Geomorphometry: Today and Tomorrow

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Abstract—**This paper summarizes the current state-of-the-art in geomorphometry and describes the innovations that are close at hand and will be required to push digital terrain modeling forward in the future. These innovations will draw on concepts and methods from computer science and the spatial sciences and require greater collaboration to produce "actionable" knowledge and outcomes.**

I. Introduction

Great strides have been in digital terrain modeling during the past 50 years spurred on by new sources of digital elevation data, the increasing use of theory to guide digital terrain modeling workflows, the specification of many new land surface parameters, the identification and extraction of landforms and other land surface objects, the improving characterization of error and uncertainty, and the development and sharing of new computer code to facilitate and support digital terrain modeling workflows. The rate of development has surged during the past 15 years, motivated by pressing environmental challenges at the meso- and topo-scales and the rapidly evolving computational resources that are now available to support digital terrain modeling applications.

The remainder of this paper is divided into three parts. The first summarizes the current state-of-the-art, the second describes the innovations that are close at hand and will be required to push digital terrain modeling forward in the future, and the third offers some conclusions.

II. Current State-of-the-Art

Most digital terrain modeling applications in biogeography, climatology, ecology, geology, geomorphology, hydrology, pedology and natural hazards are scale-specific and the results will vary with the scale over which they are cast. The user is then left with the dilemma that they cannot determine whether the failure of a model to fit perfectly is due to the model itself, or to the relatively 'coarse' resolution of the elevation data, or both [1]. Relatively little attention has been given to the topological relationships among topographic features and this state-of-affairs helps to explain why all computed surface networks are scale-dependent, fuzzy, and vague and why their undisputed calculation remains elusive [2].

The transition from cartographic to remote sensing data sources and the associated consequences – the large coverage and fine resolutions afforded by many of these new DEMs – has brought numerous changes to the typical digital terrain modeling workflow. The potential benefits are enormous: the ASTER and SRTM DEMs, for example, provide coverage for much of the globe at the 30 m resolution that could only be used for small and moderate-sized catchments until relatively recently and LiDAR provides large numbers of high-density mass points which, if processed appropriately, can provide 1-3 m DEMs with high vertical accuracy and the preservation of the terrain structure (i.e. the shape).

This transition means that most of us will not collect our own source data and prepare our own DEMs going forward and this will place an increased emphasis on the provenance of both the original data and the methods applied to them and the expertise of the people contributing the DEMs. This focus on provenance will improve the reproducibility and encourage users to consider questions surrounding the credibility (i.e. fitness-of-use) of the content for the task(s) at hand [3].

The calculation and use of land surface parameters constitute the heart of geomorphometry as we know it today. There is now more than 100 primary and secondary land surface parameters in common use [4]. The majority are primary parameters derived from square-grid DEMs that measure site-specific, local or regional characteristics without additional input. The secondary parameters are derived from ≥2 of the primary parameters and additional inputs in some instances, and focus on water flow/soil redistribution or energy/heat regimes. Many of these land surface parameters incorporate flow direction and therefore make use of one or more of the 24 flow direction algorithms that have been proposed during the past 33 years. Several of the newer algorithms combine square-grids and TINs to avoid the shortcomings associated with square-grid DEMs and to take advantage of the additional discretization provided by TINs. However, it is difficult to assess the efficacy of these flow direction algorithms, and their impact on flow accumulation and the other land surface parameters that incorporate them. Buchanan et al. [5], for example, recently calculated topographic wetness using >400 unique approaches that considered different DEM resolutions, the vertical precision of the DEM, flow direction and slope algorithms, smoothing versus low-pass filtering and the inclusion of relevant soil properties, and compared the resulting topographic wetness maps with observed soil moisture in agricultural fields.

Some applications have also focused on the extraction and classification of landforms and land surface objects. Fuzzy classification methods have featured prominently in these applications because many of the land surface objects and landforms that are of interest have fuzzy boundaries. Several others have attempted to automate and extend Hammond's [6] map of repeating landform patterns for the conterminous U.S. to the globe [7]. And finally, Dragut and Eisank [8] borrowed concepts from remote sensing and data science to first segment the DEM and then classify the objects to avoid the problems of working directly with the DEM grid cells when extracting and classifying landforms and other land surface objects.

