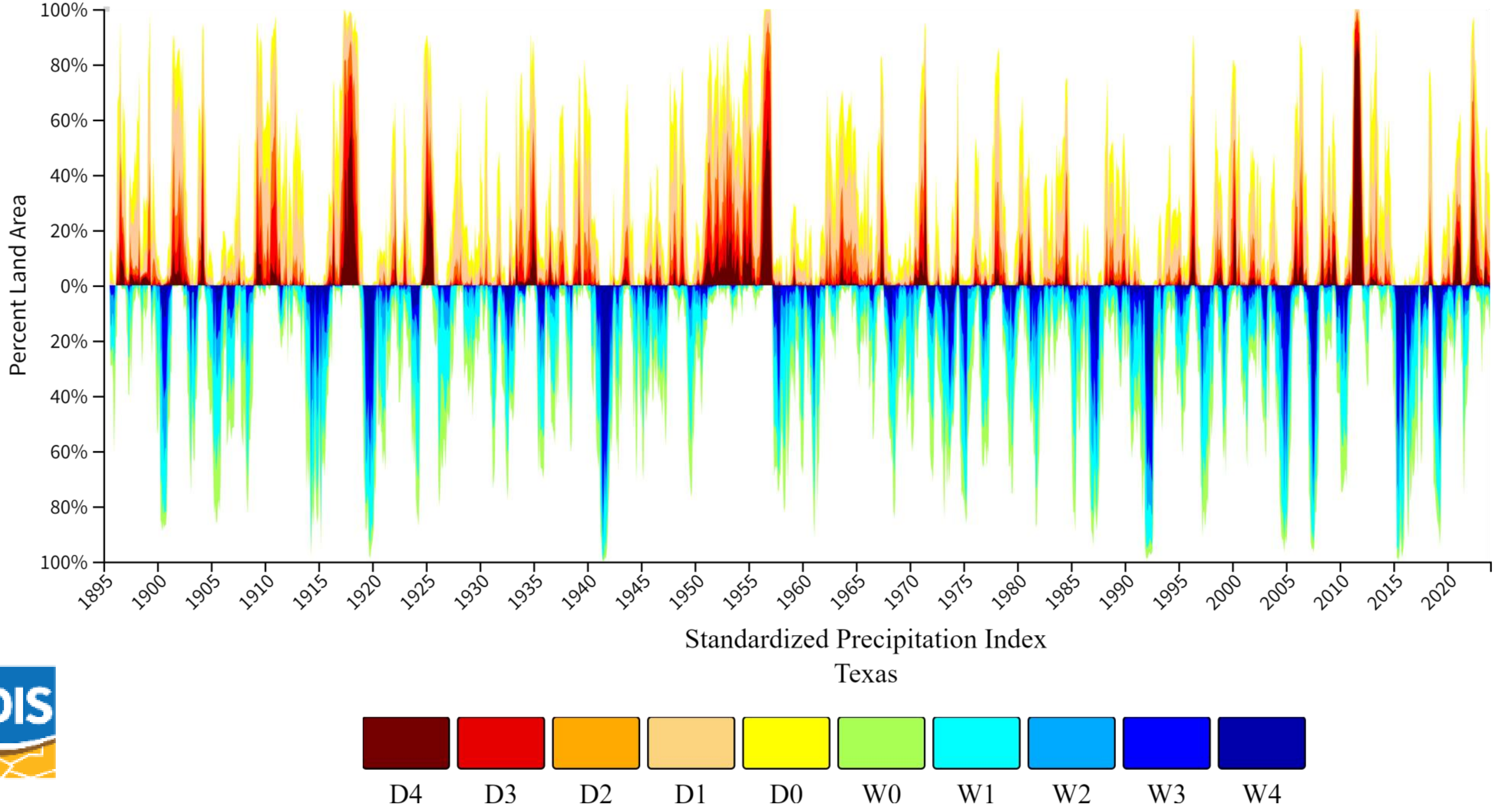
Hydrodynamic Challenges of Coastal Flood Modeling: Modeling Coastal Flooding in Drought-Prone Zones

Amin Kiaghadi, Ph.D., P.E.

“Texas is a land of perennial drought broken by the occasional devastating flood.” — National Weather Service, 1927



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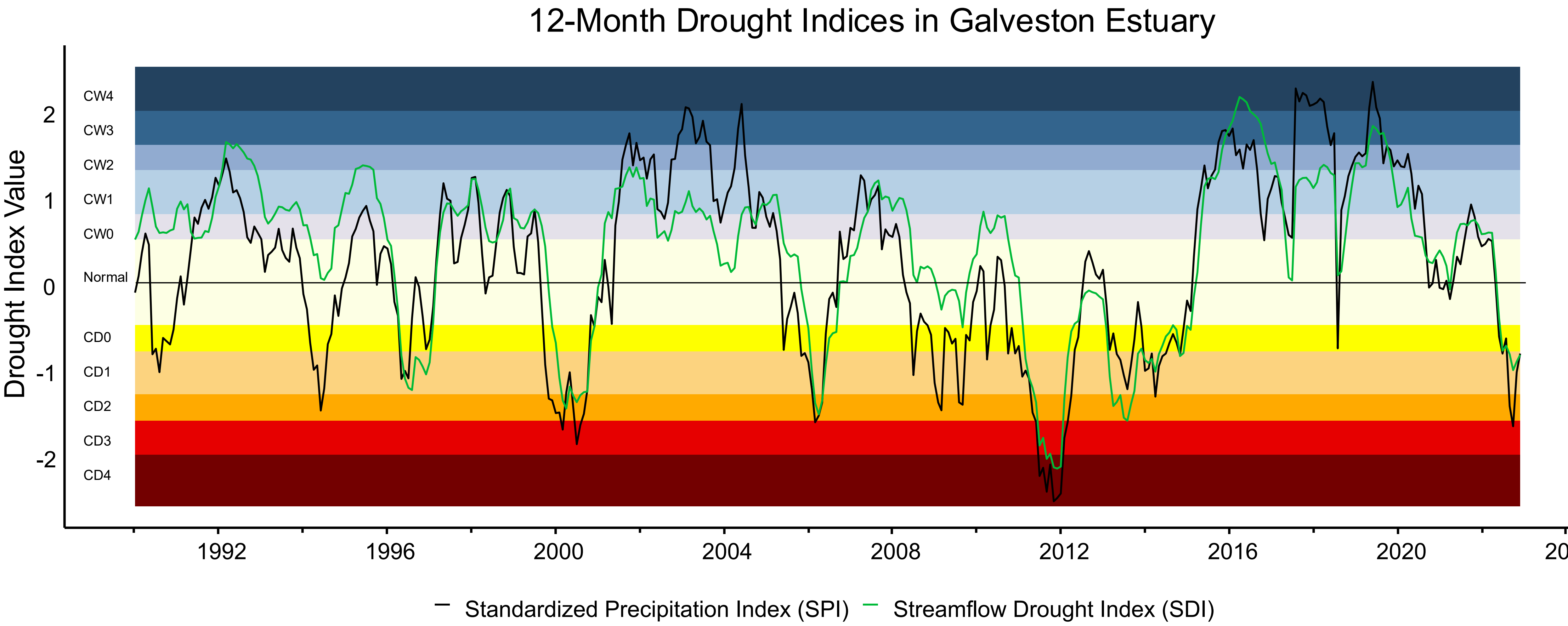


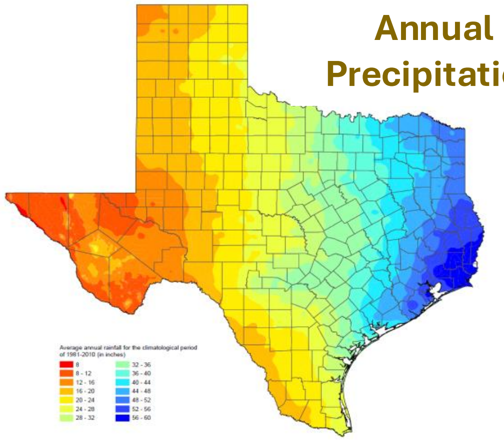
The Texas Gulf Coast is on the frontlines of change —and the defining water issues of our time

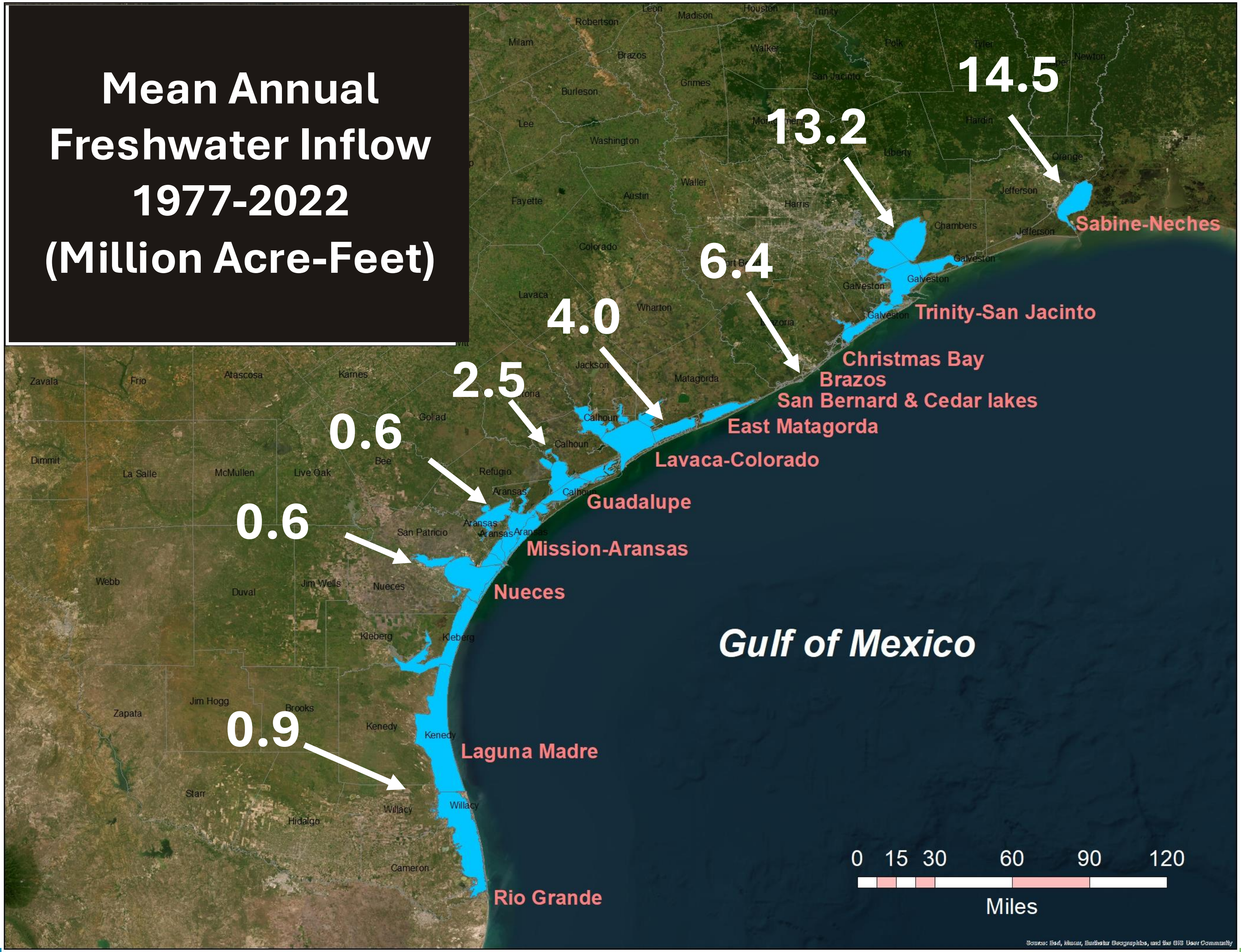
West Fork San Jacinto River near Humble, Texas after Hurricane Harvey, 2017. Image: Steve Fitzgerald, Harris County Flood Control District

Mouth of the Rio Grande, 2002
Image: Texas Parks & Wildlife

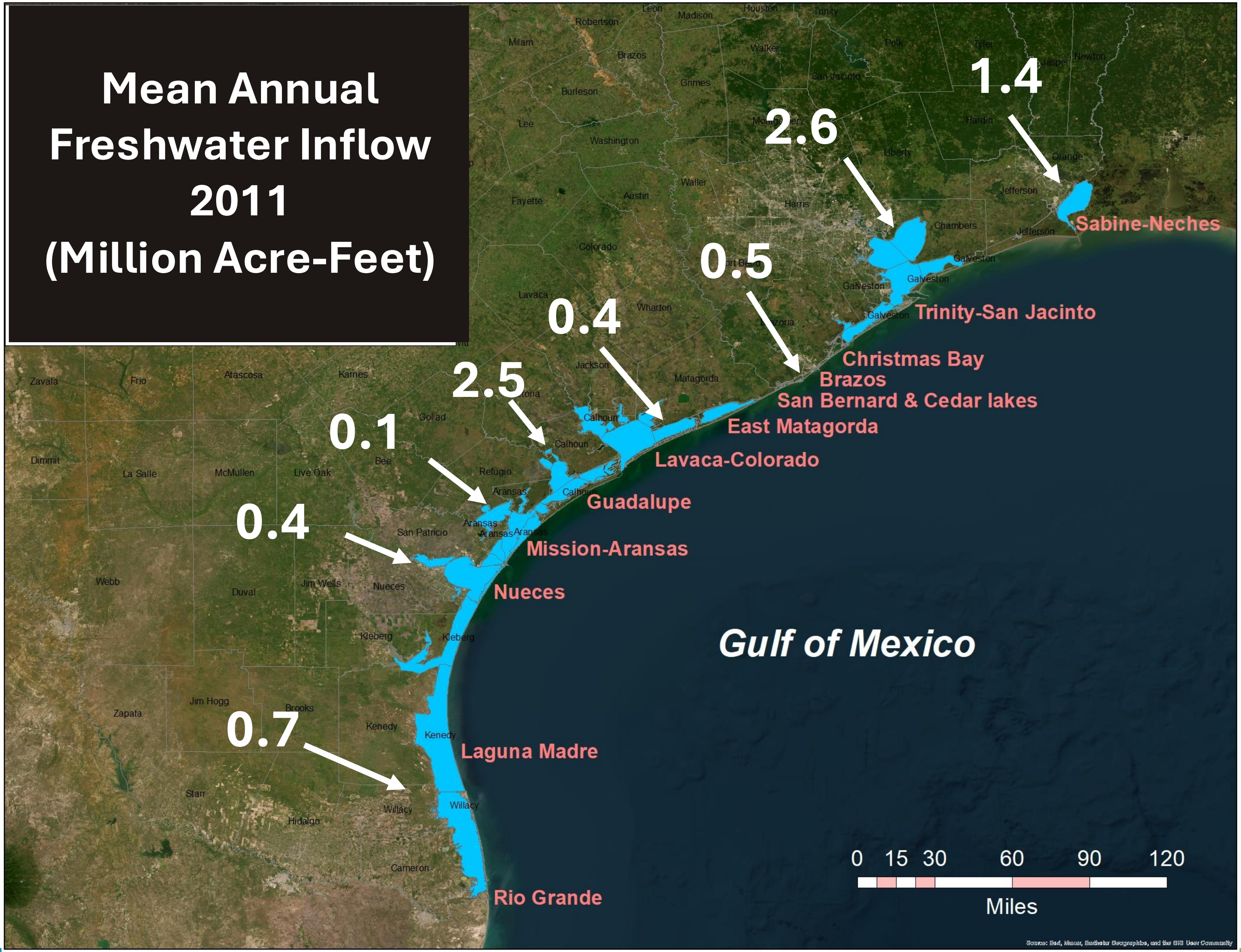
TEXAS WATER DEVELOPMENT BOARD

Freshwater inflows to Texas estuaries are driven by the precipitation gradient across the state.

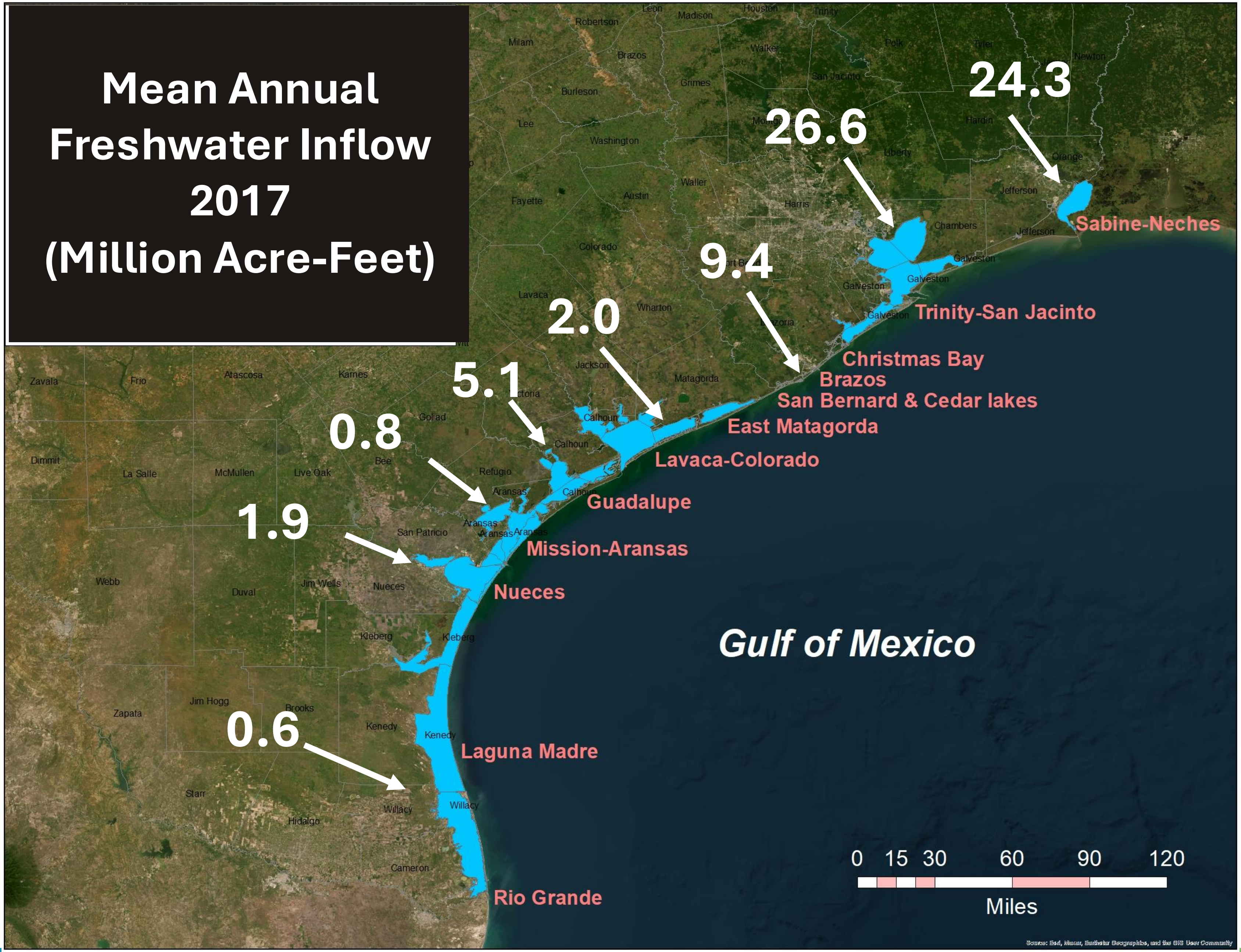




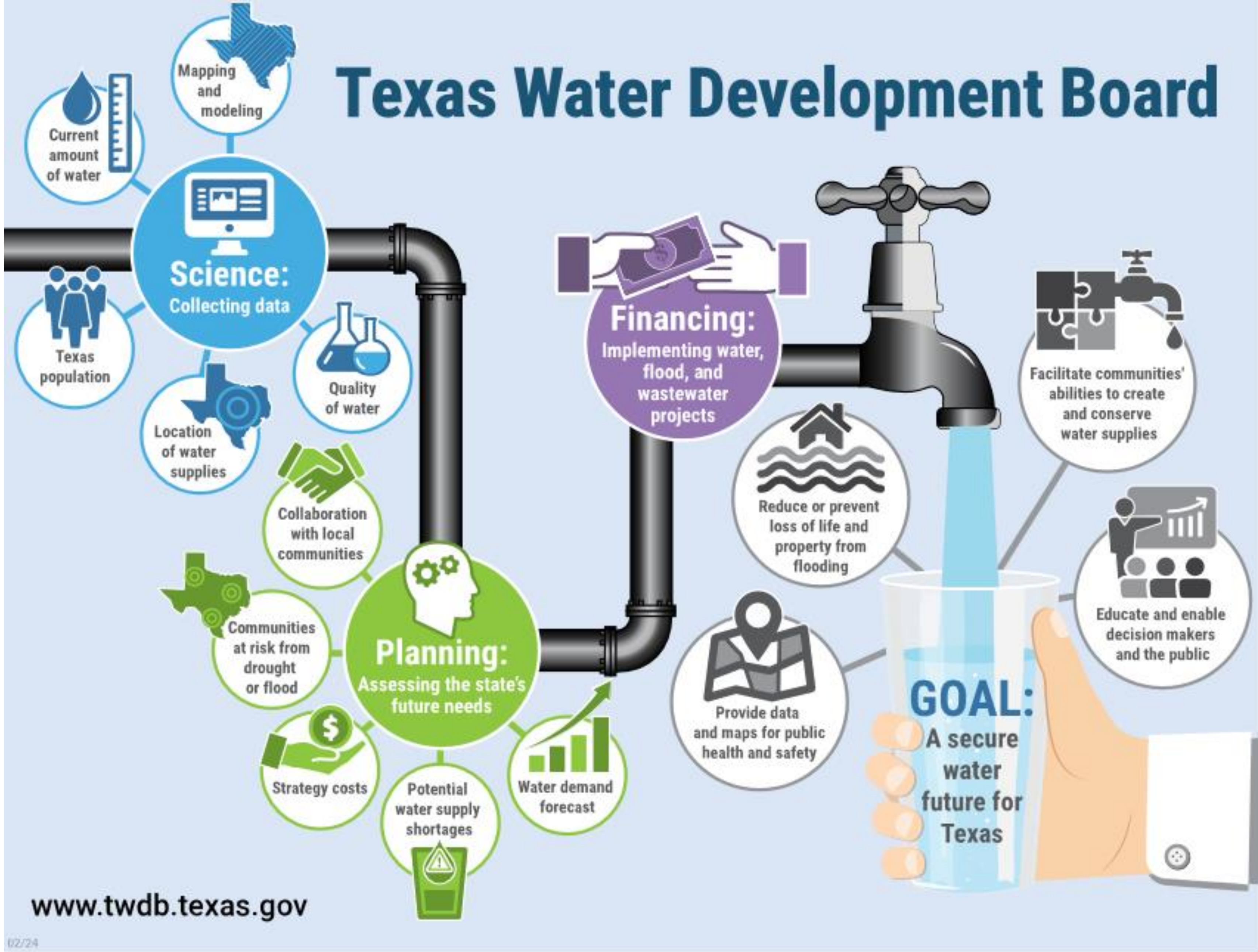
Deviation from the average: Drought



Deviation from the average: Flood

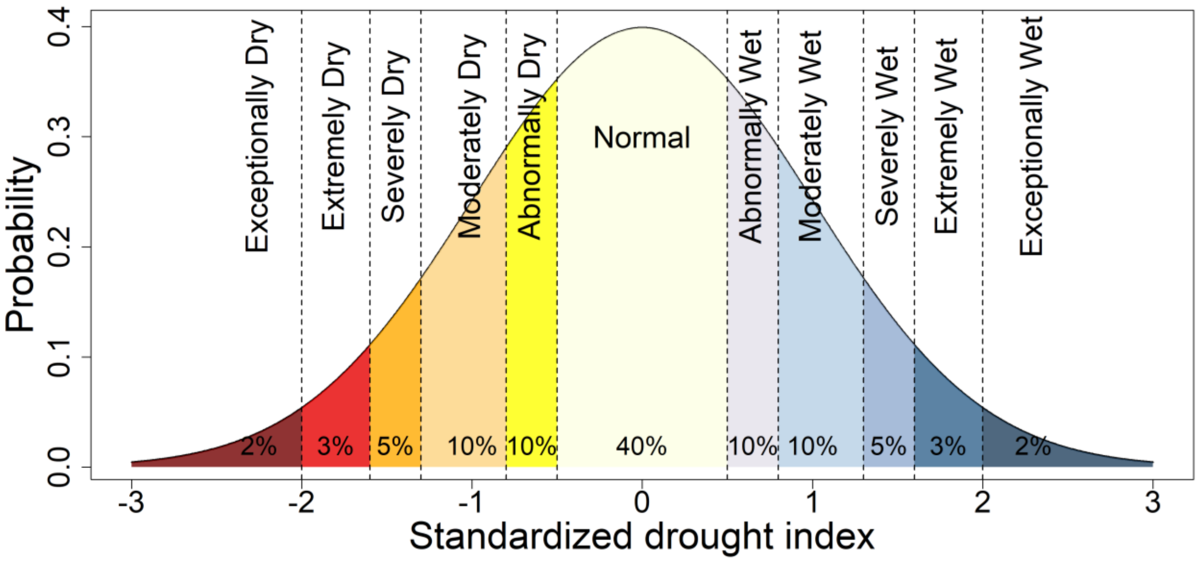


Ensuring a secure water future for Texans



Standardized Drought Indices

- **Standardized Precipitation Index (SPI)**
  - Measures precipitation deficit
  - 4-km monthly precipitation rasters by
  - PRISM group (1980 to present)
- **Standardized Streamflow Index (SSI)**
  - Captures flow deficit
  - TxRR monthly freshwater inflow (1941 to present)
- **Evaporative Demand Drought Index (EDDI)**
  - Reflects atmospheric water demand
  - 4-km EDDI rasters
  - GRIDMET (Gridded Surface Meteorological) dataset (1980 to present)
- **Coastal Salinity Index (CSI)**
  - Indicates salinity variations
  - Monthly salinity rasters from SCHISM (2000 to 2019)



