Mesh independent flow direction modeling using HexWatershed 3.0

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U.S. DEPARTMENT OF ENERGY BATTELLE

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CSDMS 2024: *Clinic 3.2*

Links to GitHub

https://github.com/changliao1025/pyflowline_tutorial

https://github.com/changliao1025/hexwatershed_tutorial

Open the MyBinder links in both repositories.

Outline

- Part I
  - Mesh
  - River networks
  - Project
  - Model structure
- Part II PyFlowline tutorial
  - Flowline simplification
  - Mesh generation
  - Topological relationship reconstruction
- Part III HexWatershed tutorial
  - Elevation
  - Stream burning and depression filling
  - Visualization and application
- Part IV Q&A

- High-level introduction to HexWatershed
- Focus is “What” not “How”
- See potential? Let’s collaborate!

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Mesh 101

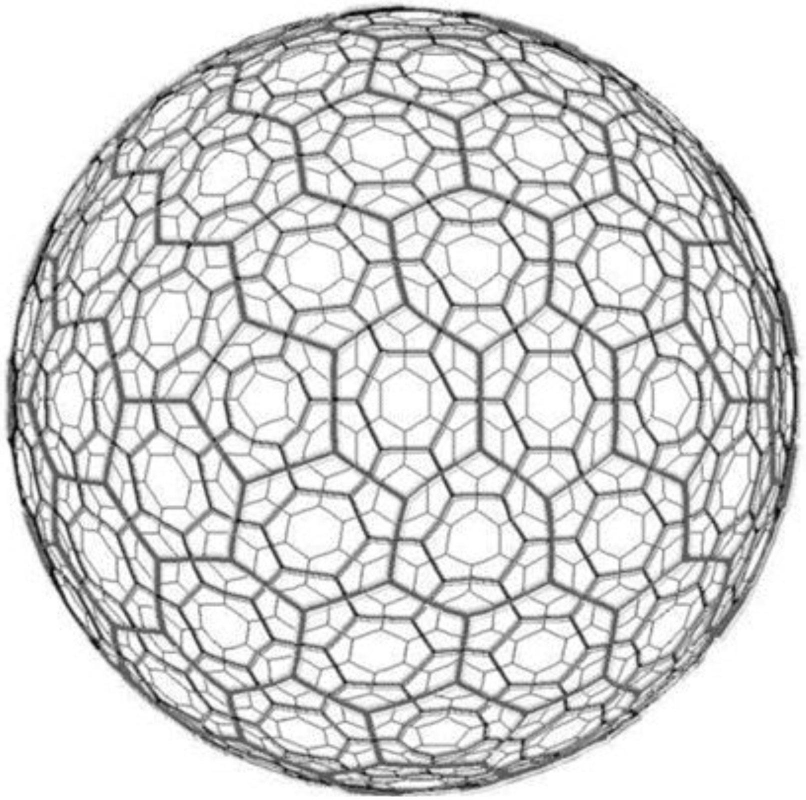
A mesh is a representation of a larger spatial domain by smaller discrete cells.

Commonly used meshes:

- Latitude-longitude mesh (0.5 * 0.5 degree, 1km at the equator, etc.)
- Projected mesh (90 * 90 m)
- Triangulated irregular network (TIN)

Less commonly used meshes:

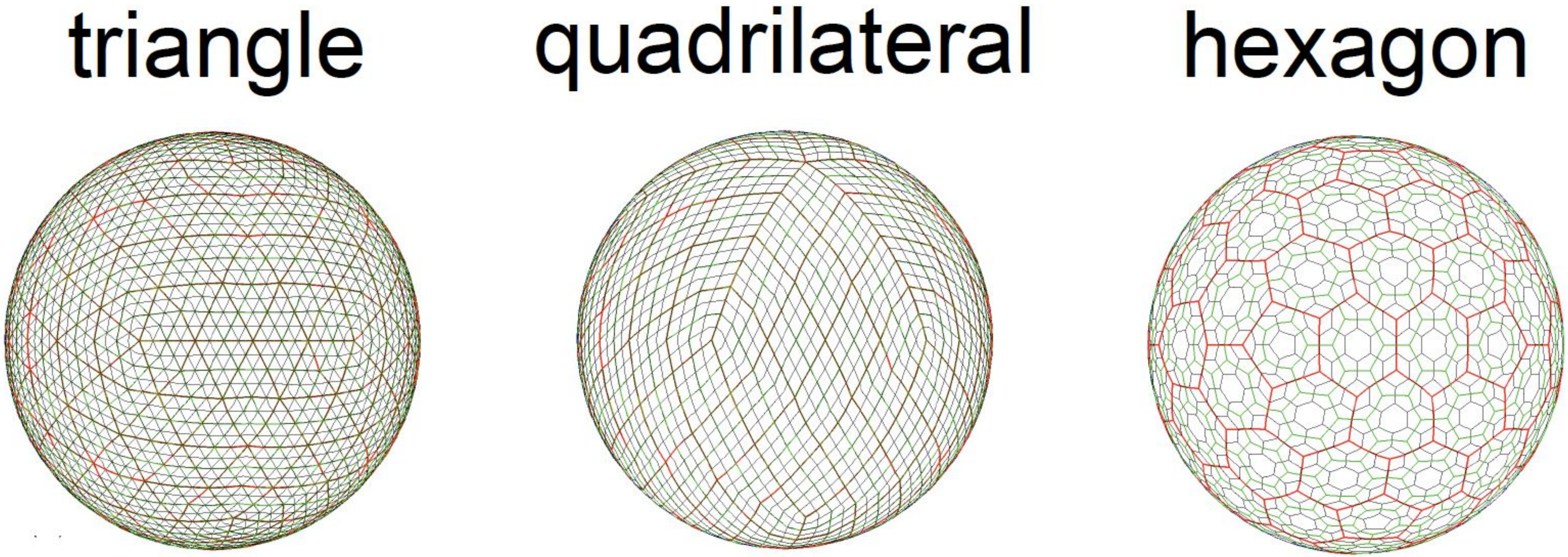
- MPAS mesh, twin/dual mesh of TIN
- Discrete Global Grid Systems (DGGS)



