Topological relationship-based flow direction modeling: stream burning and depression filling

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Key Points:

- We use topological relationships in adaptive stream burning.
- We use a mesh-independent approach to conduct depression filling.
- The model produces several flow routing parameters including flow direction.

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Abstract

Flow direction modeling consists of (1) an accurate representation of the river network and (2) digital elevation model (DEM) processing to preserve characteristics with hydrological significance. In part 1 of our study, we presented a mesh-independent approach to representing river networks on different types of meshes. This follow-up part 2 study presents a novel DEM processing approach for flow direction modeling. This approach consists of (1) a topological relationship-based hybrid breaching-filling method to conduct stream burning for the river network and (2) a modified depression removal method for rivers and hillslopes. Our methods minimize modifications to surface elevations and provide a robust two-step procedure to remove local depressions in DEM. They are mesh-independent and can be applied to both structured and unstructured meshes. We applied our new methods to the Susquehanna River Basin with different model configurations. The results show that topological relationship-based stream burning and depression-filling methods can reproduce the correct river networks, providing high-quality flow direction and other characteristics for hydrologic and Earth system models.

Plain Language Summary

Flow direction and several other flow routing attributes are important inputs for hydrologic models. Existing methods have several limitations, including only supporting rectangle mesh systems. In this study, we extend our topology-based river network representation method to define flow direction and other attributes. With its new features, our method can be used to generate high-quality flow routing parameters for hydrologic models.

1 Introduction

Flow direction field and flow routing parameters are key inputs to hydrologic and Earth system models. To generate these inputs, flow direction models must consider hydrologic features including river networks and land surfaces across different scales(Tarboton, 2003; Yamazaki et al., 2009; Wu et al., 2012; Li et al., 2013; Liao et al., 2019). Because the spatial discretizations, including the mesh system and spatial resolution of hydrologic and Earth system models, generally do not match the real-world hydrologic features, the modeled flow direction field and flow routing parameters are always conceptual. Limitations remain on how to represent different hydrologic features in the flow direction field across different scales. Most existing methods are limited to rectangle mesh systems(Nobre et al., 2011; Wu et al., 2011; Mcgehee et al., 2016; Engwirda & Liao, 2021). Currently, two primary methods exist to model flow direction field and flow routing parameters. This paper is the second part of a topological relationship-based flow direction modeling series. Readers are referred to our earlier work for additional background information(Liao, Zhou, Xu, Cooper, et al., 2022).

The first flow direction modeling method is used at the regional/watershed scale, with flow direction often generated through terrain analysis(Tarboton, 2003; Esri Water Resources Team, 2011; Liao et al., 2020). In terrain analysis, both (1) “stream burning”, a technique to enforce flow direction by modifying a raster Digital Elevation Model (DEM) at and near the river channel using a user-provided vector dataset, and (2) “depression removal”, a technique to remove local depressions within DEM so water can flow out of the domain, are used to pre-process the DEM(Hellweger & Maidment, 1997; Barnes et al., 2014; Lindsay, 2016b). After the DEM is modified, the flow direction can be defined using the elevation differences (e.g., the direction with the largest elevation drop). Many models have been developed for stream burning and depression removal since the 1980s(Hellweger & Maidment, 1997; Wesseling et al., 1997; Graham et al., 1999; Wang & Liu, 2006; Barnes et al., 2014). The stream burning method was extensively discussed in our earlier study(Liao, Zhou, Xu, Barnes, et al., 2022) and other literature(Lindsay, 2016b).

The major limitation in existing stream-burning models is their aggressive modifications to the river (and the riparian zone) elevations. These modified elevations directly alter the calculation of slope, an important flow routing parameter. The modifications are needed because the models treat the vector-based river networks as a binary mask to lower the elevations. Unlike stream burning, depression removal does not require a vector-based river network dataset as input and can be carried out before or after stream burning. Depending on how elevation is modified, depression removal can be classified into (1) depression filling, which increases the elevation of the depression(Barnes et al., 2014), and (2) depression breaching, which breaches a path from the depression towards the domain boundary. Depression filling is more computationally efficient but suffers from aggressive elevation modifications. Depression breaching does not have the aggressive modification issue, but it suffers from computational complexity(Lindsay, 2016b).

While stream burning and depression removal are different techniques, they are closely connected. A cell's elevation may be modified by both techniques so that stream burning may alter the result of depression removal or vice versa. Several studies have tried to combine stream burning and depression removal within a unified workflow to obtain consistent results(Saunders, 2000; Liao, Zhou, Xu, Barnes, et al., 2022). However, producing a hydrologic-simulation-ready DEM and its associated flow direction remains challenging as a well-established elevation manipulation scheme does not exist(Lindsay, 2016b, 2016a). Previous research proposed an alternative hybrid breaching filling method to minimize the modification to both river and land elevations(Lindsay, 2016b). The method uses a revised priority flood approach to fill the land cell depressions and river network topological relationships to breach river cell depressions.

The second flow direction modeling method is used at a continental or global scale. As discussed in our part 1 study, it is often referred to as the "upscaling" method (e.g., the Dominant River Tracing (DRT) model) because it uses high spatial resolution datasets (e.g., results from the raster DEM-based method) as guidance to define the coarse resolution (around 10 km to 200 km) cell-to-cell flow direction(Fekete et al., 2001; Davies & Bell, 2009; Wu et al., 2011). Because this method often assumes that there is always one major river channel within each large-scale mesh cell, the flow direction field is generally equivalent to the river networks. Because the upscaling method relies on high spatial resolution datasets, it does not require additional stream burning or depression removal. It derives flow routing parameters through fine-scale data synthesis.

Similar to the river network representation methods, existing flow direction models at both regional and global scales are limited to the rectangle mesh systems, although some algorithms can be extended to other mesh systems(Barnes et al., 2014). Model development based on unstructured meshes has become an emerging area of interest in hydrologic and Earth system models. In addition to the three advantages discussed in our part 1 study, model development based on unstructured meshes also address several limitations of traditional hydrologic models, including high latitude spatial distortion(Liao et al., 2020).

To the authors' knowledge the HexWatershed model, a hexagon mesh-based watershed delineation model, is the only flow direction model that includes both stream burning and depression removal and can be extended to a fully unstructured mesh framework as of this writing(Liao et al., 2020). This study extends our part 1 study(Liao, Zhou, Xu, Cooper, et al., 2022), describing a topological relationship-based river network representation method to introduce topological relationship-based stream burning and depression-filling algorithms within the HexWatershed model. We upgrade the HexWatershed model to a fully mesh-independent framework(Liao et al., 2020; Liao, Zhou, Xu, Barnes, et al., 2022; Liao & Cooper, 2022). Part 2 of the study is organized as follows. We first introduce the model algorithms. We then apply the updated model to the same coastal watershed used in the part 1 study, the Susquehanna River Basin (SRB), with different model configurations and evaluate the model performance against several characteristics and datasets (e.g., elevation, slope, and drainage area). Finally, we discuss the method's limitations and future applications in hydrologic and Earth system models.

2 Methods

2.1 Overview of HexWatershed

HexWatershed (v1.0/2.0) was originally designed as a hexagonal mesh-based watershed delineation model(Liao et al., 2020). Later on, we introduced stream burning to improve the flow direction and stream network representation at coarse spatial resolutions (Figure S1)(Liao, Zhou, Xu, Barnes, et al., 2022). Because the core stream burning algorithm within HexWatershed v2.0 is based on a rasterization-based method, the model is subject to the same limitations as existing methods.