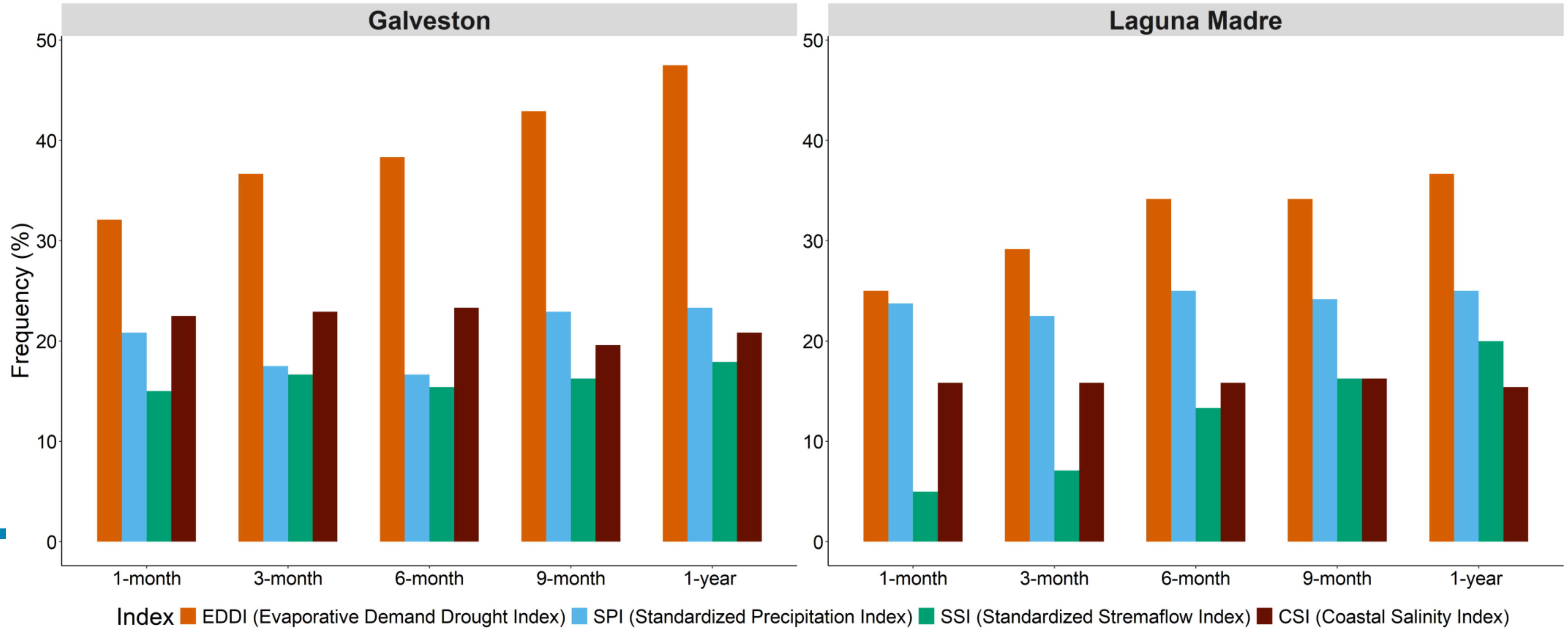
A standardized index quantifies observed parameter (e.g., precipitation) as a standardized departure from a probability distribution (e.g., gamma) that models the raw data.

The values can be interpreted as the number of standard deviations by which the observed anomaly deviates from the long-term mean.

Frequency of drought months (2000-2019)

```
library(SPEI)
get_spi <- function(prec_mat,scale){
  #apply the SPEI::spi to for every location/dates in the matrix
  spi_mat <- apply(prec_mat,1,function(x) SPEI::spi(x,scale,na.rm = T,verbose = F)$fitted)

  #Create a raster to store the spi values:
  spi_raster <- rast(prec_cr)

  values(spi_raster) <- t(spi_mat)
  Dates <- seq(from = start_date, to = Sys.Date(), by = "1 month")

  names(spi_raster) <- Dates

  spi_cropped <- terra::mask(spi_raster,estuaries)
  return(spi_cropped)
}

SPI_1mo <- get_spi(prec_mat,1)
SPI_3mo <- get_spi(prec_mat,3)
SPI_6mo <- get_spi(prec_mat,6)
SPI_9mo <- get_spi(prec_mat,9)
SPI_1yr <- get_spi(prec_mat,12)
SPI_2yr <- get_spi(prec_mat,24)
```

- 4 scripts in R ~ 500 lines of code
- The scripts will automatically compile based on the frequency of acquiring new data.



TWDB maintains 82 years (1941-2022) of freshwater inflow data

Gaged Watershed Flows

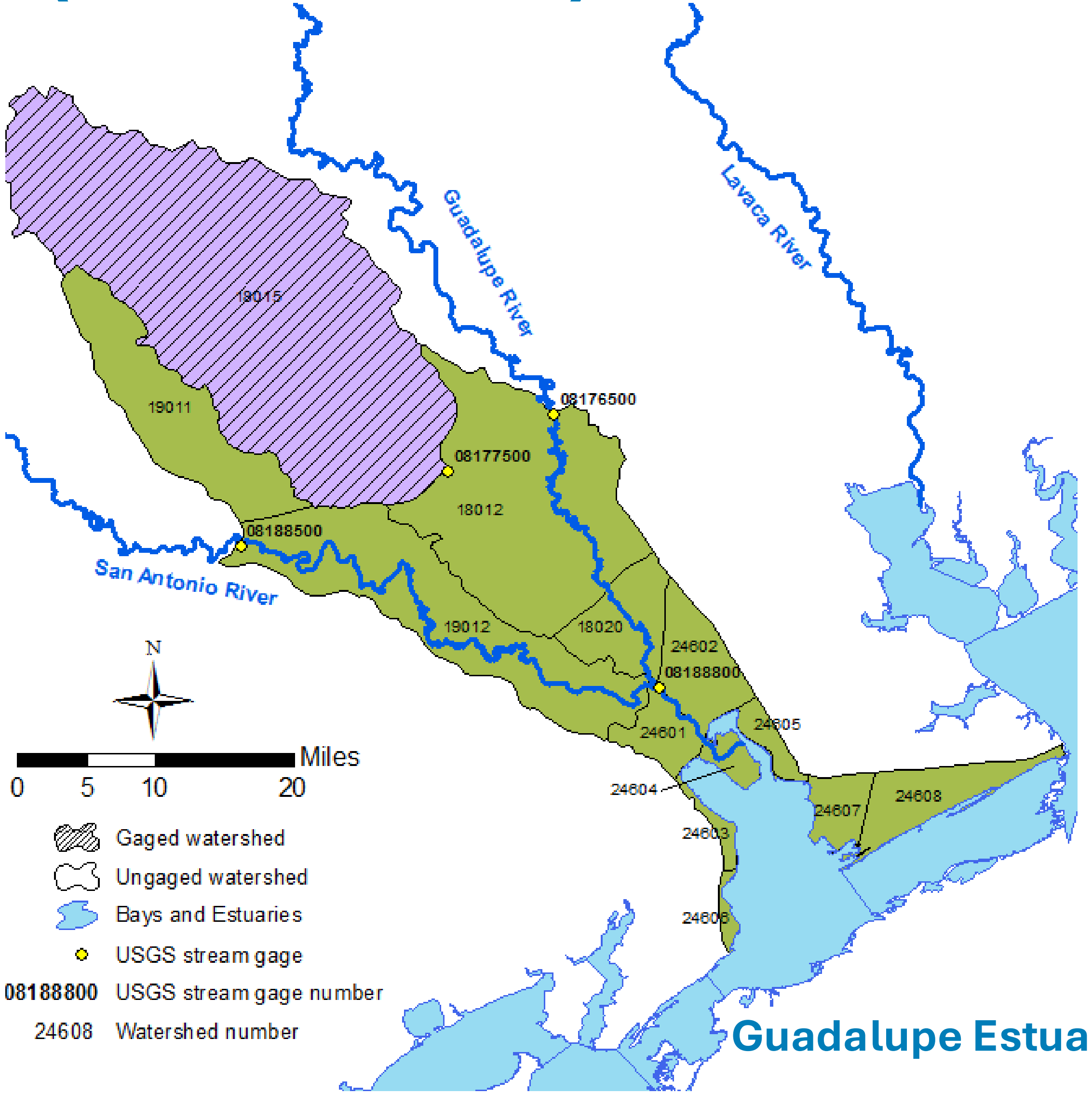
Ungaged Watershed Flows

+ Modeled (Texas Rainfall-Runoff Model)

- Diversions

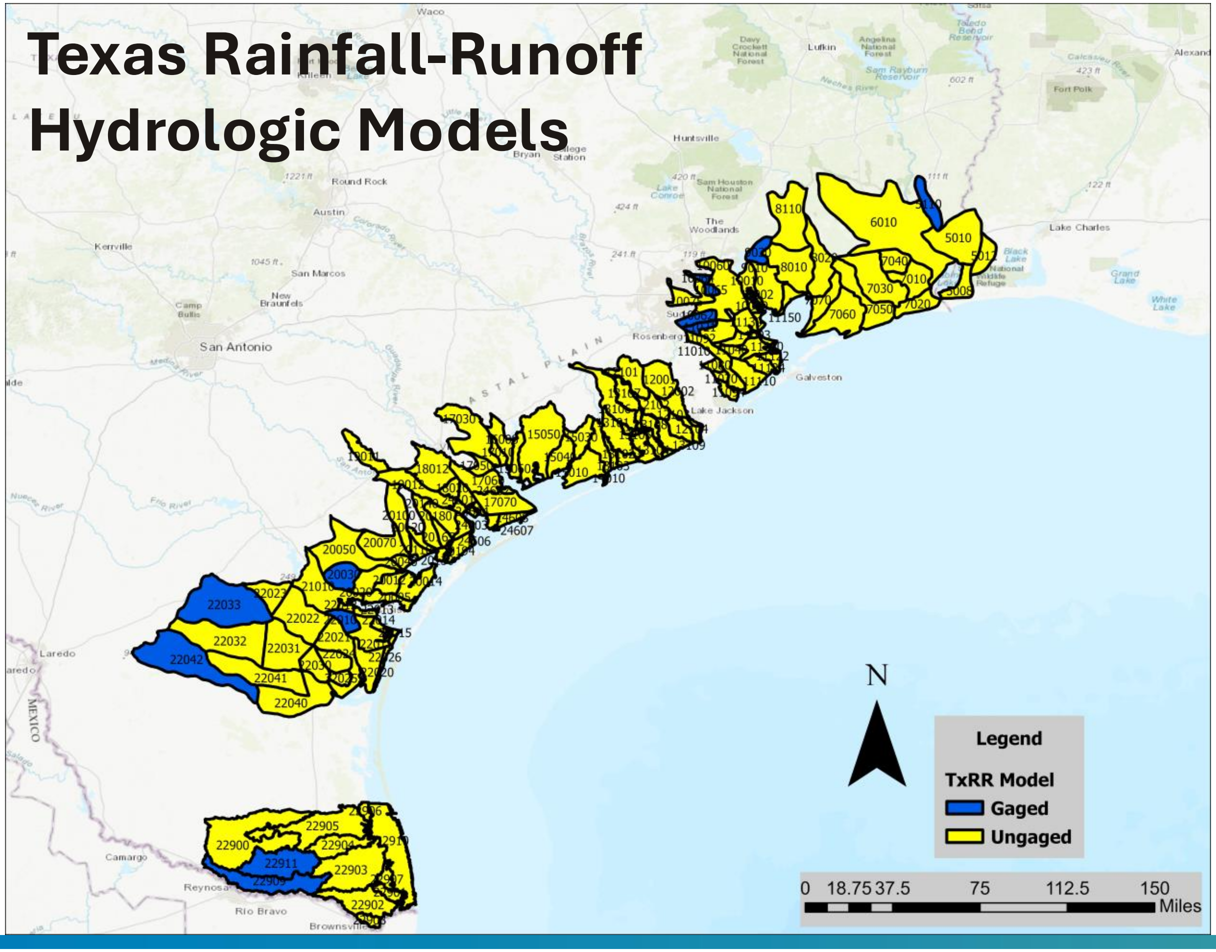
+ Returns

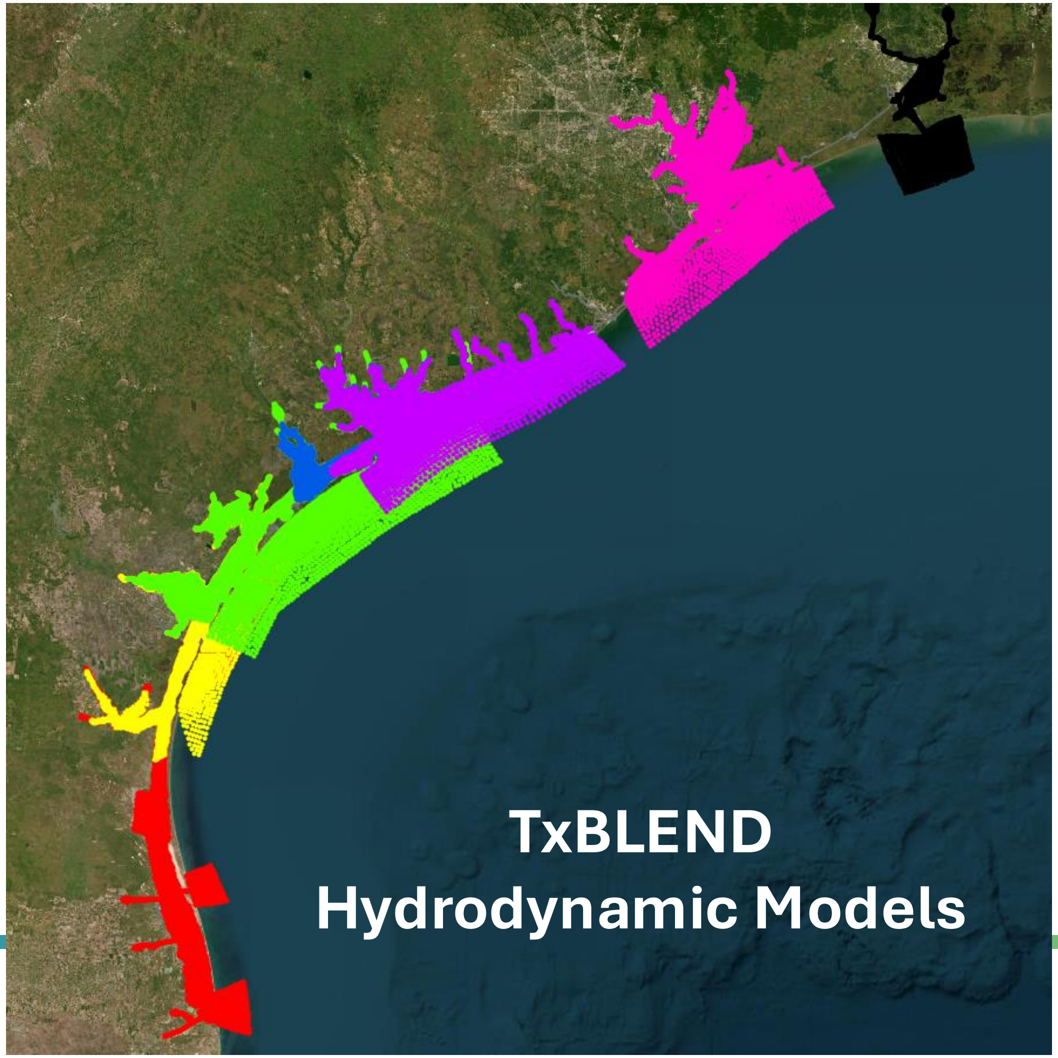
= Surface Inflows to Bay



Guadalupe Estuary

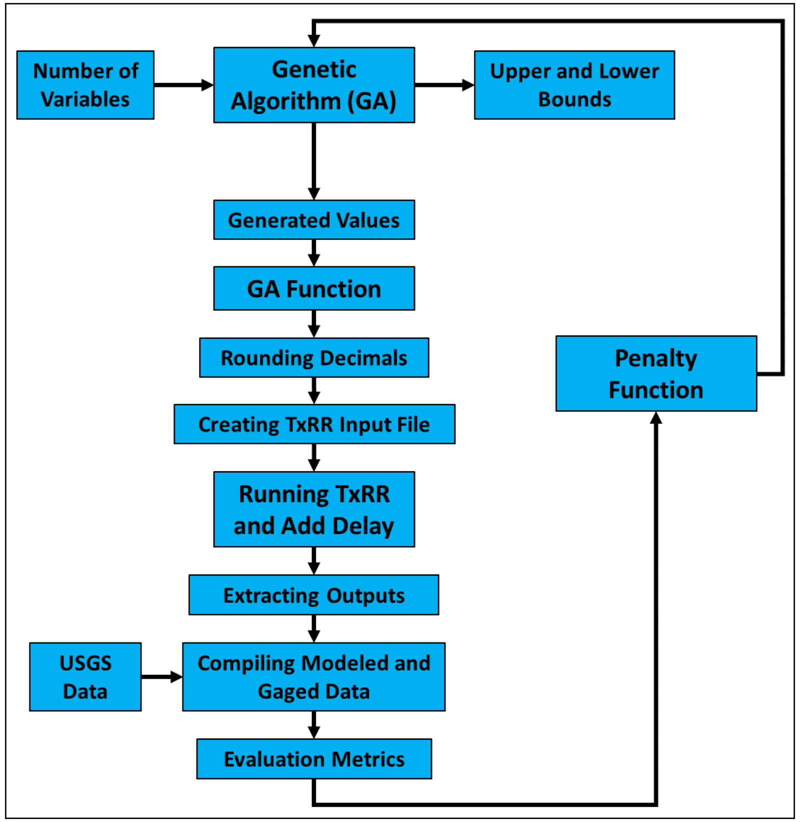
The TWDB's legacy coastal models are outdated, but simple, fast, and available for use