A number of recent applications have also tackled sources of error, the various ways uncertainty can be estimated and handled in terrain modeling workflows, how this knowledge can be used to assess 'fitness-for-use' in specific applications, and the new opportunities for multi-scale analysis and cross-scale inference afforded by the increasing availability of DEMs across a broad range of scales. A series of stellar case studies shows how the measurement of error and uncertainty accompanying terrain modeling workflows might be used to improve our understanding of predictive vegetation modeling [9], soil redistribution resulting from water erosion [10], how catchment area calculations, slope estimates and numerical simulations of landscape development [11] and the soil-water-vegetation interactions in the LPJ-GUESS dynamic ecosystem model [12] are influenced by the choice of flow direction algorithm, and how a new sub-grid TOPMODEL parameterization and the associated uncertainties influence the modeling of the spatiotemporal dynamics of global wetlands [13]. More applications like these will be needed in the future.

All of the aforementioned applications are enabled by software the supports the calculation of land surface parameters and the extraction and classification of landforms and other land surface objects. Six systems – ArcGIS, GRASS, QGIS, SAGA, TauDEM, and the Whitebox Geospatial Analysis Tools – stand out today because of the large numbers of terrain tools included, the availability of GIS functions, the large numbers of data formats supported, and the high level of interoperability.

III. Future Needs and Opportunities

A. *Provenance, Credibility, and Application-Context Knowledge*

The rapid emergence of the web and all this entails (i.e. web portals for sharing geospatial datasets, the provision of software as a service, etc.) coupled with advances in our knowledge and understanding of error and uncertainty and how these concepts can be used to clarify the 'fitness-for-use' of digital terrain modeling tools and data for specific applications bring both provenance and credibility to the fore. These elements traditionally have been handled by metadata in the spatial sciences and it will be important for the geomorphometry community to adopt and use metadata to describe digital terrain modeling methods and datasets going forward. However, this metadata may be necessary but not sufficient, and Qin et al. [14] recently used case-based formalization and reasoning methods to acquire 'application-context' knowledge. They selected 124 cases of drainage network extraction (50 for evaluation and 74 for reasoning) from peer reviewed journal articles and used these cases to determine the catchment area threshold for extracting drainage networks.

B. *Rediscovering and Using What We Already Know*

The development of global elevation datasets has brought into focus what geographers have long known; namely, the need to choose your map projections and coordinate systems carefully to suit the geographic extent of the study area of interest. The general strategy should be one in which spherical equal angular DEMs are chosen for large study areas (i.e. the globe, continents, and the catchments of large rivers) and planar square-grid DEMs are chosen for small and moderate-sized catchments. Most of today's methods were developed for planer square-grid DEMs, but Guth [15] and others have proposed algorithms for calculating some land surface parameters for spherical equal angular DEMs.

C. *Developing New Digital Terrain Modeling Methods*

The continued development of new digital terrain modeling methods like the three examples highlighted below is likely to yield substantial benefits as well. Krebs et al. [16] recently proposed a new method to assess the vertical transverse and profile curvature that provides new opportunities to measure and visualize these two land surface parameters over a large range of scales. Byun and Seong [17] proposed a new maximum depth tracing algorithm to extract more accurate stream longitudinal profiles using depression-unfilled DEMs, and Buttenfield et al. [18] compared planar distance with 8 measures of surface-adjusted distance to check whether or not the common assumption, that the improvements in distance estimation are so small that surface adjustment is not warranted, is true (or not) for specific applications.

D. *Clarifying and Strengthening the Role of Theory*

The emergence of fine resolution elevation data, such as LiDAR, also provides new opportunities to assess fundamental questions about landscape form and evolution in geomorphology as well as other domains. There are two primary ways to proceed here. The first uses theory to guide the workflow that is chosen, whereas the second relies on experiments to test one or more of our existing theories.

The first approach seeks to take advantage of our existing knowledge of how processes work. Clubb et al. [19], for example, have proposed a new algorithm for predicting channel head locations that is partly informed by the stream power equation, which is a detachment-limited model that proposes that the fluvial incision rate is proportional to stream power, which represents the energy expenditure of the flow.

The second approach noted above seeks to test existing theory and can be illustrated using the work of Jensco and McGlynn [20] which tested the relationship between upslope contributing area and the existence and longevity of the hillslope-riparian-stream shallow groundwater connectivity for a series of transects and the stream network for several watersheds in Montana. The results showed how the internal catchment landscape structure acts as a first-order control on runoff source area and catchment response in these types of landscapes.

