Improving 3D modeling with judicious semi-automatic meshing

Joseph Zhang & Fei Ye (VIMS)

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July 2025

Debunking the myths in coastal circulation modeling

Joseph Zhang et al., Ocean Modelling, Special Issue on “In silico oceanography via seamless cross-scale modeling: Are we there yet?”

Projects: UFS New York Harbor; Lake Champlain

Special Issue on Ocean Modelling:
In silico oceanography via seamless cross-scale modeling: Are we there yet?

SCHISM related papers

1. Zhang et al. (2024) Debunking the myth of coastal circulation modeling
2. Cui et al. (2024)Total water prediction at continental scale: coastal oceans
3. Zhang et al. (2025) Cross-scale prediction for the Laurentian Great Lakes
4. Yu et al. (2025) Developing a flexible data assimilation capability in a 3D unstructured-grid ocean model under Earth System Modeling Framework.
5. Pein, J., Staneva, J., Biederbick, J., Schrum, C. (2025) Model-based assessment of sustainable adaptation options for an industrialised mesotidal estuary
6. Hosseini, S.T., Pein, J., Staneva, J., Zhang, Y., Stanev, E. (2025) Impact of offshore wind farm monopiles on hydrodynamics interacting with wind-driven waves
7. Coulet, P., Durand, F., Fassoni-Andrade, A., Khan, J.,Testut, L., Toublanc, F., Guedes Santos, L., Medeiros Moreira, D. (2025) Assessment of the hydrodynamical signature of the record-breaking 2021 flood along the Amazon estuary
8.Park et al. (2025) Evaluation of a 3D Unstructured Grid Model under Different Forcing Sources.

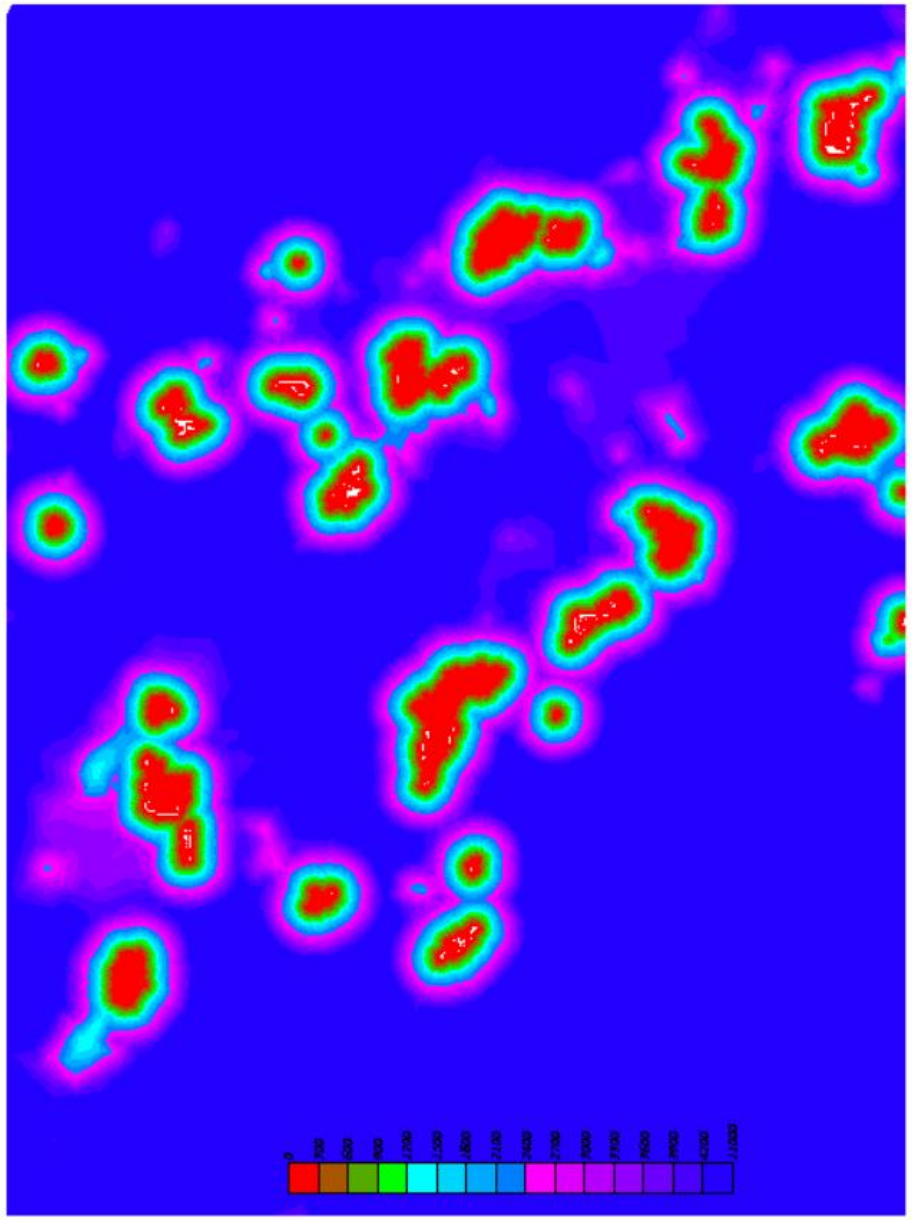
- Deadline for submission: June 20, 2025 (but a sister SI continues until Dec 2025)
- A good place to publish SCHISM related work

- Showcase SCHISM philosophy on mesh generation and defensible/rigorous modeling
  - DEM as the first and foremost factor!

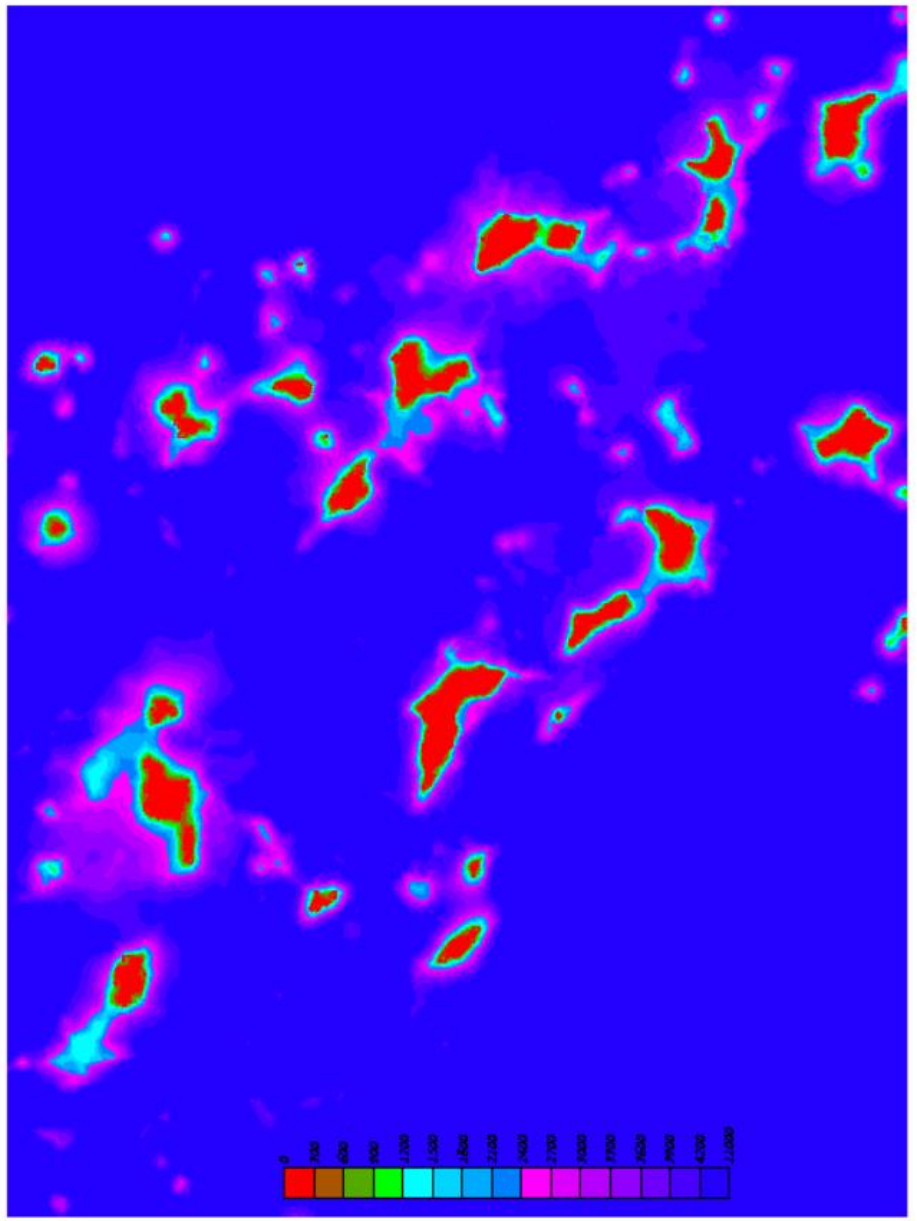
Steep slopes are everywhere!

Pacific islands

A 2D model



Gebco



Steep slopes are important!

Article

Observations of diapycnal upwelling within a sloping submarine canyon

https://doi.org/10.1038/s41586-024-07411-2

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Open access

Check for updates

Bethan L. Wynne-Cattanach[1]✉, Nicole Couto[1], Henri F. Drake[2], Raffaele Ferrari[3], Arnaud Le Boyer[1], Herlé Mercier[4], Marie-José Messias[5], Xiaozhou Ruan[6], Carl P. Spingys[7], Hans van Haren[8], Gunnar Voet[1], Kurt Polzin[9], Alberto C. Naveira Garabato[10] & Matthew H. Alford[1]

Small-scale turbulent mixing drives the upwelling of deep water masses in the abyssal ocean as part of the global overturning circulation[1]. However, the processes leading to mixing and the pathways through which this upwelling occurs remain insufficiently

- New observations were made using a dye released close to the seafloor within a sloping submarine canyon, and they provide direct evidence of strong, bottom-focused diapycnal upwelling in the deep ocean (with upwelling velocity of 100m/day, which is 10000 x stronger than global average!)
- This supports previous suggestions that mixing at topographic features, such as canyons, leads to globally significant upwelling
- The upwelling is essential for maintaining global temperature & salinity budget
- The budget would be severely distorted with bathymetry smoothing

Myths in coastal modeling

- Tremendous progress has been made in algorithm development, computational efficiency and transition into operations over the past two decades

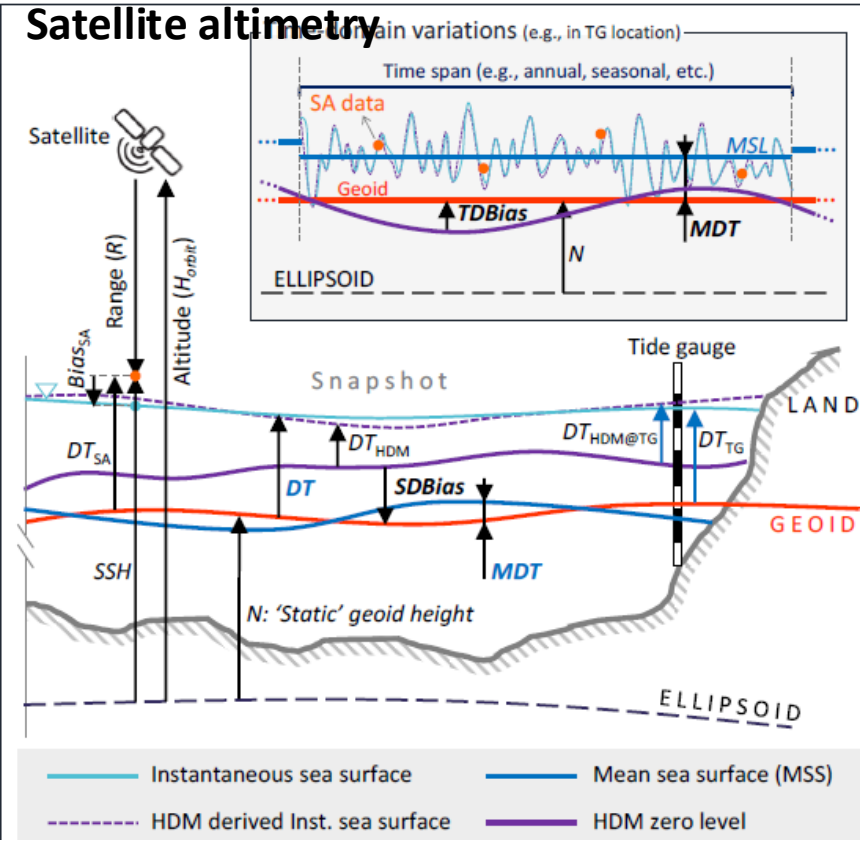
- Coastal modeling still has many 'gray' areas related to various modeling choices made by modelers
  - Equally plaguing unstructured-grid (UG) and structured-grid models
  - For UG models, mesh generation is considered an 'art': we want to democratize this via reproducible meshing tools
  - Compounded by uncertainties in observation, particularly DEM
  - Error compensation is a much more serious problem than many researchers realize
  - This is an urgent issue facing the entire community especially in light of the rapid advancement of precision in coastal observation (new ~1 cm for nearshore)
  - Coastal models need to catch up with observation!
  - It's time to re-evaluate all models

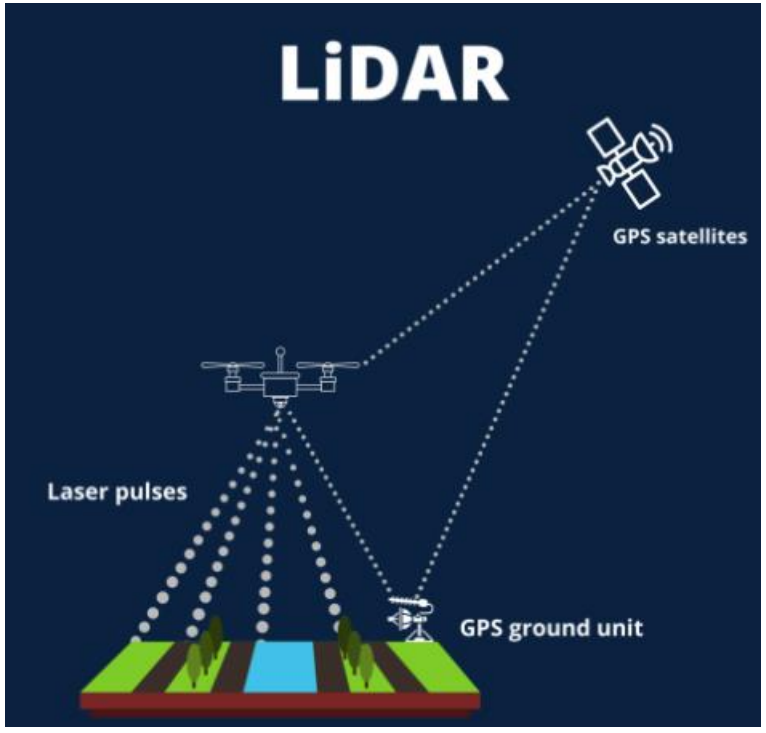
Zhang et al. (2024)

Advancement in observation

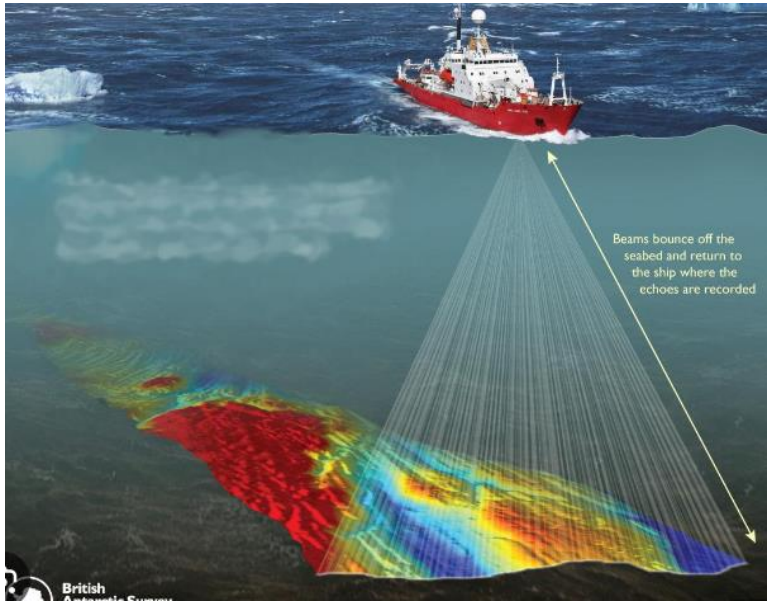
- With the advancements in sensor technology and geodetic control, it is now possible to accurately evaluate the uncertainty from all components used in data collection
- Vertical component of the TPU (2 sigma) for bathymetry DEMs using ocean mapping technologies can range between 1 cm (in situ) to 1 m (satellite), depending on the technology and water depth (Pe'eri et al., 2014)
- Modelers are running out of excuses!
  - Coastal models need to catch up!