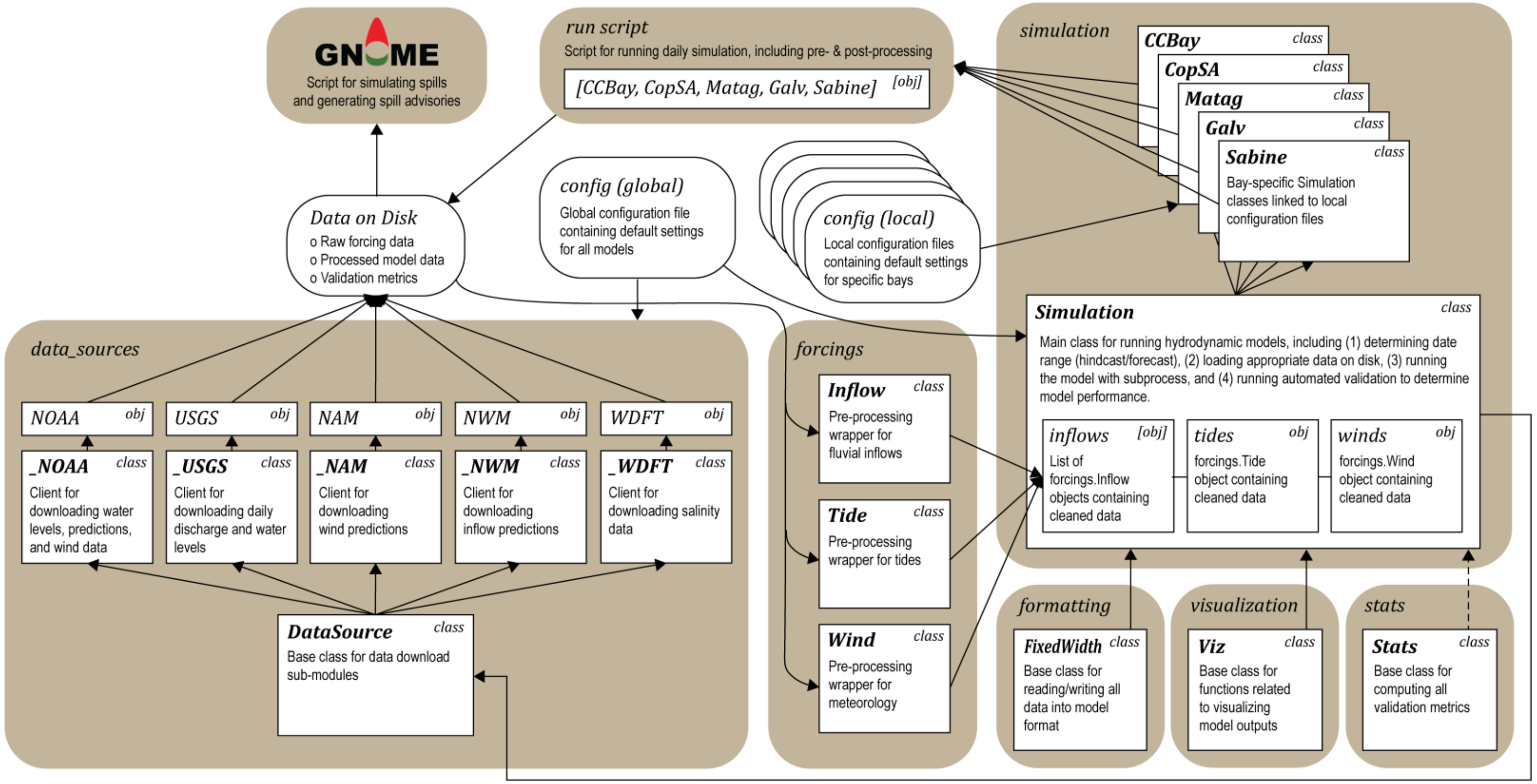


We’ve improved existing hydrologic and hydrodynamic models

TxRR Automated Calibration Using Genetic Algorithm

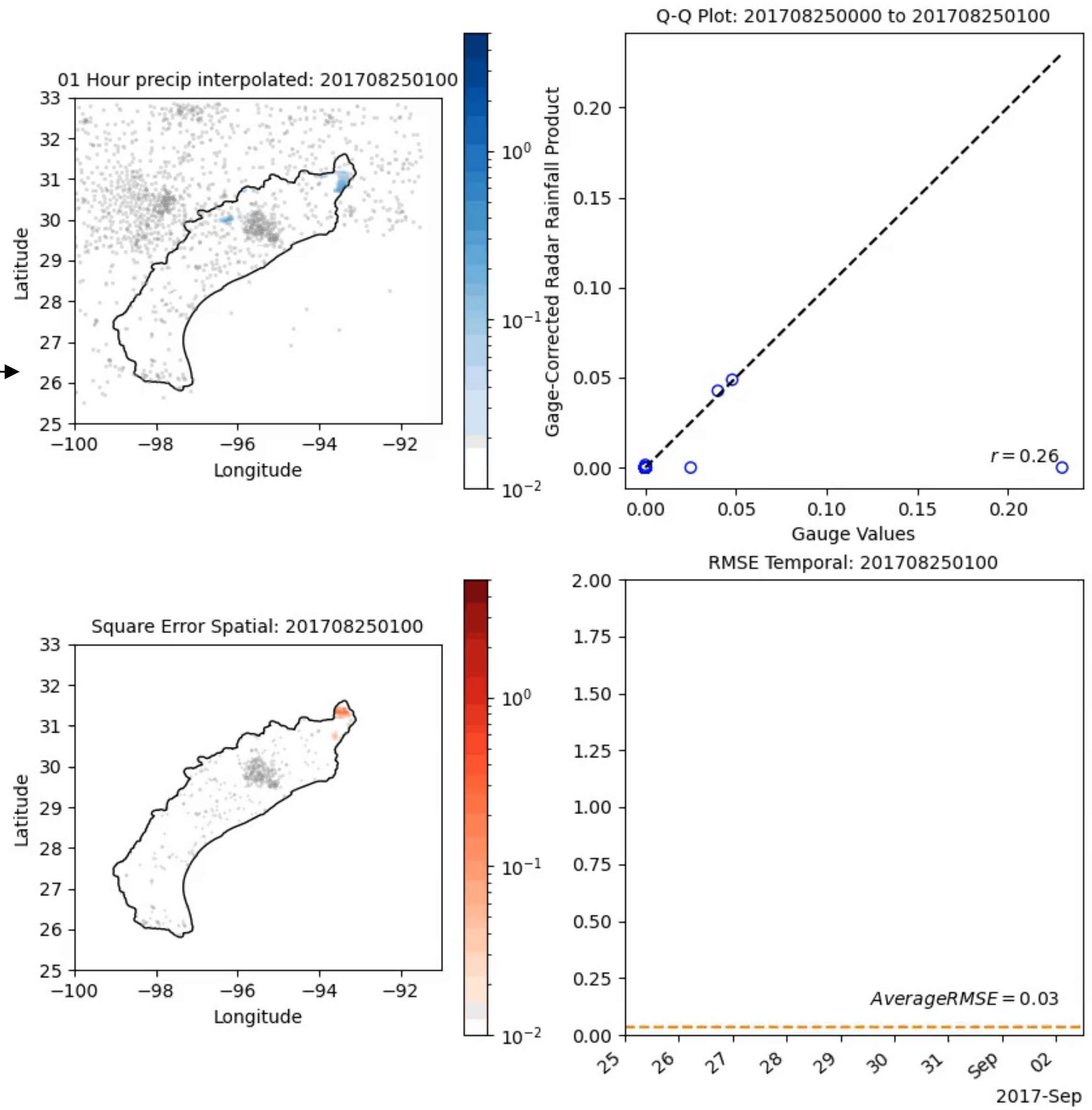


Oil Spill Modeling System TxBLEND Automated TxBLEND Validation



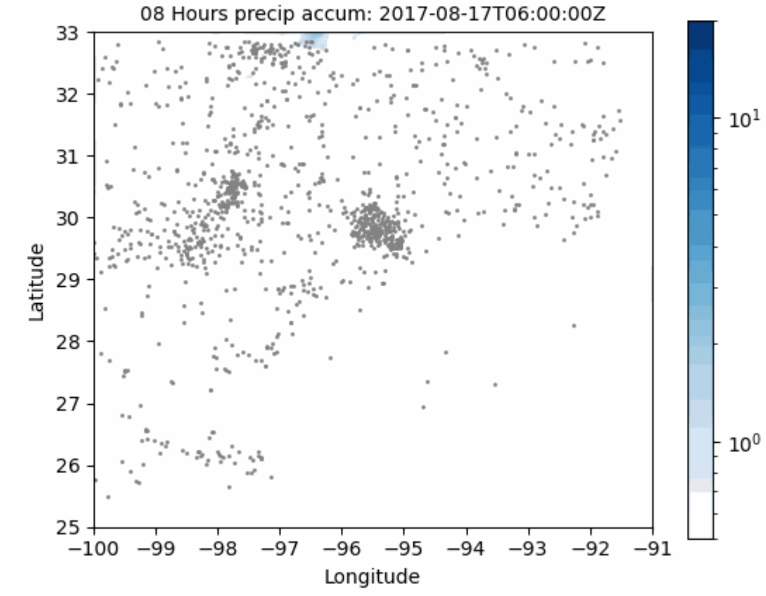
High resolution (spatial and temporal) multi-sensor/radar precipitation data stream for the entire coast of Texas

Texas Coast Bias Corrected High Resolution Rainfall Product

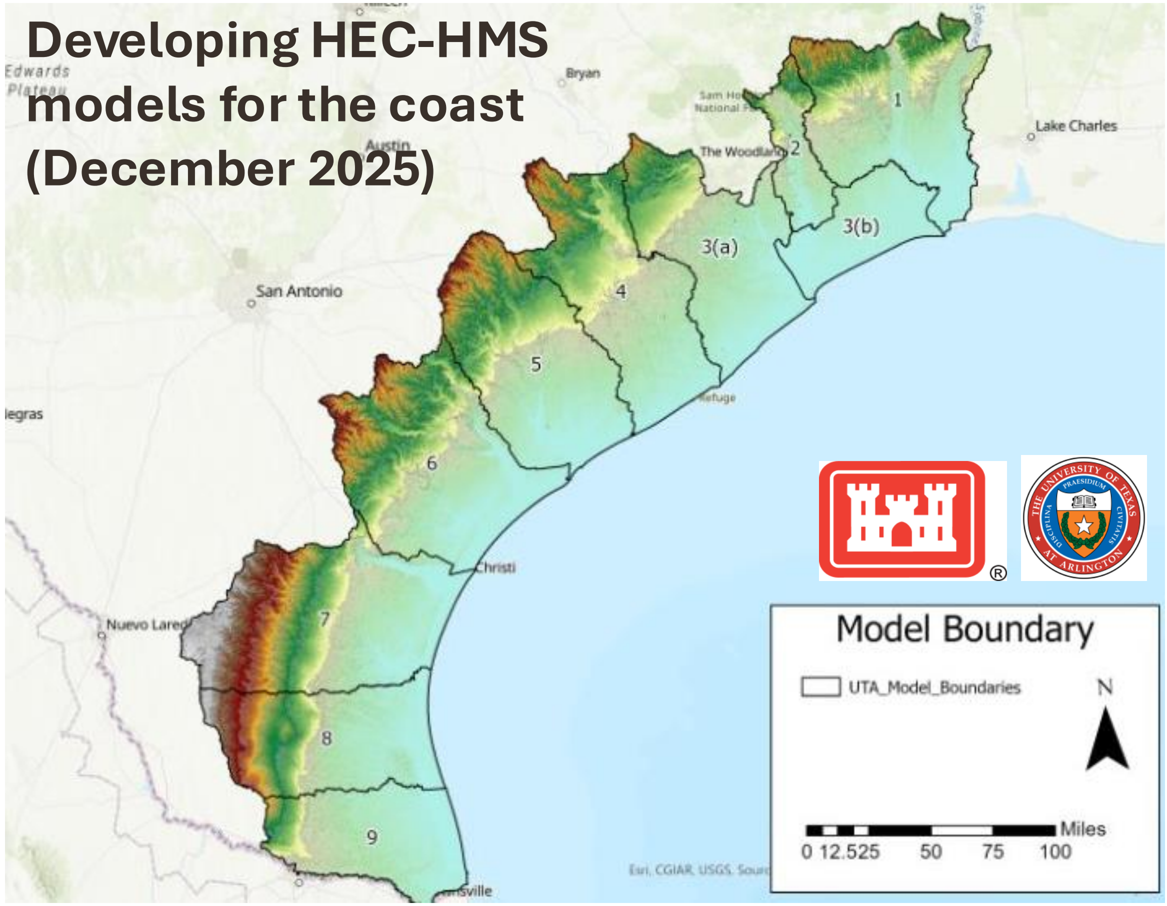


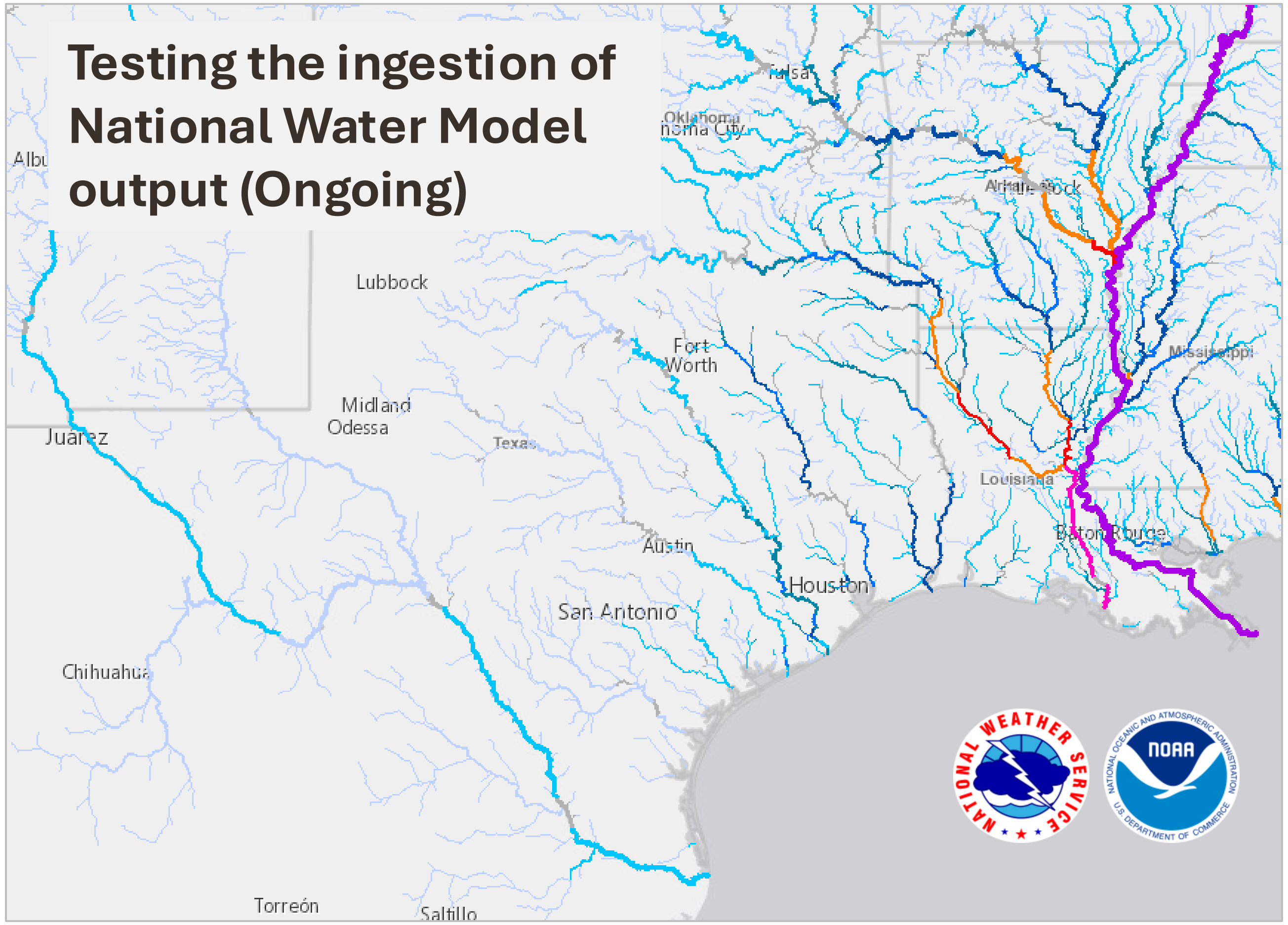
Hurricane Harvey Event:

Stage IV



We're modernizing our modeling systems by developing and testing state-of-the-art hydrologic models





https://water.noaa.gov/map

HEC-HMS 2D: Study Overview

TWDB Contract # *2401792866*

HEC-HMS 2D Example

HEC-HMS Model Development
- 5-8 Models
- 2D Flow Routing

Hydrological Parameter Estimation

Gauged Catchments: Calibration

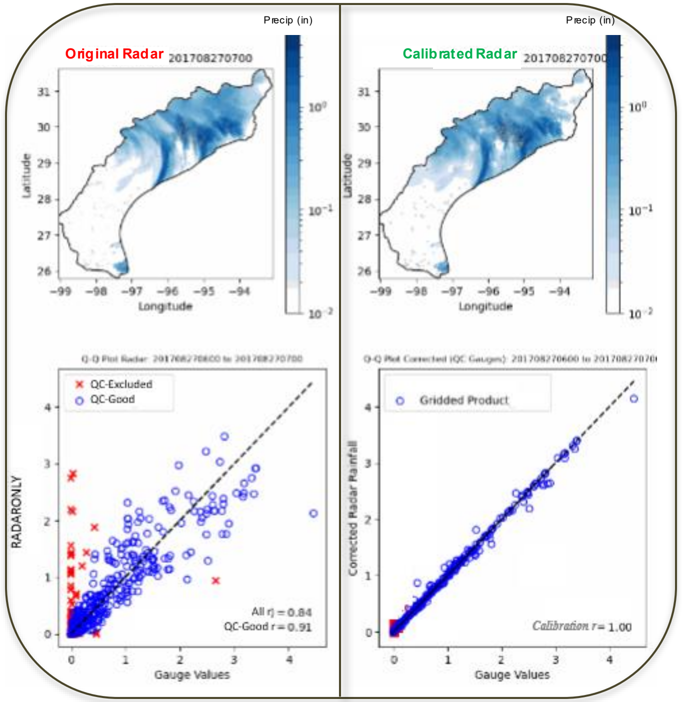
Ungauged catchments: Parameter estimation aided by spatial regression and basin characteristics analysis

Sensitivity Analysis and Model Runtime Optimization

Model Validation

Hindcasting and Automation

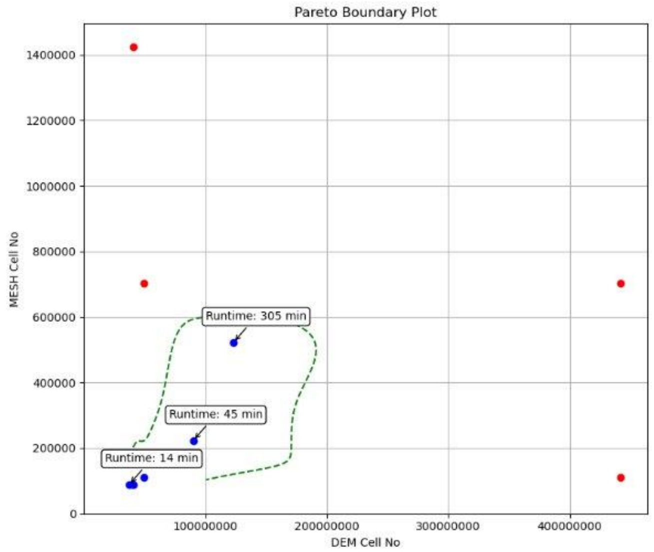
TWDB Contract #2301792723

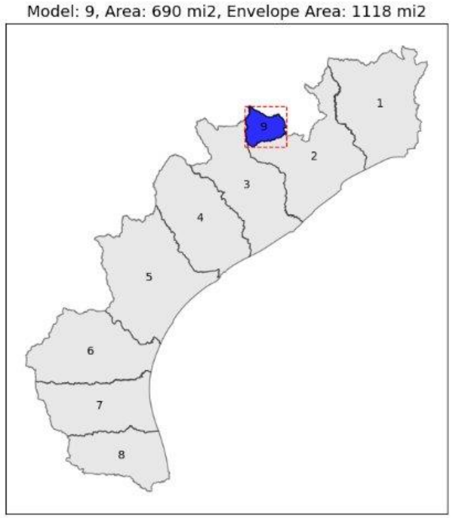


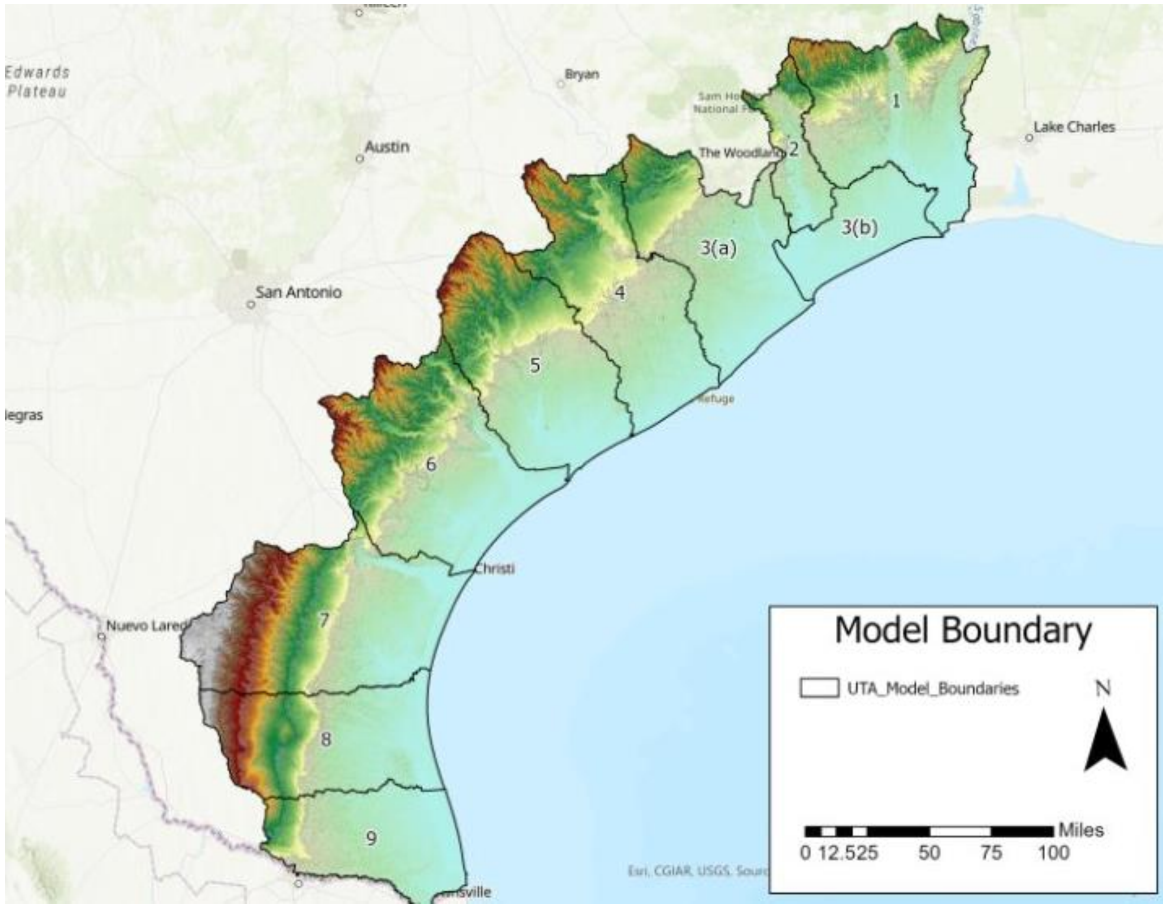
Bias-Corrected Radar Rainfall Product

HEC-HMS 2D

	DEM Grid recommended cell size (m)	Mesh recommended cell size (m)
	15	244
	19	234
	17	229
	15	229
	18	262
	14	231
	12	205
	11	182
	6	90
Max:	19	262
Avg:	14	212
Recommended	**20 m**	**250 m**