E. Developing High-fidelity Multi-resolution DEMs

The importance of multi-scale analysis and cross-scale inference will grow in the future. These applications rely on the availability of high-fidelity, multi-resolution DEMs and methods to build such DEMs. Some progress has been made but most of this work is motivated by the need or desire for accurate topographic representation across a relatively narrow range of geographic scales. There are two challenges. The first concerns the types of surfaces represented with some of the new radar and stereo optical imagery sources. The default surface is the top of the structures or vegetation and many, but not all, geomorphic applications will need a bare earth DEM. The second is the need for high-fidelity, multi-resolution DEMs that work with global environmental simulations which adopt sub-grid schemes to express topographic heterogeneity [21]. These sub-grid schemes are typically designed for empirical parameterization rather than accurate topographic representation and too much focus on the latter outcome may lead to greater uncertainties and bias.

F. Developing and Embracing New Visualization Methods

The methods to visualize digital terrain modeling results have not kept pace with the rapidly evolving computational resources and the availability and use of fine resolution DEMs which cover large areas. The map generalization projects funded as part of the NED research program in the U.S. [22] and the new tangible geospatial modeling system proposed by Petrasova et al. [23] may help to fill this gap.

G. Adopting New Computational Methods

The rapid advances in computational power and changing models of computing (i.e. cloud computing, cyberinfrastructure, interoperability, software-as-a-service) offer new opportunities to develop new analytical tools and expand the geographic extent and heft of digital terrain modeling projects. Three examples can be used to illustrate the potential benefits of these new methods.

The TerraEx [24] application, for example, is a freely available, full service web application to locate landscapes that are similar to a user-selected query and doubles as a convenient portal to support the distribution of 3 arc-second DEMs and global maps of geomorphons and terrain relief. Survilla et al. [25], on the other hand, have developed a scalable high performance topographic flow direction algorithm which eliminates the bottleneck caused by flow direction, one of the most computationally intensive functions in the current implementation of TauDEM [26]. This essentially local operation is transformed into a global operation to route flow across flat regions, by first identifying the flat areas and then using this information to reduce the number of sequential and parallel iterations needed to calculate flow direction. The third and final example by Qin et al. [27] proposes an efficient solution to calculate the differential equation for specific catchment area (SCA) proposed by Gallant and Hutchinson [28] from gridded DEMs for small- and moderate-sized catchments.

IV. Conclusions

The seven innovations highlighted in the previous section show how the adoption and use of modern computing platforms can modify the digital terrain modeling workflows that many of us have used with standalone personal computers during the past few decades and thereby advance our craft. These innovations can also be used to encourage the pursuit of digital terrain modeling projects that will produce “actionable” knowledge and outcomes. The final two applications described below show how such projects can transcend multiple scales.

In the first study, Woodrow et al. [29] examined the impacts of DEM grid resolution, elevation source data, and conditioning techniques on the spatial and statistical distribution of field-scale hydrological attributes for a small agricultural watershed in Ontario, Canada. The results showed how the decision to use one DEM conditioning technique over another and the constraints of available DEM data resolution and source can greatly impact the modeled surface drainage patterns for individual fields. These kinds of results can help with the design of best management practices for reducing soil erosion and runoff contamination within agricultural watersheds and thereby in helping to manage nonpoint source pollution at the source.

The second application is the U.S. National Water Model (NWM) project. This large, multi-disciplinary project forecasts streamflow over the continental U.S. at intervals of 1 hour, 18 hours, 10 and 30 days for 2.7 million stream reaches. The NWM uses the WRF-Hydro and Noah-MP land surface models to simulate meteorological conditions and terrestrial hydrology. Several ArcGIS Hydro and TauDEM [26] terrain modeling functions are included in WRF-Hydro and these provide the essential 'glue' and are used as part of this modeling framework to route water across the land surface to the nearest stream channel. The NWM outputs can be accessed via interactive maps (http://water.noaa.gov/map) and once incorporated in the daily workflows of the relevant agencies (public safety, water resources, etc.), they will fundamentally change the ways in which local, state, and federal agencies prepare for and anticipate floods and related water challenges.

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