DGGRID generated DGGs mesh

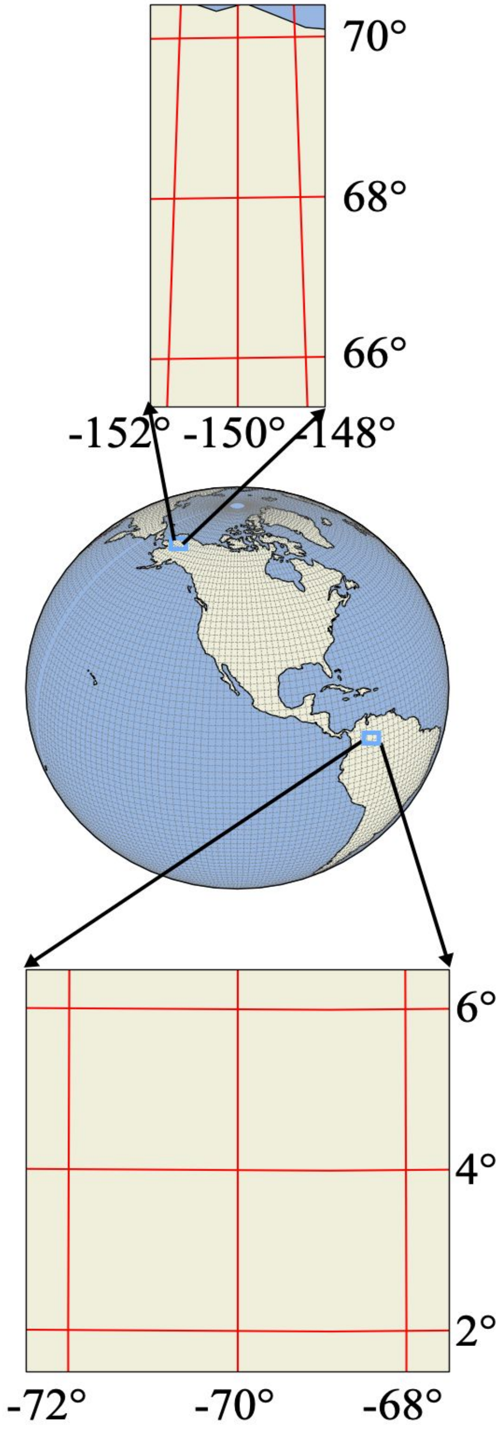
DGGs Mesh

https://github.com/sahrk/DGGRID

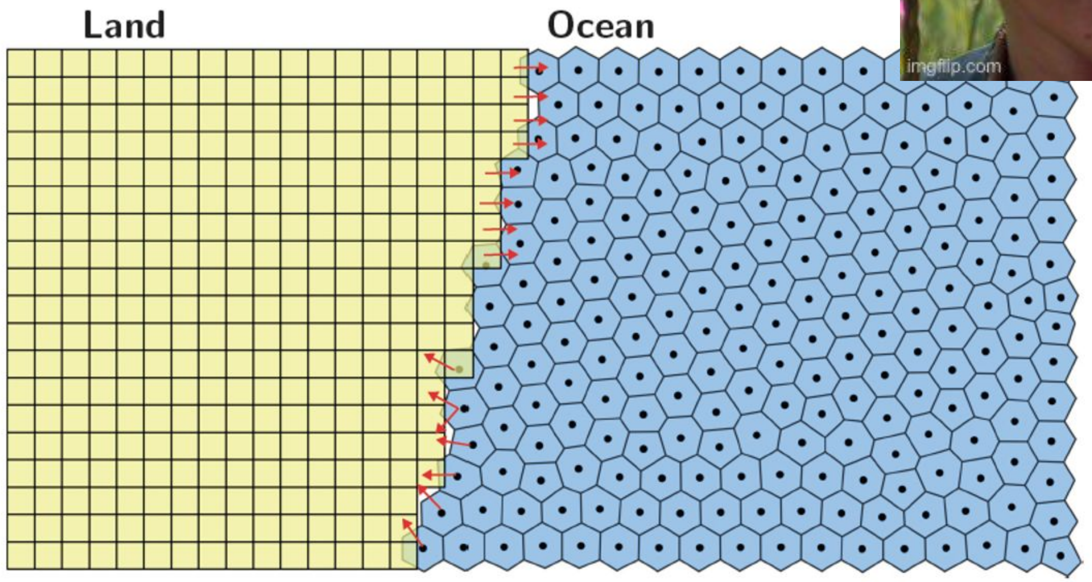


DGGRID generated DGGs mesh

Mesh Affects the Performance of Numerical Models

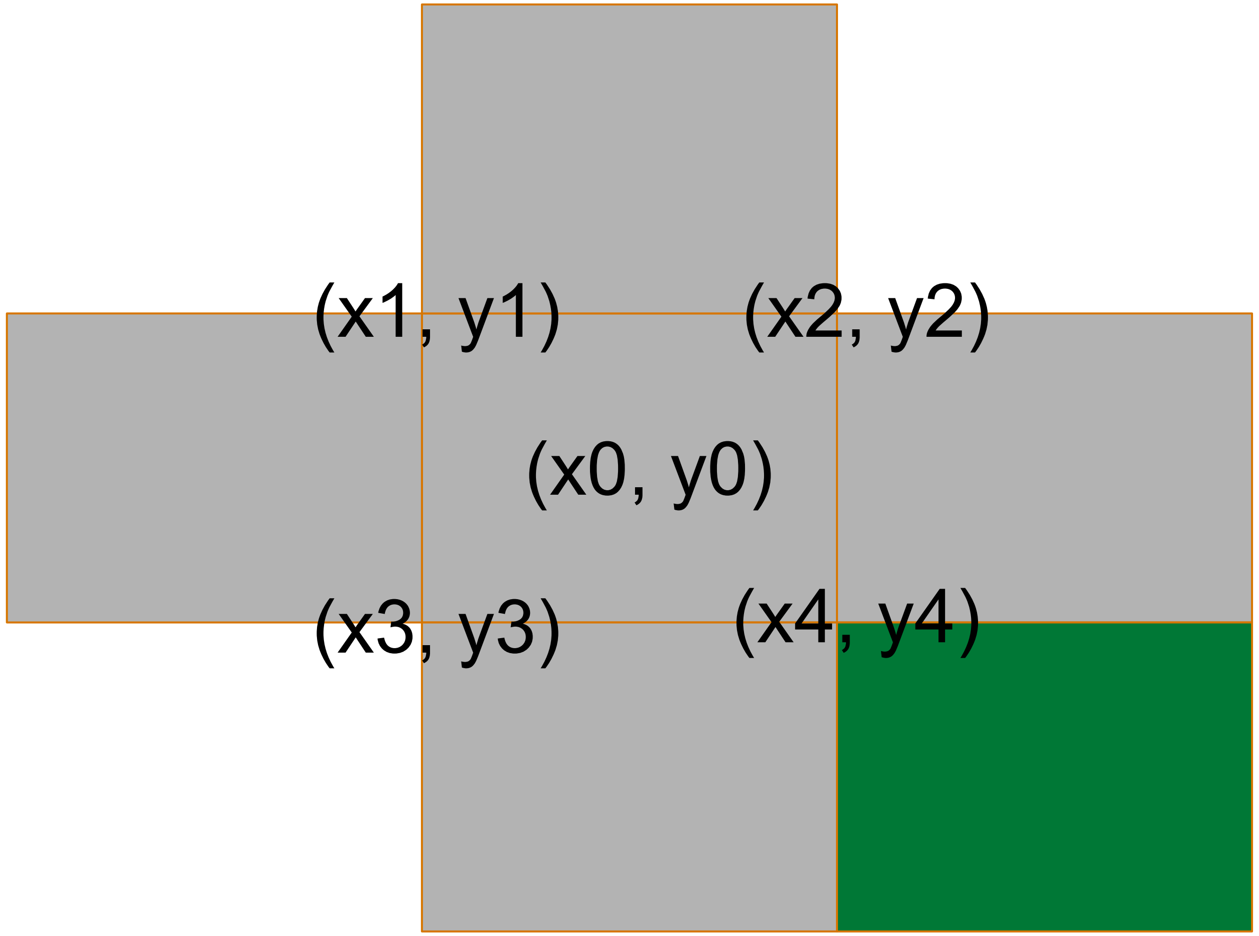


- Spatial distortion caused by latitude/longitude ratio.
- Difficulty when implementing two-way coupling between land and ocean components



Land-Ocean interface

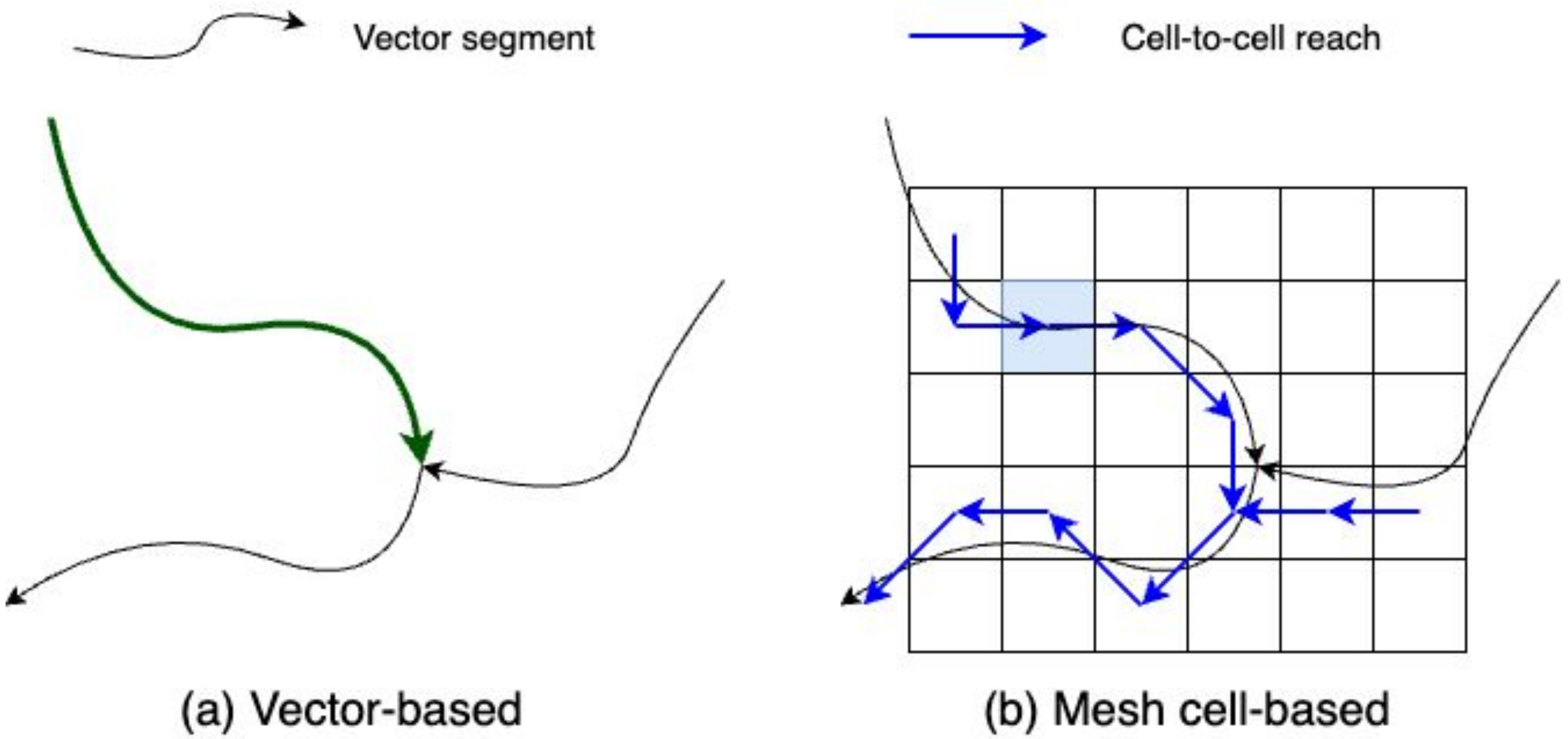
Describe a Mesh Cell and its Neighbors



- Vertex: a list of points (x, y) or (lon, lat) pair.
- Center: a point (x, y) or (lon, lat) pair.
- Edge: two connected neighboring vertices.
- Area: on a plane or sphere.
- Neighbor: index or ID.