2.2 What's new in HexWatershed

In HexWatershed v3.0, we introduced topological relationship-based stream burning and revised depression-filling algorithms. The overall workflow of HexWatershed v3.0 is similar to earlier versions, with the major difference being the use of topological relationships (Figure 1). Additional watershed characteristics including travel distance (the flow direction-based distance between each cell and its watershed outlet) are also modeled.

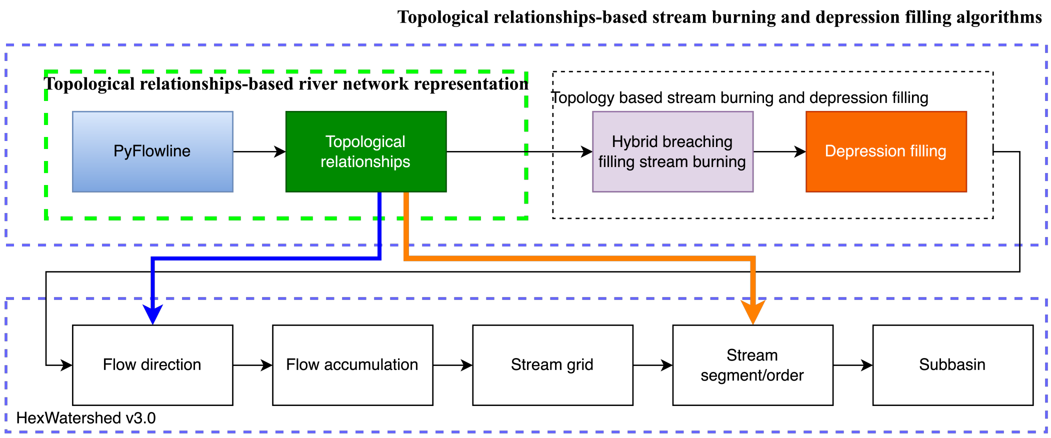

Figure 1: Workflow of the HexWatershed v3.0 model with the topological relationship-based stream burning and depression filling algorithms. Rectangles inside the green dashed rectangle are the part 1 study topological relationship-based river network representation using the PyFlowline model, which produces the topological relationships information (green rectangle). The topological relationships are used by the hybrid breaching filling stream burning algorithm (light purple rectangle), followed by the revised depression filling algorithm (orange rectangle). The topological relationships are also used by the flow direction algorithm (blue arrow) and stream segment/order definition algorithms (orange arrow).

We will first introduce the topological relationship-based stream burning and depression-filling algorithms before providing details of the mesh-independent framework.

2.3 Topological relationship-based stream burning and depression filling

The topological relationship-based stream burning and depression-filling algorithms process cell elevations using a two-step approach. First, the model processes river cells and their riparian zone land cells using a hybrid breaching filling stream burning algorithm. In this step, each river cell may be modified more than once because of the breaching algorithm. Second, the model processes the remaining land cells using a revised priority flood depression filling algorithm. Because the second step does not modify the results of the first step, this approach generates a consistent depression-free DEM with river networks burnt in.

2.3.1 Hybrid breaching-filling stream burning

The PyFlowline simulation from our part 1 study produces a JavaScript Object Notation (JSON) file that contains the neighbor and downstream information (if applicable) of each mesh cell(Liao et al., 2020). The hybrid breaching filling stream burning algorithm uses this information to adaptively fill or breach river cell elevation. The stream burning algorithm in our model is essentially a depression removal (both filling and breaching) algorithm specifically designed for river networks.

Similar to our earlier study(Liao, Zhou, Xu, Barnes, et al., 2022), the algorithm reversely searches and adjusts river cells from the outlet toward the headwater. Without significantly decreasing the outlet elevation, it adjusts the elevation of a depression river cell using either filling or breaching based on the elevation difference between the depression and a user-provided threshold. For example, if the absolute value of depression is lower than the user-provided threshold, a filling is applied. Otherwise, breaching is applied. Figure 2 provides a one-dimensional example.

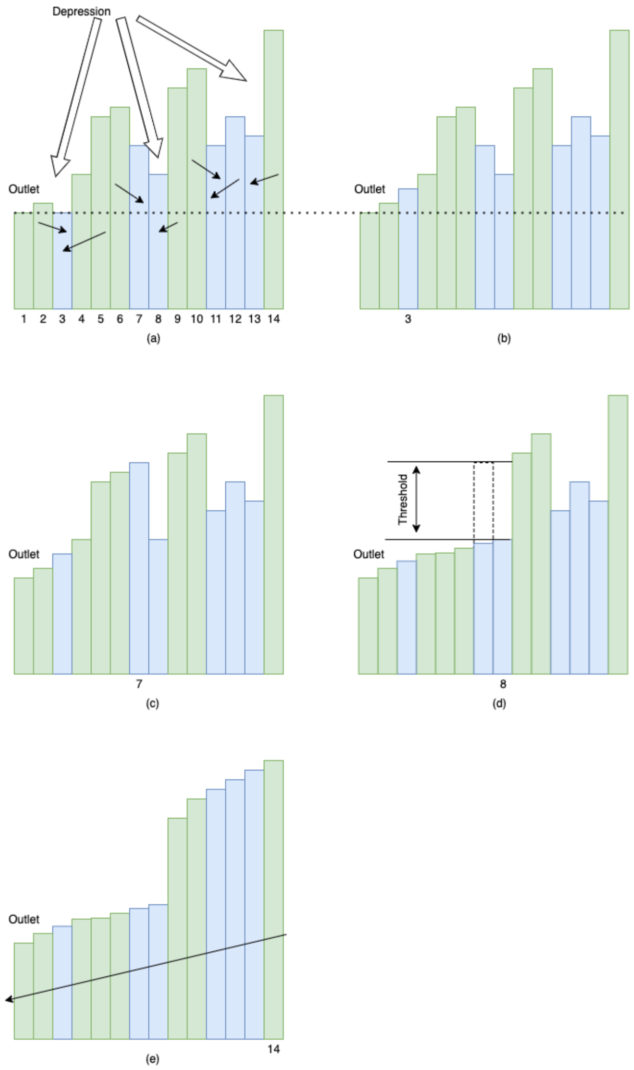

Figure 2: Illustration of the hybrid breaching filling stream burning algorithm. (a) is the original river cell elevation profile, which is the same as that in Figure S1. Each cell is marked with an index, which is also the order/step it is processed. (b) Because the depression between cells 2 and 3 is less than the user-provided threshold (e.g., 5 m), cell 3's elevation is increased by a gentle slope (e.g., 1%). (c) Similarly, cell 7's elevation is increased. (d) Because the difference between the updated cells 7 and 8 exceeds the threshold, cell 8's elevation is unchanged, while cell 7 and its downstream cells are breached if needed. (e) shows the resulting river cell elevation profile.

This algorithm runs recursively until all the river segments/reaches are processed (Figure S2). Because stream order information is also available from the PyFlowline simulation, different parameters are used for different upstream channels when a river cell is a confluence. For example, a lower percentage (e.g., 1%) is used for high-order rivers, and a higher value (e.g., 2%) is used for low-order rivers. After the river cells are processed, the land cells' elevations in their riparian zones are increased if needed.

