test-bed evaluations of the HEC-RAS parallelized code for evaluating its performance. This includes result comparisons across modeling scales and platforms for performance benchmarking.
- Generate summary tables comparing simulation cost, runtime, and result consistency

C3.3B: Develop guidelines for Nature-Based Features to reduce flood risk

Traditional benefit-cost analysis (BCA) focuses on economic metrics, making it less effective for evaluating nature-based solutions (NBS) that provide broader environmental and social benefits. As advancements continue, there is a need to refine BCA methodologies to better capture the full value of Natural and Nature-Based Features (NNBFs) within coastal infrastructure systems.

TIFF recommends that guidelines be developed for implementing NNBFs along the Texas coast and that their effectiveness in coastal flood risk reduction be assessed.

This approach will provide valuable insights into how NNBFs mitigate surge and dissipate waves, ensuring that site selection aligns with physical and local conditions while maximizing cost efficiency. Additionally, long-term monitoring systems should be implemented to quantify the lifespan and ongoing benefits of NNBFs. This will allow for data-driven assessments of their effectiveness in reducing coastal risk and evaluating cost feasibility over time. This fuller accounting of benefits can better support the adoption of NNBFs as viable, cost-effective flood mitigation strategies.

Keys actions when implementing this recommendation include:

- update benefit-cost analysis (BCA) methodologies to better account for the full range of NNBF benefits, including social and environmental factors
- establish criteria/metrics to assess NNBF efficiency in mitigating storm surge and wave energy, incorporating social, environment, and economic fact
- optimize site selection and feature sizing based on local coastal conditions
- identify and implement pilot projects to evaluate NNBF effectiveness under varying conditions
- establish a testbed to help determine the best locations, timing, and configurations for maximum flood risk reduction
- develop monitoring systems to track NNBF lifespan and performance over time
- use data-driven assessments to refine NNBF designs and improve cost efficiency
- collaborate with federal, state and other agencies, and universities to leverage on-going efforts and the lessons-learned of NNBF implementations

C3.3C: Develop rapid predictions of flooding hazards

Effective flood hazard prediction is crucial for ensuring public safety and optimizing emergency response during storm events along the Texas coast. Currently, rapid and accurate forecasting of storm surge and wave impacts is limited, making it challenging to issue timely warnings to at-risk communities. The ability to predict flooding hazards quickly enhances emergency response efforts by enabling authorities to issue evacuation orders, mobilize resources, and reduce casualties and property damage. Furthermore, these predictions aid in managing coastal flood protection systems, such as pumps, dams, and surge barriers, to protect vulnerable areas.

TIFF recommends the development of a robust, reliable, and accurate storm surge and coupled wave model for the Texas coast. This model should build on previous studies to provide enhanced predictions for total water levels and flood inundation. By incorporating large- and small-scale 3D processes, the model would improve the accuracy of simulations, ultimately supporting better decision-making in flood preparedness and response.

TIFF also recommends the evaluation of the suitability of existing web tools, such as the Interagency Flood Risk Management (InFRM) Flood Decision Support Toolbox (https://webapps.usgs.gov/infrm/fdst/) and the NWS National Water Prediction Service (https://www.weather.gov/ewx/NWPSInfo), for disseminating information to emergency managers and relevant statewide parties. The evaluation should aim to determine whether these platforms can effectively convey the complexities of coastal and compound flooding risks or if a separate platform is necessary for improved communication and visualization.

C3.3D: Develop database of flood modeling studies to enhance flood risk assessment and emergency response

The results from existing flood modeling studies could significantly enhance flood hazard analysis efforts across Texas. Many existing datasets are underutilized and could immediately benefit professionals in the field if organized in a new cyberinfrastructure.

TIFF recommends a comprehensive bibliography and database of numerical grids, computational setups for Texas wave/surge modeling, and data on storms causing coastal flooding, including storm characteristics, wave data, high-water marks, and available measurements. This database will create comprehensive coastal model metadata collections for facilitating model access and sharing among Texas stakeholders and support improved understanding of coastal flood hazard estimation through leveraging existing models and datasets. Standardized computational meshes and setups for wave and surge models should also be provided to facilitate use by researchers and practitioners.

An interactive website should be developed for easy information sharing with Texas stakeholders, and the database must be regularly updated to reflect new findings. Furthermore, the database should also include studies utilizing 3D or hybrid models, ensuring a broader representation, as current models predominantly focus on 2D approaches. This database will prevent duplication of model development efforts as huge amounts of flooding analysis are being or will be performed to support a wide range of flood resiliency projects.

Keys actions when implementing this recommendation include:

- use the TIFF Model Inventory (Supporting Material 3-14) as a test-case to compile a comprehensive bibliography and database of flood modeling studies
- share findings to support flood risk assessments, emergency planning, and coastal mitigation efforts
- develop a model management system for storing and sharing numerical grids, computational setups, and storm-related data (This system needs to be made available not only for sharing archived models, but also for the model developers to upload new models for wide dissemination.)
- provide clear guidance on how these datasets impact Texas residents and flood risk management
- include validated numerical grids and computational setups for Texas Wave/Surge Modeling
- develop standardized computational meshes to facilitate model reuse by researchers and practitioners
- build an online database for stakeholders to access and contribute data
- ensure regular updates to reflect new research and findings as more models become available
- incorporate studies using 3D or hybrid models to ensure a comprehensive approach beyond traditional 2D modeling
- investigate how the developed models – which vary in resolutions, accuracy, and other factors – can be leveraged and integrated for improved understanding of flood risk in coastal Texas

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

In Texas, wave prediction accuracy is lowest in the region containing the highest population and value –Normally Dry Land. This region is critical for flood planning and design. The challenges to accurate predictions are threefold:

1. Existing models were developed for conditions vastly different from those found over dry land, such as buildings, diverse vegetation, and rapid changes in land and structure properties.
2. Overland flooding with large waves is rare, resulting in limited datasets for model validation.
3. Significant changes in topography, vegetation, and structures during storms can lead to conditions that differ from pre-storm assumptions, affecting wave and surge properties and reducing model accuracy. This is especially problematic for dune erosion, as protective dunes often vanish during severe storms, exposing developed regions to increased flooding risk.

TIFF recommends enhancing model accuracy and reliability for overland wave prediction in Texas. Key actions include extensive data collection for model parameterization, calibration, and validation; detailed mapping of coastal areas with a focus on buildings and vegetation; detailed inventories of coastal buildings and large vegetation that are likely to withstand flooding; and high-resolution flow modeling over dry land using spectral models like SWAN or WaveWatch III. Developing a dedicated overland wave model could establish a new standard for wave predictions, ensuring more reliable forecasts and improved protection for vulnerable areas.

Partners like USACE and academic institutions could execute this initiative over 3–5 years, with an estimated annual budget of $200,000.

Keys actions when implementing this recommendation include:

- conduct extensive data collection to improve wave model parameterization, calibration, and validation
- develop detailed inventories of coastal structures and vegetation likely to withstand flooding
- use high-resolution mapping of Texas coastal areas, focusing on buildings, vegetation, and land characteristics
- incorporate dynamic changes in topography, vegetation, and structures before, during, and after storms
- implement high-resolution wave modeling over dry land using spectral models like SWAN or WaveWatchIII
- establish a dedicated overland wave model to enhance predictive capabilities

C3.3F: Automate topography and bathymetry data processing

TIFF recommends the development of automated methods to improve and standardize the representation of topo-bathymetric datasets, including engineering features like levees, in flood hazard models. This should include the creation of a standard vector representation for features such as levees, where polylines with varying widths and elevations along the line can be used for topographic processing.

Additionally, automated topographic processing methods should be developed to extract engineering features (e.g., levee, ship channel, bridge) from high-resolution LiDAR data without requiring human intervention except performing quality assurance and quality control of the final topographic products. To further enhance the process, model grid generation programs that can effectively incorporate vector polylines into model topography should be developed. A comprehensive standard database for accessing data on such features throughout Texas is also crucial for consistency and ease of use.

This initiative should leverage NOAA's Continuous Updated Digital Elevation Model (though it is limited in representing engineering structures like levees). The resulting tool should ensure that its derived products are easily usable across a range of flood hazard models, providing a more efficient and consistent means of incorporating engineering features into flood hazard assessments.

Keys actions when implementing this recommendation include:

- establish a vector-based representation for levees and similar features, using polylines with varying widths and elevations
- develop automated processing methods to extract engineering features from high-resolution LiDAR without human intervention
- create grid generation programs capable of incorporating vector polylines into model topography
- establish a standardized database for consistent access to topo-bathymetric data across Texas
- prioritize bathymetric data improvements in small channels to refine flood models

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

TIFF recommends evaluating Texas AORC data from 1979 to the near present to provide a comprehensive assessment of the data's accuracy and potential for improving flood hazard analysis and hydrologic modeling in Texas.

The evaluation would compare AORC's accuracy against rain gages and benchmark its performance against other hourly rainfall products. Additionally, rainfall events would be categorized by their association with tropical cyclones and by time of year.

The AORC is a high-resolution gridded dataset providing near-surface weather conditions across the United States. With a spatial resolution of approximately 800 meters and a temporal resolution of one hour, it includes data on precipitation, temperature, humidity, pressure, radiation, and wind components. AORC's long history (over 40 years) and fine resolution make it valuable for applications like rainfall frequency analysis and hydrologic modeling. It is particularly useful for areas such as the Rio Grande Valley, where daily rainfall measurements are often too coarse to capture localized storms, and for regions impacted by tropical cyclones, as seen during Hurricane Harvey in 2017.

TIFF recommends partnerships with the Office of the State Climatologist (TAMU) and academic institutions. The project is expected to take 6–12 months, with an estimated budget of $70,000–$100,000.

Keys actions when implementing this recommendation include:

- analyze AORC data from 1979 to the present (as available) across Texas
- compare AORC precipitation data against rain gages
- assess AORC's performance relative to other hourly rainfall products
- categorize events by association with tropical cyclones and by time of year

C3.3H: Advance Artificial Intelligence/Machine Learning techniques for flood modeling

Traditional process-based models for assessing the effects of compound flooding, while accurate, are often time-consuming and resource-intensive, making them less practical for rapid decision-making during emergency events. Coastal infrastructure operations, in particular, require fast evaluations to guide decision-making during floods, which typically necessitate "what-if" scenarios to explore various interventions and outcomes.

TIFF recommends advancing AI/ML techniques for compound flood modeling. By automating and accelerating the modeling process, these models can streamline decision-making, making it possible to respond to flood events more effectively.

Key actions include developing guidelines to enhance the interpretability of AI/ML models (e.g., moving beyond black-box approaches) to better support decision-making, conducting ongoing research into AI/ML surrogate models for more efficient simulation of compound flooding compared to traditional methods, and creating "what-if" scenario tools that enable engineers and policymakers to rapidly evaluate options for maintaining coastal infrastructure during emergencies.

Keys actions when implementing this recommendation include:

- research and develop AI/ML-based surrogate models for faster, more efficient compound flood simulations
- improve AI/ML approaches to ensure transparency and reliability in decision-making
- develop tools that allow engineers and policymakers to quickly assess intervention strategies during flood events (i.e. "what-if" scenario modeling)

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

Effective modeling should account for both catastrophic hurricanes and more frequent moderate storms, enabling communities to evaluate how engineered infrastructure, such as deep tunnels, can mitigate flooding. While urban stormwater modeling has a long history, it has not been integrated into compound flooding models that consider both coastal and urban flooding.

TIFF recommends the development of an integrated urban stormwater and flood hazard model for Texas' urbanized coastal watersheds. The effort includes evaluating ongoing efforts to model urban flooding, creating multi-scale storm models that simulate both catastrophic and moderate storms, and incorporating 2D flood modeling (e.g., HEC-RAS, Delft-3D, TRITON) into Storm Water Management Model (e.g. EPA's SWMM). Coupling the SWMM with other open source/freeware flood models will facilitate greater adaptation by diverse stakeholders.

A testbed evaluation of the integrated model and exploring alternative approaches, such as sub-grid-based models, should be performed to enhance its accuracy and application. This integrated system will help assess how urban infrastructure can improve resilience to flooding.

TIFF recommends partnerships with flood control districts and cities working on addressing challenges related to urban flooding.

Keys actions when implementing this recommendation include:

- simulate both tropical and non-tropical storms to assess how urban stormwater systems, such as deep tunnels, enhance flood resilience
- integrate a two-dimensional (2D) flood modeling component into the SWMM
- couple the SWMM with open-source/freeware flood models like HEC-RAS 2D, TRITON, or Delft3D-FM to facilitate greater adaptation by diverse stakeholders
- conduct testbed studies in Texas urbanized coastal watersheds to validate model performance
- explore alternative modeling approaches to improve accuracy and application

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

Texas bay and estuarine systems connect to the Gulf through narrow inlets that cut across barrier islands and peninsulas. These landforms act as natural buffers, protecting interior waterways from wave action and storm surge. However, their low-lying nature makes them vulnerable to overtopping and erosion during major storms, rapidly altering coastal topography.

Capturing storm-induced erosion in numerical models remains a challenge. During Hurricane Harvey, significant beach erosion near Aransas Bay (Goff et al., 2019) may have allowed additional surge to reach inland areas, leading to potential under-predictions in models like ADCIRC. These models struggle to represent rapid erosion dynamics, as they operate on coarse spatial resolutions (30–40 meters) and lack sediment transport capabilities.

TIFF recommends the enhancement of storm surge models by integrating barrier island and dune erosion processes. A more dynamic approach to modeling erosion would improve flood forecasting and post-storm reconstructions, leading to better risk assessments and coastal resilience planning. By incorporating real-time topographic changes, researchers can more accurately predict storm surge impacts and better protect vulnerable coastal communities in Texas.

Supporting research on erosion and its impact on storm surge can be deployed in project phases (if necessary):

Site-Specific Morphological Modeling

- identify high-priority sites prone to erosion (e.g., areas impacted by Hurricane Harvey, key dune-protected regions)

- use nearshore morphology models to simulate dune erosion and establish relationships between erosion and wave/surge conditions

Develop Parameterized Erosion Updates

- conduct multiple simulations to generate datasets linking erosion to storm conditions
- utilize regression models, lookup tables, machine learning, or AI to create parameterized updates for bathymetry and topography
- implement a dynamic system to update dune elevations and erosional areas every 10 minutes based on surge, wave, and current data

Integration with Surge Models

- incorporate erosion-informed updates into large-scale surge models
- test the feasibility of using a subgrid-type surge model to represent small-scale coastal features more effectively

Expansion

- apply the developed framework to additional Texas shorelines, accounting for regional variations in sediment characteristics, hard structures (e.g., seawalls), and erosion-resistant layers
- develop a methodology for predicting potential barrier island breaches in advance

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

When large areas are flooded (e.g., Hurricane Harvey), strong winds have the ability to provide an additional forcing to tilt the water surface (i.e., pushing water upwind). When the wind stops or changes direction, the water pushed upwind will be redistributed and can cause further flooding.

The problems associated with wind-forcing over shallow water were discussed by Li & Hodges (2019), who implemented an ad hoc increase in drag for shallow marshes to prevent unrealistic acceleration by wind. The underlying problem is that wind-drag models are derived from studies of deep water where only a wind boundary layer exists near the surface. In shallow waters, the wind boundary layer overlaps with the bottom boundary layer, leading to nonlinear turbulent interactions that have not been studied. Although there is perhaps more theory available for waves propagation over shallows, the evolution of waves in shallow waters under short fetches is not well studied. There do not appear to be any models that presently can be applied to represent the development of wind-waves in shallow flooded areas.

TIFF recommends the following investments to address this knowledge gap:

- establish theoretical frameworks for the coupled wind/wave/bottom boundary layer interactions in shallow water environments
- use laboratory experiments and high-resolution Computational Fluid Dynamics (CFD) models to validate the theory and gain insights into wind, wave, and bottom boundary layer interactions
- perform field experiments to examine how theoretical and laboratory results translate to full-scale conditions
- use theory, laboratory data, CFD results, and field data to create a model equation that links wind speed to effective wind stress, considering water depth, velocity, and bottom roughness
- integrate both large- and small-scale processes into the model to enhance its accuracy

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

Current coastal flood hazard assessments often underestimate water levels by neglecting the compound effects of storm surge and precipitation-driven flooding. This is particularly critical in Texas coastal watersheds, where hurricane storm surge and hurricane-induced rainfall riverine flooding interact in complex ways. Traditional statistical methods, such as bivariate copulas, are limited by data constraints and basin variability, making them insufficient for capturing the full range of flood hazards.

TIFF recommends expanding the USACE PCHA model agnostic framework to improve compound flood hazard characterization. This enhancement would integrate high-resolution numerical modeling, machine learning, and stochastic uncertainty (e.g., antecedent conditions like soil saturation, which vary based on local geography). Leveraging synthetic storm results from prior regional studies would also support a framework that can be consistently applied across Texas coastal basins.

Key actions when implementing this recommendation include:

- Improve the USACE's PCHA framework by integrating additional probability methods beyond observation-based approaches, such as the use of Hurricane Rainfall Models and the use of seasonal correlation between flow and intensity applied in the JPM framework
- Develop a flexible, model-agnostic framework that can be applied consistently across Texas coastal basins
- Incorporate variability in antecedent conditions (e.g., soil saturation) to refine flood risk estimates based on local geography
- Utilize synthetic storm results from prior studies, such as the Coastal Texas Study, to reduce computational cost and apply widely-accepted regional storm surge information and statistics; explicitly represent interactions between tropical cyclone storm surge and rainfall-induced water levels to capture compound flood hazards.
- Apply the improved JPM framework in select Texas coastal watersheds to assess accuracy and reliability
- Conduct validation studies with historical and synthetic storm events to refine methodology

C3.4B: Develop a Tropical Cyclone Rainfall Generator

TIFF recommends the development of a high-resolution (hourly, 0.05-degree) rainfall generator for statewide application in Texas to generate rainfall fields for all synthetic TCs used in compound flood hazard assessments for the coastal Texas region. Building on USACE's 2020 study which established a set of 660 synthetic TCs for evaluating flood risks, the effort involves quantifying uncertainty and bias in tropical rainfall models by leveraging historical rainfall datasets. This high-resolution rainfall generator will support improved flood hazard assessments.

TIFF recommends partnerships with the Office of the State Climatologist (TAMU) and academic institutions.

The project timeline is expected to range from 6 months to 3 years, depending on the required level of detail and prior experience with similar developments. The estimated total cost is between $100,000 and $200,000.

Keys actions when implementing this recommendation include:

- use historical rainfall data to assess and correct biases in existing TC rainfall models
- create an hourly (0.05-degree) TC rainfall generator tailored for Texas
- produce bias-corrected and probabilistic rainfall datasets for all 660 synthetic TCs in the

USACE Coastal Texas Study (2020)

- utilize AI/ML to analyze rainfall distribution relative to storm tracks and generate realistic rainfall patterns within hurricane rain bands

C3.4C: Quantify sensitivities of existing models to wind forcing, bathymetry, bottom friction, and turbulence, with an initial emphasis on bathymetry

TIFF recommends the improvement of bathymetric data (particularly for small-scale features like channels and barrier islands) to resolve the associated computational challenges in flood hazard models. Errors in bathymetry and topography also contribute to significant inaccuracies inland hydraulics, coastal hydrodynamic and storm surge models. While higher-resolution data like LiDAR and satellite imagery enhance accuracy, they provide only a snapshot in time, leading to potential errors in areas undergoing frequent changes, especially in urban regions. Computational challenges arise in resolving small-scale features, such as channels and barrier islands, impacting model performance.

Additionally, TIFF recommends research to improve regional models like WRF for operational forecasting to enhance wind predictions in storm surge models. The primary source of uncertainty in storm surge simulations is attributed to wind forcing, which is a major driver for both surge and waves. Accurate wind predictions are crucial for reliable surge forecasts, especially when hurricane track and intensity are uncertain. Operational meteorologic models, despite improvements in numerical precision and higher resolution, do not guarantee error-free results. For instance, Hurricane Ian (2022) deviated from its predicted landfall location, showcasing the challenge in forecast accuracy. Regional models like WRF, tested at 1-5 km resolution in the Gulf, reveal fine-scale features but are not yet operational for forecasts.

TIFF also recommends the development of a framework for quantifying uncertainty in bottom friction, using measured data, to improve flood hazard model predictions. Bottom friction, determined by formulations like Manning's n, introduces another source of error in storm surge predictions. The Manning's n formula, dependent on sea-surface bottom characteristics, becomes more pronounced in shallow waters, influencing flooding severity over inundated land. Despite recent efforts to estimate bottom friction from measured data, this research is in its early stages and lacks a comprehensive framework for uncertainty quantification and parameter estimation.

C3.4D: Conduct retrospective modeling of historic landfalling hurricanes using High-Resolution weather or coupled models

Understanding historical storm impacts is crucial for improving predictive models and better protecting lives and infrastructure. However, hurricane modeling is limited by the lack of high-resolution observational data before the 2000s, reducing the accuracy of flood and wind hazard assessments, particularly in data-scarce regions. While many flood models rely on modern datasets, validating them against past events enhances their reliability.

TIFF recommends a retrospective analysis of major landfalling hurricanes from the early 1960s to the 1990s using high-resolution modeling techniques. This analysis will provide data to calibrate and validate flood models while also supporting wind hazard assessments for periods before the availability of High-Resolution Rapid Refresh weather forecasting models.

Simulating past hurricanes will offer insights into their potential impact on today's coastal infrastructure, aiding in the refinement of evacuation plans, resilience strategies, and building codes. Additionally, understanding historical hurricane behavior will contribute to long-term assessments of storm intensity and frequency, informing climate adaptation efforts.

TIFF recommends a partnership with the Office of the State Climatologist at TAMU, federal agencies (e.g., NOAA, USACE), industries, and consulting firms such as Oceanweather Inc. (https://www.oceanweather.com/) for the implementation of this effort.

The effort is expected to take 1 to 3 years, depending on the historical scope. The estimated cost ranges from $100,000 to $350,000, with the higher end supporting simulations of additional storms, such as Hurricanes Carla (1961) and Beulah (1967), and alternative storm path scenarios. (Hurricane Carla is particularly important for wind analysis, while Hurricane Beulah is significant for rainfall impacts.)

TIFF recommends prioritizing these hurricanes for analysis and incorporating perturbed simulations to assess potential storm impacts under alternative tracks. Deliverables should include high-resolution wind and rainfall data, validated against historical observations, to improve understanding of past hurricane impacts and enhance future modeling efforts.

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

Texas has the opportunity to set a national standard for compound flood modeling. As the largest economy among hurricane-prone states, and second only to Florida in population at risk, Texas faces urgent challenges from hurricane and tropical storm flooding. To address these challenges, TIFF recommends establishing the TxCFF: a sustainable, updateable, and state-of-the-art system for compound flood assessment. TxCFF will integrate models, analysis tools, and workflows to support planning, development, recovery, and emergency response along the Texas coast. This framework will provide linkages to existing databases, seamless data transfer between models, a user interface for setting up and executing coupled models, plug-and-play APIs, and integrated output datasets from component models into coherent datasets for analysis and visualization. Over time, it will evolve into a robust platform for evaluating and managing compound flooding across multiple projects.

The TxCFF would consist of:

- wind and pressure model
- ocean circulation model
- wind/wave model (far field and near field)
- flood inundation (hydraulics) model for river flow and landscape flooding
- upland runoff model (hydrology)
- stormwater drainage model
- groundwater model
- flood hazard analysis tools
- code for coupling the various flood inundation component model
- coupling to external meteorological (storm) models/data sets for historic and synthetic storms
- code for calibration, validation, and testing of inundation models
- code for ingesting flood inundation model results into flood hazard analysis
- code for visualizing inundation and hazard analysis results
- code for input/output
- code for user customization

Initially, TxCFF could start as documented workflows for coupling models and data, supported by pre- and post-processing tools. These workflows can then be codified into a software framework emphasizing reusability, accessibility, scalability, training, and uncertainty management. Development will require long-term funding, a consistent project team, and collaboration with agency-sponsored modeling projects. By building on vetted workflows and testbeds, TxCFF can grow incrementally into a central resource for scalable and integrated flood modeling across Texas with an active user community supported with training resources.

1. **Identify and Prioritize Testbed Locations**: Making the final decision on the sites to be implemented and order of implementation should carefully consider the level of stakeholder engagement and resources that can be allocated, the scale of the storms and adjacent flooding area that require modeling, data availability,, the dominate flood hazards to ensure a balanced mix between the different drivers, e.g. coastal and inland, the geographic characteristics, both land and water, of the area, and the overall resources available to the project. Flexibility to employ and compare different compound hazard analyses levels and flood inundation models would be an added benefit. The details of the identified test-bed location for TXCFF implementation was discussed in section C.

2. **Test Candidate Models for a TxCFF**:
   - select relevant models based on the findings of the TIFF literature review and input from scientists/engineers familiar with the testbed site (This selection should take into consideration the existing models and hazard analyses in the testbed study region for leveraging resources.)
   - develop and apply testing strategies to evaluate each discipline model with respect to:
     - how the model algorithm influences the practical coupling algorithms
     - whether implementation is through source code changes or in/out data stream
     - stability and convergence conditions for coupling
     - whether an interface region is needed between models
     - identifying model boundaries and handling boundary movement
     - handling disparities in model time steps and grid size
     - effectiveness of parallelization of the model; test cases for proving coupling viability
     - availability of graphical users interfaces
     - user guides, documentation, and training material.

   (This action should connect discipline scientists/engineers with framework software engineers to ensure analyses consider both model-specific and framework-level impacts.)

3. **Evaluate Software Framework Fundamentals**: identify the critical methods for model integration and data exchange (i.e., selection of coding language for the framework) considering:
   - the utility of existing frameworks like the Earth System Modeling Framework
   - needs for coupling data communication
   - standard data libraries and metadata standards to be included
   - approach used for parallelization across different models to ensure efficient computing; definition of "best practices" to be used in writing framework code
   - systematic approaches and supporting data for testing and code validation

   (This work should proceed in parallel with candidate model testing to ensure framework and coupling decisions are aligned. The deliverables will be an alpha version of the TxCFF and guidelines on coding conventions, libraries, and inter-team communication to ensure project compatibility.)

4. **Develop TxCFF Best Practices** - Develop best practices and training materials to broaden adoption of the TxCFF. These should emphasize basin- or location-agnostic approaches by

using probabilistic methods for inputs and boundary conditions, consistently sampled from fitted distributions. For example, engineers might suggest a certain infiltration sub-model, but the input parameters could be selected by sampling distributions fit to historical records.

5. **Evaluate Coupling Methods for Candidate Models**:
   - select and test candidate models
   - investigate coupling interfaces across:
     - ocean and flood inundation
     - upland runoff and flood inundation
     - stormwater system and flood inundation
     - stormwater system and upland runoff
     - groundwater with flood inundation, stormwater system, and upland runoff
     - wind/wave with flood inundation
     - meteorological forcing with all models

   (Coupling must be developed and coded by multidisciplinary teams, working collaboratively and transparently to ensure consistency across interfaces. Each project team should coordinate directly with the compound flooding framework team to define input/output data, manage spatial and temporal interpolation, and guide development.)

6. **Develop and Evaluate Boundary Placement Among Models**: Develop a methodology and code to automatically set and adjust coupling boundaries as needed. This requires analyzing diverse testbeds under different modeling scenarios and establishing guidance on which model outputs to use in overlapping regions. From a compound hazard perspective, boundaries should be positioned within a single model wherever possible, ensuring that boundary conditions represent only one driver at a time.

7. **Grid Generation for Coupled Model System**: Develop a consistent, automated methodology for creating and testing coupled model grids to support multiple testbed sites along the Texas coast. This approach should leverage existing initiatives and focus on efficiency, reliability, and standardized practices. Key tasks include automating extraction of ground elevation data (e.g., TxGIO LiDAR) into grid meshing systems; updating grids routinely to reflect geomorphic changes and urban growth; and providing guidance on discretization resolutions and standardized parameters (e.g., Manning's n). These measures will streamline model development, maintain up-to-date domains, and ensure consistency in model configuration and application, supporting faster innovation and more reliable outputs for coastal resilience planning.

8. **Heuristics for the Use of Simplified Models**: Develop heuristic algorithms to guide users on the relative importance of different compound flooding components under specific conditions. For example, if upland rainfall is low and soils are unsaturated, a heuristic might recommend disabling hydrological modeling. These heuristics can rely on general knowledge of forcing scales and landscape characteristics and may suggest pre-defined workflows for users. Heuristics may need to be customizable for specific locations, with different parameters for areas such as Houston-Galveston Bay versus Brownsville. Screening hazard tools (e.g., HL-0, HL-1) can help identify major drivers, and bivariate copulas can be extended to trivariate analyses to assess additional factors, such as groundwater, in compound flooding.

9. **Develop Coupled Model Inputs/Outputs**: Models within the framework will have varying input and output formats that must be standardized by the framework. This action involves collaborating with hazard analysts, discipline engineers/scientists, and potential users to define flexible, practical data methods. Wherever possible, standard libraries and file formats (e.g., netCDF, HDF5, JSON) should be used. Metadata should follow community standards, such as the Climate Forecast Metadata conventions. Data cataloging and curation practices should ensure proper access and retrieval. Tools for community-based visualization and analysis should also be developed.

10. **Automate Calibration, Validation, and Comparison with Observations**: Traditionally, calibration, validation, and comparison with observations have relied on user expertise. For TxCFF testbed sites, automated approaches should be developed to standardize these tasks, preventing model adjustments outside their intended scope. This system will increase confidence in model outputs, especially for users lacking expertise in specific compound flood disciplines.

11. **Develop Targeted Training Courses for TxCFF User Groups**: Include an introduction to compound hazard analysis, covering probabilistic inputs, synthetic storms, and integration of model outputs to generate hazard curves and flood maps.
    - **For Modelers**: Focus on using testbed models to create, run, and analyze compound flooding cases, including making "what-if" changes to assess storm scenarios, land development, and other impacts.
    - **For Testbed Model Developers**: Expand expertise to extend testbed models and hazard analyses to other regions and more complex scenarios, supporting the broad adoption of TxCFF across the Texas Coastal Plain.
    - **For Managers (academia, industry, government)**: Provide guidance on the capabilities and limitations of TxCFF, interpreting model outputs, and formulating relevant "what-if" questions for planning and decision-making.

12. **Integrate Numerical Flood Modeling with Flood Hazard Analysis**: Evaluate compound flood hazards at different hazard levels using the testbed and/or its sub-basins. Analyses can leverage existing models, new TxCFF models, or published compound hazard studies. These results can be compared with individual hazard models such as CHS for storm surge/waves or inland flood frequency analyses. Integrated model outputs can be used to generate hazard curves and flood inundation maps. Additionally, multi-level meta-model approaches tested in pilot studies can be applied to characterize basin-specific impacts on event probabilities (e.g., HL-3 Extended JPM). Uncertainty in inputs, model outputs, and hazard estimates can be incorporated to improve overall hazard assessment.

13. **Address Nonstationarity and Future Planning**: To account for natural and anthropogenic factors, the framework should include inland and coastal impacts that can exacerbate flood risk (i.e., sea-level rise, higher storm surge risks, and shifting rainfall patterns, as well as land-use changes from population growth and urbanization). Incorporating these projections ensures resilience in infrastructure development and flood mitigation planning. Several methods exist to characterize future conditions. Numerical physical models currently incorporate sea-level rise for JPM-based models (Nadal-Caraballo et al., 2020). Statistical approaches, such as Bayesian networks, surrogate modeling, and Bayesian updating, can quantify changes in tropical cyclone frequency, rainfall patterns, and land-use impacts, providing insights into evolving risks. These methods help stakeholders prioritize interventions and adapt flood protection strategies over time (Liu et al., 2025 [unpublished manuscript]).

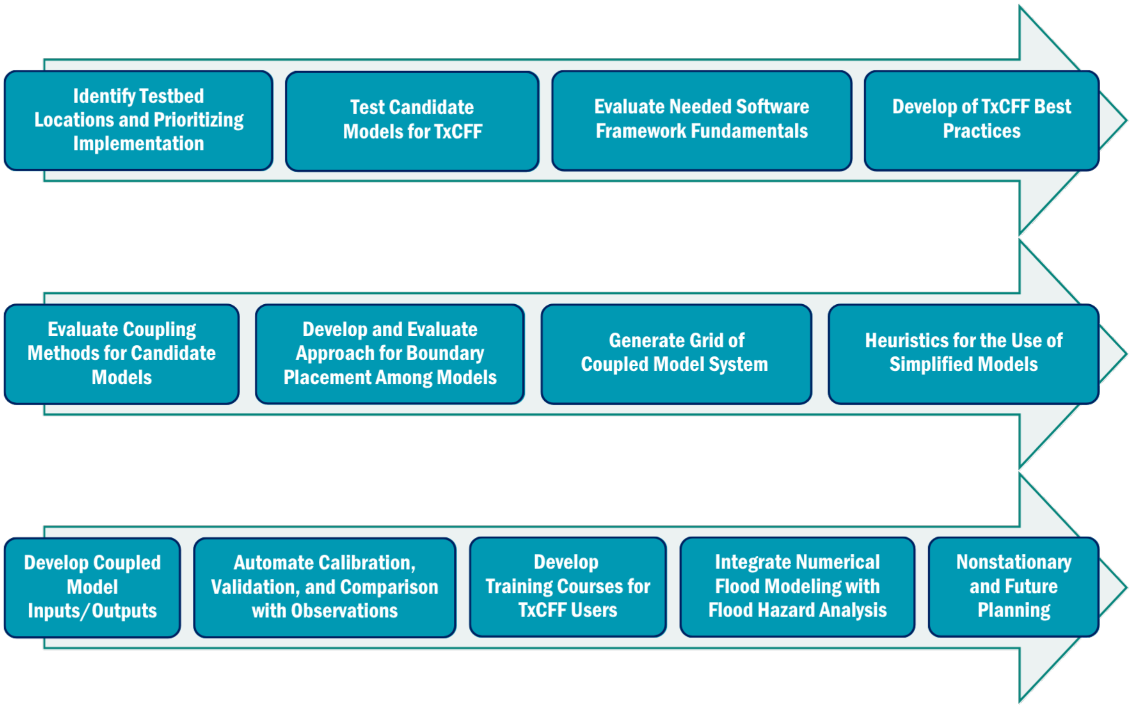


Figure 3-8. Tasks/steps to build the TxCFF.

Storm surge from Hurricane Ike ©Scott Pena, Flickr

Priority Testbed Locations for Building TxCFF Capabilities

Figure 3-9. Houston/Galveston priority testbed region.

HOUSTON/GALVESTON REGION TESTBED CHARACTERISTICS

This complex system of bays and backwater estuaries is protected by barrier islands is fed by multiple large and smaller rivers, including the San Jacinto and Trinity Rivers. The coastal area features a gently sloping shoreline connected to a large continental shelf, which has important implications for coastal flooding. The region is well-documented with extensive data available for model validation, including storm surge and fluvial flooding events. Vegetation in the region is primarily composed of marshes and grasslands, which influence local hydrology and need to be considered in flood modeling frameworks. This combination of factors makes Houston/Galveston an ideal location for testing compound flood scenarios involving both coastal surge and riverine inflow.

Serving the fifth largest metro-area in the U.S., the vital hub at the Port of Houston is the second busiest port in the U.S. (by tonnage) supporting a broad industrial base (energy, oil refining, manufacturing, aeronautics, transportation, health care), along with fishing, recreation and tourism.