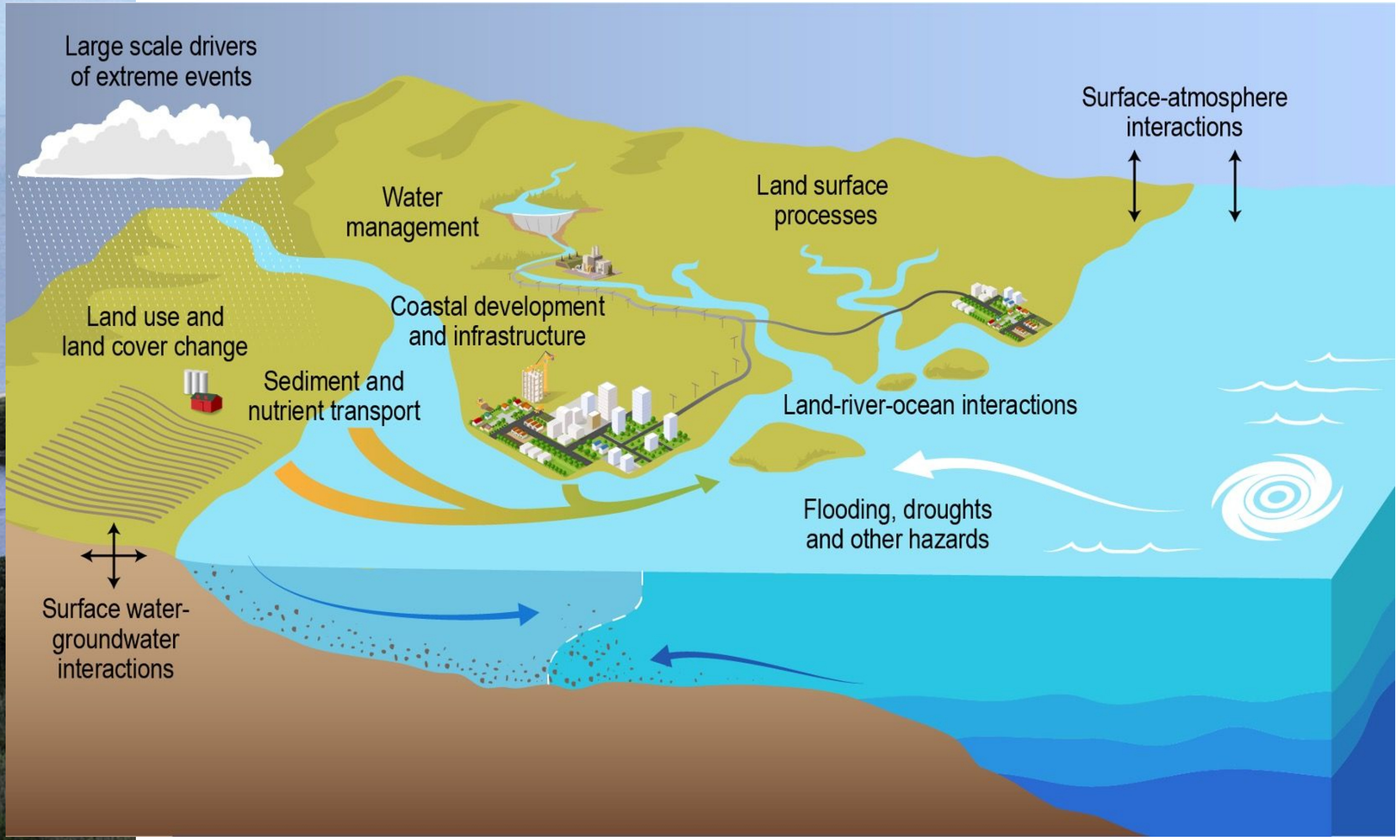
River Networks, and maybe Lakes, too.

(Conceptually) River networks are vector line segments.



Numerical models often require river networks to be mesh cell-based.

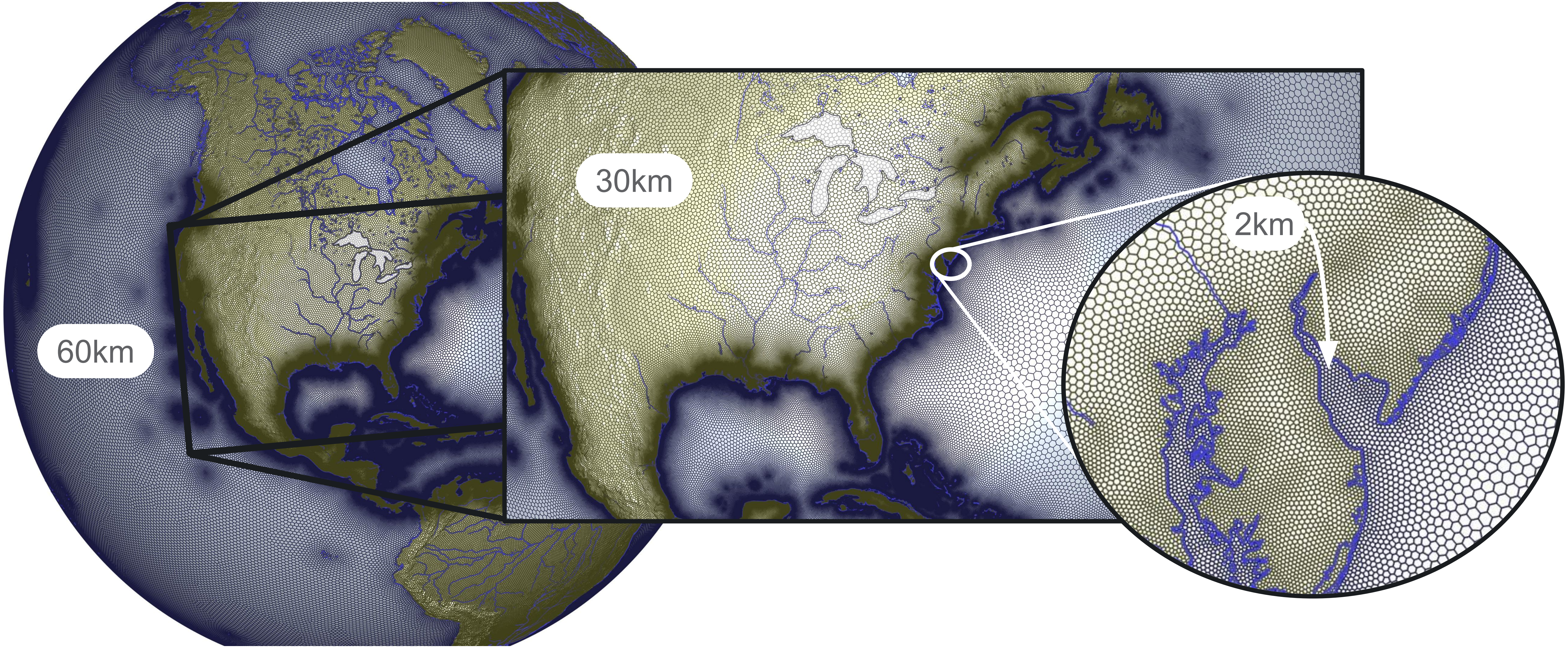
Project Background



ICoM is a multi-institutional effort led by the Pacific Northwest National Laboratory and funded by the U.S. Department of Energy (DOE). Our long-term vision is to deliver a robust predictive understanding of **coastal evolution** that accounts for the complex, multi-scale interactions among physical, environmental, and human systems.