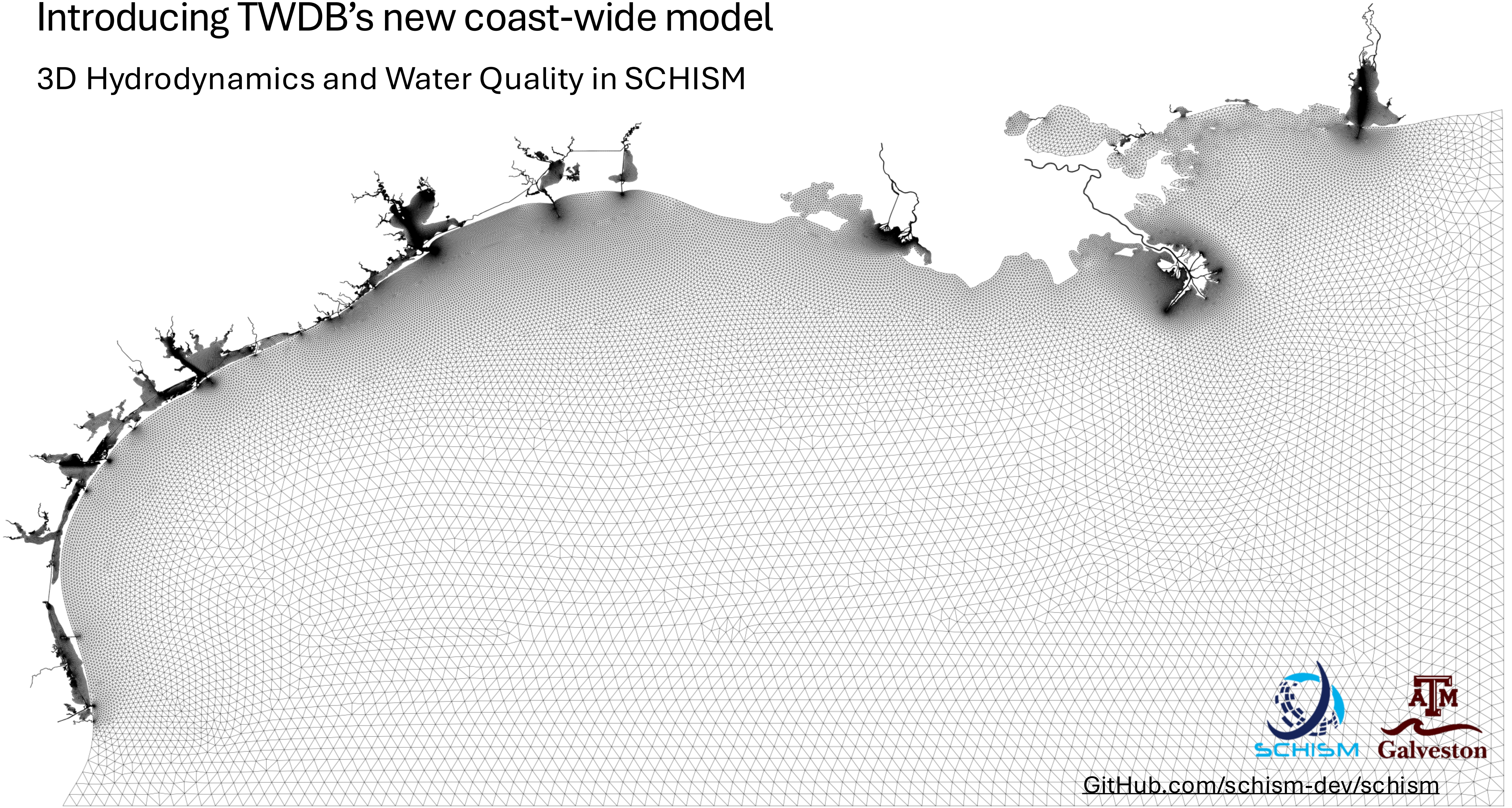






Introducing TWDB’s new coast-wide model

3D Hydrodynamics and Water Quality in SCHISM



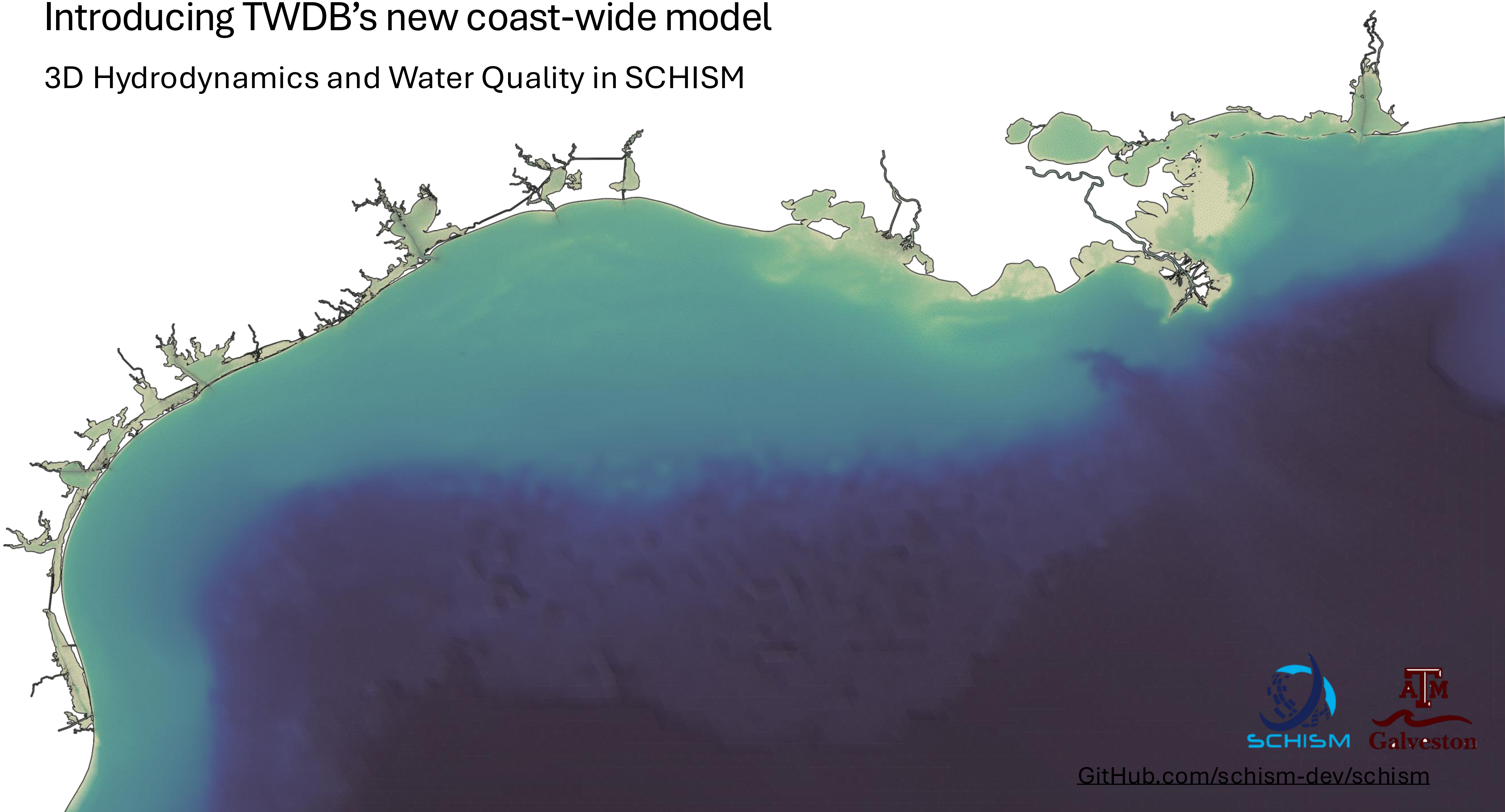
SCHISM

Galveston

GitHub.com/schism-dev/schism

Introducing TWDB's new coast-wide model

3D Hydrodynamics and Water Quality in SCHISM

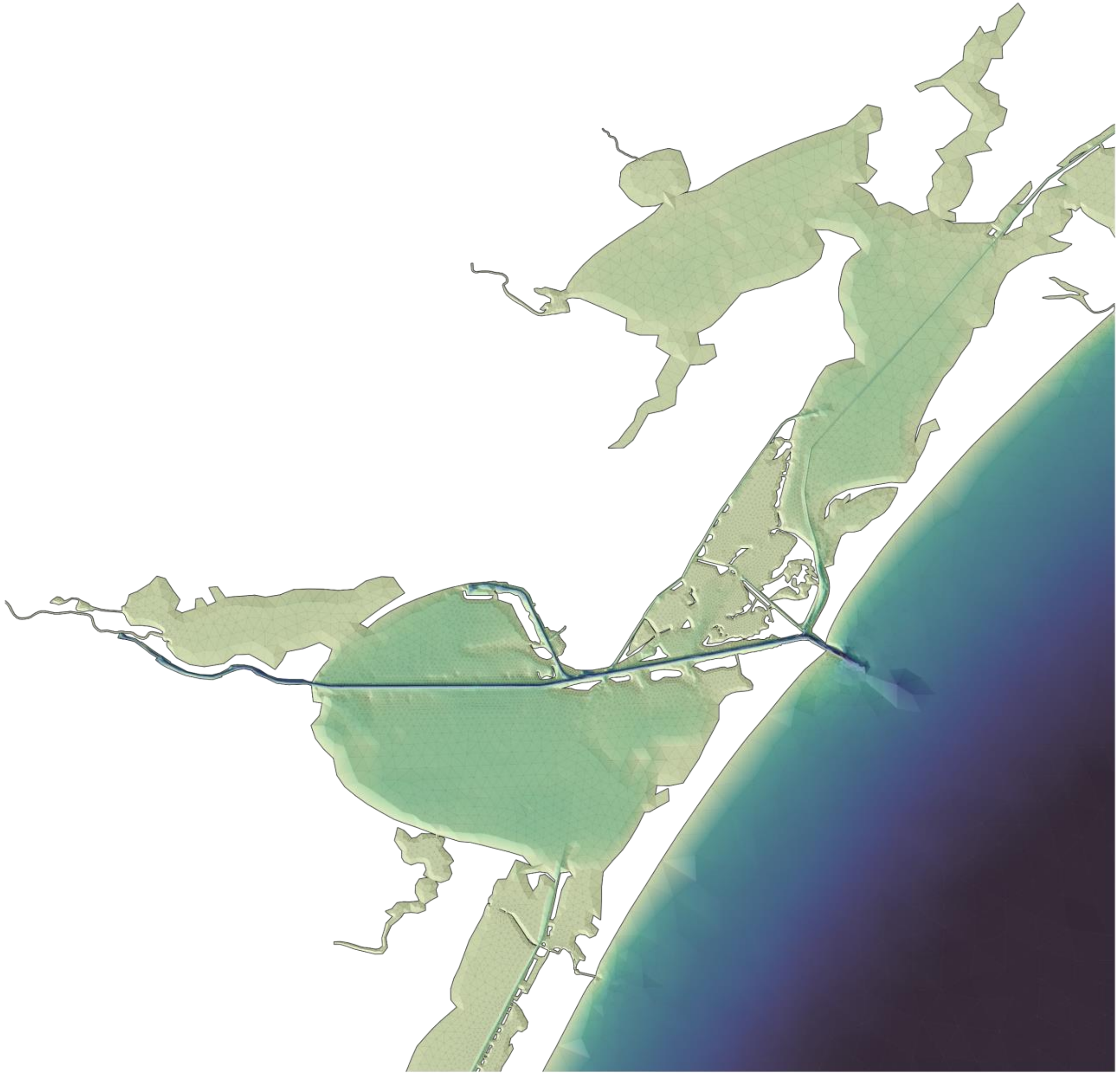


SCHISM

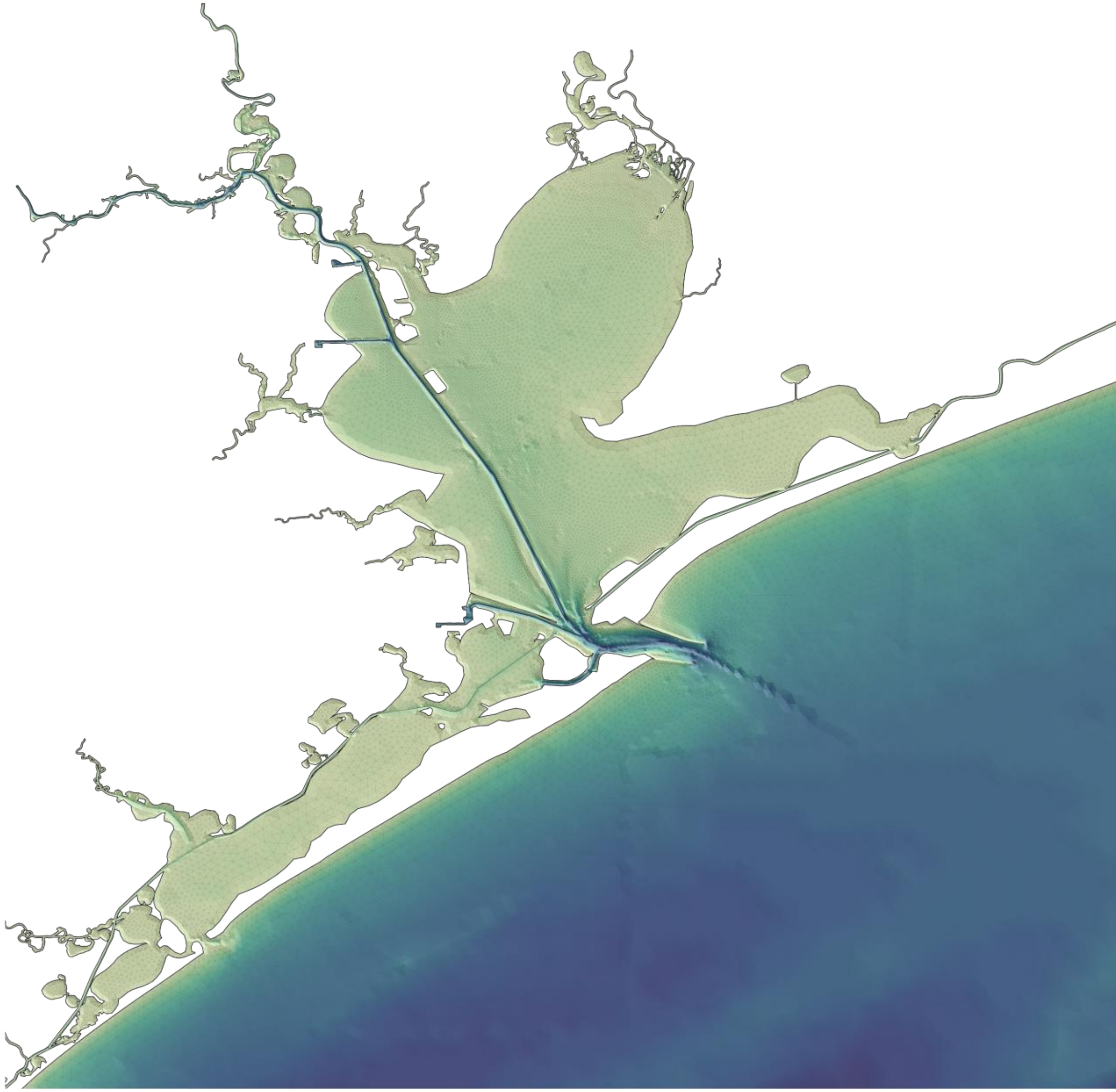
Galveston

GitHub.com/schism-dev/schism

Corpus Christi Bay

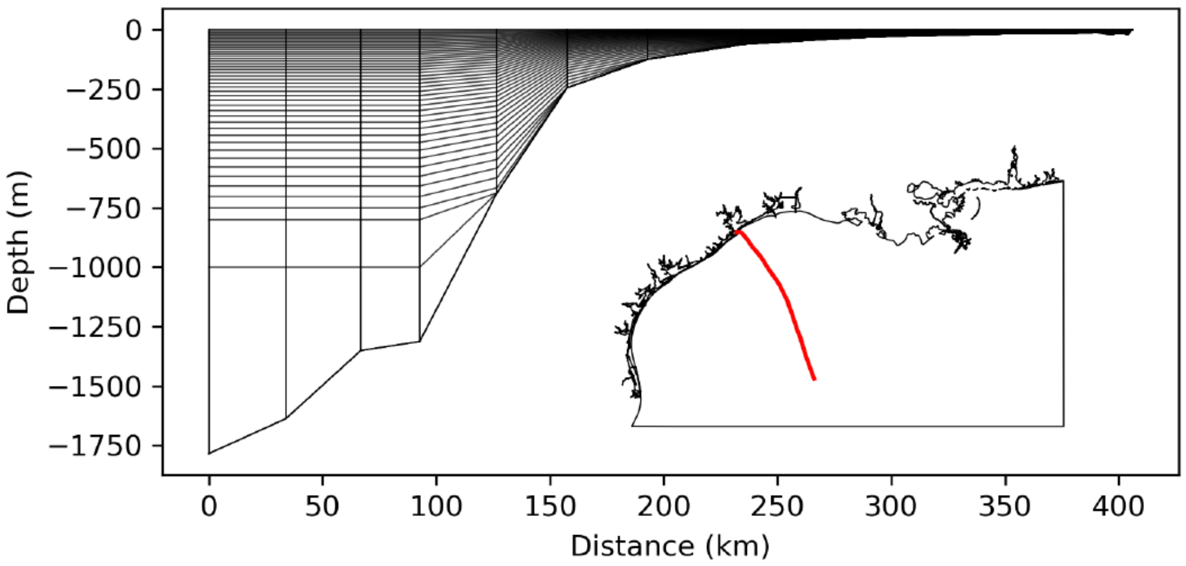


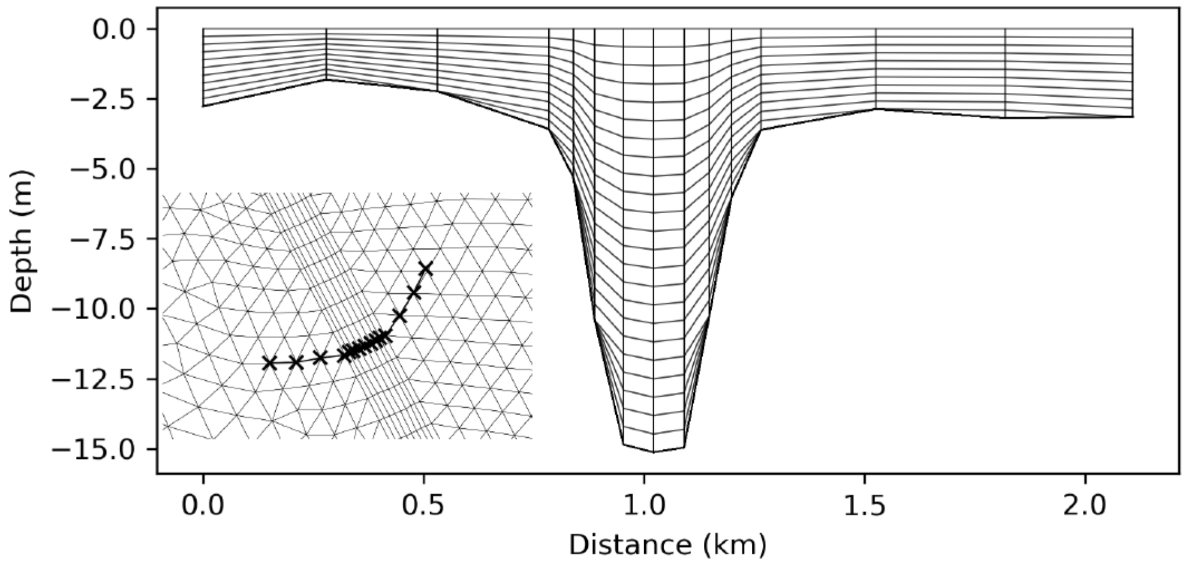
Galveston Bay



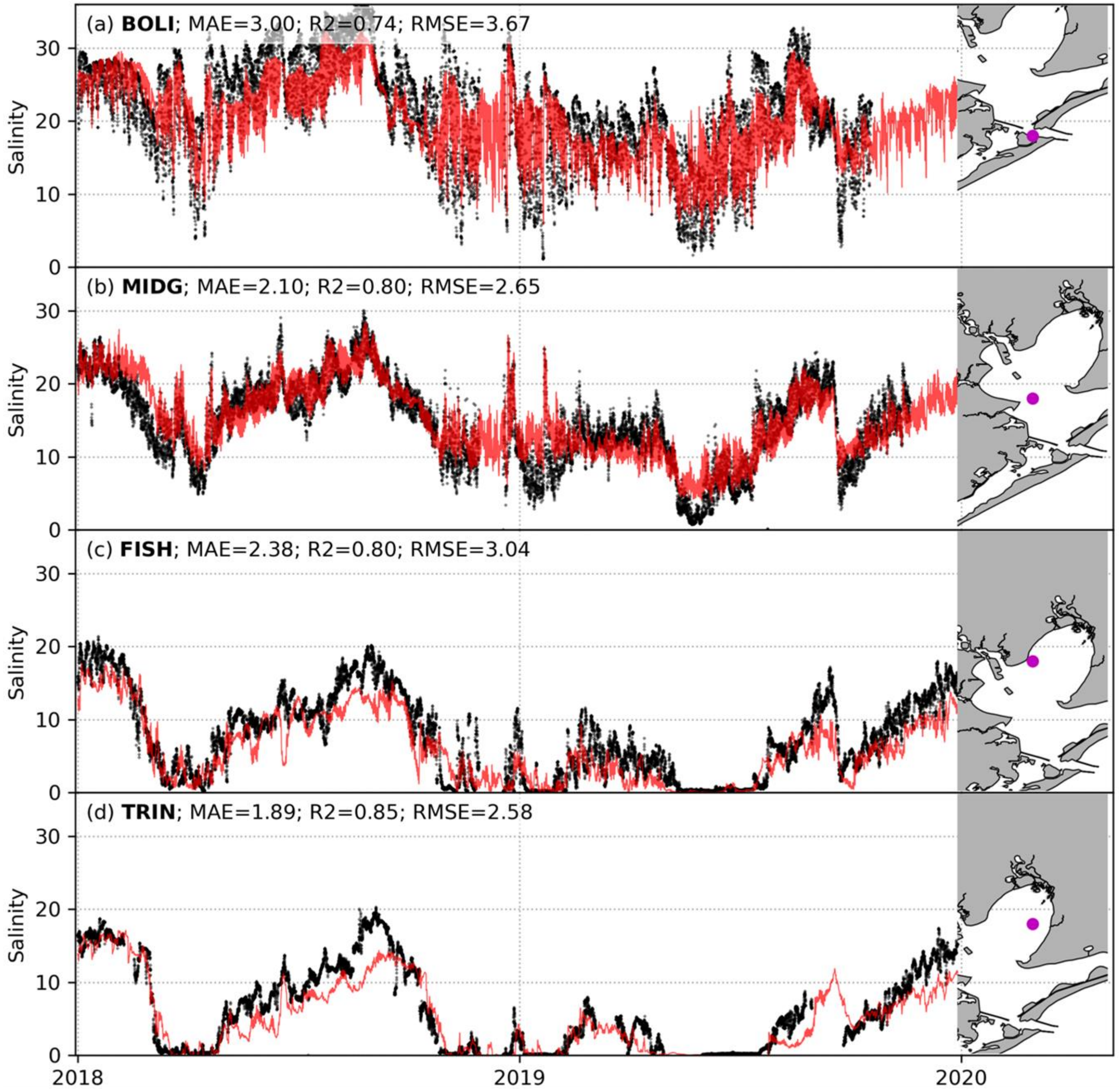
SCHISM: The next generation of ocean modeling

- Finite Element Model (FEM) with 188,395 elements (118,200 nodes)
- Horizontal resolution varies from 10km in gulf to ~30m in shipping channels
- Vertical resolution varies, with between 10 and 47 layers
- Two tracers (salinity and temperature)
- Fluvial inflows from 25 largest rivers (USGS gages)
- Open boundary forced with tidal harmonics and global HYCOM outputs
- Meteorology from Global Forecast System (GFS)





TEXAS WATER DEVELOPMENT BOARD



The New State of the Art for Texas

We have been working closely with collaborators at TAMUG for past two years to refine and calibrate the model.