Problem Recognition:	TC impacts normal during fall on Galveston Island and the Bolivar Peninsula, but Hurricane Ike and then Harvey highlighted the inner Bay risk and risk of compound-rainfall hurricane flooding
Dominant Physical Processes:	Coastal surge and wave; Rainfall induced riverine flooding; Rainfall induced overland flooding; Poor drainage
Model Types for Dominant Processes:	Hydrodynamic and wave models; Rainfall and hydraulic models (including 2D, drainage structures); Rainfall and hydrologic models; Urban drainage models
Coupling and Probabilistic Approaches:	1- or 2- way coupling between coastal and inland models; unlikely to have linked compound flooding (HL-2) due to relative size and regulation of rivers; challenge using observation-based approaches (HL-0 and HL-1) due to limited surge records inside the bay, unless high uncertainty acceptable; boundary conditions need to consider that inland model can incorporate urban drainage

Rivers/Streams Causing Fluvial, Pluvial Areas, GWs Areas:	• Galveston Bay is the seventh largest estuary in the U.S. (1500 km^2), with a maximum natural depth of 3 meters (unusually shallow) (4 areas: Galveston Bay proper, East Bay, West Bay, and Trinity Bay)
	• Surrounded by marshes, prairies, and urbanized areas
	• Three outlets from the bay: Bolivar Roads between Galveston Island and the Bolivar Peninsula, San Luis Pass at the West end of Galveston Island, and Rollover Pass across Bolivar Peninsula
	• The major rivers that outlet into Galveston Bay are the Trinity and San Jacinto Rivers
	  ◦ The Trinity River is 885 kilometers long and drains 46,400 km^2 with an average annual flow of 7 *10^9 m^3/year.
	  ◦ The Trinity River Basin has the largest population and largest number of cities of any watershed in Texas
	  ◦ The San Jacinto River is a short 137 kilometers, draining 10,200 km^2 with an annual flow of 1.68 * 10^9 m^3/year

Data Availability:	• **Water levels and tides**: NOAA Tides and Currents Stations (Morgans Point/Barbours Cut, Rollover Pass, Eagle Point, Galveston Bay, Galveston Pier 21); USGS coastal water levels; Texas Coastal Ocean Observation Network (TCOON) (historical dataset) • **Flow and river stage**: HCFCD Flood Warning System, TWDB Water Data for Texas (TRIN: Mid-Trinity, OLDR: Old River, FISH: Trinity Bay near Baytown, and BOLI: Bolivar Roads), TexMesoNet, USGS National Water Information System (NWIS) • **Precipitation Gages**: HCFCD Flood Warning System, NOAA Global Historical Climatology Network, sub-hourly point gages, Cooperative Observer Network (COOP) • **Precipitation Reanalysis datasets**: PRISM (Parameter-elevation Relationships on Independent Slopes Model), NCEP Stage IV, AORC • **Bathymetry**: TWDB - Texas Coastal Lidar Mapping Project (Upper Coast Lidar, 04/2018)
Possible Use Cases:	Operational for emergency management, regulation of the San Jacinto River; risk-based design and planning use for coastal levee design and other mitigation efforts
Community Support, Model Maintenance, and Distribution:	• **National**:CHS for surge hazard curves and model results • **Statewide**:TWDB, Trinity River Authority • **Local**: HCFCD and Flood Warning System • **Non-Profit**: Trinity Improvement Association
Existing Models (Probability and Numerical):	• **Compound Models**: Hurricane Harvey Compound Models: SCHISM, (Huang et. al. 2021), Delft3D-FM (Lee et al. 2024), ADCIRC (Loveland et al. 2021); Lower Clear Creek and Dickinson Bayou Compound Flooding: ADCIRC and HEC-RAS; JCBP-TX at Trinity River Basin; GLO River Basin Flood Study: bivariate copula analysis; UT-Austin/TWDB project on transition zones in compound flooding: ADCIRC • **Surge and Wave Models**: CHS-CTX coastal hazard analysis and accompanying CSTORM model water level results: ADCIRC and STWAVE; Coastal Texas Protection and Restoration Feasibility Study (CTXCS): ADCIRC and STWAVE; Sabine Pass to Galveston Bay Coastal Storm Surge and Wave Hazard Assessment: ADCIRC & STWAVE; Hindcast and Validation of Hurricane Ike (2008): SWAN and ADCIRC • **Inland Models**: InFRM Watershed Hydrology Assessment for the Trinity River Basin: HEC-HMS, Riverware, Flood Frequency Analysis; GLO River Basin Flood Study: HEC-HMS and HEC-RAS • **Others**: Assessment of Reliability of Levees at Port Arthur: ADCIRC and GSSHA; Galveston Bay Larval Transport Study: AdH model and Particle Tracking Model

Figure 3-10. Freeport priority testbed region.

FREEPORT REGION TESTBED CHARACTERISTICS

West of Galveston Bay, the Brazos River debouches directly to the Gulf without the protection of a barrier island – which is unique to major basins on the Texas Coast. Pluvial mechanisms could interact directly with storm surge from the Gulf in this large coastal area between the extensions of Galveston and Matagorda Bays. The area is heavily industrialized and protected by levees, pumps and stormwater systems withing large industrial areas, which may behave differently than a community-based system.

The economic area is stabilized by chemical plants and hosts a far smaller population than the Galveston area. A hurricane flood protection system (levee system protecting 45 sq mi) was built in the 1960s to protect from riverine flooding and coastal storm surge events from the Gulf. The watershed is managed for flood control both upstream and near the coast.

Problem Recognition:	Flooding events within the near coast area are primarily from high river flows after heavy rains upstream and/or hurricanes and tropical storms from the Gulf Coast that cause severe flooding; A new flood control project, part of the Sabine Pass to Galveston Bay project, has been in design.
Dominant Physical Processes:	Tropical cyclones and tropical storm induced flooding due to surge and rainfall; Rainfall induced riverine flooding from coastal and upstream storms; Levee and gate controlled near coast, upstream heavily regulated reservoirs
Model Types for Dominant Processes:	Hydrodynamic and wave models; Rainfall, H&H models, able to represent flood mitigation controls. Large reservoir models.
Coupling and Probabilistic Approaches:	• 1-way coupling between coastal and inland models most likely because Brazos River and most of its drainage area outlets directly to the Gulf. • Irregular updates to management of flood controls and regulation upstream may challenge observation-based hazard approaches (HL-0 and HL-1), though surge and rainfall records are long. • Urban and flood controls need to be well represented by coupled models
Rivers/Streams Causing Fluvial, Pluvial Areas, GWs Areas:	• Brazos River outlets directly into Gulf, unique on the Gulf coast for major rivers. • The Brazos River is 2060 kilometers long (the second longest in Texas) and drains 111,000 km^2 discharging the largest volume to the Gulf of 7.5 * 10^9 m^3/yr. • Oyster Creek largest tributary that feeds Brazos River • Areas near the coast are heavily industrialized, largely paved, leveed, and managed for flood control
Data Availability:	• **Water levels and tides**: NOAA Tides and Currents Stations (Freeport Harbor), USGS Coastal Water Levels, TCOON (historical dataset) • **Flow and River Stage**: TWDB Water Data for Texas (SURF), TexMesoNet, USGS NWIS • **Precipitation Gages**: NOAA Global Historical Climatology Network, sub-hourly point gages, COOP • **Precipitation Reanalysis datasets**: PRISM, NCEP Stage IV, AORC

Possible Use Cases:	Operational for emergency management and operation of flood controls, possibly upstream reservoir releases; Risk based design and planning use for coastal levee design and gate controls
Community Support, Model Maintenance, and Distribution:	• **National**: CHS for surge hazard curves and model results • **Statewide**: TWDB • **Local**: Velasco Drainage District, Brazos River Authority (regulates upper Bravos reservoirs)
Existing Models (Probability and Numerical):	• **Compound Models**: JCBP-TX at Brazos River Basin; Freeport TX Bivariate Joint Probability study; GLO River Basin Flood Study: bivariate copula analysis; UT Austin/TWDB project on transition zones in compound flooding: ADCIRC • **Surge and Wave Models**: CHS-CTX coastal hazard analysis and accompanying CSTORM model water level results: ADCIRC and STWAVE; CTXCS: ADCIRC and STWAVE; Sabine Pass to Galveston Bay Coastal Storm Surge and Wave Hazard Assessment: ADCIRC & STWAVE • **Inland Models**: H&H Models: USACE CWMS HEC-RAS, Brazos River Authority 1D, Fort Bend County 1D/2D; GLO River Basin Flood Study: HEC-HMS and HEC-RAS


Brazos Harbor Inlet in Freeport, Texas ©USACE

Figure 3-11. Rio Grande/Lower Laguna Madre priority testbed region.

RIO GRANDE/LOWER LAGUNA MADRE REGION TESTBED CHARACTERISTICS

This region includes the outlets of the Rio Grande as well as various tributaries and canals into the shallow lagoon, and South Bay, which are separated from the Gulf by barrier islands with less distinct bypasses than Galveston Bay. The Rio Grande/Laguna Madre region is one of the most historically understudied areas along the Texas coast, with no major H&H models near the coast and limited data for flood concerns.

This region is home to a growing urban and rural population, many of whom are underserved and particularly vulnerable to extreme flood events. The region provides a fertile delta for agriculture and is highly susceptible to river flooding from the Rio Grande, and current models are insufficient due to the scarcity of reliable data. The area's economic importance is increasing, but it remains one of the most vulnerable regions in Texas in terms of flood risk and disaster resilience. Establishing a testbed in this region would provide valuable insights into flood hazards in data-poor areas, particularly in relation to riverine flooding and future disaster scenarios.

Problem Recognition:	The effects of a tropical storm or hurricane can go well inland past the Texas coast; Heavy rainfall, flooding, and even tornadoes can occur several hundred miles into the interior parts of the state; Large historical impactful historical hurricanes moved slowly down the coast dropping large amounts of rain which ran off as the surge from the wind and storm drove water level up.
Dominant Physical Processes:	Coastal surge and wave; rainfall induced riverine flooding; rainfall induced overland flooding
Model Types for Dominant Processes:	Hydrodynamic and wave models; rainfall, H&H models (allowing for complex flood control project)
Coupling and Probabilistic Approaches:	1- or 2- way coupling between coastal and inland models. May require 2-way coupling because of complexity of transition zone; unlikely to have linked compound flooding (HL-2) due to perennial nature of rivers; challenge using observation-based approaches (HL-0 and HL-1) due to limited data; models may need to include impact of low water and groundwater table
Rivers/Streams Causing Fluvial, Pluvial Areas, GWs Areas:	• The Rio Grande drains 128,000 km^2 over its 3060 kilometers length but only drains about 0.8 *10^9 m^3/yr due to heavy use for irrigation and impoundment in two large reservoirs. There is an estimated 11.7-day response time (Jane et al. 2022) of the river to rainfall • Lower Rio Grande Flood Control Project covers 180 miles of the Rio Grande from Penitas, Texas to the Gulf, which operates two large diversion dams, levees and lateral drains, and a pumping plant and conveyance channel • Surface water drainage is apportioned by inter-state and international compacts • Large pluvial areas North of the Rio Grande along the coast may produce challenging to model inflow into the Laguna Madre

Data Availability:	• **Water levels and tides**: NOAA Tides and Currents Stations (Freeport Harbor), USGS Coastal Water Levels, TCOON (historical dataset) • **Flow and River Stage**: TWDB Water Data for Texas (SURF), TexMesoNet, USGS NWIS • **Precipitation Gages**: NOAA Global Historical Climatology Network, sub-hourly point gages, COOP • **Precipitation Reanalysis datasets**: PRISM, NCEP Stage IV, AORC • **Bathymetry**: USGS South Texas LiDAR (04/2019)
Possible Use Cases:	Operational for emergency management, regulation of canals and reservoirs; risk-based design and planning use for coastal flood protection management
Community Support, Model Maintenance, and Distribution:	• **National**: CHS for surge hazard curves and model results • **Statewide**: TWDB • **Local**: Rio Grande Flood Control Project
Existing Model (Probability and Numerical):	• **Compound models**: CBP-TX at Rio Grande Basin; GLO River Basin Flood Study: bivariate copula analysis; UT Austin/TWDB project on transition zones in compound flooding: ADCIRC • **Surge and Wave Models**:CHS-CTX coastal hazard analysis and accompanying CSTORM model water level results: ADCIRC and STWAVE; CTXCS: ADCIRC and STWAVE • **Inland Models**:FEMA BLE; GLO River Basin Flood Study (HEC-HMS and HEC-RAS) • **Other**: Transboundary Rio Grande Watershed Model water-balance model using the Basin Characterization Model, and construction of an integrated hydrologic flow model with MODFLOW-One-Water Hydrologic Flow Model (referred to as One Water)

Figure 3-12. Beaumont/Port Arthur priority testbed region.

BEAUMONT/PORT ARTHUR REGION TESTBED CHARACTERISTICS

This region includes the Neches and Sabine Rivers (and their tributaries) feeding into Sabine Lake, which subsequently connects to the Gulf of Mexico. The Beaumont/Port Arthur region is a critical economic zone with urban centers and industrial infrastructure, making it highly vulnerable to both riverine and coastal flooding. The presence of large river systems and the availability of significant historical flood data make this region a prime candidate for testing complex compound flood modeling. Vegetation in the region is a mix of grasslands and forests, and these natural features play a significant role in floodwater retention and runoff dynamics. This region is prone to heavy rainfall events and river flooding, particularly during tropical storms and hurricanes. The Sabine River’s connection to both Texas and Louisiana makes it an ideal testbed for understanding regional water management, cross-state coordination, and the interaction between riverine and coastal flooding.

Figure 3-13. Corpus Christi priority testbed region.

CORPUS CHRISTI REGION TESTBED CHARACTERISTICS

This region is characterized by a large bay with inflow from the Nueces River and Osos Creek that is separated from the Gulf by a large barrier island, creating a natural defense against storm surges. Despite limited river inflow from the Nueces River, the Corpus Christi region remains economically significant due to its major ship channel and ports. The region's smaller continental shelf, relative to the upper Texas coast, makes it particularly vulnerable to rapid storm surge events. The mix of urban and rural land use further complicates flood modeling in this area. Given its unique geomorphology and economic importance, Corpus Christi would serve as an important testbed for evaluating coastal flood hazards, particularly those driven by storm surges and limited riverine contributions.

Figure 3-14. Matagorda Bay priority testbed region.

MATAGORDA BAY REGION TESTBED CHARACTERISTICS

This region is fed by the Colorado River, Lavaca Rivers and smaller creeks, and multiple watersheds including adjacent pluvial areas, the bay and extensions are protected by barrier islands. The Matagorda Bay region is a critical habitat for a wide range of bird species and other wildlife. This area is more rural than the nearby Houston/Galveston and Corpus Christi regions and has significant ecological importance. Furthermore, this region is home to the South Texas Nuclear Power Plant. The region's exposure to both riverine flooding and coastal storm surges makes it a valuable testbed for examining compound flood dynamics, especially where environmental conservation intersects with industrial infrastructure. Testing models here could provide insights into balancing flood protection with habitat preservation.

Figure 3-15. Brownsville/South Padre Island priority testbed region.

BROWNSVILLE/SOUTH PADRE ISLAND REGION TESTBED CHARACTERISTICS

This southernmost part of coastal Texas is vulnerable to both riverine flooding from the Rio Grande and coastal storm surges. The Brownsville/South Padre Island area is subject to intense tropical storms and hurricanes. The area is economically important, with tourism on South Padre Island and international trade through the Port of Brownsville. It is also vulnerable to both riverine flooding from the Rio Grande and coastal storm surges. Although part of the larger Rio Grande/Laguna Madre region, this smaller area could serve as an additional testbed to focus specifically on the effects of tourism, cross-border trade, and the interaction between the Rio Grande's hydrology and coastal hazards.

3.5 The Future of Texas Integrated Flood Modeling

Texas has seen and will continue to see extreme flooding that is intensified by compound flooding — the combined effects from storm surge, river overbanking, extreme rainfall, and groundwater (see Supporting Material 3-1). Engineering/science models and analysis tools can be used to quantify flood inundation and predict the statistical probabilities of flood hazards (depth, extent, duration), but the present state-of-the-science is limited in its ability to handle compound flooding. Specifically, present models and tools are fragmented by discipline (hydrology, rainfall flooding, river overbank flooding, coastal flooding, flood hazard analysis) and require an extraordinary level of scientific/engineering skill to integrate into flood analysis for any given location or purpose (see Understanding Flood Modeling, as well as the report for Themes 1 and 2 of Dawson et al, 2024). The summary findings of these literature reviews are provided in the following section. Refer to Supporting Materials 3-3 through 3-9 for detailed information on these literature reviews.

There is an urgent need for a coherent, reusable approach to analyzing coastal compound flooding that can be widely accessed and applied by state agencies, local governments, and engineering contractors. The TxCFF is a collaborative and integrative software framework that can link models, analysis tools, and engineering/science expertise for efficient and widespread quantification of flood inundation and hazards along the Texas Coastal Plain. Such efforts would build on the existing state-of-the-science and require both professional-level large-scale software development and specific applied research tasks in model integration. Creating the TxCFF requires a decade-long commitment to funding the computational and human resources to 1) build and maintain the framework and 2) operate and educate. Data management is a non-trivial challenge that requires integration over existing federal, state, and local data sources. The TxCFF can be built in pieces beginning with testbed locations. The most effective path forward requires commitments from project managers of individual coastal flooding projects to support the TxCFF concept and direct funding towards building reusable tools within the proposed framework.

Building the TxCFF will not be quick or easy; however, it will be well worth the effort. With an operational TxCFF both state and local agencies will be able to better evaluate 1) flood hazards and risks, 2) potential impacts of new development, and 3) planning for resiliency. The TxCFF and its user-training tools will make flood analysis cheaper for commercial developers and agencies employing engineering contractors: that is, enormous sums are presently wasted on engineering studies that "reinvent the wheel" by building models/tools from scratch for each project. The proposed TxCFF provides a reusable framework that builds its capabilities with each project, which will reduce costs while providing more comprehensive and reliable analyses.

TIFF Component 3 Implementation in the Lower Rio Grande Valley

TIFF will expand its implementation into the LRGV, encompassing Starr, Hidalgo, Willacy, and Cameron Counties. Leveraging findings and recommendations from previous phases, TIFF will address the intensifying challenges of compound flooding (where riverine, coastal, and pluvial flood sources interact) within this highly flood-prone region.

CORE TIFF COMPONENT 3 OBJECTIVES AND ANTICIPATED OUTCOMES FOR THE LOWER RIO GRANDE VALLEY

1. **Compound Flood Risk Characterization** - To capture the complex interactions of flood drivers in the LRGV, Component 3 will provide a cross-disciplinary modeling performance evaluation of multi-model configurations to inform future system integration and compound flooding representation.

   These configurations will simulate compound flood events using a testbed approach incorporating

models from different disciplinary domains:

- **Coupled ADCIRC–STWAVE**: a widely adopted storm surge modeling system previously applied for coastal Texas
- **HEC-RAS**: a commonly used model for riverine and watershed flood analysis
- **AdH**: primarily applied for hydrodynamic simulation in estuarine and nearshore environments

2. **Development of a Screening-Level Compound Flood Analysis Tool** - Bivariate analysis techniques (e.g., Santos et al., 2019; Kim et al., 2023) have been applied to assess compound flood hazards, but they are often implemented using ad-hoc custom scripts. Currently, no standardized tool exists that supports seamless integration of bivariate flood analysis within H&H modeling workflows. To address this gap, TIFF Component 3 will enhance the USACE Hydrologic Engineering Center's Statistical Software Package (HEC-SSP) by incorporating bivariate analysis capabilities. Tool performance will be tested in a data-rich testbed (e.g., Dickinson Bayou) and a data-limited environment in the LRGV to assess robustness under various data conditions. These improvements will allow for consideration of dependency between rainfall and surge events, improving hazard estimation compared to current methods that assume independence and support for screening-level joint probability modeling of coastal hazards (essential for feasibility-level flood risk assessments).
3. **Remote Sensing and Machine Learning Applications** - TIFF will utilize satellite imagery and machine learning algorithms to identify flood extents of historical storms for supporting flood model calibration and validation efforts, especially valuable for under-monitored and resource-constrained areas such as the LRGV region.


Storm over South Padre Island, Texas © David, Adobe Stock

4. **Exploration of Nature-Based Solutions** - TIFF will complete a comprehensive literature review to examine the feasibility of integrating nature-based flood mitigation strategies into the LRGV's flood management planning. Emphasis will be placed on sustainable and climate-resilient solutions and low-impact infrastructure alternatives to conventional hard-structure flood defenses.
5. **Model Inventory Update for the LRGV Region** - TIFF will review and assess the initial inventory of meteorologic, hydrologic, hydraulic, estuarine, and surge models compiled by the GLO's LRGV study vendor and TWDB's RFPGs and provide feedback and recommendations to ensure alignment with future inland and coastal hazard identification needs.

TIFF Component 3 aims to:

- advance the **science and operationalization of compound flood modeling**
- deliver **scalable tools** for both screening-level and planning-level risk assessments
- promote **data-informed decision-making** in flood resilience and infrastructure investment
- lay the groundwork for integrating **innovative and nature-based approaches** into long-term flood mitigation efforts in the LRGV and beyond

The combination of climate variability, land use change, and recurring tropical systems such as Hurricanes Beulah, Hanna, and Dolly has significantly increased the region's vulnerability. Compounding this issue is the limited availability of high-resolution data. In response, Component 3 will create a robust, integrated modeling platform to support data-driven, adaptive flood hazard identification, the development of compound flood analysis tools, and testbed evaluations for future flood planning and resilience in the LRGV.

Hurricane warning sign on a Houston freeway ©Andrea Quintero Olivas, Adobe Stock

4 Component 4: Planning and Outreach

Component 4 ensures that targeted users' flood planning and mitigation needs are incorporated into the data and modeling frameworks and the findings from various efforts are well communicated. A close collaboration among TIFF, CHARM, TDIS, RFPGs, and GLO's River Basin Flood Studies Providers was required to achieve such a goal. TIFF also supported expansion and improvement of flood planning in Texas by incorporating the new findings into the existing planning tools or recommending the creation of new tools. Finally, TIFF worked to balance local cost-effective flood risk management with regional flood risk considerations.

4.1 What is Planning and Outreach?

"Planning and Outreach," as defined under TIFF Component 4, are collaborative and adaptive processes that ensure flood planning and mitigation efforts are informed by the needs of both technical and non-technical stakeholders, that results are effectively communicated to them, and that compound flooding is appropriately considered during the planning phase. These processes involve integrating target user perspectives into data and modeling frameworks, refining tools and communication strategies, and aligning planning scenarios with regional and state-level priorities. Achieving this requires close coordination among TIFF, CHARM, the RFPGs, and the GLO's RBFS.

"Planning and Outreach" also covers the development of educational materials, outreach strategies, and planning tools that reflect the realities of compound flooding and diverse community vulnerabilities. By combining technical expertise with stakeholder engagement, Planning and outreach helps shape flood risk solutions that are inclusive, scalable, and grounded in the lived experiences of Texas communities.

4.2 Why Planning and Outreach Matters to Texas

Texas faces a wide range of flood risks—from coastal surge to inland flash flooding—affecting communities that differ vastly in geography, infrastructure, and vulnerability. In this context, Planning and outreach becomes a cornerstone of effective flood resilience. It ensures that technical solutions are not developed in isolation, but are shaped by the lived experiences, priorities, and knowledge of local stakeholders. Planning and outreach is not just about disseminating information; it is about building trust, fostering collaboration, and ensuring that flood mitigation strategies are informed by the people and places they are designed to protect. By engaging communities early and often, this approach helps create more equitable, transparent, and durable flood planning outcomes across the state.

4.3 The Guiding Objectives of TIFF Component 4

The overarching goal of Component 4 is to ensure that flood planning and mitigation needs are incorporated into the data and modeling frameworks and the findings from various efforts are well communicated. Achieving such a goal requires close collaboration among TIFF, CHARM, RFPGs, and the GLO's RBFS Study Providers.

In support of the expansion and improvement of flood planning in Texas, TIFF incorporated new findings into vetted recommendations and guidelines and worked to balance local cost-effective flood risk management with regional flood risk considerations. This effort consisted of nine individual tasks listed below:

1. Establish a TAT to support Component 4
2. Coordinate with the RFPGs and stakeholders to identify flood planning and mitigation scenarios

consistent with regional flood planning efforts, beginning by establishing a working relationship with RFPGs or their Coastal Liaisons to identify TIFF end-users

3. Develop and implement a comprehensive outreach plan to engage RFPGs and other stakeholders regarding flood planning and mitigation efforts. Annually reassess user needs regarding flood planning and mitigation efforts and requirements and provide the results by updating the comprehensive outreach plan and preparing an annual progress report
4. Support the development of flood communications and educational materials
5. Investigate the opportunities to balance local cost-effective flood risk management analysis with regional flood risk considerations
6. Perform a literature review on planning tools and develop a list of data modeling needs for planning tools
7. Evaluate and provide feedback on the initial inventory of planning datasets (e.g., parcel data, structure characteristics, first-floor elevation, building codes, demographics, etc.) provided by GLO RBFS Study Providers
8. Make recommendations pertinent to flood planning and outreach/communication to GLO

Storm Alberto at Surfside Beach, Texas ©Brandon Bell

4.4 Approach to Objectives

TIFF's approach to Component 4 was built on a collaborative, user-centered framework designed to elevate flood planning across Texas by integrating stakeholder perspectives into planning tools and communication strategies. Through sustained engagement with the Coastal Liaisons of the RFPGs, CHARM, TDIS, and the GLO's RBFSs, TIFF identified critical gaps in communication, data integration, and alignment between local and regional planning efforts. TIFF's multi-year outreach plan emphasized inclusivity, transparency, and strategic coordination, leveraging existing initiatives to avoid redundancy and maximize impact.

To support informed planning decisions, TIFF conducted a targeted planning model inventory alongside a literature review to assess the tools and resources available for flood analysis and project evaluation. This inventory distinguished between resource tools, data access platforms, and planning models—each serving a unique role in defining affected areas, estimating consequences, and evaluating the likelihood of achieving desired outcomes. Consultations with flood modelers and planners confirmed that compound flood model outputs must be formatted consistently to support planning applications. The interface between planners and modelers—particularly during model design—was identified as a critical point where assumptions must be clearly defined to ensure applicability and relevance. As a result, TIFF recommends that future agency coordination efforts include a standardized requirement for all funded flood-related projects to submit three critical shapefiles (location, scope, and impact area) to the funding agency and other relevant recipients. (see Recommendation C2.4B: Standardize Grantee Shapefiles).

Recognizing that effective communication is essential to meaningful flood planning, Component 4 prioritized the integration of target user needs into data and modeling frameworks—an effort that both built upon and was deeply integrated with Component 2. Together, these components formed a cohesive strategy to ensure that technical outputs were not only scientifically rigorous but also accessible and relevant to diverse audiences. Through collaboration with Study Providers from the UT-Austin, TIFF advanced a unified approach to flood risk communication, aligning outreach and visualization efforts to reflect real-world perspectives and support both technical and non-technical users from the outset. Together, Components 2 and 4 developed the *The TIFF Communication Guidelines*, a product of literature reviews, stakeholder workshops, and surveys conducted with TFMA attendees and three prioritized target-user groups: property owners, renters, and individuals with LEP. These groups were selected due to their heightened vulnerability to coastal flooding and the potential benefits of improved risk messaging. *The TIFF Communication Guidelines* underscore the importance of designing flood-related tools and visualizations with the user in mind from the beginning (not just at the conclusion) marking a deliberate shift from "end-user" to "target user" terminology. This integrated approach ensures that flood risk information is not only scientifically accurate but also accessible, actionable, and tailored to the communities it aims to serve.

Despite the dedication of numerous agencies and organizations working to address flood risk across Texas, this comprehensive and adaptive approach revealed a persistent challenge: the absence of a centralized coordinating entity to unify the state's flood-related efforts. Fragmented data systems, overlapping initiatives, and missed opportunities for synergy continue to hinder progress. In response, TIFF recommends the establishment of a Texas Flood Coordination Office (TFCO) within an existing state agency. This office would serve as a central hub to streamline flood planning efforts, maintain an official statewide database, provide technical support, and foster collaboration across jurisdictions. By institutionalizing coordination beyond the current volunteer-based model, the TFCO would ensure that state and federally funded projects are more impactful, equitable, and aligned with the evolving needs of Texas communities facing increasing flood risks.

ZOOMING IN: TIFF'S PRIORITY RECOMMENDATION FOR ONGOING COASTAL FLOOD PLANNING AND OUTREACH

Establish a Texas Flood Coordination Office (TFCO) (TIFF Recommendation C4.5B)

Flooding poses a persistent and growing threat to communities, infrastructure, and ecosystems across Texas. To better prepare for and respond to these challenges, state and regional flood planners need coordinated access to information, planning tools, and technical support.

Currently, multiple state and federal agencies, private and non-profit organizations, and academic institutions are engaged in efforts to raise awareness and respond to floods. However, without a centralized coordinating body, the extensive work being done often overlaps, creating redundancies, inefficiencies, and missed opportunities to leverage project outcomes.

TIFF recommends Texas legislators establish a Texas Flood Coordination Office (TFCO) within an existing state agency.

The TFCO would:

- centralize and streamline flood-related efforts
- create and maintain an official statewide database of past and ongoing projects
- provide technical support to state and regional planners
- enhance collaboration among agencies, institutions, and stakeholders
- reduce redundancy and maximize the impact of state and federal investments
- formalize and expand beyond the current volunteer-based efforts

KEY OBJECTIVES OF THE TEXAS FLOOD COORDINATION OFFICE

By centralizing information and oversight, the TIFF-informed TFCO will enhance the state's ability to manage and mitigate flood risks efficiently. The TFCO will 1) centralize state- and federally funded flood projects in one central body, 2) facilitate collaboration among stakeholders to build partnerships and shared solutions, 3) maintain a central archive of project outcomes and share findings with stakeholders, 4) reduce redundancy to ensure efficient use of state and federal resources, and 5) report to the Legislature on the state of flood projects and recommend improvements for flood management.

1. **Centralized Oversight of Flood Projects** - The TFCO will oversee all state and federally funded flood-related projects, ensuring that efforts are aligned, complementary, and not duplicated. The Office will maintain a central database of ongoing and completed projects (including information on scope, funding, and progress) to improve coordination and transparency. This oversight will help decision-makers allocate resources more effectively and ensure future flood projects address the state's most pressing needs.

2. **Facilitation of Collaboration** - The Office will actively encourage collaboration among state agencies, academic institutions, non-profits, and private sector organizations to promote innovation and more effective flood management. It will serve as a neutral convener, bringing stakeholders together to foster partnerships and shared solutions. This coordinated approach will help break down silos, align diverse expertise towards state goals, and lead to more efficient project implementation.

3. **Archiving and Dissemination of Findings** - All project outcomes, data, reports, and findings will be archived in a central repository managed by the TFCO. This information will be made accessible to all relevant parties, promoting transparency and knowledge sharing. The TFCO will ensure that results from projects are effectively disseminated among key stakeholders and can be leveraged in future flood mitigation efforts. By disseminating project findings, the Office will ensure that valuable insights from past projects inform future flood mitigation efforts.

4. **Reduction of Redundancy** - Through its oversight and coordination roles, the TFCO will reduce unnecessary duplication

of effort by identifying overlaps among projects and redirecting resources to unmet state needs. This leveraging of project outcomes will prevent wasted investments in repetitive research or narrowly scoped projects and inform new initiatives. This efficient use of state and federal resources will maximize the impact of available funding and ensure that flood management efforts address a broader range of needs across Texas.

5. **Legislative Reporting and Recommendations** - The TFCO will provide regular reports to the Texas Legislature that highlight the status of flood projects, identify gaps in the state's approach, and recommend improvements for flood management and response. These reports will ensure that decision-makers are equipped with up-to-date, evidence-based information. The Office will work closely with legislators, providing the latest research and field-tested solutions to help shape policies that are more responsive, effective, and sustainable in reducing flood risks statewide.

ORGANIZATIONAL STRUCTURE AND RESOURCES

The TFCO could be housed within a state agency involved in flood science, flood planning, flood funding, and floodplain management. Although the Office could be established as a separate entity, utilizing an existing agency may reduce the overhead and administrative burden. The TFCO would be staffed by a small team of experts in flood management, project coordination, and data archiving. This team would work in close collaboration with existing staff at the TWDB (or other selected agency), leveraging existing resources and expertise. Initial funding for the TFCO could come from state appropriations, with additional support from federal grants or partnerships with non-profit organizations and private companies involved in flood-related efforts.

Flooding is an urgent and ongoing threat in Texas, and the current landscape of flood-related efforts is fragmented and inefficient. By establishing the TFCO, the state can enhance its flood management efforts, streamline coordination across sectors, and ensure that all projects contribute to a more resilient and prepared Texas.

4.5 Implementation of Objectives

Objective 1: Establish a Planning and Outreach TAT

To advance the goals related to Planning and Outreach, TIFF established a dedicated TAT composed of experts in stakeholder engagement, public communication, regional planning, and community resilience. This team plays a central role in ensuring that flood planning efforts across Texas are inclusive, transparent, and responsive to the needs of diverse target users. Drawing from disciplines such as behavioral science, urban planning, and data visualization, the Planning and Outreach TAT was tasked with bridging the gap between technical modeling and community priorities, ensuring that flood mitigation strategies are informed by the people and places they are designed to protect.

Under the leadership of Dr. Amin Kiaghadi, Manager of the Coastal Science Department at TWDB, who also serves as the Component 2 Champion, the Planning and Outreach TAT benefitted from interdisciplinary guidance and strategic coordination across components. Dr. Kiaghadi brings a unique blend of technical expertise and leadership to the role, with a background in environmental engineering and computational sciences. His experience overseeing coastal resilience and flood planning projects positions him to support the integration of outreach strategies with data-driven planning tools. The TAT works closely with RFPGs, Coastal Liaisons, CHARM, and the GLO's RBFS Study Providers to identify key stakeholders, assess user needs, and align flood mitigation scenarios with regional planning efforts.

The Planning and Outreach TAT also supports the development of educational materials and communication guidelines that reflect the realities of compound flooding and regional disparities. Their work complements efforts under Component 2, particularly in the co-development of The TIFF Communication Guidelines. These guidelines, informed by literature reviews, stakeholder workshops, and statewide surveys, prioritize the needs of property owners, renters, and individuals with LEP (groups especially vulnerable to coastal flooding). Ultimately, the TAT serves as a strategic engine for elevating flood planning across Texas, helping to balance local cost-effective solutions with broader regional resilience, and fostering a planning ecosystem built on trust, equity, and shared purpose.

The following advisors were selected to serve as members of the Component 4 TAT based on their expertise in stakeholder engagement, regional and community planning, public communication, and the design and delivery of flood-related outreach and educational tools:

COMPONENT 4 TECHNICAL ADVISORS

- Andrew Ernest, Research, Applied Technology Education and Service (RATES)
- Ataul Hannan, Harris Country Flood Control District
- Augusto Sanchez, Cameron County
- Bridget Scanlon, UT-BEG
- Britt Corley, USACE
- Caroline McCabe, USACE-SWF
- Christopher Emrich, University of Central Florida
- Daniel Arriaga, TAMU-IDRT
- Greg Waller, NWS-WGCRFC
- Hanadi Rifai, University of Houston
- Javier Guerrero, RATES
- Jet Hays, GLO
- Jianhong-Jennifer Ren, TAMUK
- John Kucharski, USACE-HEC
- Jon Thomas, USGS
- Katharine Teleki, Teleki Consulting
- Katie Landry-Guyton, NOAA
- Keri Stephens, UT-Austin
- Kiersten Stanzel, Coastal Bend Bays & Estuaries Program
- Lisa Marshall, TCEQ
- Liv Haselbach, Lamar
- Melisa Gonzalez, LRGVDC
- Mike Quimet, TDEM
- Reem Zoun, TWDB
- Rick Hallman, NWS
- RoseMarie Klee, TxDot
- Saji Varghese, USACE
- Siddharth Saksena, Virginia Tech
- Steven Mikulencak, Texas AgriLife - CHARM
- Teal Harrison, Adaptation International
- Tom Jester, USACE
- Tori Johnson, U.S. Naval Academy
- Wes Birdwell, TFMA

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

To initiate a collaborative foundation for identifying end-user needs and aligning with regional flood planning priorities, TIFF met with the Coastal Liaisons of the RFPGs on September 1, 2021. This engagement marked the beginning of a relationship aimed at integrating local insights into the development of flood planning and mitigation scenarios consistent with broader regional efforts. Several participants from this initial meeting later joined the TAT, further strengthening the connection between regional expertise and the evolving direction of the TIFF project.

MEETING WITH REGIONAL PLANNING GROUPS OR THEIR COASTAL LIAISONS TO IDENTIFY TIFF END USERS

The TIFF planning project incorporates a collaborative approach by engaging experts from governmental agencies, academia, and stakeholders with regional experience. To identify end-user needs, and to leverage the existing efforts in Texas, TIFF set up a meeting with the Coastal Liaisons of the RFPGs. See Supporting Material 4-1 for meeting invitation, agenda, and notes.

A calendar invite with the meeting agenda was sent on July 20, 2021. A total of 38 people received the invitation. The Coastal Liaison RFPG meeting was held virtually on a Zoom platform on Wednesday, September 1, 2021, from 9:00 to 11:00 AM. The meeting was hosted by The Meadows Center for Water and the Environment. A total of 36 people (Coastal Liaisons, other interested RFPG members, TWDB employees who support RFPGs, facilitation team, and SC members) participated in the meeting. The meeting was a success with regards to opening a dialogue between the RFPG Coastal Liaisons and TIFF. The liaisons identified and discussed many important issues that will be considered during the development of the TIFF deliverables. The Coastal Liaisons also expressed their willingness to be informed on TIFF milestones and to continue providing feedback to the TIFF.

The Coastal Liaison RFPG meeting (Supporting Material 4-1) began with the TWDB and the GLO providing background information on the TIFF planning project, compound flooding, and a big picture overview on how the TIFF project connects with ongoing statewide flood planning efforts. The three TIFF partners were all present at the meeting and expressed the important role that the Coastal Liaisons and RFPG members play in helping to identify the end-users of the TIFF project. It was clearly communicated that the outcome of this meeting and the future involvement of TIFF in state flood planning efforts was not meant to generate any additional workload for the RFPGs. However, the SC members stated that they believe the more input from the RFPGs, especially the Coastal Liaisons, that could be given during this collaborative process, the more likely the TIFF recommendations can support the flood planning process for all that participate in the future.

During the meeting, various participants shared their thoughts and concerns related to flood planning for the communities they serve and talked about the challenges, both unique to their region and/or the ones that are common across the coast, to flood planning efforts throughout the state. A summary of these points is provided below:

- Local drainage districts and regional flood planners indicated there are often challenges faced by those groups downstream from decisions made by upstream groups. Furthermore, the ability to include these decisions from upstream planners into local models for flood planning in downstream districts would be very helpful.
- Concerns were expressed throughout the meeting about avoiding redundancy and duplication in flood planning efforts. It is one of the TIFF goals to avoid these duplicative efforts through careful documentation and cataloging of flood planning efforts throughout the state and building relationship at local, regional, state, and federal levels.
- There were concerns from some participants about more isolated or rural communities not being able to receive financial or planning assistance from state or federal sources due to a complex application process and lack of resources available to those communities. It was agreed that this concern was a problem and efforts are being made to improve processes going forward to address these concerns.
- Meeting participants would like to keep up with TIFF progress and stay updated but were unsure of the best way to communicate. A quarterly to bi-annually communication effort was suggested. The virtual meeting platform works well for most all.