Integrating leading expertise and data resources across the U.S. Department of Energy (DOE) complex, a new research project—the Interdisciplinary Research for **Arctic Coastal Environments** (InteRFACE)—is designed to improve fundamental understanding of change in arctic coastal systems.

Mesh Improves the Performance of Numerical Models



MPAS mesh

(Darren Engwirda, etc. https://github.com/dengwirda/jigsaw)

Relevant Publications

- Simulation of **Compound Flooding** using River-Ocean Two-way Coupled E3SM Ensemble on Variable-resolution Meshes. Journal: Journal of Advances in Modeling Earth Systems
- Feng, D., Tan, Z., Engwirda, D., Liao, C., Xu, D., Bisht, G., Zhou, T., Li, H.-Y., and Leung, L. R.: Investigating **Coastal backwater effects** and flooding in the coastal zone using a global river transport model on an unstructured mesh, Hydrol. Earth Syst. Sci., 26, 5473–5491, https://doi.org/10.5194/hess-26-5473-2022, 2022.
- Liao, C., Zhou, T., Xu, D., Cooper, M. G., Engwirda, D., Li, H.-Y., & Leung, L. R. (2023). Topological relationship-based flow direction modeling: Mesh-independent river networks representation. *Journal of Advances in Modeling Earth Systems*, 15, e2022MS003089
- Liao, C., Zhou, T., Xu, D., Tan, Z., Bisht, G., Cooper, M. G., et al. (2023). Topological relationship-based flow direction modeling: Stream burning and depression filling. *Journal of Advances in Modeling Earth Systems*, 15, e2022MS003487.

HexWatershed Version History

Version 1 (2020)

- Elevation based depression filling
- Only supports hexagon
- Written in C++11.

Version 2 (2022)

- Rasterization-based stream burning
- Topological relationship-based stream burning

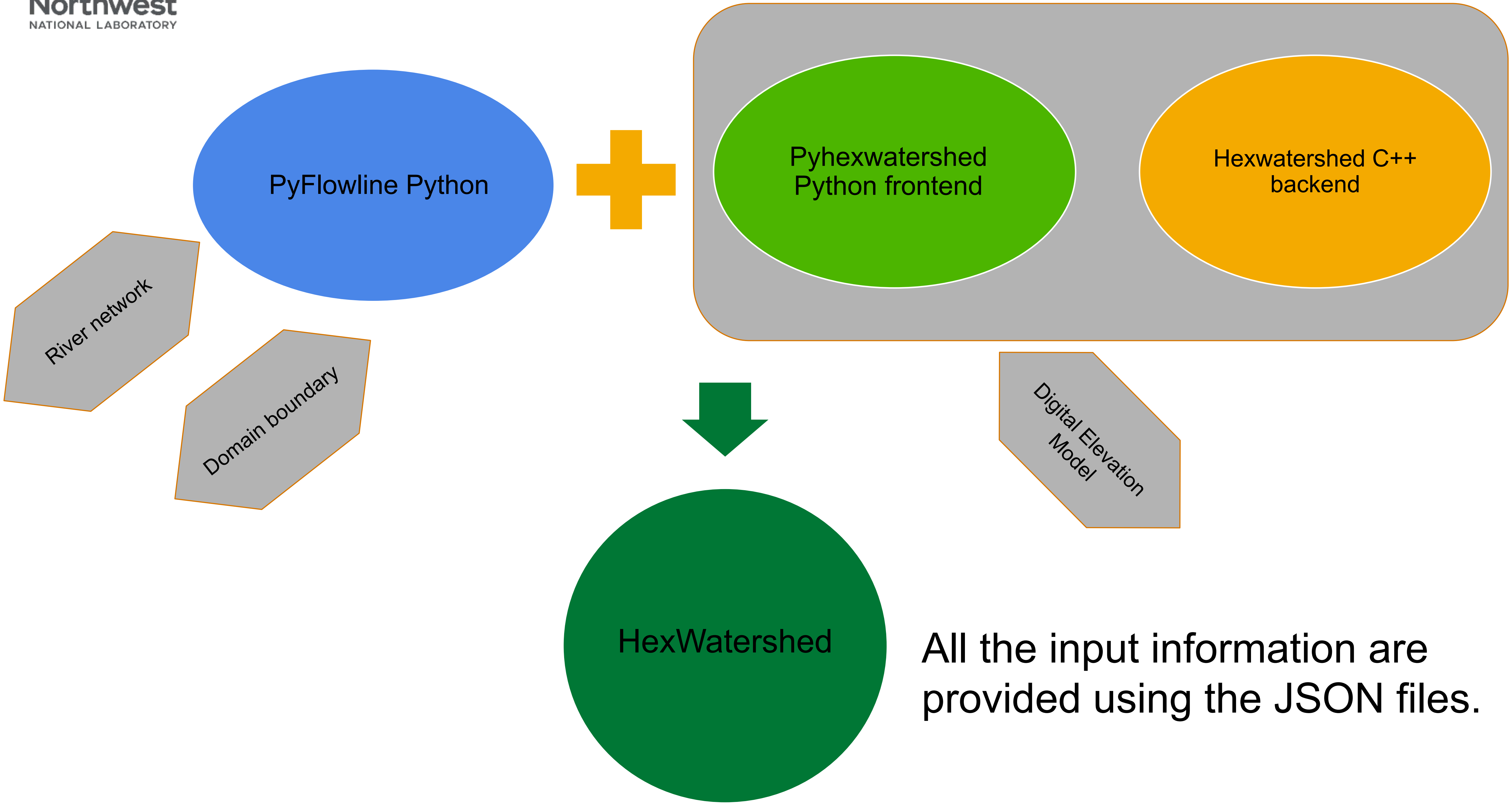
Version 3 (2023)

- Topological relationship-based river network representation
- Topological relationship-based stream burning
- Fully support unstructured meshes (DGGs)
- Hybrid Python and C++ structure

Version 4 (ongoing)

- Lake burning
- Hillslope
- Integration with GeoVista/VTK
- Global application
- Checkpoint

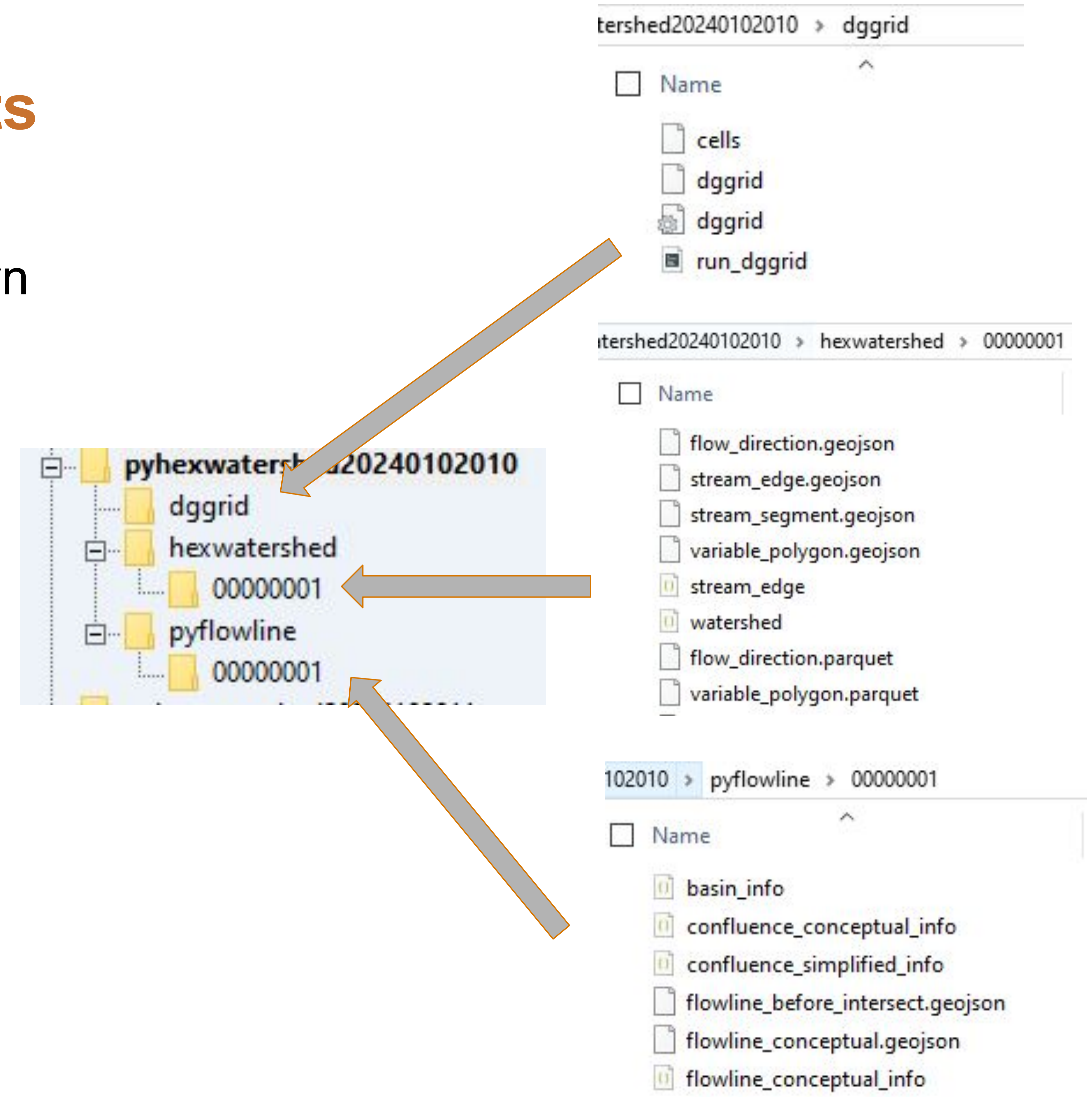
Model Structure and Inputs



All the input information are provided using the JSON files.

