GEOMORPHOMETRY PERUGIA ITALY 2025 JUNE 9-13

Reflections on Geomorphometry and Hydrology

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1

Abstract—**Watershed and stream network delineation, along with the extraction of hydrologic information from digital elevation models (DEMs), are fundamental concepts that bridge hydrology and geomorphometry. Terrain analysis methods transform a simple grid of elevation values into richly structured datasets of hydrologically useful quantities derived from the terrain flow field. These methods are now widespread and support numerous hydrologic modeling and analysis efforts. This presentation will reflect on the ideas, concepts, algorithms, and code for hydrologic terrain analysis, providing examples of achievements and discussing future challenges and opportunities. It will begin with a description of watershed and channel network delineation, focusing on identifying topographic scale and objectively setting thresholds for channel initiation. Next, the presentation will review the D-infinity multiple flow direction model, which addresses limitations associated with single flow direction models. Following this, generalized terrain-based flow analysis will be presented as an approach to developing a broad class of terrain quantities derived from a non-circulating flow field. Examples and code logic to achieve this will be provided. Height Above Nearest Drainage (HAND), that has become popular in flood inundation modeling, will be discussed as a special case of distance downslope from generalized flow analysis. The computation of HAND using D-infinity flow directions and its application in determining channel hydraulic properties for flood mapping will be described. The open-source Terrain Analysis Using Digital Elevation Models (TauDEM) software, which performs many of the computations illustrated, will be highlighted.**

I. Introduction

A terrain flow data model that represents flow processes at and near the Earth's surface underpins much hydrologic terrain analysis and the computation of the rich set of terrain derivatives used in hydrology (Fig. 1). The input is a raw digital elevation model (DEM), comprising elevation values on a grid. This basic information is used to derive further hydrology-related spatial fields that enrich the information content of this basic data. The first step is to remove spurious sinks, commonly by filling [1, 2], but, where possible, using carving [3] or optimization [4] approaches that are less altering of the input data. Then, a flow field is defined. Flow directions based on topographic slope are computed from each grid cell to one or more neighboring grid cells, serving as a numerical representation of the flow field. This enables the calculation of a rich set of highly structured flow-related terrain information, including flow accumulation and other quantities based on the propagation of information up or downslope along flow directions, as well as logically linked catchments, watersheds, and channel networks.

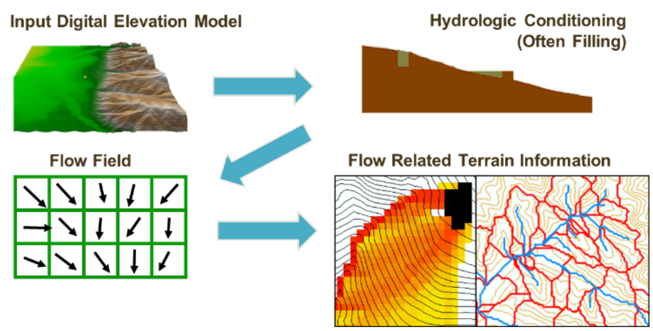

Figure 1. General Terrain Flow Data Model used to enrich the information content of a digital elevation model (DEM). Starting from a simple grid DEM, a rich set of data structures and information useful for hydrologic analysis is derived.

II. Objective Channel Network Delineation

Where do channels begin? The drainage network is an important topographic feature commonly extracted and mapped from digital elevation model (DEM) data. Hydrologic processes differ on hillslopes and in channels, and it is important to recognize and account for this in DEM-based channel network delineation. The scale of the channel network used controls the scale of hillslope and channel model elements in a hydrologic model. Topographic texture and drainage density vary across different landscapes, necessitating methods to objectively map channels that account for this variability.