The dialogue initiated with the Coastal Liaisons of the RFPGs revealed a critical need to better understand the broader impacts of local and regional flood planning efforts, particularly the upstream/downstream dynamics and interactions across adjacent watersheds. This insight directly informed the direction of the TIFF project and led to the addition of a new objective (Objective 5), which focuses on investigating opportunities to bridge and communicate between project-based solutions and regional planning-scale strategies.

This expanded focus reflects TIFF's commitment to responsive planning and its evolving role in supporting integrated flood mitigation across Texas. Notably, this is a highly complex and challenging topic, especially when considering the implications of compound flooding. The nonlinear consequences of such events—where multiple flood drivers interact—can significantly alter both the planning phase and the effectiveness of solutions at different scales. These dynamics underscore the need for deeper understanding and more adaptive approaches, which will be discussed further in subsequent sections. More research is required in this domain to successfully add coordination and impact evaluations into planning matrices.

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

With the goal of improving the resiliency response of Texans impacted by coastal flooding, TIFF developed an Outreach Plan to become a trusted and reliable source of recommendations, guidelines, and standards for coastal flood risk modeling and planning. This multi-year plan was developed by the SC and refined through ongoing collaboration with the TAT members (see Supporting Materials 4-2 and 4-3 for more details). An initial draft was prepared in Year One and evolved over Years Two and Three based on expert feedback and TIFF's continued work. The approach was designed to serve both technical and nontechnical stakeholders, emphasizing inclusivity and strategic alignment. To maximize impact and avoid redundancy, TIFF leveraged existing initiatives (e.g., TDIS, CHARM) and built upon foundations established by other flood-focused programs.

THE OUTREACH PLAN

The Outreach Plan relies on five elements as shown in Figure 4-1: expert collaboration; an inclusive bottom-up approach; an inclusive and transparent scientific approach; a commitment to avoiding redundancy; leveraging existing efforts and building relationships, and identifying technical and non-technical target-users and how to best communicate flood information to those target users (see Supporting Material 4-4 for more information).

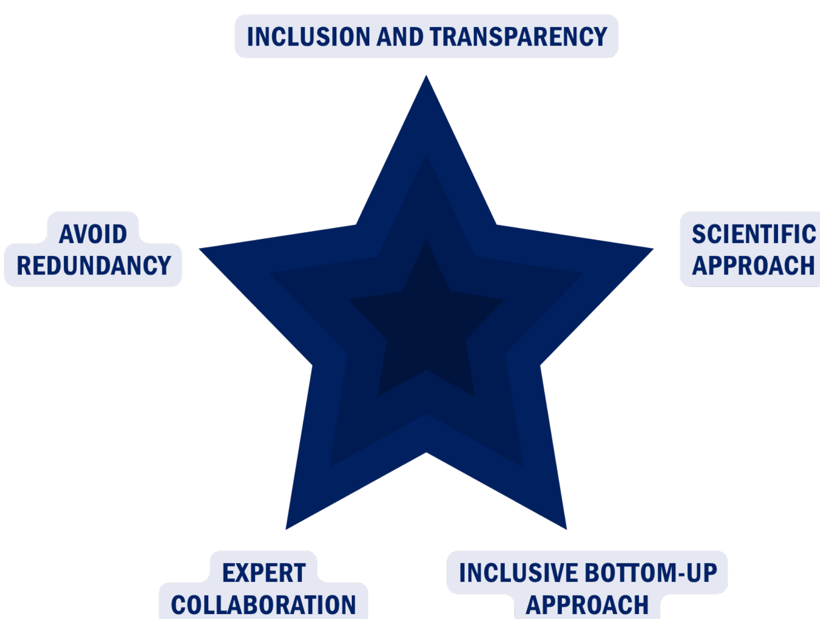


Figure 4-1. The TIFF star shows the five major elements of trust for building a reliable brand among the Framework's end-users.

Expert Collaboration

TIFF collaborated with experts in the field of coastal flooding and engaged specialists across multiple disciplines to leverage key knowledge, incorporate end-user feedback, and ensure the development of valued and relevant TIFF products. The TAT members (96 people among the four components) are well-known experts in various aspects of coastal flooding including data monitoring, new monitoring technologies, data management and visualization, modeling, planning, and outreach. TIFF interacted with technical end-users through interactive meeting opportunities and other direct forms of communication (e.g., surveys, workgroups, emails, etc.). Figure 4-1 lays out the general execution approach used by TIFF to execute all TIFF project efforts and shows where in the process the TATs will be consulted for feedback.

The ultimate goal for TIFF is the pioneering of a new collaborative effort to address compound flooding impacts in Texas and establishing the TIFF project as a benchmark for future efforts in this field. The state and federal agencies that support the TIFF efforts are recognized leaders in flood science, planning, and mitigation. The TIFF project is funded through GLO, where several successful programs are already in place to improve the livelihood and success of Texans recovering from natural disasters. Likewise, TWDB stewards several successful community programs to provide assistance to those impacted by flood and storm related effects. Both partner federal agencies (USACE and USGS) are recognized leaders for their expert contributions to modeling and data collection science. These agencies both have a strong history of partnering with state agencies such as GLO and TWDB to improve the safety and lives of the communities they serve.

Inclusive Bottom-Up Approach

It is well-established that the engagement of end-users in the creation of any new product or idea will lead to a higher likelihood of the use of new products once they are available to a community at large. The early engagement and inclusion of the end-users in development of project deliverables is one way to build trust among technical and nontechnical end-user groups. TIFF seeks to connect with nontechnical end-users through leveraged assistance from existing agency programs already engaged with these communities on similar topics. Once perspectives are collected, then the process of creating solutions in the form of guidelines and recommendations to meet end-user needs can progress. TIFF is working closely with researchers from the Moody College of Communication at UT-Austin who are conducting surveys and interviews to gather information on how potential end-users could benefit from TIFF products. Communities and individuals that could benefit directly from the guidelines and model recommendations made by TIFF, such as those living in areas where compound flooding may be a concern, will be able to provide feedback on their needs and concerns for local areas through established agency programs, as discussed in more detail in Outreach Plan and TIFF End-Users.

Scientific Approach, Inclusion, and Transparency

Expert collaboration in all four components of the TIFF planning project will help ensure that the guidelines, recommendations, and all related TIFF products are created through a holistic scientific approach. As mentioned earlier, the SC is comprised of individuals and agencies that have made valuable contributions to the field of flood science and are committed to using a sound scientific approach to develop recommendations that will be useful to end-users. To further these efforts, the SC collaborates with technical experts in the field of flood science beyond the TIFF associated agencies. It is the belief of all the SC members that a logical scientific approach must be behind any of the TIFF Recommendations in order for these recommendations to prove useful to, and become trusted by, all potential TIFF end-users. To create a useful product, it is imperative to first understand the needs of those end-users that will use the product in future applications. To this end, the SC looks to include input at all possible end-user levels (through direct and indirect outreach) and to consider feedback on the needs of both technical and non-technical end-users in the development of TIFF guidelines, recommendations, and related products. Going forward, TIFF project efforts will focus on gathering these perspectives directly from technical end-users and indirectly from nontechnical end-users through interactive opportunities and established programs. Inclusion of the perspectives and needs of these end-users will assure that the TIFF products generated from this project are useful, helpful, and trusted by the communities they are intended to assist. The SC believes in keeping TIFF project activities transparent and open to anyone with interest in flood planning and mitigation. To achieve this, the SC will make final products available to the public and post project updates on the website. Furthermore, all data gathered or collected (if any) by the TIFF planning project will be shared with the public through TDIS.

Avoid Redundancy

In addition to ensuring that all TIFF guidelines and recommendations are created via a sound scientific process with expert collaboration, TIFF is committed to avoiding redundancy and duplicative efforts. Through an extensive effort to communicate with project managers across Texas on planned and ongoing flood related data and model driven projects, TIFF cataloged many important projects related to flood preparedness in Texas. By recognizing and cataloging so many flood-related efforts already in place across the state, TIFF may help avoid project duplication efforts statewide and provide end-users with a helpful comprehensive project overview. Avoiding redundancy is a key component of creating useful and relevant TIFF products.

The efforts put forth by the TIFF project to provide a holistic view of all related flood science work efforts in the state is novel in its approach and function. The benefits of having a comprehensive database where project information can be added and updated as needed will be evident in the funds and man-hours saved as redundancy is avoided from duplicative efforts. It is the intention to make this database available through methods that will be further developed. The existence of a comprehensive database to reference flood science projects that are currently ongoing or completed will significantly improve efforts to avoid project redundancy. Individual members of the SC participate in various meetings to update stakeholders on TIFF progress, as well as to inform the SC on the progress of other projects. The Texas Flood Organizing Group, Galveston Bay Council, Southeast Texas Flood Coordination Study, and GLO Combined Flood Studies could be named as a few of these meetings.

OUTREACH PLAN AND TIFF END-USERS

TIFF is a continuously evolving planning project designed to generate products responsive to end-user needs, including final recommendations to improve planning tools for coastal flooding and its associated risks. A non-biased, scientific approach is prioritized to ensure the reliability of TIFF products in the communities they are designed to help. TIFF potential products can be categorized into three groups: 1) recommendations for new projects (e.g., need for data acquisition and model generation); 2) technical guidelines for planning tools, modeling frameworks, data management and visualization, and new monitoring technologies; and 3) information on coastal flooding for the general public. The target end-users for the first two products are different from the latter; thus, the TIFF outreach efforts will focus on reaching two basic groups of end-users. Those with a more technical background will be considered as 'technical end-users', while those that may lack that technical background but would still greatly benefit from the TIFF guidelines and recommendations will be referred to as 'nontechnical' end-users. Every possible effort will go into collecting information and feedback on the needs of these two end-user groups to generate TIFF products. Please see Supporting Material 4-4 for more information related to the Outreach Plan and TIFF end-users.

Leveraging Existing Efforts and Building Relationships

TIFF's outreach strategy was significantly strengthened by leveraging existing efforts and cultivating strategic relationships with key partners across Texas. Collaboration between TIFF and CHARM leadership led to a shared commitment to identify community needs, gather feedback, and disseminate TIFF guidelines through CHARM's community-driven planning tools. Engagement with the TWDB Community Assistance Program further expanded TIFF's reach by establishing a coordinated effort to engage nontechnical end-users. This collaboration also informed a new contract between TWDB and the UT-Austin's School of Communication, designed to support future TIFF initiatives. Coordination with RFPGs, particularly their Coastal Liaisons, opened a productive dialogue around regional flood planning priorities and helped align TIFF deliverables with broader statewide efforts. Additionally, collaboration with the GLO's Texas Coastal Resiliency Master Plan (TCRMP) provided valuable insights into coastal hazard mitigation and recovery, enhancing TIFF's understanding of technical advisory processes and informing future planning. Collectively, these partnerships ensured that TIFF's work remained grounded in existing expertise, responsive to community needs, and aligned with ongoing flood resilience initiatives across the state.

Updates and Outcomes of the Outreach Plan

To fulfill the goals of this objective, TIFF successfully developed and implemented a comprehensive outreach strategy that engaged regional planning groups, technical experts, and non-technical stakeholders throughout the duration of the project. This strategy was continuously refined through annual reassessments of user needs and feedback mechanisms, ensuring that outreach efforts remained responsive, inclusive, and effective.

- **Sustained Expert Collaboration** - TIFF maintained strong relationships with TDIS, CHARM, the GLO, and other key experts and stakeholders across all Components of the project including extensive collaboration with the TATs, including regular consultation and feedback loops throughout the duration of the project.
- **Component-Specific Workshops** - TIFF hosted Component-specific workshops aimed at facilitating targeted discussions around coastal flood modeling, data visualization, and planning tools. These sessions were designed to gather actionable insights from both technical and non-technical participants, while also promoting cross-agency collaboration and knowledge sharing. Serving as a cornerstone of the project's engagement strategy, the workshops played a critical role in refining TIFF deliverables and ensuring they remained aligned with the evolving priorities of regional planning groups and community stakeholders.
- **Integrated Flood Modeling Brown Bag Seminar Series** - TIFF launched the Integrated Flood Modeling Brown Bag Seminar Series to foster dialogue and broaden engagement around cutting-edge flood modeling and analysis tools. This monthly, informal seminar brought together experts, planners, and community representatives to explore critical advancements that support flood resiliency planning, emergency response, and water resource decision-making. By leveraging existing outreach programs and agency networks, the series also encourages participation from non-technical stakeholders, creating an accessible platform for sharing research, case studies, and lived experiences. (See Supporting Material 3-17 for more information).
- **Annual Reassessment and Plan Updates** - TIFF conducted annual evaluations of stakeholder needs using surveys, interviews, and feedback sessions. Insights from these assessments guided updates to the comprehensive outreach plan, helping ensure its alignment with evolving flood planning and mitigation priorities. The evaluations also informed the preparation of annual progress reports, which documented outreach activities, summarized stakeholder engagement outcomes, and offered recommendations to shape future efforts.
- **Academic and Conference Presentations** - TIFF shared project updates and outcomes through presentations at universities and professional conferences, including the TFMA annual conference. These engagements helped disseminate findings, foster academic dialogue, and strengthen connections with researchers, practitioners, and policy leaders across Texas.
- **Technical Surveys and interviews with non-technical audiences** - To better understand how flood risk information is perceived and utilized by non-technical audiences, TIFF conducted a series of targeted assessments. These included a TFMA survey focused on evaluating the effectiveness of flood risk communication and visualization guidelines, informal interviews with TFMA conference attendees to gather qualitative insights, and a statewide survey designed to test elements of the flood

information design and communication guidelines developed during the project. These efforts provided valuable feedback on the clarity, accessibility, and usefulness of flood-related materials, informing refinements to outreach tools and enhancing stakeholder engagement across diverse communities.

Objective 4: Support the development of flood communications and educational materials

While identifying effective strategies for communicating flood risk, Study Providers and TAT members recognized significant overlap between Component 2 (Data Management and Visualization) and Component 4 (Planning and Outreach). Data visualization emerged as a powerful tool for conveying flood risk, underscoring the importance of integrating technical design with a deep understanding of target users. To improve coastal flood UIs, it is essential to consider the needs and perspectives of these users throughout the design process, not just at its conclusion. *The TIFF Communication Guidelines* developed under both Components 2 and 4 are complementary and mutually reinforcing. Accordingly, the conclusions of Component 4 Objective 4 (focused on supporting the development of flood communications and educational materials) are presented in tandem with Component 2 Objective 4. This integrated approach reflects a broader shift in terminology and practice, replacing “end-user” with “target user” to emphasize the importance of early and continuous stakeholder involvement in the design and delivery of flood-related tools and messaging.

Objective 6: Perform a literature review on planning tools and develop a list of data modeling needs for planning tools

Rather than conducting a traditional literature review, TIFF undertook a targeted inventory analysis of existing planning tools used by federal, state, and local agencies to support flood risk reduction decision-making. This effort focused on cataloging tools based on their purpose, applications, data requirements, limitations, key takeaways, and publicly available resources or websites. The goal was to assess how these models evaluate and compare the performance of flood mitigation alternatives, and to identify opportunities for aligning H&H model outputs with planning support needs.

The analysis was conducted in collaboration with coastal flood modeling engineers and planners, ensuring that technical insights were grounded in practical planning contexts. Through this process, TIFF identified several critical opportunities to enhance planning decisions by integrating compound flood risk modeling. These include improving problem identification by recognizing all contributing hazards and ensuring model domains reflect the full extent of potential consequences; incorporating life safety considerations that account for the timing, duration, and spatial extent of multi-source flooding; and developing methods to measure comprehensive benefits that reflect agency priorities and community values, including equity and environmental justice. While structural damage is more readily quantified, compound flooding can produce varied economic impacts across populations – affecting income, mobility, access, and long-term property value.

This section is organized to guide readers through the implications of compound flood events on planning, the mechanics of consequence modeling, and how compound risk can be incorporated into USACE planning frameworks. It also outlines practical applications, technical considerations, and the planning formulation process, including subtopics such as problem identification, alternative evaluation, approved economic models, benefit categories, and a detailed planning model inventory.

PLANNING MODEL INVENTORY

TIFF conducted an inventory analysis (see Table 4-1 for a sample and Supporting Material 4-5 for the full inventory) alongside a literature review to evaluate the planning tools and models used by agencies in flood risk reduction efforts. The inventory categorizes available resources into data access tools, area-specific resources, and planning models. Data tools provide information on area characteristics and future scenarios to support alternative development and identification of affected zones, while planning models estimate the consequences of specific alternatives and assess the likelihood of achieving desired outcomes.

Table 4-1. Planning model inventory example: Hydrologic Engineering Center Flood Damage Reduction Analysis (HEC FDA).

Main Purpose	Conducts integrated hydrologic engineering and economic analysis of flood risk management plans using risk analysis procedures for formulating and evaluating flood risk management measures
Applications	This model is appropriate for evaluation of performance of a non-erodible, solid feature, such as a wall or levee. The software 1) stores hydrologic and economic data necessary for an analysis, 2) provides tools to visualize data and results, 3) computes expected annual damage and equivalent annual damages, 4) computes assurance of annual exceedance probability and as required for NFIP Accreditation Recommendation, and 5) implements the risk analysis procedures described in EM 1110-2-1619
Data Needs	H&H profiles of water depth for 8 flood frequencies (2-yr, 5-yr... 500-yr) flood events and study reaches and index points Structure inventory that details types, condition, elevation, size and location of assets, Depreciated Replacement Cost Estimate Geographic extent of study area
Limitations	This model is appropriate for evaluation of performance of a non-erodible, solid feature, such as a wall or levee The analysis relies on an events-based evaluation framework
Takeaway	This is an approved tool for USACE project that supports in depth feasibility studies
Website	https://www.hec.usace.army.mil/software/hec-fda/

The review, developed in collaboration with coastal flood modeling engineers and planners, aimed to align H&H model outputs with planning needs. Consultations confirmed that compound flood model outputs must be formatted consistently to integrate effectively with planning models. The interface between flood planners and modelers is critical during model design, where underlying assumptions shape the relevance and applicability of outputs. Future agency coordination should ensure the inventory reflects the types of planning decisions and models in use.

The analysis identified opportunities to enhance planning through compound flood modeling by:

1. **Improving problem identification** - accounting for all flood sources and ensuring model boundaries encompass the full area of impact.
2. **Addressing life safety risks** - considering how timing, duration, and extent of flooding from multiple sources affect safety outcomes.
3. **Defining comprehensive benefit measurement** - capturing broader agency and community values—such as equity and environmental justice—requires recognizing the varied and often hard to quantify economic impact of flooding, including effect on income, mobility, access, and property value.

Supporting Material 4-5 summarizes current tools and applications, while relevant H&H modeling resources are discussed in Supporting Materials 3-5.

Consequences of Compound Flood Events on Planning Efforts

Flooding in coastal and riverine areas does not always stem from a single, isolated hazard. In many systems, compound flooding, the convergence of different flood drivers such as storm surge, riverine flows, and intense rainfall, can produce inundation depths that exceed those from individual events. These overlapping processes become particularly significant in areas where inland flooding meets coastal tides or storm surge, known as *transition zones*. Traditional methods of evaluating flood risk often focus on either riverine or coastal hazards independently, potentially underestimating the true extent of flood exposure. Thoroughly modeling compound flooding improves understanding of where and when higher flood levels may occur, offering vital insights for planning, design, and policy decisions.

Determining the differences in water levels caused by compound flooding is not merely an academic exercise. Transition zones may experience greater water levels during the compound event than in either of the individual events, thereby leading to higher risk. Incorporating compound flooding into models can reveal variations in both severity and spatial distribution of flood impacts, potentially altering the overall risk perception withing the study area. A more accurate assessment of how multiple hazards interact may provide deeper insights into the most effective strategies for managing and mitigating risk.

From both an economic and engineering standpoint, accurately capturing these overlapping hazards is crucial for effectively diagnosing and evaluating the overall hazard. If economic models (and subsequent analyses) that estimate consequences of flooding fail to account for and reflect the extra water contributed by another flood source, several serious risks may arise:

- **Inaccurately capturing damages** - Two inaccuracies can occur. If multiple sources are not modeled comprehensively, fewer assets may appear to be flooded and the depth of water at flooded structures may be understated/overestimated. Simultaneously, benefits from addressing one flood source may overstate overall risk reduction since additional sources of flood depth are not captured.
- **Geographic boundaries limit potential solutions** - Structural solutions that may perform well on a regional scale to reduce multiple risks may not be considered or justified as a result of inaccurately defining the extent of the flood vulnerability. A smaller scale feature (e.g., a levee) designed for one hazard may not be as beneficial under a more complex joint-flood scenario.
- **Life safety and residual risk** - All flood hazards include uncertainty, and compound events are more variable in extent and consequences. Incomplete flood extents and depths may limit risk reduction or misinform agencies and residents of the overall life safety hazard. Oversimplifying the potential flood hazard may reduce awareness of natural hazards, likelihood to evacuate or take protective measures.

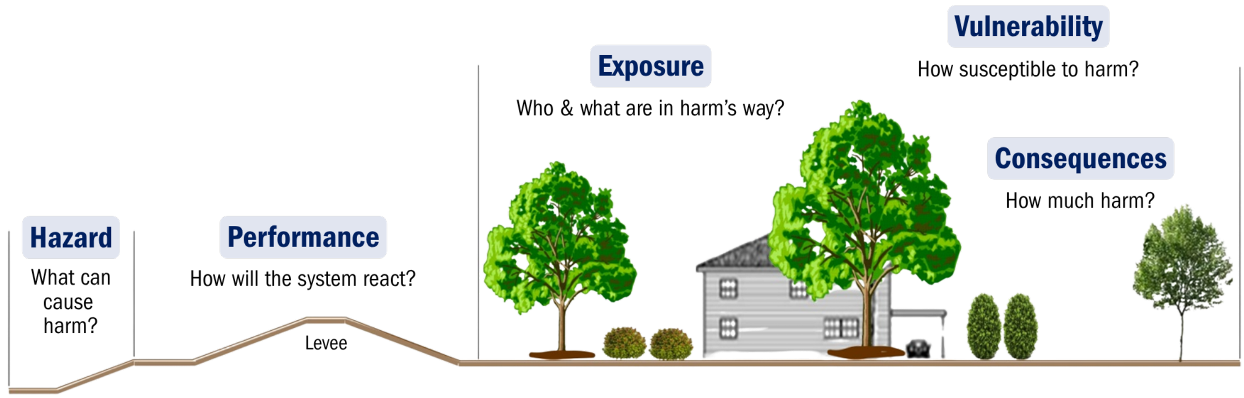
How Do Models Calculate Consequences?

Economic models estimate flood consequences by combining H&H output, such as flood depth and extent of inundation, with damageable assets in the study area. Each agency applies its own procedures to define benefits and quantify damage reduction from proposed solutions, with the level of modeling rigor often reflecting the significance of the decision and agency priorities. FEMA and the U.S. Department of Housing and Urban Development (HUD) are two federal agencies that fund flood risk reduction actions, that have developed simpler benefit estimation tools to support agency applicants and partners in computation of flood damages. The GLO flood planning effort includes development of a low complexity tool to support consequence estimates to support state flood plan project screening and recommendations.

USACE policies for flood consequence modeling require that the results are reproducible and consistent across all regions. Benefit-Cost Analysis (BCA) is a key component to project justification for authorization and construction. To illustrate the modeling choices and their influence on the resulting consequence estimates, this section will describe the USACE economic modeling approach and highlight importance variations in the results depending on the study area conditions and source of flood hazard.

Any consideration of how to best account for compound flood risk within USACE models requires an understanding of how risk is estimated within the models. USACE describes risk as a function of the hazard (what causes harm), the performance of any protective elements (e.g., levees, seawalls), and the consequences of flooding. Those consequences themselves are functions of exposure (what's in harm's way) and vulnerability (what happens when it's exposed to the hazard).

Risk = f(Hazard, Performance, f(Vulnerability, Exposure))



Hazard + Performance + Exposure + Vulnerability + Consequences = Risk

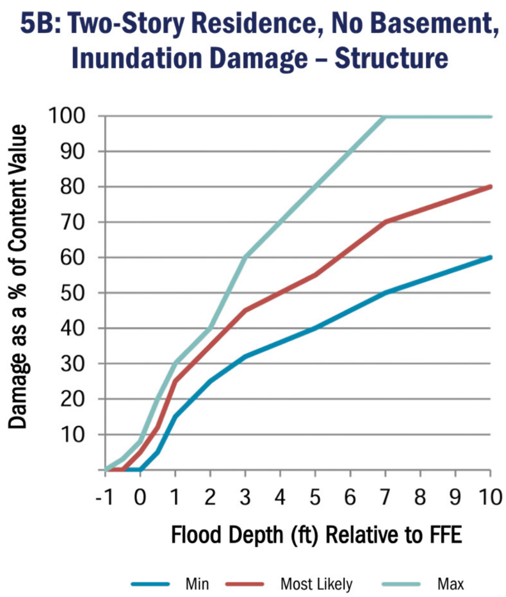
(probability & severity of adverse consequences)

Figure 4-2. ER 1105-2-101 risk assessment for flood risk management studies.

In both coastal and riverine USACE models, flood hazard is typically represented by the maximum water level observed during a storm event, despite the range of engineering inputs involved. The Generation 2 Coastal Risk Model (G2CRM), a Monte Carlo-based life-cycle model, incorporates storm hydrographs along with tide, sea level change, and wave data to compute total water levels at each time step. However, the G2CRM only uses the peak value to estimate consequences. Similarly, the HEC-FDA 2.0 riverine model (though not event-based) relies on depth grid rasters to represent water surface elevations for a set of annual exceedance probability (AEP) events and selects the highest water level for consequence analysis. Other tools such as HAZUS and Delf-FIAT follow a comparable approach, using depth grids to identify the maximum inundation level across the study area during a given event.

In these models, the maximum water level is the representation of the hazard and is used to determine consequences. Consequences tend to be the physical damage caused by the hazard, and that physical damage is calculated on an asset-by-asset basis. That water level experienced by each asset is compared to each structure's first floor elevation (FFE), which is defined as the sum of the ground elevation and the structure's foundation height. The relative distance between the maximum water level and the FFE is referenced against the structure's user-assigned depth-damage curve (DDF). DDFs are monotonically increasing functions which have been developed via empirical study that show the relationship between flood depth and damage as a percentage of structure value. The value yielded by the DDF at the water depth represents the percent damage, relative to the structure's value, that the structure takes in that storm event.

As an example: if the maximum water level experienced in a storm event by a structure is 12 feet NAVD88 and the structure's FFE is 10 feet, the water is 2 feet above the FFE. If the structure is a two-story residence with no basement, we can use the North Atlantic Coast Comprehensive Study's Prototype 5B DDF to determine the most likely percentage of structure value the structure will lose. Here, the structure is expected to lose 20% of its structure value as a result of the inundation. If its structure value is $500,000, then the dollar-denominated damage of that structure in the event is $100,000.



Prototype 5B: Two-Story Residence, No Basement, Inundation Damage – Structure			
Flood Depth	Min	Most Likely	Max
-2	0	0	0
-1	0	0	2
-0.5	0	1	3
0	0	5	8
0.5	5	10	10
1	9	15	20
2	15	20	25
3	20	25	30
5	25	30	40
7	40	50	55
10	50	60	70

Figure 4-3. The 5B depth-damage function from the North Atlantic Coast Comprehensive Study.

The purpose of the example above is to demonstrate that, in USACE models such as HEC-FDA and G2CRM, the hazard is primarily represented by maximum water level. (Other models may also account for damages from waves and erosion as well, though this is beyond the scope of this discussion.) While hazards may differ in other fundamental ways, including temperature, velocity, salinity, and duration, these factors are often accounted for on the DDF side (e.g., higher-duration storms may require the use of steeper DDFs) rather than on the hazard side.

How Can Compound Flood Fisk be Accounted for Within USACE Planning Models?

As maximum water level is one of the key factors that determine damages, anything that can change the maximum water level in a given event has the capacity to change consequences. An event with multiple flood sources may have higher water levels in transition zones than events with only one flood hazard, so accounting for compound flooding is needed to accurately represent the consequences of these compound floods.

An integrated approach that accounts for different types of events, along with their associated probabilities, is needed. To account for compound flood risk within USACE models, the inputs that represent the water levels will have to be adjusted. The needed adjustments will differ based on the model being used and its unique coastal or riverine inputs.

- For HEC-FDA 2.0, that adjustment can be with the depth grid raster. These rasters are used to show the maximum water surface elevation at each point in a study area in each modeled event (the 50%, 20%, 10%, 5%, 2%, 1%, .5%, and .2% AEP events). To integrate compound flooding into risk assessment, teams can use depth grids that include multiple sources of flooding while ensuring that the reoccurrence interval is adjusted based on the probability the joint event occurs.
- For G2CRM, the storm hydrographs within the h5 files may need to be adjusted. Model areas may need to be split up to reflect which areas only have one risk driver and transition zones where there are multiple risk drivers.

Of note is that, when describing compound flood risk, what's being described is often multiple independent events happening at the same time. Consider a 10-year (10% AEP) rainfall event occurring during a 10-year (10% AEP) surge event: if these are independent events, the joint probability of the joint event is 1% AEP (10% * 10%). Note that when considering compound floods there are many different types of events that can occur with 1% AEP, including (but not limited to) a 1% AEP rainfall event, a 1% AEP surge event, and the simultaneous 10% AEP rainfall and surge events. These different types of events, and their related reoccurrence intervals, may all need to be accounted for within the modeling.

PLANNING APPLICATIONS

Planning applications can be considered in two broad categories to assess the intersection of the compound flood modeling framework:

1. **Technical analysis regularly conducted by agencies that develop riverine and coastal flood risk management plans** - The technical analysis category includes the planning steps that apply H&H model outputs to study area conditions to characterize flood risk and consequences, develop potential solutions, and support plan comparisons. These analyses are the “plan formulation” efforts of the USACE or other federal agencies, such as FEMA or HUD. These efforts typically follow standard processes to ensure consistent and fair evaluation and comparison of potential Flood Risk Management (FRM)/Coastal Storm Risk Management (CSRM) projects (see Supporting Material 4-5 and 3-15 for more information). State, regional, or local agencies conduct planning studies in cooperation with federal agencies or may develop flood studies, plans for funding, or coordination with relevant funding sources to establish and address regional flood priorities. This category of analyses compares the necessary model inputs to ensure compatibility of planning tools with new H&H output data and where compound flood model outputs can better support planning decisions.
2. **Considering end-users who incorporate risk considerations in various policy decisions such as infrastructure investment, land use, public safety, insurance, and more** - The second category reflects the broader consideration of flood risk in development, financing, and operational decisions regarding the siting and operation of infrastructure. This category informs data development and supports the inclusion of compound flood risk in multiple contexts. Outreach efforts will seek an understanding of existing end-users to improve the type of information and compound flood risk information that can support current planning decisions and expand consideration of flood risk across multiple applications.

TECHNICAL APPLICATIONS

Planners conduct technical plan formulation efforts with methods to support the comparison of alternative performance and selection. Performance assessment methods differ in overall function and specificity across agencies based on the project authority, funding source or program, and the scale of the proposed project. Projects proposed for funding by or in coordination with USACE or FEMA mitigation grants require consistent evaluation of cost benefits to ensure a replicable process is applied to identify and approve selected projects fairly.

Considering the technical analysis that planners and economists conduct raises several primary themes to ensure that the compound flooding framework will support existing planning efforts. The USACE plan formulation studies require analyzing performance and comparing cost and benefit streams over time to justify a project. Specific models are required to model the expected performance of potential flood risk solutions in coastal and riverine settings. These models each require specific hydrologic and hydraulic model outputs to translate the WSEs and conditions expected for each flood condition with the physical study area conditions. These models are briefly described in Supporting Material 4-5, which summarizes the model application and model input needs.

The first focus of evaluating the integration of planning tools and the TIFF integrated framework was to confirm that the H&H model output would be compatible with continued application of most agencies existing planning and economic models. In other words, any H&H output for compound flooding that improves the specificity of flood risk information can only improve the study outcome if it is clearly understood and compatible with the existing planning tools and models. If the output is produced in new or different units or formats, it would not readily support planning and economic analysis and the team since it would not be compatible with the existing planning tools and models.

Consultation with H&H modelers clarified that the compound flood modeling system output format would not differ from the current H&H modeling (i.e., pluvial, fluvial, and surge flood model) output format. The H&H output will reflect the flood risk from compound events but will be ready for import into the planning models in the necessary format, and compatibility is not a concern. Rather, the assumptions underlying the H&H model development will reflect the additional aspects of compound flood risk in the analysis. The H&H model design will require collaboration between the planner and the hydraulic modelers to reflect the appropriate boundary conditions and the H&H conditions that produce the best H&H output to support the planning considerations. Customizing the H&H model design presents an opportunity to base decisions on the most applicable hydraulic and hydrologic conditions that will require exploration of the types of decisions that planners make in different flood studies across different agencies.

PLANNING FORMULATION AND EVALUATION STEPS

Planners supporting plan formulation within a flood risk study combine H&H model outputs with study area conditions to produce relevant information to support the plan formulation phases, including:

1. Problem Identification and Preliminary Alternative Formulation

Identifying the water resources problem to be solved is a critical first step in formulating and defending a flood risk management project. The baseline condition combines H&H and physical conditions to define the flood risk exposure of study area assets, populations, and physical conditions, and diagnose applicable risk mechanisms.

A key aspect of the problem identification phase is to characterize the flood risk mechanism with sufficient detail to recognize the actual risk mechanism and not a symptom of the flood risk. A compound flood risk modeling system will support a thorough definition of the applicable risks and their interrelationship. Inundation mapping of the "Without Project Condition" often supports the preliminary diagnosis of the scale of the problem and conceptual structures and non-structural solutions that could address the hazard. The USACE refers to the individual structures as "features" or "measures" (e.g., channel improvement, detention ponds, seawalls), and "scales" refer to the size of the features. Since compound flood hazards may produce very different inundation maps under different scenarios, modelers and planners will want to define the best formats to convey the inundation extent, depth, and duration to communicate the variable consequence of the flood risk.

The problem identification step is an opportunity for the modelers and planners to clarify whether compound flood modeling is necessary for the study. The relative impact of coastal flooding may dominate inland flooding contributions (or vice versa), and a complex model may only be necessary for some study areas. To support Texas state flood planning proposals over time, future detailed modeling studies are needed to identify the criteria and areas where tidally influenced waterways (whether now or in projected future conditions), significant riverine flood heights, or physical conditions warrant the additional time and specificity of compound flood modeling.

Until those detailed modeling studies are performed, planning for modeling coastal floods may consider the following three sources of coastal flood extents for the Texas coast as an initial estimate of the extent of regions to investigate compound flooding:

- USACE CTXCS ADCIRC model domain (Melby et al, 2021)

- FEMA 0.2% AEP coastal limit of inundation (FEMA, 2011)
- NOAA Maximum of the Maximum (MOM) Envelope of High Water based on the Sea, Lake, and Overland Surges for Hurricanes (SLOSH) hurricane modeling

NOAA's MOM data, which identifies an envelope of inundation limits from several category five hurricanes, extends beyond FEMA's 0.2% AEP flood area but does not exceed the CTXCS model domain. The GLO's River Basin Flood Studies also considered these three sources to identify the preliminary regions where the H&H modeler needs to consider rainfall-runoff and surge events for flood hazard estimations. Measure screening and the initial alternative development can be completed by applying engineering expertise about the function and cost of potential risk reduction measures and comparing them to the maximum potential damages that a study might address with an alternative. As compound flood modeling provides a more detailed understanding of the coincident flood sources, planners will have additional clarity on how the multiple risk mechanisms impact the study area, which will support the preliminary evaluation of appropriate risk management strategies.

2. Alternative Performance Evaluation

Although models and analyses differ across agencies and authorities, all flood risk studies will combine the H&H model outputs with a structure inventory of damageable resources and assets in the study area to quantify baseline damages in the existing and future without project conditions. Supporting Material 4-5 lists the most frequently used planning models. TIFF's outreach will compare and expand the list of existing models and their application by other agencies. USACE studies require approved models to translate the H&H conditions in the study area into quantified consequences by integrating the H&H conditions with an inventory of assets, such as structures, contents, and other infrastructure. The economic models that complete this analysis vary based on several characteristics, which include the flood risk mechanism, the function of the structure proposed to manage the flood risk, and the physical conditions in the study area.

APPROVED ECONOMIC MODELS

The USACE policy requires consistent application of this analysis and designates specifically approved models for specific applications. The ERDC G2CRM is applied for an events-based simulation of life cycle function of a structural or non-structural measure. ERDC Beach FX is required to estimate the benefits of beach fill or a soft sediment solution to coastal flooding, and the HEC-FDA is required for riverine or coastal studies that propose a structural measure that is not erodible over time.