Tested on in-situ water level, salinity, temperature, and currents from multiple source organizations.

The result provides **unprecedented** spatial coverage and accuracy in Texas bays and estuaries.

Note: Daily forecasts and hindcasts soon to be freely available to public

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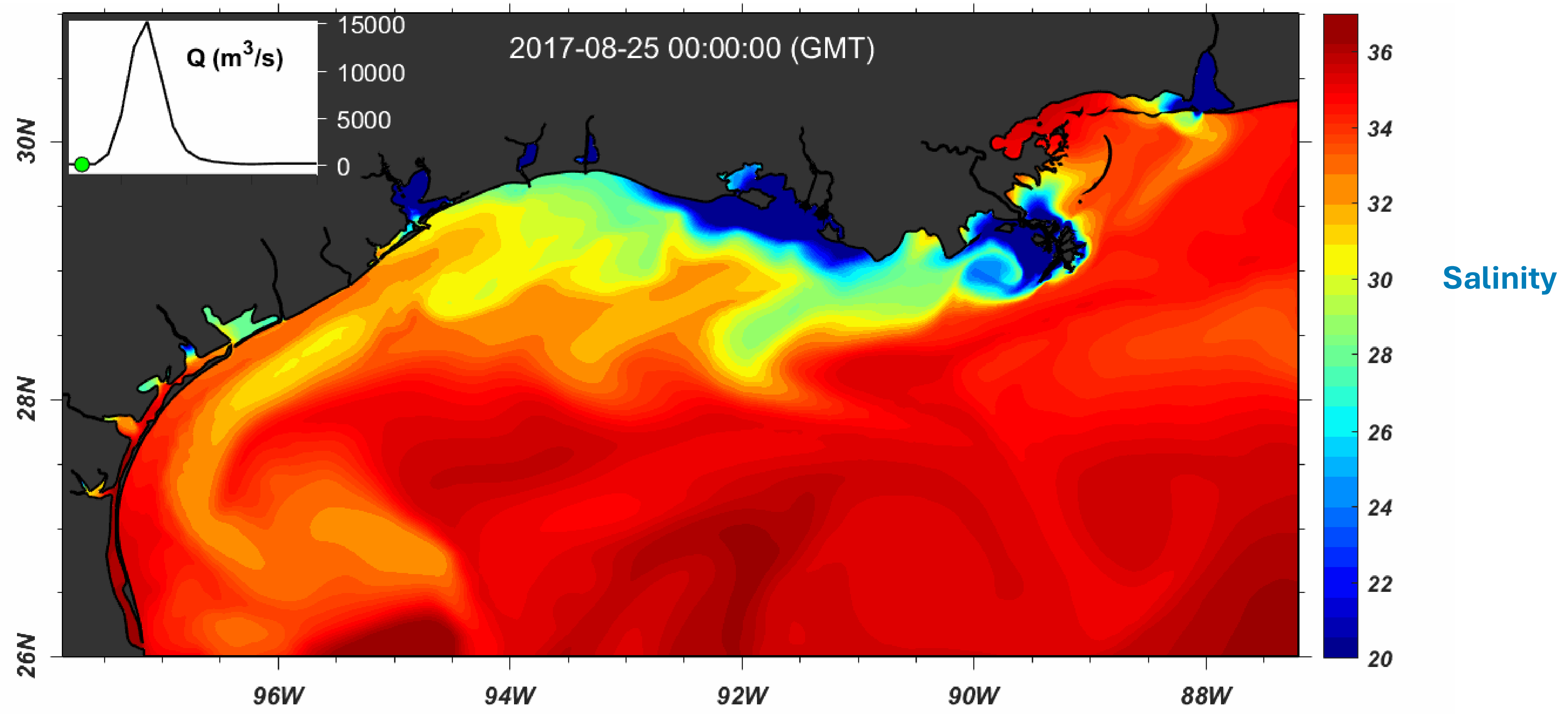
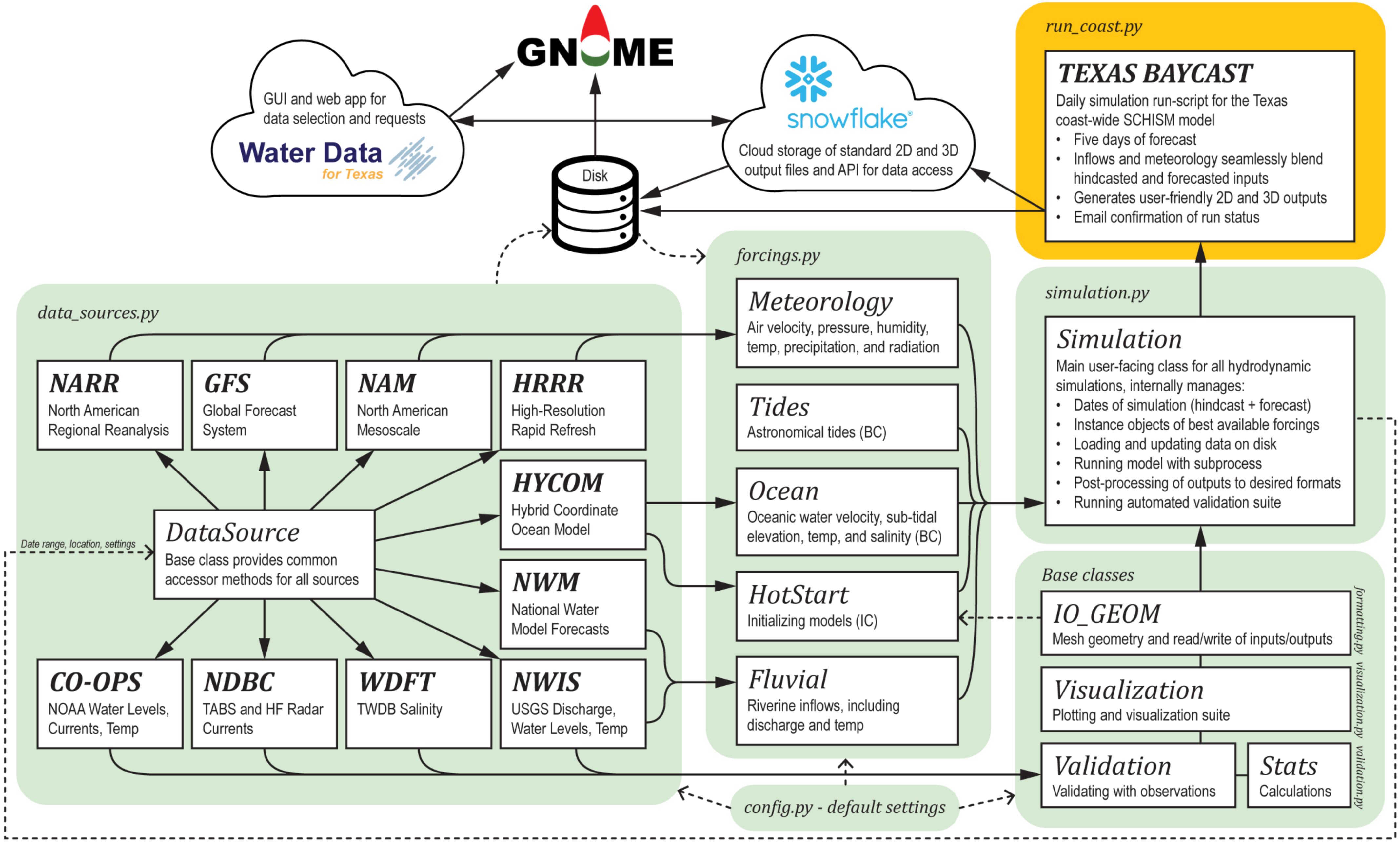
SCHISM was successfully tested for simulating Hurricane Harvey



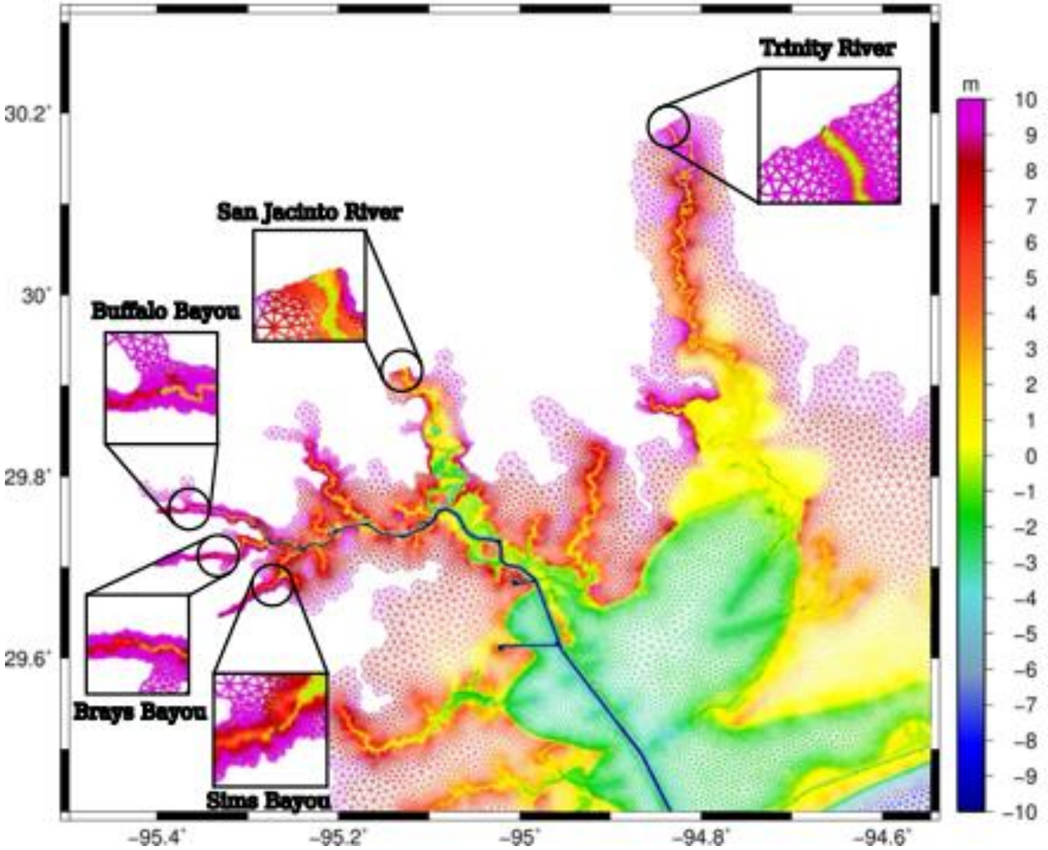
TEXAS WATER DEVELOPMENT BOARD

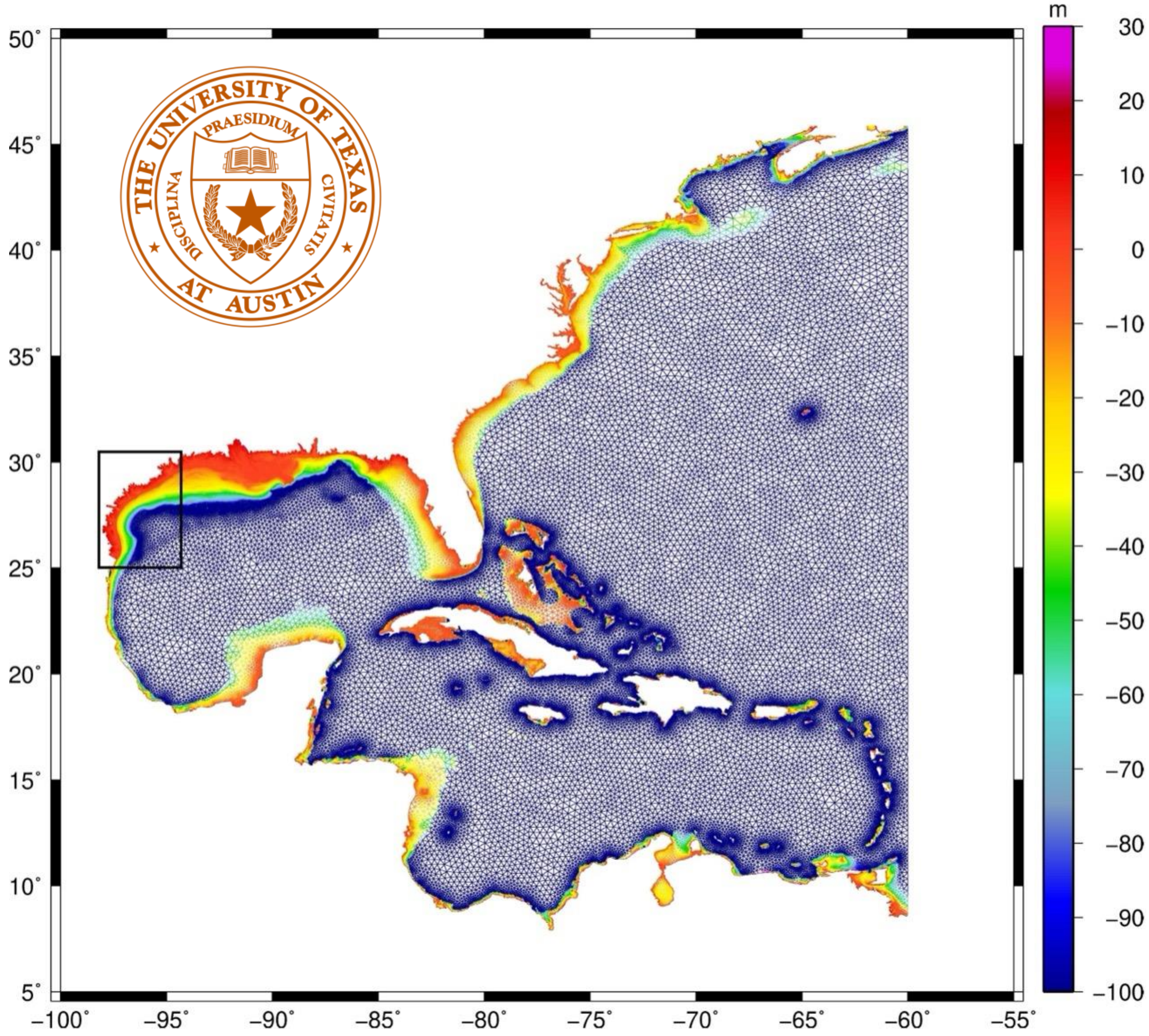


GNOME
GUI and web app for data selection and requests
Water Data for Texas
snowflake
Cloud storage of standard 2D and 3D output files and API for data access
Disk
run_coast.py
TEXAS BAYCAST
Daily simulation run-script for the Texas coast-wide SCHISM model
• Five days of forecast
• Inflows and meteorology seamlessly blend hindcasted and forecasted inputs
• Generates user-friendly 2D and 3D outputs
• Email confirmation of run status
forcings.py
Meteorology
Air velocity, pressure, humidity, temp, precipitation, and radiation
Tides
Astronomical tides (BC)
Ocean
Oceanic water velocity, sub-tidal elevation, temp, and salinity (BC)
HotStart
Initializing models (IC)
Fluvial
Riverine inflows, including discharge and temp
simulation.py
Simulation
Main user-facing class for all hydrodynamic simulations, internally manages:
• Dates of simulation (hindcast + forecast)
• Instance objects of best available forcings
• Loading and updating data on disk
• Running model with subprocess
• Post-processing of outputs to desired formats
• Running automated validation suite
Base classes
IO_GEOM
Mesh geometry and read/write of inputs/outputs
Visualization
Plotting and visualization suite
Validation
Validating with observations
Stats
Calculations
formatting.py
visualization.py
validation.py
data_sources.py
NARR
North American Regional Reanalysis
GFS
Global Forecast System
NAM
North American Mesoscale
HRRR
High-Resolution Rapid Refresh
HYCOM
Hybrid Coordinate Ocean Model
DataSource
Base class provides common accessor methods for all sources
Date range, location, settings
NWM
National Water Model Forecasts
CO-OPS
NOAA Water Levels, Currents, Temp
NDBC
TABS and HF Radar Currents
WDFT
TWDB Salinity
NWIS
USGS Discharge, Water Levels, Temp
config.py - default settings

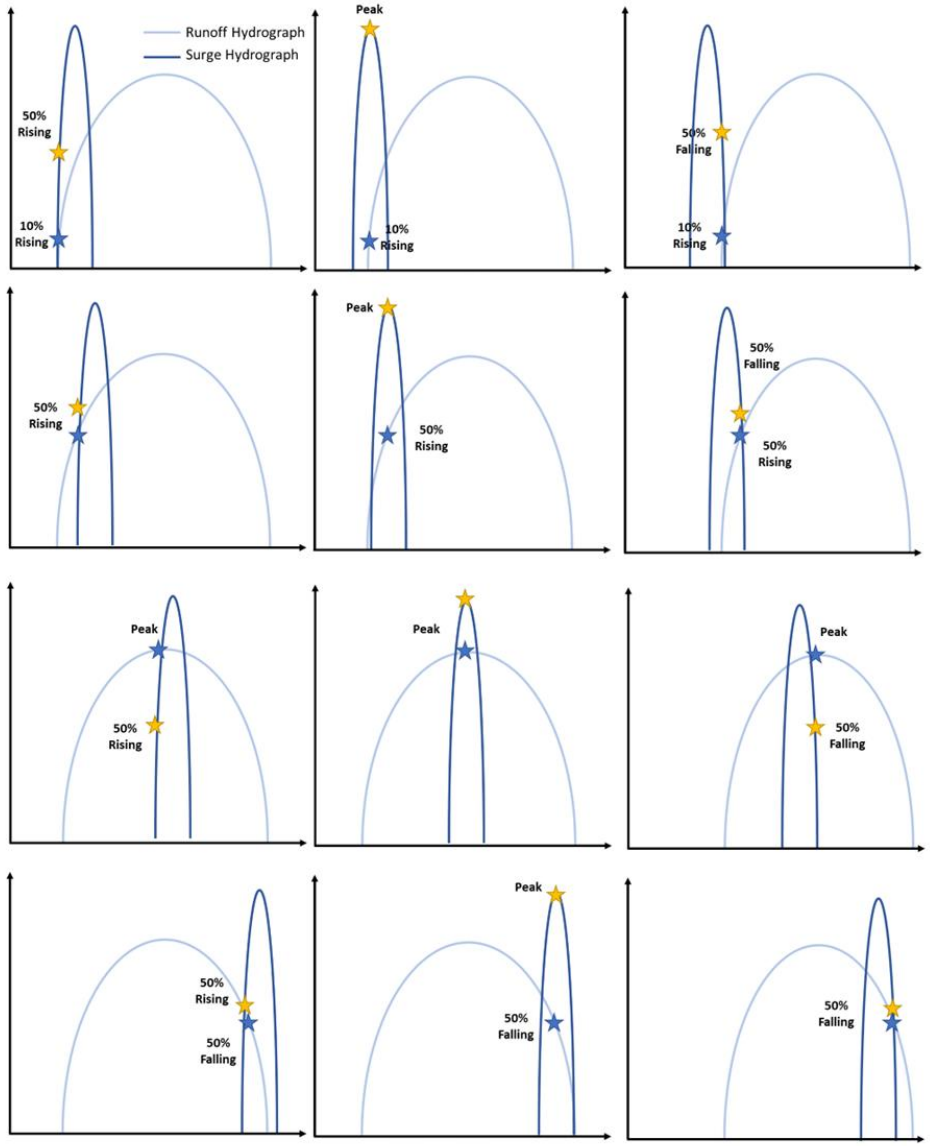
Transition zones for compound flooding (ADCIRC model)

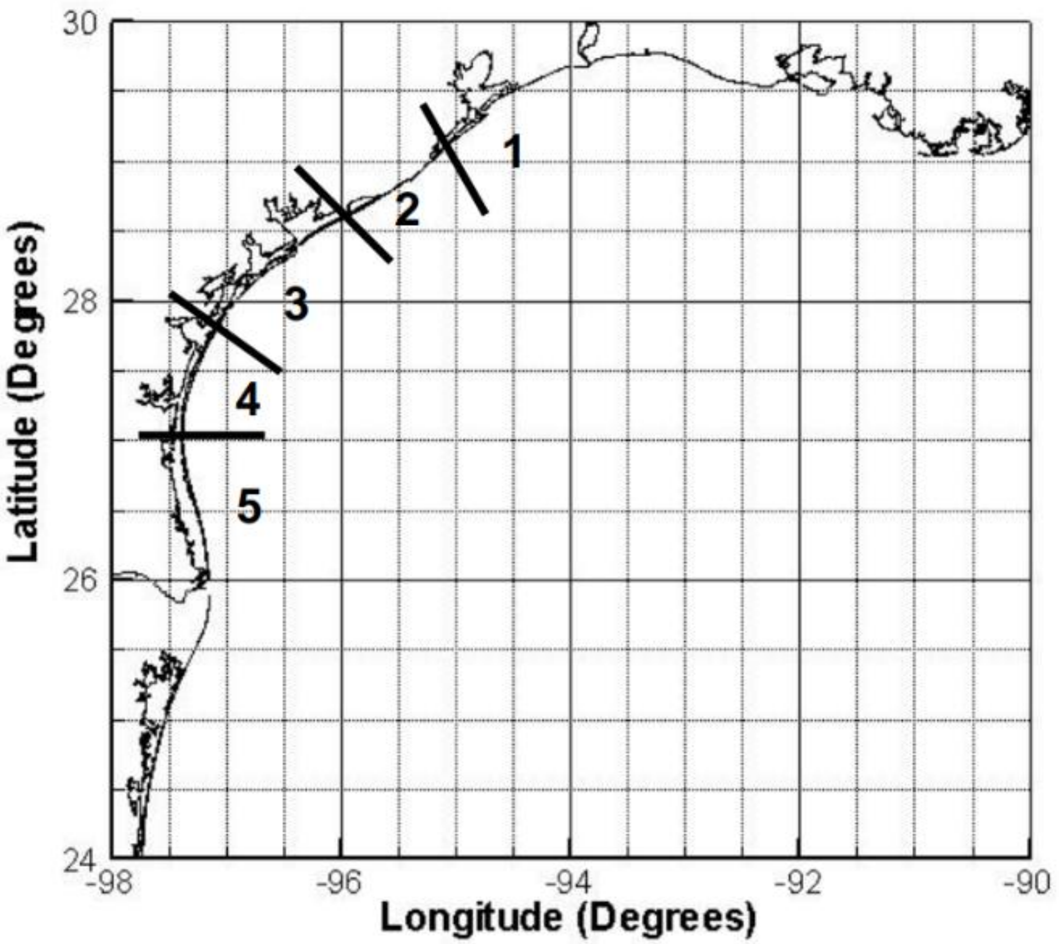
- New mesh contains 15 million finite elements
- Resolution of Texas rivers and floodplains is 30m
- 45 Major Texas rivers added