The topological relationships feature can also be turned off (Table S1). This converts the river networks from the PyFlowline JSON file to a binary mask. As a result, the model runs in a traditional rasterization-based stream burning method and only applies depression filling in the river cells and their riparian zone land cells.

2.3.2 Revised priority-flood depression filling

Unlike our earlier study(Liao, Zhou, Xu, Barnes, et al., 2022) which processes both river and land cells in the depression filling algorithm, this new revised algorithm pushes the river cells and their riparian zone land cells into the queue without changing their elevations. As a result, the priority queue does not form a "closed boundary".

2.4 Mesh-independent framework

To support unstructured mesh systems(Ringler et al., 2013; Sahr, 2015; Engwirda, 2017), HexWatershed v3.0 includes several changes. First, it supports all mesh systems from the mesh-independent PyFlowline model(Liao, Zhou, Xu, Cooper, et al., 2022). However, the definitions of neighboring cells in PyFlowline and HexWatershed v3.0 are not always the same (Text S1). For example, a rectangle cell in PyFlowline has only 4 neighbors. In contrast, the same cell may have 8 neighbors (4 face neighbors + 4 vertex neighbors) in HexWatershed (Text S1).

Second, in a projected coordinate system (PCS), flow accumulation is often represented using the total number of upslope cells that contribute to the current cell. The total drainage area can be calculated by multiplying the flow accumulation by the cell area, which is a constant. In an unstructured mesh, the cell area is not constant. To resolve this, we use the geodesic area of each cell when calculating the flow accumulation.

Third, HexWatershed v3.0 supports continental to global scale simulation, which is enabled by the design of the PyFlowline model. PyFlowline allows for multi-outlet modeling to generate multiple river basin networks within a single mesh. Based on this, HexWatershed v3.0 performs stream burning and depression filling for multiple watersheds in one simulation.

3 Model application

3.1 Study area and data

We applied the model to the same study area used in our part 1 study, the Susquehanna river basin (Figure S3). We use the same baseline datasets from our part 1 study. However, the user-provided river networks in this study represent the conceptual river networks produced from our part 1 study. Additionally, we also obtained the DEM dataset from the United States National Elevation Dataset (NED). Spatial datasets and maps were produced using Python packages including Matplotlib and GDAL(Hunter, 2007; Gillies & others, 2007; GDAL/OGR contributors, 2019; Liao, 2022b; Liao & Cooper, 2022; Liao, 2022a).

3.2 Model setup

To evaluate the performance of the HexWatershed v3.0, we ran the model under different configurations with case indices used for illustrations (Tables S1 and 1). The resolutions and case indices differ from those in our part 1 study.

Table 1: Simulation configurations with case indices. The illustrations and analyses all use the same indices.

	5 km		40 km	
Mesh	Without topology	With topology	Without topology	With topology
Latlon	1	2	3	4
Square	5	6	7	8
Hexagon	9	10	11	12
MPAS ($3 \sim 10$ km)	13	14		

For structured meshes, we ran 2 different spatial resolutions (5 km and 40 km). For unstructured mesh, i.e., the Model for Prediction Across Scales(MPAS) mesh, we used a variable resolution mesh with cell lengths varying from 3 km to 10 km. To demonstrate the effect of the topological relationship-based stream burning algorithm, we ran two simulations (without and with the topological relationships) for each resolution. The supplementary materials contain the high-resolution meshes (overlapped with flow direction) of Cases 2, 6, 10, and 14 (Figures S4-S7).

3.3 Results and analysis

Although the new algorithms affect many results, we only present major watershed characteristics often used by hydrologic and Earth system models, such as surface slope and flow direction.

3.3.1 Surface elevation

The modeled surface elevations with and without topological relationships exhibit significant differences near river cells. When the topological relationships feature is turned off, the modeled river cell elevations dramatically decrease due to the large threshold (i.e., 100 m) applied. As a result, the river networks are also visible (e.g., Cases 1, 5, and 9 in Figure 3). The dramatic modification is also widespread from the headwater to the outlet.

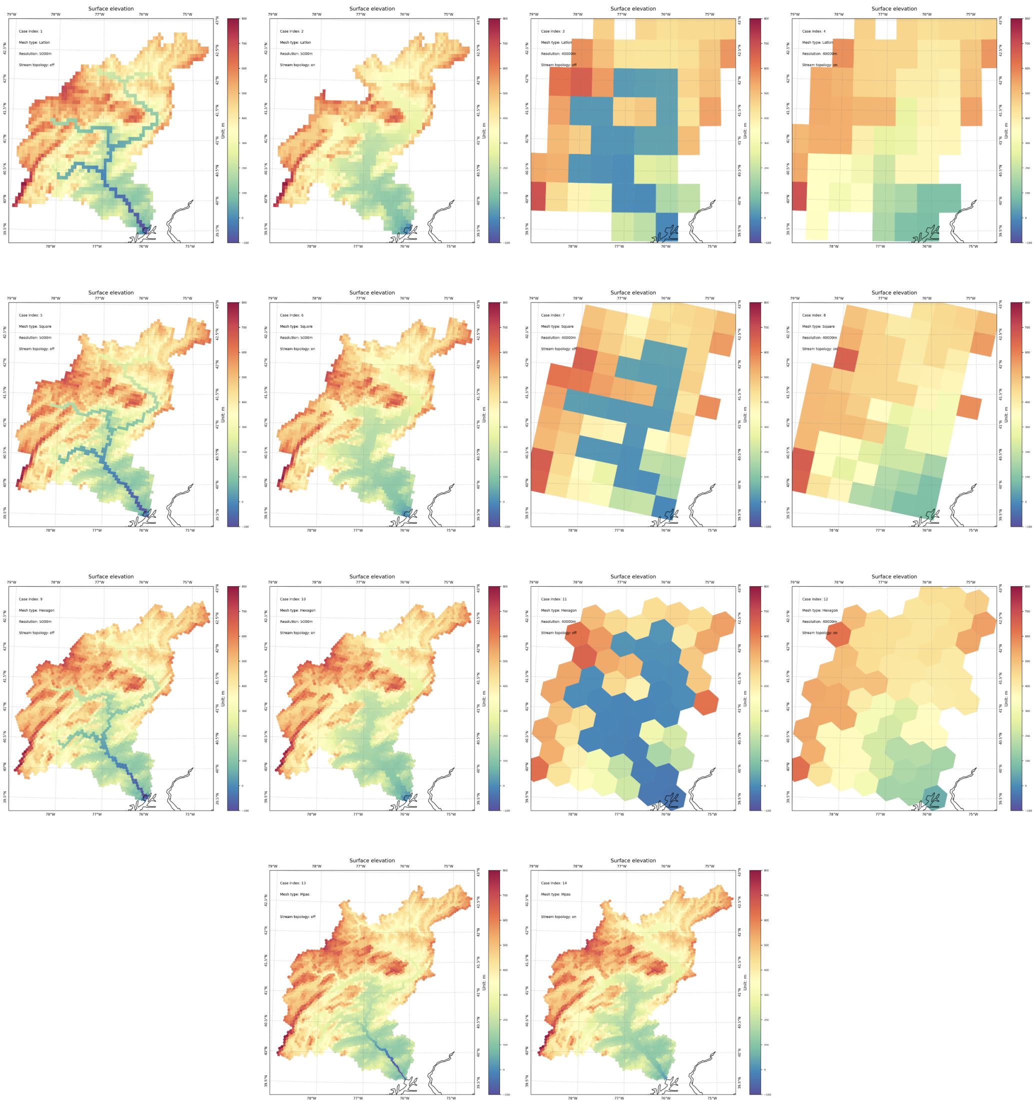

Figure 3: The spatial distributions of modeled surface elevation in Cases 1 to 14 (unit: m)(Table 1). Because the topological relationships feature is turned off in cases with odd indices (e.g., 1, 3, 5, and 7), the river cell elevations are much lower than the corresponding cases with even indices (e.g., 2, 4, 6, and 8).