A new model, Coastal Hazards Analysis and Risk Toolkit (CHART), is currently being developed by the USACE in consultation with technical users. A development goal is to create modular or scalable applications of H&H modeling and economic functions that adjust the complexity and data needs for use in multiple phases of FRM studies. Technical analysis can require repetitive updates, or model runs as FRM studies evaluate alternative plans in increasing detail over study phases. The engineering functions of the model are the initial components under development. Once operational, the H&H module will feed data that supports the economic evaluation of many project benefits and planning considerations. The model will support the typical quantification of expected flood damages with detailed consideration of depth and timing of inundation. It will also support life safety risks by characterizing water flow depth, direction, and velocity. When completed, the CHART model will combine engineering and economic analysis in multiple phases of USACE plan formulation. The model intends to improve the efficiency of data collection, input, and model setup and support FRM studies with two tools:

1. **Scoping tool** - A user will see the expected annual damages for coastal hazards in the defined study area to support consideration of the elements to include in the study scope.

2. **Feasibility tool** - This tool is being designed to replace the functionality of Beach-FX and G2CRM with a modular lifecycle analysis modeling framework. It will rely on well-developed engineering and economic models that work as a system and have been developed with the appropriate level of detail.

One important input to the economic models that quantify plan performance is the depth damage function, which correlates the depth of flooding with the resulting proportional damage per type of structure and is applied to estimate overall dollar damages. The depth damage function is derived outside of the economic model, based on research of storm history, and updated over time to estimate the percent damage for structures per foot of water. An economist selects each study's relevant depth damage function based on the flood risk mechanism, flooding duration, and salinity. At present, in areas vulnerable to flood risk from multiple sources, H&H models typically simulate the coastal or riverine conditions of the dominant risk and reflect one representative input to capture an average or likely contribution of water from the other risk mechanism. H&H modelers, economists, and planners may need to review the existing depth damage functions to address their applicability in compound flood modeling.

Compound flood risk analysis with current planning tools will require a sequence of analyses to assess how multiple flood risks impact the study area. Effective problem identification requires H&H outputs that support thorough flood hazard descriptions. A preliminary list of the necessary information is below:

- geographically scalable H&H data across the study area that allow for reach delineation according to similar asset types in contiguous extents or comparable water levels and which include geocoded unique identifiers for assets within the 500-year inundation extent
- refined depth damage functions or appropriate combination of damages to reflect compound flood risk sources and to reflect the importance of water current/velocity for life safety considerations
- individual flood risk mechanism probabilities and frequencies of each risk mechanism: fluvial, pluvial, storm surge or wave, and years of record; depth, timing, and duration of flooding of individual flood risk mechanism
- designation of "transition zones" where co-occurrence and dependence of flood mechanisms exist, such as coastal deltas or tidally influenced bayous or water bodies
- timing and dependency of flooding from respective risk mechanism
- probabilities and frequencies for distinct flood risk mechanisms in the transition zones clarify the timing and duration of flood water levels, the dominant component of the flooding mechanism, and the joint probability of multiple flood risk mechanism occurrence and impact on non-linear water level response

BENEFIT CATEGORIES AND TYPES

Cost benefit analysis is the most common way to measure the performance of flood risk management. It quantifies the flood damage reduction in dollars to structures and contents in the study area. Cost-effectiveness is reflected by the benefit-to-cost ratio and net benefits, which demonstrate whether anticipated benefits from the alternative are greater than the implementation cost. Benefit categories reflect agency priorities and include fundamental benefits measured in dollars and non-dollar-denominated metrics.

Plan performance and cost-effectiveness are measured with dollar-denominated benefits with the same planning and H&H tools applied to characterize the flood risk problem. Benefit categories represent monetary and non-monetary beneficial outputs of alternative plans. Additional metrics are applied to capture broader benefits categories, quantified in dollars or other units, or qualitative comparisons of effectiveness. Agencies evaluate proposed flood risk management projects against different benefit standards based on the applicable authority and funding source. Therefore, benefit types across different agencies may capture similar effects but with slightly different definitions and guidance for tabulation. The current emphasis within the USACE and multiple agencies presents an opportunity to define additional metrics to assess broader agency and societal objectives. TIFF outreach included an interagency workshop (Supporting Material 4-6) to clarify shared evaluation criteria and explore additional impacts informed by more detailed H&H model outputs.

USACE feasibility studies evaluate and display plan benefits in four accounts established by the U.S. Water Resource Council's 1983 Principles and Guidelines for Water and Related Land Implementation Studies (P&G). The four accounts are Net Economic Development (NED), Environmental Quality (EQ), Regional Economic Development (RED), and Other Social Effects (OSE). The benefits and effects of all four accounts (P&G 1983) are considered during the plan formulation process, and plan selection emphasizes the plan that reasonably maximizes net NED benefits, which is summarized below. Per the guidance in the memorandum from Assistant Secretary of the Army, Civil Works, dated January 5, 2021, Comprehensive Documentation of Benefits in Decision Document, studies should also identify a plan that reasonably maximizes total net benefits in the NED, EQ, RED, and OSE accounts. The four benefits categories are summarized below:

1. The NED account includes consideration of a measure's potential to meet the planning objective to reduce storm damages, decrease costs of emergency services, lower flood insurance premiums, and consider project costs. Costs and benefits used to evaluate the NED objective are not fully calculated at this stage; however, estimates can be made to gauge the overall cost-effectiveness of a measure for this initial screening. The NED account takes into consideration the effects of relative sea level change and a measure's adaptability to such changes.
2. The RED account includes consideration of the potential regional economic impacts of flooding. The Institute for Water Resources RED Procedures Handbook (2011-RPT-01) defines RED impacts as regional employment and/or income losses under the Future Without Project condition. Based on guidance from this handbook, the RED analysis evaluates the regional economic consequences of flooding and sea level rise (SLR) using FEMA benefit-cost analysis methodologies.
3. The EQ account considers ecosystem restoration, water circulation, noise level changes, public facilities and services, aesthetic values, natural resources, air and water quality, cultural and historic preservation, and other factors covered by the National Environmental Policy Act.
4. The OSE account includes considerations for the preservation of life, health, and public safety; community cohesion and growth; tax and property values; and the displacement of businesses and public facilities. For evaluation purposes, the OSE account is inclusive of the planning objectives to maintain recreation and safe evacuation routes, and the planning constraint to avoid conflict with legal requirements.

Objective 5: Investigate the opportunities to balance local cost-effective flood risk management analysis with regional flood risk considerations

TIFF's approach to investigating the balance between local cost-effective flood risk management and broader regional considerations was shaped by extensive stakeholder engagement, including dialogue with the Coastal Liaisons of the RFPGs. These conversations revealed a pressing need to understand how upstream/downstream dynamics and adjacent watershed interactions influence planning outcomes. Compound flooding (where multiple flood drivers converge) amplifies the consequences of flood events and introduces nonlinear impacts that complicate both the planning phase and the effectiveness of mitigation strategies. This complexity is further heightened when trying to reconcile project-specific interventions with regional-scale solutions, each presenting distinct tradeoffs in terms of cost, feasibility, and long-term resilience.

To address these challenges, TIFF emphasized a multidisciplinary, adaptive planning framework that integrates localized actions within a regional context. While project-specific outcomes may offer timely relief in constrained areas, regional approaches can layer mitigation strategies, reduce inundation across broader footprints, support critical infrastructure, and potentially reduce the overall cost at larger spatial scales. However, these solutions often require extensive coordination, consensus-building, and shared investment across jurisdictions. By incorporating scalable modeling and economic analysis, TIFF aims to support informed decision-making that reflects the interconnected nature of flood hazards and promotes sustainable, equitable outcomes across Texas communities.

REGIONAL VERSUS PROJECT-SPECIFIC SOLUTIONS

Flood risk frequently manifests most acutely in geographically constrained areas (e.g., topographic low points or narrow river passages) where water accumulation or flow restriction becomes pronounced. These localized vulnerabilities may appear straightforward to address through targeted interventions, such as enhancing channel conveyance capacity or implementing diversion strategies to protect critical assets. However, regional approaches, which evaluate solutions within a larger area (e.g., a watershed versus a more discrete area like a specific stretch of river, tributary, or confluence) may be more cost-effective by considering all sources of water and combining multiple approaches to reducing flood risk.

Regional project scales may layer flood risk measures to address multiple routes of flood exposure and achieve a robust system. A system of measures can address flood risk on multiple levels and adapt more easily over time as physical conditions in the area change and risk grows. By reducing inundation across a larger area, the regional project may achieve more benefits that support economic conditions and improve life safety, such as keeping transit resources operational or preserving evacuation routes. Regional solutions across a larger scale may also incorporate a variety of natural and structural features to reduce erosion, attenuate waves, and detain flood water that might not be feasible in a smaller flood footprint or project. In some cases, a regional approach can share costs across jurisdictions or agencies and reduce the economic burden on flood prone communities or subdivisions.

Regional solutions offer the potential for broad-scale impact but often require informed participation and sustained funding commitments from multiple agencies. Achieving alignment across jurisdictions demands extensive consensus-building to define shared objectives and clarify problem statements. When structural measures (e.g., such as walls, culverts, or overflow areas) span multiple boundaries, collaboration among diverse partners can introduce complexity in feature design, alignment, and cost-sharing. These efforts may also result in uneven distribution of aesthetic impacts, dislocation, or real estate acquisition requirements.

While regional approaches can be more cost-effective in the long term, they are frequently challenged by the need for compromise, coordinated budgeting, and relocation logistics. To address these challenges, adaptive strategies (e.g., phased buyouts, incremental elevation of protective features, or staged implementation) can help mitigate initial disruptions. Over time, these actions support lower-risk community growth while preserving the integrity and scalability of regional flood mitigation efforts.

Each geographic location and flood source presents distinct challenges, requiring tailored approaches to flood risk reduction. The tradeoffs between regional and local-scale solutions should be carefully evaluated throughout key stages of the flood study process—including problem characterization, alternative development and screening, and assessment of potential impacts. No study area or hazard is identical, and the appropriate scale of intervention will depend on a range of factors, including hydrologic complexity, community priorities, and long-term resilience goals. Larger study areas may support extended periods of analysis and accommodate greater variability in flood risk over time, particularly as storm intensity and frequency increase. In contrast, localized solutions may offer timely protection and help preserve critical assets, though they must be considered within the broader context to ensure compatibility with regional strategies and future adaptation needs.

Flood risk studies should be scoped with an awareness of surrounding land uses and flood sources, and with a multidisciplinary team using available resources to define the problem, investigate the interrelationship with adjacent studies or flood risks, and to be thorough in the analysis to recognize and mitigate for inducing damages in one community while sending high water volumes into neighboring areas. Study scoping should recognize flood hazards can be interconnected, and that cost-effective solutions are definable across many extents. Reduced flood depths within a study area can induce flooding to adjacent communities if modeling is not reflecting downstream impacts under multiple conditions. To support this effort, TIFF recommends the establishment of a Texas Flood Coordination Office within an existing state agency to centralize flood efforts, maintain an official database, provide technical support, enhance collaboration, reduce redundancy, and optimize state and federal project impact beyond current volunteer-based efforts (Recommendation C4.9D).

Several initial steps to support cost effective flood risk projects that are scaled to address the current and future risk and the affected community will benefit from engineering tools and portals to support the evaluation of relevant factors. It is unrealistic to expect that a study schedule or budget to model all the surrounding consequences, but existing resources can be leveraged to inform investment decisions.

Defining the flood hazard requires a comprehensive understanding of the compound impacts of multiple flood sources. In most instances, H&H modeling may confirm that one flood risk dominates the secondary risk, which might confirm that compound flood modeling may not be necessary. However, secondary damage drivers can exacerbate flood impacts and should not be underemphasized. Compound flooding is typically most evident in the transition zone, and the transition zones differ across studies due to many physical characteristics. While intuition suggests that defining the transition zone could guide economic modeling, this analysis shows that compound flooding intensifies impacts even far inland. This may be due to lack of drainage capability, where the water cannot flow out to the receiving body/ocean during a coastal storm event. Therefore, the transition zone is an important consideration, but not the only one.

Resources to support evaluation of multiple flood hazard sources and can inform the flood study and alternative comparisons. H&H and economic models that can identify transition zones are evolving to reduce the time and cost required to complete a flood study. A new model, CHART, is currently under development by the USACE in consultation with technical users. A development goal is to create modular or scalable applications of H&H modeling and economic functions that adjust the complexity and data needs for use in multiple phases of FRM studies. Technical analysis can require repetitive updates, or model runs as FRM studies evaluate alternative plans in increasing detail over study phases. The engineering functions of the model are the initial components under development. Once operational, the H&H module will feed data that supports the economic evaluation of many project benefits and planning considerations. The model will support the typical quantification of expected flood damages with detailed consideration of depth and timing of inundation. It will also support life safety risks by characterizing water flow depth, direction, and velocity. When completed, the CHART model will combine engineering and economic analysis in multiple phases of USACE plan formulation. The model intends to improve the efficiency of data collection, input, and model setup and support FRM studies.

While the ultimate vision is to create a modular compound flooding tool that reduces duplicative modeling and calibration steps, the earliest functioning component of the larger suite of tools will support a pre-assessment of potential benefits as a preliminary screening step. The modular parts of CHART that will supersede the existing HEC-FDA and G2CRM economic models will be in development for several years. This model, or a similar interface should be available for communities to understand the surrounding and interrelated flood hazards at the beginning of a flood study. To support consistent, scalable, and context-sensitive flood modeling, future efforts should include the development of a checklist by H&H modelers and economists. This tool would guide model design based on study location and dominant flood sources, using GIS shapefiles and bivariate analysis to ensure thorough assessment of data need and hazard complexity.

What's the Value in Calculating Consequences and Risk Driven by Compound Flooding?

In general, there are two main ways to account for compound flooding: a stepwise (sequential) approach and a simultaneous (joint) analysis. A stepwise approach often looks like this:

- Model a coastal surge event (e.g., 10-year surge) and generate a depth grid
- Model a riverine event (e.g., 10-year river flood) and generate a depth grid
- For each structure, pick the higher damage from these two independent grids—so as not to "double count" the same structure's damage from two floods at once. This creates a single raster from which we can draw flood elevations for damage calculations.

This is straightforward and avoids double counting of damages from two events which may not have occurred independently. However, a stepwise analysis doesn't capture what happens if the water surfaces from each source actually combine to produce even deeper flooding in certain areas. A stepwise approach also does not need to only consider the maximum damage from any one event. Another alternative would be to sum the damages or to pick a value in between the maximum from one and the summed damages. Each solution has an issue. Using the maximum will undercount damages; using the summed value will overcount damages; and selecting a value between the two is likely to be arbitrary.

Alternatively, a simultaneous analysis seeks to combine the multiple sources of flooding into a single hazard event. Here is a simple instance of simultaneous analysis for joint hazard event presented when those events are independent.

- If the chance of a 10-year riverine flood happening at the exact same time as a 10-year surge is truly independent, a 1% joint probability is achieved (0.1 × 0.1).
- Engineering teams then generate a joint depth grid that reflects the combined hydraulic response (i.e., the potential that tides, waves, and the river all push water inland at once).
- The result may be higher water levels in certain transition zones than either single event alone would produce.

Simultaneous analysis will likely provide a better representation of the compound hazard, in that it explicitly captures the interplay of water from multiple sources. This may demonstrate higher calculatable damages in transition zones, potentially shifting the alternatives that are considered and selected, and may also show the need for more robust, comprehensive measures.

To demonstrate the impacts of accounting for compound flooding, the USACE team put together a case study estimating consequences from compound events using the two separate methodologies outlined above: the stepwise analysis, taking the maximum damage from both events; and a simultaneous analysis, calculating the damage in the joint event.

For the case study, the National Structure Inventory 2 (NSI2) was used. The NSI2 is a system of databases containing point-based structure inventories with associated fields. Each point represents a physical structure in the study area. The data leveraged from the NSI2 included:

- structure location
- structure value
- foundation height
- occupancy type

Water depth grids were taken from the Oso Bay region, developed through the GLO RBFS for a variety of individual and joint events. These WSEs are not a final product and are only used to illustrate economic consequences of each event. The depth of water in each event at each point was extracted. These elevations were then reduced by the structure's foundation height, providing a depth above FFE for each asset in each storm event.

The occupancy types within the NSI2 were used to assign a DDF to each structure. Sources for the DDFs included the NACCS and prototype curves from the Institute for Water Resources. For each storm event, the water level above FFE was referenced to the DDF to determine the percent damage the asset would take in the storm. The percentage was then multiplied by the structure value to determine the dollar-denominated damage taken by the asset in the storm. This methodology is similar to what would be used in a USACE feasibility study, though this analysis does not explicitly consider uncertainty and is a simple spreadsheet exercise.

Using the various depth grids described above, three comparisons are available, each comparing a stepwise consideration of damages from two events against the simultaneous calculation of damages from the joint event:

- stepwise surge 50-year, riverine 10-year vs. joint 500-year
- stepwise surge 10-year, riverine 10-year vs. joint 100-year
- stepwise surge 10-year, riverine 5-year vs. joint 50-year

Recall that, in the stepwise tests, the damage is the maximum of either of the events. In the table below, the joint damages are compared to the stepwise damages. In the larger, less frequent events, the joint damages are substantially higher (e.g., in the 500-year compound event, damages are 40% higher), while in the more frequent events, there is less difference between the two events. It is important to clarify that the stepwise evaluation does not represent or create a true joint-probability event. Instead, it separately models two distinct flood events (for instance, a 10-year surge and a 10-year riverine event) and then combines results by selecting the maximum damages at each location. This method does not reflect the actual probability of these events occurring simultaneously; rather, it simply provides a basic estimate of damages if both events were considered independently. The difference shown in the final column represents risk that would not be captured in a stepwise approach, risk is increased both spatially (i.e. new structures affected) and in intensity (i.e., individual structures receive more inundation).

Table 4-2. Joint versus step-wise damage comparisons on select events.

Scenarios	Joint Damage ($)	Stepwise Damage ($)	% Difference
Surge 50-year, Riverine 10-year	21,953,000	14,634,000	40%
Surge 10-year, Riverine 10-year	14,489,000	13,163,000	10%
Surge 10-year, Riverine 5-year	9,913,000	9,955,000	0%

The maps below illustrate a range of flood scenarios to highlight how different flooding conditions affect structures within the study area. Each scenario categorizes the impacted structures based on the primary flood driver—riverine flooding (blue), coastal storm surge (green)—or identifies those significantly impacted by compound flooding (red). The red dots specifically indicate assets where the damages from a simultaneous flood event exceed the damages captured by assessing either the riverine or surge event independently by at least 10%. Thus, these red points represent impacts that traditional stepwise modeling would not effectively capture. This is clearly emphasized in Figure 4-4 below, where a significant portion of structures, even some of those far inland, experience exacerbated inundation compared to a 10-year riverine event on its own.

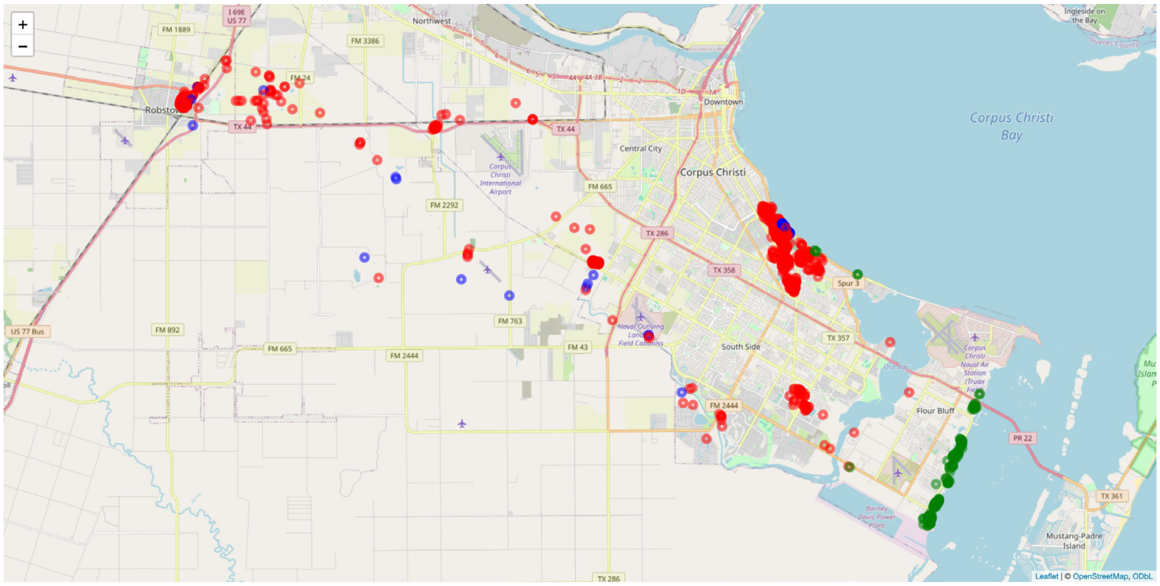


Figure 4-4. Joint 500-year event (surge 50-year, riverine 10-year).

The damage estimates summarized below clearly indicate that riverine flooding is the predominant flood hazard within the study area. Damage associated with riverine flooding substantially exceeds that caused by coastal surge events, highlighting riverine sources as the primary driver of economic losses. For example, the 100-year riverine flood alone results in significantly higher damages compared to a comparable coastal surge event.

However, while riverine flooding clearly dominates the overall damage profile, the introduction of coastal conditions—even minor surge events—can exacerbate impacts in specific localized areas, particularly within transition zones or regions with limited drainage capability. Thus, although riverine hazards primarily drive flood damages in this specific study area, the potential compounding effects introduced by simultaneous coastal events remain critical to accurately evaluating the total risk. This observation underscores the importance of explicitly considering joint flooding scenarios within flood risk analyses.

Table 4-3. Damages from all 100-year events.

Event Type	Total Damage
100-Year Surge Only	$30,330,000
100-Year Riverine Only	$71,850,000
100-Year Joint - 1-Year Riverine, 100-Year Surge	$43,760,000
100-Year Joint - 10-Year Riverine, 10-Year Surge	$14,490,000

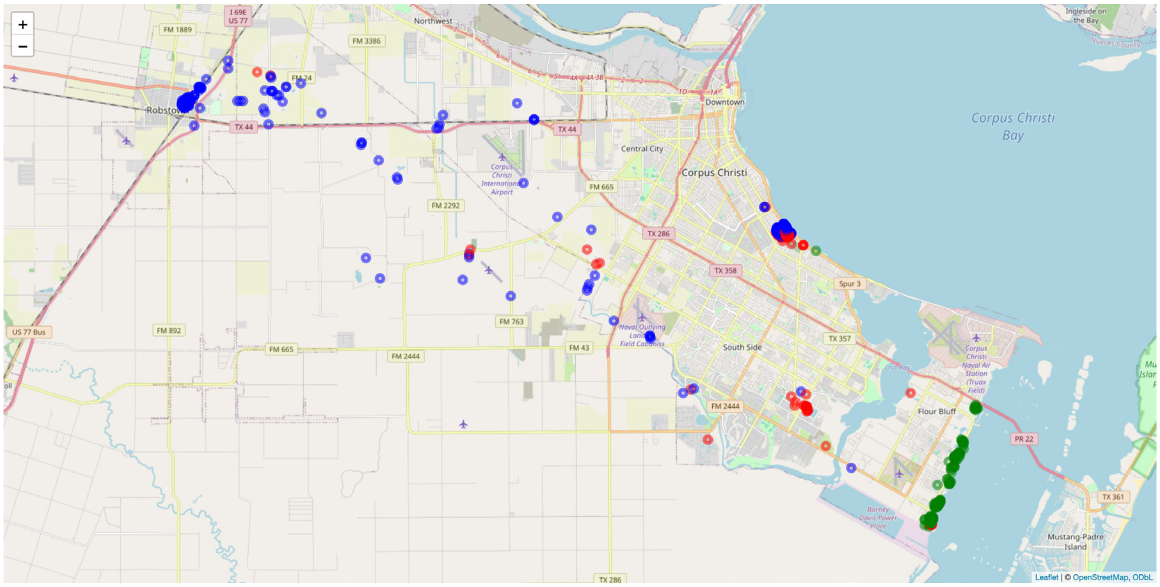


Figure 4-5. Joint 100-year event (surge 10-year, riverine 10-year).

There are significantly more assets affected by joint flooding in the joint 500-year event map (denoted by the red dots) than in other events in general. This is an intuitive finding: with smaller joint events, the effects may be localized, but with larger events, there is more interaction between the hazards, which leads to deeper water and higher damages. In this case study, the 100-year and 500-year joint events saw higher damages, whereas the 50-year event did not. Other study areas may be more or less sensitive to compound flooding. The 100-year joint event (10-year surge and 10-year riverine) shows fewer red dots, indicating that the compounding effects in more frequent scenarios are comparatively localized. Additionally, examining the individual 100-year riverine and surge events separately reveals distinctly different spatial damage patterns, emphasizing that flood impacts vary substantially depending on the flood driver involved. Riverine flooding predominantly affects inland areas along watercourses, while surge-driven flooding primarily impacts coastal zones. This spatial comparison underscores the importance of explicitly modeling compound flooding scenarios, particularly larger, less frequent events. It also highlights that effective flood risk management requires understanding not only the magnitude but also the spatial distribution of compound flood impacts to ensure appropriate and targeted mitigation measures.

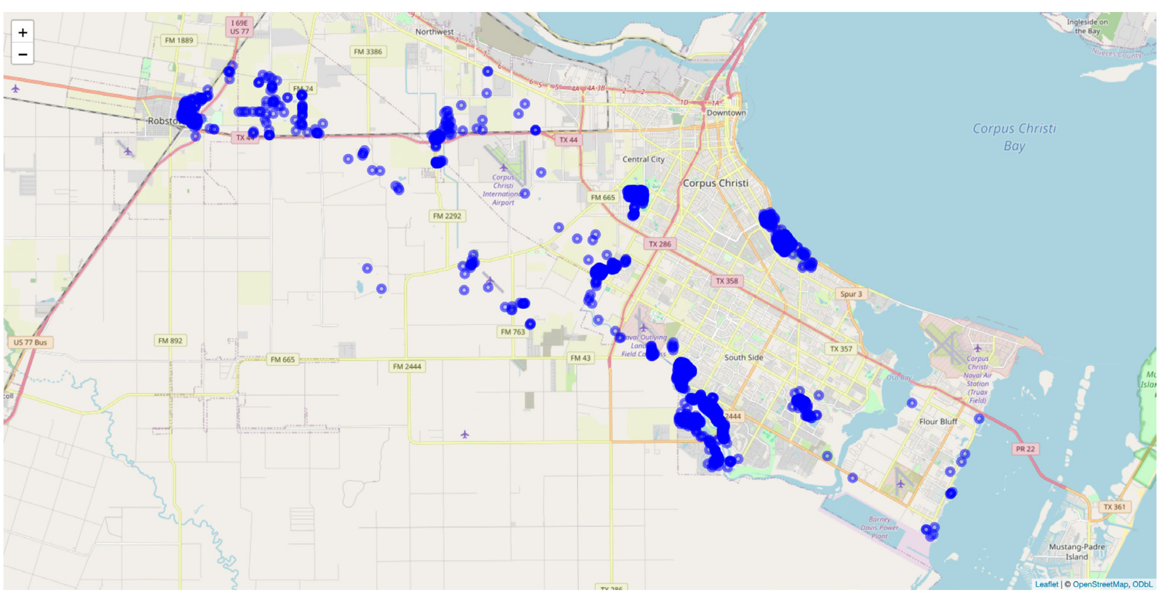


Figure 4-6. Riverine 1% AEP.

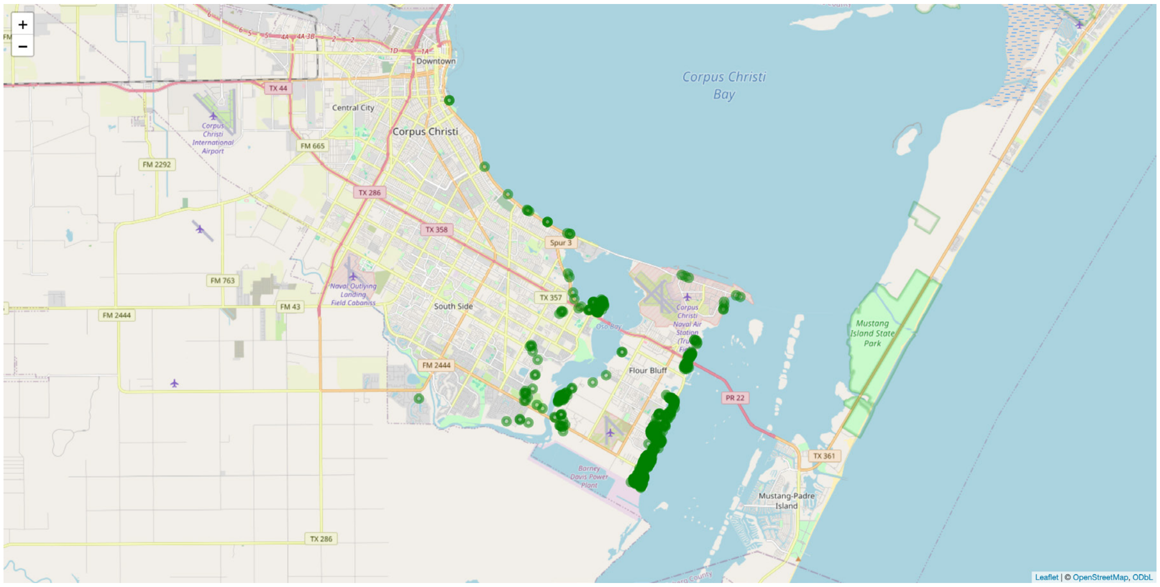


Figure 4-7. Surge event 1% AEP.

FLOOD RISK MANAGEMENT POLICY APPLICATIONS

Compound Flood Planning Decision Support Workshop

TIFF hosted a Compound Flood Planning Decision Support Workshop with 16 participants on April 18, 2024. The purpose of the workshop was to evaluate existing decision-support tools and models currently used in flood risk management studies or planning decisions and to identify the needs related to H&H model outputs for Compound Risk Analysis. The workshop also identified opportunities to improve decision-making through compound flood modeling and improve the H&H outputs to better align with the planning objectives.

Access to accurate and understandable information about compound floods is crucial for making informed decisions related to flood risk planning. It helps to broaden the understanding of the model output, provides valuable insights for planners and agencies responsible for managing flood risks, enhances existing planning tools, minimizes residual risk, and advances research. Yet, understanding compound flooding is challenging because of the simultaneous occurrence of multiple flood hazards, often in close succession, and their combined impacts on the Texas coastal zone.

The workshop gathered insights from the TIFF Planning and Outreach TAT (Component 4 TAT) members and a mix of agency planning experts to identify planning decision needs and information gaps to develop strategies to address these challenges while promoting collaboration among practitioners and researchers working on flood risk planning decisions. Please see Supporting Material 4-6 additional details.

Regional Considerations of Flood Risk Management Consequences Evaluation

A central goal in evaluating and proposing FRM projects is to identify a cost-effective feature and scale that will perform under a certain range of statistically likely events for the study area. Cost effectiveness is typically assessed via cost benefit analysis, which compares all costs, including construction, real estate, and operation and maintenance costs of the proposal to the expected economic benefits of its operation (typically flood damage reduction benefits). The largest component of economic benefits accrues as estimated reductions in flood damage and other losses with the project in place. However, the pursuit of a cost-effective project can often result in the selection of a smaller project area with dense development that can produce benefits that exceed the construction and operation cost of the structure. As a result, the traditional comparison of alternative solutions may overlook regional approaches to reduce flood risk.

Regional consequences of flood risk can impact individual and economic circumstances that aren't easily captured in a typical cost benefit analysis.

Recent regional flood planning initiatives by agencies such as TWDB GLO illustrate how incorporating regional perspectives can reveal broader flood management opportunities. TWDB, for instance, mandates that proposed projects avoid negative downstream impacts, thus encouraging regional-scale conveyance and detention solutions.

The State Flood Plan provides the opportunity to address drainage issues, which is not typically eligible for cost share through USACE and is an insightful way to address risk from varying sources in potential regional scales. Several communities collaborated for regional flood studies and characterizations, to assess larger geographic areas and broad sources of flooding.

Regional scale evaluations may reveal effective interventions to address flooding through improved definition of flood risk and flood sources. The recognition of drainage inadequacies also highlights the opportunity to scale solutions to address multiple sources of flooding, whether pluvial, fluvial or coastal. The combination of different flood drivers such as storm surge, riverine flows, and intense rainfall adds complexity to defining overall flood hazard, which further complicates the identification of an effective solution. This compound flooding in coastal and riverine areas can be an important reason that regional solutions may prove more cost-effective over the long term. Compound flooding rarely respects administrative or hydrologic boundaries; in many cases, the confluence of surge and river flows can push flooding well beyond the immediate coastline or the typical floodplain. If planning focuses narrowly on one hazard in a localized area, broader solutions (e.g., upstream detention areas, integrated levee systems that extend to coastal barriers, or regional water management strategies) might be overlooked. Therefore, this effort focuses on the approach of estimation of consequences of compound flooding as it will provide additional insights in evaluating FRM solutions within the larger consideration of regional risk and impacts.

Current Flood Risk Management Programs

The State of Texas has authorized regional flood planning efforts (Flood Planning, TWDB) that expand the state agency focus from simply partnering with federal efforts to developing regional priorities to create a statewide plan. The State of Texas has funded flood risk management studies independently and in cooperation with others for many years. GLO has cost-shared many USACE feasibility studies and continues to support infrastructure investments across the state. Recent programs managed by GLO and the TWDB have significantly increased the state's participation in FRM efforts and demonstrate the growing awareness of the flood risk in the region.

GLO's regionalized studies in Western, Central, Eastern, and LRGV, based on Texas' major river basins, will evaluate mitigation and abatement strategies to reduce disaster impacts and increase community resiliency. The studies will consider structural and nonstructural infrastructure improvements, coding and zoning practices, and regional communication and control as each relates to flood control.

The CDBG-funded program will provide technical support for region-specific development of flood risk projects for further implementation through USACE or other authorities. The program managers coordinate the program with USACE and other federal agencies to ensure that proposals are consistent with agency standards to maximize the potential for project implementation.

GLO is currently implementing the Combined River Basin Studies, which will result in detailed flood risk information and mitigation strategies for the 49 counties that received a presidential disaster declaration due to Hurricane Harvey's impact and four counties in the LRGV that received a presidential disaster declaration for flooding in 2015 and/or 2016.

Concurrently, TWDB formed 15 statewide RFPGs to conduct planning processes resulting in regional flood plans. These plans have contributed to the 2024 Texas State Flood Plan development. GLO's Combined River Basin Flood Studies program is a one-time planning effort, and the data and information produced by GLO will be utilized to support current and future Texas State Flood Plans (led by the TWDB) and inform TDIS. TDIS will house critical flood risk information for the state through an accessible online dashboard. GLO and TWDB's planning processes will include stakeholder engagement throughout the implementation to ensure the diverse needs and interests of the state are incorporated. Preliminary reports from the regional flood planning groups include recommendations that range from improved flood modeling to specific projects.

Flood Risk Management Policy Development Opportunities

Larger FRM policy development opportunities are open to further definition following coordination and outreach. Opportunities exist to refine risk considerations across multiple agencies and business decisions to improve existing sighting and land use decisions and expand awareness of risk exposure and residual risk in areas where projects have been implemented.

Policy considerations within agencies implementing FRM solutions may include broadening study authorization types, refining cost share decisions, and funding appropriations. Many federal projects only address flooding along the main stem of a bayou and could leave residual risk in tributaries or risk related to unaddressed pluvial flooding. While several federal projects have successfully reduced flood damage, there are still structures vulnerable to flood damage.

Opportunities exist to characterize specific sources of flood hazard and associated risk. Many areas are vulnerable to multiple hazards, and a coordinated evaluation of the latest data will identify areas for interagency efforts to address compound flooding from riverine and coastal risk and where pluvial and riverine flooding coexist. The Texas State Flood Planning program and other flood mitigation/ risk management efforts may not be limited to specific business lines that confine the focus of federal participation and funding.

Floodplain delineations on flood insurance rate maps (FIRMs) are a primary means of identifying and communicating flood or compound flood hazards. However, the flood hazards represented on FIRMs are the coastal and fluvial hazards and do not include pluvial hazards. Some areas are exposed to multiple flood sources. Additionally, while FIRMs are a useful tool, they are based on models with embedded assumptions. They present a single base flood elevation associated with the 1% ACE event, but there is a range of potential outcomes for a rainfall event. Flood inundation during a rainfall event depends on various hydrologic and hydraulic conditions which can vary. Furthermore, most strategies are necessarily backward-looking and ingest observed information. The duration of the observational record and the nature of the observations impact the accuracy of the statistical rainfall or flow estimates.

Compound flooding analysis can improve:

- emergency planning and response, such as evacuation advisories, pre-storm preparation, resource positioning to support emergency response, and post-event recovery
- infrastructure siting and operation decisions include site selection, design, and resilience planning
- larger policy considerations of risk and insurance needs and costs of flood risk

Incomplete Compound Flood Representation in Flood Planning

Planning decisions are made by comparing the overall performance of potential alternatives against relevant metrics to identify the best action, applications obviously differ across the types of decisions to be made and the agency authority. If the modeling results misdiagnose the initial flood risk or the expected risk reduction of one or more alternatives, the ramifications of that decision may be more serious than time and funds spent on the analysis.