Geographic zones used on Q-Q Plots

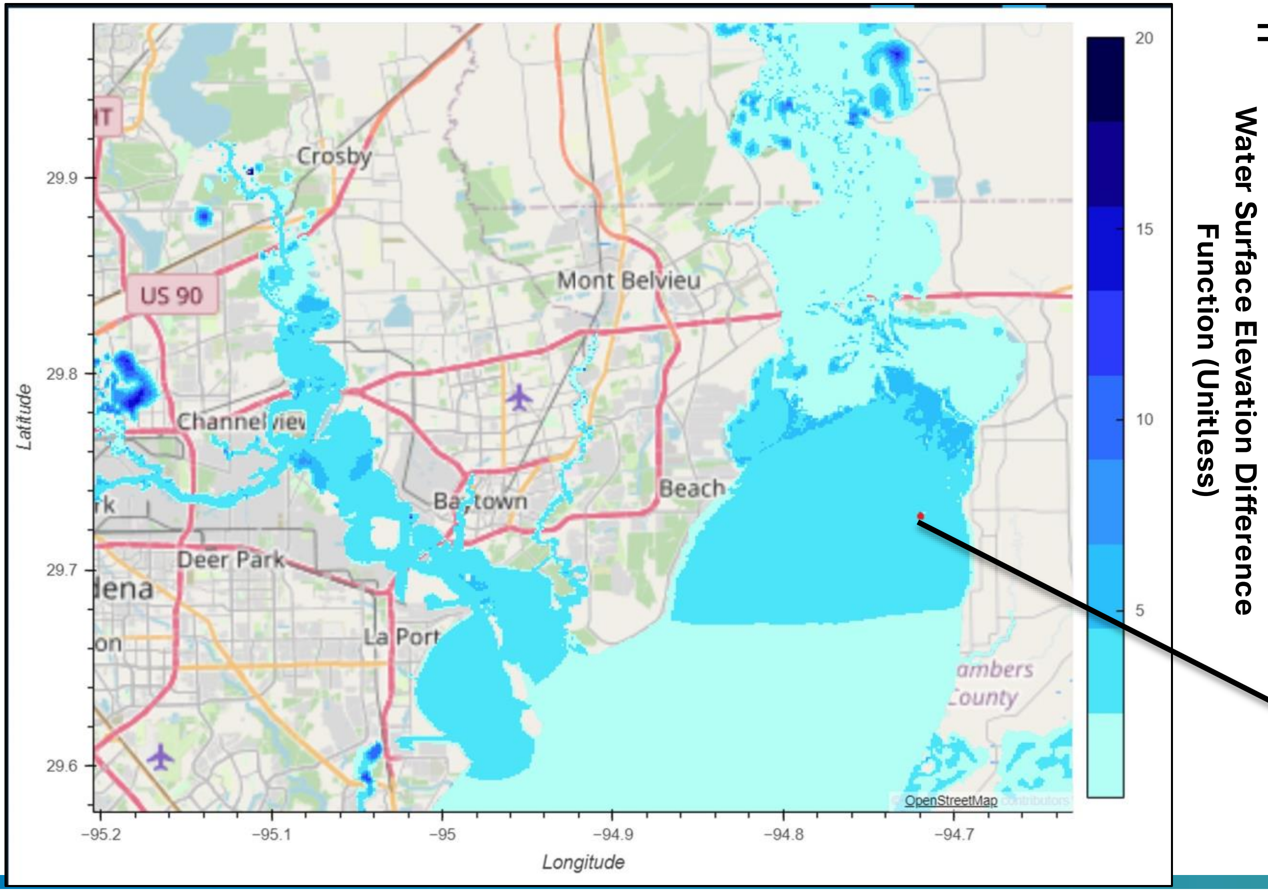


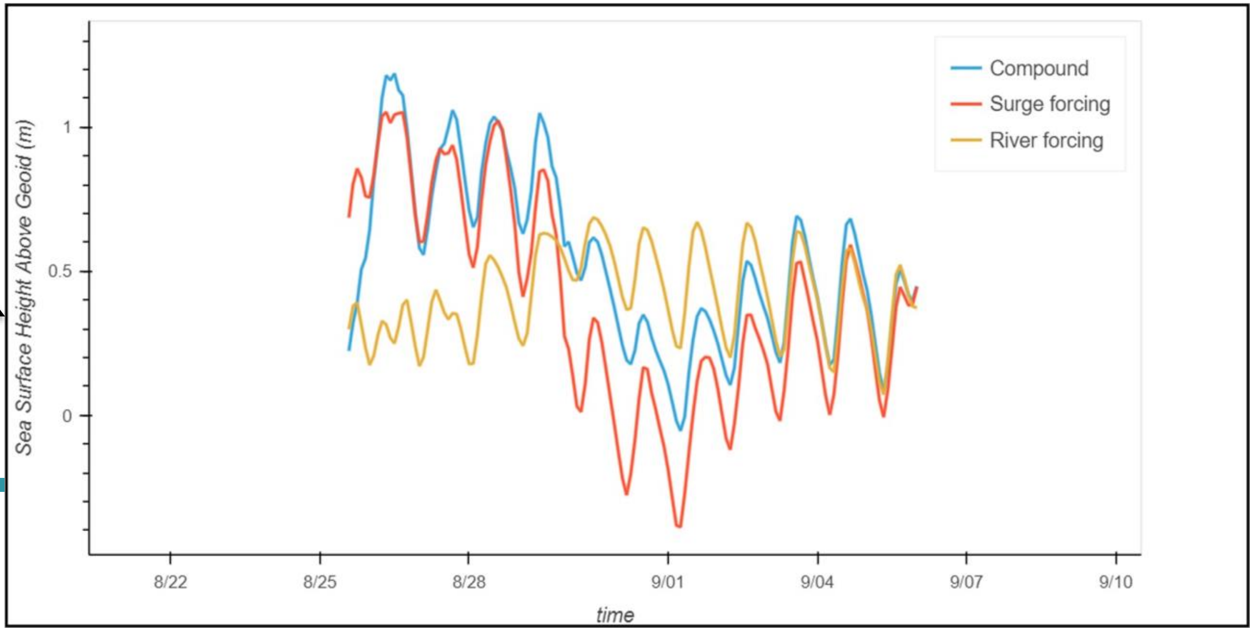


TEXAS WATER DEVELOPMENT BOARD

Transition zones for compound flooding

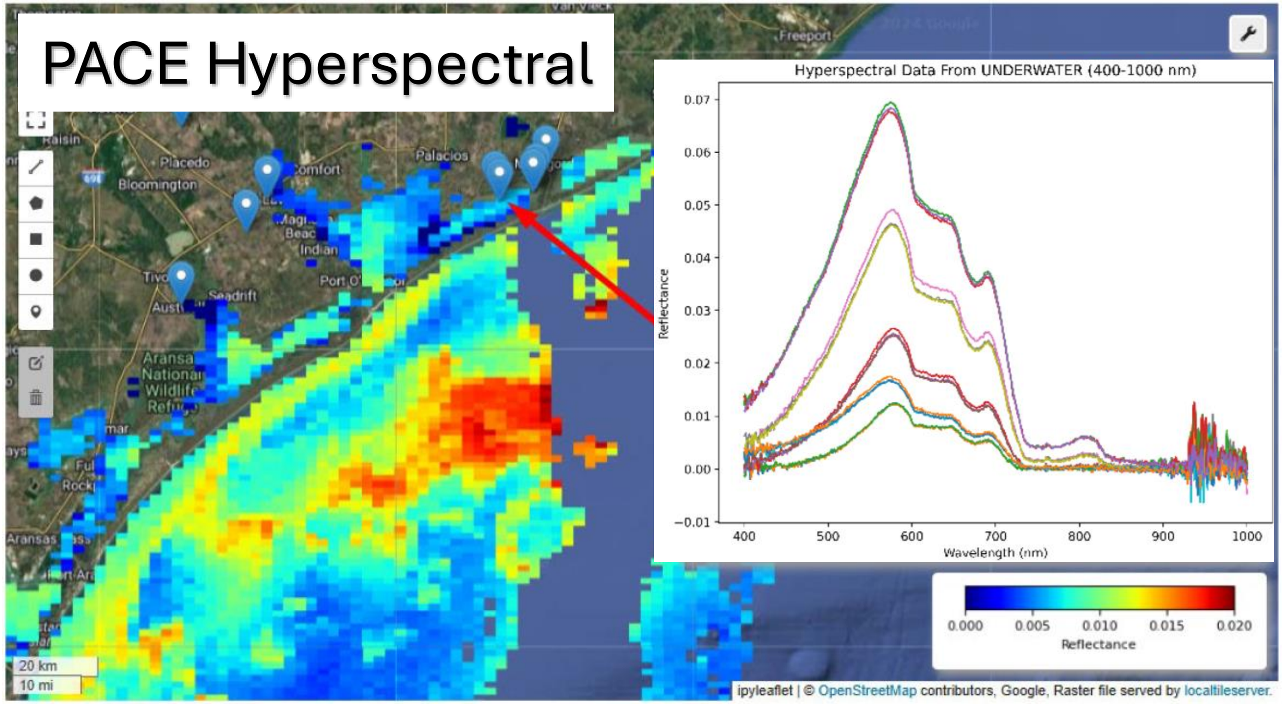
$$compoundness = \min(RMSE(WSE_{rivers+surge}, WSE_{surge}), RMSE(WSE_{rivers+surge}, WSE_{rivers}))$$





Characterizing sedimentation patterns with hyperspectral remote sensing

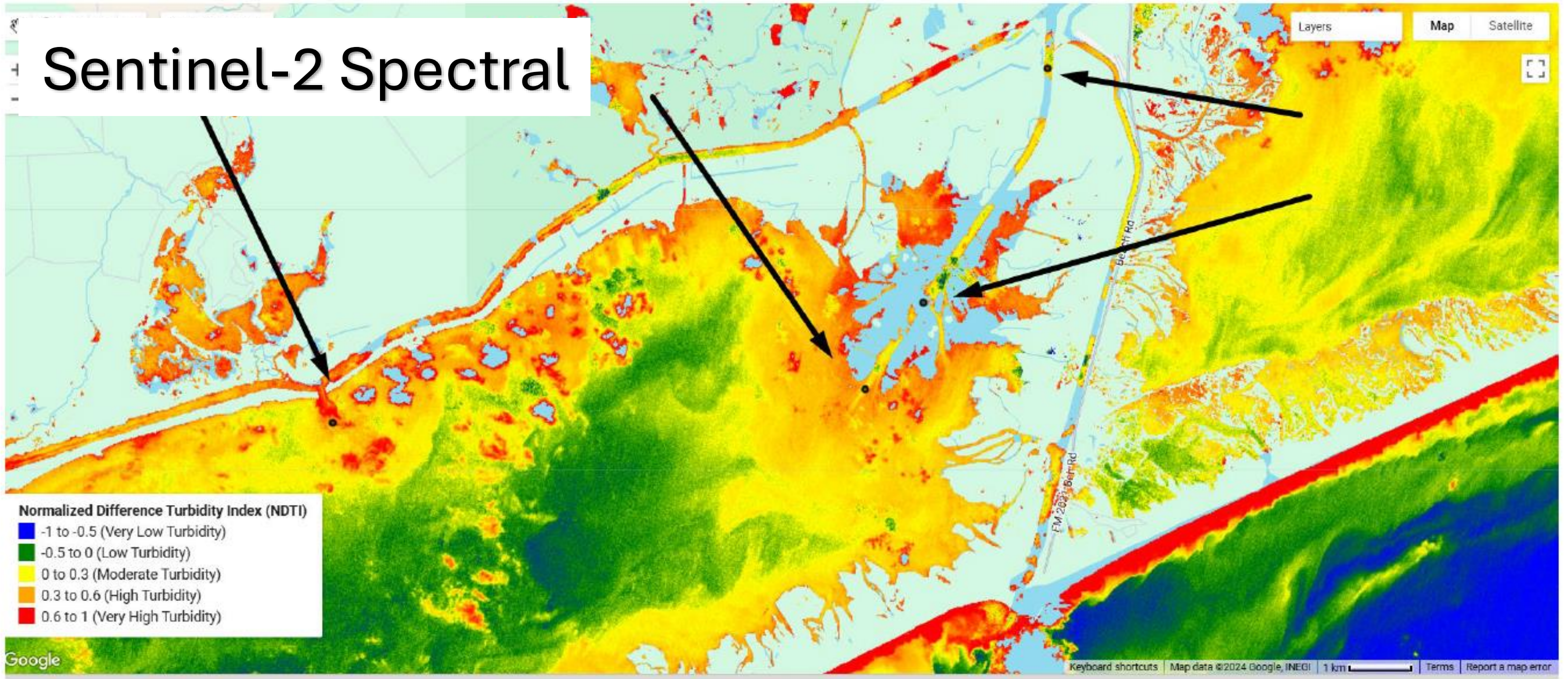
Contract with UH for two years of sediment monitoring through field samples, satellite hyperspectral data, and drone-based optical data surveys.



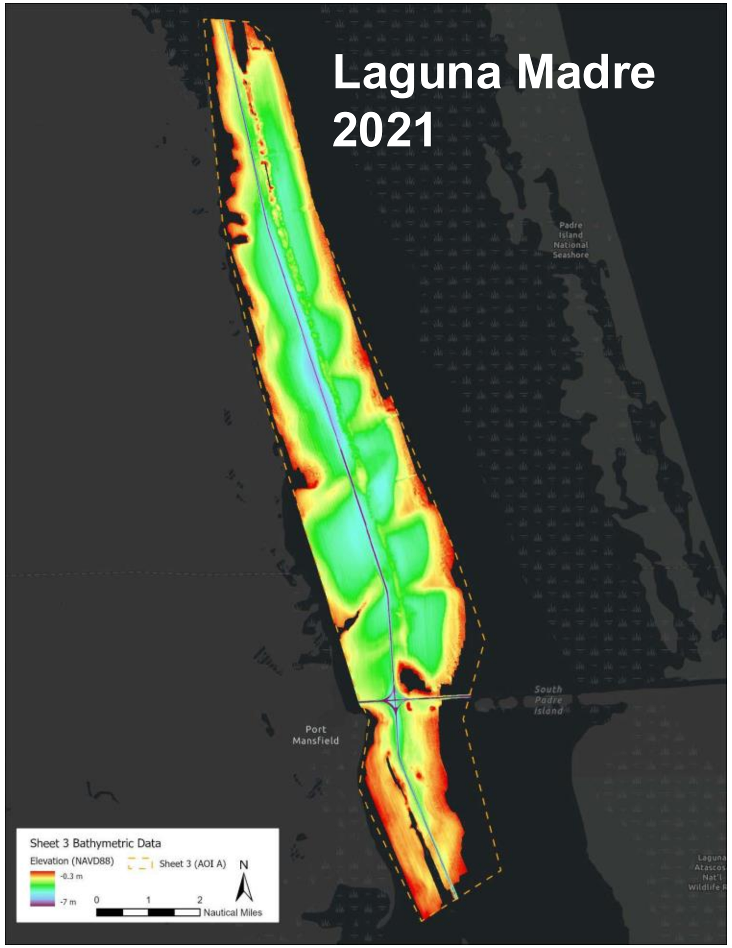
Evaluate changes to TSS and flocculation in Trinity and Matagorda bays.

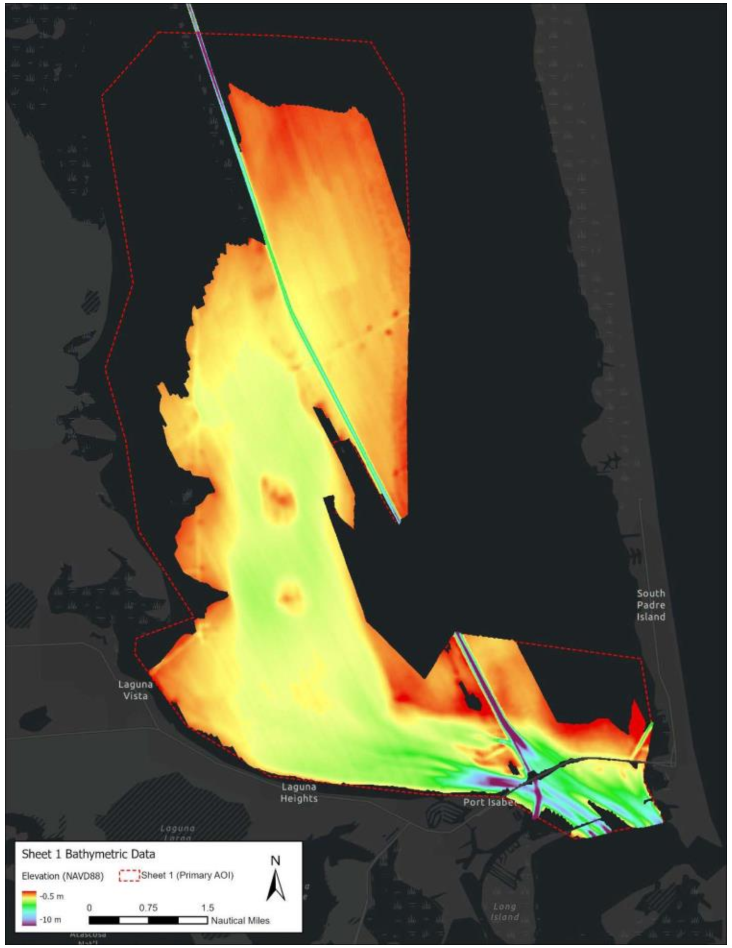
Determine optimal algorithm for inverting TSS concentration in Texas coastal waters.

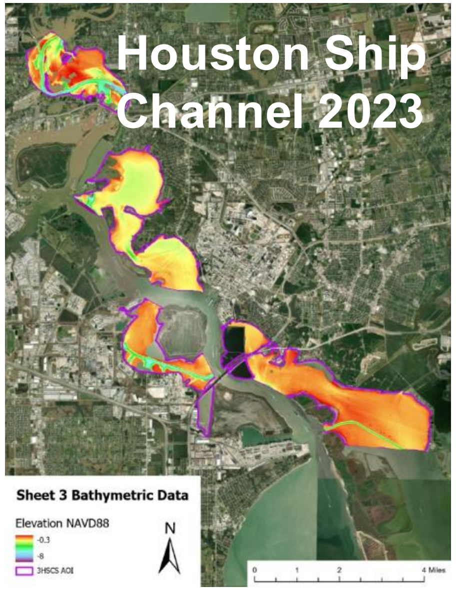
Infer deposition from changes to concentration along streaklines.

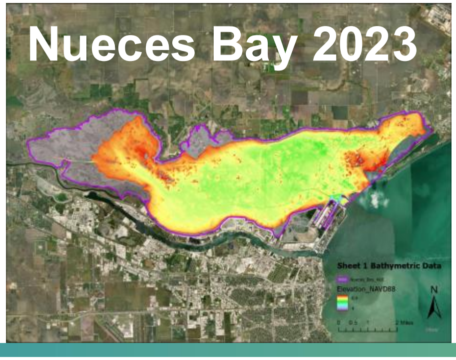


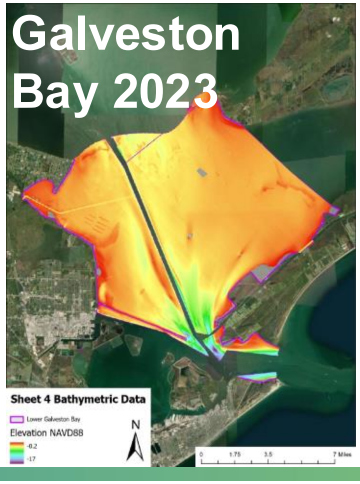
TWDB and TxGIO filled critical bathymetry data gaps based on recommendations for priority areas











TEXAS WATER DEVELOPMENT BOARD

TxGIO

Texas Integrated Flooding Framework

Funding Partner

Texas General Land Office

Implementation Team

Texas Water Development Board

U.S. Army Corps of Engineers - Galveston District

U.S. Geological Survey - Oklahoma-Texas Water Science Center

Facilitation Team

The Meadows Center for Water and the Environment at Texas State University

Texas Integrated Flooding Framework

DATA COLLECTION | VISUALIZATION | MODELING | PLANNING

A collaboration between the Texas Water Development Board, the U.S. Geological Survey, the Army Corps of Engineers, and the Texas General Land Office.

Texas Water Development Board | USGS science for a changing world | US Army Corps of Engineers

WILL…	WILL NOT…
• create a set of recommendations, guidelines, and frameworks to improve the modeling, data collection, data management, visualization, planning, and outreach efforts in the future. • continue to look for opportunities to further flood science and coordination.	• produce individual products (i.e., models or datasets). • change the scope of any other project/effort funded by the TWDB, GLO, or others.

The TIFF execution plan for working with stakeholders and obtaining information for useful and trusted recommendations

MISSION:

Texas Integrated Flooding Framework leverages expertise and resources to bring about the best information to enhance coastal flood risk planning and mitigation.

VISION:

Texas Integrated Flooding Framework empowers Texans with reliable information to increase flood resiliency.

The 4 TIFF Components

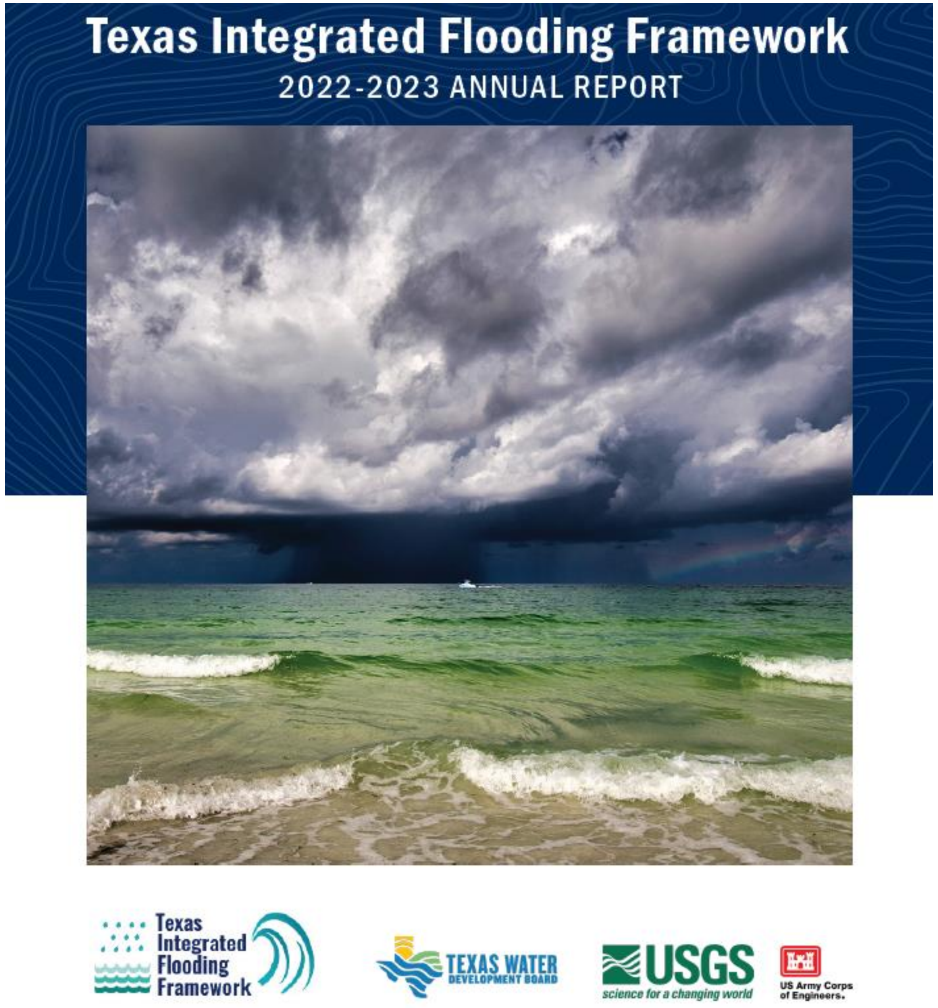
Data & Monitoring Gap Analysis	Data Management & Visualization	Integrated Flood Modeling Framework	Planning & Outreach
Establish a plan for obtaining continuous and up-to-date data critical for compound flood monitoring and modeling across inland, coastal, and ocean systems.	Ensure that any coastal flood-related data and model outcomes can be properly visualized for both technical and non-technical end-users.	Develop conceptual model-coupling workflows for assessment of flooding hazard in the Coastal Texas Region.	Ensure flood planning and mitigation needs for various end users are incorporated into the data and modeling frameworks.