In contrast, when the topological relationships feature is turned on, modeled river cell elevations are closer to their riparian zone cell elevations (e.g., Cases 2, 6, 10, and 14 in Figure 3).

We also extracted the elevation profiles from the watershed outlet to a United States Geological Survey (USGS) gauge site (Site ID: 01497842) on the main channel. The results show that when the topological relationships feature is turned on, the model is able to produce more realistic elevation gradients along the channel (Figure 4). However, the modeled elevations are still overestimated compared to the NED datasets (Text S2).

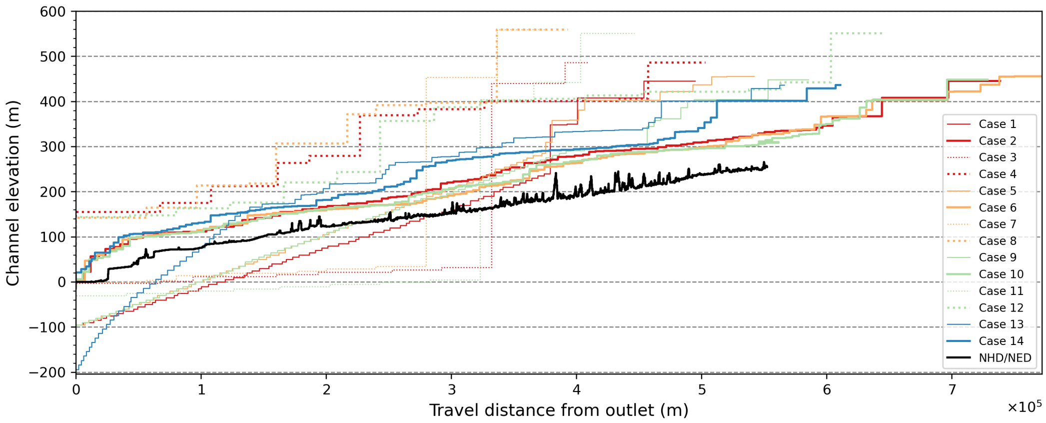

Figure 4: River elevation (m) from the outlet to the main channel upstream USGS gage site 01497842 (travel distance in m) for Cases 1 to 14 and the National Hydrography Dataset(NHD)/NED (Table 1). The x-axis is the travel distance from the outlet, and the y-axis is the elevation. The black line represents the elevation profile from the NED datasets. Different cases have a different number of data points due to resolution differences. The NED datasets are not depression-free.

The topological relationships feature also has a significant impact on the distributions of domain-wide channel elevations (Figure 5). In general, the average river channel elevations are much higher with the feature turned on than when it is turned off.

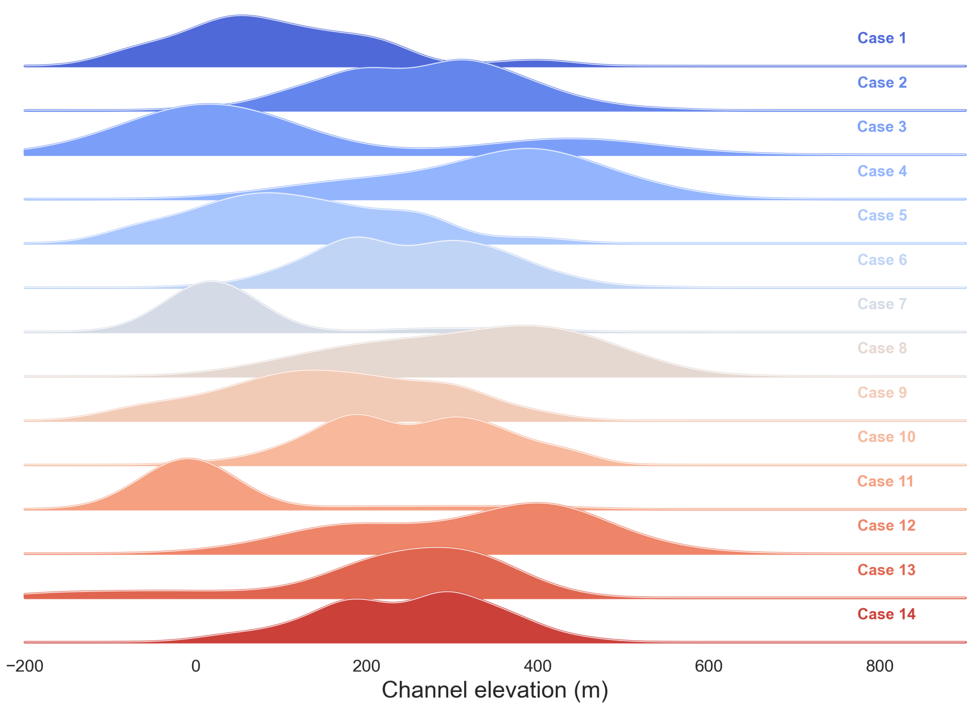

Figure 5: Density functions of the river channel elevation (m) from Cases 1 to 14 (Table 1).

3.3.2 Surface slope

Because the model calculates the between-cell slope from the depression-free surface elevation, the spatial patterns of the modeled slope with and without topological relationships are generally similar. Significant differences can appear near the river cells.

The density functions of the channel slope show that the average channel slope is smaller when the topological relationships feature is turned on than when it is turned off (Figure S8). This is consistent with the elevation profiles (Figure 4).

Because the river cell elevations substantially decrease when the topological relationships feature is turned off, the slopes between the river cells and their riparian zone cells are much larger than when this feature is turned on (Figure 6).