TauDEM (https://hydrology.usu.edu/taudem) implements methods [5-7] that use curvature-related quantities as weights in flow accumulation, with a threshold based on a t-test to identify a statistically significant break in the constant stream drop property [8] as the stream delineation threshold is reduced. This method adapts to spatial variability in drainage density. The result is a weighted support area threshold, selected objectively using the t-test, that maps the highest resolution drainage network with a mean drop of first-order streams not significantly different from the mean drop of higher-order streams. In this way, a channel network consistent with empirical geomorphological properties is delineated.

III. D-Infinity

Tarboton [9] introduced the D-infinity (D∞) multiple flow direction method, which determines flow direction as the steepest downward slope on eight triangular facets formed in a 3x3 cell window centered on the cell of interest. The most common procedure for routing flow over a terrain surface represented by a grid DEM is the eight-directional (D8) method [10]. In this model, the direction of steepest descent towards one of the eight (cardinal and diagonal) neighboring grid cells is used to represent the flow field [10]. However, the D8 approach is limited because it can assign flow to only one of eight possible directions, each separated by 45° in a square grid [9, 11]. Multiple flow direction methods [9, 12, 13] have been suggested to address the limitations of D8. These methods proportion the outflow from each element between one or more downslope elements, introducing dispersion (spreading out) into the flow while representing downslope flow in an average sense. The D∞ multiple flow direction model [9] was designed to balance consideration of grid bias and numerical dispersion by routing flow on average along a path perpendicular to the contours (Fig. 2).

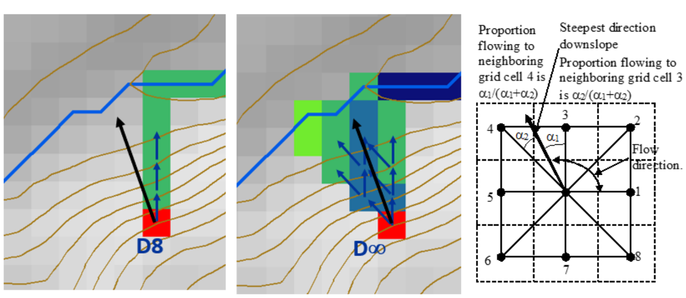

Figure 2. Single and Multiple Direction Representation of Terrain Flow Field.

IV. Generalized Terrain-Based Flow Analysis

Tarboton and Baker [14] introduced a general method for flow analysis that exploits flow field information for the calculation of a rich set of flow-based derivative surfaces, named flow algebra. The formalism developed applies to any non-circulating (non-looping) flow field, and flow directions used in flow algebra can be derived from any potential surface. The principles of flow algebra have been used to develop a number of specialized terrain-flow related quantities and proximity measures in TauDEM, including upslope and downslope distance proximity measures [15], transport-limited accumulation for modeling sediment erosion and transport, decaying accumulation useful for tracking a substance subject to decay or attenuation, and retention-limited runoff generation with run-on (Fig. 3). Generalized terrain-based analysis tools are framed as functions that capture terrain-flow effects in a general way, giving users the flexibility to use them with other inputs to meet their needs.

```
Global P, (r,c), q
FlowAlgebra(i)
for all k neighbors of i
   if Pki>0
      FlowAlgebra(k)
next k
```

$$q_i = \max\left(\sum_{\{k:P_{ki}>0\}} P_{ki} q_k + r_i - c_i, 0 \right)$$

```
return
```

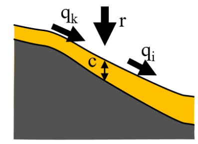

Figure 3. Flow algebra formulation for retention-limited runoff generation with run-on.

V. Height Above Nearest Drainage (HAND) and Flood Inundation

Height Above Nearest Drainage (HAND) is a special case of distance down proximity measure to an arbitrary target, with the target being a stream and distance measured vertically (Fig. 4).