Satellite altimetry





Single beam survey



Three guiding principles for ocean modelling

1. **Bathymetry is a first order forcing in coastal domains**
    - Observation-derived DEM data should not be smoothed or otherwise manipulated beyond the resolution of the numerical grid

2. **Oceanographic processes are driven across multiple scales**
    - Grids must be as high resolution and extend over as large a domain as required by the processes and known forcing (and allowed by computational limits). This includes some ultra localized processes

3. **Assessment should focus on processes**
    - Traditional quantitative error metrics, while useful, are not a substitute for feature-based metrics and should not distract or mislead high-fidelity representation of processes

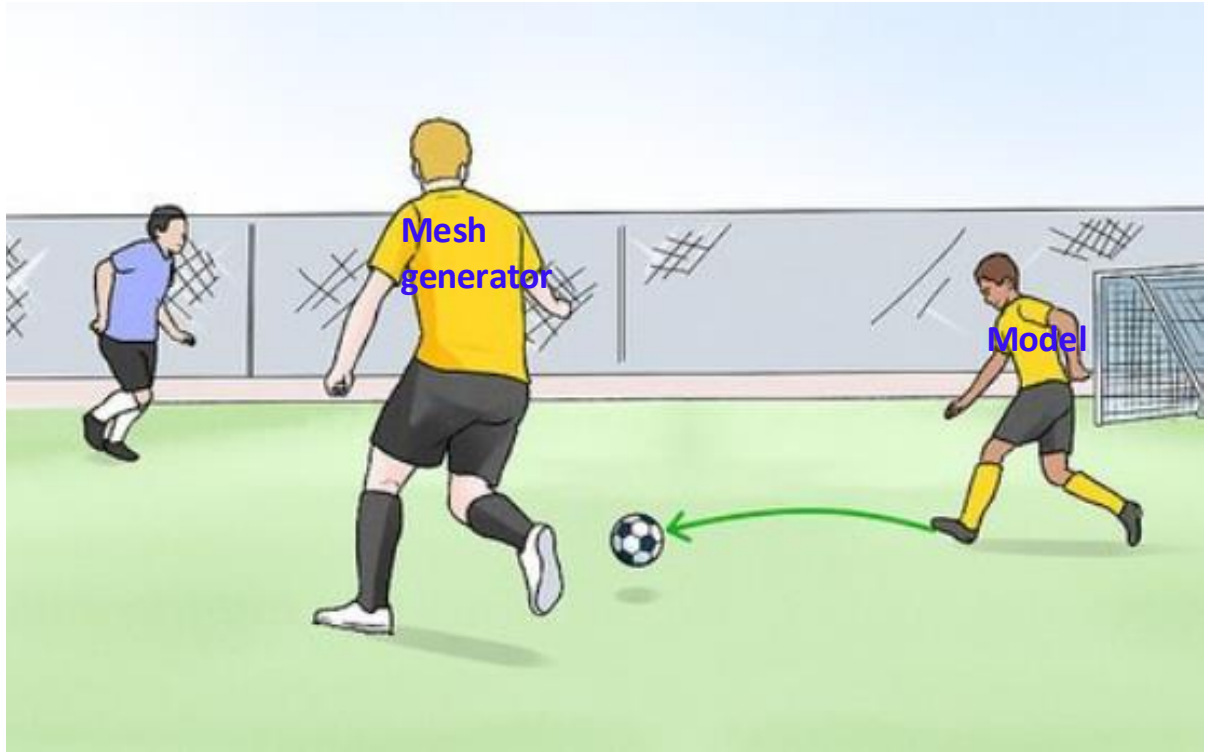
Zhang et al. (2024)

3D modeling….

DEM, DEM, DEM

Mesh generation approaches

Conventional approach (model centric): blame the mesh generator



SCHISM approach (DEM centric)

Mesh generation for SCHISM

- **Any reasonable mesh should pass**
- **Relentless pursuit of realistic representation of DEM …**
- **Mesh revision only in regions of interest**

Mesh generation principle

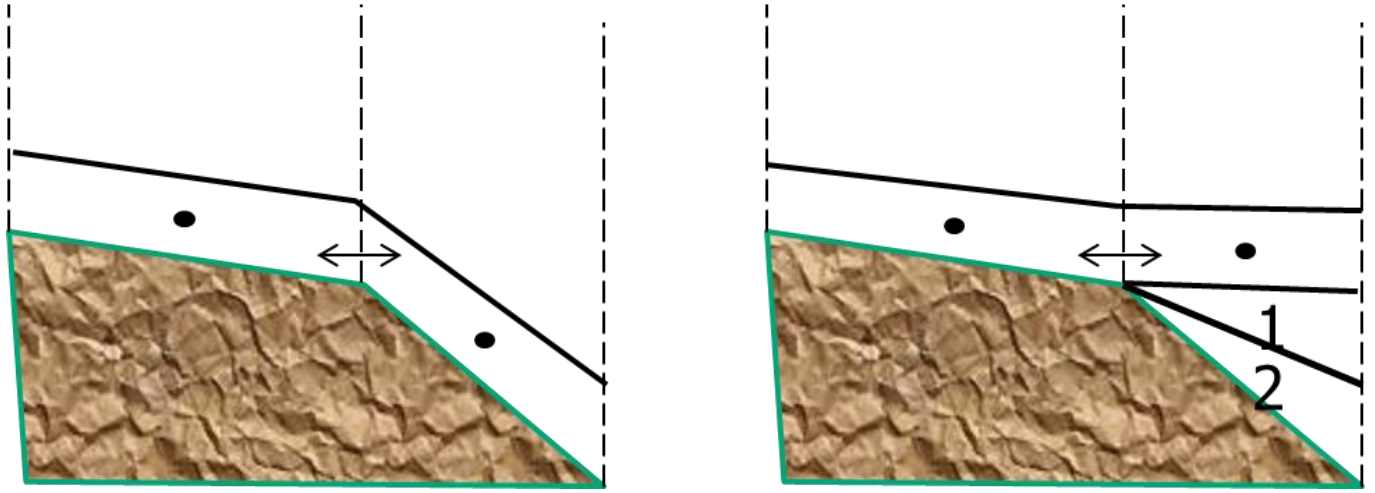
- **Mesh is merely a representation (approximation) of the DEMs**
- **Mesh serves at the pleasure of DEM (not the other way around)**

model centric vs DEM centric

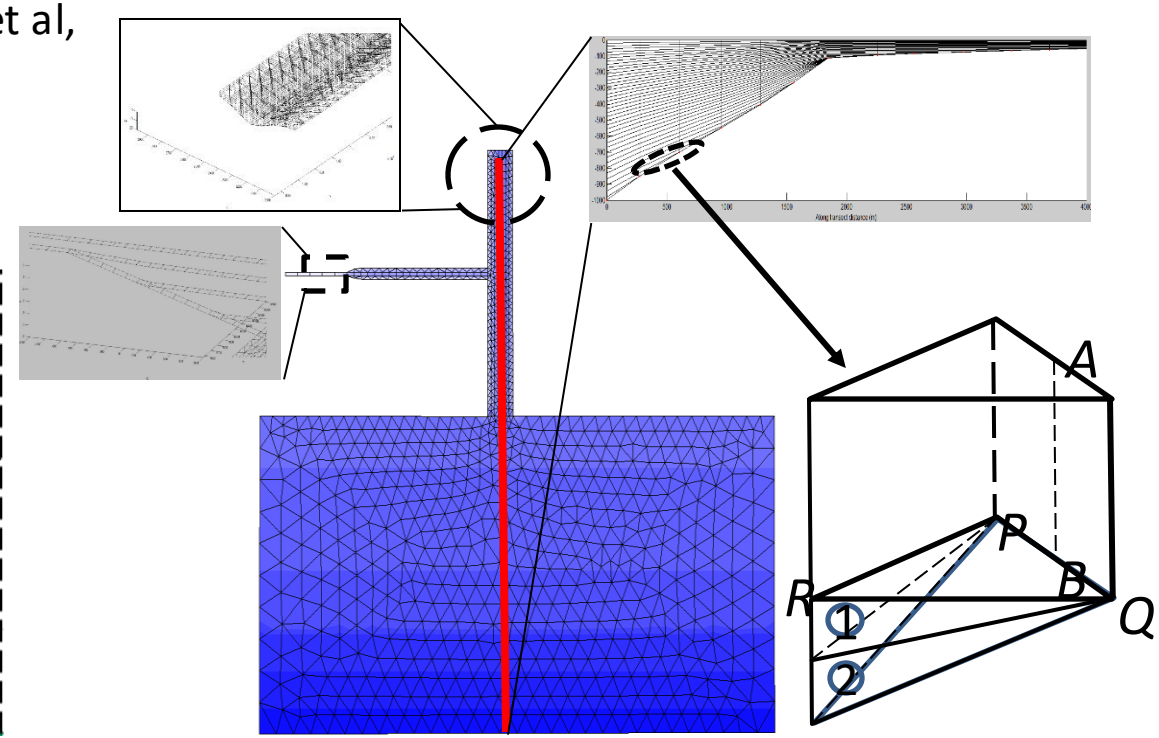
SCHISM's Polymorphism: great news for bathymetry

- Underpins efficiency and flexibility, as well as accuracy (PGE, diapycnal mixing; DEM)
- Underlying bathymetry can be accurately and faithfully captured
  - Steep slopes are everywhere in oceans and estuaries!
  - Most models manipulate DEM to suit their needs. This has detrimental effects on physical or biological processes (Ye et al. 2018; Cai et al. 2020, 2021; Zhang et al. 2024)
  - Bathymetry has been shown to be first-order forcing in coastal & global oceans (e.g., ocean salinity budget, Wynne-Cattanach et al, Nature, 2024)

Spurious diapycnal mixing

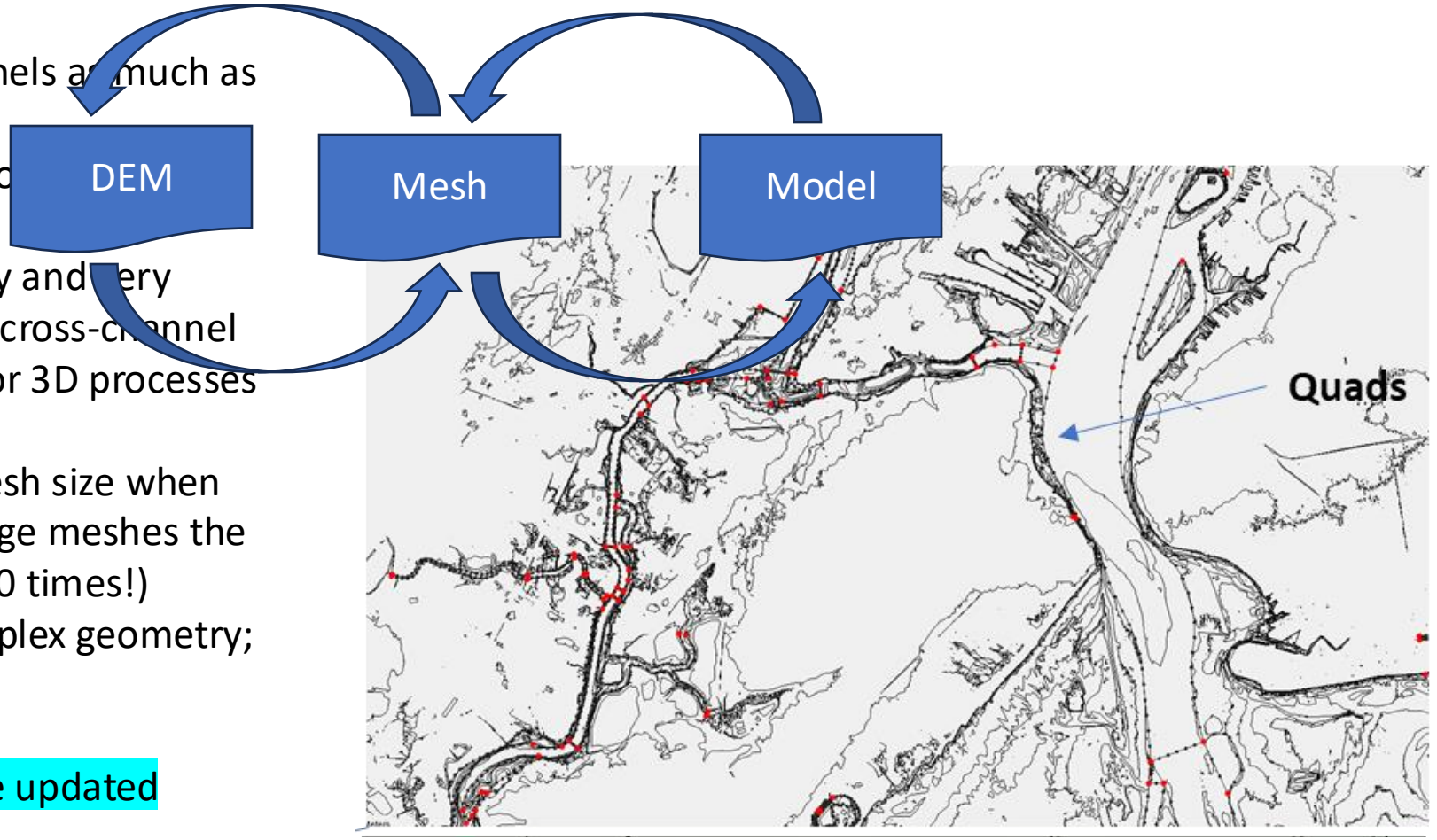


PGE



Mesh generation: NY Harbor

- **Channels** play a pivotal role for many coastal and estuarine processes: high-gradient zones are usually found in and around the channels
- An important task for mesh generation is to accurately resolve the channels
  - Surprisingly, few models (UG or SG) pay attention to resolving channels due to various limitations
  - Interestingly, most models try to use fine resolution near the shoreline, where the 3D processes are less pronounced
- SCHISM's way of meshing channels
  - Use quadrilaterals to represent channels as much as possible to achieve three goals
    - Flow-aligned quads are known to be more accurate
    - Unlike triangles, quads can easily and very precisely control the along- and cross-channel resolution, which is important for 3D processes like tracer transport
    - They significantly reduce the mesh size when there are many channels (for large meshes the savings can be on the order of 10 times!)
  - Quads are inflexible in following complex geometry; use triangles to provide flexibility



- Must revise the mesh whenever DEMs are updated

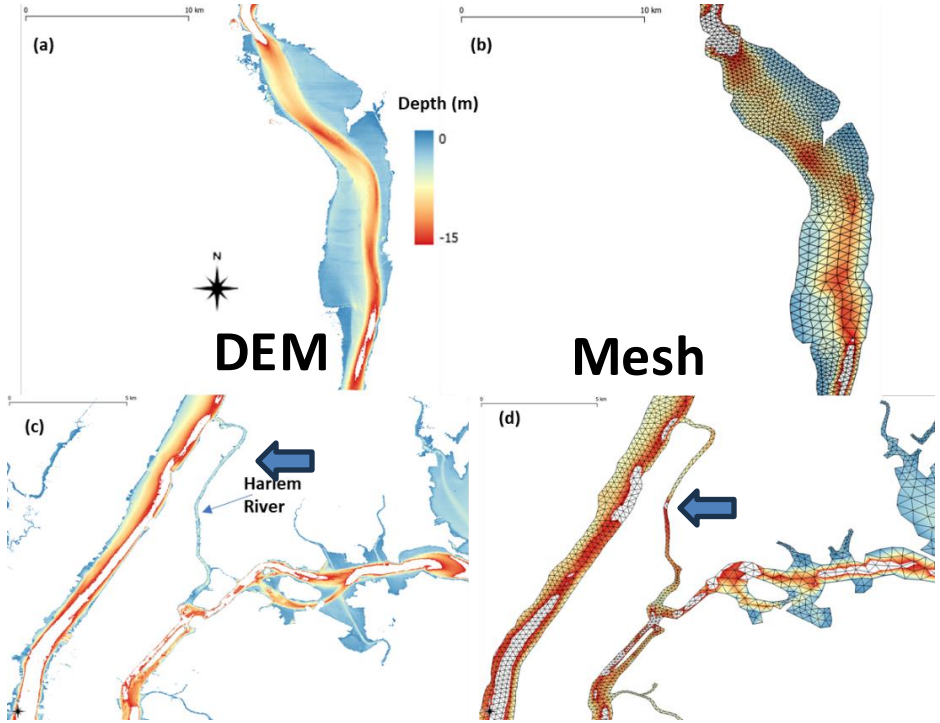
Myth #1

Myth #1: Since DEMs have errors/uncertainties, modelers can freely manipulate them to improve the model
Response: Manipulating DEMs leads to **systemic changes** that are hard to rectify. The defensible approach is to work with data provider to rectify the DEM errors and redo the mesh after that.

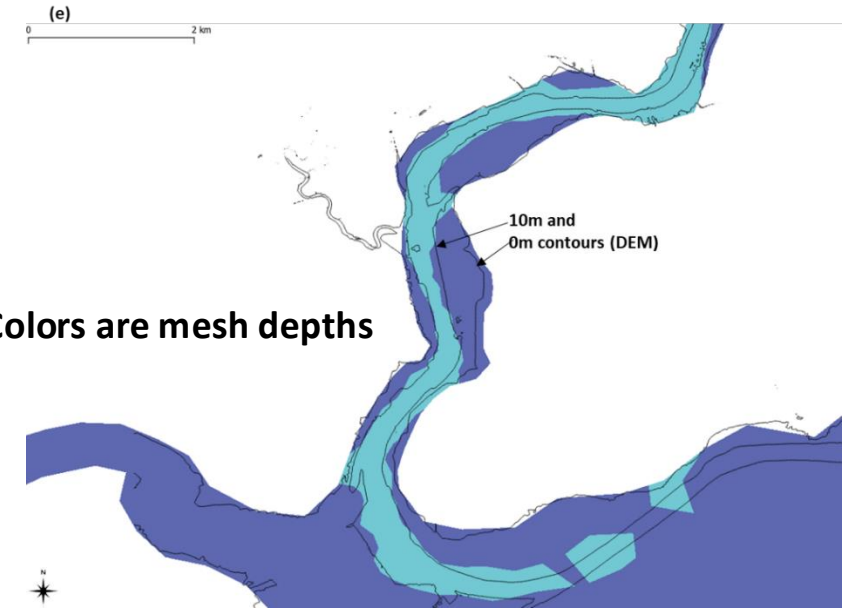
Observation based bathymetry data should be treated just like other types of observation (e.g., surface elevation)!