Structural FRM solutions are typically justified by balancing study objectives with cost-effective design and scale of conveyance or detention features. The detailed analysis above highlights how traditional methods to evaluate riverine or coastal hazards independently may underestimate the true extent of flood exposure. Compound flood modeling supports more informed planning decisions with a more accurate portrayal of when and where higher flood levels can occur, critical insights for planning, design, and policy decisions.

If comparisons are made with an inaccurate depiction of the flood hazard, it may only justify a scale or design that is based on underestimated consequences. Smaller features may perform less reliably in practice and may not provide the level of protection to property and life safety than was expected. The risk is multiplied if land use decisions increase the investment in the area under the expectation that flood risk has been managed for current and future conditions. Several contributing factors to the decision risk are described below.

Inaccurately Capturing Benefits

Overstating benefits can occur when flood hazards are analyzed separately. A project designed to protect against one hazard (e.g., coastal surge) may appear to yield benefits for a structure that remains susceptible to another hazard (e.g., riverine flooding). As a result, benefits might be claimed for assets still at risk during a compound event. If stepwise analysis understates the depth of flooding in portions of the study area, as demonstrated in the case study, benefits from multiple sources will be understated, and funds may be expended to design and implement an inadequate type or scale of risk reduction.

This combination can inflate the perceived cost-effectiveness of some projects (those narrowly addressing one hazard) while undervaluing more comprehensive, multi-hazard approaches. Factoring in compound flooding helps ensure that benefit-cost analyses reflect the true scope of potential damages, and thus the full suite of benefits from solutions that address multiple flood sources simultaneously. As a result, fewer alternatives may be shown to be justified, physical extents of proposed solutions may be too narrow, or some alternatives may be screened due to cost if the true flood vulnerability is underestimated.

Limited Geographic Boundaries and Regional Interventions

Compound flooding rarely respects administrative or hydrologic boundaries; in many cases, the confluence of surge and river flows can push flooding well beyond the immediate coastline or the typical floodplain. If planning focuses narrowly on one hazard in a localized area, broader solutions (e.g., upstream detention areas, integrated levee systems that extend to coastal barriers, or regional water management strategies) might be overlooked. By recognizing and mapping where overlapping flood sources are likely, planners can identify a more expansive set of opportunities for reducing risk across wider geographic extents. This could mean connecting inland and coastal projects, investing in multi-purpose storage basins that regulate both storm surge inflow and river discharge, or collaborating with neighboring jurisdictions to manage shared waterways. This also means that opportunities for larger regional management measures may be overlooked, such as partnerships between cities or counties. Missing these solutions not only impedes comprehensive flood mitigation but may also increase costs over the long term by requiring piecemeal fixes for compound flooding after the fact. In many coastal watersheds, different agencies or jurisdictions hold responsibility for inland versus coastal flood management. If each group operates under a single-hazard lens, opportunities for collaborative, system-wide solutions may be missed. A thorough compound flood analysis forces communities, state agencies, federal entities, and other stakeholders to consider how floodwaters move across geographic and administrative boundaries. This can spur cooperative projects, creating efficiencies in implementation and ensuring that each investment addresses the combined hazards rather than only one side of the problem. Regional-scale solutions may provide more cost-effective interventions that are more easily adaptive over time, as flood vulnerability and population density increase.

Real-world Risk to Individuals and Communities

More significantly, the analysis may understate real-world risk to those that live and work in a given project area. A more accurate, integrated assessment helps avoid overcounting benefits and more accurately describes risk by ensuring that project outcomes reflect the full range of flood drivers. All flood hazard includes uncertainty, and compound events are more variable in extent and consequences. Incomplete flood extents may limit risk reduction or misinform agencies and residents of the overall life safety hazard. Oversimplifying the potential flood hazard may reduce awareness of natural hazards or the likelihood of residents evacuating or taking protective measures.

Objective 7: Evaluate and provide feedback on the initial inventory of planning datasets provided by the GLO Combined Flood Study Groups

To evaluate and provide feedback on the initial inventory of planning datasets provided by the GLO RBFS, TIFF leveraged the development of the CDS web application under Component 1. Rather than a static review, this dynamic platform enabled an interactive assessment of key datasets (e.g., parcel boundaries, structure characteristics, first-floor elevations, building codes, and demographic indicators) by integrating them into a centralized, user-friendly interface. The CDS not only streamlined data exploration and gap identification but also laid the groundwork for improved flood modeling, planning, and collaboration across agencies, ensuring that coastal communities are better equipped to prepare for and respond to future flood events.

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

As TIFF's ultimate legacy will be the set of recommendations, guidelines, and frameworks to improve the performance, understanding, and communication of flood science, it was imperative that the final recommendations made by TIFF be vetted and optimized by coordinated peer review so that they can be made actionable without hesitation by implementing entities. This coordinated peer review was structured around the component Objectives, in that the Objectives were used to query whether the existing list of potential recommendations completely addressed the goals of the project (Supporting Material 2-16).

Matagorda Harbor during Hurricane Nicholas © Supportstorm, Flickr

Table 4-4. Component 4 objectives and associated recommendations.

Component Objective	Associated Recommendation(s)
Establish a TAT to support Component 4	Objective met by TIFF. No further recommendations.
Coordinate with the RFPGs and stakeholders to identify flood planning and mitigation scenarios consistent with regional flood planning efforts, beginning by establishing a working relationship with RFPGs or their coastal liaisons to identify TIFF end-users	Objective met by TIFF. No further recommendations.
Develop and implement a comprehensive outreach plan to engage regional planning groups and other stakeholders regarding flood planning and mitigation efforts	Objective met by TIFF. No further recommendations.
Annually reassess user needs regarding flood planning and mitigation efforts and requirements and provide the results by updating the comprehensive outreach plan and preparing an annual progress report	Objective met by TIFF. No further recommendations.
Support the development of flood communications and educational materials	C4.5A: Incorporate Flood Literacy in K-12 Education C4.5B: Establish TDIS Online Learning Center C4.5C: How to Use Flood Risk Maps for Preparedness
Investigate the opportunities to balance and communicate between project-based and regional planning scale solutions	C4.6A: Establish State Flood Communication Officer C4.6B: Enhance Texas Coastal Structures Inventory C4.6C: Develop a Framework for Hazard and Loss Assessments
Perform a literature review on planning tools and develop list of data modeling needs for planning tools	Objective met by TIFF. No further recommendations.
Evaluate and provide feedback on the initial inventory of planning datasets (e.g., parcel data, structure characteristics, first-floor elevation, building codes, demographics, etc.) provided by the GLO Combined Flood Study Groups	Objective met by TIFF. No further recommendations.
Make recommendations pertinent to flood planning and outreach/communication to GLO	C4.9A: Adopt specialized graphics to reach Target Users C4.9B: Texas Flood.org Branding Campaign C4.9C: Better Understand Stakeholder Social Norms as Related to Flood Decision-making C4.9D: Establish a Texas Flood Coordination Office

TIFF RECCOMMENDATIONS, PLANNING AND OUTREACH

C4.5A: Incorporate flood literacy in K-12 education

Texas K-12 education curriculum includes content regarding the water cycle and drought. Elementary schools often collaborate with local fire departments to teach fire preparedness (e.g., "Stop, Drop, and Roll") and K-12 schools conduct drills for various hazards such as tornadoes. Despite Texas being highly vulnerable to flooding, students receive little to no instruction on how floods occur, their risks, or how to prepare for them.

Countries like Japan prioritize flood education and use virtual and augmented reality, along with serious games, to teach students about flooding and tsunamis. These interactive methods equip students with critical decision-making skills in emergencies.

Texas should develop and incorporate flood awareness and preparedness education into K-12 schools. A plan is needed to outline ways to introduce flood-related topics into science, geography, and emergency preparedness curricula, as well as the use of interactive and technology-driven learning tools.

Key actions when implementing this recommendation include:

- Determine the process, feasibility, and timeline for incorporating flood education into the Texas K-12 curriculum
- Review existing literature on flood education initiatives both in Texas and internationally to identify best practices; pinpoint gaps and specific needs for Texas K-12 students; determine the most suitable grade levels for integrating flood education. Identify existing educational content (from outside of Texas) that could be adapted for use, including K-12 programs that enhance parental awareness, identifying specific lessons, games, or activities that can be shared with parents to increase adult flood awareness; recommend content development, including interactive tools like augmented reality and serious games, aligned with Texas K-12 learning standards
- Interactive or web-based tools will require maintenance, content management, and updates.
- Determine if the incorporated flood education increased flood literacy in K-12 classrooms, improving students' capacity to respond effectively and appropriately to given flood risk information

Incorporating flood literacy in K-12 education is a crucial investment, estimated at $300,000 over the span of two years. To effectively explore how flood education can be incorporated into the Texas K-12 curriculum, the project team should have strong ties to the Texas Education Agency (TEA) and a solid understanding of Texas Essential Knowledge and Skills (TEKS) standards. This will help identify relevant existing content and determine what new materials need to be developed.

C4.5B: Establish the Texas Disaster Information System online learning center to enhance access to flood-related educational resources

State and federal agencies, along with academic institutions, offer a wealth of educational resources on flood-related topics, including compound flood modeling, data gathering, visualization, and management. These resources include workshops, webinars, and expert-led seminars that provide valuable insights into research, data, and ongoing flood-related projects. However, despite the abundance of available content, there is no centralized platform where these materials are systematically stored and easily accessible for future reference. As a result, critical knowledge is often scattered across different organizations, making it difficult for professionals, policymakers, and researchers to efficiently access and utilize these resources.

To address this gap, it is crucial to create an online learning center within TDIS. This platform would serve as a comprehensive repository for flood-related educational materials, including recorded webinars, research presentations, and training modules. A centralized resource hub would enhance accessibility to critical flood-related knowledge, provide professional education credits continuing education hours which are required for various professional license renewals such as PE and CFM, and foster greater collaboration among agencies, academic institutions, and flood management professionals.

By establishing this learning center, Texas can strengthen workforce education, improve flood preparedness, and ensure that critical expertise remains readily available for researchers, decision-makers, and practitioners.

Key actions when implementing this recommendation include:

- **Planning and Development** - Conduct a survey to identify priority content and existing educational resources from agencies, academic institutions, and professional organizations. Technical requirements for content hosting, search functionality, and credit tracking will be defined, and a video hosting platform will be selected. This action will build a searchable library with keyword tagging and design an intuitive interface for easy navigation.

- **Content Collection and Integration** - Gather existing videos, slides, and presentations from past workshops and seminars, collaborating with relevant agencies and experts and leverage any existing flood educational materials developed/collected by federal and state agencies. Materials will be tagged, categorized, and updated quarterly for continued relevance. Materials will not be created. This action should also conduct beta testing with key users and refine the platform based on feedback.
- **Launch and Ongoing Maintenance** - Promote the platform through TDIS, TWDB, professional organizations, and academic networks, with a virtual kickoff webinar. This work will require one full-time employee for content management and updates. Maintain cloud storage, engage with stakeholders, and ensure the platform evolves with user needs.
- **Flood Literacy Evaluation** - Determine if the online learning center increased flood literacy in target user groups, improving their capacity to respond effectively and appropriately to given flood risk information.

This recommendation can be implemented for an estimated annual cost of $85,000 – $108,000. The estimated cost for implementation is $300,000. The project team must have established connections with TEA and a strong understanding of TEKS requirements. TIFF recommends the Texas Floodplain Management Association help coordinate this effort because it has established a national program for professional certification of floodplain managers.

C4.5C: How to use flood risk maps for preparedness

As floods become more frequent and severe, Texas must enhance community resilience by ensuring local stakeholders understand and act on flood risk information. Flood maps are essential for assessing risks, but many residents and local officials struggle to interpret them accurately, hindering preparedness and response efforts.

TIFF recommends partnering with the Texas Division of Emergency Management to coordinate workshops that help local emergency managers, community coordinators, and residents learn how to read and interpret flood maps. The workshops should engage community members by encouraging feedback and updating local data. Involving the community in data collection and decision-making will foster a sense of shared responsibility.

By the end of the project, stakeholders, including residents and officials, will collaborate effectively on flood preparedness, with flood risk maps becoming a common tool in decision-making and community resilience planning.

Keys actions when implementing this recommendation include:

- Fostering understanding around related flood risk map symbols and uncertainties
- Developing skills to evaluate the impact of different flood scenarios
- Engaging workshop participants in flood preparedness activities
- Integrating flood maps with other relevant data, such as demographic information and land use, to provide a comprehensive understanding of flood risks

C4.6A: Establish State Flood Communication Officer for interorganizational coordination

Effective coordination among agencies involved in flood-related projects is essential for improving preparedness, response, and mitigation. As floods become more frequent and severe, Texas needs a centralized communication strategy. However, without clear leadership, agencies may operate in silos, reducing efficiency and policy alignment. Texas already employs state experts, such as the State Demographer, who provide policy guidance. A similar role focused on flood communication coordination would bridge gaps between agencies and ensure a unified approach.

This individual would serve as a liaison among agencies, organizations, and policymakers to streamline communication and advise the Governor and Legislature on science-based flood policies. Additionally, they would coordinate efforts between scientific research, insurance, and policy sectors to ensure alignment in mitigation planning and response. Drawing from successful models in other states, they would also develop best practices for interagency collaboration.

With the establishment of this role, Texas can enhance efficiency, foster collaboration, and strengthen flood management efforts. A dedicated expert will ensure that science, policy, and risk mitigation strategies work together, ultimately improving the state's resilience to flooding.

Key actions when establishing a State Flood Communication Officer include:

- **Research Comparable Roles and Craft Proposal** - Review the guidelines and responsibilities of similar state advisory roles, such as the State Demographer and Chief Resilience Officers, to inform the structure and best practices for the new position.

- **Role Definition and Options for Organizational Integration** - Define the role's scope and authority within the TFCO. Integrate the role within an existing state flood agency while expanding its authority and responsibilities. Assist organizations in developing effective flood preparation plans and materials. Align and incentivizing local, regional, and state flood projects for cohesive efforts. Establish data-sharing mechanisms with academic institutions and funding agencies, such as through Open Science Platforms (OSP). Ensure every agency with a flood-related mission designates a representative to support coordination efforts.

- **Allocate Resources** - Focus on securing the necessary funding and resources to ensure the position is adequately staffed and supported.

By following this approach, Texas can create an impactful role that enhances interagency coordination, strengthens flood preparedness, and fosters a unified flood management strategy.

C4.6B: Enhance Texas coastal structures inventory for better planning and mitigation following disasters

Effective flood management hinges on critical infrastructure decisions, including site selection, design, and resilience planning. These decisions directly impact the state's ability to mitigate flood risks and protect communities. However, one of the most significant gaps in current flood management is the lack of real-time monitoring infrastructure, such as localized weather stations and water level gages for both surface and groundwater. These tools are indispensable for predicting flood hazards with greater accuracy and improving preparedness efforts across regions prone to flooding. Increased monitoring infrastructure would provide better situational awareness and early warning systems, allowing communities and local governments to respond more proactively to flood risks.

To address these challenges, TIFF recommends partnerships among local, state, and federal agencies to enhance the inventory and data collection related to Texas' coastal structures. This collaboration would streamline the gathering of crucial information, improve planning, and strengthen mitigation strategies, ensuring that flood management efforts are more targeted and effective. Additionally, Texas can build a more comprehensive, efficient, and proactive flood management system, capable of tackling the increasing frequency and severity of flood events across the state.

C4.6C: Develop a framework for hazard and loss assessments to support insurance, planning, and prediction

Flooding and other natural disasters in Texas cause significant damage each year, impacting communities, infrastructure, and economic stability. To improve planning, insurance assessments, and predictive capabilities, TIFF recommends the development of a comprehensive hazard and loss assessment framework for Texas.

Currently, hazard and loss assessments are fragmented, relying on disparate data sources, costly post-disaster inspections, and varying building codes across communities. A structured, statewide framework would provide consistent, high-quality data to inform decision-making, reduce uncertainties, and support mitigation planning.

Key actions when developing a framework for assessing hazards and losses in Texas include:

- **Database Development and Enhancement** - Develop and maintain a centralized, regularly updated database to support hazard and loss assessments. This database will include essential information such as building age, construction standards, and historical flood regulations (e.g., NFIP adoption, freeboard requirements, and International Building Code compliance). TIFF recommends various agencies partner to enhance TWDB's building footprint database, ensuring improved data accuracy and coverage.

- **Flood Risk Model Development** - Establish model functionality requirements and certification criteria for accurate risk assessment. This development includes assessing the feasibility of creating a Texas-specific flood model that incorporates local flood level data, damage estimates, and loss metrics. The models will be designed to ensure compatibility with Benefit-Cost Analysis (BCA) requirements, supporting state and federal grant applications.

- **Post-Disaster Data Collection Strategy** - Improve data collection following disaster events. Strategies will be developed to address challenges such as lost high-water marks and overwhelmed local officials. Additionally, community participation in recording flood depths using simple methods like photo documentation and height measurements should be encouraged.

- **Cumulative Impact and Mitigation Tracking** - Expand assessments beyond catastrophic events to include the cumulative impact of minor flooding, which often goes unrecorded but can still degrade infrastructure and property values over time. This tracking will also improve tracking of mitigation efforts and loss avoidance, ensuring that valuable data is preserved for future analysis.

By implementing this framework, Texas can move toward a data-driven, proactive approach to flood risk management with a comprehensive framework that accounts for a wide range of losses, beyond just structural inundation. This includes social impacts and disruptions to essential services, providing a more holistic understanding of disaster consequences.

C4.9A: Adopt specialized graphics for use across state and local agencies to reach Target Users

Many local communities in Texas still rely on outdated FEMA brochures when conducting flood outreach, which often lack the necessary updates to effectively communicate with today's audiences. Recent research by UT Austin identified three key target user groups and a unified statewide message that resonates with Texas culture. The next step is to bring these findings to life through impactful, localized graphics.

To address this, TIFF recommends updating and finalizing graphics for the TPWD's outreach materials. These graphics will target three key audiences identified by TIFF: property owners, property renters, and individuals with limited English proficiency. By modernizing these visuals, TWDB can ensure that flood risk communication is more effective and culturally relevant and encourage their use across both state and local agencies.

Key actions when updating graphics used for TWDB messages for specific target user groups include:

- **Design and Finalization of Graphics** - Create visuals targeting the four three audiences, adhering to accessibility standards, and using simple colors and fonts compatible with basic programs like PowerPoint. This standardization ensures that local officials, regardless of technical expertise, can easily edit and customize the visuals to meet their community's needs.

- **Review and Approval Process** - Conduct focus groups with representatives from the three prioritized audiences to evaluate how effectively the graphics communicate key messages. Additionally, the graphics will be reviewed to ensure consistency with the state's flood risk messaging.

- **Production and Distribution** - Make the graphics available in both digital formats (e.g., PDFs, PowerPoint slides) and print formats. Host the graphics on the TDIS to make them easily accessible for local agencies, along with instructions for downloading and customizing the materials for their specific communities.

- **Flood Literacy Evaluation** - Determine if the updated and specialized graphics increased flood literacy in the three target user groups, improving their capacity to respond effectively and appropriately to given flood risk information.

- **Evaluate Priority Groups at Risk to Define Target Users** - The number of priority groups that can benefit from improved TWDB communications about flooding risks is vast. Each group tends to include heterogeneous sub-groups that need to be carefully evaluated to define clear, specific target users of interest for future work.

C4.9B: TexasFlood.org branding campaign

TIFF research showed that TexasFlood.org, despite being a key resource for flood information, has limited engagement with its target audiences. To increase awareness, graphics should be finalized and a comprehensive campaign promoting the website and its resources should be launched to emphasize flood preparedness and risk management.

The campaign will incorporate clear metrics to track website traffic and user engagement, ensuring measurable success and ongoing improvement. TIFF research also suggests evaluating the impact of the messages after launch to ensure they resonate with the target audiences and effectively drive engagement. Regular assessments will help refine the approach and keep the materials relevant.

TIFF recommends establishing a branding campaign for TexasFlood.org, including the finalization of graphics tailored to the identified audiences, strategic outreach to increase awareness, and a robust evaluation process to track the effectiveness of the campaign. By integrating a clear branding strategy with evaluation and metrics, this effort aims to enhance the website's visibility and ensure that flood-related resources are accessible and actionable for Texans across the state.

Key actions when creating a branding campaign for TexasFlood.org include:

- **Branding Campaign** - Develop and execute a comprehensive campaign aimed at raising awareness of TexasFlood.org and its flood-related resources. The finalized graphics will be used to create outreach materials and advertisements tailored to the four identified audiences. Multiple channels, such as social media and partnerships with relevant agencies, will be leveraged to maximize reach and engagement with the public.

- **Website Metrics and Tracking** - Establish clear metrics to track website traffic, engagement, and user interactions. These metrics will help monitor the campaign's effectiveness, refine strategies, and identify any gaps in outreach efforts.

- **Evaluation** - Periodic evaluations of the messages and materials post-launch. Feedback will be gathered from target audiences, and data will be analyzed to assess whether the graphics and messages resonate with each group. Based on the findings, materials will be adjusted and updated to ensure they remain relevant and impactful.

C4.9C: Better understand stakeholder social norms as related to flood decision-making

Research consistently shows that social norms—being influenced to engage in a behavior because of trusted others—are a strong predictor of Texans' flood-related decisions. These trusted individuals are often peers rather than experts, highlighting the need for a deeper understanding of how social influence shapes decision-making in flood preparedness, response, and recovery.

TIFF recommends targeted experiments, surveys, and focus groups to explore the various forms of flood-related decision-making. By analyzing how different social groups influence perceptions and actions, these studies can identify the most effective ways to disseminate flood information. Insights from this research can then be used to develop communication strategies that leverage peer networks, ensuring that critical flood-related messages resonate with and motivate communities to take protective action.

The estimated cost is $245,000, which includes participant compensation to ensure representative data. Testing people with limited English proficiency should be prioritized to improve accessibility and effectiveness. A key research objective should be to assess how well individuals understand the documentation involved in purchasing a home. For example, do they know whether the home is located in a designated flood zone?

Key actions to implement this recommendation include:

- **Social Norms Studies (Two Experiments)** - Study how social norms impact flood-related decisions (e.g., buying insurance, creating evacuation plans, home selection). The role of information sources will be examined, including trust and domain-specific trust. The studies will also test evidence-based messaging strategies that integrate social norms, assessing their effects on risk perception and cognitive load.
- **Key-Logging Study** - Analyze how peer-shared flood experiences influence decisions and identify the most effective messengers. Community-driven approaches, such as using promotoras (lay health workers) for flood communication will also be explored. Additionally, surveys, interviews, and focus groups reflecting Texas' demographics, with a focus on people with limited English proficiency, will be conducted.

C4.9D: Establish a Texas Flood Coordination Office to optimize state and federal project impact

Flooding poses a persistent and growing threat to communities, infrastructure, and ecosystems across Texas. To better prepare for and respond to these challenges, state and regional flood planners need coordinated access to information, planning tools, and technical support.

Currently, multiple state and federal agencies, private and non-profit organizations, and academic institutions are engaged in efforts to raise awareness and respond to floods. However, without a centralized coordinating body, the extensive work being done often overlaps, creating redundancies, inefficiencies, and missed opportunities to leverage project outcomes.

TIFF recommends Texas legislators establish a Texas Flood Coordination Office (TFCO) within an existing state agency.

The TFCO would:

- centralize and streamline flood-related efforts
- create and maintain an official statewide database of past and ongoing projects
- provide technical support to state and regional planners
- enhance collaboration among agencies, institutions, and stakeholders
- reduce redundancy and maximize the impact of state and federal investments
- formalize and expand beyond the current volunteer-based efforts

Truck picking up trash and debris outside of neighborhoods devastated by Hurricane Harvey ©Eric, Adobe Stock

By centralizing information and oversight, the TFCO will enhance the state's ability to manage and mitigate flood risks efficiently.

The TFCO is a crucial and ongoing investment. Key actions when implementing this recommendation include:

- **Initial Setup** - Establish the TFCO within an existing state agency (e.g., TDEM or TWDB) to minimize overhead. Form a small interdisciplinary team of flood management experts supported by 1-2 administrative staff. Build long-term partnerships with external agencies, academic institutions, and stakeholders.
- **Content Collection** - Compile an archive of state and federally funded flood projects through agency website reviews, outreach to academic and agency contacts, and calls for input from stakeholders and the public. Develop quality control standards to tag, categorize, and store materials for long-term use, data analysis, and sharing.
- **Project Management** - Maintain and update a comprehensive database of flood projects annually. Analyze project outcomes to identify research gaps and emerging needs.
- **Data Sharing and Collaboration** - Disseminate project outcomes and data to stakeholders to promote transparency and knowledge sharing. Identify opportunities to build on existing results and reduce redundancy. Foster collaboration among agencies, institutions, and organizations. Provide regular updates to the Texas Legislature on flood projects, outcomes, and policy recommendations.

4.6 The Future of Texas Planning and Outreach

TIFF's Planning and Outreach efforts laid the groundwork for a more inclusive, adaptive, and user-centered approach to flood resilience across Texas. By integrating target user perspectives into planning tools, modeling frameworks, and communication strategies, Component 4 emphasized the importance of aligning technical outputs with the lived realities of communities facing flood risk. The multi-year Outreach Plan prioritized transparency, strategic coordination, and the leveraging of existing initiatives such as CHARM and TDIS. This foundation ensures that future flood planning efforts are not only technically sound, but also socially responsive and regionally aligned.

A key advancement in this component was the shift from "end-user" to "target user," reflecting a broader commitment to early and continuous stakeholder involvement. This shift was reinforced through joint efforts with Component 2, where data visualization emerged as a powerful tool for communicating flood risk. *The TIFF Communication Guidelines,* developed through literature reviews, stakeholder workshops, and a statewide survey, offer a roadmap for designing outreach materials and planning tools that resonate with property owners, renters, and individuals with LEP. These guidelines will continue to inform future efforts to ensure that flood risk communication is clear, actionable, and equitable.

TIFF also conducted a targeted inventory analysis of planning tools used by federal, state, and local agencies to support flood risk reduction decisions. This cataloging effort identified opportunities to align H&H model outputs with planning support needs, particularly in the context of compound flooding. To support this alignment, H&H modelers and economists are encouraged to develop a checklist to guide model design and scale based on the nature of the study and its geographic context. This checklist should be informed by GIS shapefile reviews and bivariate analysis of contributing or dominant flood sources, helping ensure comprehensive consideration of data and modeling needs.

By integrating upstream/downstream dynamics and adjacent watershed interactions into planning scenarios, TIFF highlighted the need for regional-scale solutions that transcend administrative boundaries. This approach also helps mitigate the risk of inducing damages in one community while increasing flood volumes in neighboring areas—a concern that underscores the importance of modeling downstream impact under multiple conditions.

Future Planning and Outreach efforts will build on this foundation by promoting scalable modeling, economic analysis, and collaborative investment strategies that reflect the interconnected nature of flood hazards. As part of this evolution, TIFF supports the development and release of a modular compound flooding tool, such as CHART, designed to reduce duplicative modeling and calibration steps. While the full suite of modular components will take several years to develop, an initial interface should support pre-assessment of potential benefits as a preliminary screening step, helping communities recognize surrounding and interrelated flood hazards at the outset of a study.

To ensure long-term impact, TIFF recommends the establishment of a centralized flood communication coordination role within the state. Modeled after successful examples in other policy domains, this individual would serve as a liaison among agencies, researchers, and policymakers—streamlining communication, advising leadership, and fostering interagency collaboration. By institutionalizing coordination and aligning science, policy, and mitigation strategies, Texas can enhance its preparedness and response capabilities. The future of Planning and Outreach lies in its ability to unify diverse efforts, elevate community voices, and deliver flood resilience strategies that are both technically robust and socially grounded.

TIFF Component 4 Implementation in the Lower Rio Grande Valley

As part of TIFF's continued evolution, Component 4 expanded into the LRGV to address region-specific challenges in flood risk communication and planning. Recognizing the unique geographic, cultural, and socioeconomic dynamics of the area, TIFF prioritized direct engagement with local stakeholders to better understand the needs of both technical and nontechnical audiences. Structured interviews, facilitated workshops, and a community learning exchange event formed the backbone of this outreach effort, with a particular emphasis on Spanish-speaking communities and experiential learning techniques. These activities tested culturally tailored communication strategies (e.g., hands-on demonstrations and localized flood maps) to enhance comprehension of flood hazards and promote protective actions. Early findings revealed that practical demonstrations, especially those focused on sandbag use and drainage system awareness, significantly increased participant confidence and intent to implement mitigation measures.

TIFF's work in the LRGV reflects a broader commitment to ensuring that flood planning and mitigation efforts are informed by the people and places they are designed to protect. By gathering feedback and perspectives through direct involvement with regional stakeholders, TIFF continues to refine its data and modeling frameworks to better incorporate the needs of diverse target users. These insights are not only shaping the development of new outreach materials and planning tools but also informing updates to existing platforms. As new findings emerge from the LRGV and other regions, TIFF will support their integration into statewide planning efforts—either by enhancing current tools or recommending the creation of new ones that more accurately reflect compound flood risks and community priorities.


Port Aransas Beach © Jonathan Cutrer

Central to this effort is TIFF's ongoing investigation into the balance between local cost-effective flood risk management and broader regional considerations. In the LRGV, where inland and coastal flood dynamics often intersect, this balance is particularly critical. TIFF's approach emphasizes the importance of scalable solutions that can be adapted to local contexts while contributing to regional resilience. By aligning planning scenarios with upstream/downstream interactions and cross-jurisdictional coordination, TIFF aims to identify opportunities for more efficient, equitable, and durable flood mitigation strategies.

Looking ahead, TIFF's implementation in the LRGV will serve as a model for expanding flood planning efforts across Texas. Through continued stakeholder engagement, adaptive planning frameworks, and a commitment to inclusive communication, Component 4 will help ensure that flood risk management strategies are not only technically robust but also socially grounded. By fostering collaboration among agencies, communities, and technical experts, TIFF is building a more resilient Texas—one that is prepared to meet the challenges of compound flooding with clarity, coordination, and shared purpose.

Sunrise over Matagorda Bay the day after Hurricane Beryl © Gage, Adobe Stock

TIFF Facilitation

Facilitation has been called an art, a science, and a skill backed by research suggesting that successful facilitators are active bridging agents, interlocutors, or innovation brokers who are respected and trusted in their specialist area. A facilitator can play many roles including providing visionary leadership, nurturing a network, getting things organized, selling a new idea, creating space for dialogue, and running effective meetings. Notably, there are three main roles a facilitator plays: convener, moderator, and catalyst. A convener brings together the relevant actors and stimulates interaction. A moderator gets the actors to collaborate by managing their differences and supporting processes of mutual learning. A catalyst stimulates the actors to think out of the box and develop and implement new and bold solutions (Brouwer et al., 2015).

To support the needs of the TIFF project, facilitation included these three main roles in addition to expert elicitation (to engage the more than 100 technical advisors) and science communication (to engage and resource the variety of audiences who will hopefully utilize the information resulting from the TIFF process). Early in the partnership, TIFF's partner agencies embraced the importance of third-party facilitation in meeting this mission and navigating some of the inevitable challenges of a large multi-agency research and engagement effort. Some key areas of the project were identified for the role of project facilitator:

- eliciting the needed expertise to inform the future of Texas flood science
- creating a unique, overarching identity for TIFF outside of the identities of the sponsoring agencies
- designing and implementing engagement activities to maximize inputs to the project
- addressing potential conflicts within the SC and partner agencies
- addressing potential conflicts of interest or conflicting opinions within the various external expert communities
- creating communication tools and documents to convey project milestones and gathered expertise
- interpreting technical information so that it could be received by target audiences, and
- streamlining the delivery and implementation of the project

TIFF centered on expert engagement and elicitation and getting feedback from key scientific and user communities. "Expert elicitation is a formal and systematic process for obtaining and quantifying expert judgment in order to characterize the uncertainty about decision critical quantities. It does not create new knowledge; instead, it characterizes the state of knowledge about some issue or quantity that is uncertain," (USACE, 2018). The vision was to create communities of expertise to guide and vet the research and recommendations resulting from the TIFF effort. These expert communities were also meant to serve their respective areas of research and support the eventual implementation of recommendations that might result from the TIFF findings. Internally, it was often said that more than anything, ***TIFF is about relationships***.

Effective elicitation and synthesis of collective expertise benefits from neutral third-party facilitation, which provides an unbiased check on project sponsors whose expertise and familiarity with the subject matter may introduce bias or limit the potential scope of topic exploration. A third-party facilitator is also beneficial in collaborative governance structures where parties are working together to make decisions outside of (and in addition to) their typical decision-making hierarchies (e.g., the TIFF SC). Facilitation provides structure and guides the process of group interactions to help teams work effectively and make high-quality, inclusive decisions. Rather than directing content or outcomes, the facilitator's role is to create an environment that supports participants in doing their best thinking and working together to achieve (and be accountable to) their shared goals. As the lead process designer, the facilitator can help to balance or override power dynamics or resolve conflicts that might otherwise result from non-facilitated partner collaborations.

As mentioned above, facilitation is both an art and a science: the art lies in the facilitator's ability to identify and understand desired outcomes and creatively adapt and respond to changing information and group dynamics; the science involves understanding how individuals and groups think, learn, behave, and develop in order to design effective processes. In addition to guiding the process, the facilitator also serves as a process steward and accountability partner, maintaining focus on the group's commitments, tracking progress, and ensuring that next steps and deliverables are clear and acted upon. While they remain neutral in content, facilitators reinforce alignment with group objectives and timelines, supporting momentum and accountability across complex, multi-stakeholder efforts.

One often overlooked role of a Facilitator is that of process designer. Once the project goals and stakeholder needs are identified and understood, it is the Facilitator who creates the process to meet the project's needs. "Process" is designed to maximize three elements to ensure a satisfying outcome: 1) trust, 2) data/information, and 3) operating structure (Moore, 2014). For TIFF, trust-building was an element in the work of the SC as well as a target for communications with the TATs; transparency and accountability around shared data and information was emphasized throughout; a comprehensive outreach plan to engage regional planning groups and other stakeholders regarding flood planning and mitigation efforts was created; and special care was given in designing roles and responsibilities amongst the SC and Facilitation Team as well as with the external participants of TIFF.

The Meadows Center for Water and the Environment

The Meadows Center at Texas State University served as the Facilitators for TIFF, playing a critical role in project operations by staying on the pulse of the project to fine-tune processes and ensure every step advanced our collective goal to elevate Texas's resilience to flooding. The Meadows Center is unique in its facilitative capacity. Established as trusted neutral convener for more than 20 years, as well as an applied research center that brings technical expertise to communities across the state to address water challenges, the Meadows Center occupies a unique niche in science communication.

Carrie Thompson was identified as the Lead Facilitator for the TIFF project with Anna Jones serving as a co-facilitator and communications lead. Desiree Jackson joined the effort in 2024 as co-facilitator and project coordinator, along with Rikki Weaver (Flood Framework Coordinator, TWDB) as project coordinator. Early implementation of the project also included key contributions from Sara Omar (Kearns and West), Nic Terasewicz (Program Associate, Meadows Center), and Luci Cook-Hildreth (Grant Specialist, TWDB).

The TIFF Project Charter

Successful facilitation requires that project sponsors share power and authority with the Facilitator, deferring to their expertise as a key element of the project's design and delivery.

The Meadows Center led the development of the TIFF Charter, establishing the project's Leadership Team as the SC (made up of sponsoring agencies) plus the Facilitation Team (led by the Meadows Center for Water and the Environment), and clarified expectations for the roles:

1. *The **Steering Committee** helps to facilitate, coordinate, and integrate concerns, ideas, and early findings and recommendations into rapidly evolving TIFF activities. This includes giving advice and input to the framework and identifying issues in advance for technical discourse and deliberation by the TATs. The SC is scheduled to meet on a bi-weekly basis, commits to working diligently to keep the process on schedule, and to bring forth as quickly as possible any concerns that may affect the schedule.*

2. *The **Facilitation Team** is responsible for providing pre- and post-meeting facilitation support and to prepare for, facilitate, debrief, and support offline collaboration and stakeholder engagement. This includes:*
    - *Coordinate, draft, and finalize meeting agendas and meeting materials in consultation with the SC*
    - *Assist in developing meeting handout packets when necessary*
    - *Shepherd content development, maintain and provide records of agendas and action items*
    - *Provide and operate webinar platforms*
    - *Identify scheduling needs and notify participating members of scheduling needs in a timely manner*
    - *Facilitate TAT meetings, including meetings to prepare and debrief TAT meetings.*
    - *Take notes during TAT meetings, summarize decisions and action items at the end of the meeting, and develop internal and external facing meeting and summary reports.*
    - *Provide conflict resolution and process design services as needed.*
    - *Provide additional outreach materials as agreed upon with the SC. This may include, but is not limited to interviews, surveys, polls, factsheets, handouts, webpages, or videos.*
    - *Develop supporting tools (e.g., meeting agendas, facilitation plans, and logistics and coordination plans)*
    - *Provide a process that supports constructive and productive dialogue, helping groups remain focused on their charges and agreed-upon scopes of work.*
    - *Offer process skills to support open, balanced, respectful dialogue and problem-solving.*

    The Facilitation Team is also responsible for providing quarterly progress reports, including:
    - *descriptions of tasks completed and in-progress*
    - *percent completion of tasks in-progress*
    - *updates to overall project schedule as warranted*
    - *descriptions of potential issues or challenges encountered and strategies to mitigate issues affecting the scope, budget, or timeline.*
    - *invoices at the satisfactory completion of each task*
    - *detailed schedule based on project milestones*

The Charter and related discussions also guided decisions around the TIFF Mission and Vision, TIFF Components, TIFF membership, Charter purpose and objectives, roles and responsibilities, ground rules for interaction, SC and TIFF decision-making process, information management and sharing, general communication protocols, TAT meeting schedule targets, and goals for the Final Report.

