Mesh independent flow direction modeling using HexWatershed 3.0

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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!
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

triangle  quadrilateral  hexagon

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.
Describe a Mesh Cell and its Neighbors

- **Vertex**: a list of points \((x, y)\) or \((\text{lon}, \text{lat})\) pair.
- **Center**: a point \((x, y)\) or \((\text{lon}, \text{lat})\) 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.
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

(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


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

PyFlowline Python + Pyhexwatershed Python frontend + Hexwatershed C++ backend

River network
Domain boundary
Digital Elevation Model
HexWatershed

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

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 (pyhexwatershed)
   `conda create --name hexwatershed`
   `conda activate hexwatershed`
   `conda install -c conda-forge hexwatershed`

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

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