- Reproducible script for loading DEM onto mesh/grid is a minimum standard

Bathymetry smoothing/widening



Channel widening

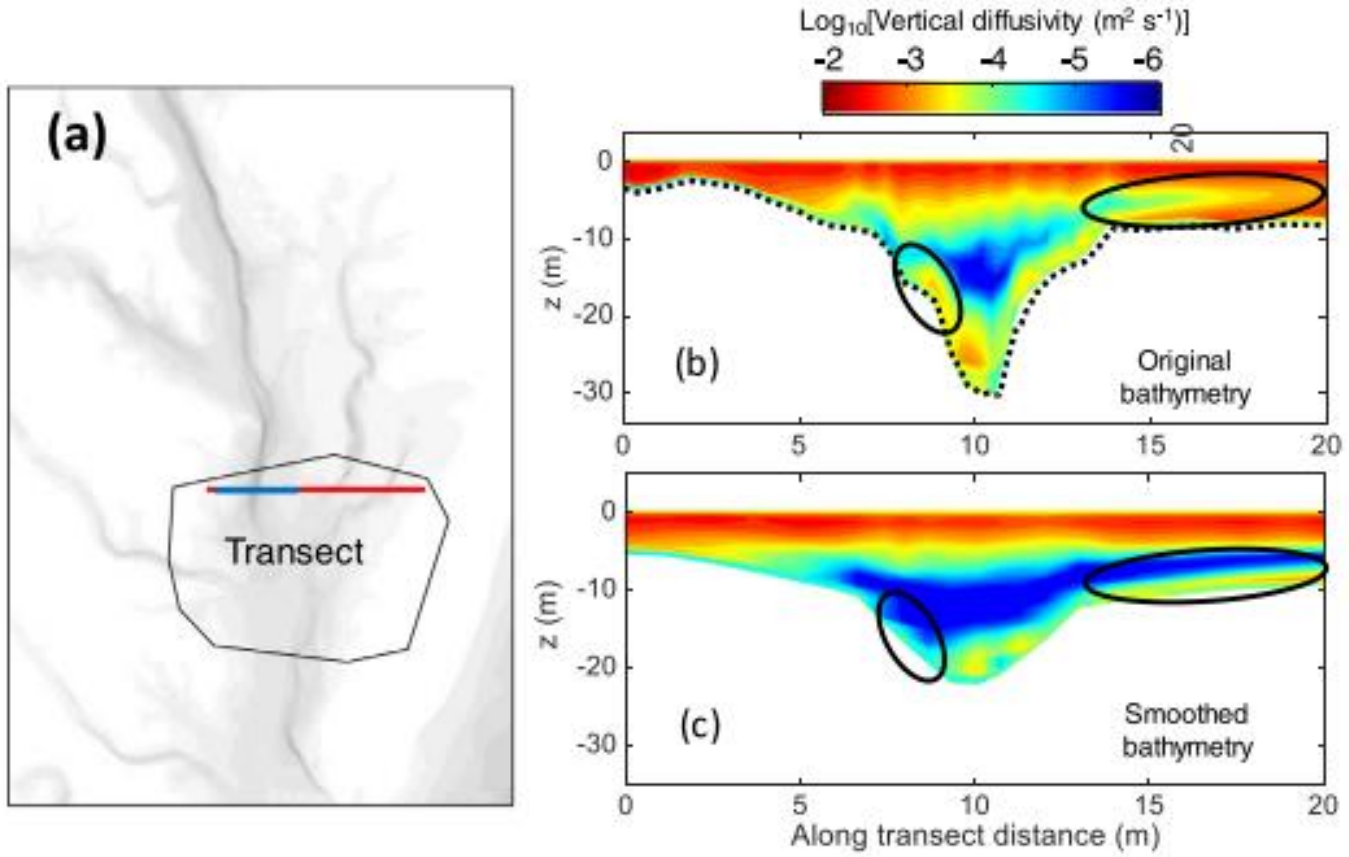


Zhang et al. (2024)

Myth #1: impact on mixing process

Turbulence mixing pattern is fundamentally altered by bathymetry smoothing/manipulation

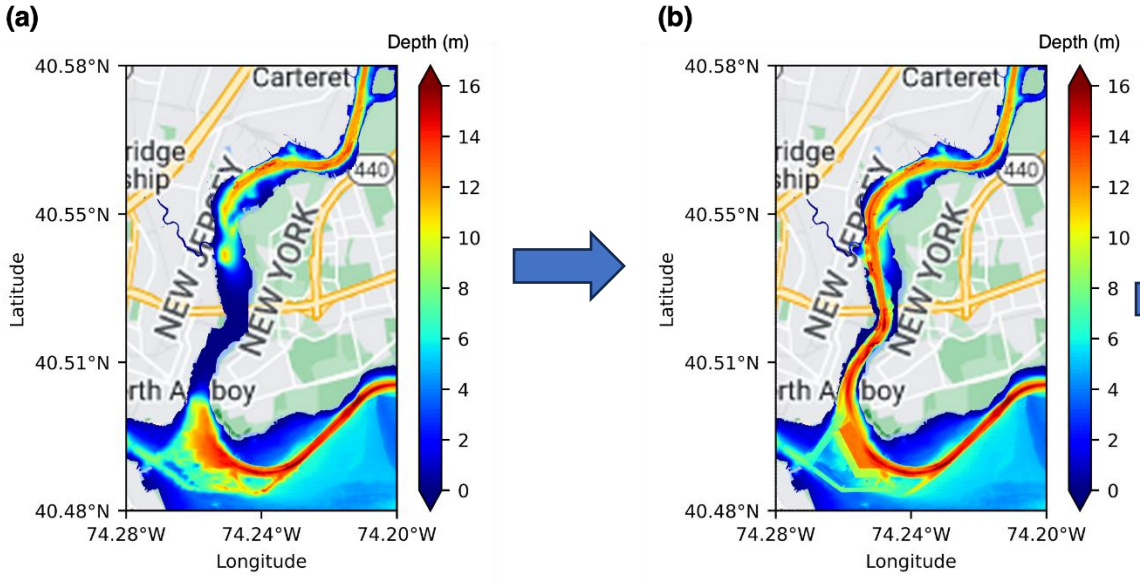
- **Low-mixing zone extended into shallows**
- **High mixing in sharp corner/steep slopes is missing**
- **Exaggeration of channelized intrusion**



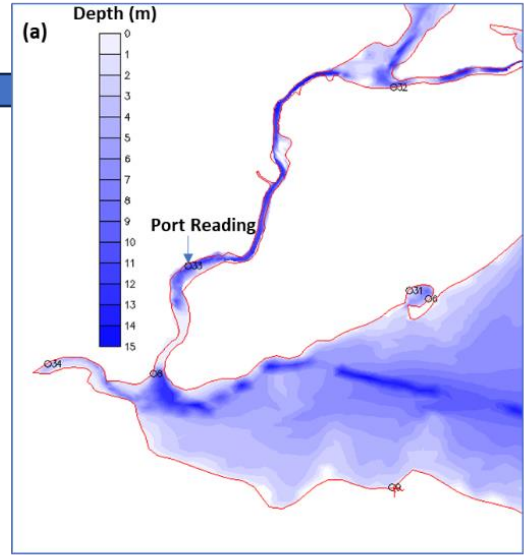
Ye et al. (2018)

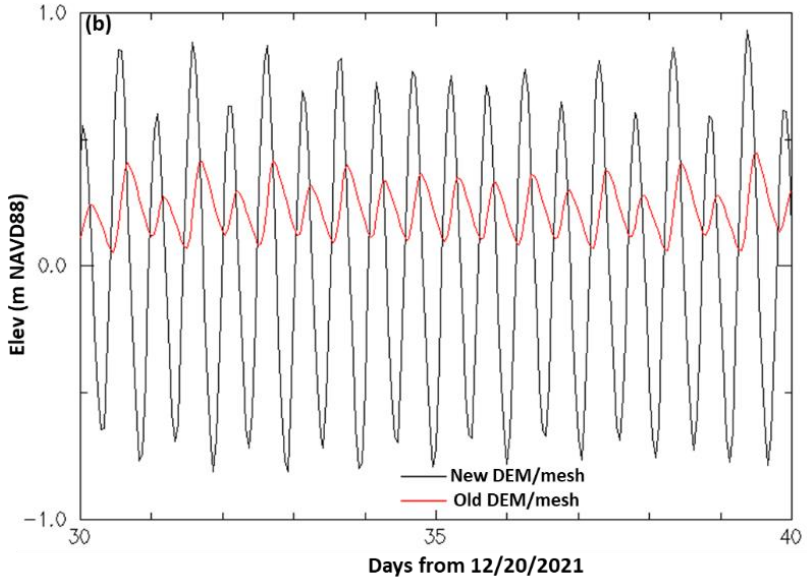
Myth #2

Myth #2: Modelers can decide how to rectify DEM errors
Response: our results for NYH and elsewhere (Ye et al. 2018, Cai et al. 2021) clearly indicated system changing biases will result from bathymetry smoothing/manipulation, which is several orders of magnitude larger than the DEM uncertainties (TVU)
Success story for NYH: rectifying DEM errors is one of the best ways to improve model, as it removes a major error source and avoids error compensation; work with DEM providers!



Tidal propagation was partially blocked with old DEM



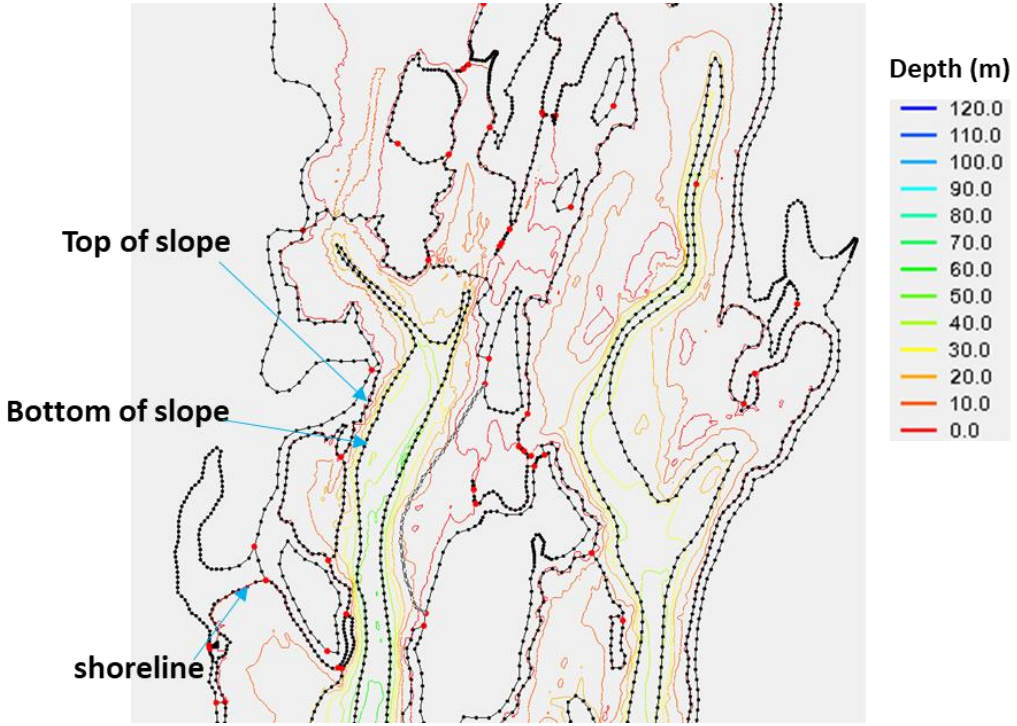


Zhang et al. (2024)

Mesh generation near steep slopes

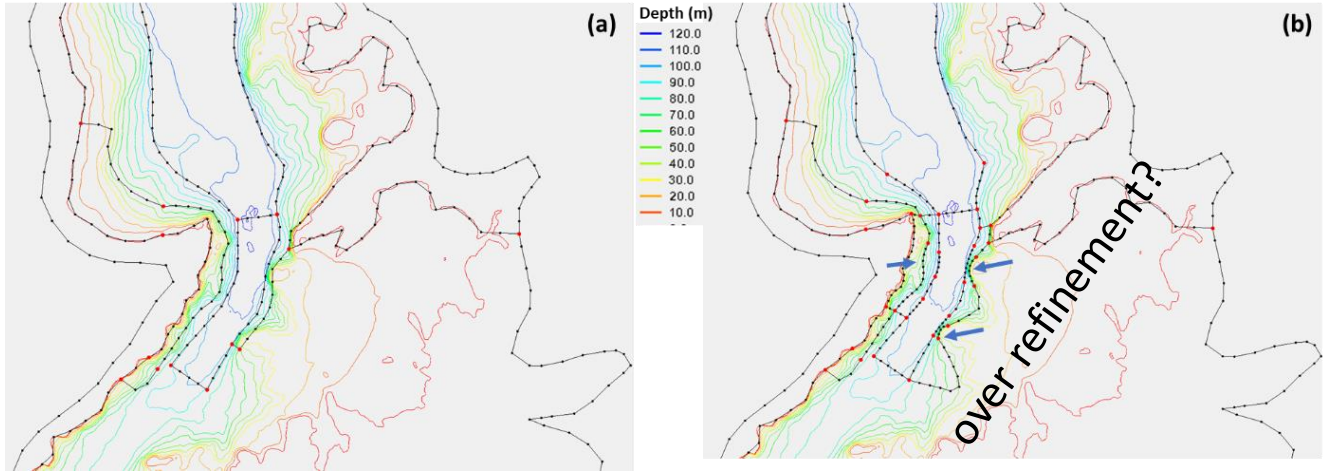
- Mesh generation/revision should also be based on evidence
- First-order task for mesh generation is to capture processes

SMS map

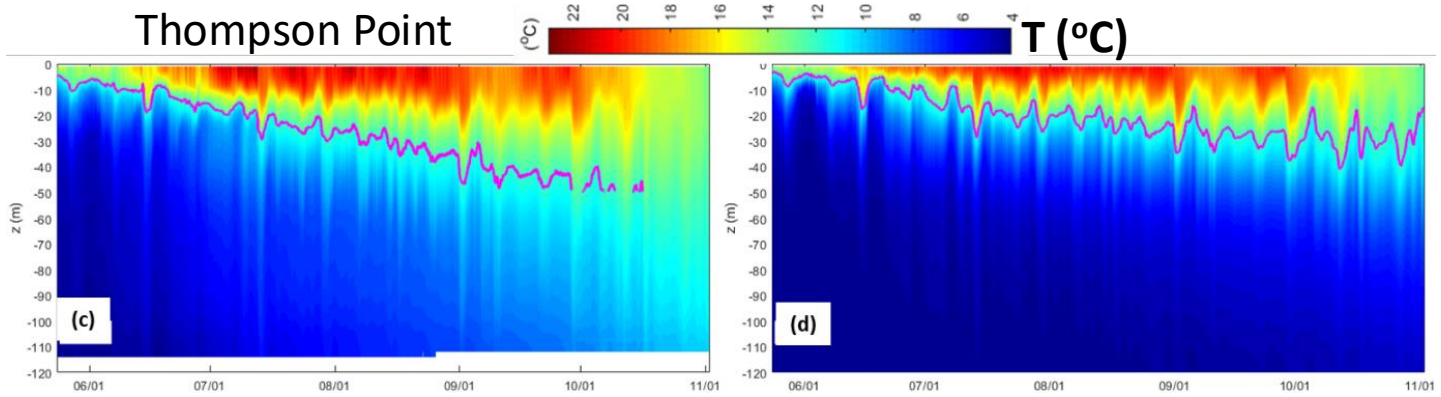


Two different meshing approaches near Thompson Point (steepest slope)

- Over-refinement led to dx < dz (cf. hydrostatic assumption)