Facilitation Deliverables

The Facilitation Team played a critical role in orchestrating TIFF's operations, providing an objective perspective on project outcomes, and allowing the SC to fully participate in technical discussions with the TATs. Throughout the project, the Facilitation Team maintained close coordination and frequent communication with the SC to ensure that all activities remained aligned with TIFF's vision, while also adapting to shifting needs, timelines, and deliverables.

For the purposes of this project, facilitation tasks were organized under five core areas:

1. **Convening Stakeholders** - To support engagement across technical experts and stakeholders, the Facilitation Team led the planning and facilitation of technical workshops and TAT meetings. This included coordinating logistics for both virtual and in-person events, developing meeting agendas and process outlines, and supporting offline collaboration before and after each session. The team also prepared executive summaries to capture and communicate the technical information generated through these engagements and maintained clear communication with TAT members and other stakeholders. Planning and debrief meetings with the SC helped ensure that each session was well-supported with tailored materials and resources.

2. **Project Management** - The Facilitation Team advised the SC on strategic, efficient, and effective approaches to engage technical experts and gather their feedback on technical considerations, methodologies, and recommendations across all four project components. This included organizing meetings to convene the Leadership Team for team building and strategic project planning, as well as arranging meetings with the SC and collaborating agencies. The team helped coordinate the peer-review process between the SC and TAT members, ensuring that draft project materials and recommendations were reviewed collaboratively, and also maintained a centralized cloud-based filing system (via Microsoft Teams) for shared access to project materials.

3. **Communications and Branding** - To support cohesive and consistent communication, the Facilitation Team led the design and production of project materials aligned with the TIFF brand (i.e., executive summaries, fact sheets, infographics, flyers/handouts, and other materials as needed). This work involved developing a comprehensive brand and style guide that defined the project's visual identity. The guide outlined the use of project and partner logos, established primary color palettes for text and headers, secondary color palettes for backgrounds and supporting graphics, and specified fonts for headline, subheadline, and body text. This attention to detail helped present a unified, professional face to both internal and external audiences.

4. **Preparing Annual and Final Reports** - The Facilitation Team supported the compilation and development of reports for each of the four project components, as prepared by the SC, for inclusion in the TIFF annual and final reports. This involved coordinating with the SC to brainstorm, draft, and edit both written content and visual elements. The team also finalized the formatting of the print reports, ensuring appropriate acknowledgment and inclusion of logos and branding for co-authoring entities and funders. Electronic versions of the annual and final reports were shared with co-author entities for use on their websites or distribution channels, in addition to submitting the final deliverables to the GLO.

   Throughout the implementation of the TIFF project, it was essential to reflect on the annual findings and recommendations from each of the four components, highlighting achievements and lessons learned in developing an integrated framework to equip local, regional, and state entities with the information and tools needed for comprehensive regional compound flood planning and mitigation along the Texas coast.

   To support the preparation of both annual and final reports, the Facilitation Team coordinated with the SC to ensure all report deliverables aligned with the project's vision and met desired standards for aesthetics and messaging. This collaboration included co-developing both draft and final versions of the TIFF annual and final reports by contributing to the brainstorming, drafting, and editing of written content and visual elements. The Facilitation Team also compiled and integrated component-specific reports developed by the SC into cohesive, comprehensive TIFF annual and final reports. This involved applying finalized formatting, incorporating logos and branding, and ensuring proper acknowledgement of co-authors and funders. Completed reports were distributed electronically to co-author entities for use on their websites and other platforms, and final deliverables were submitted to GLO.

5. **Website Updates** - The Facilitation Team lead creative design work to ensure consistent use of TIFF's branding elements and information as agreed upon with the SC (i.e., webpages, visuals and graphic design, file organization, and other materials as needed). This included optimizing the webpage content's appearance to enhance user experience and accessibility. A workflow was also established with the SC for web content creation, review, approval, and publishing.

Facilitation Strategies

TIFF's ultimate legacy is the articulation of disciplinary and organizational cross-cutting priorities for understanding and communicating compound flooding, vetted for immediate implementation. As such, it was crucial to ensure consistent TIFF communications and branding, execute productive and engaging meetings that encourage democratic decision-making, and report progress towards achieving the project's desired outcomes.

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

As illustrated in the TIFF Structure and Development section of this report, TIFF has a very complex structure. An early (and key) facilitation strategy was to create a "TIFF" identity that could be recognized by participants – separate from the identities of is partner agencies.

The Facilitation Team worked closely with the SC to develop the TIFF Brand Guide, which outlined guidance on logos, color palettes, and font styles. This mechanism established a consistent visual project identity and ensured that all project communications and materials (i.e., executive summaries, fact sheets, infographics, flyers, and handouts) aligned with the TIFF brand. To promote consistent communication externally, a lead facilitator was designated to communicate with TAT members using a single email address. This approach minimized confusion, reduced the risk of mixed messages, and fostered more personalized relationships between the Facilitation Team and TAT members. Rather than relying on partner agencies to promote the project through various channels, the team developed a dedicated website to serve as the central hub for TIFF materials. This ensured a single point of access for project reports, recommendations, and resources. By applying the TIFF Brand Guide, the team created a consistent and professional appearance across all project materials.

Equally important was the use of a singular email address and centralized point of contact for all facilitation-related communication. The TIFF Charter established that the Facilitation Team would lead all email communications. Establishing the Lead Facilitator as the singular voice of TIFF served two important purposes: 1) hearing from one individual simplified and humanized the project for external audiences, created a more streamlined experience for stakeholders, and promoted a sense of personal accountability among participants engaging with the process; and 2) this allowed SC members to more fully participate as expert members of their respective TATs.

Accessible Communication of Complex Information

Facilitators helped make technical material more understandable by synthesizing dense content into summaries, visuals, and plain-language explanations. Curated presentation materials, workshop summaries, and structured feedback loops helped stakeholders understand highly technical content and contribute meaningfully. This enabled broader engagement and ensured that the project's outcomes were communicated in accessible and actionable formats. Additionally, to foster participatory learning and greater engagement in key elicitation exercises, the Facilitation Team tested and utilized a variety of multi-modal interactive tools and formats to best meet the needs of participants with different learning styles and asynchronous availability.

Neutrality, Transparency, and Responsiveness to Advisor Input

The promise of TIFF was to gather the best minds in each discipline related to coastal flooding and ask for their critical review of the project's goals, implementation, and ultimate outcomes. To ensure that the advisors had the promised influence, the project consistently embraced change in response to the feedback, worked with power imbalances between the participating experts and the partner agencies, and dealt with any arising conflict.

Process documentation is an often-underestimated component of successful facilitation and is key to demonstrating neutrality and providing the transparency necessary to keep all participants on equal footing. Significant effort went into distilling the technical deliberations and making all materials accessible to the TAT members.

Designing and Delivering Effective Meetings

Facilitation can be a powerful tool to help groups work together more effectively, resulting in improved knowledge exchange and enhanced learning. Through intentional process design, the Facilitation Team made a lasting impact in achieving TIFF's desired outcomes by reinforcing alignment, sustaining engagement and communication, and serving as an accountability partner to the SC. These efforts helped TIFF maintain momentum and consistency throughout a multi-year, multi-agency planning process.

Engagement Tools for Participation and Feedback

The facilitation approach provided space for authentic engagement. Through carefully designed meetings, adaptive tools, and inclusive communication strategies, the team ensured that TAT expert feedback was effectively incorporated into the development of TIFF's 42 draft recommendations. This feedback loop grounded the final recommendations in real-world expertise and positioned TIFF as both a technically sound and stakeholder-informed initiative.

Together, these efforts built a strong, recognizable brand identity that reinforced TIFF's mission and vision.

Facilitation Activities

To support engagement across technical experts and stakeholders, the Facilitation Team led the planning and facilitation of four types of meetings:

1. **Leadership Team Meetings** were used to establish and clarify project outcomes and deadlines. The Facilitation Team leveraged Microsoft Teams and SharePoint (cloud-based, centralized collaboration and filing platforms compatible with SC requirements) to host regular coordination and planning/debrief meetings with the SC. These platforms also supported team building, strategic planning, and broader project management efforts. Early on, the Facilitation Team gathered information about the project and participants, collaborating with the SC to refine the project's purpose and identify desired outcomes. Based on these discussions, the team developed a TIFF Leadership Team Charter. The Charter was a process design that served as a blueprint for how the group would work together, manage conflicts (e.g., scheduling tensions), and stay aligned on goals. The Charter outlined the project scope, roles, responsibilities, and norms of collaboration. Although not

a legal agreement, it represented a shared commitment among team members to participate and contribute meaningfully to the project. It was treated as a living document, updated as needed to reflect evolving agreements and needs.

2. **Component Champion Meetings** were used to prepare for each Component's TAT engagements. The Facilitation Team worked closely with Champions to confirm the TAT's requirements and co-develop meeting agendas aligned with Component objectives. This included identifying the necessary materials (e.g., reports, surveys), ensuring that crucial support roles were in place (e.g., speakers, panelists, moderators), and tying each agenda item to specific outcomes. The goal was to ensure each meeting was purposeful, well-supported, and results-driven.

3. **Component TAT Meetings** convened technical experts to synthesize knowledge, share feedback, and guide the project from vision to execution. The Zoom virtual platform was utilized to facilitate technical workshops and TAT meetings/events. Zoom polls and Whiteboards, Qualtrics Surveys, Survey123 (for mapping areas of priority), Miro boards, Mentimeter, Google Jamboards, and more were used to elicit TAT expertise and ensure engagement.

   Before each meeting, the Facilitation Team organized meeting logistics and developed meeting materials (such as meeting agendas, facilitation plans, and logistics and coordination plans) to ensure the limited time was effectively used. At the start of each meeting, the Facilitation Team clarified its role to support the TAT in navigating its work and staying focused on its objectives. Facilitators remained responsive to group dynamics and unexpected challenges, adjusting as needed while maintaining forward momentum. Through steady presence and confidence in the process, the Facilitation Team helped TATs build a shared understanding, navigate through project complexities, and make informed decisions. The goal was to ensure that each meeting concluded with a sense of progress and gratitude, reinforcing the TAT's contribution to the project's overarching goals and outcomes.

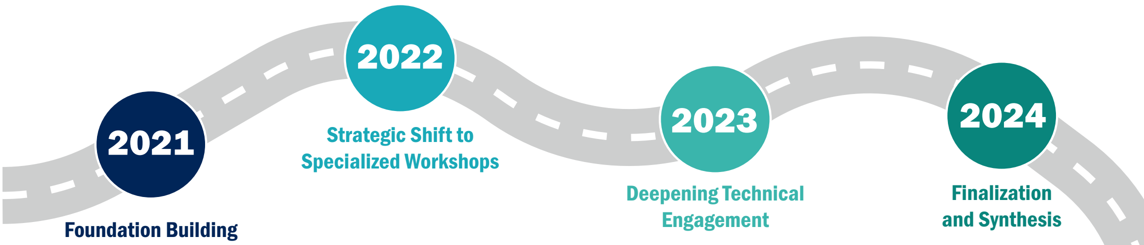
   The Facilitation Team prepared executive summaries of technical information discussed or produced during TAT meetings and technical workshops hosted by TIFF, or as requested by the SC. The Facilitation Team also led communications and information distribution to technical experts and TATs and other stakeholders, to support online and offline collaboration and stakeholder engagement. Outreach strategies and materials beyond meetings included interviews, surveys, polls, fact sheets, handouts, infographics, videos, and other educational tools.

4. **Ad Hoc Workshops and Coordination Meetings** were convened to address unforeseen needs that arose for each Component's TAT. Because the complexities of project delivery sometimes deviated from the original schedule (specifically the scheduling of component contract deliverables), the Facilitation Team organized coordination meetings with the Leadership Team and individual calls with Component Champions to clarify workshop objectives. These ad hoc workshop and meetings ensured that priority topics, questions, and challenges identified by the TAT were acknowledged and addressed accordingly.

PROJECT SCHEDULE

The Meadows Center's facilitation activities evolved over the course of the TIFF project to support its dynamic needs and maintain momentum (Figure 5-1). Below is a year-by-year summary of key milestones from 2021 through 2024.

TIFF PROJECT SCHEDULE



2021
- TIFF Leadership Team Charter
- TIFF Brand Guide
- All Component TAT Kick-Off Meeting
- Coastal Liaison Regional Flood Planning Groups Meeting
- First TAT Component Meetings

2022
- Bathymetry Workshop
- Data Classification Workshop
- Data Gap Analysis Workgroup
- TFMA Technical Conference
- Subsidence Workshop

2023
- Second TAT Component Meetings
- 3rd International Workshop on Waves, Storm Surges and Coastal Hazards
- Texas Nearshore Wave Data Workshop
- Integrated Flood Modeling Brown Bag Seminar Series

2024
- Rio Grande Valley RFPG Meeting
- TFMA Technical Conference
- Compound Flood Planning Decision Support Workshop
- End-User Workshop
- Model Coupling Workshop
- TIFF Year Two Report Webinar
- Third TAT Component Meetings: Vetting Recommendations

Figure 5-1. Timeline illustrating key project milestones.

2021: Foundation Building

In its first year of implementation, TIFF strategically focused on establishing a strong foundation for stakeholder engagement, project identity, and collaborative governance. The Facilitation Team worked closely with the SC to co-develop critical structures and launch the first series of TAT and stakeholder engagements.

Key activities and engagements included:

- **TIFF Leadership Charter**: Defined the project's mission, vision, and general execution approach; established targets for TAT meeting schedules; and clarified the roles and responsibilities of the SC, Facilitation Team, and Components 1–4.
- **TIFF Brand Guide**: Created a consistent project identity by outlining guidance on logos, color palettes, and font styles for all communications and materials.
- **TIFF Components (1–4)**: Finalized a membership list of 96 confirmed TAT participants across all components, including details on initial TAT nominees and final membership as of June 2021, as confirmed by the SC.
- **TAT Kick-Off Meeting, all components (April 5)**: TIFF's first meeting brought together participants from federal and state agencies, academia, and regional entities to introduce the TIFF partners and Facilitation Team, and to orient attendees to TIFF's scope, timeline, and structure.
- **Coastal Liaison Meeting with RFPGs (September 1)**: Held a virtual session with RFPG representatives to discuss how TIFF tools and data could support ongoing regional planning.
- **First Round of Component-Specific TAT Meetings (December 6-9)**: Convened four virtual meetings for each component, marking the beginning of sustained technical engagement.

2022: Strategic Shift to Specialized Workshops

The second year of TIFF was marked by a responsive approach that directed focus to areas where momentum is gathering in the technical communities around data collection, integrated modeling, flood communication, and flood planning. This included ongoing coordination with the project's key Texas stakeholders, such as the GLO River Basin Study Groups, CHARM, TDIS, and TWDB's RFPGs, as well as distinguished academics and experts serving as TAT members. These efforts led TIFF to adopt a workshop model focused on emerging priorities within each component, which in turn broadened national engagement around cutting-edge flood science.

A total of four topic workshops were held across all Components (1-4):

- **Bathymetry Workshop (May 2022)**: Participants explored needs and standards for bathymetric data along the Texas coast.
- **Data Classification Workshop (May 2022)**: This workshop engaged TAT members in identifying consistent classification schemes for flood-related data.
- **Data Gap Analysis Workgroup (July 2022)**: TIFF facilitated a TAT workgroup to analyze and prioritize gaps in coastal flood data across Texas.
- **Subsidence Workshop (September 2022)**: This workshop convened experts to discuss coastal land subsidence and its role in flood risk.

2023: Deepening Technical Engagement

In its third year, TIFF undertook outreach efforts to clarify data needs for incorporating compound flood modeling outputs into traditional tools and models, and proposed guidelines to best balance scheduling and practical application concerns. TIFF engaged regional planners, stakeholders, and technical end users to better understand the planning needs and tools required for more informed regional decision-making. Additionally, TIFF worked with priority end user groups (property owners, property renters, and individuals with LEP) to identify their decision-making needs regarding datasets, modeling, and visualization.

Major facilitation activities included:

- **Second Round of TAT Component Meetings (March 22-23)**: Held virtually, these meetings leveraged interactive platforms, such as Google Jamboard and Poll Everywhere, to review and prioritize technical recommendations.
- **International Workshop on Waves, Storm Surges, and Coastal Hazards (October 1-6)**: TIFF designed and presented a project poster and gathered expert input on coastal dynamics and modeling frameworks.
- **Texas Nearshore Wave Data Workshop (November 2)**: A virtual session was hosted to evaluate wave monitoring needs for coastal flood modeling.
- **Integrated Flood Modeling Brown Bag Seminar Series (July 2023-April 2024)**: TIFF led a seven-part seminar series on integrated flood modeling, featuring expert discussions on innovative modeling strategies and tools.

2024: Finalization and Synthesis

The final year of TIFF centered on synthesizing the questions, feedback, and findings gathered from all components, TATs, and stakeholders engaged throughout Years One through Three. This comprehensive synthesis, combined with ongoing outreach and engagement, led to the development of 42 potential TIFF recommendations. These recommendations aim to improve flood hazard characterization in the Texas coastal region, help coastal communities better prepare for future floods and safeguard lives and property, and support regional flood planning and mitigation efforts.

Engagement highlights included:

- **TFMA 36th Annual Meeting (2024)**: TIFF was featured via an exhibitor booth and direct engagement with regional flood professionals.
- **Compound Flood Planning Decision Support Workshop (April 18)**: The team facilitated a session focused on aligning TIFF outputs with planning needs at the local and regional level.
- **Best Practices in Identifying Stakeholder Needs Workshop (June 28)**: TAT members gathered to discuss best practices for communicating flood information to end user groups.
- **Model Coupling Workflow Workshop (August 6)**: The Facilitation Team guided a technical discussion around integrating inland and coastal flood models.
- **TIFF Year Two Report Webinar (August 8)**: TIFF delivered a virtual presentation of the Year Two Report, showcasing progress and setting the stage for final TAT engagements.
- **Third Round of TAT Component Meetings – Vetting Recommendations (September-December)**: Hosted final meetings for each component to vet, refine, and confirm the 41 TIFF recommendations based on expert and stakeholder input.

Storm clouds over the Corpus Christi ship channel in Port Aransas, Texas ©Marcus Calderon

The TIFF Recommendations Process

From September to December 2024, the Facilitation Team coordinated the third series of individual TAT Component meetings. These meetings served as a culminating step in the TIFF engagement process, bringing together TAT members to revisit their original Component objectives, refine draft Component recommendations that resulted from TIFF's research partners and the Years One and Two Reports, and propose additional Recommendations to more fully meet the original TIFF objectives.

The TATs were guided through a review and refinement process to finalize the TIFF Recommendations included in this report:

1. Reintroduction to Objectives: Meetings began with a review of the component's original objective list, highlighting two to three objectives as the focus for that meeting.
2. Review of Supporting Material: Champions or Study Providers presented relevant background information and led Q&A sessions to ensure participants were prepared to engage thoughtfully.
3. Review existing recommendations
    a) Instead of a poll, facilitators posed the question live and collected feedback via chat or audio: Is the recommendation sufficient as written, or do enhancements need to be made? If not, the group collaborated to revise the language.
    b) The question was then re-asked to confirm consensus on the updated version.
4. Optimize recommendation language
5. Evaluate whether the recommendations fully addressed the highlighted objective. If any participant answered "No," facilitators supported the development of additional recommendation proposals.
6. Propose new recommendations, as needed
7. Once all proposals were gathered, or if all agreed the objective was considered addressed, facilitators guided the group in defining implementation details (partners/stakeholders, resources/costs, and time considerations).
8. Consider key partners or stakeholders; estimated resources or costs; and time sensitivities, deadlines, and deliverables.
9. If any additional recommendations required further context or clarification, the Component Champion or Study Provider(s) would present supporting materials and lead a Q&A discussion.
10. This process was repeated for all recommendations under the highlighted objective.
11. Once consensus was reached, the TAT Review phase concluded for that objective.
12. For participants unable to attend, or needing more time, follow-up surveys were distributed after select meetings. These surveys mirrored the meeting discussions and included the same TAT Review and Certification questions.
13. Once all necessary recommendations and implementation details were complete, the TAT Certification phase concluded.

The TAT Review and Certification phases were repeated for each set of highlighted objectives throughout the September-December meetings, covering as many objectives and recommendations as time allowed.

Following this third series of TAT individual component meetings, a *TIFF Components 1-4 Survey: Technical Advisor Feedback on Potential Recommendations* was distributed to capture the final TAT review of all potential recommendations for all Components (1-4). Additionally, the SC identified 20 key technical advisors across the four components to conduct a more in-depth review of recommendations identified as SC priorities. All collected feedback throughout this engagement process was used to shape the final set of TIFF Recommendations. Every recommendation was reviewed by the SC, which made the final decision on whether to incorporate the TATs' input.

After collecting all feedback, the SC had a debriefing with the Facilitation Team to discuss the findings. Together, they used the insights from TAT members and coordinating agencies to refine the TIFF Recommendations. The final recommendations were then formatted into one-page handouts for sharing with potential funders. See the TIFF Recommendations section for detailed handouts.

Facilitation Lessons Learned

While TIFF should be lauded as a breakthrough for collaborative science and the advancements it will bring to Texas' ability to plan and respond to flood, the project has also offered some important lessons for future interagency collaborative efforts. This section reflects on both what worked well and where limitations surfaced, offering actionable insights for future efforts involving cross-disciplinary collaboration and facilitation. These lessons point to the importance of embedding facilitation early on, clearly defining roles, and maintaining open communication across teams:

- **Flexibility in facilitation strategies is essential** - The process designed for the implementation of TIFF centered around a feedback loop. An initial vision was presented to the identified Technical Advisors with the hope and expectation that the advisors would guide the project in new directions. While the project was greatly enhanced by its flexibility and responsive approach, the contracts, staffing, and deadlines governing the project did not allow for the degree of adaptation that best suited the outcomes.

  When project deliverables and timelines evolved, the Facilitation Team had to continually adapt its approach, shifting from general engagement to more specialized workshops, adjusting meeting formats, and revisiting timelines. Flexibility proved critical in maintaining engagement despite uncertainty.

- **Interactive tools increase engagement across audiences** - The use of tools like Qualtrics, Miro, Zoom Whiteboards, Poll Everywhere, and Survey123 helped engage both technical and non-technical participants in virtual settings. These platforms allowed for real-time feedback, continuous input, and visual collaboration, making complex content more accessible and interactive. It is important to note that time should be spent teaching participants how to use the interactive tools, along with regular check-ins to assist with any difficulties. Time should also be built in to allow facilitators to learn and test these tools.

- **Consistent documentation supports continuity** - Meeting notes, executive summaries, and synthesis materials helped maintain momentum and institutional memory, especially when staff turnover, shifting roles, or timeline extensions occurred. Reliable documentation became a key tool for knowledge transfer and decision-making.

- **Long-term expert collaboration sustains momentum** - TIFF was designed to build a cross-disciplinary, multi-institutional network of experts. When regular engagement was possible, expert input greatly improved the quality of technical outputs. Sustained collaboration must be prioritized to retain continuity, trust, and momentum over time.

- **Facilitation role should be embedded into the project design from the start** - While TIFF recognized the importance of the facilitation role from the start, there were implications from having the Facilitation Team brought on as contractors after some of the initial project decisions had already been made. The SC successfully folded the Facilitation Team into the Leadership Team and fully supported the facilitation role, but the process continued to be constrained by some of the early structural decisions that were made before the engagement strategy could be developed.

Challenges That Shaped These Lessons

TIFF is a model for science collaboration and eliciting expertise to guide public decision-making. The project brought together experts who might not have otherwise had an avenue to engage in this kind of collaborative work, placing them directly in the driver's seat to shape TIFF's outcomes. This interagency and interdisciplinary coordination responded to an immediate need, enhancing Texas's coastal flood resiliency, and condensed what might have taken decades into a quick and efficient cycle of research and peer review. This pace, at times, came at the expense of facilitation. Over the course of the four-year endeavor, several challenges emerged that limited the full potential of facilitation. Consideration of these obstacles offers design opportunities for future collaborative, multi-agency projects.

- **Divided coordination roles between the SC and the Facilitation Team** - There is a natural tension between the project management role and the facilitation role. This can create redundancies, slow communication, and dilute accountability. The partner agencies each carried multiple project roles (e.g., Component management, contract management, research coordination) which, at times, resulted in canceled planning sessions and gaps in internal coordination. Project delays led to delayed outreach to TATs and reduced opportunities for expert review and stakeholder engagement.
- **Contracts are not the best tools for "flying the plane as we build it"** - True to its word, TIFF is an adaptive endeavor, responding to the input and guidance of the experts engaged in the project. The scope of the project envisioned during the contracting phase greatly changed multiple times over the four years. The TIFF Leadership Team stayed committed to delivering the optimal outcomes and absorbed mounting calls for changed schedules, additional workshops, and enhanced coordination with study providers. This came at the cost of internal budgets, delayed project timelines, and ultimately reductions in the frequency and planning available for TAT engagement.
- **Underestimation of the facilitation needs** - If facilitation is viewed as a delivery function only (versus a guiding principle in overall process design), the associated work can be underestimated and undervalued resulting in a lack of sufficient funding, delayed inclusion in planning conversations, and missed opportunities for strategic alignment.
- **Conflict of interest concerns challenged crucial coordination with the Facilitation Team** - Because the Meadows Center was a contracted entity that hypothetically could have competed for other project contracts, the SC developed deliverables and deliverable schedules for key aspects of the project without the participation of the Facilitation Team. Due to the timing and contracting pressures of the overall TIFF project, the deadlines of these contracts were independent of the deadlines associated with the TAT engagement and annual report deadlines. This provided a key challenge in regard to having the engagement goals be the driving influence on sequencing/timing of technical work and expert review. Ultimately, the structural limitations around potential conflicts of interest undermined the facilitators' ability to serve as process stewards, co-creating in collaboration with the SC.

Power sharing has inherent challenges, and there are trade-offs with any collaborative process design. Based on these learnings, some recommendations to consider for facilitated interagency collaboratives include: 1) facilitation considerations have to be included from the start and before final process decisions are made, 2) facilitation contracts should be as flexible as possible to allow for changes in project delivery that best suit the project, and 3) non-compete clauses should be considered for all interagency contractors to eliminate unnecessary complexity and ensure that all project partners are unencumbered and can be fully participatory in key decisions.

Texas Integrated Flooding Framework Recommendations

Updated October 2025

The TIFF Recommendations are the culmination of five years of collaborative research, technical engagement, and expert consensus. More than 125 national experts representing state and federal agencies, academic institutions, and local governments contributed to this integrated framework that seeks to equip local, regional, and state entities – and households – with the compound flood risk information and tools needed for comprehensive flood planning and mitigation.

These 42 actionable Recommendations are organized by focus area:

1. Improved Data and Monitoring Gap Analysis
2. Improved Data Management and Visualization
3. Improved Integrated Flood Modeling
4. Improved Flood Communications

Each TIFF Recommendation can be funded and pursued independently or aligned within broader, multi-agency initiatives to advance integrated flood resilience across the state. The TIFF Recommendations been formatted for convenient printing and distribution to support advocacy for their implementation, either individually or as a part of a coordinated effort.

Suggested citation and additional context: Texas Integrated Flooding Framework, *2025 Final Report Recommendations to GLO* (Texas Water Development Board, U.S. Army Corps of Engineers, U.S. Geological Survey, Meadows Center for Water and the Environment) https://texasflood.org/tools-library/tiff/reports.html

ENHANCE THE COASTAL DATA SURFER (CDS)

Strengthen partnerships between TIFF, TDIS, and GLO's Combined River Basin Flood Study to develop the framework, infrastructure, and software for displaying, inventorying, and evaluating data to support flood planning, modeling, mapping, and mitigation along the Texas coast.

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

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

Project phases and deliverables should align with other agency flood and hazard mitigation planning cycles, such as the TWDB 2024-2028 Regional Flood Plan. Ongoing maintenance costs vary annually and should be allocated across project phases. Agencies can collaborate on funding different phases or use a cost-sharing formula. Key costs include cloud hosting, data storage, production, User Interface/User Experience components, security services, and technical debt management.

IMPLEMENTATION NOTES

The CDS is a crucial and ongoing investment. Key actions when implementing this recommendation include:

- **Define metadata standards**: Develop metadata standards in collaboration with partner agencies (TIFF, TDIS, GLO, USGS)
- **Deploy beta version**: Gather user feedback and assess usability
- **Integrate spatial data**: Enable data gap analysis and improve decision-making
- **Conduct follow-up evaluations**: Use user feedback to refine functionality
- **Perform a data gap analysis**: Identify evolving data needs, including critical hydrologic, hydrodynamic, meteorologic, and socio-economic datasets
- **Plan maintenance and three-year updates**: Align with regional flood planning cycles
- **Identify cost-effective data hosting**: Explore shared responsibilities for deploying the CDS

ADDITIONAL INFORMATION

The following additional information regarding the implementation of this Recommendation to develop a CDS was elicited from the expert advisors to the Texas Integrated Flooding Framework process:

- **Define metadata standards in collaboration with partner agencies (TIFF, TDIS, GLO, USGS)**: Using TDIS's Data Management Query Tool project as a reference, develop metadata standards to categorize hydraulic and hydrologic models in Texas, ensuring consistency for future data input and updates.
- **Deploy beta version**: Gather user feedback from scientists, modelers, engineers, and other stakeholders to assess usability based on searchability, metadata effectiveness, and dataset availability.
- **Integrate spatial data**: Facilitate users in performing data gap analysis and improving decision-making by optimizing the CDS to support structured data, informing future planning and modeling needs (e.g., identifying where to expand continuous monitoring, improve flood emergency response, etc.).
- **Conduct follow-up evaluations**: Gather user feedback to refine its functionalities and implement necessary updates and optimizations to improve overall performance.
- **Perform data gap analysis**: Identify evolving data needs, including critical hydrologic, hydrodynamic, meteorologic, and socioeconomic datasets. Conduct an initial inventory to assess dataset availability, followed by targeted gap analyses to prioritize modeling approaches. Enhance the CDS to support temporal data searches linked to study requirements.
- **Plan maintenance and three-year updates**: Align maintenance and three-year updates with regional flood planning cycles**.** Create a dashboard feedback mechanism and a working group email alias to facilitate continuous updates. Expand API capabilities for improved search functionality, feedback submission, and dataset additions, adhering to FAIR (Findable, Accessible, Interoperable, and Reusable) data principles. Validate metadata completeness and system integrity through expert reviews, while integrating new methodologies and datasets to address gaps. Catalog machine-readable data with a defined metadata schema and explore opportunities for data digitization.
- **Identify cost-effective data hosting**: Explore shared responsibilities for deploying the CDS, including the potential for TDIS to provide long-term hosting. Align hosting strategies with USGS-led data gap analyses to maximize efficiency and cost-effectiveness.

EXPAND MEASUREMENT NETWORKS

Augment existing measurement networks to include under-sampled locations, prioritizing areas by flood frequency and severity.

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

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

Potential partners include the Texas Councils of Governments for coordinating emergency management and providing inundation photos to enhance observations, the TWDB for expertise in socio-economic flood risk factors, and TxGIO as a potential service provider for imagery data storage. Organizations managing local sensor networks, such as the Southeast Coastal Ocean Observing Regional Association, may also contribute to this effort. Key stakeholders include county agencies and non-profits that can serve as community organizers and connectors.

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

IMPLEMENTATION NOTES

The expansion of measurement networks is a cost-effective investment. Key actions when implementing this recommendation include:

- **Perform data gap analysis**: Identify under-sampled areas based on flood frequency, severity, and proximity to vulnerable infrastructure and populations
- **Assess exposure and damage**: Evaluate data availability and gaps for assessing exposure and damage, incorporating socio-economic factors to refine flood models
- **Expand sensor networks**: Expand local sensor networks and explore funding opportunities through local jurisdictions
- **Standardized data integration**: Develop best-practice guidelines for verifying and incorporating diverse datasets into flood models, ensuring consistency across studies. One potential resource for this work is the IDRT pilot community data collection tool, which includes a survey, training process, and web portal for displaying results. This tool could be adapted for other regions
- **Improve data completeness**: Address significant data gaps by integrating anecdotal sources, such as citizen science contributions, local agency data, timestamped inundation photos, and media reports

NEARSHORE WAVE DATA COLLECTION NETWORK

Establish a nearshore wave data collection network along the Texas coast to address critical data gaps and enhance understanding of extreme wave events, improve daily flood forecasting, and strengthen coastal risk assessment

TIFF recommends establishing a nearshore wave data collection network along the Texas coast to address critical data gaps, enhance understanding of extreme wave events, improve daily flood forecasting, and strengthen coastal risk assessment.

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

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

IMPLEMENTATION NOTES

The Nearshore Wave Data Collection Network is a crucial and ongoing investment. Key actions when implementing this recommendation include:

- **Conduct inventory and gap analysis**: Assess nearshore wave data along the Texas coast
- **Select instrumentation**: Deploy offshore buoys, nearshore sensors, and shore-based sensors
- **Deploy monitoring stations**: Ensure resilience to extreme weather
- **Integrate models and forecasting**: Incorporate real-time data into wave, surge, and inland flood models to enhance forecasting
- **Managing and sharing data**: Establish a centralized platform for real-time data sharing and long-term storage
- **Plan long-term maintenance and partnerships**: Coordinate with federal and state agencies (NOAA, GLO, USACE, USGS, Gulf of Mexico Coastal Ocean Observing System, National Oceanographic Partnership Program)
- **Develop QC/QA guidelines**: Identify monitoring station locations and integrate data into flood models

ADDITIONAL INFORMATION

The following implementation information was elicited from the expert advisors to the Texas Integrated Flooding Framework process. For more information, see the TIFF Final Report at TexasFlood.org.

- **Conduct inventory and gap analysis**: Perform a comprehensive inventory and gap analysis of nearshore wave data along the Texas coast to improve understanding of extreme wave events and flood forecasting. Use existing models and datasets to identify priority regions based on coastal infrastructure, population growth, and risk factors. Experts recommend focusing on areas with inconsistent wave measurements, such as Galveston Bay, Port Arthur's Pleasure Island, Keller Bay, Carancahua Bay, and Port Aransas.
- **Select instrumentation**: Deploy three types of wave measurement instruments: offshore buoys with independent power supplies that report data every 30–60 minutes, nearshore sensors transmitting real-time directional and non-directional wave data, and shore-based sensors activated during inundation events. Prioritize cost-effective solutions, such as Spotter buoys, and GPS integration into existing systems, such as TDIS or TAMU's Texas Automated Buoy System. Consideration should be given to the costs of maintenance, data transmission, storage, analysis, and dissemination, which may exceed the costs of instrumentation.
- **Deploy monitoring stations**: Identify and secure station locations, ensuring resilience against extreme weather. Assess permitting requirements for buoy deployments and integration with NOAA's National Data Buoy Center. Develop nearshore and shore-based monitoring infrastructure (may require specialized platforms).
- **Integrate models and forecasting**: Incorporate real-time data into wave, surge, and inland flood models to enhance forecasting. Hourly forecasts will cover the entire Texas coast, including bays, by combining observational data with model outputs. Existing models will be adapted to seamlessly integrate with new datasets.
- **Managing and sharing data**: Establish a centralized platform for real-time data sharing and long-term storage. High-resolution (15-minute interval) and high-frequency (6 Hz or higher) wave data, including wave height, period, and direction, will support model calibration and validation. Store raw data in barometric-corrected NetCDF format per climate and forecast metadata standards, ensuring permanent availability for post-event analysis.
- **Plan long-term maintenance and partnerships**: Build partnerships with federal and state agencies (NOAA, GLO, USACE, USGS, Gulf of Mexico Coastal Ocean Observing System, National Oceanographic Partnership Program) for sustained data collection and funding. Engagement with contractors, private entities, universities (TAMU), and industry will support short-term spot measurements. Estimated costs include $100,000–$1,000,000 per year for measurements, $200,000 per year for modeling (with potential increases for model development), and $500,000 for initial buoy deployment. Assess additional funding needs for network expansion and explore collaborative funding strategies to distribute maintenance costs.
- **Develop QC/QA guidelines**: Collaborate with partner agencies to identify monitoring station locations, collect wave measurements, and integrate real-time data into flood models. Ensuring consistency for long-term data sharing and storage.

A CENTRALIZED SUBSIDENCE MONITORING DASHBOARD

Develop and maintain a Centralized Subsidence Monitoring Dashboard to serve as a comprehensive, user-friendly platform to consolidate, analyze, and utilize subsidence data

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

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

Streamlining access to subsidence information and analyses will empower stakeholders to develop informed, effective strategies for mitigating the risks associated with subsidence in Texas.

Subsidence districts, such as the Houston-Galveston Subsidence District, can play a key role by utilizing their existing monitoring stations. These stations could also help expand monitoring efforts to other subsidence areas across the state.