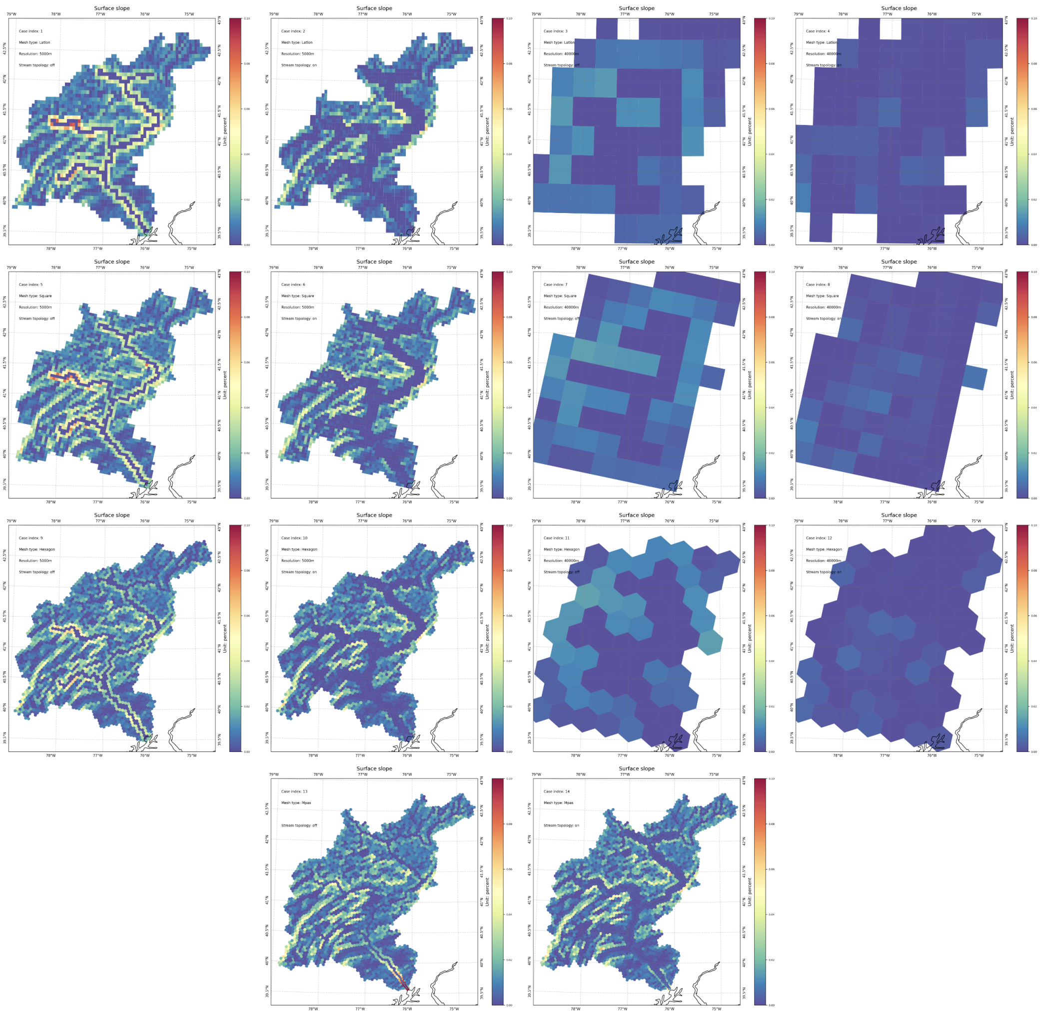

Figure 6: Spatial distributions of the modeled surface slope from Cases 1 to 14 (Table 1). Because the river cell elevations in cases with odd indices (e.g., 1, 3, 5, and 7) are lower than in cases with even indices (e.g., 2, 4, 6, and 8), the slopes near these cells are much larger.

The density functions of the riparian zone slopes show that the average riparian zone slope is more than 10 times larger when the topological relationships feature is turned off than when it is turned on. Their distributions are less affected by mesh types and resolutions when it is turned on (Figure 7).

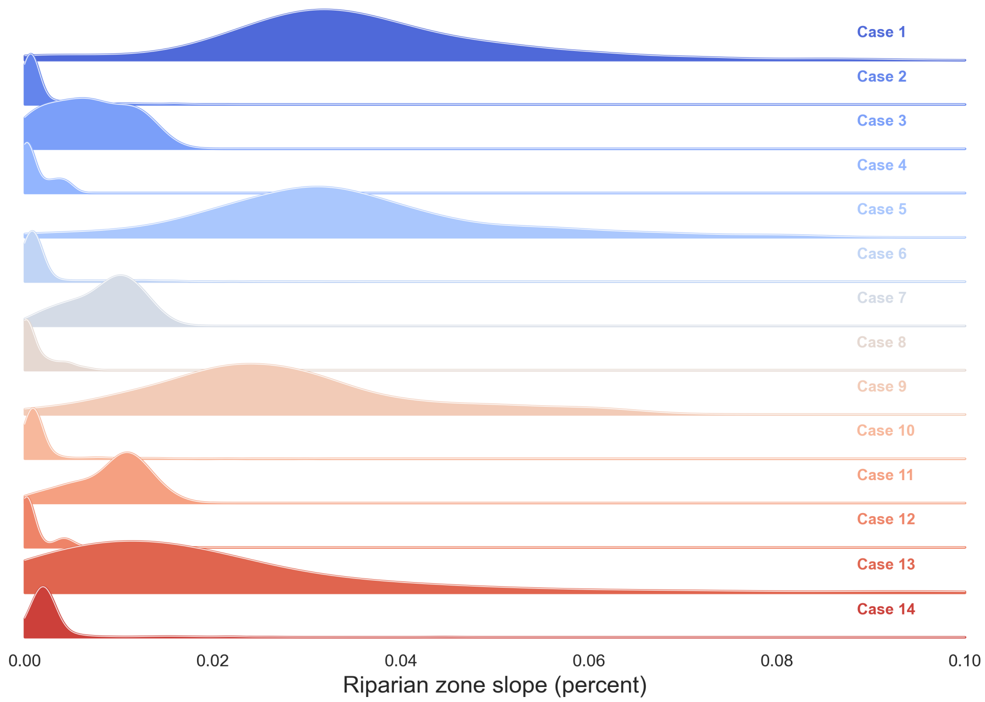

Figure 7: Density functions of the river riparian zone slope (percent) from Cases 1 to 14 (Table 1).

3.3.3 Flow direction

When the topological relationships feature is turned off, the model cannot reproduce flow direction fields that precisely follow the user-provided river networks, especially at coarse resolutions (e.g., Cases 3, 7, and 11 in Figure 8). Specifically, the modeled flow direction fields cannot resolve river meanders and confluences.

In contrast, when the topological relationships feature is turned on, the modeled flow direction fields exactly overlap the user-provided river networks regardless of mesh type and resolution (e.g., Cases 2, 4, and 14 in Figure 8).