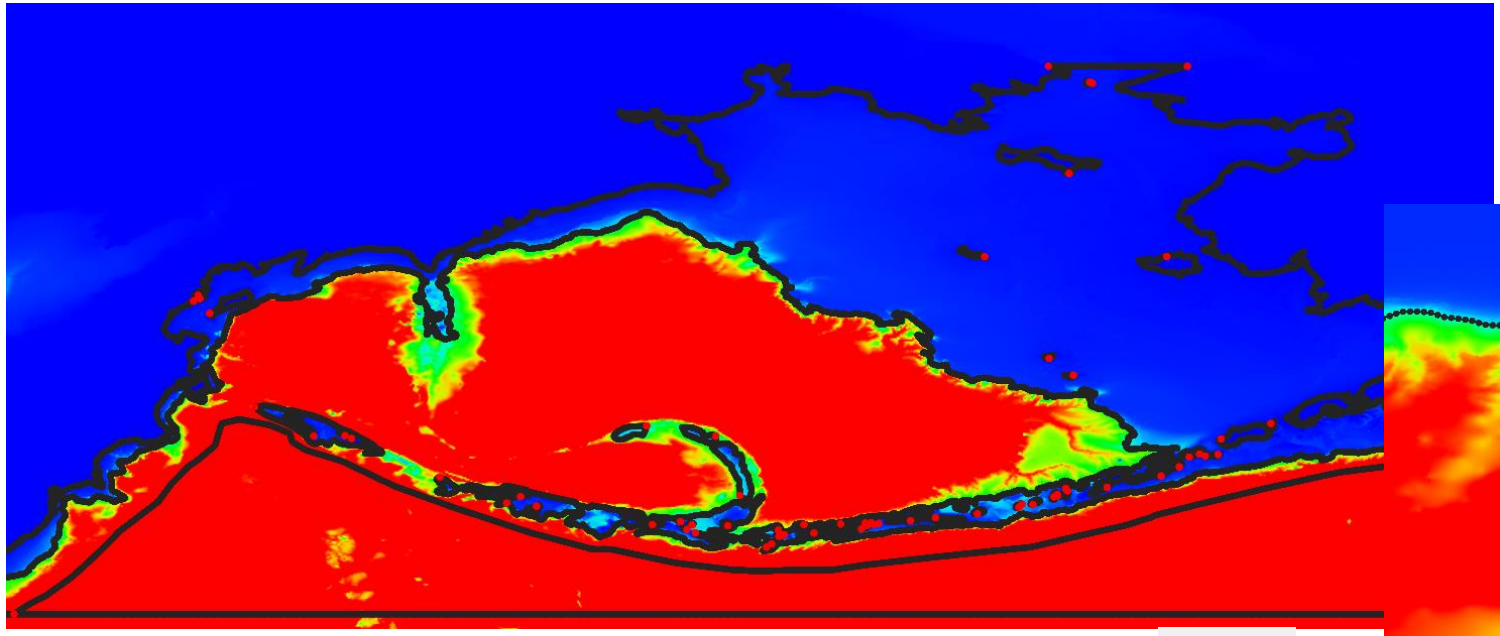


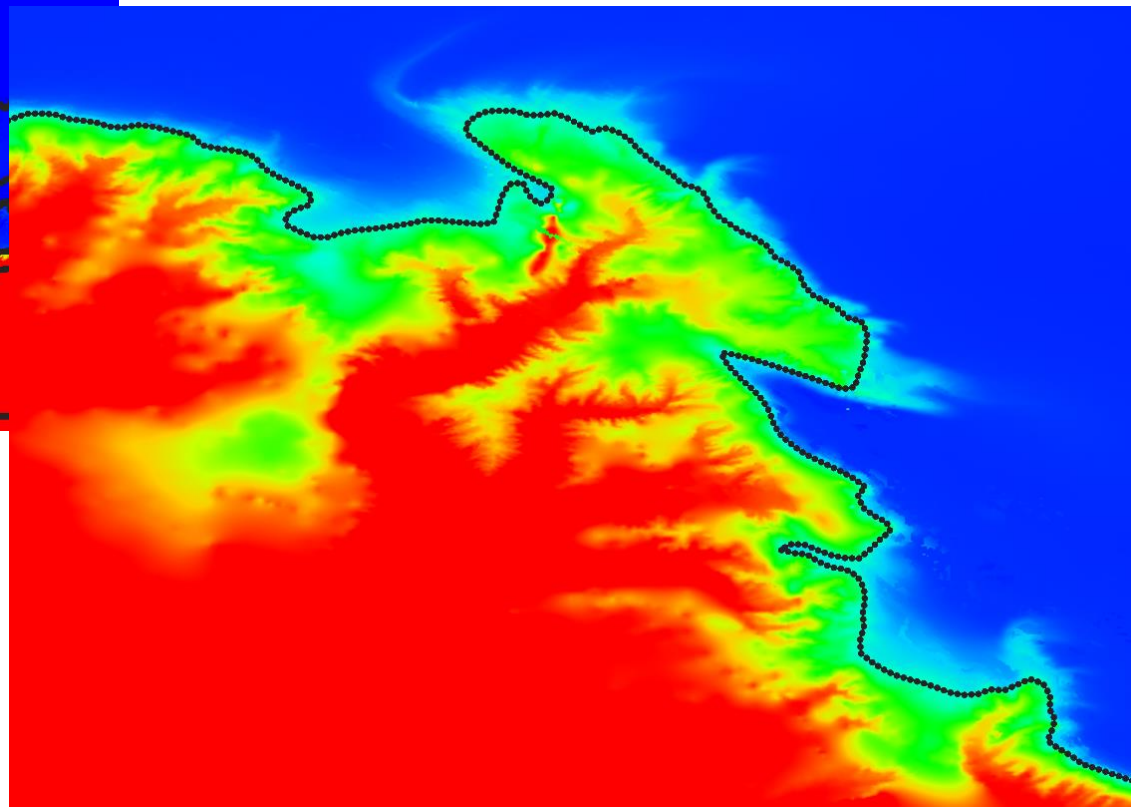
Thompson Point

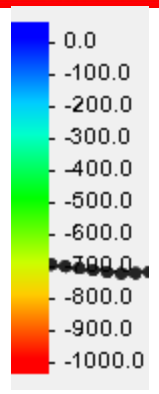


Mesh generation for sub-mesoscale cases

- Submesoscale processes become feasible when the horizontal resolution is comparable or smaller than depth
- Those processes have smaller temporal scales, so require smaller dt (60s)
- Mesh generation for such cases needs to take advantage of UG's ability to represent bathymetric features like steep slopes







Mesh generation in the coastal transition zone for compound flood simulations

- **Capturing channel connectivity**
  Resolving narrow and shallow channels

- **Simulating compound floods**
  Accurately representing the interaction of coastal surge, riverine floods, and pluvial floods

- **Supporting compound flood modeling**
  Backbone of NOAA's STOFS-3D

Ye et al., 2023. A parallel Python-based tool for meshing watershed rivers at continental scale. Environmental Modelling & Software, 166, p.105731.

Ye et al., (under review). Ocean Modelling.

Next week's presentation

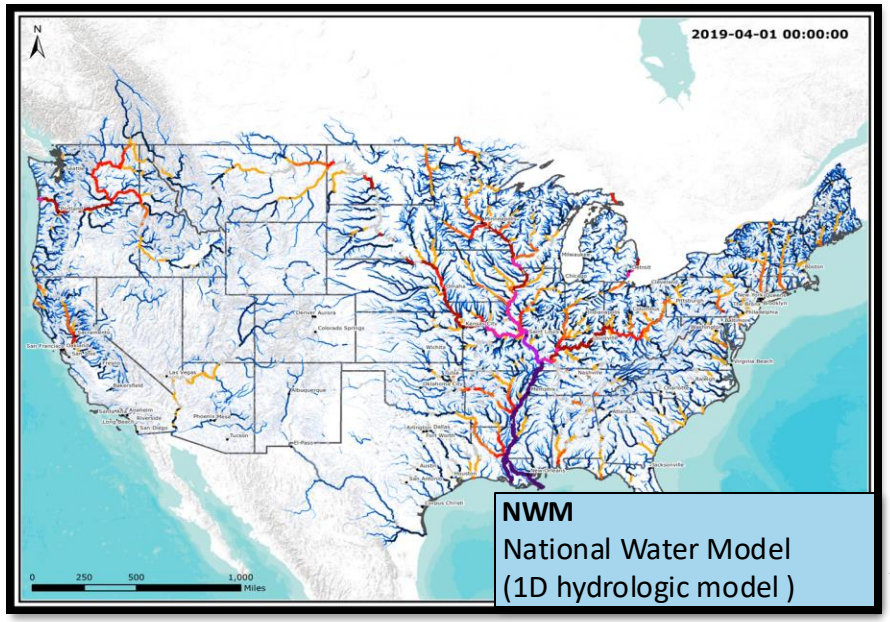
August 5, 2025, 1 pm US EST

Saeed Moghimi, Felicio Cassalho, Soroosh Mani. Toward a fully automatic mesh generator with application to 3D compound flooding study

LaPlace, Louisiana; Hurricane Ida 2021.
[AP Photo/Steve Helber]

Hurricane Ida traps Louisianans, shatters the power grid - KSTP.com 5 Eyewitness News

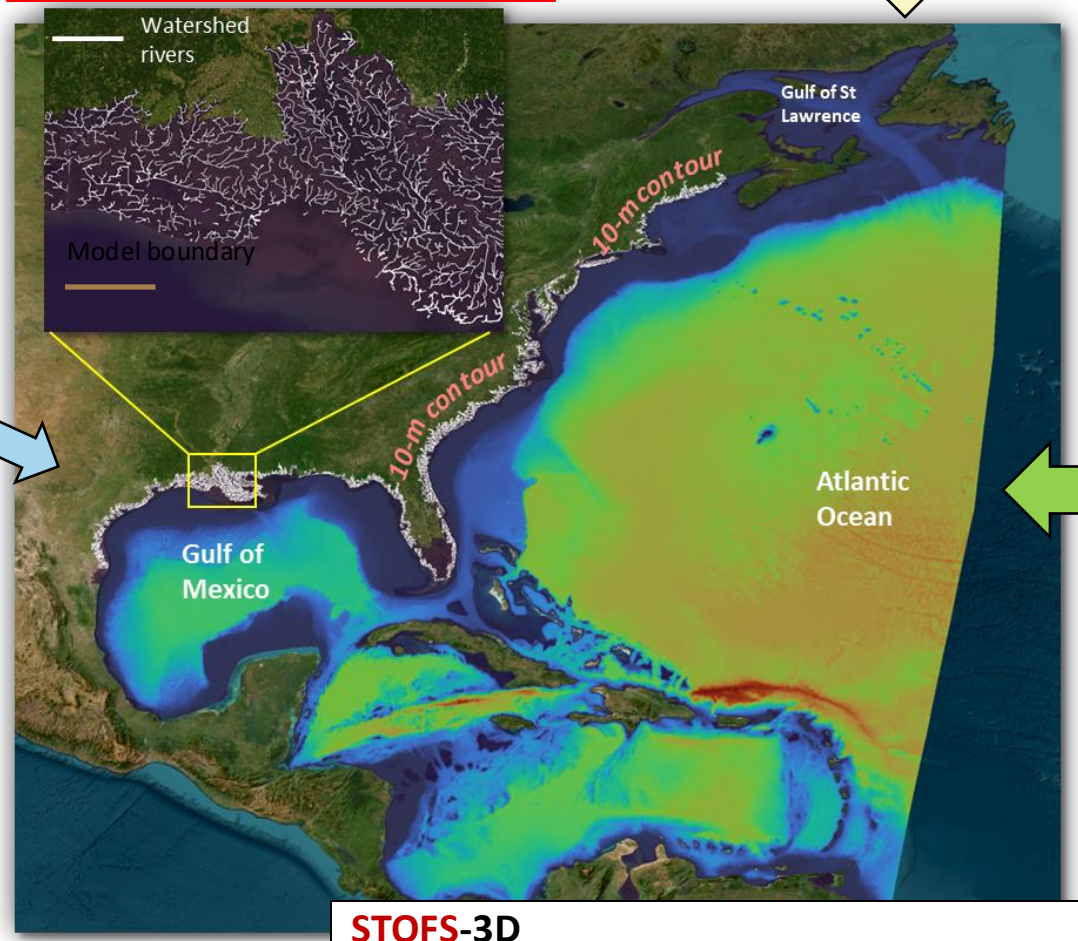
Modeling Framework: STOFS-3D-Atlantic



NWM
National Water Model
(1D hydrologic model)

Coastal transition zone
Connecting hydrologic and hydrodynamic regimes

Atmospheric Forcing from the
Operational NCEP HRRR



Ocean Boundary forced by **RTOFS**

3D baroclinic simulation

Horizontal grid
3 million nodes and 6 million elements

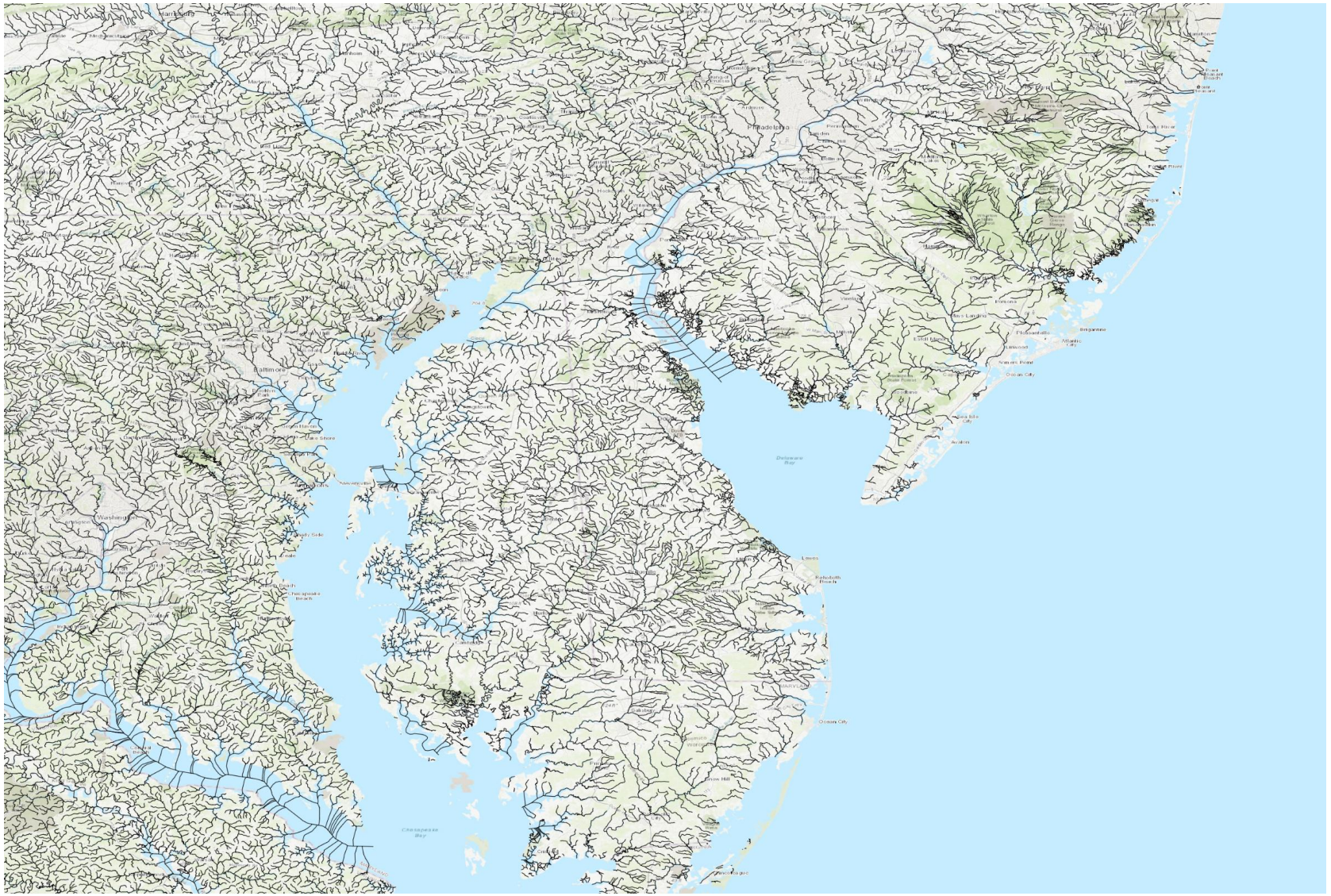
Vertical grid (terrain following)
9 levels on average; 43 layers in the deepest ocean
1 layer in shallow waters and coastal watersheds,
>40% of the grid cells are **2D**

Performance
> 100 × real time on NOAA's WCOSS2

STOFS-3D
3D component of the National Ocean Service
Surge and Tide Operational Forecasting System

Modeling Framework: STOFS-3D-Atlantic | Coverage of the coastal transition zone

River segments from National Water Model



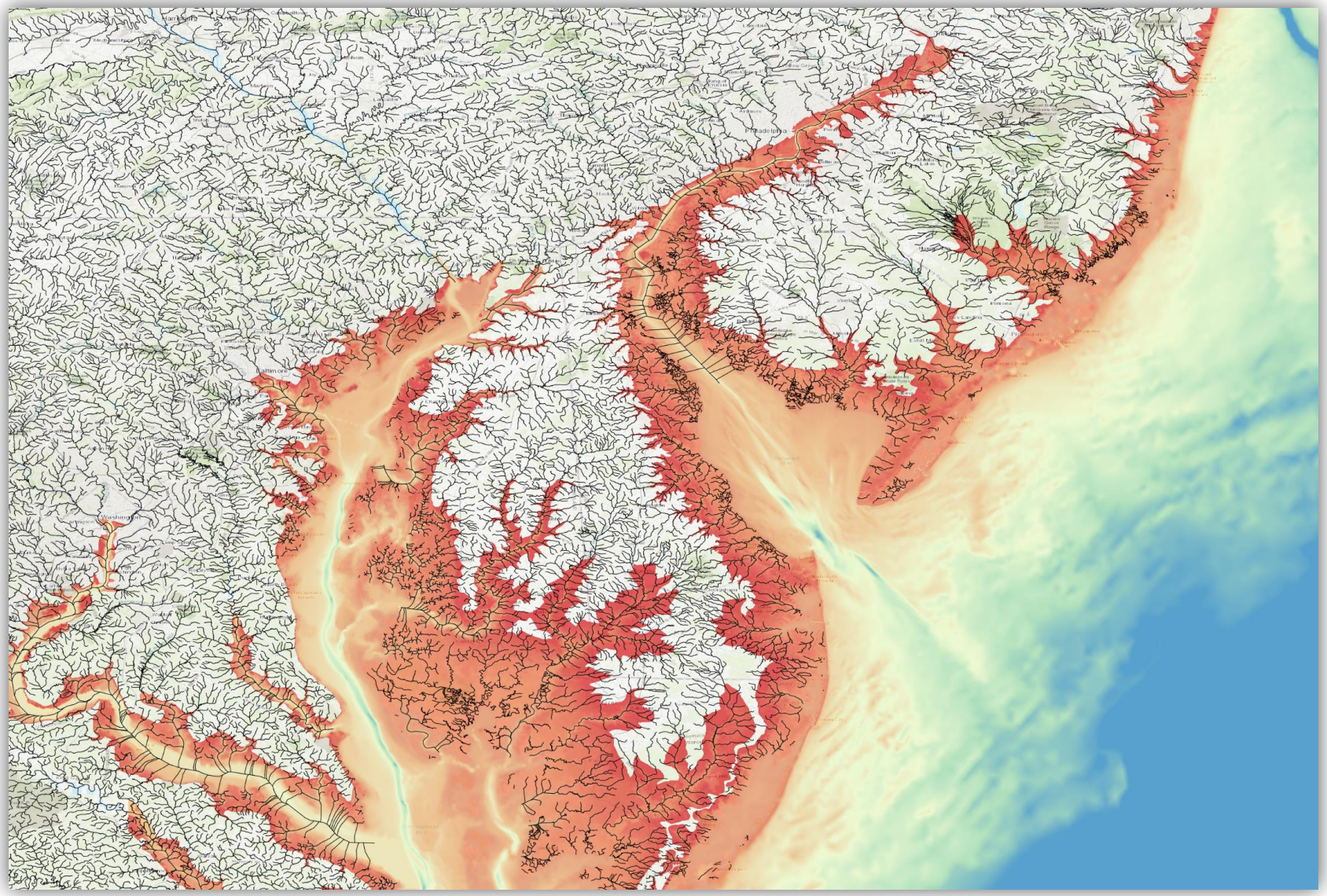
- **Hydrologic models** lack estuarine and tidal processes
- **Ocean models** struggle with efficiency and robustness when extended inland