IMPLEMENTATION NOTES

The Centralized Subsidence Monitoring Dashboard is a crucial and ongoing investment, estimated at $200,000–$400,000. Key actions when implementing this recommendation include:

- **Conduct needs assessment and planning**: Engage stakeholders to define requirements for data sources, tools, and QC/QA processes; collaboration with experts is critical to outline technical specifications for integrating InSAR data and create a detailed project plan with timelines and budgets
- **Integrate data and develop the platform**: Partner with agencies, universities, and private entities to consolidate subsidence data into a centralized repository that meets accessibility standards, incorporates InSAR data, and implements algorithms for calculating subsidence rates
- **Establish quality control**: Develop QC/QA protocols to ensure data accuracy and establish ongoing validation with periodic updates
- **Test with users**: Conduct iterative testing with stakeholders to gather feedback and refine functionality and usability
- **Launch and support**: Launch the dashboard, promote its use, provide training, and establish systems for regular updates and tool enhancements

HIGH-RESOLUTION LAND COVER DATA TO ENHANCE FLOOD MODELS

Collect, process, and integrate C-CAP High-Resolution 1-m Land Cover Data for the entire Texas coast and provide guidelines on implanting the datasets into Texas coastal flood modeling systems

This data provides more detailed surface distinctions – such as urban structures, vegetation, and water bodies – compared to traditional 30-meter datasets, which are essential for flood impact prediction and management.

This data will:

- improve understanding of water flow dynamics and land cover effects
- enhance flood simulations for infrastructure
- support assessments of sea-level rise and coastal changes
- align flood management with federal standards, fostering better coordination with NOAA, FEMA, USACE, and other agencies

Integrating this high-resolution data into coastal flood models will improve flood resilience by enhancing flood simulations, supporting response efforts, and informing long-term planning.

TIFF recommends partnerships with NOAA, TxGIO, and state and local stakeholders to ensure seamless data accessibility and effective implementation.

IMPLEMENTATION NOTES

Key actions when implementing this recommendation include:

- testbed numerical model studies for performance evaluations
- developing guidelines for integrating high-resolution land cover data into existing coastal flood models to improve flood simulation accuracy

The data will support flood resilience planning tools used by TWDB, local governments, and emergency management agencies.

The total budget is estimated to be between $1–$3 million for all Texas coastal counties.

The project timeline is 1-3 years, with future updates occurring every 5–10 years, based on funding and demand.

BATHYMETRIC DATA FOR PRIORITY AREAS

Collect bathymetric data at priority areas along the Texas coast to address critical data gaps, strengthen coastal flood modeling efforts, and improve flood forecasting

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

TIFF recommends collecting critical bathymetric data in priority areas along the Texas coast, as identified by project Technical Advisors, to significantly improve the accuracy of coastal flood modeling and forecasting. Agencies could collaborate to better coordinate bathymetry data acquisition and leverage limited funding.

The cost of bathymetric acquisition depends on the type of water body (shallow, deep, or river), the size of the project, and the collection method. Agencies can collaborate on funding different actions or use a cost-sharing formula. Assess additional funding needs for expanding coastal measurement.

IMPLEMENTATION NOTES

Key actions when implementing this recommendation include:

- **Identify and secure monitoring locations**: Focus on priority areas identified by experts, such as Nueces Bay, Lower Galveston Bay, Sabine Lake, and Laguna Madre
- **Integrate data**: Incorporate data into wave, surge, and inland flood models to enhance forecasting
- **Establish centralized sharing**: Create a platform for data sharing and long-term storage
- **Build partnerships**: Coordinate with federal agencies (e.g., NOAA, USGS) and state agencies (e.g., TWDB, TDIS) for sustained data collection and funding
- **Develop QC/QA guidelines**: Standardize process for identifying monitoring station locations and integrating data into flood models

TESTING SITES FOR WATER MONITORING DEVICES

Design, install, and operate coastal testing sites that evaluate water monitoring devices to ensure their reliability, operational effectiveness, and compliance with regulatory standards

Emerging monitoring technologies are essential for improving data accuracy and flood planning. Traditional datasets often fail to capture the complexities of the coastal environment, but innovative sensing technologies can help bridge these gaps. To ensure reliability, these technologies must be tested against established methods in real-world coastal conditions.

TIFF recommends partnering with local, state, and federal agencies to design, install, and operate coastal testing sites to evaluate water-monitoring devices. These sites will evaluate the performance of existing and prototype monitoring devices under tidal fluctuations, salinity, sedimentation, biofouling, and extreme weather.

Key objectives include assessing device reliability, longevity, accuracy, and regulatory compliance. To integrate seamlessly with legacy monitoring programs and regulatory applications, data from new technologies must align with established sensing methods.

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

IMPLEMENTATION NOTES

Key actions when implementing this recommendation include:

- Site selection and design
- Equipment selection and installation
- Data collection and monitoring
- Environmental resilience assessment
- Data analysis
- Long-term sustainability

Partnerships with traditional monitoring agencies (e.g., USGS) and other entities (e.g., universities, flood control districts, and non-profits) should be encouraged where feasible. Leveraging existing monitoring sites for technology evaluations can support new methods while filling spatial monitoring gaps with cost-effective solutions.

One recommended technology for testing is disposable, biodegradable flood level sensors, which provide short-term data collection in communities with limited funding. Designed to last six months, these sensors offer lower data quality and are not a replacement for traditional gages.

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

ADDITIONAL INFORMATION

The following additional information regarding the implementation of this Recommendation to operate testing sites for water monitoring devices was elicited from the expert advisors to the Texas Integrated Flooding Framework process:

- **Site selection and design**: Partner with local experts to identify optimal coastal site(s) and design modular, durable platforms that support multiple devices while meeting permitting requirements
- **Equipment selection and installation**: Implement a standardized process for selecting and installing sensors for wave height, water quality, and weather parameters, ensuring proper calibration and accuracy
- **Data collection and monitoring**: Develop a real-time data acquisition system with remote access and automated alerts for malfunctions
- **Environmental resilience assessment**: Evaluate device performance under dynamic coastal conditions, tracking uptime, recalibration needs, and resistance to salinity and biofouling
- **Data analysis**: Enable stakeholders to assess data quality, reliability, and operational resilience, ensuring alignment with agency requirements
- **Long-term sustainability**: Establish a self-sustaining model through subscription fees, grants, partnerships, and sponsorships

ASSESS HIGH-FREQUENCY RADAR ACCURACY FOR WAVE MEASUREMENTS

Assess the ability of high-frequency (HF) radar systems in enhancing the accuracy of wave and current measurements for coastal analysis

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

To assess the accuracy of HF radar data, comparative studies with in-situ measurements (e.g., buoy and vessel-based data) are necessary.

In Sabine Lake and Galveston Bay, where few buoys are available, offshore studies comparing HF radar data with TAMU's TABS and NOAA buoys are recommended. These studies will help evaluate HF radar performance under varying environmental conditions and establish correlations between different monitoring technologies.

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

IMPLEMENTATION NOTES

The assessment of HF radar data accuracy is a crucial investment. Key actions when implementing this recommendation include:

- **Collect data and conduct comparative studies**: Identify available in-situ monitoring stations (e.g., TABS and NOAA buoys) for comparative studies; temporary buoys will be deployed where necessary, particularly in Sabine Lake and Galveston Bay, where in-situ data is limited; comparative studies will be conducted between HF radar data and buoy/vessel-based observations to evaluate performance under different environmental conditions
- **Conduct long-term evaluation**: Assess the reliability of HF radar systems over time. Seasonal and extreme weather event impacts on HF radar measurements will also be analyzed
- **Engage stakeholders and report findings**: Leverage collaborations with GLO, GCOOS, NOAA, and other coastal management entities to share findings; interim and final reports summarizing results, challenges, and recommendations will be published; guidelines for integrating HF radar data into broader coastal management strategies should be developed

STUDY USER INTERACTIONS WITH FLOOD RISK VISUALIZATIONS

Conduct research to examine how flood risk understanding and gaze patterns change when users interact with multiple modes of flood risk visualizations and communication tools, such as Buyers Aware, the CHARM online platform, and dashboards being compiled by IDRT and UT-Austin

To improve flood risk communication, TIFF recommends conducting research examining how individuals' gaze patterns shift when interacting with different modes of flood risk visualization. This study will bring people into a visualization lab to evaluate the effectiveness of different visualization modes in enhancing flood risk awareness and test how different modes of interaction influence user engagement and comprehension. This includes in situ testing, mobile device testing, and using eye-tracking with visualizations, potentially gamifying the process. Results from this study could accelerate understanding of what works for communication and complement efforts to assess emerging technology.

By analyzing gaze patterns, researchers can gain insights into how people engage with visual tools, where they focus their attention, and how well they absorb the risk-related content. This research should focus on testing existing and developing flood risk visualization tools used in Texas, such as the Buyers Aware platform, the CHARM online tool, and dashboards being developed by IDRT and UT-Austin. This research should also consider the usefulness of technologies for communicating model outputs. By studying how users interact with these tools, we can refine their design to enhance user comprehension and decision-making, ultimately improving flood preparedness and response efforts.

The estimated cost for this research is $225,000, covering eye tracking software and hardware, virtual and augmented reality equipment, immersive software, and research design and execution. Costs may be reduced if access to existing eye-tracking and keystroke-tracking equipment is obtained.

IMPLEMENTATION NOTES

Key actions when implementing this recommendation include:

- **Conduct literature review**: Review interactive and active learning technologies, including user studies and data/analytics workflows, as well as developing serious games and exploring how to engage adults in playing them
- **Conduct eye-tracking and virtual-reality studies**: Observe how gaze behavior changes when different visual representations of flood risk are shown to participants
- **Run a key-logging study**: Combine with previous studies to determine where participants interact with flood risk information on the web, analyzing their search behavior and physical actions while seeking out flood risk data
- **Assess responses to misinformation**: Study how people respond to misinformation across a continuum of flood risk levels (low to high) to understand effects on decision-making

ASSESS PUBLIC EVACUATION DECISION-MAKING

Assess how local knowledge influences evacuation decisions during a flood event to improve emergency planning and response

TIFF recommends conducting experiments, surveys, and focus groups along the Texas Coast to explore how local knowledge influences evacuation decisions. This research should assess public perceptions of media reports, trust in local authorities, and confidence in sources like meteorologists and emergency managers. It should also use a mixed methods approach to identify barriers to evacuation and common assumptions, while incorporating insights from local emergency managers and meteorologists.

Evacuation decisions are complex, influenced by both the probability of events and the potential consequences. Local knowledge, media coverage, and personal experiences shape how communities process this information. A critical question is how past disasters, local media, and community knowledge affect residents' decisions to evacuate or stay.

Hurricanes have a particularly dramatic impact on life-or-death decisions for coastal communities. While flood maps can aid decision-making, many residents do not follow local emergency managers' advice and instead rely on their own judgment. Understanding this decision-making process is essential for improving evacuation strategies and can help guide improvements in effective communication and messaging during a disaster.

IMPLEMENTATION NOTES

The estimated implementation cost is $450,000. Participants should be compensated to ensure representative data. Key actions when implementing this recommendation include:

- **Review State Operations Center practices**: Interview Texas Division of Emergency Management (TDEM) experts with multi-event experience to identify opportunities to improve evacuation processes by leveraging better information aids, and to provide guidance on messaging strategies to inform the public about evacuation decisions
- **Conduct qualitative studies in coastal communities**: Interview evacuees to understand decision drivers (reasons for evacuating, costs, influence of flood models or navigation apps) and compare public perceptions with the technical information used by experts
- **Experimental test tools**: Use the findings from the qualitative study to design experiments testing the effectiveness of flood maps and navigation apps in aiding evacuation decisions

REPLACE THE "FREQUENCY-BASED TERMINOLOGY" (I.E., "100-YEAR FLOOD")

Conduct research on how numerical reasoning and confidence in interpreting probabilities affect public understanding of uncertainty in flood communication and decision-making, and develop alternative language to replace frequency-based terms such as "100-year" and "1% chance-per-year"

A significant challenge in flood risk communication is the language used to describe the probability of experiencing a flood. Research has shown that longer timeframes, such as 100 or 500 years, are difficult for people to grasp, making it harder for them to accurately assess their risk.

TIFF recommends research to explore how numerical reasoning and confidence in using probability estimates influence the public's understanding of uncertainty in flood communication. This research should also focus on developing alternative language to replace frequency-based terms such as "100-year flood" and "1% chance per year," which often confuse and mislead the public.

The estimated implementation cost is $175,000. To ensure representative data, participants should be compensated. Designing the study to compare findings across both English and Spanish is crucial, as many Texas residents prefer Spanish.

IMPLEMENTATION NOTES

Key actions when implementing this recommendation include:

- **Interview target user groups**: Conduct a systematically designed set of interviews with specific target user groups to identify alternative language and timeframe communication options
- **Run an online experimental survey**: Test Texans in these target groups to identify which language options best influence decision-making, attitudes, confidence, response efficacy, and related factors; consider using the Subjective Numeracy Scale and common probability frames used in flood communication
- **Train language models**: Use the results from the interviews and online survey to train small language models on the specific language used in different coastal and compound flood scenarios, including mapping preferred terms in coastal areas and considering multilingual aspects
- **Evaluate flood literacy**: Determine whether alternatives to frequency-based terminology increase flood literacy in target user groups and improve their capacity to respond effectively to risk information

IMPLEMENT THE TIFF GUIDELINES FOR COASTAL FLOOD INFORMATION DESIGN AND COMMUNICATION

Agencies should follow The TIFF Communication Guidelines when designing information visualizations and communication tools to effectively convey flood risk to both general audiences and specific groups affected by coastal flooding

To improve the clarity and accessibility of flood risk information, TIFF developed Guidelines for Coastal Flood Information Design and Communication, which should be followed when developing flood risk maps, visualizations, and communication tools. These guidelines are best practices for presenting flood risk in a way that is clear, transparent, and user-friendly. Their use will ensure that both general audiences and those directly affected by coastal flooding can accurately interpret and respond to the information.

TIFF recommends that TWDB lead this effort, because it serves as the designated State Coordinating Agency for the National Flood Insurance Program in Texas and provides both flood mitigation and protection planning and assistance. TWDB can coordinate partnerships between government organizations, Texas legislators, state funding agencies, flood tool developers, business owners, non-profits, and universities, to promote the adoption of these Guidelines.

IMPLEMENTATION NOTES

To ensure widespread adoption of the guidelines and improvements in how flood risk is communicated to the public and decision-makers, key actions when implementing this recommendation include:

- **Develop a promotional campaign**: Produce an asynchronous video walkthrough explaining the guidelines; host the public video on the TIFF website; secure expert consensus and seek endorsement from state-level decision-makers
- **Provide training and case studies**: Offer training on applying the guidelines effectively and use the Texas Water Data Hub and the Texas Disaster Information System as case studies to illustrate best practices.
- **Evaluate flood literacy**: Determine whether implementing the TIFF Guidelines increases flood literacy for general audiences and specific groups affected by coastal flooding and improves their ability to act appropriately on risk information

FLOOD RISK REDUCTION PLANNING CARDS

Create Flood Risk Reduction Planning Cards as an accessible user-friendly flood planning tool

Flood risk maps, visualization tools, and coastal management information portals are essential for raising public awareness and driving action at individual, local, and national levels. These tools help residents, policymakers, and emergency responders understand flood risks, prepare for disasters, and make informed decisions about mitigation and adaptation. However, despite their potential, they often fail to effectively communicate flood risk to general audiences. When flood risk information is not clearly presented, non-technical users may misinterpret the data, either overestimating or underestimating the actual risk. Miscommunication can lead to poor decision-making, reducing the effectiveness of flood preparedness and response efforts.

To address this issue, a more structured approach is needed to ensure that flood risk information is presented clearly and accessibly. TIFF recommends the creation of Flood Risk Reduction Planning Cards based on the TIFF Guidelines for Coastal Flood Information Design and Communication. These cards would serve as a toolkit for planners to better organize and prioritize flood risk reduction activities, providing a structured framework for developing and implementing effective strategies to target and reach their specific audiences.

The cards would also encourage data-driven discussions during the flood risk planning process and offer a visually appealing, user-friendly design to improve engagement and usability. By integrating these planning cards into flood communication efforts, communities can enhance their ability to interpret flood risk data, plan for future events, and build greater resilience against flooding.

TIFF recommends partnerships between academic institutions, planning organizations, state funding agencies, cities and towns, flood control districts, and regional flood planning groups to develop and implement Flood Risk Reduction Planning Cards.

IMPLEMENTATION NOTES

Key actions when implementing this recommendation include:

- **Conduct competitive analysis and market research ($50,000–$100,000)**: Conduct a review of existing card decks (e.g., augmented reality 32-card deck), platforms where card decks are marketed (e.g., game crafters), typical costs, and the target audiences that purchase such cards
- **Develop the card deck ($50,000–$100,000)**: Design and create the Flood Risk Reduction Planning Cards based on insights from the competitive analysis and market research, using the TIFF Guidelines for Coastal Flood Information Design and Communication
- **Test and evaluate with users ($50,000–$100,000)**: Assess the cards' effectiveness and gather user feedback to refine and update them for continued improvement

SHARE LESSONS OF TEXAS' FLOOD HISTORY

Create a public resource to share information about historical floods in Texas, helping residents understand past events and make informed decisions

Effectively visualizing and disseminating flood-related information is essential for improving public understanding of flood risks. Accurate and accessible flood data can help communities, decision-makers, and emergency responders interpret complex models and datasets, leading to better preparedness, response, and long-term resilience. However, flood information is often scattered across multiple sources, making it difficult for residents to access and use in decision-making.

To address this gap, TIFF recommends developing a public resource documenting historical floods in Texas, hosted by TDIS. This resource would serve as a centralized platform for residents to explore past flood events and understand their potential future risks. An interactive map interface would allow users to visualize flood events by location, making it easier to see where and when major floods have occurred. Each recorded flood event would include key details such as dates, impacted areas, and the extent of flooding, offering a comprehensive historical record.

The resource should also incorporate predictive insights by integrating flood forecasts and return period data. This would provide users with a clearer picture of potential future flood risks based on historical patterns. By combining historical data with predictive modeling, this tool would enhance public awareness and support more effective flood risk management across Texas.

IMPLEMENTATION NOTES

Keys actions when implementing this recommendation include:

- **Define "major flood" criteria:** Use indicators such as loss of life, property damage, rainfall amounts, and other agreed metrics
- **Generate event summaries:** Create tables for each recorded flood event with dates, impacted areas, and extent of flooding
- **Integrate predictive insights:** Incorporate flood forecasts and return-period data into the public resource
- **Evaluate the interface:** Gather user feedback on the interactive map and iterate to improve usability and understanding

STANDARDIZE GRANTEE SHAPEFILES

Implement a standardized requirement for all funded flood-related projects to include three critical shapefiles to the funding agency

Flood-related projects in Texas involve various stakeholders, including local governments, state agencies, and non-profits, who work to improve flood management and response. However, a lack of coordination can lead to overlapping efforts, inefficient use of resources, and missed collaboration opportunities.

TIFF recommends a standardized requirement for all funded flood-related projects to submit three critical shapefiles to the funding agency and other relevant recipients. These shapefiles will provide spatial data on the project's location, scope, and impact area. This standardized approach will allow agencies to quickly identify overlaps between projects, assess geographic synergies, and reduce redundancy.

By incorporating these shapefiles into project planning and evaluation processes, stakeholders can better understand the spatial relationships between ongoing and proposed projects, ensuring that funding is directed toward projects that complement each other. This will not only streamline resource allocation but also foster comprehensive planning and clarity in project objectives, ultimately enhancing flood preparedness, mitigation, and response across Texas.

IMPLEMENTATION NOTES

Key actions when implementing this recommendation include:

- **Develop submission guidelines**: Specify shapefile formats, metadata standards, and protocols
- **Secure interagency adoption**: Obtain agreement from relevant agencies to adopt the guidelines and standards
- **Designate stewardship**: Assign an office or database to manage and analyze shapefile submissions
- **Integrate into funding processes:** Add shapefile submission requirements to project scopes and funding application processes

ALTERNATIVES TO MENU-DRIVEN DASHBOARDS TO BETTER REACH TARGET USERS

Explore alternatives to using menu-driven dashboards to help target users find the flood risk information they need to make flood-related decisions

Generative AI (GenAI), including prompt engineering and large and small language models, presents an opportunity to modernize flood risk visualization and communication. Human-AI teaming enables more intuitive information retrieval and organization, making critical data more accessible.

TIFF recommends a study to assess how GenAI can better help target users find the flood risk information they need for decision-making. Following the study, a Texas-specific GenAI Flood Risk Tool can be developed for broader implementation. This "Texas GenAI Flood Risk Tool" will feature a prompt coaching system to guide users in writing effective prompts, ensuring they receive accurate and actionable responses. It will also define the necessary datasets for the tool and test how different target users interact with it.

IMPLEMENTATION NOTES

If the resources are not available to implement the entirety of this recommendation at once, the following describes how it could be made a multi-phase approach:

- **Build a GenAI Flood Risk Tool proof of concept (two focus groups; ~$225,000)**: Identify at least five public target users and two official target users for the study; conduct background research to assess these users' flood information needs, leveraging existing research funded by Texas agencies; carry out initial focus groups of 30-50 participants and in-person lab experiments to analyze how users search for flood information, utilizing methods such as eye-tracking, virtual reality-based eye-tracking, and think-aloud protocols; consider online experiments; conduct a follow-up focus group of 18-36 participants to help participants learn prompt-writing techniques and refine their queries to obtain more effective flood-related information
- **Develop the GenAI Flood Risk Tool (one focus group; ~$700,000)**: Build on the findings from the proof-of-concept research, applying the insights gained to the same target users; identify necessary datasets, visual information, and flood-specific small language model requirements; conduct usability testing of the designed system using the same research methods from the proof-of-concept study, with a sample size of 30-50 participants per group
- **Evaluate flood literacy**: Determine if the alternatives to menu-driven dashboards increased flood literacy in target users, improving their capacity to respond effectively and appropriately to given flood risk information

ADVANCE HYDRAULIC MODELING SIMULATIONS WITH HEC-RAS DISTRIBUTED-MEMORY PARALLELIZATION

Advance the HEC-RAS distributed-memory parallelization to facilitate computationally intensive hydraulic model simulations

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) model is widely used for flood hazard characterization in Texas coastal watersheds but faces computational limitations, especially in flat terrain where inter-basin flow transfers affect flood extent and depth. Current modeling requires breaking very large watersheds into smaller sections, creating edge-matching issues and making real-time flood response impractical.

TIFF recommends a distributed-memory parallelization approach to enable HEC-RAS to run across multiple nodes in a High Performance Computing (HPC) environment, significantly reducing simulation times from days to minutes. Faster computations will improve flood planning, emergency response, and the ability to incorporate high-resolution (1m) Texas LiDAR data for more accurate topographic representation in the model.

Enhancing HEC-RAS with HPC capabilities would also support integration with coastal surge models, improving compound flood hazard assessments critical for the Texas coast, enabling more efficient and accurate flood hazard evaluation.

IMPLEMENTATION NOTES

Keys actions when implementing this recommendation include:

- Analyze and identify performance bottlenecks in the 2D HEC-RAS computational engine source code
- Develop and validate a small model domain test case for ongoing testing
- Implement MPI-based parallelization using a single-program–multiple-data approach
- Ensure physical structures remain local to individual subdomains during decomposition
- Map local arrays to global arrays and manage inter-CPU data communication
- Perform GUI integration and iterative testing for usability and functionality
- Verify code accuracy and scalability as processor counts increase
- Provide guidance on optimal subdomain sizing for performance and load balancing
- Perform test-bed evaluations of the HEC-RAS parallelized code for evaluating its performance, including comparisons of results across modeling scales and platforms for performance benchmarking
- Generate summary tables comparing simulation cost, runtime, and result consistency

GUIDELINES FOR NATURE-BASED FEATURES TO REDUCE FLOOD RISK

Develop guidelines for installing and evaluating nature-based features along the Texas coast for efficiency in coastal flood risk reduction

Traditional benefit-cost analysis (BCA) focuses on economic metrics, making it less effective for evaluating nature-based solutions (NBS) that provide broader environmental and social benefits. As advancements continue, there is a need to refine BCA methodologies to better capture the full value of Natural and Nature-Based Features (NNBFs) within coastal infrastructure systems.

TIFF recommends that guidelines be developed for implementing NNBFs along the Texas coast and that their effectiveness in coastal flood risk reduction be assessed.

This approach will provide valuable insights into how NNBFs mitigate surge and dissipate waves, ensuring that site selection aligns with physical and local conditions while maximizing cost efficiency. Additionally, long-term monitoring systems should be implemented to quantify the lifespan and ongoing benefits of NNBFs. This will allow for data-driven assessments of their effectiveness in reducing coastal risk and evaluating cost feasibility over time. This fuller accounting of benefits can better support the adoption of NNBFs as viable, cost-effective flood mitigation strategies.

IMPLEMENTATION NOTES

Key actions when implementing this recommendation include:

- Update BCA methodologies to better account for the full range of NNBF benefits, including social and environmental factors
- Establish criteria/metrics to assess NNBF efficiency in mitigating storm surge and wave energy, incorporating social, environmental, and economic factors
- Optimize site selection and feature sizing based on local coastal conditions
- Identify and implement pilot projects to evaluate NNBF effectiveness under varying conditions
- Establish a testbed to help determine the best locations, timing, and configurations for maximum flood risk reduction
- Develop monitoring systems to track NNBF lifespan and performance over time.
- Use data-driven assessments to refine NNBF designs and improve cost efficiency
- Collaborate with federal, state, and other agencies, and universities to leverage on-going efforts and the lessons learned of NNBF implementations

RAPID PREDICTIONS OF FLOODING HAZARDS

Develop rapid predictions of flooding hazards for Texas decision-making and emergency response

Effective flood hazard prediction is crucial for ensuring public safety and optimizing emergency response during storm events along the Texas coast. Currently, rapid and accurate forecasting of storm surge and wave impacts is limited, making it challenging to issue timely warnings to at-risk communities. The ability to predict flooding hazards quickly enhances emergency response efforts by enabling authorities to issue evacuation orders, mobilize resources, and reduce casualties and property damage. Furthermore, these predictions aid in managing coastal flood protection systems, such as pumps, dams, and surge barriers, to protect vulnerable areas.

TIFF recommends the development of a robust, reliable, and accurate storm surge and coupled wave model for the Texas coast. This model should build on previous studies to provide enhanced predictions for total water levels and flood inundation. By incorporating large- and small-scale 3D processes, the model would improve the accuracy of simulations, ultimately supporting better decision-making in flood preparedness and response.

TIFF also recommends the evaluation of the suitability of existing web tools, such as the Interagency Flood Risk Management Flood Decision Support Toolbox (https://webapps.usgs.gov/infrm/fdst/) and NWS National Water Prediction Service (https://www.weather.gov/ewx/NWPSInfo), for disseminating information to emergency managers and relevant statewide parties. The evaluation should aim to determine whether these platforms can effectively convey the complexities of coastal and compound flooding risks or if a separate platform is necessary for improved communication and visualization.

DATABASE OF FLOOD MODELING STUDIES

Develop a bibliography and database of flood modeling studies and datasets to enhance flood risk assessment and emergency response

The results from existing flood modeling studies could significantly enhance flood hazard analysis efforts across Texas. Many existing datasets are underutilized and could immediately benefit professionals in the field if organized in a new cyberinfrastructure.

TIFF recommends a comprehensive bibliography and database of numerical grids, computational setups for Texas wave/surge modeling, and data on storms causing coastal flooding, including storm characteristics, wave data, high-water marks, and available measurements. This database will create comprehensive coastal model metadata collections for facilitating model access and sharing among Texas stakeholders and support improved understanding of coastal flood hazard estimation through leveraging existing models and datasets. Standardized computational meshes and setups for wave and surge models should also be provided to facilitate use by researchers and practitioners.

An interactive website should be developed for easy information sharing with Texas stakeholders, and the database must be regularly updated to reflect new findings. Furthermore, the database should also include studies utilizing 3D or hybrid models, ensuring a broader representation, as current models predominantly focus on 2D approaches. This database will prevent duplication of model development efforts as huge amounts of flooding analysis are being or will be performed to support a wide range of flood resiliency projects.

IMPLEMENTATION NOTES

Key actions when implementing this recommendation:

- Use the TIFF Model Inventory (Supporting Material 6-14) as a test case to compile a comprehensive bibliography and database of flood modeling studies
- Share findings to support flood risk assessments, emergency planning, and coastal mitigation efforts
- Develop a model management system for storing and sharing numerical grids, computational setups, and storm-related data (this system needs to be made available not only for sharing archived models, but also for the model developers to upload new models for wide dissemination)
- Provide clear guidance on how these datasets impact Texas residents and flood risk management
- Include validated numerical grids and computational setups for Texas Wave/Surge Modeling
- Develop standardized computational meshes to facilitate model reuse by researchers and practitioners
- Build an online database for stakeholders to access and contribute data
- Ensure regular updates to reflect new research and findings as more models become available
- Incorporate studies using 3D or hybrid models to ensure a comprehensive approach beyond traditional 2D modeling
- Investigate how the developed models – which vary in resolutions, accuracy, and other factors – can be leveraged and integrated for improved understanding of flood risk in coastal Texas

ENHANCE WAVE MODELS AND DATA TO IMPROVE ACCURACY IN POPULATED AREAS

Enhance wave models and associated data collections for better representation of wave transformation overland

In Texas, wave prediction accuracy is lowest in the region containing the highest population and value—Normally Dry Land. This region is critical for flood planning and design. The challenges to accurate predictions are threefold:

1. Existing models were developed for conditions vastly different from those found over dry land, such as buildings, diverse vegetation, and rapid changes in land and structure properties.

2. Overland flooding with large waves is rare, resulting in limited datasets for model validation.

3. Significant changes in topography, vegetation, and structures during storms can lead to conditions that differ from pre-storm assumptions, affecting wave and surge properties and reducing model accuracy. This is especially problematic for dune erosion, as protective dunes often vanish during severe storms, exposing developed regions to increased flooding risk.

TIFF recommends enhancing model accuracy and reliability for overland wave prediction in Texas.

Key actions include extensive data collection for model parameterization, calibration, and validation; detailed mapping of coastal areas with a focus on buildings and vegetation; detailed inventories of coastal buildings and large vegetation that are likely to withstand flooding; and high-resolution flow modeling over dry land using spectral models like SWAN or WaveWatch III. Developing a dedicated overland wave model could establish a new standard for wave predictions, ensuring more reliable forecasts and improved protection for vulnerable areas.

IMPLEMENTATION NOTES

Partners like the U.S. Army Corps of Engineers and academic institutions could execute this initiative over 3–5 years, with an estimated annual budget of $200,000.

Key actions when implementing this recommendation include:

- Conduct extensive data collection to improve wave model parameterization, calibration, and validation
- Develop detailed inventories of coastal structures and vegetation likely to withstand flooding
- Use high-resolution mapping of Texas coastal areas, focusing on buildings, vegetation, and land characteristics
- Incorporate dynamic changes in topography, vegetation, and structures before, during, and after storms
- Implement high-resolution flow modeling over dry land using spectral models like SWAN or WaveWatchIII
- Establish a dedicated overland wave model to enhance predictive capabilities

AUTOMATE PROCESSING OF TOPOGRAPHY AND BATHYMETRY

Develop an automation tool for high-resolution Texas topographic and bathymetric data processing

TIFF recommends developing automated methods to improve and standardize the representation of topobathymetric datasets, including engineering features such as levees, in flood hazard models. This should include the creation of a standard vector representation for features such as levees, where polylines with varying widths and elevations along the line can be used for topographic processing.

Additionally, automated topographic processing methods should be developed to extract engineering features (e.g., levees, ship channels, bridges) from high-resolution LiDAR data without requiring human intervention, except for performing quality assurance and quality control of the final topographic products. To further enhance the process, model grid generation programs should be developed that effectively incorporate vector polylines into model topography. A comprehensive standard database for accessing data on such features throughout Texas is also crucial for consistency and ease of use.

This initiative should leverage NOAA's continuously updated Digital Elevation Model, though it is limited in its ability to represent engineering structures such as levees. The resulting tool should ensure that its derived products are easily usable across a range of flood hazard models, providing a more efficient and consistent means of incorporating engineering features into flood hazard assessments.

IMPLEMENTATION NOTES

Key actions when implementing this recommendation include:

- Establish a vector-based representation for levees and similar features, using polylines with varying widths and elevations
- Develop automated processing methods to extract engineering features from high-resolution LiDAR without human intervention
- Create grid generation programs capable of incorporating vector polylines into model topography
- Establish a standardized database for consistent access to topo-bathymetric data across Texas
- Prioritize improvements to bathymetric data in small channels to refine flood models

EVAUATE THE ANALYSIS OF RECORD FOR CALIBRATION

Evaluate the Analysis of Record for Calibration (AORC) data across Texas for potential flood hazard analysis uses

TIFF recommends evaluating Texas AORC data from 1979 to the near present to provide a comprehensive assessment of the data's accuracy and potential for improving flood hazard analysis and hydrologic modeling in Texas.

The evaluation would compare AORC's accuracy against rain gages and benchmark its performance against other hourly rainfall products. Additionally, rainfall events would be categorized by their association with tropical cyclones and by time of year.

The AORC is a high-resolution gridded dataset providing near-surface weather conditions across the United States. With a spatial resolution of approximately 800 meters and a temporal resolution of one hour, it includes data on precipitation, temperature, humidity, pressure, radiation, and wind components. AORC's long history (over 40 years) and fine resolution make it valuable for applications like rainfall frequency analysis and hydrologic modeling. It is particularly useful for areas such as the Rio Grande Valley, where daily rainfall measurements are often too coarse to capture localized storms, and for regions impacted by tropical cyclones, as seen during Hurricane Harvey in 2017.

IMPLEMENTATION NOTES

TIFF recommends partnerships with the Office of the State Climatologist (Texas A&M University) and academic institutions. The project is expected to take 6–12 months and have an estimated budget of $70,000–$100,000.

Key actions when implementing this recommendation include:

- Analyze AORC data from 1979 to the present (as available) across Texas
- Compare AORC precipitation data against rain gages
- Assess AORC's performance relative to other hourly rainfall products
- Categorize events by association with tropical cyclones and by time of year

ADVANCE ARTIFICIAL INTELLIGENCE/MACHINE LEARNING TECHNIQUES FOR FLOOD MODELING

Traditional process-based models for assessing the effects of compound flooding, while accurate, are often time-consuming and resource-intensive, making them less practical for rapid decision-making during emergency events. Coastal infrastructure operations, in particular, require fast evaluations to guide decision-making during floods, which typically necessitate "what-if" scenarios to explore various interventions and outcomes.

TIFF recommends advancing AI and machine learning (AI/ML) techniques for compound flood modeling. By automating and accelerating the modeling process, these models can streamline decision-making, making it possible to respond to flood events more effectively.

Key actions include developing guidelines to enhance the interpretability of AI/ML models (e.g., moving beyond black-box approaches) to better support decision-making, conducting ongoing research into AI/ML surrogate models for more efficient simulation of compound flooding compared to traditional methods, and creating "what-if" scenario tools that enable engineers and policymakers to rapidly evaluate options for maintaining coastal infrastructure during emergencies.

IMPLEMENTATION NOTES

Key steps to implement this recommendation include:

- Research and develop AI/ML surrogate models to accelerate and improve the efficiency of compound flood simulations
- Improve AI/ML approaches to ensure transparency and reliability in decision-making
- Develop tools that allow engineers and policymakers to quickly assess intervention strategies during flood events (i.e.,"what-if" scenario modeling)

INTEGRATE URBAN STORMWATER AND FLOOD HAZARD HYDRODYNAMICS MODEL APPLICATIONS

Develop an integrated model application by coupling an urban stormwater model with a flood hazard hydrodynamic model, and assess its effectiveness through test-bed evaluations in Texas urbanized coastal watersheds

Effective modeling should account for both catastrophic hurricanes and more frequent moderate storms, enabling communities to evaluate how engineered infrastructure, such as deep tunnels, can mitigate flooding. While urban stormwater modeling has a long history, it has not been integrated into compound flooding models that consider both coastal and urban flooding.

TIFF recommends the development of an integrated urban stormwater and flood hazard model for Texas' urbanized coastal watersheds. The effort includes evaluating ongoing efforts to model urban flooding, creating multi-scale storm models that simulate both catastrophic and moderate storms, and incorporating 2D flood modeling (e.g., HEC-RAS, Delft-3D, TRITON) into Storm Water Management Model (e.g. EPA SWMM). Coupling Storm Water Management Model with other open source/freeware flood models will facilitate greater adaptation by diverse stakeholders.

A test-bed evaluation of the integrated model and exploring alternative approaches, such as sub-grid-based models, should be performed to enhance its accuracy and application. This integrated system will help assess how urban infrastructure can improve resilience to flooding.

IMPLEMENTATION NOTES

TIFF recommends partnerships with flood control districts and cities working on addressing challenges related to urban flooding.

Key actions when implementing this recommendation include:

- Simulate both tropical and non-tropical storms to assess how urban stormwater systems, such as deep tunnels, enhance flood resilience
- Integrate a two-dimensional (2D) flood modeling component into the SWMM
- Couple the SWMM with open-source/freeware flood models like HEC-RAS 2D, TRITON, or Delft3D-FM to facilitate greater adaptation by diverse stakeholders
- Conduct testbed studies in Texas urbanized coastal watersheds to validate model performance
- Explore alternative modeling approaches to improve accuracy and application

QUANTIFY THE IMPACTS OF EROSION ON STORM SURGE

Support research on erosion and its impact on storm surge

Texas bay and estuarine systems connect to the Gulf of America through narrow inlets that cut across barrier islands and peninsulas. These landforms act as natural buffers, protecting interior waterways from wave action and storm surge. However, their low-lying nature makes them vulnerable to overtopping and erosion during major storms, rapidly altering coastal topography.