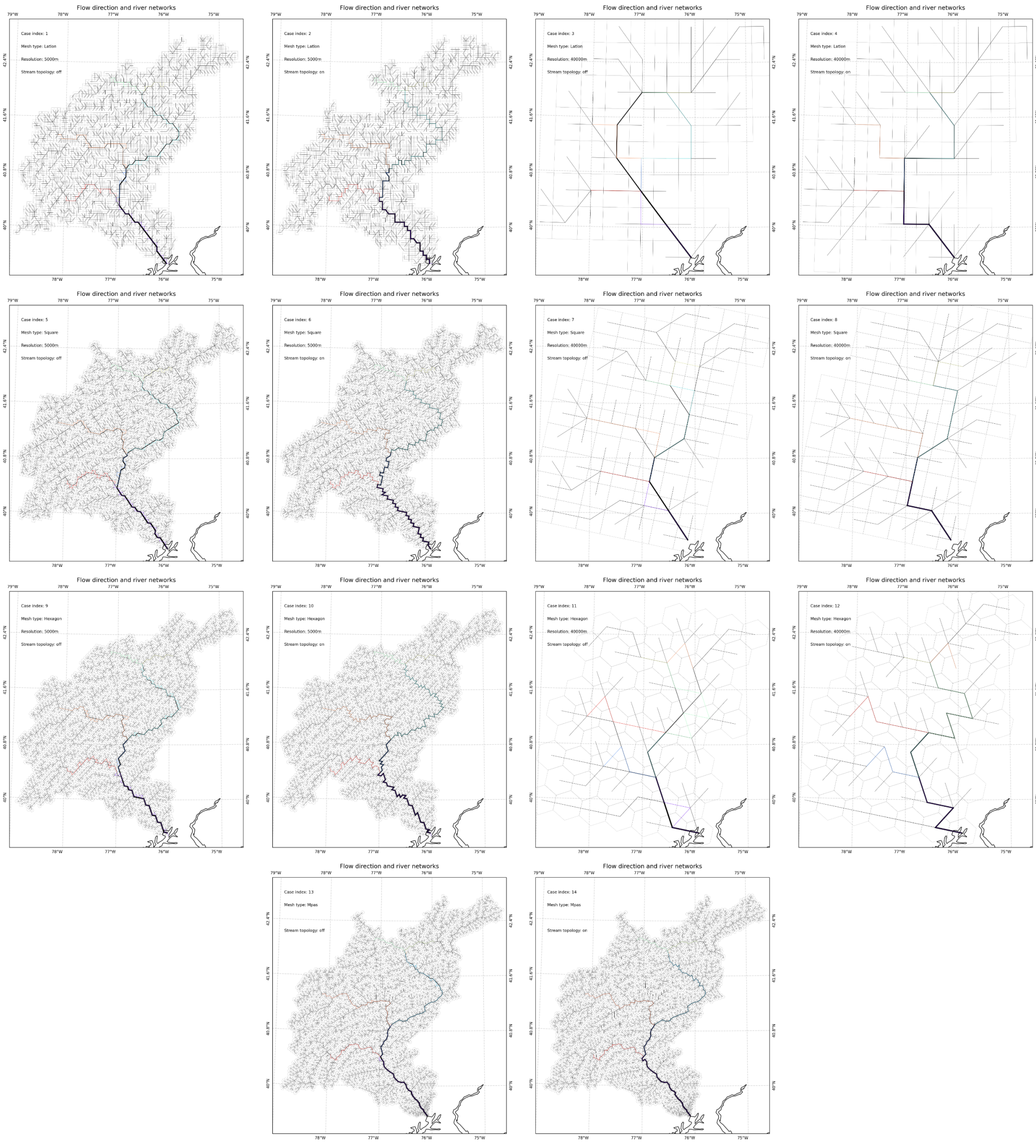

Figure 8: Modeled flow direction fields from Cases 1 to 14 (Table 1). The black line features represent flow direction fields with the drainage area scaled as the line thickness. The colored line features are the user-provided river networks from the PyFlowline simulation. When the topological relationships feature is turned on, the modeled flow direction fields are consistent with the user-provided river networks.

3.3.4 Drainage area

Because drainage area is calculated based on cell area and flow direction, the modeled drainage area varies with mesh type and resolution. When the topological relationships feature is turned off, the spatial patterns of modeled drainage areas from different meshes are similar at high resolutions. However, they differ significantly at coarse resolutions (e.g., Cases 3 and 6 in Figure 9).

In contrast, the drainage area spatial patterns from different meshes are very similar when the topological relationships feature is turned on across all tested resolutions (e.g., Cases 4, 8, and 12 in Figure 9).

At high mesh resolution, turning on the topological relationships feature better captures flow direction near river channels (e.g., Cases 13 and 14 in Figure 9).

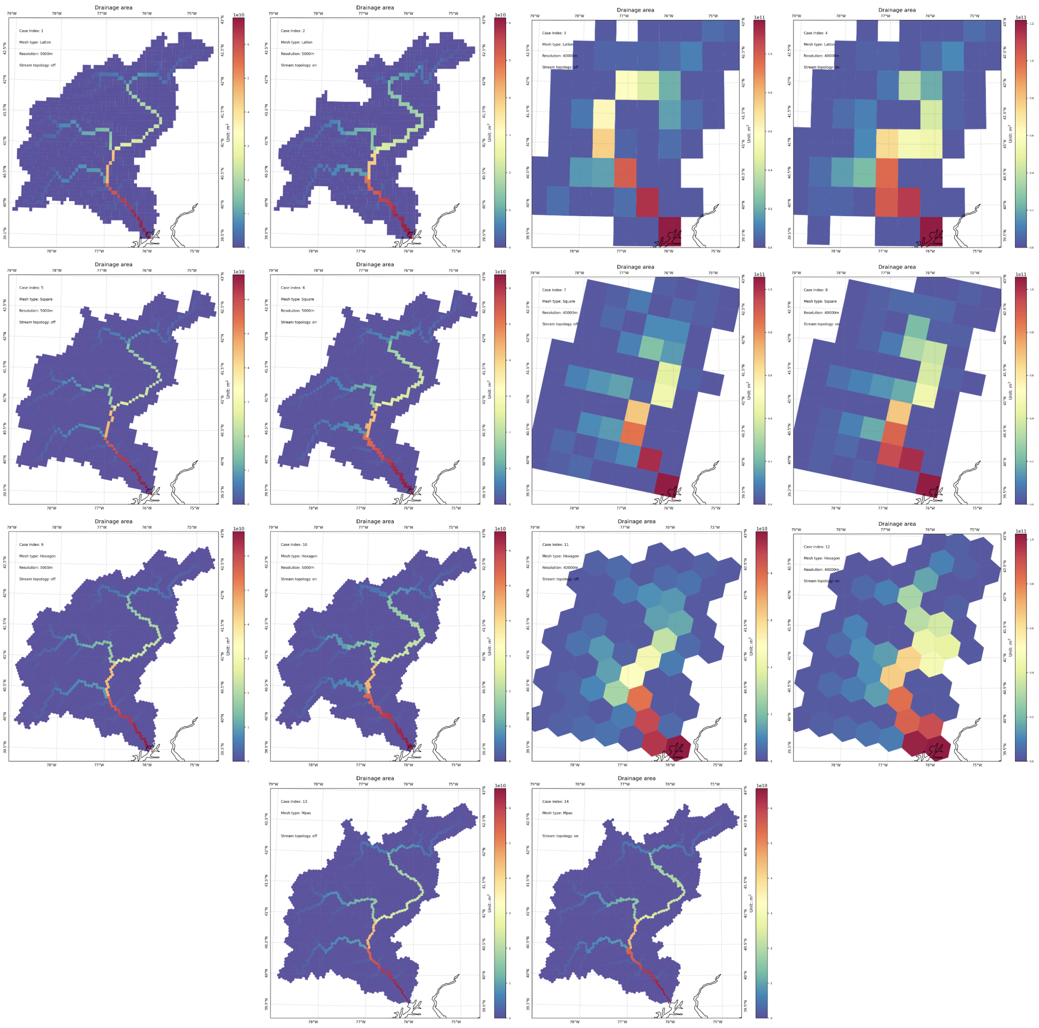

Figure 9: The modeled drainage area from Cases 1 to 14 (m^2)(Table 1).

All cases underestimated the total drainage area by 5% to 10% at high spatial resolution. This is primarily caused by missing portions at the upper boundary (e.g., Cases 2 and 10 in Figure 9). The numbers of cells in all cases suggest that the MPAS mesh includes more cells than other meshes due to its refinement near the watershed outlet (Figure S9).

In contrast, all cases overestimated the total drainage area by as much as 30% (Figure 10) at coarse spatial resolution. This is primarily because the model frequently includes cells that are partially within the watershed (less than 50% in total area) during the stream-burning process.