Resolving small rivers in an unstructured mesh is key
→ Mesh must be continuously adaptable to evolving high-resolution DEM

Modeling Framework: STOFS-3D-Atlantic

Coverage of the coastal transition zone

River segments from National Water Model



- **Hydrologic models** lack estuarine and tidal processes
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✓ *STOFS-3D domain covers the coastal transition zone — bridging ocean and watershed processes*

Resolving small rivers in an unstructured mesh is key
→ Mesh must be continuously adaptable to evolving high-resolution DEM

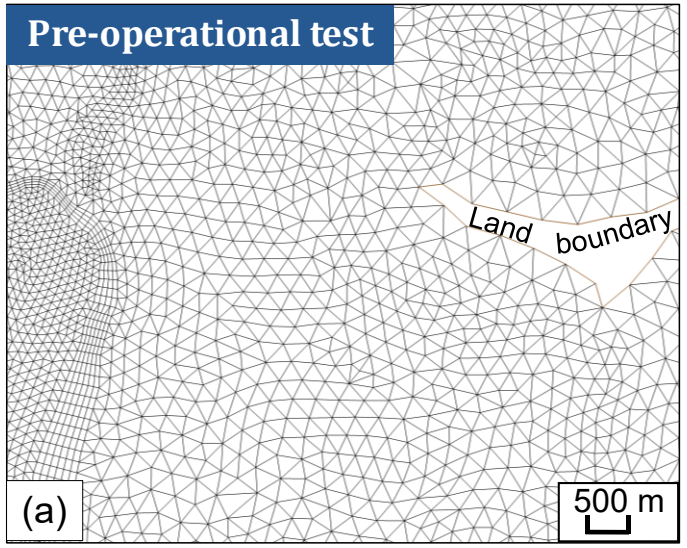
Hind cast study of Florence 2018:
Resolving small creeks improves flow routing locally and significantly reduces errors on the high water marks (HWMs)

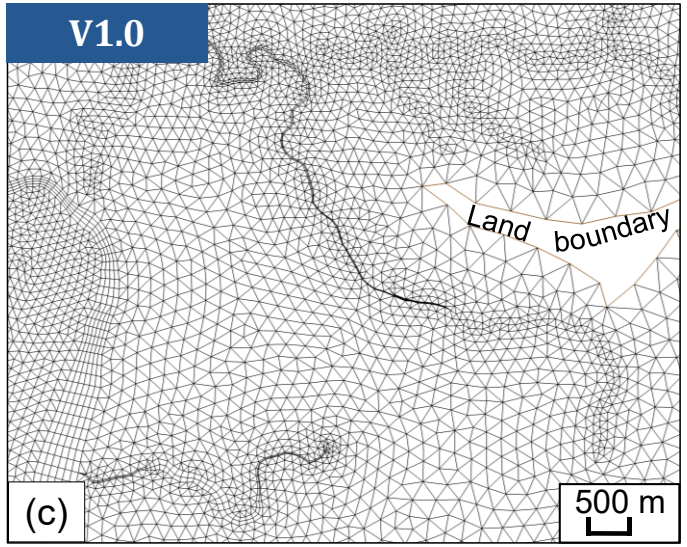
Ye et al. (2021) on Hurricane Florence

Ye, F., Huang, W., Zhang, Y.J., Moghimi, S., Myers, E., Pe'eri, S. and Yu, H.C., 2021. A cross-scale study for compound flooding processes during Hurricane Florence. *Natural Hazards and Earth System Sciences*, *21*(6), pp.1703-1719.

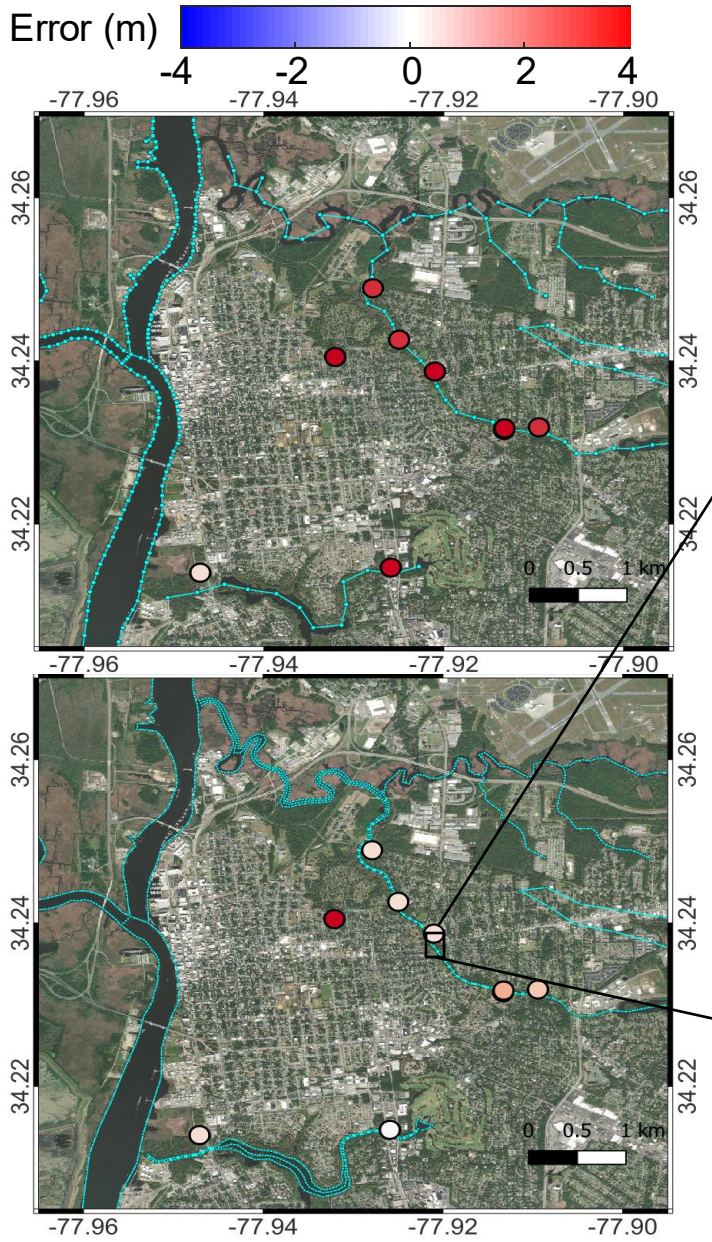
Importance of water delivery | Hurricane Florence 2018 | Burnt Mill Creek, Wilmington, North Carolina

Model grid





Red color means large over-predictions



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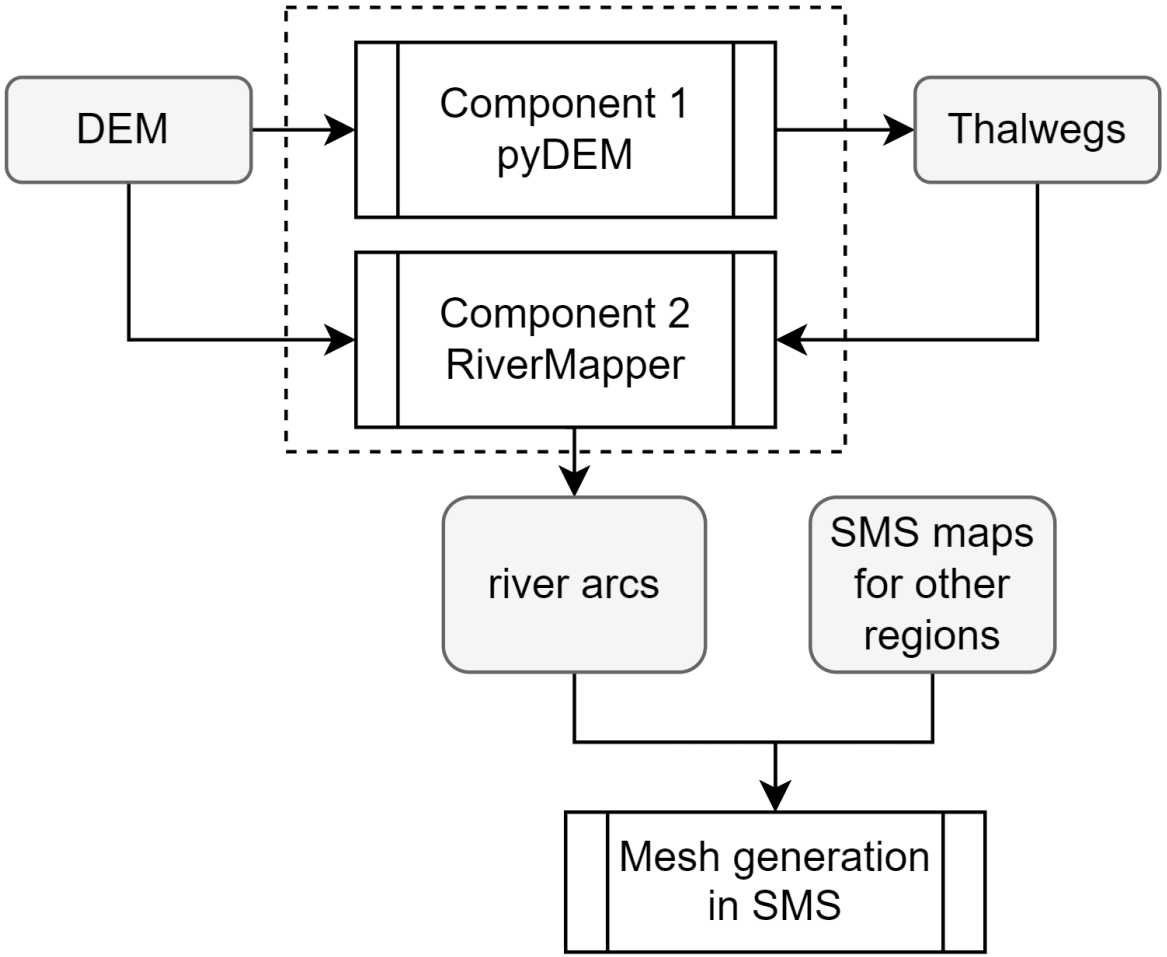
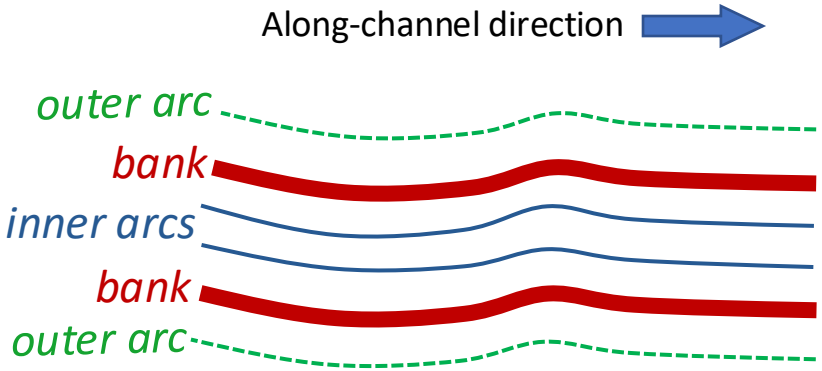
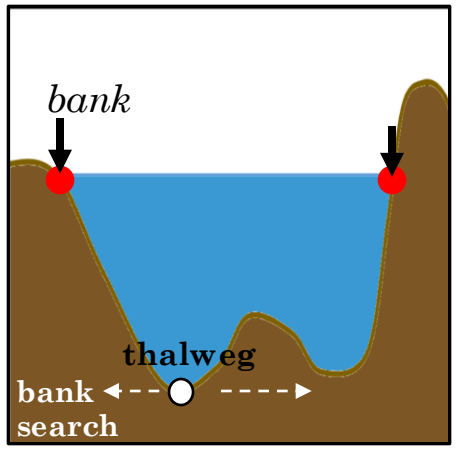
Enhancing Channel Representation through DEM-Driven Meshing

RiverMeshTools Public https://github.com/schism-dev/RiverMeshTools

- *Parallelized python scripts*
- *~ 4-5 hours for the STOFS-3D-Atlantic domain*







Fully DEM driven,
Better DEM → better mesh

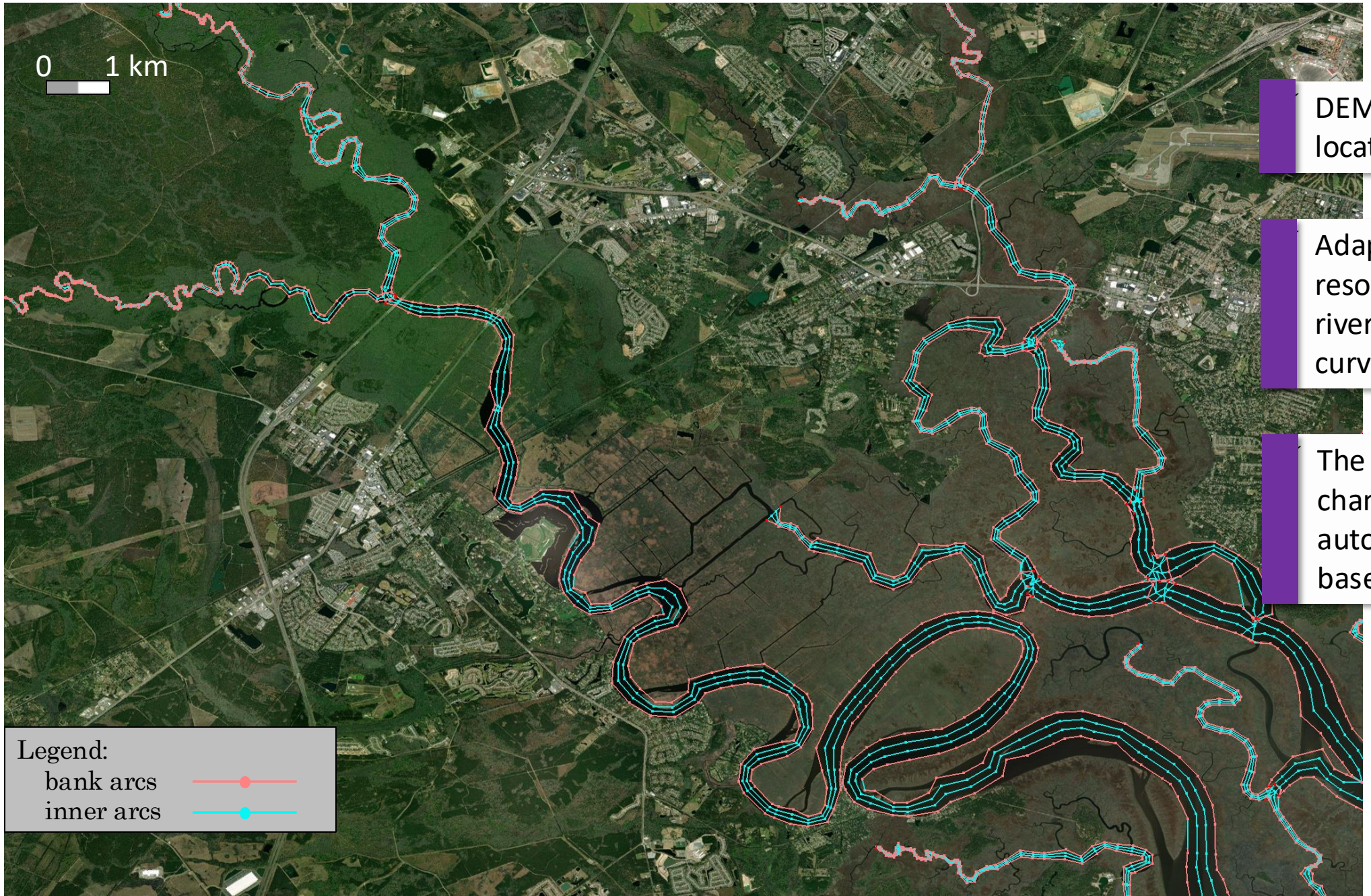
Efficient for continental-scale meshing (e.g., East Coast + Gulf)

A fully automated tool developed by NOAA OCS:

OCSMesh Public

Felicio's talk

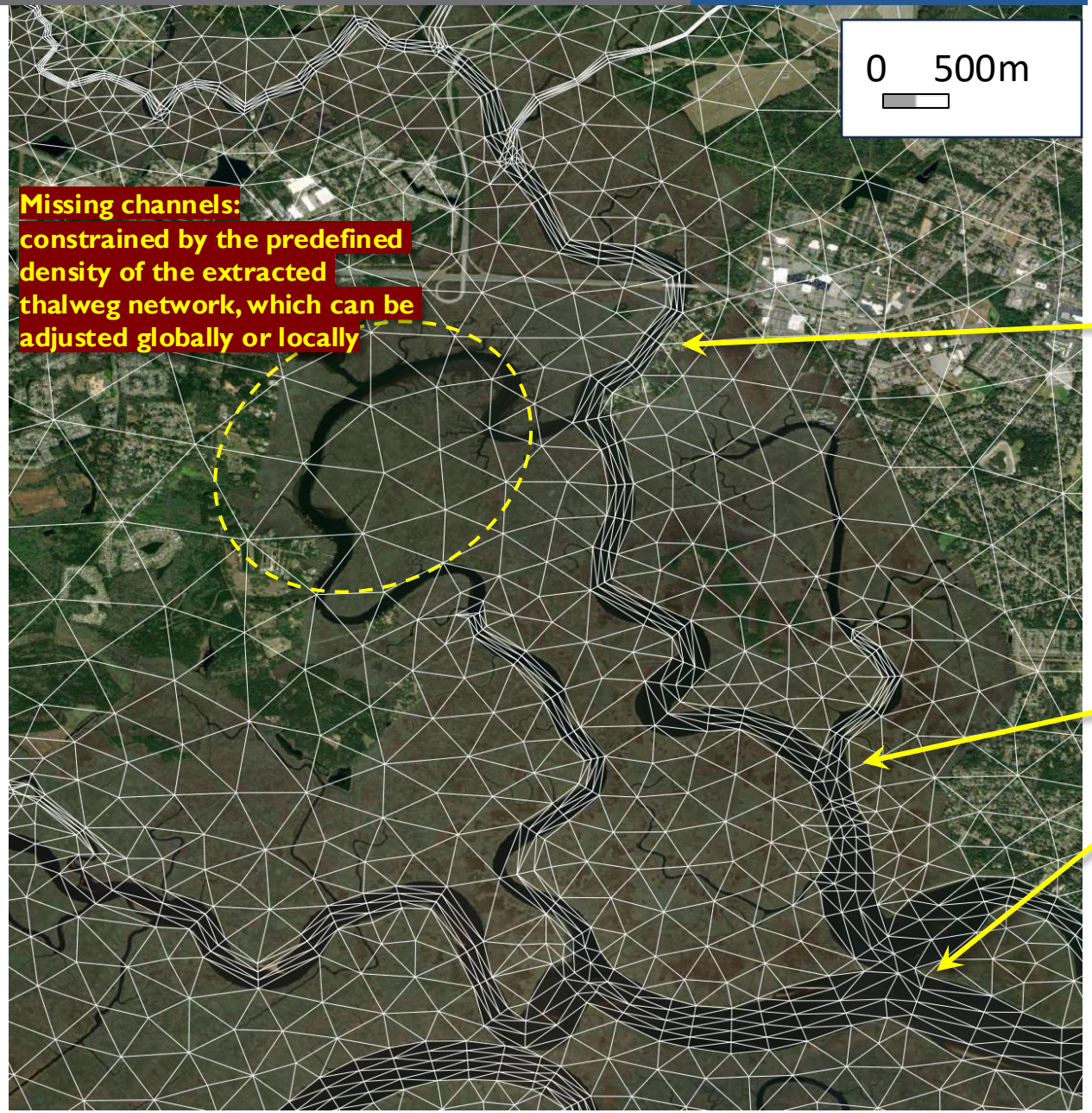
Enhancing Channel Representation | RiverMeshTools



- DEM-based bank locations
- Adaptive along-channel resolution based on river width and curvature.
- The number of cross-channel divisions are automatically adjusted based on channel width

Enhancing Channel Representation

RiverMeshTools



Both along- and cross-channel directions are resolved, regardless of the river size (down to a few meters)!