Capturing storm-induced erosion in numerical models remains a challenge. During Hurricane Harvey, significant beach erosion near Aransas Bay (Goff et al., 2019) may have allowed additional surge to reach inland areas, leading to potential under-predictions in models like ADCIRC. These models struggle to represent rapid erosion dynamics, as they operate on coarse spatial resolutions (30–40 meters) and lack sediment transport capabilities.

TIFF recommends the enhancement of storm surge models by integrating barrier island and dune erosion processes. A more dynamic approach to modeling erosion would improve flood forecasting and post-storm reconstructions, leading to better risk assessments and coastal resilience planning. By incorporating real-time topographic changes, researchers can more accurately predict storm surge impacts and better protect vulnerable coastal communities in Texas.

IMPLEMENTATION NOTES

Key actions when supporting research on erosion and its impact on storm surge include:

- **Conduct site-specific morphological modeling**: Identify high-priority sites prone to erosion (e.g., areas impacted by Hurricane Harvey, key dune-protected regions); use nearshore morphology models to simulate dune erosion and establish relationships between erosion and wave/surge conditions
- **Develop parameterized erosion updates**: Conduct multiple simulations to generate datasets linking erosion to storm conditions; utilize regression models, lookup tables, machine learning, or AI to create parameterized updates for bathymetry and topography; implement a dynamic system to update dune elevations and erosional areas every 10 minutes based on surge, wave, and current data
- **Integrate with surge models**: Incorporate erosion-informed updates into large-scale surge models; test the feasibility of using a subgrid-type surge model to better represent small-scale coastal features
- **Expanded applications**: Apply the developed framework to additional Texas shorelines, accounting for regional variations in sediment characteristics, hard structures (e.g., seawalls), and erosion-resistant layers; develop a methodology for predicting potential barrier island breaches in advance

QUANTIFY WIND-DRIVEN INLAND FLOWS TO ENHANCE FLOODING MODELS

Address the lack of inland flooding models that include wind and wave stresses via a coordinated research effort to quantify the physics of wind-driven flows in shallow flooding

When large areas are flooded (e.g., Hurricane Harvey), strong winds can provide additional forcing to tilt the water surface (i.e., pushing water upwind). When the wind stops or changes direction, the water pushed upwind will be redistributed, potentially causing further flooding.

The problems associated with wind forcing over shallow water were discussed by Li & Hodges (2019), who implemented an ad hoc increase in drag for shallow marshes to prevent unrealistic wind acceleration. The underlying problem is that wind-drag models are derived from studies of deep water, where only a wind boundary layer exists near the surface. In shallow waters, the wind boundary layer overlaps with the bottom boundary layer, leading to nonlinear turbulent interactions that have not been studied. Although more theory is available on wave propagation over shallow waters, the evolution of waves in shallow waters under short fetches is not well studied. There are no models that can presently be applied to represent the development of wind-waves in shallow flooded areas.

TIFF recommends the following investments to address this knowledge gap:

- Establish theoretical frameworks for the coupled wind/wave/bottom boundary layer interactions in shallow water environments
- Use laboratory experiments and high-resolution Computational Fluid Dynamics (CFD) models to validate the theory and gain insights into wind, wave, and bottom boundary layer interactions
- Perform field experiments to examine how theoretical and laboratory results translate to full-scale conditions.
- Using theory, laboratory data, CFD results, and field data, create a model equation that links wind speed to effective wind stress, considering water depth, velocity, and bottom roughness
- Integrate both large- and small-scale processes into the model to enhance its accuracy

Citation: Li, Z., & Hodges, B. R. "Model Instability and Channel Connectivity for 2d Coastal Marsh Simulations." Environmental Fluid Mechanics, vol. 19, 2019, pp. 1309-38. doi: 10.1007/s10652-018-9623-7.

ADVANCE USE OF THE JOINT PROBABILITY METHOD IN COMPOUND HAZARD ASSESSMENT

Current coastal flood hazard assessments often underestimate water levels by neglecting the compound effects of storm surge and precipitation-driven flooding. This is particularly critical in Texas coastal watersheds, where hurricane storm surge and hurricane-induced rainfall riverine flooding interact in complex ways. Traditional statistical methods, such as bivariate copulas, are limited by data constraints and basin variability, making them insufficient for capturing the full range of flood hazards.

TIFF recommends expanding the U.S. Army Corps of Engineers' (USACE) Probabilistic Coastal Hazard Analysis (PCHA) model agnostic framework to improve compound flood hazard characterization. This enhancement would integrate high-resolution numerical modeling, machine learning, and stochastic uncertainty (e.g., antecedent conditions like soil saturation, which vary based on local geography). Leveraging synthetic storm results from prior regional studies would also support a framework that can be consistently applied across Texas coastal basins.

IMPLEMENTATION NOTES

Key actions when implementing this recommendation include:

- Improve the USACE's PCHA framework by integrating additional probability methods beyond observation-based approaches, such as the use of Hurricane Rainfall Models and the use of seasonal correlation between flow and intensity applied in the joint probability method framework
- Develop a flexible, model-agnostic framework that can be applied consistently across Texas coastal basins
- Incorporate variability in antecedent conditions (e.g., soil saturation) to refine flood risk estimates based on local geography.
- Utilize synthetic storm results from prior studies, such as the Coastal Texas Study, to reduce computational cost and apply widely accepted regional storm surge information and statistics. Explicitly represent interactions between tropical cyclone storm surge and rainfall-induced water levels to capture compound flood hazards
- Apply the improved joint probability method framework in select Texas coastal watersheds to assess accuracy and reliability
- Conduct validation studies with historical and synthetic storm events to refine methodology

A TROPICAL CYCLONE RAINFALL GENERATOR

Develop a high-resolution statewide parametric tropical cyclone rainfall generator

TIFF recommends the development of a high-resolution (hourly, 0.05-degree) rainfall generator for statewide application in Texas to generate rainfall fields for all synthetic tropical cyclones used in compound flood hazard assessments for the coastal Texas region. Building on the U.S. Army Corps of Engineers 2020 study, which established a set of 660 synthetic tropical cyclones for evaluating flood risks, the effort involves quantifying uncertainty and bias in tropical rainfall models by leveraging historical rainfall datasets. This high-resolution rainfall generator will support improved flood hazard assessments.

IMPLEMENTATION NOTES

TIFF recommends partnerships with the Office of the State Climatologist (Texas A&M University) and academic institutions.

The project timeline is expected to range from 6 months to 3 years, depending on the required level of detail and prior experience with similar developments. The estimated total cost is between $100,000 and $200,000.

Key actions when implementing this recommendation include:

- Use historical rainfall data to assess and correct biases in existing tropical cyclone rainfall models
- Create an hourly (0.05-degree) tropical cyclone rainfall generator tailored for Texas
- Produce bias-corrected and probabilistic rainfall datasets for all 660 synthetic tropical cyclones in the USACE Coastal Texas Study (2020)
- Utilize AI/ML to analyze rainfall distribution relative to storm tracks and generate realistic rainfall patterns within hurricane rain bands

QUANTIFY SENSITIVITIES OF EXISTING MODELS

Quantify the sensitivities of model results to uncertainties in wind forcing, bathymetry, bottom friction, and turbulence, with an initial emphasis on bathymetry

TIFF recommends improving bathymetric data (particularly for small-scale features such as channels and barrier islands) to address the computational challenges associated with flood hazard models. Errors in bathymetry and topography also contribute to significant inaccuracies in inland hydraulics, coastal hydrodynamic, and storm surge models. While higher-resolution data such as LiDAR and satellite imagery enhance accuracy, they capture only a snapshot in time, leading to potential errors in areas undergoing frequent change, especially in urban regions. Computational challenges arise in resolving small-scale features, such as channels and barrier islands, impacting model performance.

Additionally, TIFF recommends research to improve regional models, such as WRF, for operational forecasting to enhance wind predictions in storm surge models. The primary source of uncertainty in storm surge simulations is wind forcing, which is a major driver of both surge and waves. Accurate wind predictions are crucial for reliable surge forecasts, especially when the hurricane track and intensity are uncertain. Operational meteorologic models, despite improvements in numerical precision and higher resolution, do not guarantee error-free results. For instance, Hurricane Ian (2022) deviated from its predicted landfall location, showcasing the challenge in forecast accuracy. Regional models like WRF, tested at 1-5 km resolution in the Gulf, reveal fine-scale features but are not yet operational for forecasts.

TIFF also recommends developing a framework to quantify uncertainty in bottom friction using measured data to improve flood hazard model predictions. Bottom friction, as represented by formulations such as Manning's n, introduces another source of error in storm surge predictions. The Manning's n formula, which depends on sea-surface bottom characteristics, becomes more pronounced in shallow waters, influencing flooding severity across inundated land. Despite recent efforts to estimate bottom friction from measured data, this research is in its early stages and lacks a comprehensive framework for uncertainty quantification and parameter estimation.

RETROSPECTIVE MODELING OF HISTORIC LANDFALLING HURRICANES

Conduct a retrospective analysis of major landfalling hurricanes from the early 1960s to the 1990s, using high-resolution weather or coupled models

Understanding historical storm impacts is crucial for improving predictive models and better protecting lives and infrastructure. However, hurricane modeling is limited by the lack of high-resolution observational data before the 2000s, reducing the accuracy of flood and wind hazard assessments, particularly in data-scarce regions. While many flood models rely on modern datasets, validating them against past events enhances their reliability.

TIFF recommends a retrospective analysis of major landfalling hurricanes from the early 1960s to the 1990s using high-resolution modeling techniques. This analysis will provide data to calibrate and validate flood models while also supporting wind hazard assessments for periods before the availability of High-Resolution Rapid Refresh weather forecasting models.

Simulating past hurricanes will offer insights into their potential impact on today's coastal infrastructure, aiding in the refinement of evacuation plans, resilience strategies, and building codes. Additionally, understanding historical hurricane behavior will contribute to long-term assessments of storm intensity and frequency, informing climate adaptation efforts.

IMPLEMENTATION NOTES

TIFF recommends a partnership with the Office of the State Climatologist at TAMU, federal agencies (e.g., NOAA, USACE), industries, and consulting firms such as Oceanweather Inc. (www.oceanweather.com) for the implementation of this effort.

The effort is expected to take 1 to 3 years, depending on the historical scope. The estimated cost ranges from $100,000 to $350,000, with the higher end supporting simulations of additional storms, such as Hurricanes Carla (1961) and Beulah (1967), and alternative storm path scenarios. (Hurricane Carla is particularly important for wind analysis, while Hurricane Beulah is significant for rainfall impacts.)

TIFF recommends prioritizing these hurricanes for analysis and incorporating perturbed simulations to assess potential storm impacts under alternative tracks.

Deliverables should include high-resolution wind and rainfall data, validated against historical observations, to improve understanding of past hurricane impacts and enhance future modeling efforts.

THE TEXAS COASTAL FLOODING FRAMEWORK (TxCFF)

Develop the Texas Coastal Flood Framework for compound flood assessment to support flood recovery and emergency response efforts along the Texas coast

Texas has the opportunity to set a national standard for compound flood modeling. As the largest economy among hurricane-prone states and second only to Florida in population at risk, Texas faces urgent challenges from hurricane and tropical storm flooding. To address these challenges, TIFF recommends establishing the TxCFF—a sustainable, updatable, and state-of-the-art system for compound flood assessment. TxCFF will integrate models, analysis tools, and workflows to support planning, development, recovery, and emergency response along the Texas coast. This framework will provide linkages to existing databases, seamless data transfer between models, a user interface for setting up and executing coupled models, plug-and-play APIs, and integrated output datasets from component models into coherent datasets for analysis and visualization. Over time, it will evolve into a robust platform for evaluating and managing compound flooding across multiple projects.

The TxCFF would consist of:

- wind and pressure model
- ocean circulation model
- wind/wave model (far field and near field)
- flood inundation (hydraulics) model for river flow and landscape flooding
- upland runoff model (hydrology)
- stormwater drainage model
- groundwater model
- code for coupling the various flood inundation component model
- coupling to external meteorological (storm) models/data sets for historic and synthetic storms
- code for calibration, validation, and testing of inundation models
- code for ingesting flood inundation model results into flood hazard analysis
- flood hazard analysis tools
- code for visualizing inundation and hazard analysis results
- code for input/output
- code for user customization

TxCFF could start as documented workflows for coupling models and data, supported by pre- and post-processing tools. These workflows can then be codified into a software framework emphasizing reusability, accessibility, scalability, training, and uncertainty management. Development will require long-term funding, a consistent project team, and collaboration with agency-sponsored modeling projects. By building on vetted workflows and testbeds, TxCFF can grow incrementally into a central resource for scalable, integrated flood modeling across Texas, with an active user community supported by training resources.

ADDITIONAL INFORMATION

The following implementation information was elicited from the expert advisors to the Texas Integrated Flooding Framework process. For more information, see the TIFF Final Report at TexasFlood.org.

- **Identify testbed locations and prioritize implementation**: Select and prioritize testbed sites based on stakeholder resources, hazard types, geographic characteristics, and data availability
- **Test candidate models for TxCFF**: Evaluate and select models through testbeds to ensure effective coupling, transparency, and collaboration across disciplines (see TIFF Literatures Reviews (Appendix Component 3) on modeling approaches for a more detailed discussion)
- **Evaluate software framework fundamentals**: Define coding standards, data exchange methods, and validation processes to build an alpha version of the TxCFF. The infrastructure provided by the Texas Advanced Computing Center should be considered before spending major resources on commercial cloud providers
- **Develop TxCFF best practices**: Establish coding and modeling best practices with training to ensure consistent, broad use of the framework
- **Evaluate coupling methods for candidate models**: Determine effective strategies for coupling ocean, river, stormwater, and other models at shared boundaries
- **Develop and evaluate boundary placement**: Create methods to set and adapt coupling boundaries that minimize computational noise and reflect physical drivers
- **Generate grids for coupled models**: Develop automated, standardized tools for creating and updating model grids across Texas testbeds
- **Create heuristics for simplified models**: Build algorithms to guide when simplified or partial models can be used instead of full complexity
- **Develop coupled model inputs/outputs**: Standardize input/output formats, metadata, and visualization tools to integrate diverse models
- **Automate calibration and validation**: Design automated systems for model calibration, validation, and observational comparison to reduce bias and increase confidence
- **Develop training courses**: Provide targeted training for modelers, developers, and managers to expand TxCFF use and understanding. This training should include a streamlined process teaching “students” how to update flood hazard models using outputs from multiple “what-if” scenarios
- **Integrate flood modeling with hazard analysis**: Combine numerical models with probabilistic hazard analysis to generate hazard curves and inundation maps
- **Address nonstationarity and future planning**: Account for natural and anthropogenic factors and land-use projections into models to support adaptive flood risk planning

FLOOD LITERACY IN K-12 EDUCATION

Incorporate flood education and preparedness into K-12 education to prepare students and families for the increasing risks posed by extreme weather events

Texas K-12 education curriculum includes content regarding the water cycle and drought. Elementary schools often collaborate with local fire departments to teach fire preparedness (e.g., "Stop, Drop, and Roll") and K-12 schools conduct drills for various hazards such as tornadoes. Despite Texas being highly vulnerable to flooding, students receive little to no instruction on how floods occur, their risks, or how to prepare for them.

Countries like Japan prioritize flood education and use virtual and augmented reality, along with serious games, to teach students about flooding and tsunamis. These interactive methods equip students with critical decision-making skills in emergencies.

Texas should develop and incorporate flood awareness and preparedness education into K-12 schools. A plan is needed to outline ways to introduce flood-related topics into science, geography, and emergency preparedness curricula, as well as the use of interactive and technology-driven learning tools.

IMPLEMENTATION NOTES

Key actions when implementing this recommendation include:

- Determine the process, feasibility, and timeline for incorporating flood education into the Texas K-12 curriculum
- Review existing literature on flood education initiatives, both in Texas and internationally, to identify best practices
    - Pinpoint gaps and specific needs for Texas K-12 students
    - Determine the most suitable grade levels for integrating flood education
    - Identify existing educational content (from outside of Texas) that could be adapted for use, including K-12 programs that enhance parental awareness, identifying specific lessons, games, or activities that can be shared with parents to increase adult flood awareness
    - Recommend content development, including interactive tools like augmented reality and serious games, aligned with Texas K-12 learning standards
- Interactive or web-based tools will require maintenance, content management, and updates
- Determine whether incorporating flood education increased flood literacy in K-12 classrooms, improving students' capacity to respond effectively and appropriately to given flood risk information

Incorporating flood literacy into K-12 education is a crucial investment, estimated at $300,000 over 2 years. To effectively explore how flood education can be incorporated into the Texas K-12 curriculum, the project team should have strong ties to the Texas Education Agency and a solid understanding of Texas Essential Knowledge and Skills standards. This will help identify relevant existing content and determine what new materials need to be developed.

A TDIS ONLINE LEARNING CENTER

Establish a publicly accessible Texas Disaster Information System (TDIS) Online Learning Center to enhance access to, and organization of, flood-related educational resources

State and federal agencies, along with academic institutions, offer a wealth of educational resources on flood-related topics, including compound flood modeling, data gathering, visualization, and management. These resources include workshops, webinars, and expert-led seminars that provide valuable insights into research, data, and ongoing flood-related projects. However, despite the abundance of available content, there is no centralized platform where these materials are systematically stored and easily accessible for future reference. As a result, critical knowledge is often scattered across different organizations, making it difficult for professionals, policymakers, and researchers to efficiently access and utilize these resources.

To address this gap, it is crucial to create an online learning center within TDIS. This platform would serve as a comprehensive repository for flood-related educational materials, including recorded webinars, research presentations, and training modules. A centralized resource hub would enhance accessibility to critical flood-related knowledge, provide professional education credits continuing education hours which are required for various professional license renewals such as Professional Engineer and Certified Floodplain Manager, and foster greater collaboration among agencies, academic institutions, and flood management professionals.

By establishing this learning center, Texas can strengthen workforce education, improve flood preparedness, and ensure that critical expertise remains readily available for researchers, decision-makers, and practitioners.

IMPLEMENTATION NOTES

Key actions when implementing this recommendation include:

- **Planning and development**: Conduct a survey to identify priority content and existing educational resources from agencies, academic institutions, and professional organizations; technical requirements for content hosting, search functionality, and credit tracking will be defined, and a video hosting platform will be selected; this action will build a searchable library with keyword tagging and design an intuitive interface for easy navigation

- **Content collection and integration**: Gather existing videos, slides, and presentations from past workshops and seminars, collaborating with relevant agencies and experts, and leverage any existing flood educational materials developed/collected by federal and state agencies; materials will be tagged, categorized, and updated quarterly for continued relevance; materials will not be created; this action should also conduct beta testing with key users and refine the platform based on feedback

- **Launch and ongoing maintenance**: Promote the platform through TDIS, TWDB, professional organizations, and academic networks, with a virtual kickoff webinar; this work will require one full-time employee for content management and updates; maintain cloud storage, engage with stakeholders, and ensure the platform evolves with user needs

- **Evaluate flood literacy**: Determine if the online learning center increased flood literacy in target user groups, improving their capacity to respond effectively and appropriately to given flood risk information

This recommendation can be implemented at an estimated annual cost of $85,000–$108,000. The estimated implementation cost is $300,000. The project team must have established connections with the Texas Education Agency and have a strong understanding of Texas Essential Knowledge and Skills requirements. TIFF recommends that the Texas Floodplain Management Association help coordinate this effort, as it has established a national program for the professional certification of floodplain managers.

PREPAREDNESS EDUCATION CAMPAIGN ON HOW TO USE FLOOD RISK MAPS

Integrate flood risk maps and management into community engagement and preparedness

As floods become more frequent and severe, Texas must enhance community resilience by ensuring local stakeholders understand and act on flood risk information. Flood maps are essential for assessing risks, but many residents and local officials struggle to interpret them accurately, hindering preparedness and response efforts.

TIFF recommends partnering with the Texas Division of Emergency Management to coordinate workshops that help local emergency managers, community coordinators, and residents learn how to read and interpret flood maps. The workshops should engage community members by encouraging feedback and updating local data. Involving the community in data collection and decision-making will foster a sense of shared responsibility.

By the end of the project, stakeholders, including residents and officials, will collaborate effectively on flood preparedness, with flood risk maps becoming a common tool in decision-making and community resilience planning.

IMPLEMENTATION NOTES

Key actions when implementing this recommendation include:

- Fostering understanding around related flood risk map symbols and uncertainties
- Developing skills to evaluate the impact of different flood scenarios
- Engaging workshop participants in flood preparedness activities
- Integrating flood maps with other relevant data, such as demographic and land-use information, to provide a comprehensive understanding of flood risks

A STATE FLOOD COMMUNICATION OFFICER

Create a State Flood Communication Officer to support interorganizational coordination between agencies and organizations involved in flood-related communications

Effective coordination among agencies involved in flood-related projects is essential for improving preparedness, response, and mitigation. As floods become more frequent and severe, Texas needs a centralized communication strategy. However, without clear leadership, agencies may operate in silos, reducing efficiency and policy alignment. Texas already employs state experts, such as the State Demographer, who provide policy guidance. A similar role focused on flood communication coordination would bridge gaps between agencies and ensure a unified approach.

This individual would serve as a liaison among agencies, organizations, and policymakers to streamline communication and advise the Governor and Legislature on science-based flood policies. Additionally, they would coordinate efforts between scientific research, insurance, and policy sectors to ensure alignment in mitigation planning and response. Drawing from successful models in other states, they would also develop best practices for interagency collaboration.

With the establishment of this role, Texas can enhance efficiency, foster collaboration, and strengthen flood management efforts. A dedicated expert will ensure that science, policy, and risk mitigation strategies work together, ultimately improving the state's resilience to flooding.

IMPLEMENTATION NOTES

Key actions when establishing a State Flood Communication Officer include:

- **Research comparable roles and craft proposal:** Review the guidelines and responsibilities of similar state advisory roles, such as the State Demographer and Chief Resilience Officers, to inform the structure and best practices for the new position
- **Role definition and options for organizational integration:** Define the role's scope and authority within the Texas Flood Coordination Office; integrate the role within an existing state flood agency while expanding its authority and responsibilities; assist organizations in developing effective flood preparation plans and materials; align and incentivize local, regional, and state flood projects for cohesive efforts; establish data-sharing mechanisms with academic institutions and funding agencies, such as through Open Science Platforms; ensure every agency with a flood-related mission designates a representative to support coordination efforts
- **Allocate resources:** Focus on securing the necessary funding and resources to ensure the position is adequately staffed and supported

By following this approach, Texas can create an impactful role that enhances interagency coordination, strengthens flood preparedness, and fosters a unified flood management strategy.

ENHANCE TEXAS COASTAL STRUCTURES INVENTORY

Enhance the Texas coastal structures inventory and data, enabling better planning and more effective mitigation requests following disasters

Effective flood management hinges on critical infrastructure decisions, including site selection, design, and resilience planning. These decisions directly impact the state's ability to mitigate flood risks and protect communities. However, one of the most significant gaps in current flood management is the lack of real-time monitoring infrastructure, including localized weather stations and water-level gauges for both surface and groundwater. These tools are indispensable for predicting flood hazards with greater accuracy and improving preparedness efforts across regions prone to flooding. Increased monitoring infrastructure would provide better situational awareness and early warning systems, allowing communities and local governments to respond more proactively to flood risks.

To address these challenges, TIFF recommends partnerships among local, state, and federal agencies to enhance the inventory and data collection related to Texas' coastal structures. This collaboration would streamline the gathering of crucial information, improve planning, and strengthen mitigation strategies, ensuring that flood management efforts are more targeted and effective. Additionally, Texas can build a more comprehensive, efficient, and proactive flood management system, capable of tackling the increasing frequency and severity of flood events across the state.

A FRAMEWORK FOR HAZARD AND LOSS ASSESSMENTS

Develop a framework for assessing hazards and losses in Texas to support insurance, planning, and prediction efforts

Flooding and other natural disasters in Texas cause significant damage each year, impacting communities, infrastructure, and economic stability. To improve planning, insurance assessments, and predictive capabilities, TIFF recommends the development of a comprehensive hazard and loss assessment framework for Texas.

Currently, hazard and loss assessments are fragmented, relying on disparate data sources, costly post-disaster inspections, and varying building codes across communities. A structured, statewide framework would provide consistent, high-quality data to inform decision-making, reduce uncertainties, and support mitigation planning.

IMPLEMENTATION NOTES

Key actions when developing a framework for assessing hazards and losses in Texas:

- **Database development and enhancement**: Develop and maintain a centralized, regularly updated database to support hazard and loss assessments; this database will include essential information such as building age, construction standards, and historical flood regulations (e.g., NFIP adoption, freeboard requirements, and International Building Code compliance); TIFF recommends that various agencies partner to enhance the Texas Water Development Board's building footprint database, ensuring improved data accuracy and coverage

- **Flood risk model development**: Establish model functionality requirements and certification criteria for accurate risk assessment; this development includes assessing the feasibility of creating a Texas-specific flood model that incorporates local flood level data, damage estimates, and loss metrics; the models will be designed to ensure compliance with benefit-cost analysis requirements and to support state and federal grant applications

- **Post-disaster data collection strategy**: Improve data collection after disasters; strategies will be developed to address challenges such as lost high-water marks and overwhelmed local officials; community participation in recording flood depths using simple methods, such as photo documentation and height measurements, should be encouraged

- **Cumulative impact and mitigation tracking**: Expand assessments beyond catastrophic events to include the cumulative impact of minor flooding, which often goes unrecorded but can still degrade infrastructure and property values over time; this tracking will also improve mitigation efforts and loss avoidance, ensuring that valuable data is preserved for future analysis

By implementing this framework, Texas can move toward a data-driven, proactive approach to flood risk management that accounts for a wide range of losses beyond just structural inundation. This includes social impacts and disruptions to essential services, providing a more holistic understanding of disaster consequences.

SPECIALIZED GRAPHICS FOR USE ACROSS STATE AND LOCAL AGENCIES TO REACH TARGET USERS

Update graphics used for TWDB messages for three TIFF selected target user groups (property owners, property renters, and people with limited English proficiency). Encourage adoption of graphics across state and local agencies

Many local communities in Texas still rely on outdated FEMA brochures when conducting flood outreach, which often lack the necessary updates to effectively communicate with today's audiences. Recent research by UT Austin identified three key target user groups and a unified statewide message that resonates with Texas culture. The next step is to bring these findings to life through impactful, localized graphics.

To address this, TIFF recommends updating and finalizing graphics for the Texas Water Development Board's outreach materials. These graphics will target three key audiences identified by TIFF: property owners, property renters, and people with limited English proficiency. By modernizing these visuals, TWDB can ensure that flood risk communication is more effective and culturally relevant, and encourage their use across both state and local agencies.

IMPLEMENTATION NOTES

Key actions when updating graphics used for TWDB messages for specific target user groups include:

- **Design and finalization of graphics**: Create visuals targeting the three audiences, adhering to accessibility standards, and using simple colors and fonts compatible with basic programs like PowerPoint; this standardization ensures that local officials, regardless of technical expertise, can easily edit and customize the visuals to meet their community's needs
- **Review and approval process**: Conduct focus groups with representatives from the three prioritized audiences to evaluate how effectively the graphics communicate key messages; additionally, the graphics will be reviewed to ensure consistency with the state's flood risk messaging
- **Production and distribution**: Make the graphics available in both digital formats (e.g., PDFs, PowerPoint slides) and print formats; host the graphics on the Texas Disaster Information System to make them easily accessible for local agencies, along with instructions for downloading and customizing the materials for their specific communities
- **Flood literacy evaluation:** Determine whether the updated, specialized graphics increased flood literacy among the three target user groups, improving their capacity to respond effectively and appropriately to given flood risk information
- **Evaluate priority groups at risk to define target users:** The number of priority groups that can benefit from improved TWDB communications about flooding risks is vast; each group tends to include heterogeneous subgroups that need to be carefully evaluated to define clear, specific target users for future work

TEXAS FLOOD.ORG BRANDING CAMPAIGN

Create a branding campaign, along with evaluation, for TexasFlood.org and the currently available resources for Texans

TIFF research showed that TexasFlood.org, despite being a key resource for flood information, has limited engagement with its target audiences. To increase awareness, graphics should be finalized and a comprehensive campaign promoting the website and its resources should be launched to emphasize flood preparedness and risk management.

The campaign will incorporate clear metrics to track website traffic and user engagement, ensuring measurable success and ongoing improvement. TIFF research also suggests evaluating the impact of the messages after launch to ensure they resonate with the target audiences and effectively drive engagement. Regular assessments will help refine the approach and keep the materials relevant.

TIFF recommends establishing a branding campaign for TexasFlood.org, including the finalization of graphics tailored to the identified audiences, strategic outreach to increase awareness, and a robust evaluation process to track the effectiveness of the campaign. By integrating a clear branding strategy with evaluation and metrics, this effort aims to enhance the website's visibility and ensure that flood-related resources are accessible and actionable for Texans across the state.

IMPLEMENTATION NOTES

Key actions when creating a branding campaign for TexasFlood.org include:

- **Branding Campaign:** Develop and execute a comprehensive campaign aimed at raising awareness of TexasFlood.org and its flood-related resources; the finalized graphics will be used to create outreach materials and advertisements tailored to the four identified audiences; multiple channels, such as social media and partnerships with relevant agencies, will be leveraged to maximize reach and engagement with the public

- **Website metrics and tracking:** Establish clear metrics to track website traffic, engagement, and user interactions; these metrics will help monitor the campaign's effectiveness, refine strategies, and identify any gaps in outreach efforts

- **Evaluation:** Periodic evaluations of the messages and materials post-launch; feedback will be gathered from target audiences, and data will be analyzed to assess whether the graphics and messages resonate with each group; based on the findings, materials will be adjusted and updated to ensure they remain relevant and impactful

BETTER UNDERSTAND FLOOD DECISION-MAKING OF PUBLIC STAKEHOLDERS

Design experiments/surveys/focus groups on social norms to gain insights into how to influence public stakeholders' flood-related decisions

Research consistently shows that social norms—being influenced to engage in a behavior because of trusted others—are a strong predictor of Texans' flood-related decisions. These trusted individuals are often peers rather than experts, highlighting the need for a deeper understanding of how social influence shapes decision-making in flood preparedness, response, and recovery.

TIFF recommends targeted experiments, surveys, and focus groups to explore the various forms of flood-related decision-making. By analyzing how different social groups influence perceptions and actions, these studies can identify the most effective ways to disseminate flood information. Insights from this research can then be used to develop communication strategies that leverage peer networks, ensuring that critical flood-related messages resonate with and motivate communities to take protective action.

The estimated cost is $245,000, which includes participant compensation to ensure representative data. Testing people with limited English proficiency should be prioritized to improve accessibility and effectiveness. A key research objective should be to assess how well individuals understand the documentation involved in purchasing a home. For example, do they know whether the home is located in a designated flood zone?

IMPLEMENTATION NOTES

Key actions when implementing this recommendation include:

- **Social norms studies (two experiments):** Study how social norms impact flood-related decisions (e.g., buying insurance, creating evacuation plans, home selection); the role of information sources will be examined, including trust and domain-specific trust; these studies will also test evidence-based messaging strategies that integrate social norms, assessing their effects on risk perception and cognitive load

- **Key-logging study:** analyze how peer-shared flood experiences influence decisions and identify the most effective messengers; community-driven approaches, such as using promotoras (lay health workers) for flood communication, will also be explored; additionally, surveys, interviews, and focus groups reflecting Texas' demographics, with a focus on people with limited English proficiency, will be conducted

A TEXAS FLOOD COORDINATION OFFICE (TFCO)

Establish a Texas Flood Coordination Office within an existing state agency to centralize flood efforts, maintain an official database, provide technical support, enhance collaboration, reduce redundancy, and optimize state and federal project impact beyond current volunteer-based efforts

Flooding poses a persistent and growing threat to communities, infrastructure, and ecosystems across Texas. To better prepare for and respond to these challenges, state and regional flood planners need coordinated access to information, planning tools, and technical support.

Currently, multiple state and federal agencies, private and non-profit organizations, and academic institutions are engaged in efforts to raise awareness and respond to floods. However, without a centralized coordinating body, the extensive work being done often overlaps, creating redundancies, inefficiencies, and missed opportunities to leverage project outcomes.

TIFF recommends Texas legislators establish a TFCO within an existing state agency.

The TFCO would:

- centralize and streamline flood-related efforts
- create and maintain an official statewide database of past and ongoing projects
- provide technical support to state and regional planners
- enhance collaboration among agencies, institutions, and stakeholders
- reduce redundancy and maximize the impact of state and federal investments
- formalize and expand beyond the current volunteer-based efforts

By centralizing information and oversight, the TFCO will enhance the state's ability to manage and mitigate flood risks efficiently.

IMPLEMENTATION NOTES

The TFCO is a crucial and ongoing investment. Key actions when implementing this recommendation include:

- Establish the TFCO within an existing state agency (e.g., TDEM or TWDB) to minimize overhead; form a small interdisciplinary team of flood management experts supported by 1-2 administrative staff; build long-term partnerships with external agencies, academic institutions, and stakeholders
- Compile an archive of state and federally funded flood projects through agency website reviews, outreach to academic and agency contacts, and calls for input from stakeholders and the public; develop quality control standards to tag, categorize, and store materials for long-term use, data analysis, and sharing
- Maintain and update a comprehensive database of flood projects annually; analyze project outcomes to identify research gaps and emerging needs
- Disseminate project outcomes and data to stakeholders to promote transparency and knowledge sharing; identify opportunities to build on existing results and reduce redundancy; foster collaboration among agencies, institutions, and organizations; provide regular updates to the Texas Legislature on flood projects, outcomes, and policy recommendations

Appendices: Supporting Materials

TIFF Structure and Development

- A-1 Technical Advisory Team Invitation

Component 1 – Data and Monitoring Gap Analysis

- 1-1 Datasets in the Coastal Data Surfer
- 1-2 Data Inventory Results
- 1-3 Data Classification Workshop Summary
- 1-4 Data Gap Analysis Workshop Summary
- 1-5 Bathymetric Workshop Summary
- 1-6 Subsidence Workshop Summary
- 1-7 TIFF Wave Data Mapping Survey

Component 2 – Data Management and Visualization

- 2-1 TIFF Guidelines for Coastal Flood Information Design and Communication
- 2-2 TIFF Flood Risk Communication Survey with TFMA
- 2-3 TIFF Component 2 Technical Advisory Team Meeting 1
- 2-4 TIFF Component 2 Technical Advisory Team Meeting 2
- 2-5 Existing Coastal User Interfaces Inventory (Excel)
- 2-6 Existing Coastal User Interfaces Inventory (Attribute Tables)
- 2-7 Literature Review on Coastal User Interfaces, Visualization, Flood Communication, and Education
- 2-8 Literature Review on Visualization, User Interfaces, and User Experience
- 2-9 Literature Review on Identification of Target Users and Needs
- 2-10 Literature Review and AI Exploration Method
- 2-11 Best Practices in Identifying Stakeholder Needs around Flooding Workshop
- 2-12 Exploring Rural and Urban Population Differences
- 2-13 TIFF Component 2 & 4 Technical Advisory Team Meeting 3

Component 3 – Integrated Flood Modeling Framework

- 3-1 Literature Review on Meteorological Modeling and Analysis
- 3-2 Literature Review on Hydrodynamic Hydraulic Modeling and Analysis
- 3-3 Literature Review on Estuarine Large-Scale Coastal Surge Modeling and Analysis
- 3-4 Literature Review on Wave Modeling and Analysis
- 3-5 Literature Review on Compound Flood Modeling and Analysis

- 3-6 Literature Review on Probabilistic Flood Hazard Analysis
- 3-7 Literature Review on Relevant USACE Studies for Flood Hazard Assessment in the Coastal Texas Region
- 3-8 Coastal Flood Applications in Texas
- 3-9 Compound Flooding in Texas
- 3-10 Model Coupling Workshop
- 3-11 Advancing Coastal Flood Modeling in Texas
- 3-12 Summary Report of Existing and Ongoing Statewide Flood-Related Studies / Statewide Projects Inventory (Excel)
- 3-13 Model Inventory Evaluation
- 3-14 Model Inventory Metadata Tables
- 3-15 Description of the Modeling Software
- 3-16 Model Inventory Meteorological Metadata Tables
- 3-17 TIFF Integrated Flood Modeling Brown Bag Seminar Series
- 3-18 Workflow Evaluations in Testbed Projects
- 3-19 Model-Coupling Workflow Development for Assessing Compound Flooding Hazards

Component 4 – Planning and Outreach

- 4-1 TIFF Coastal Liaisons of the Regional Flood Planning Groups Meeting
- 4-2 TIFF Component 4 Technical Advisory Team Meeting 1
- 4-3 TIFF Component 4 Technical Advisory Team Meeting 2
- 4-4 Comprehensive Outreach Plan
- 4-5 Planning/Economic Tools, Models, and Resources
- 4-6 Compound Flood Planning Decision Support Workshop

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