Model Outputs

- ➢ Each component has its own output directory.
- ➢ Each directory contains various outputs
  - dggrid (if used): mesh
  - pyflowline: river network, etc
  - hexwatershed: flow direction, etc.
- ➢ Files are organized by domains.
- ➢ Geospatial data formats for easy visualization



Installation

- CMake 3.28 and above
- C++ compiler 8.1.0 and above
- Conda 4.10 and above (anaconda or miniconda)
- QGIS visualization (optional)

1. Create a folder for this tutorial:
   mkdir hexwatershed_tutorial
   cd hexwatershed_tutorial
2. Download C++ backend:
   git clone
   https://github.com/changliao1025/hexwatershed.git
   mkdir build
   cd build
3. Compile and build
   cmake .. -DCMAKE_CXX_COMPILER=g++-11
   make install
4. Install Python package (*py*hexwatershed)
   conda create --name hexwatershed
   conda activate hexwatershed
   conda install -c conda-forge hexwatershed

If you encounter any issue, please refer to the documentation.

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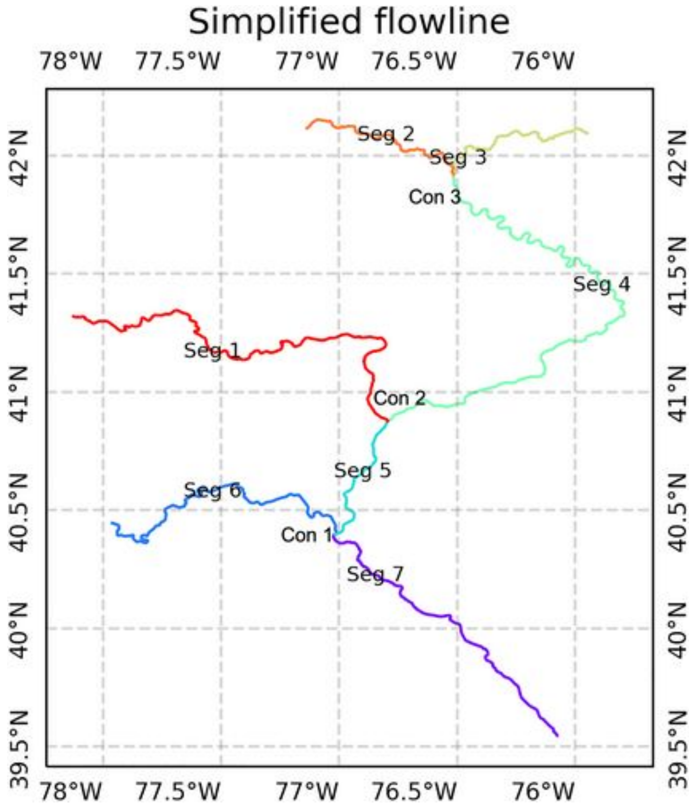
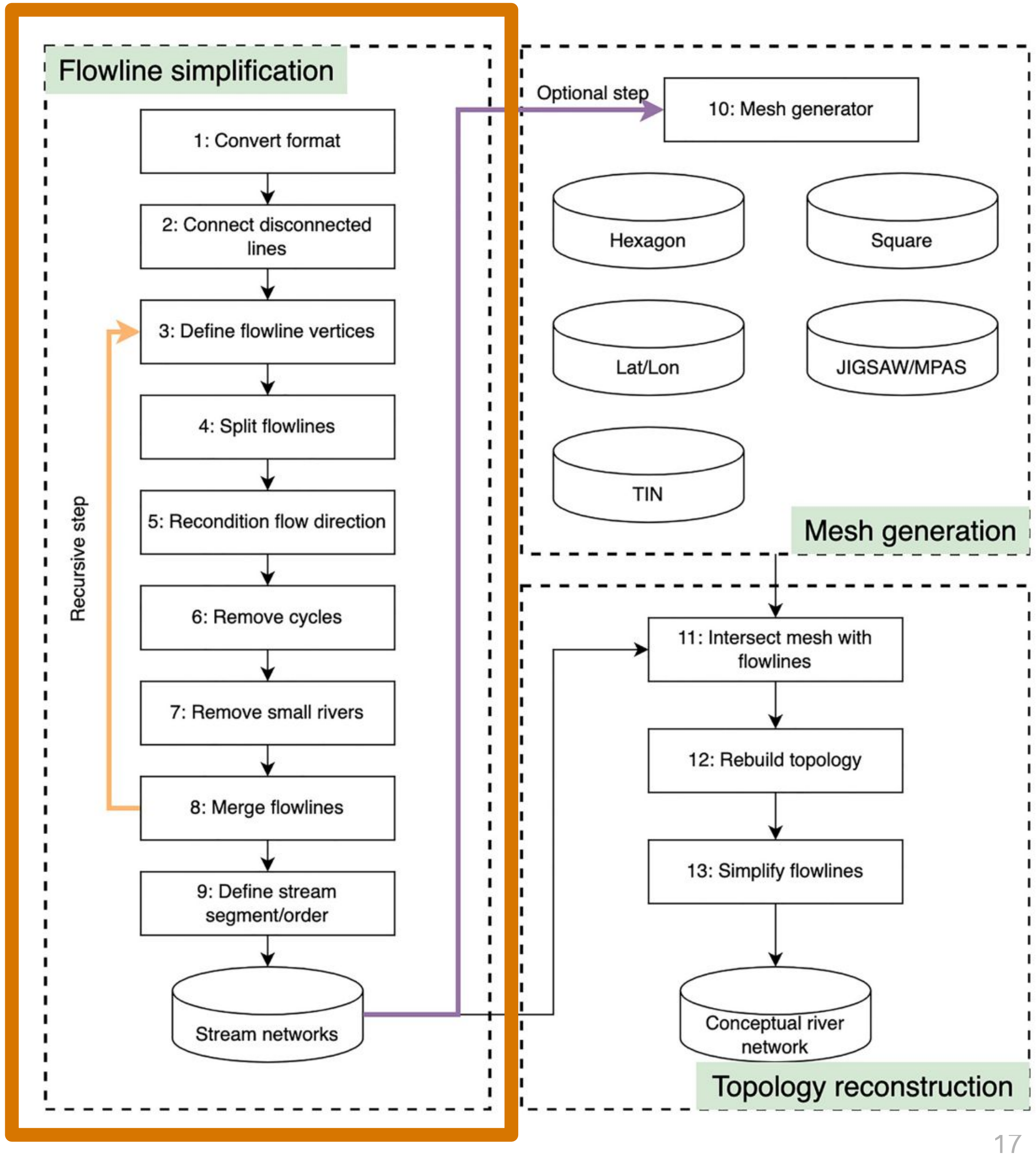
Flowline simplification

Preprocess flowlines for mesh intersection

- Remove loops/braided rivers
- Remove small rivers
- Re-assign stream index and order