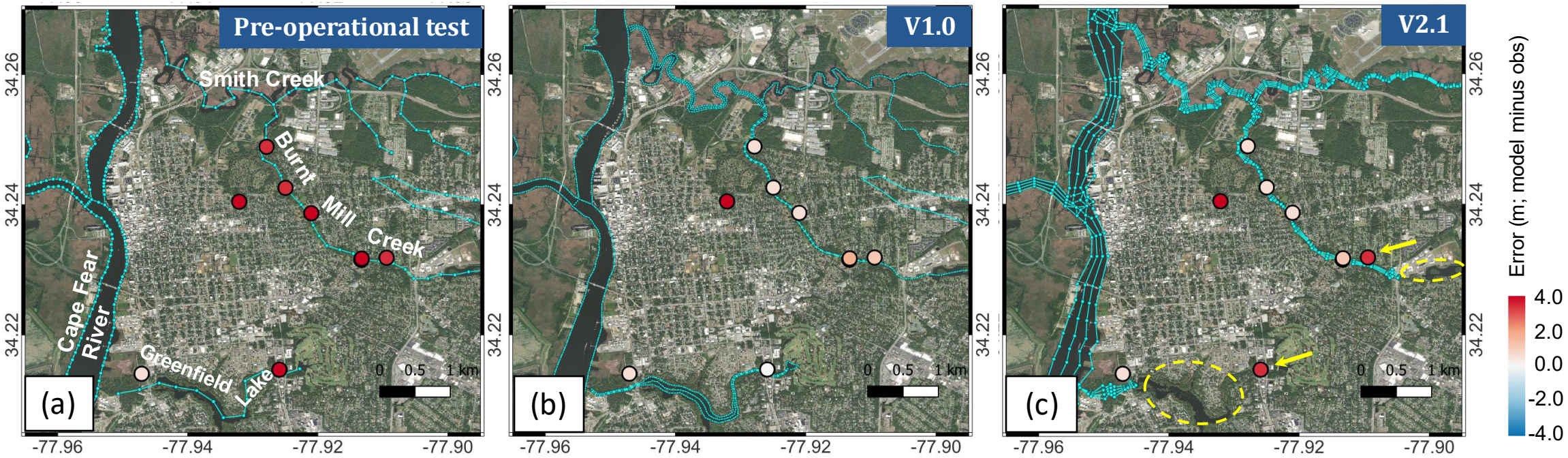
Quasi-1D representation of the channels (with long and thin elements) keeps the mesh size moderate. The aspect ratio can also be tuned.

Automatic clean-up at river intersections based on spatially varying snapping thresholds (e.g., 25% of the local channel width).

Skew elements are inevitable when the rivers are not clearly defined in the DEM; SCHISM is resilient to mesh quality.

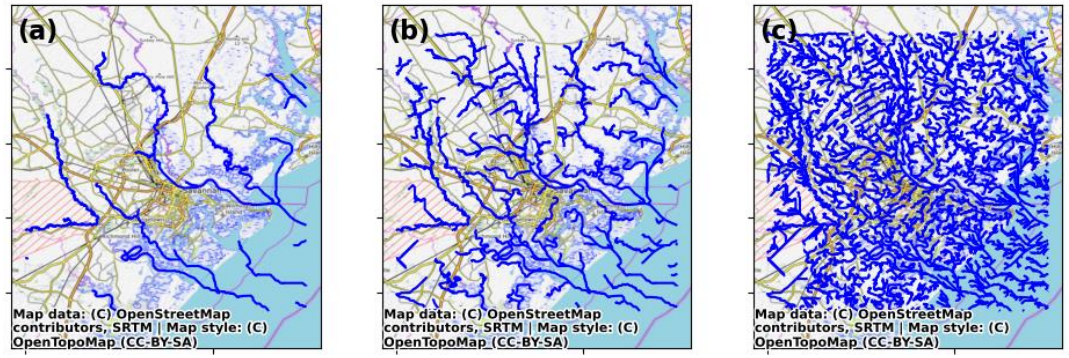
Relentless pursuit of realism

Enhancement of channel representation | Hindcast v2.1 | Hurricane Florence 2018



- Automatic arcs are as good as the manual arcs in terms of HWM prediction (Ye et al., 2023).

- Two points (yellow arrows) are outside thalweg coverage; the granularity can be adjusted if required

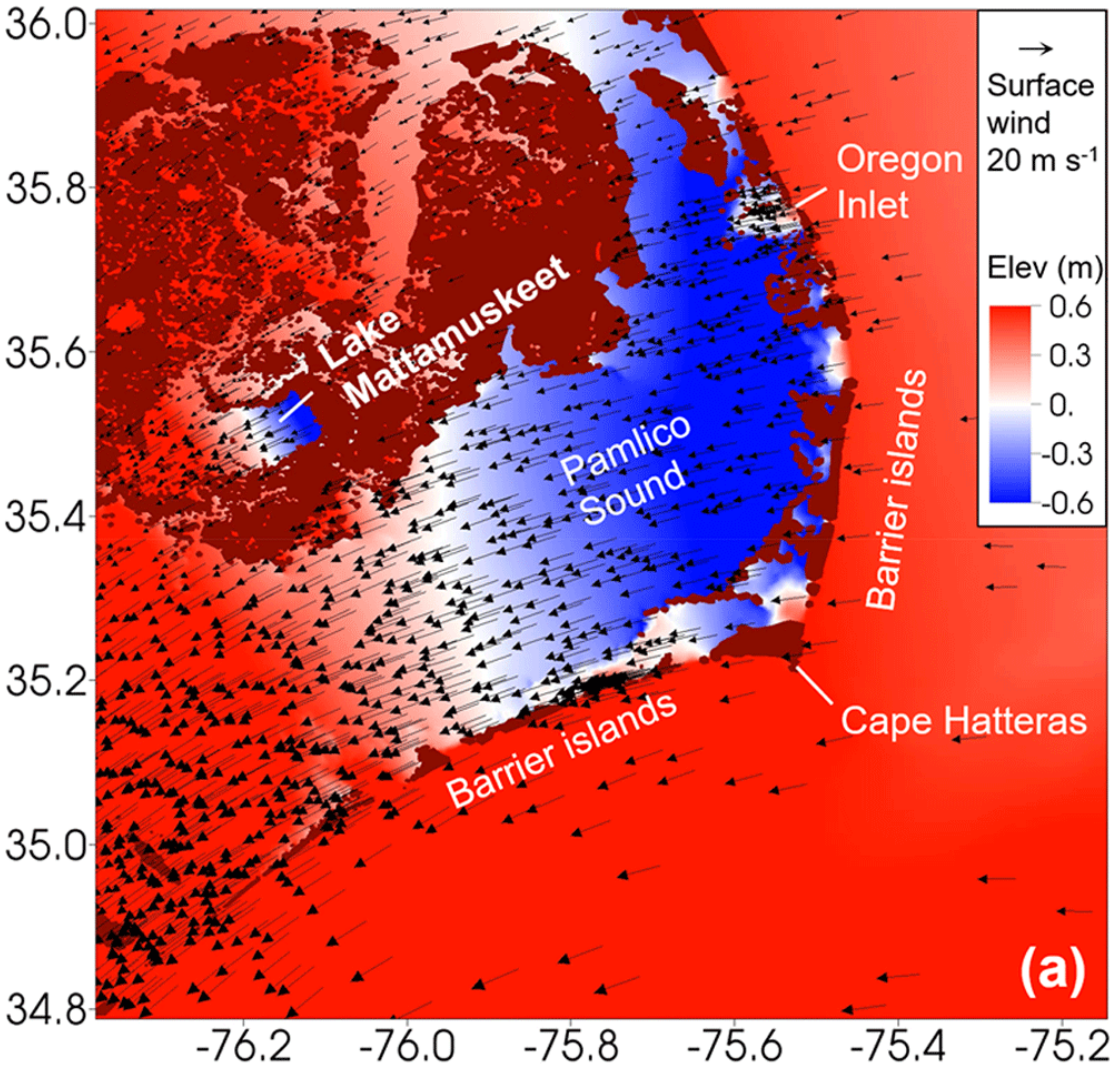


Greatly shortens the development cycle of an operational forecast

Improved DEM
New requirements
→ New mesh → New forecast

Other features generated by RiverMeshTools

Barrier Islands

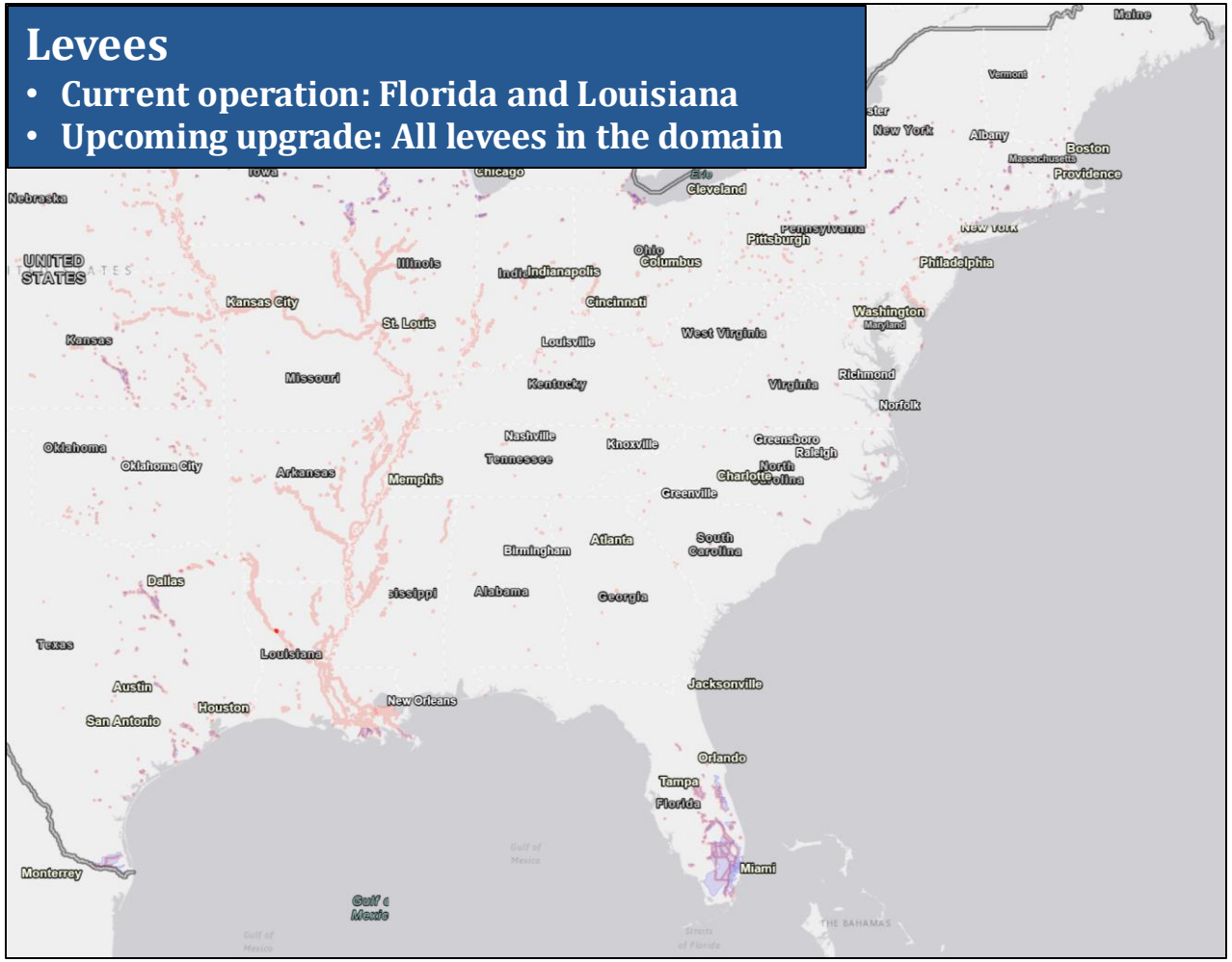


Other features generated by RiverMeshTools

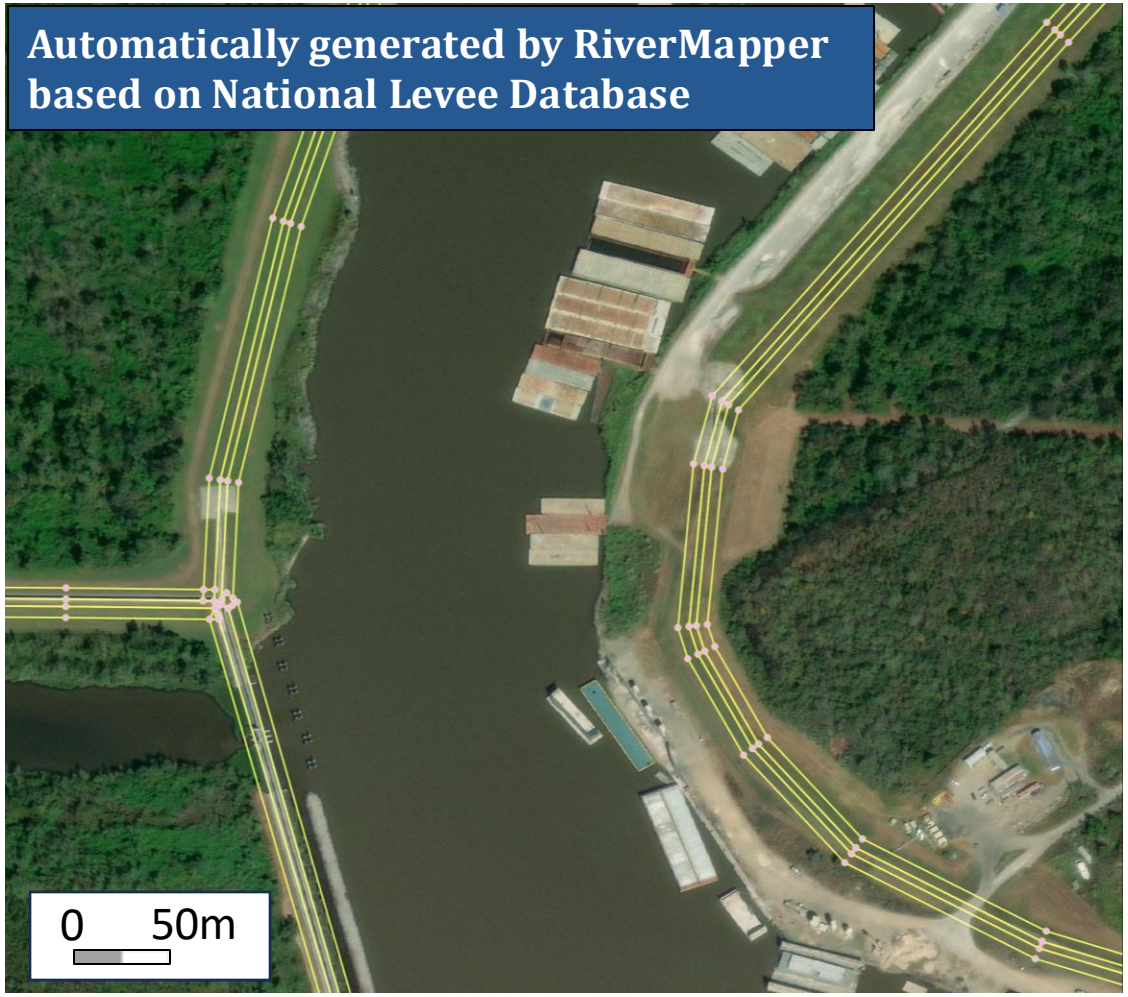
Levees

Levees

- Current operation: Florida and Louisiana
- Upcoming upgrade: All levees in the domain