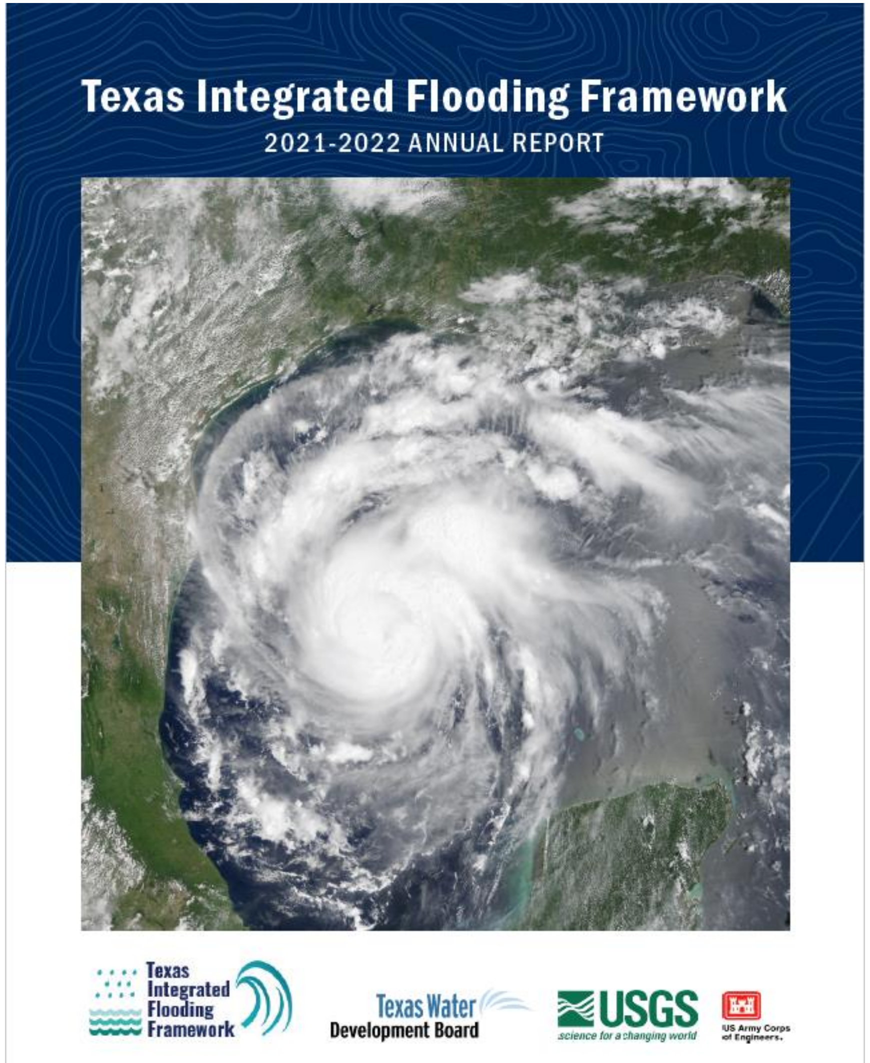
TIFF Technical Advisory Teams (TATs)

Groups of technical experts from academia, local, state, federal agencies and other organization serve as the source of expertise guiding the TIFF project from vision to execution.

- Adaptation International
- AQUAVEO LLC
- Center for Space Research - UT Austin
- Coastal Bend Bays & Estuaries Program
- Coastal Emergency Risks Assessment - Louisiana State University
- DSI LLC
- Federal Emergency Management Agency
- Harris Country Flood Control District
- Harte Research Institute
- Institute for a Disaster Resilient Texas, Texas A&M University-Galveston
- Iowa Flood Center
- January Advisors
- National Oceanic and Atmospheric Administration
- National Weather Service
- National Weather Service - West Gulf River Forecast Center
- NOAA/National Ocean Service, Center for Operational Oceanographic Products and Services
- Princeton University
- Region 5 Flood Planning Group (Neches River), Lamar University
- Seahorse Coastal Consulting
- Southwestern Division Office
- Texas A&M - Institute for a Disaster Resilient Texas
- Texas A&M AgriLife/Community Health and Resource Management (CHARM)
- Texas A&M- College Station
- Texas A&M- Corpus Christi
- Texas A&M University- Kingsville
- Texas Advanced Computing Center
- Texas Commission on Environmental Quality
- Texas Department of Transportation
- Texas Disaster Information System
- Texas Division of Emergency Management
- Texas Floodplain Management Association
- Texas General Land Office
- Texas Natural Resources Information System
- Texas Spatial Reference Center, TAMU Corpus
- Texas Water Development Board
- The University of Iowa
- The University of Texas at Austin
- The University of Texas Rio Grande Valley
- The Water Institute of the Gulf
- United States Geological Survey
- United States Naval Academy
- University of Central Florida
- University of Georgia
- University of Houston
- University of North Carolina at Chapel Hill
- University of North Florida
- University of Notre Dame
- University of Texas - Arlington
- University of Texas at Austin
- University of Texas Rio Grande Valley
- US Army Corps of Engineers - Engineer Research and Development Center
- US Army Corps of Engineers - Fort Worth District
- US Army Corps of Engineers – Galveston District
- US Army Corps of Engineers - Hydrologic Engineering Center
- US Geological Survey
- Utah Water Research Laboratory - Utah State University
- Virginia Institute of Marine Science
- Virginia Tech
- West Consultants

TIFF Website and Annual Reports

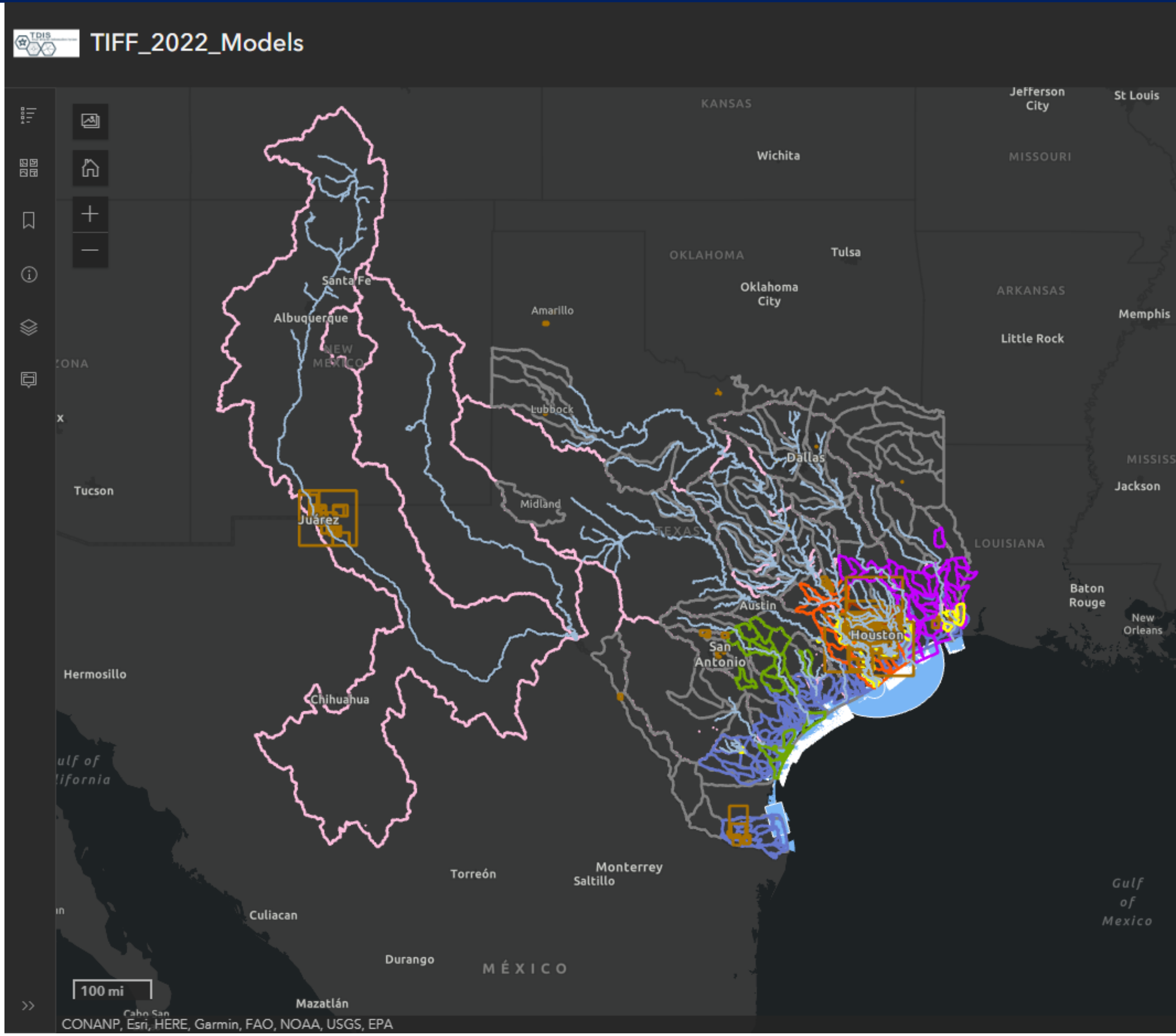




Model Inventory Development

Model Metadata Template

- ✓ Study Title
- ✓ Study Objective
- ✓ Model software name
- ✓ Model software version
- ✓ Model Type
- ✓ Model Dimension
- ✓ Model Coverage
- ✓ Model Calibration event/time period
- ✓ Model Validation event/time period
- ✓ Model Update History
- ✓ Model Developer POC
- ✓ Additional Comments



COMPREHENSIVE LITERATURE REVIEW

- Wave Action
- Meteorological Modeling
- Techniques for probabilistic compound flood hazard modeling and analysis specific to the coastal Texas region
- Compound Flooding Processes (and models related to coastal, inland, and riverine flooding)
- summary of grey literature, particularly focusing on relevant flood modeling and probabilistic hazard analysis pertinent to the USACE Texas studies
- Hydrological and Hydraulic Modeling
- Estuarine and Large-Scale Coastal Surge Modeling

http://higssoftware.com/research-paper-with-literature-review.php

HYDROLOGIC/HYDRAULIC

Description of the hydraulic processes represented by the 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.	The 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)	modelling of culverts, weirs, bridges, pumps, gates, direct discharges, dambreak, energy losses, tabulated structures. Reservoir operations modeling: MIKE HYDRO Basin module
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) Sediment transport simulations (MIKE 21C module)

HYDROLOGIC/HYDRAULIC

Description of the hydrological processes represented by the models.

Colors indicate different degrees of complexity of the different processes (green = high complexity, orange = medium, red = low, 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	Top model
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 e	Muskingum	None	Muskingum	Muskingum	None	Kinematic	Diffusive	Dynamic
Sewers	None	None	None	None	None	None	Yes	Yes	Yes

HYDROLOGIC/HYDRAULIC

Comparison of the process complexity represented in the considered hydrological models

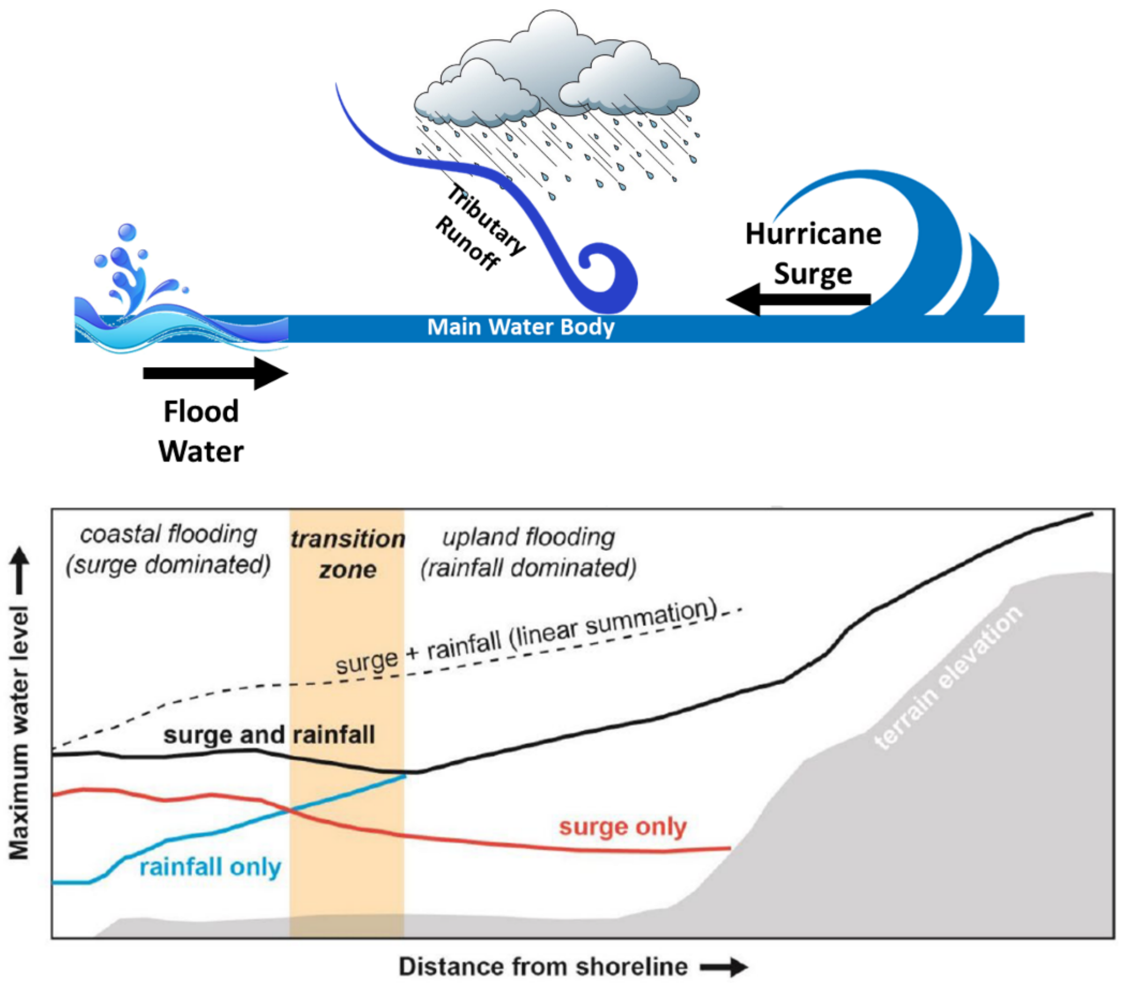
Model	Complexity	Scale range	Hydraulics	Urban	Structures	Use	Ease of use	Support	Active	Wide applicability
HEC-HMS	Moderate	Small to Large	No	Good	Good	Planning	High	High	Yes	Yes, suitable for a variety of hydrologic problems, such as flood forecasting, reservoir operations, water quality, and climate 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.

ESTUARINE AND LARGE-SCALE COASTAL SURGE MODELING

SWOT (Strengths, Weaknesses, Opportunities, and Threats) Analysis for storm surge models

Model	Strengths	Weaknesses	Opportunities	Threats
ADCIRC	Validated for TX storms. Large and diverse user base Parallelized for HPC Tightly coupled with SWAN Inputs from many wind products Open source Runs in forecast mode	Mostly 2D; 3D not well-developed No stabilization for advection Mass balance issues	Growing user base New global model Widely adopted by NOAA and USACE and internationally	Software outdated. Meshing is difficult. Sustainability not certain
SCHISM	Validated for recent storms. Open source Tightly coupled with wave model Validated in 2D and 3D modes	High fidelity model for entire Texas coast yet to be implemented. No storm surge results for Texas. No published validation for Texas	Ongoing active development Adopted by NOAA and international community. User group is growing.	Development largely by one group Code has been around for a short time. Experience is limited. Parallel performance unknown
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	No high-fidelity model for the Texas coast Did not show good parallel performance compared to ADCIRC in intercomparison tests	Can be employed to study storm surge, internal waveswaves, and biogeochemical processes Can include nested spatial domains	Mostly employed for the US East Coast. Has not been used for Texas except in intermodal comparison project
DELFT3D/ DFLOW-FM	Very large user base Very flexible code with many modeling options Development supported by a large organization Capable of 2D and 3D modes	Performance for Texas coast questionable Would need further development	Sustainable over the long haul Possibility to do beach erosion and 3D	Code development is outside the U.S. Training is expensive Needs more validation
ADH	Validated for storms across US Capable of Multiphysics simulations. Advanced numerical scheme, robust to advective problems Includes groundwater transport	Not fully open source. Requires sophisticated linear and nonlinear solvers	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 numeric Open source 2D and 3D	No TX model 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	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

COMPOUND FLOOD MODELING



The figure is an adapted version of figures from Kiaghadi (2018) and Bilskie et al. (2018)

Examples of Compound Flood Models

Process-based Modeling Systems

Should include all components: hydrology, hydraulics, ocean circulation, and waves.

1-way coupled modeling systems
1) ADCIRC + HEC-RAS + HEC-HMS
2) SCHISM + HEC-HMS, SCHISM+NWM

Loose 2-way coupled model systems
ADCIRC + WASH123D (missing waves?)

Tight 2-way coupled model systems
1) FVCOM + SWMM + Flood Potential Model
2) CSTORM + ADCIRC + AdH + STWAVE

Integrated Model
None with all components

Reduced Physics Models

May be missing some components

Static Flood Model
1) HAND
2) Pin2Flood

Simplified Momentum Model
1) SFINCS
2) LISFLOOD-FP

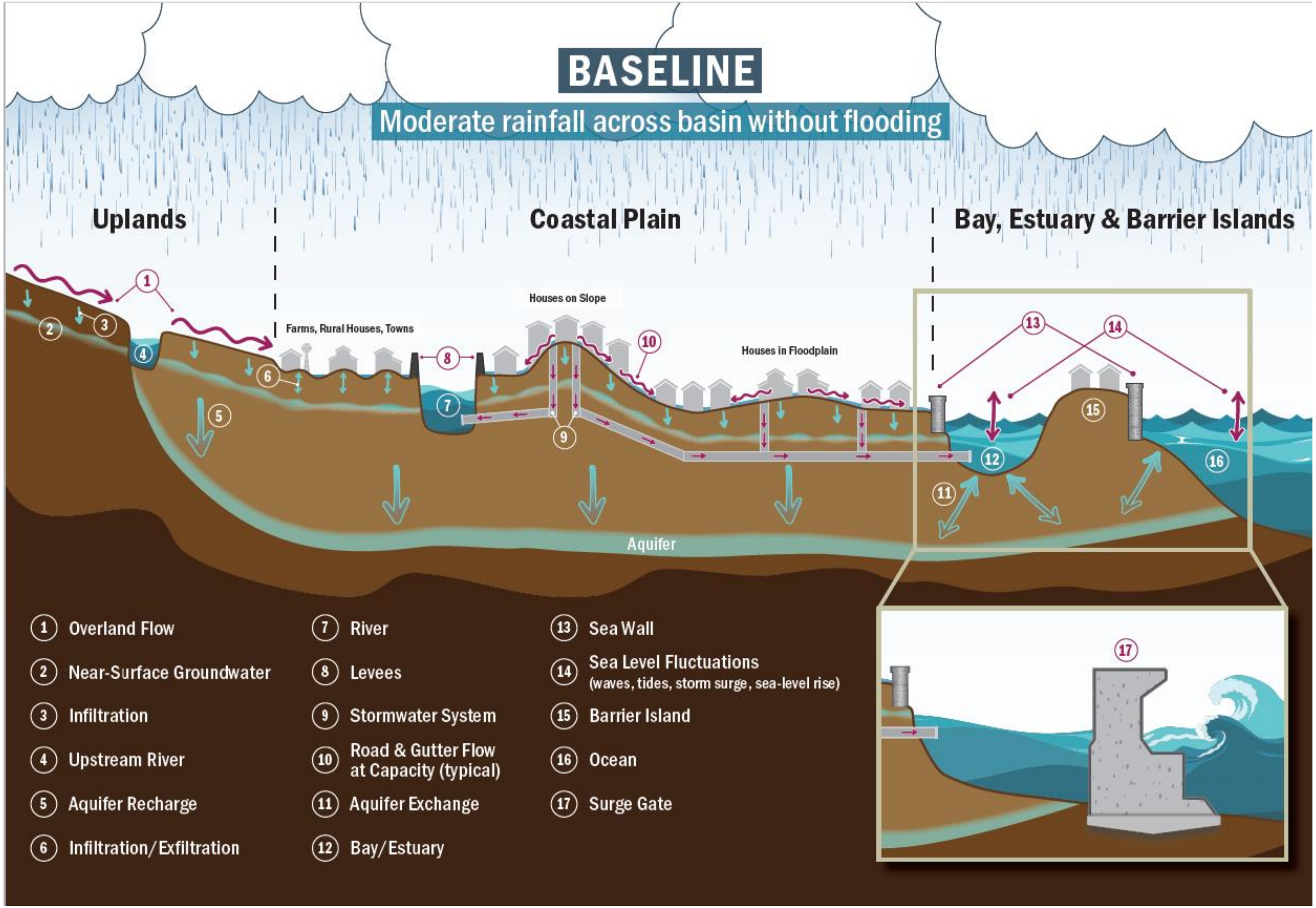
Data-driven Models

Joint Distribution Function
1) Copula Function
2) Logistic Model

Dependence Analysis
1) Correlation Coefficient
   1. Kendall's Rank
   2. Upper tail dependence
2) Distribution Function
   1. Threshold Excess Method
   2. Point Process Method