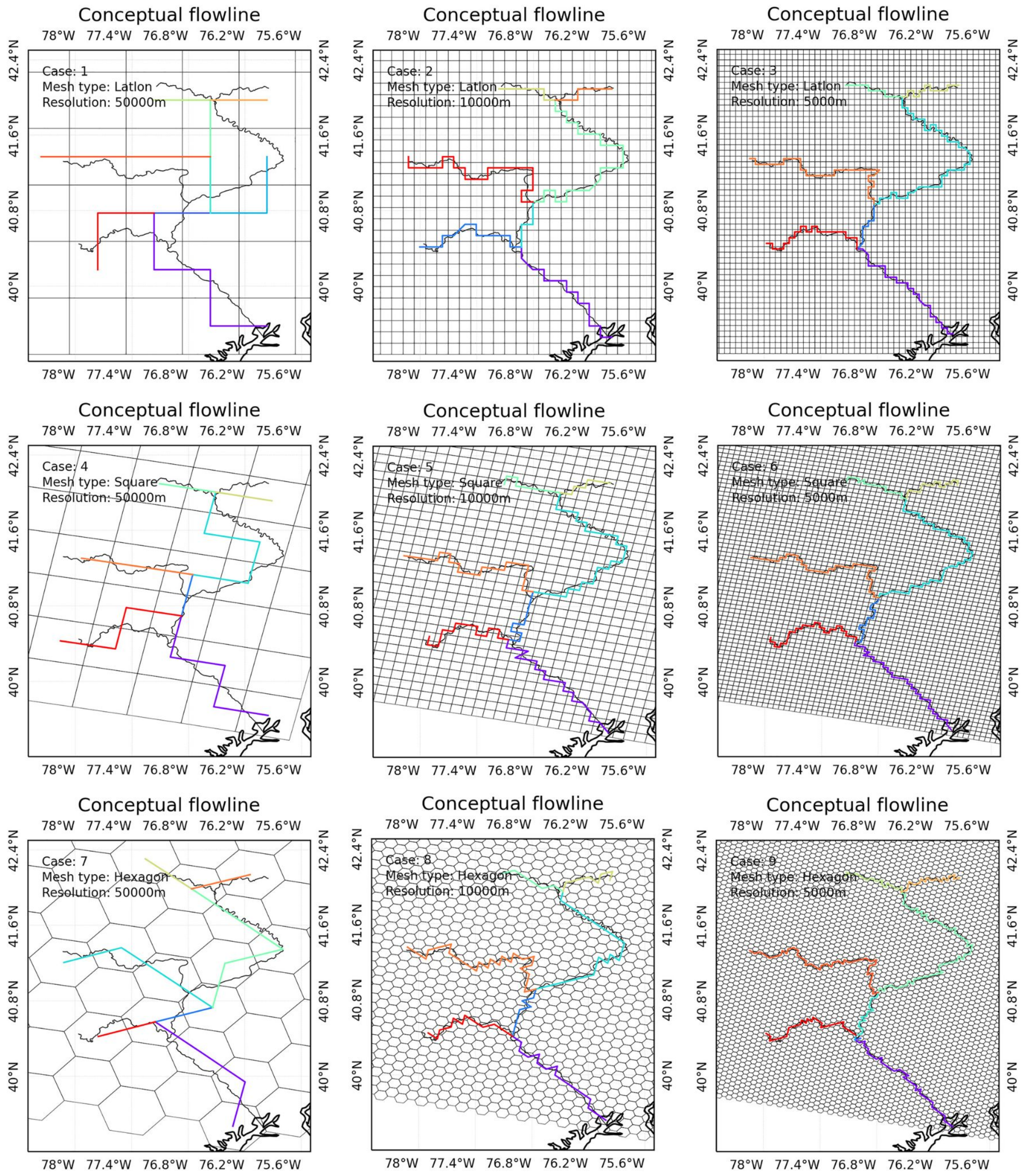
Outcome:
A river network with index in the minimal format.



Mesh Generation

Generate a mesh that can be used for intersection.

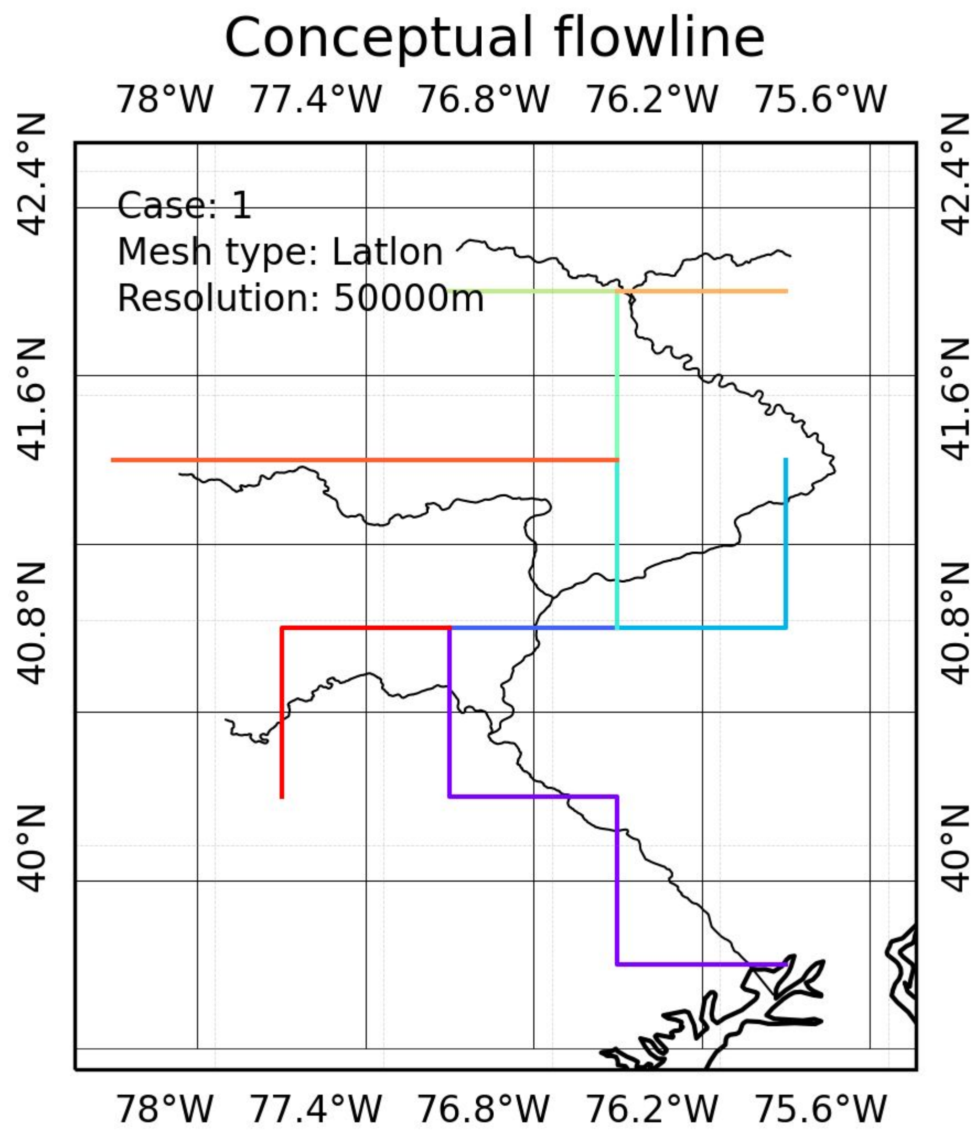
- Built-in APIs for simple structured meshes (lat-lon, hexagon, projected)
- **APIs to run DGGRID**
- APIs to read MPAS mesh
- …
- (DEM not required … but can be supplied to define the domain)



Topological Relationship Reconstruction

Turn simplified river networks into mesh cell-based river networks

- Resolve parallel rivers
- Preserve river meander
- Preserve river confluence
- …



Note: not all mesh cells have river network.
(that is done in HexWatershed)

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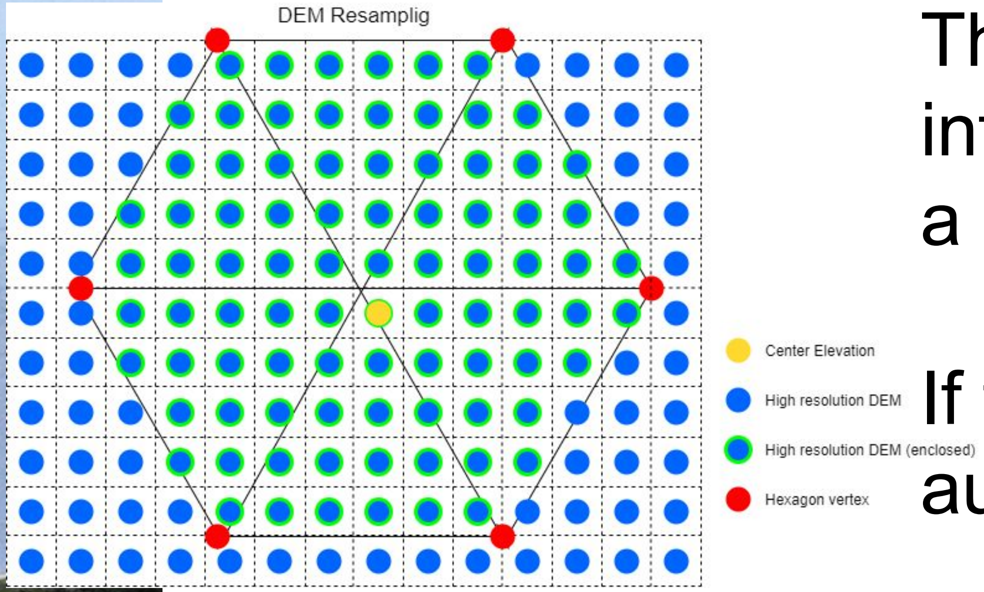
Elevation Assignation



The mesh and the river networks do not have elevation information, and this function will assign each mesh cell with a mean elevation based on the DEM.