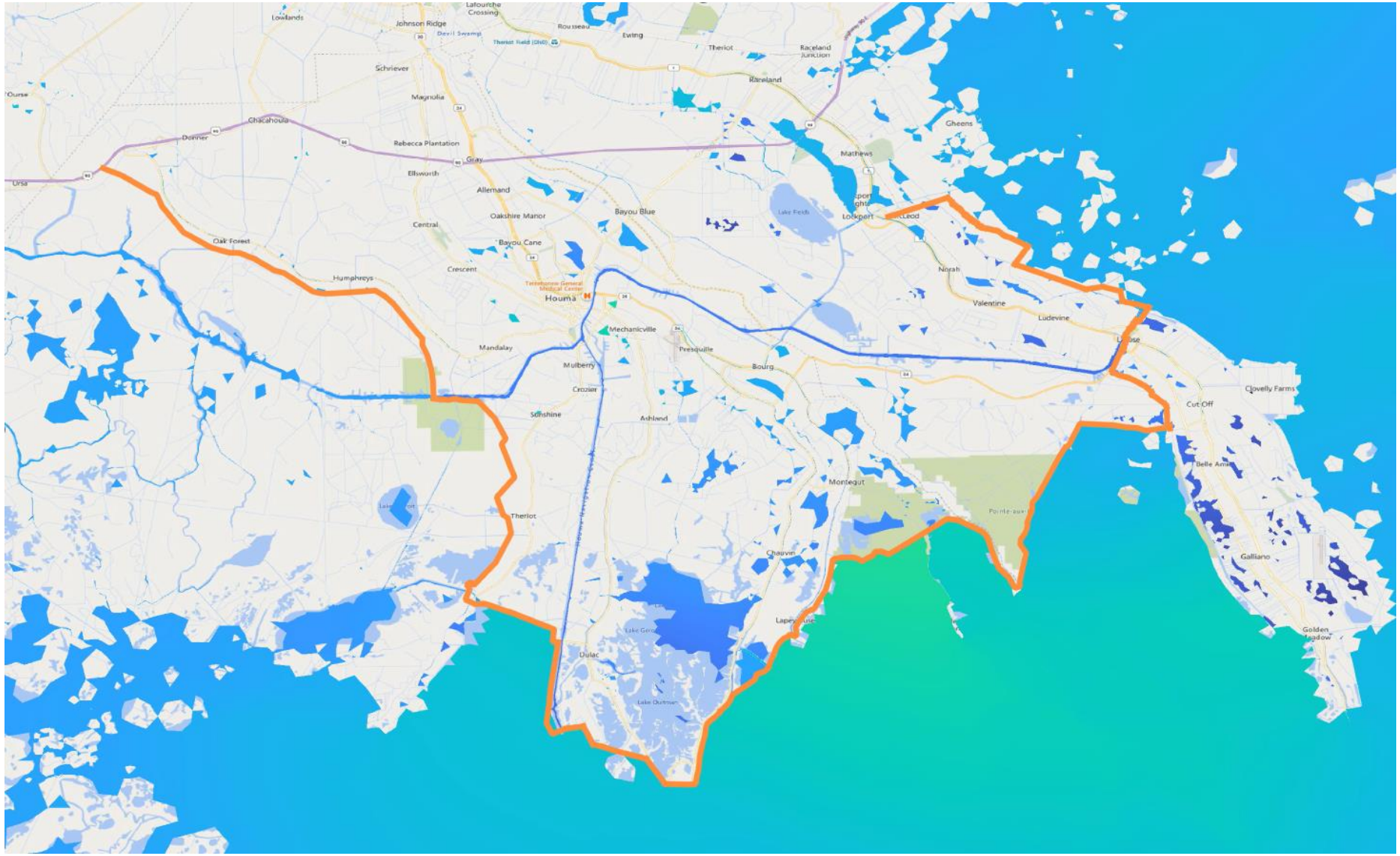


Automatically generated by RiverMapper based on National Levee Database



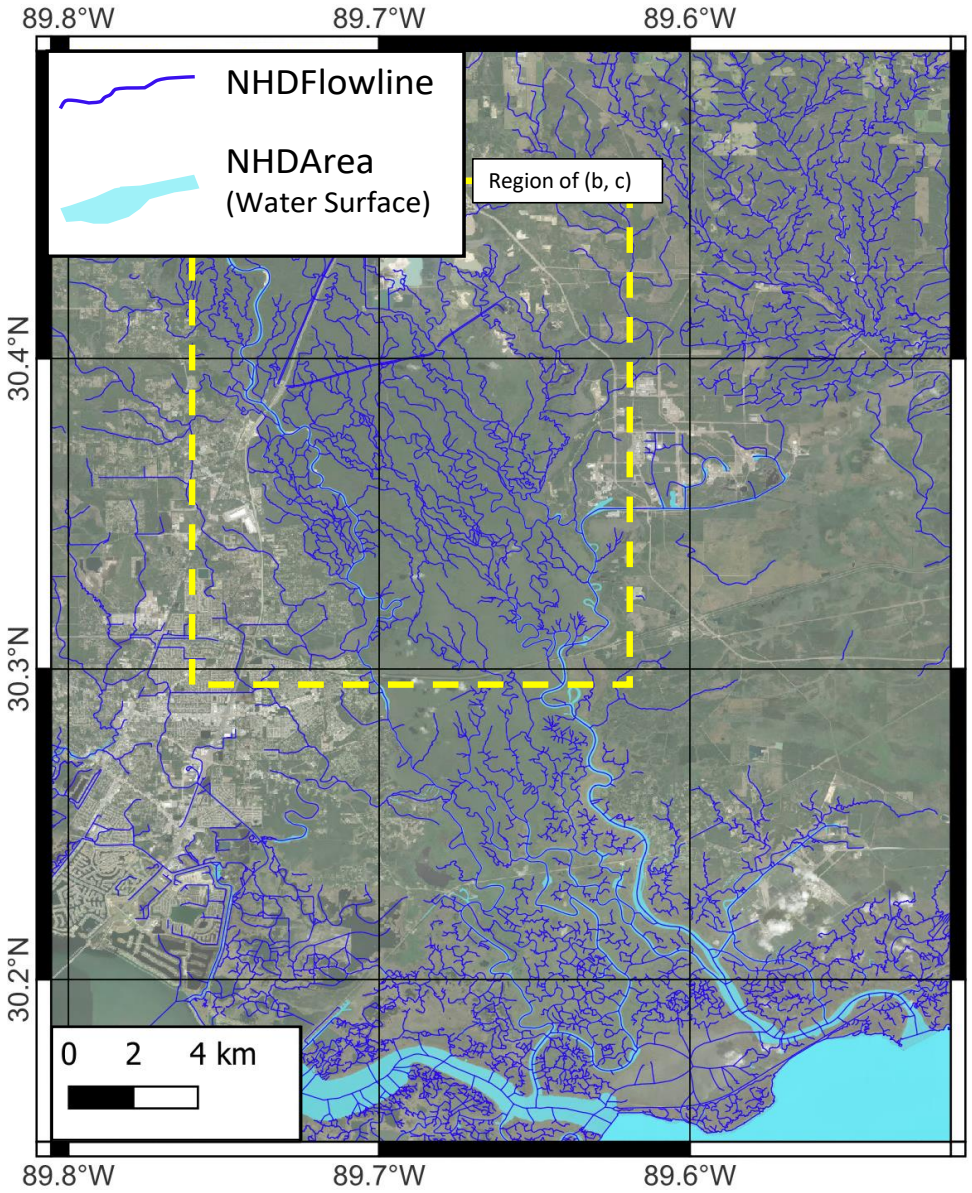
- Non-federal levees are implemented through stakeholder engagement
- The inclusion of the Morganza-to-the-Gulf (MTG) project leads to more realistic inundation patterns in Terrebonne and Lafourche parishes, LA
- No overtopping detected during Hurricane Francine 2024 with the MTG implemented.

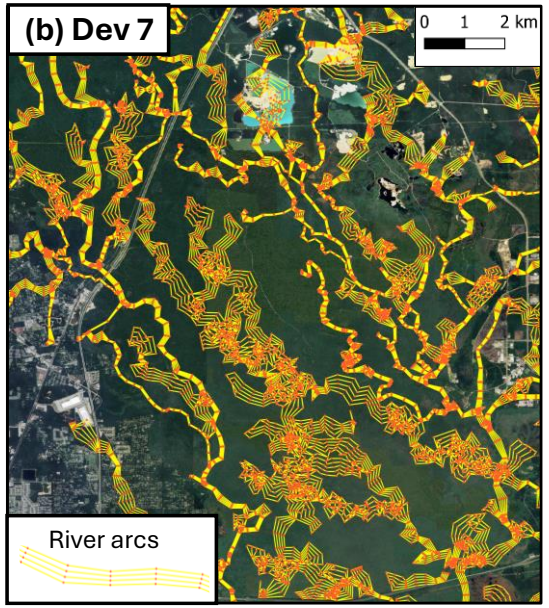
Forecasted water level upon the landfall of Hurricane Francine (2024)

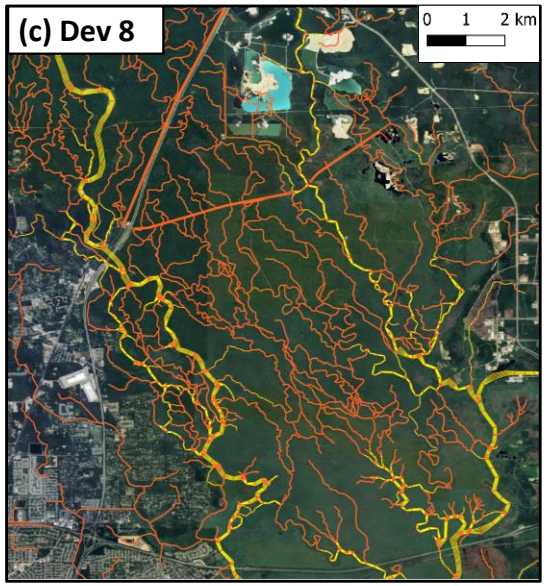


Development for future upgrades | Alternative meshing option based on NHD

NHDPlus v2 (HighRes) is used as a surrogate where DEM quality or resolution is insufficient







DEM-based river arcs,

- chaotic where DEM does not resolve the small rivers

NHD-based river arcs,

- much cleaner but an estimated channel depth is needed
- Useful for on-demand forecast by blending the locally refined mesh with the background STOFS-3D mesh

☛ Felicio's talk

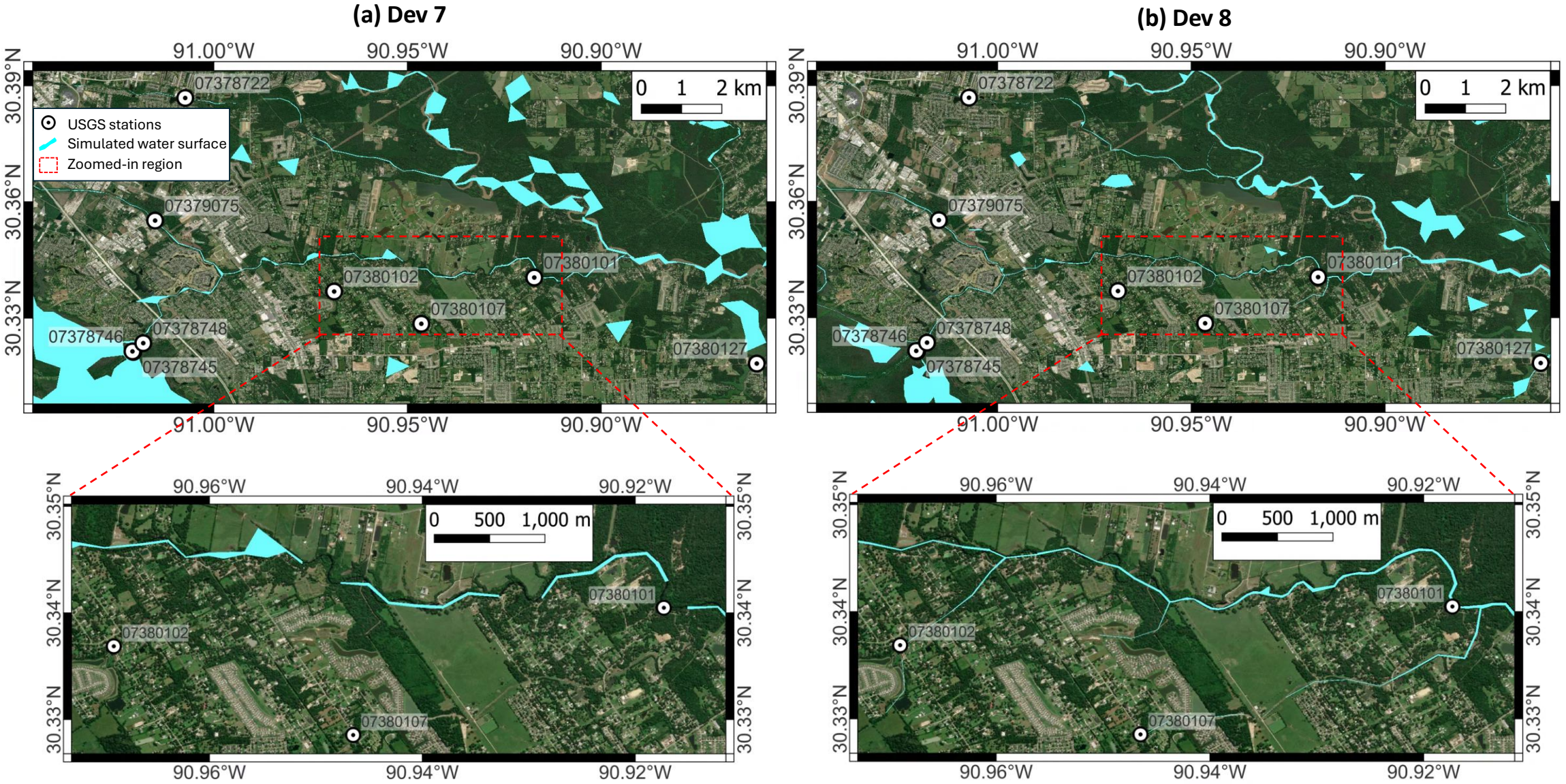
Development for future upgrades | Alternative meshing option based on NHD

Resolving tiny creeks among residential areas

Important for local inundation patterns.

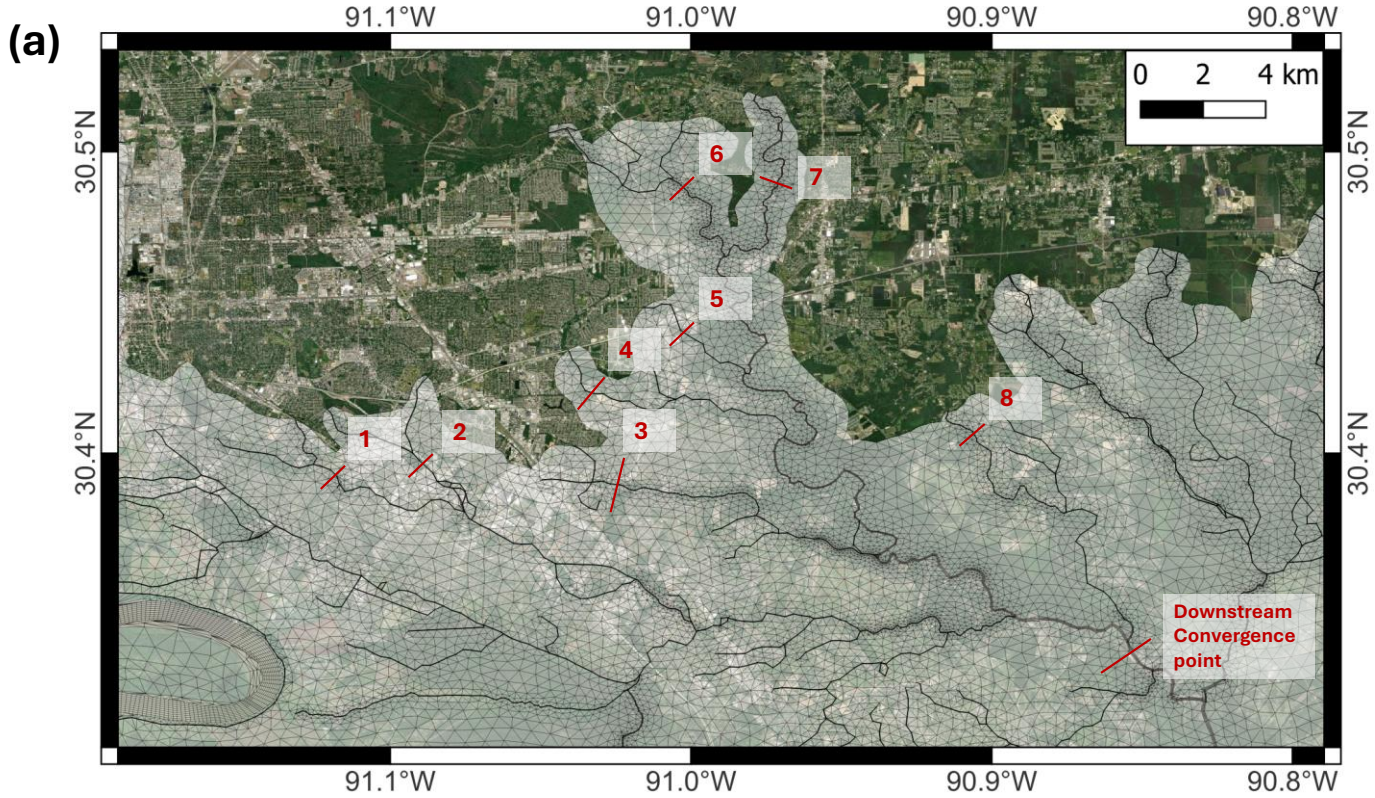
There is no strict limit on finest resolution in SCHISM