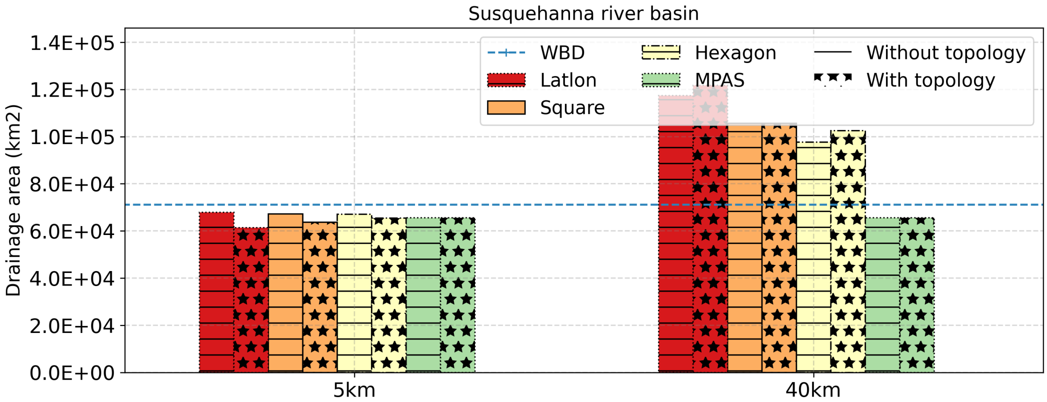

Figure 10: Drainage area at the watershed outlet from Cases 1 to 14 (km^2) (Table 1). The x-axis is the mesh resolution (5km and 40km), and the y-axis is the drainage area (km^2). The dashed line is the reference drainage area from the Watershed Boundary Dataset (WBD). MPAS-based cases are plotted in both resolutions.

3.3.5 Travel distance

Similar to drainage area, travel distance depends on flow direction and is calculated using accumulated cell center-to-center distance. The modeled travel distances have similar spatial patterns at high resolutions regardless of mesh type and resolution. The topological relationship feature does not have a significant impact on travel distance. This is because a cell can have a similar travel distance even with different flow directions (Figure S10).

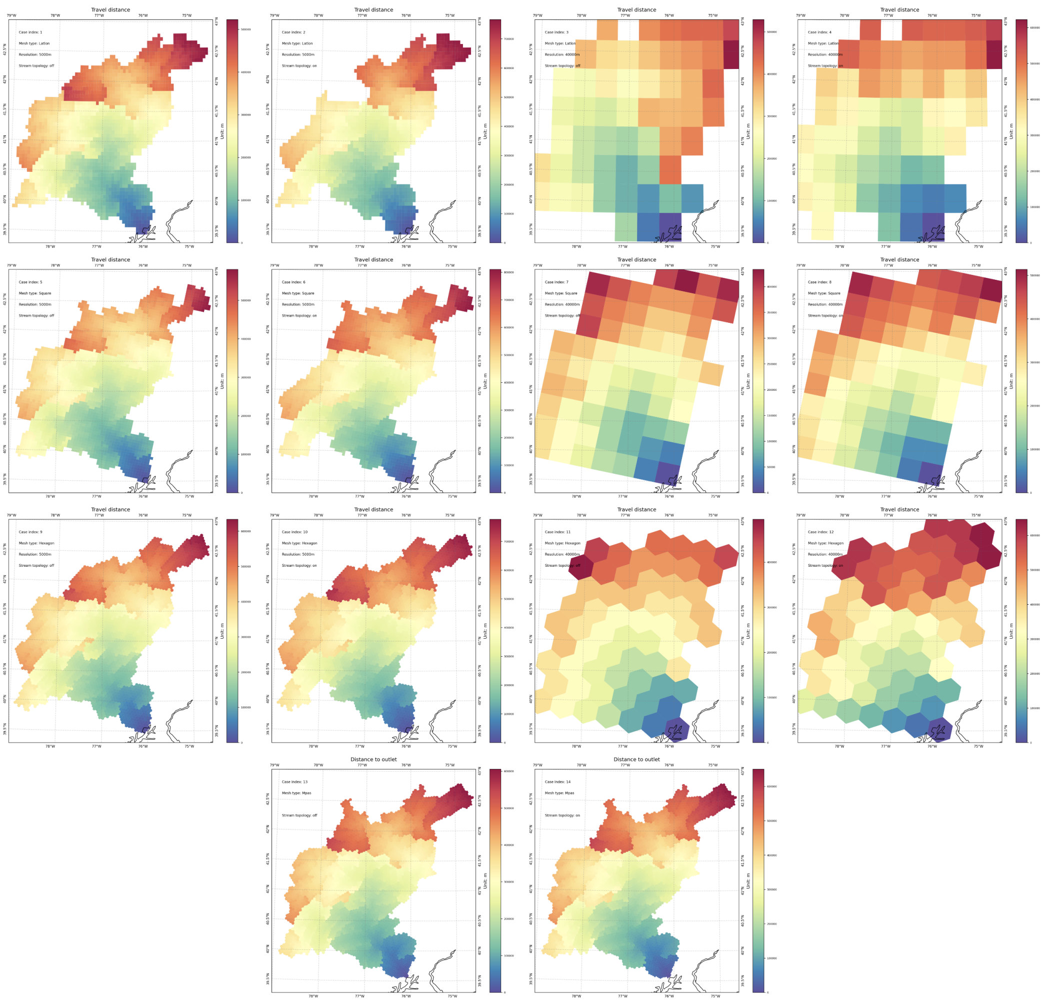

Figure 11: The modeled travel distances from Cases 1 to 14 (Table 1).

The scatter plot between the observed and modeled travel distances suggests that the model can reasonably capture the travel distance, especially when the topological relationship feature is turned on. First, when this feature is turned off at the high spatial resolution, the flow direction often takes shortcuts and the model often underestimates the travel distance (e.g., Cases 1, 5, 9, and 13 in Figure 12). In contrast, when it is turned on and the flow direction precisely follows the river channel, the modeled travel distances are larger and maybe even be greater than observations (e.g., Cases 2, 6, 10, and 14). Second, compared with structured meshes, MPAS mesh-based cases underestimate travel distance because the river cells are aligned with real-world river channels. Third, a strong correlation ratio exists between the observed and modeled travel distances when the topological relationship feature is turned on. This ratio depends on the mesh type. For example, the ratio for the structured latlon, square, and hexagon meshes are 1.04, 1.04, and 1.03, respectively. Finally, Case 14 performs similarly to the DRT model at 1/16 degree resolution ($\sim 7\,\text{km}$) near the watershed outlet. The DRT model uses the actual flowlines to represent the travel distance(Wu et al., 2011).