If the outlet cell has no valid elevation, the model will automatically search upstream until a valid one is found.

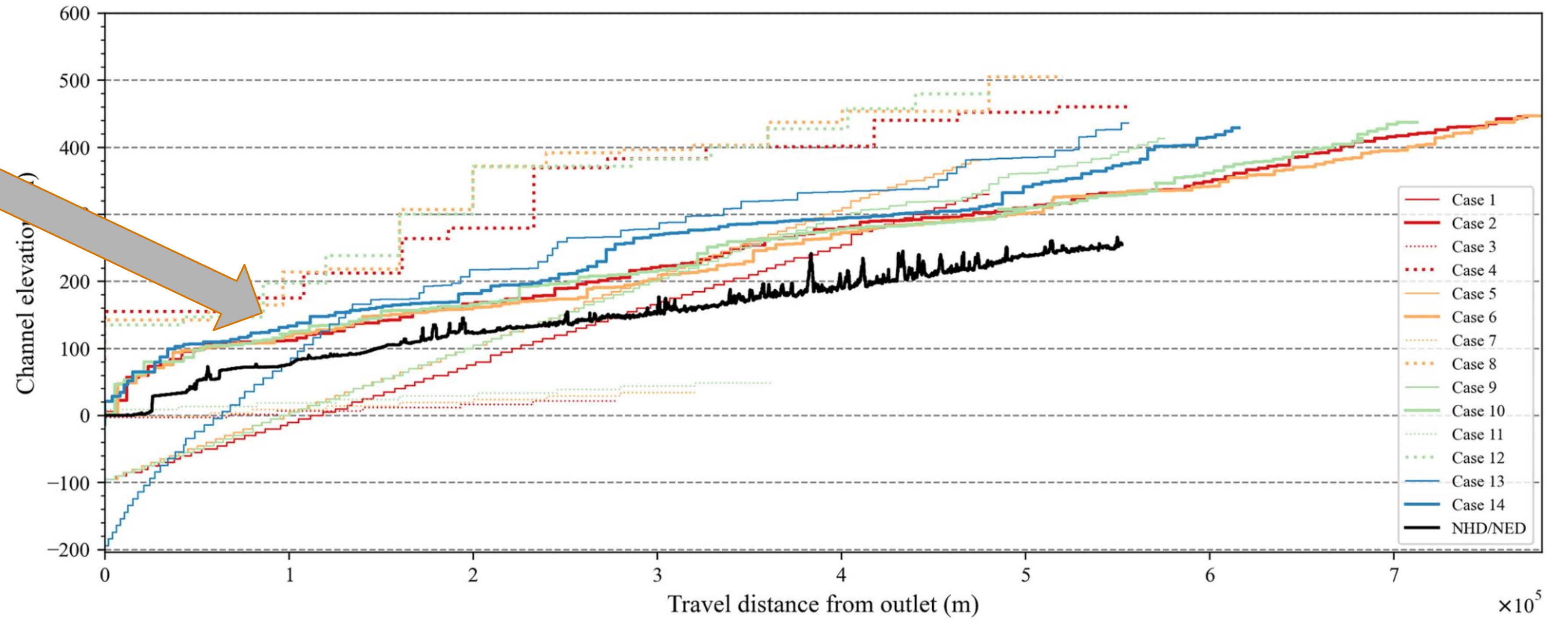
Tips:

1. Make sure the DEM covers the whole domain, it is recommended to clip the DEM using the same domain boundary;
2. Check the DEM nodata, as they will be excluded during calculation.

Topological Relationship-based Stream Burning

HexWatershed uses the PyFlowline generated river networks (with upstream-downstream topology) to modify elevation in the river networks and near the riparian zones, thus produces:

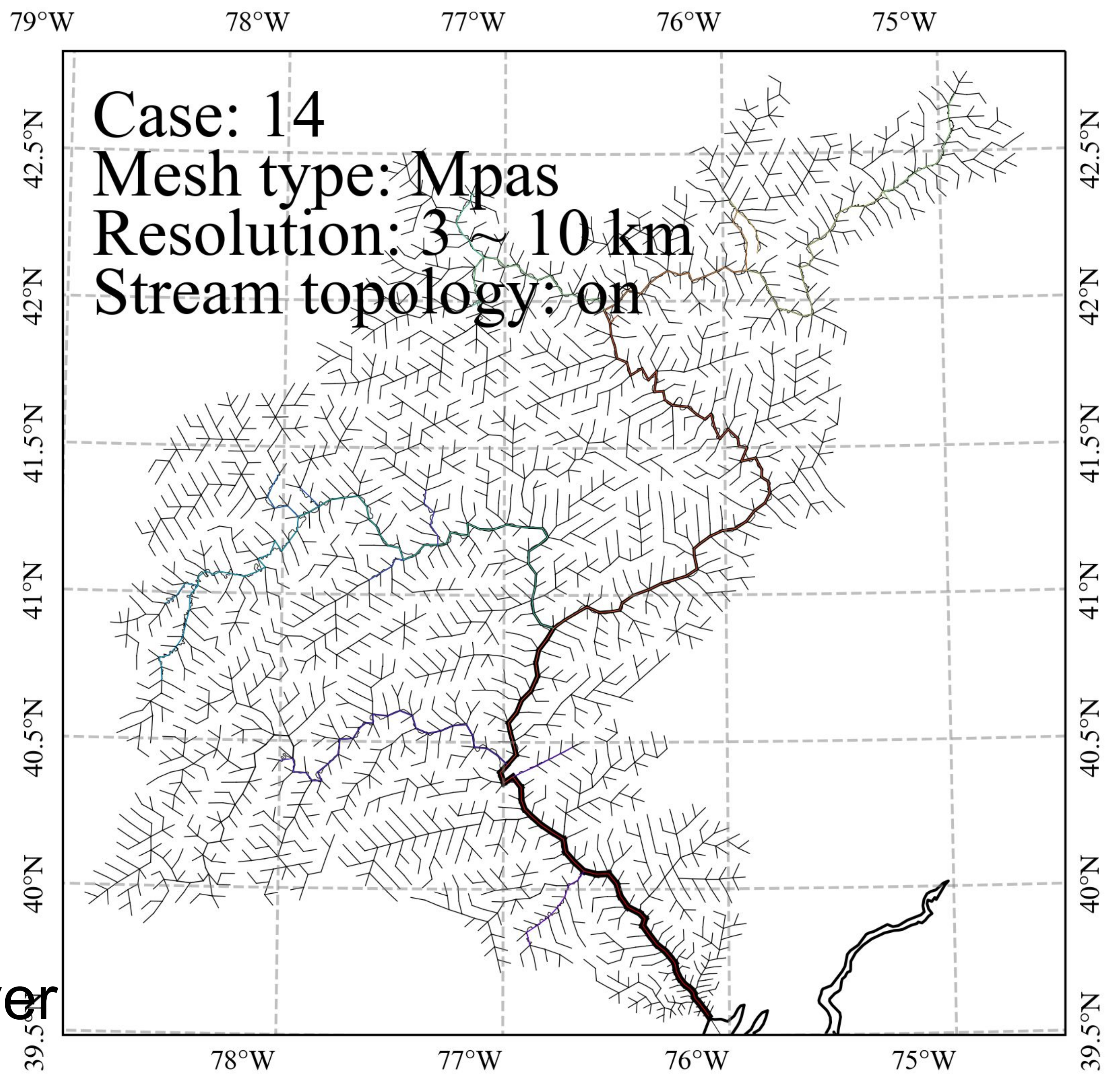
- flow direction in the river networks that are consistent with PyFlowline generated river networks
- river channel elevation and slopes with minimal modifications.