Qualitative improvement in the connectivity of small rivers and creeks



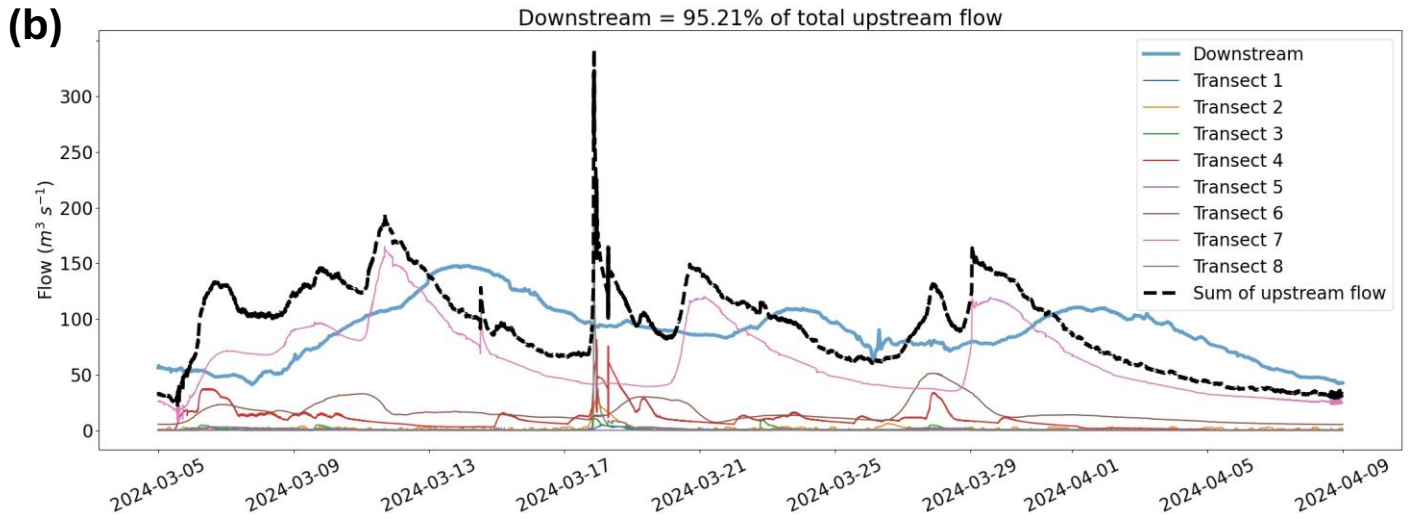
Development for future upgrades | Alternative meshing option based on NHD

Test on the channel connectivity and routing:
Eight tributaries feeding a common downstream convergence point



Downstream flow (**thick blue line**)
versus
total upstream flows (**thick black line**):

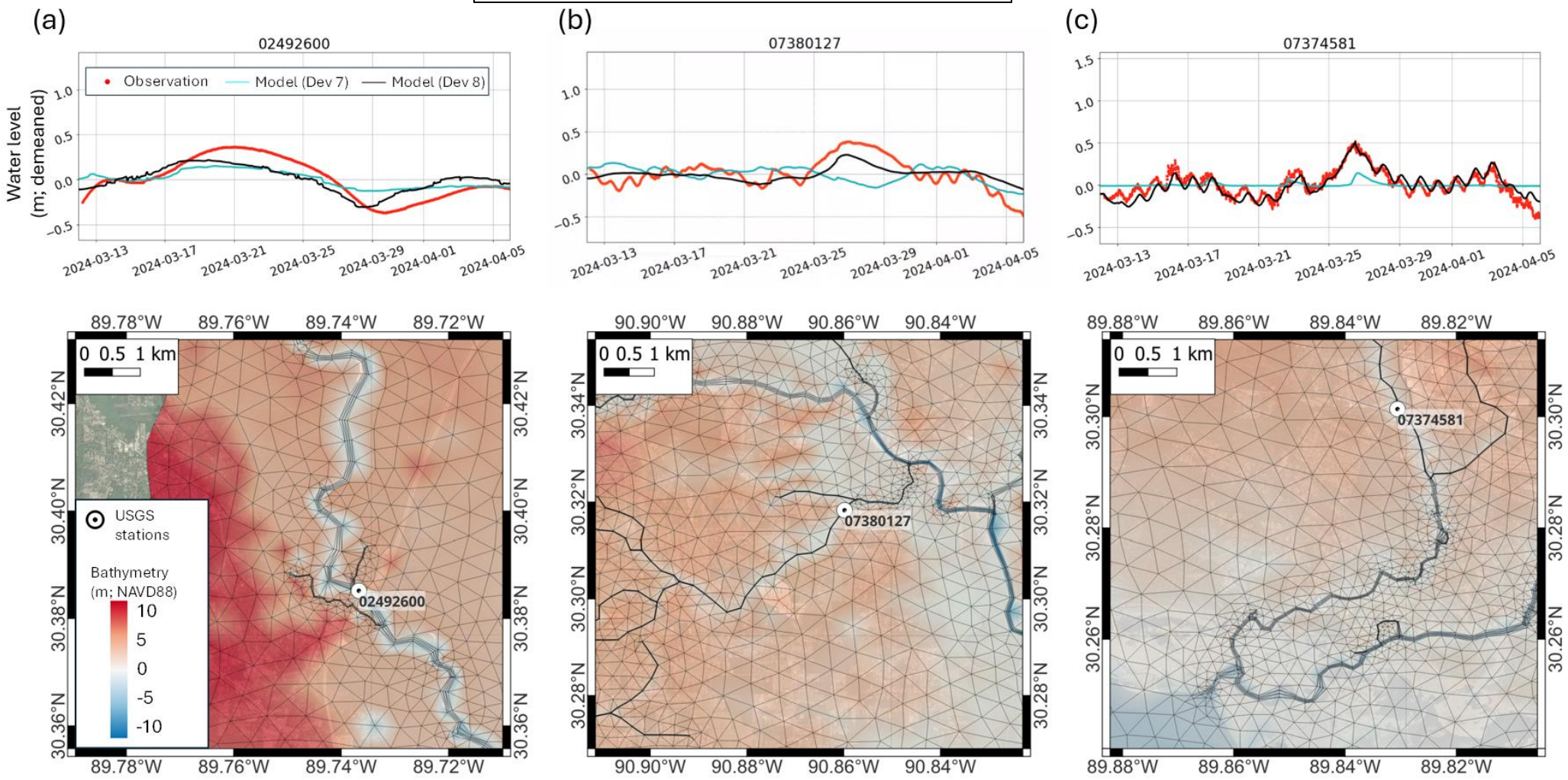
- 95% of upstream flow is successfully routed to the target node
- Validates integrity of hydraulic connectivity and mesh construction



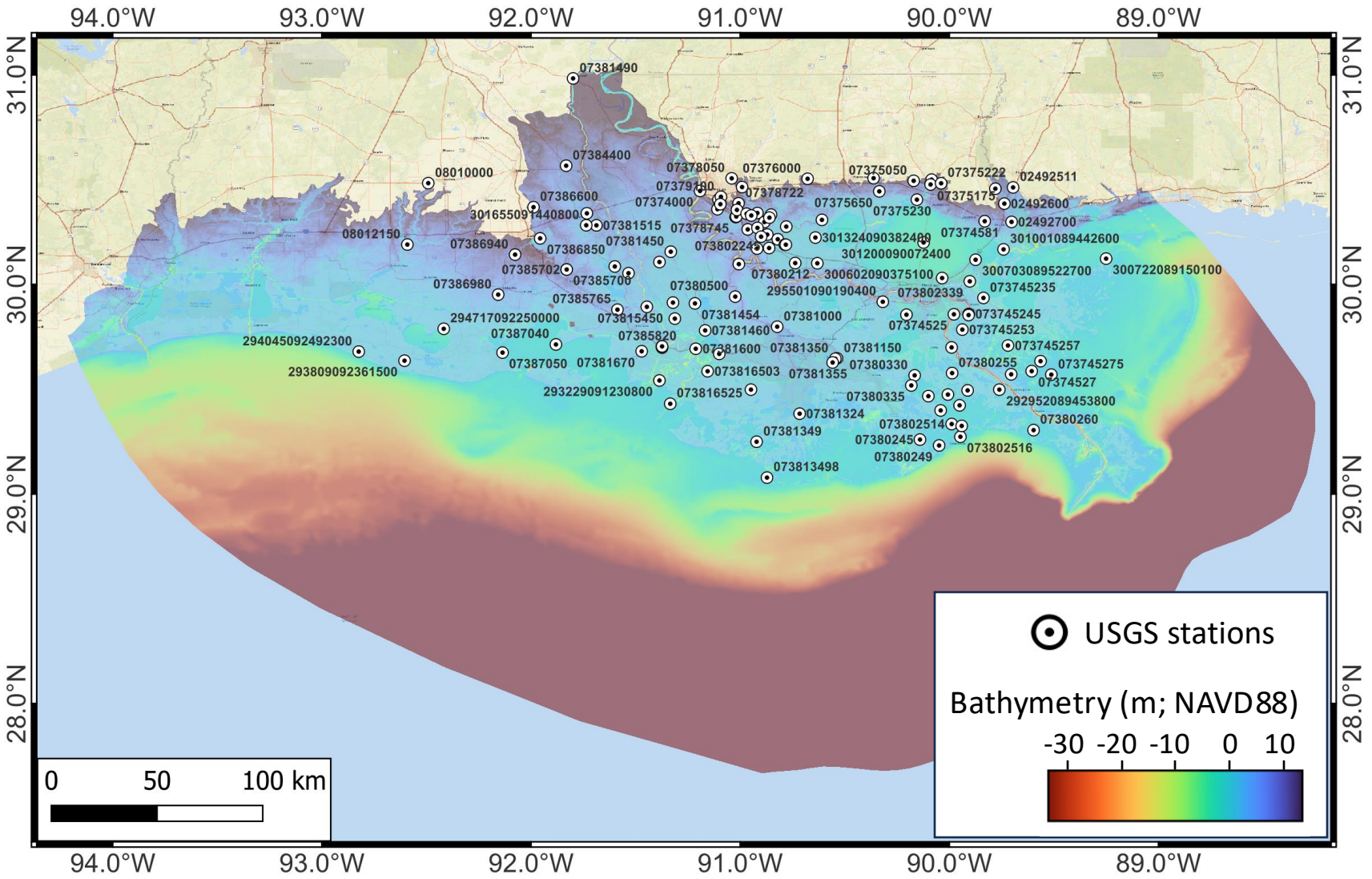
Ye et al. (in review)

Better DEM and meshing in the coastal transition zone → Improved water level prediction at USGS stations

OBS Old results **New results**



Development for future upgrades | Calibration at inland stations in the coastal transition zone



Better DEM and meshing in the coastal transition zone

Improved water level prediction at USGS stations

Error statistics of simulated water surface elevation at USGS stations

	Unbiased RMSE (cm)	Bias (cm)	RMSE (cm)	MAE (cm)
Dev 7	19.0	89.4	107.4	104.8
Dev 8	16.9	15.3	59.7	56.9

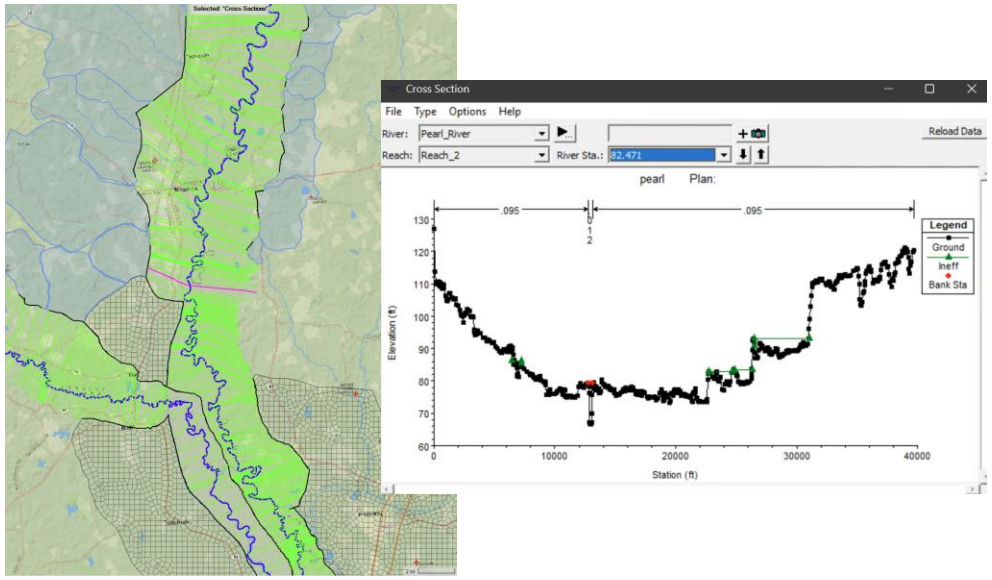
We would like to thank Jeffrey J. Danielson (USGS) for preparing and recommending the 2022 CoNED Topobathymetric Digital Elevation Models (NGOM-2 TBDEM)

Working directly with DEM providers

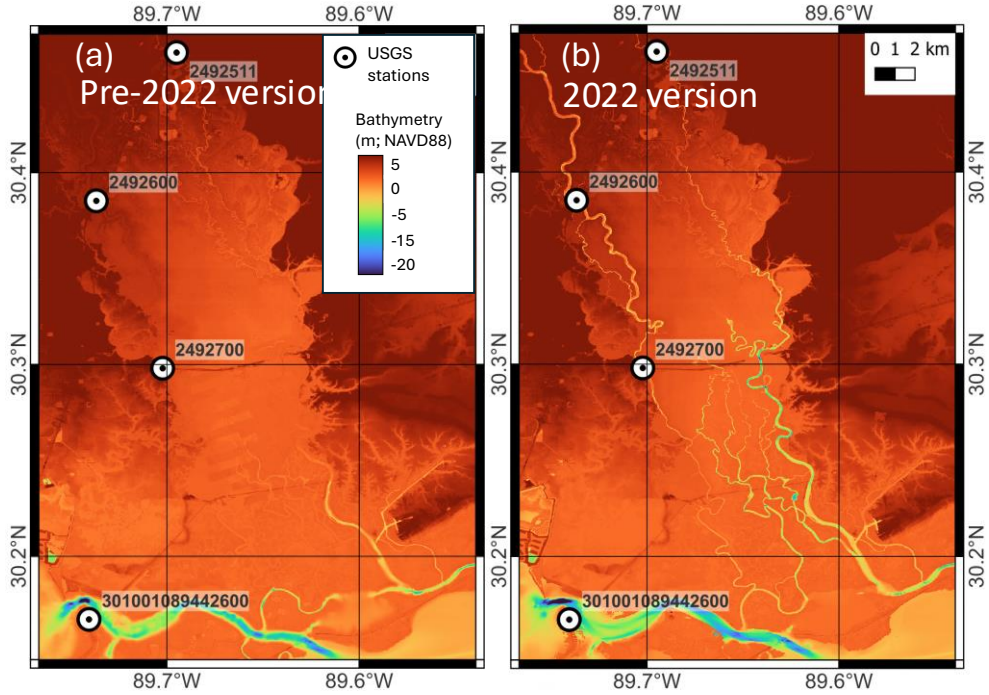
We would like to thank

- **Shachak Pe'eri** (NOAA NOS) for coordinating the DEM rectification in the New York Harbor study.
- **NOAA OCS** for improving the **BlueTopo** dataset and developing the Python package BlueTopo (https://github.com/noaa-ocs-hydrography/BlueTopo) to facilitate its access.
- **David Welch** (Lower Mississippi River Forecast Center, NOAA NWS) for sharing HEC-RAS models of the Mississippi and Atchafalaya Rivers, which include detailed bathymetry data.
- **Jeffrey J. Danielson** (USGS) for preparing and recommending the 2022 CoNED Topobathymetric Digital Elevation Models (NGOM-2 TBDEM).

HEC-RAS transects



CoNED around Pearl River, Louisiana

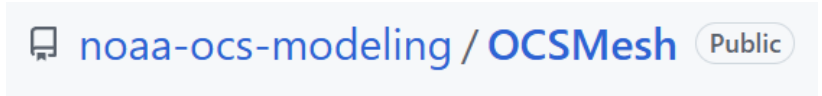


Publicly accessible on GitHub

- **RiverMeshTools**:
  Automatic feature arc extraction for watershed channels

- **STOFS-3D-Atl setup script**:
  Automated configuration for compound flood simulations

- **OCSMesh**:
  Automated mesh preparation tool developed by NOAA OCS for coastal ocean modeling applications.



August 5, 2025, 1 pm US EST. Saeed Moghimi, Felicio Cassalho, Soroosh Mani. Toward a fully automatic mesh generator with application to 3D compound flooding study

Defensible 3D modeling via judicious meshing

- SG or UG model alike, entire workflow (from DEM to analysis) should be defensible & reproducible
- Faithful representation of DEM in the models should underpin coastal modeling
  - Improvement in DEM should lead to improved model skill
- Detailed guidelines are now available for mesh generation for SCHISM, that are centered on honoring the underlying DEM and capturing processes
- Semi- and fully automatic meshing tools represent a new paradigm
  - Eddying regime with steep slopes: delineate regimes but avoid sharp tra in resolution
  - Coastal regime: liberal use of mesh constraints to capture import (channels, levees etc)
  - Successfully applied to watershed meshing for compound flood
  - No formal limit on finest resolution allowed
  - Relentless pursuit of realism with these new tools
  - Even adaptable, on-demand mesh (OCSMesh)