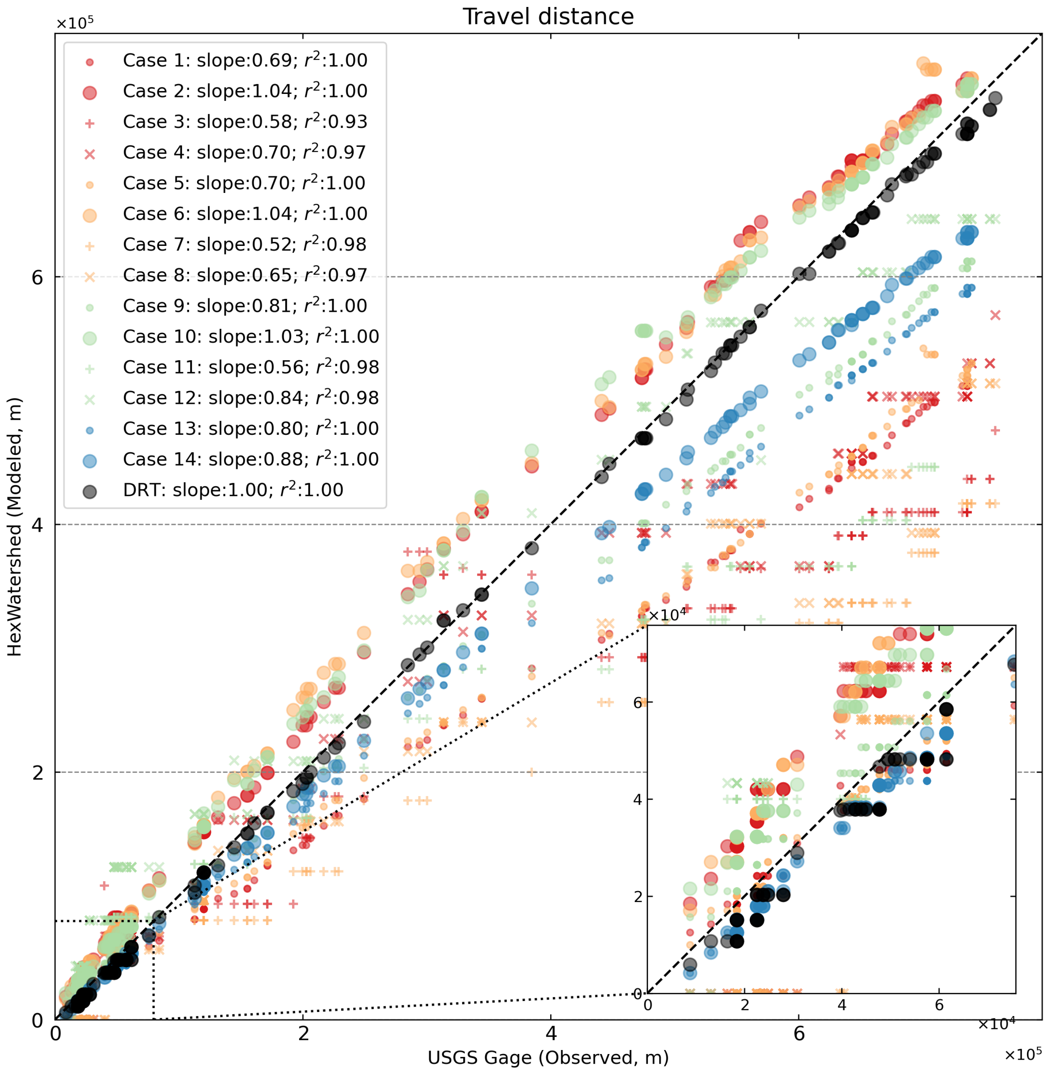

Figure 12: Comparison between the USGS measured and modeled travel distances at 160 NWIS sites from Cases 1 to 14 and the DRT datasets (Table 1). The black circles represent the DRT model datasets at 1/16 degree resolution.

4 Discussion

4.1 Importance of topological relationships in stream burning

Model simulations from Cases 1 to 14 demonstrate that the topological relationship-based stream burning can minimize modification to river and land elevations. This is because the adaptive hybrid breaching filling algorithm uses topological relationships to adjust elevations on demand (Figure 3)(Lindsay, 2016b). As a result, the updated DEM can be used to directly model river channel and riparian zone slopes that meet hydrologic model requirements. However, the comparison between modeled DEM and NED datasets suggests that the model parameters, i.e., the filling ratio and breaching threshold, should be tested to improve further model performance (Figure 4). The flow direction algorithm considers both the topological relationships and elevation gradient, allowing it to define flow direction fields that are consistent with the user-provided conceptual river networks (Figures S4-S7).

However, because these capabilities depend on the topological relationships modeled by PyFlowline, the limitations from the part 1 study propagate into this study.

4.2 Depression filling

Unlike the method from our earlier study(Liao, Zhou, Xu, Barnes, et al., 2022), our new method separates stream burning and depression filling into two steps and significantly simplifies the workflow.

First, the new method demonstrates that, if carefully designed, we can conduct full-domain depression removal sequentially to include different hydrologic features (e.g., lakes, rivers, and land) without introducing additional model complexity. The results remain consistent after the final step.

Second, because stream burning minimizes the modification to the river (and its riparian zone) elevations, the improvements will also improve depression filling for the remaining land cells.

4.3 Watershed characteristics across scales

The hydrologic processes in hydrologic and Earth system models are not at the same spatial scales as the mesh resolutions. As a result, representing watershed characteristics across scales is critical. Our simulation cases suggest that some characteristics, such as the travel distance, can be reconstructed from the conceptual travel distance by a scale factor (Figure 12). However, reconstruction remains challenging for other characteristics. For example, river segment and river order information can differ from case to case. Even in the same case, the modeled stream segment and order outputs can vary from the user-provided values because of the flow accumulation threshold(Lin et al., 2021). In some scenarios, preserving these values is preferred to maintain consistency (the orange arrow in Figure 1). Another example is drainage area, as all cases either underestimate or overestimate the total drainage area. This is mainly caused by the missing portions or the partially included/excluded cells at basin margins (Figures 9 and S9).

4.4 Limitations

This study has a few limitations:

1. Currently, we only consider the immediate neighbors as the river channel buffer zone in the stream burning algorithm, which means the single-cell resolution determines the buffer zone width. An adaptive buffer zone width that includes more than immediate neighbors is needed when the riparian zone width is larger than the mesh resolution.
2. The elevation gradient near the river mouth is generally smoother compared to the vicinity of the headwaters (Figure 4). As a result, the filling and breaching parameters should be adaptive, considering the mesh resolution and distance to the watershed outlet. In some cases, a dam may alter the elevation profile. These parameters should also depend on the location of the river channel (Figure 4).
3. The model should include other hydrologic features such as watershed boundary and (endorheic) lakes in the workflow. For example, it is possible to include watershed boundaries in the mesh generation process to allow the model to improve the drainage area without missing the marginal areas. Similarly, we should include lakes in the mesh generation and depression removal processes to consider fill-spill scenarios(Barnes et al., 2020).

5 Conclusions

In this study, we extended our part 1 study to develop a mesh-independent topological relationship-based flow direction model (HexWatershed v3.0). We applied the model in different configurations to the Susquehanna River Basin. The results show that our model minimizes modification to the river and land elevations and produces high-quality flow direction fields and other flow routing parameters. We suggest that hydrologic and Earth system models with a flow routing component should adopt our method, especially for unstructured mesh-based simulations.

Acknowledgments

This research was funded as part of the multi-program, collaborative Integrated Coastal Modeling (ICoM) project and the Interdisciplinary Research for Arctic Coastal Environments (InteRFACE) project through the Department of Energy, Office of Science, Biological and Environmental Research program, Earth and Environment Systems Sciences Division, Earth System Model Development (ESMD) program area. The data used for model simulations can be downloaded through the USGS website (`https://www.usgs.gov/national-hydrography`). The HexWatershed model can be installed as a Python package (`https://github.com/changliao1025/pyhexwatershed`)(Liao, 2022a). The data and code used in this paper are available from `https://github.com/DOE-ICoM/liao-etal_2022_hexwatershed_james`. A portion of this research was performed using PNNL Research Computing at Pacific Northwest National Laboratory. PNNL is operated for DOE by Battelle Memorial Institute under contract DE-AC05-76RL01830.

Conflict of Interest

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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