Depression Filling

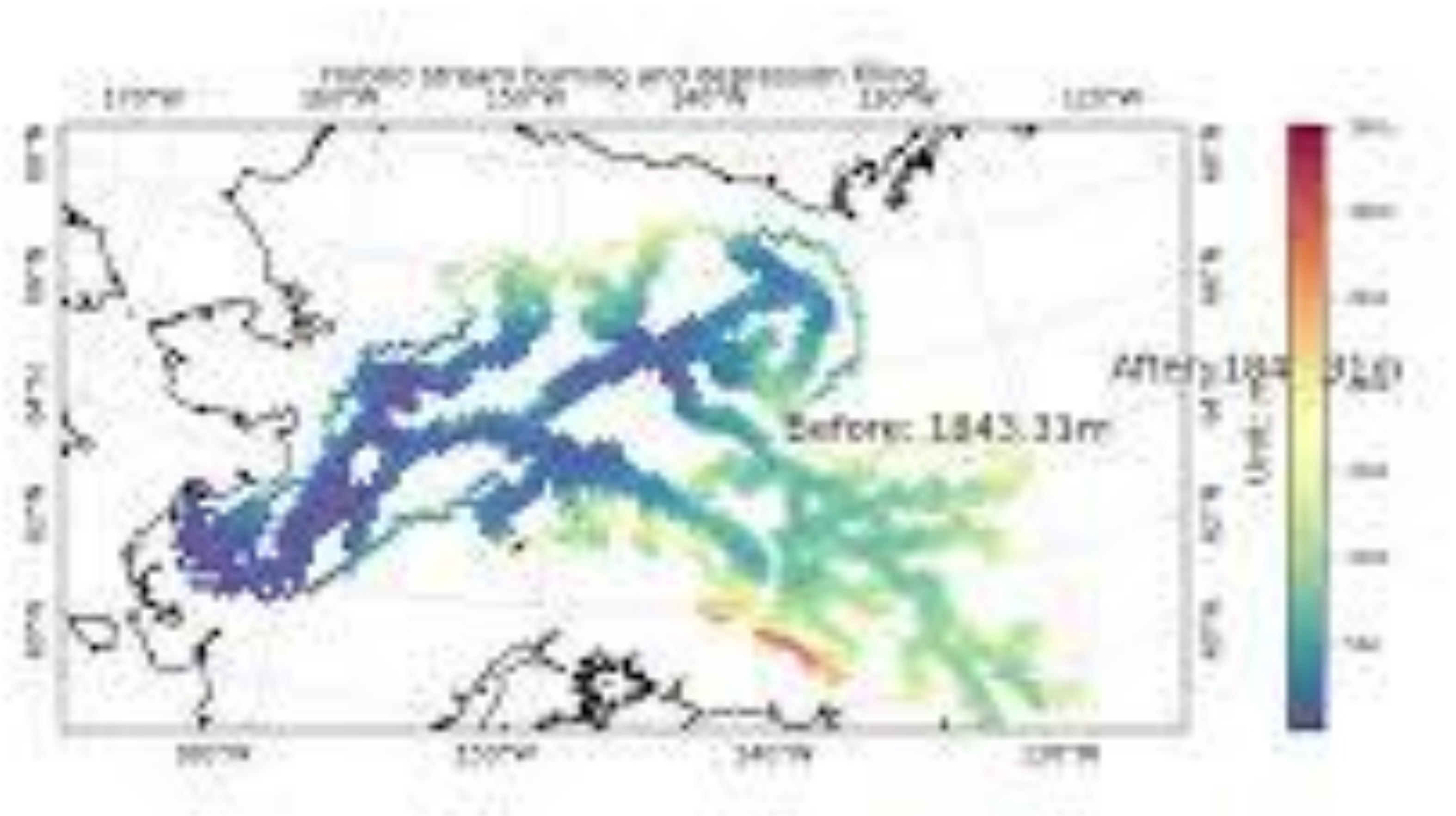
An upgraded "priority-flood" depression filling that:

- accepts unstructured meshes
- considers the stream burning (does not modify river/riparian zone elevations from previous step).



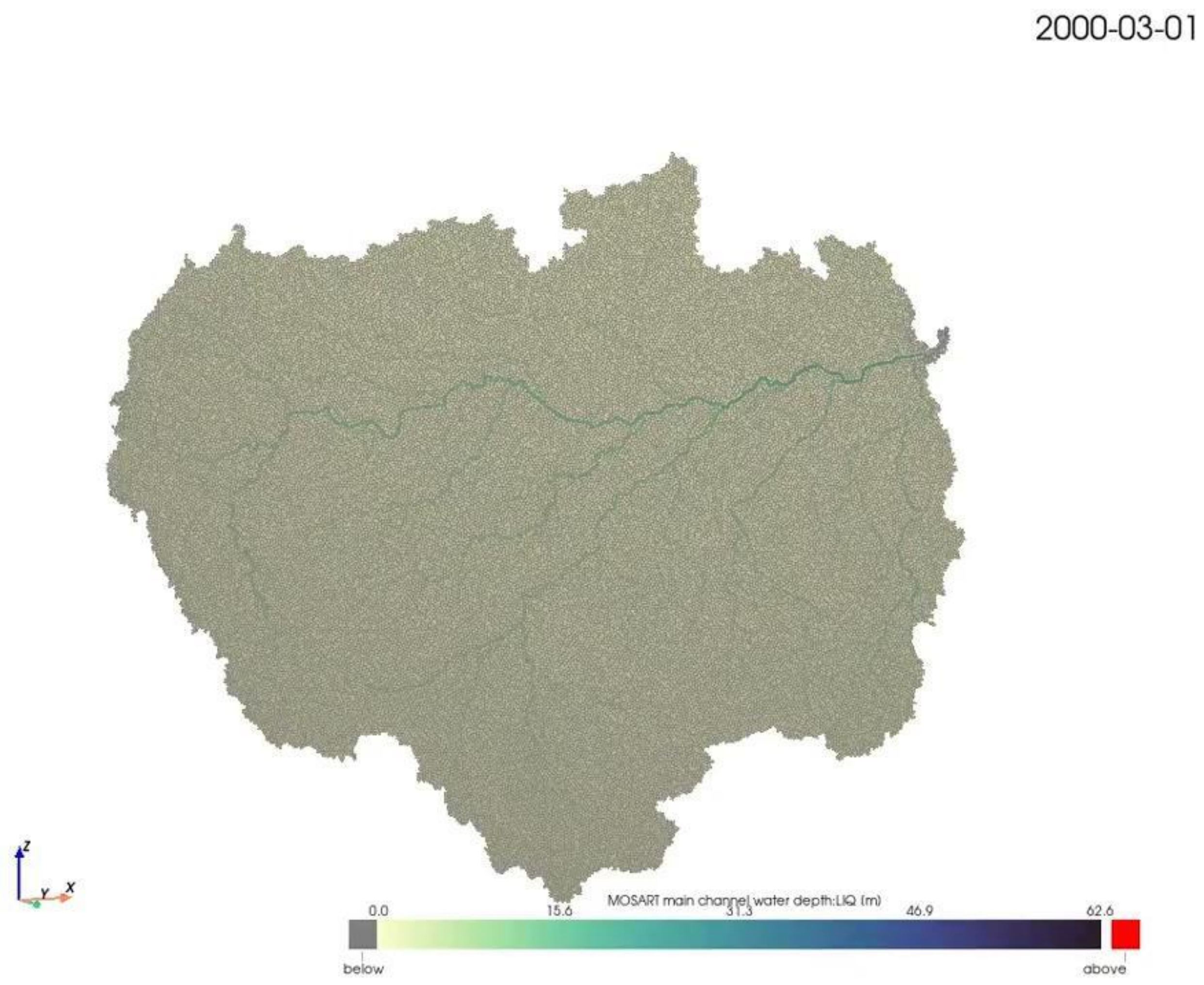
Note: now all mesh cells have "virtual" river networks.

Hybrid Stream Burning and Depression Filling



Visualization

- QGIS and other tools, model outputs use GeoJSON and Parquet formats, which supports data science (i.e., Hadoop ecosystem).
- Built-in APIs, based on PyEarth, Cartopy and Matplotlib
- GeoVista integration (planned).



MOSART modeled time series river depth in Amazon (GeoVista).

Applications

- ❑ E3SM MOSART simulation in the east coast, USA.
- ❑ E3SM MOSART simulation in Alaska, USA.
- ❑ E3SM MOSART simulation in Amazon river basin, South America.
- ❑ …

HexWaterhsed modeled flow direction in the Antarctic.

How to Use HexWatershed in your Projects

- ❑ Decide the domain/watershed boundary (vector)
- ❑ Prepare the original river network (vector) and outlet location
- ❑ Prepare the Digital Elevation Model (DEM) data (raster)
- ❑ Choose the mesh type and resolution
- ❑ Prepare the configuration files
- ❑ Run the simulation

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Acknowledgments

- HexWatershed is supported by PNNL LDRD, DOE ICoM/InteRFACE/NGEE-Tropics projects.
- HexWatershed is built on collaborations and open-source projects:
  - DGGRID/JIGSAW
  - RichDEM
  - GeoVista
  - Cartopy
  - GDAL
  - RapidJSON

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Thank you