AI/ML
1) Fast Surrogate
   1. ANN
   2. SVM
   3. LSTM
   4. Kriging
2) Flood Risk Prediction
   1. CNN
   2. SVR
   3. ELM
   4. k-neighbor
1) Flood Visualization
   1. GAN

Key Compound Flood Analysis Considerations



- ❖ Flood Inundation Modeling
- ❖ Flood Hazard Analysis

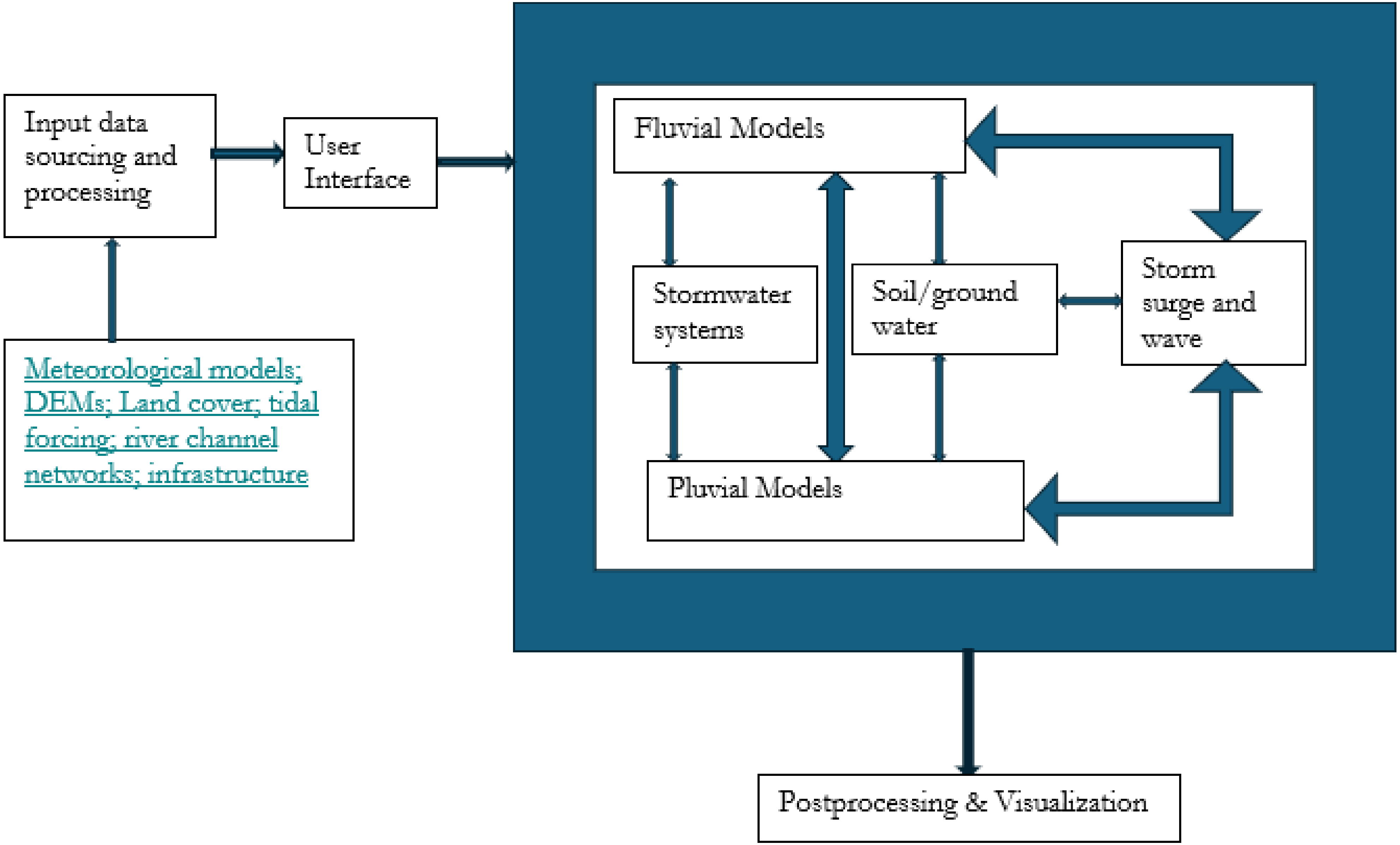
Types of compound flood inundation modeling systems

Type of Model	Characteristics	Purposes	Computing Requirements
Flood Inundation model I (FI-I)	Full physics equations in a single code base.	Validation of water elevations Engineering design Sensitivity studies	High.
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 FI-I	Medium to high
Flood Inundation model III (FI-III)	Full physics and/or reduced physics in a software frameworks for coupling codes	Same as FI-I	High
Flood Inundation model IV (FI-IV)	Reduced physics and/or low resolution in a single code base	Real-time forecasting Sensitivity studies	Low.
Flood Inundation Hybrid models (PB-H)	Combination of physics-based components, surrogate models and/or AI/ML components	Real-time forecasting Sensitivity studies Uncertainty quantification	Variable
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

Compound Flood Hazard Analysis levels

Hazard Analysis Level	Characteristics	Purposes	Computing Requirements; Uncertainty
Hazards Level 0 (HL-0): Independent Scenarios Screening Level	Data-driven 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
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
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
Hazards Level 3 (HL-3): Extended JPM	Coastal model and inland 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, however, may have increase in uncertainty due to additional parameters and models.

Conceptual Texas Coastal Flood Framework



Key Considerations for Texas Coastal Flood Framework Development (TxCFF)

https://www.dreamstime.com/considerations-human-mind-pictured-as-word-inside-head-to-symbolize-relation-psyche-d-illustration-image172337119

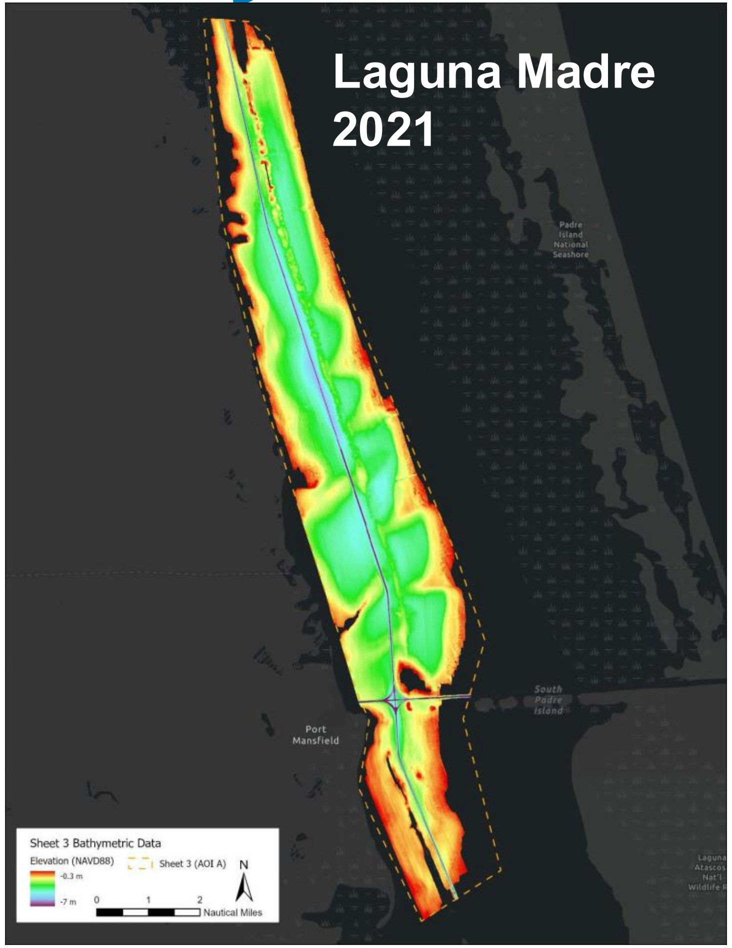
- **Component models should be**
  - validated for Texas
  - computationally efficient
  - have the support of a development team and an active user community
- **The software framework structure should be**
  - portable
  - extensible
  - capable of plug-and-play application programming interfaces
  - flexible enough so that individual components can be turned off
- **The framework should**
  - facilitate inter-model comparisons
  - enable users to evaluate which models are most useful in different situations
  - provide the capabilities to build and test methods for uncertainty quantification, sensitivity analysis, hazard analysis, and parameter estimation
- **In building the framework projects should assess available tools and software and develop new ones**
  - for pre-processing, especially mesh generation
  - for post-processing of results, visualization, interactive graphs, and communication of results to stakeholders

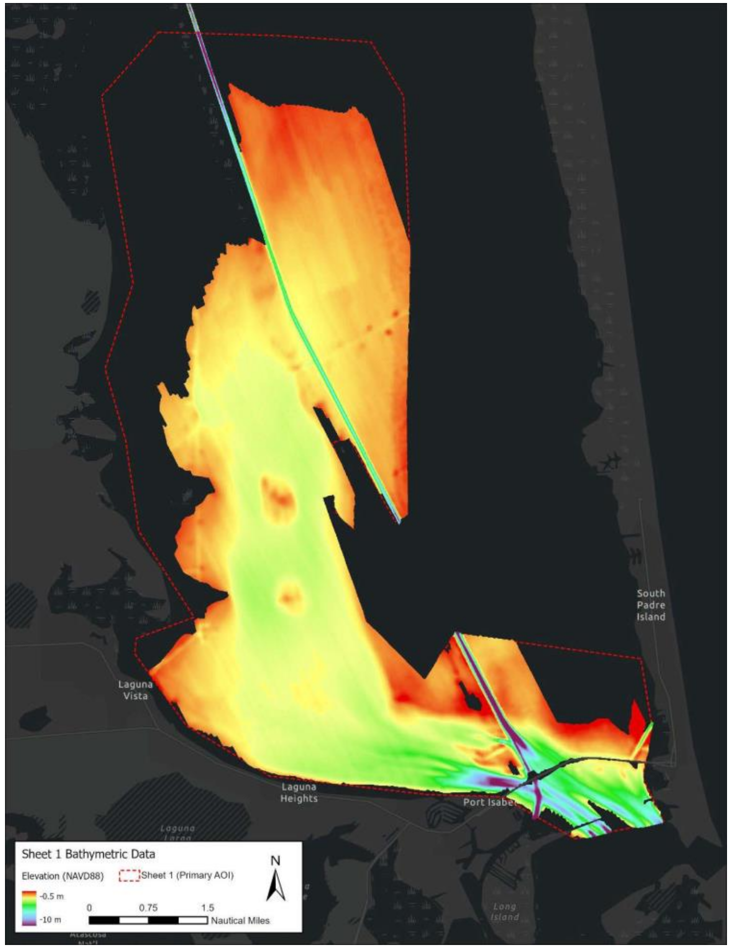
STEPS TO BUILD Texas Coastal Flood Framework (TxCFF)

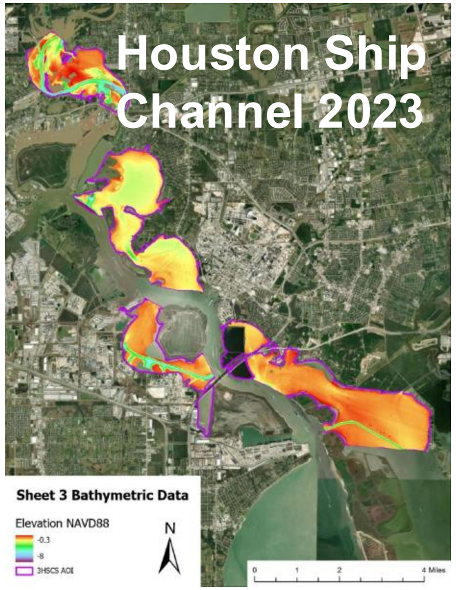
- *Grid generation of coupled model system*
- *Development of Coupled Model Inputs/Outputs*
- *Automated calibration, validation, and comparison with observations*
- *Development of Training Courses for CFMF Users.*
- *Integration of Inundation Flood modeling with Flood Hazard Analysis*

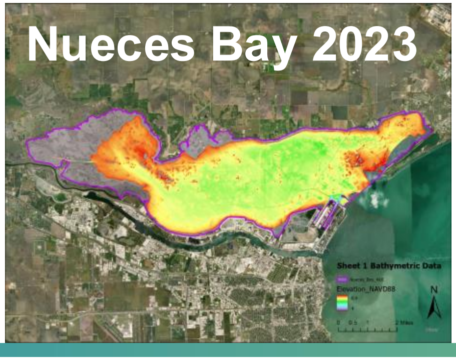
- *Identify Testbed Locations and Prioritize Implementation*
- *Test Candidate Models*
- *Evaluate the Needed Software Framework Fundamentals*
- *Develop Coastal Compound Flood Modeling Framework (CFMF) best practices*
- *Evaluate Coupling Methods for Candidate Models*
- *Develop & Evaluate approach for Boundary Placement Between Models*

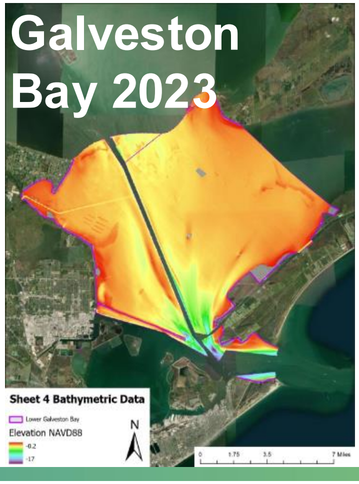
TIFF in Action: TWDB and TxGIO filled critical bathymetry data gaps based on recommendations for priority areas









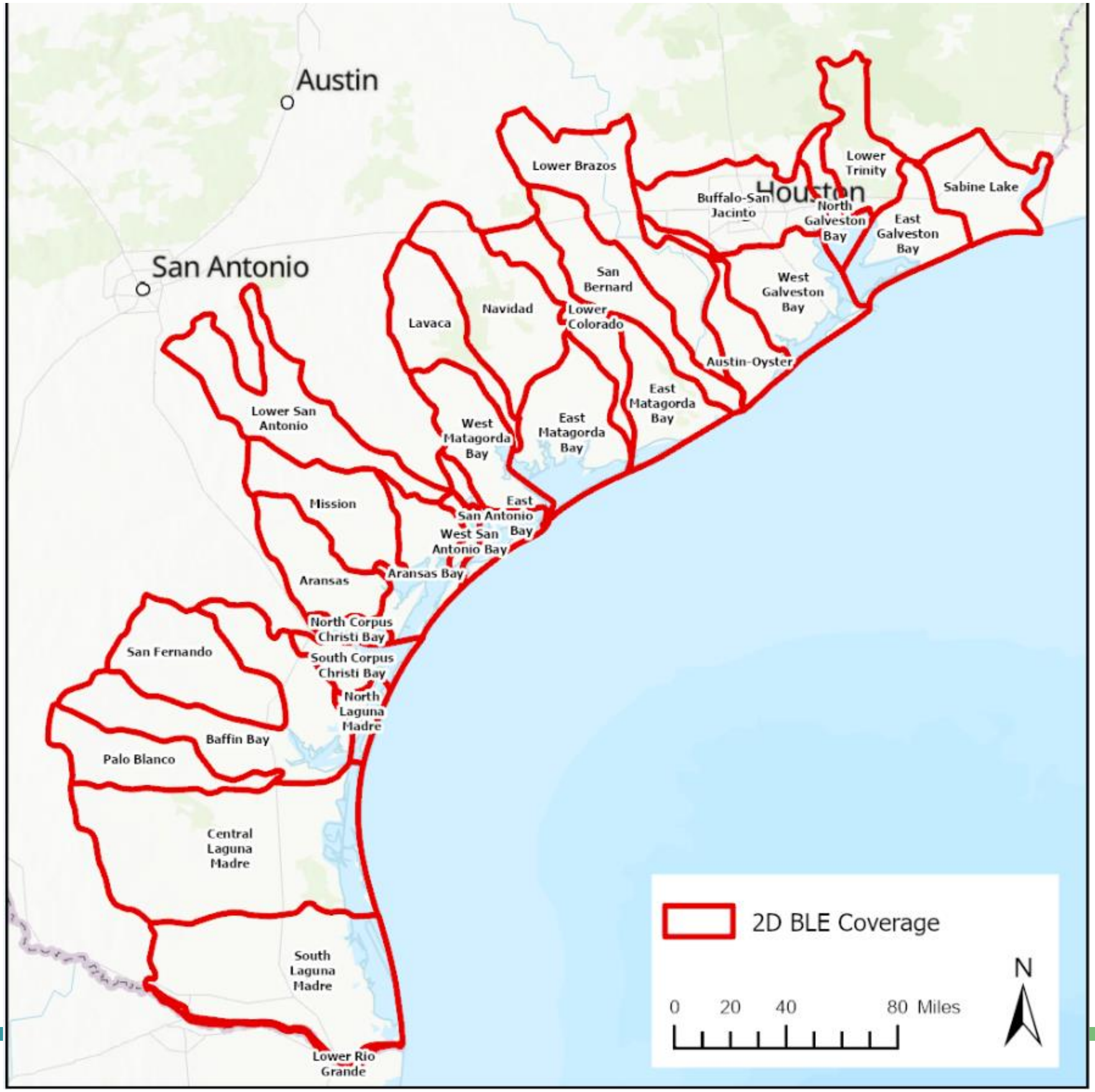


TIFF IN ACTION: HEC-RAS DISTRIBUTED-MEMORY PARALLELIZATION

Project Duration: 2 years
Estimated Budget: $1.4M
Implementation Agencies: *USACE (SWG, MMC, HEC), TWDB& UT-Austin*

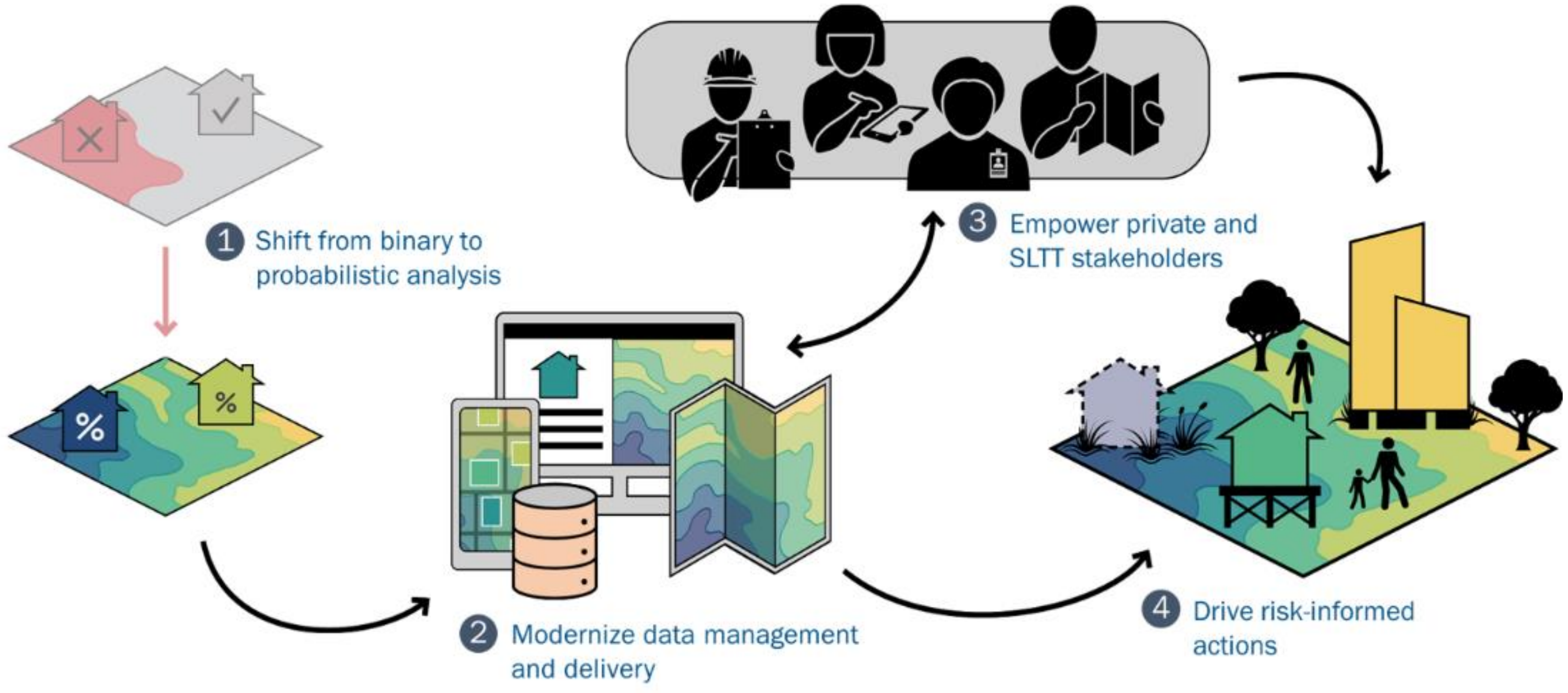
Project Benefits

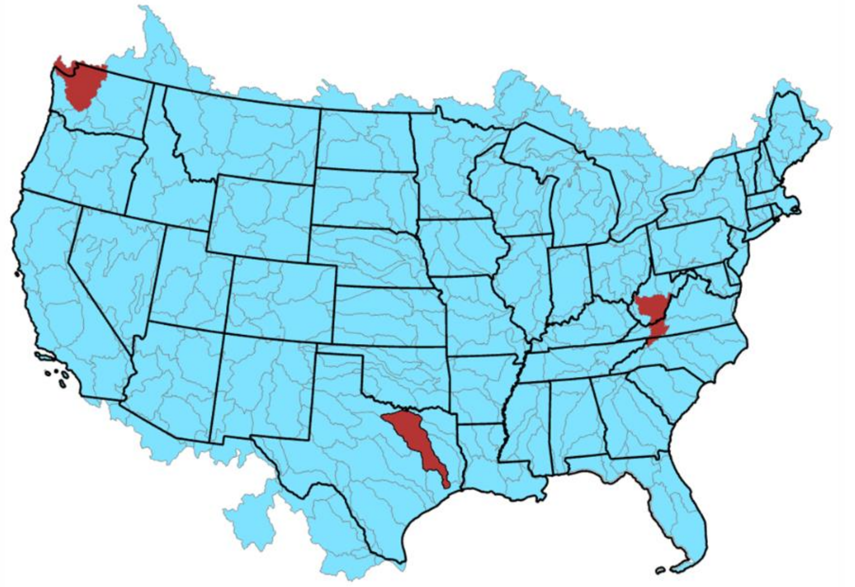
- **Reduce Computational Time**
  - Large-scale HEC-RAS model simulations from days to just tens of minutes.
- **Enhance Model Scalability**
- **Facilitate Large-Scale Project Implementation**
- **Inter-Basin Flow Simulation**
- **Future Coupling with Coastal Models**
- **Real-time Emergency Flood Response**



TEXAS WATER DEVELOPMENT BOARD

FEMA's Future of Flood Risk (FFRD) Data Initiative





HEC-RAS Parallelization will be game changer

Questions/Discussion

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