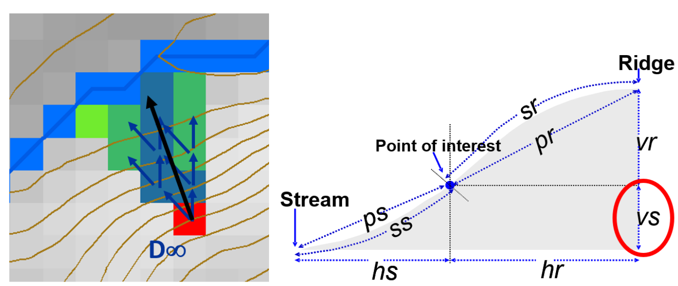

Figure 4. HAND evaluated using TauDEM D∞ Vertical Distance Down function [15]. Vertical distance to stream is evaluated as weighted average over multiple flow paths resulting in a "smooth" height above nearest drainage layer.

HAND supports flood inundation mapping. Once the depth of flow in a stream is determined, the area and depth of flood inundation can be mapped. By dividing streams into reaches or segments, the area draining to each reach can be isolated, and a series of threshold depths applied to the grid of HAND values in that isolated reach catchment to determine inundation volume, surface area, and wetted bed area. Dividing these by length yields reach average cross-section area, width, and wetted perimeter, information useful for hydraulic routing and stage-discharge rating calculations in hydrologic modeling (Fig. 5) [16].

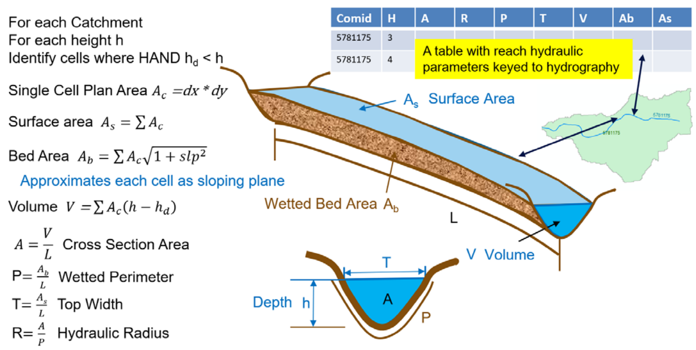

Figure 5. HAND-based derivation of "reach scale" hydraulic properties. Note that DEM topography should represent riverbed elevations [16].

VI. Conclusions and Future Challenges

The DEM-based terrain flow data model enables the representation of flow processes at and near the Earth's surface and the derivation of a wide variety of information useful for the study of hydrologic processes. Starting from a simple DEM, one can compute slope, flow direction, drainage area, catchments, watersheds, channel networks, and multiple other flow-related quantities useful in hydrologic modeling and analysis. Much of this capability has been implemented in the freely available open-source TauDEM software, which includes both D8 and D∞ options for representing the flow field. It includes a number of functions derived using flow algebra, which generalizes the recursive flow accumulation methodology using both downslope and upslope logic. Queue-based approaches have been used to develop parallel methods that implement flow algebra logic.

Future challenges and opportunities include leveraging increasingly high-resolution data, such as from LiDAR, and integrating datasets from various sources and resolutions, including both vector and raster data. High-resolution DEMs present computational challenges, necessitating the use of emerging cloud and high-performance computing capabilities, as well as advancements in data structures and formats. DEMs with resolutions finer than approximately 5 meters introduce topographic details at scales smaller than typical topographic flow, requiring new methods to effectively utilize such data. Additionally, the objective channel network mapping problem remains unsolved, presenting opportunities to employ object detection approaches that blend remote sensing and high-resolution LiDAR data with traditional terrain analysis techniques.

VII. Acknowlegments

Thank you to the International Society for Geomorphometry for inviting me to present a keynote at this conference. Over the years TauDEM has been developed with funding from the US Army Research and Development Center (awards W912HZ-11-P-0338, W9124Z-08-P-0420), NOAA (Grant NA06NOS4190167), NASA (award NAG5-7521) and the US National Science Foundation (EAR-9318977). I appreciate this support. Numerous colleagues have collaborated in this work including Teklu Tesfa, Yan Liu, Ahmet Yildirim, Dan Watson, Kim Schreuders, Shaowen Wang, Dan Ames, Xing Zheng, David Maidment.

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