



Frontiers in Geomorphometry and Earth Surface Dynamics: Possibilities, Limitations and Perspectives

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Abstract. Geomorphometry, the science of quantitative land-surface analysis, has become a flourishing interdisciplinary subject, with applications in numerous fields. The interdisciplinarity of geomorphometry is its greatest strength and also one of its major challenges. Gaps are still present between the process focussed fields (e.g. soil science, glaciology, volcanology) and the technical domain (such as computer science, statistics...) where approaches and theories are developed. Thus, interesting geomorphometric applications struggle to jump between process-specific disciplines, but also struggle to take advantage of advances in computer science and technology. This special issue is therefore focused on facilitating cross-fertilization between disciplines, and highlighting novel technical developments and innovative applications of geomorphometry to various Earth-surface processes. The issue collects a variety of contributions which fall into two main categories: *Perspectives* and *Research*, further divided into ‘Research and innovation techniques’ and ‘Research and innovative applications’. It showcases potentially exciting developments and tools which are the building blocks for the next step-change in the field.

1 Introduction

25 Elucidating the dynamics of Earth surface processes through analysis of Digital Elevation Model (DEMs), or 'geomorphometry' (Evans et al., 2003; Hengl and Reuter, 2008), has become a flourishing interdisciplinary subject, with applications in numerous fields (e.g., geomorphology, planetary science, archaeology, geo-biology, natural hazards, and computer science). The Earth's morphology can be measured at all scales, from macro (e.g. globally via space missions), to micro (e.g. using laser scanners and most recently structure-from-motion techniques). These datasets have broad applications 30 to all kinds of processes, both natural and anthropogenic (Tarolli and Sofia, 2016; Tarolli, 2014), and they underpin much modern geomorphological research.

Conceptually any analysis in geomorphometry is a two-step process. Firstly, data must be obtained and their accuracy assessed. Second, these data must be integrated into modelling, or into portraying and understanding the specific process of interest. There are advantages and disadvantages of each method, technique and topographic datatype, which vary depending on the



objectives of the analysis. Often, however, significant weaknesses or methodological limitations exist, which prevent us from gaining the insights into processes that we otherwise might. The interdisciplinarity of geomorphometry is its greatest strength and also one of its major challenges. Specifically, process-focussed fields (e.g. soil science, glaciology, volcanology) use their own set of established geomorphometric approaches, and geomorphological specialists often play a key role in developing 5 these. However, these specialists in turn struggle to incorporate the most innovative approaches and theory being developed in the associated technical domains (such as, computer vision, machine learning, and statistics), or even approaches being used in neighbouring disciplines. So, interesting geomorphometric applications struggle to jump between process-specific disciplines, but also struggle to take advantage of advances in computer science and technology.

If we are to best exploit the wealth of information held within DEMs it is important to i) gather knowledge about the current 10 technical state-of-the-art in order to consolidate and disseminate established advances; ii) evaluate stubbornly unproductive areas to identify key future challenges and opportunities; iii) provide specific and innovative case studies to assist in cross-disciplinary communication; iv) provide clear and understandable translations from the technical domains where algorithms and techniques find their basis.

In light of the challenges set out above, this special issue in Earth Surface Dynamics highlights current frontiers in 15 geomorphometry. In order to collect recent research advancements and motivate further research in this direction, we organized a ‘Frontiers in geomorphometry’ session at the European Geosciences Union General Assembly in 2015, and it has continued successfully since then. The session was focused on facilitating cross-fertilization of best practice across disciplines, highlighting novel technical developments, and showcasing innovative applications of geomorphometry to various Earth-surface processes. The issue collects a variety of contributions, which fall into two main categories: *Perspectives* and *Research*, 20 where *Research* is further divided into ‘Research and innovative techniques’ and ‘Research and innovative applications’. The collected *Perspective* works are reviews of state-of-the-art developments as applied to geomorphometry, with a forward-looking component seeking to identify opportunities and challenges. They are intended to stimulate discussion and new experimental approaches. The papers in the *Research* section present developments of novel techniques, or showcase innovative application(s) of existing methods.

25 2 Frontiers

2.1 Perspectives

The collected perspectives investigate three major questions. i) Physical processes, including anthropogenic feedbacks sculpt 30 planetary surfaces (e.g., Earth’s). A fundamental tenet of geomorphology is that mapping and, increasingly, quantifying the shapes produced can yield insights into the processes. However, the precision and accuracy of mapped data are not well understood. So, how good are these geomorphological data that underpin analyses, and how can we more objectively investigate this? ii) The human brain has a remarkable capability for identifying patterns in complex, noisy datasets, and then applying this knowledge to problem solving. Can we transfer and replicate this ability via computational means, to advance



geosciences? iii) One of the most recent revolution in geomorphology is the multiview photogrammetry, or Structure-from-Motion (SfM) technique (Fonstad et al., 2013; Micheletti et al., 2015; Smith et al., 2015; Westoby et al., 2012). What are the key developments and potential future avenues for research in this field, and how do they relate to geomorphometry?

To respond to the first point, Hillier et al. (2015) introduce synthetic DEMs. This perspective reviews the possible approaches 5 to the generation of artificial DEMs. highlighting their limitations, potential, and the opportunities for application. Realistic synthetic DEMs offer a way to assess and understand geomorphological data, allowing users to proceed with uncertainty-aware landscape analysis to examine physical processes.

Valentine and Kalnins (2016) offer an overview about machine learning and its potential in geosciences. Learning algorithms come from the computer science world, and they are designed to replicate the human approach of inferring information from 10 a dataset, and then apply that information predictively. In this work, the authors provide a review of the existing applications in geosciences, and discuss some of the factors that determine whether a learning algorithm approach is suited to geomorphological problems.

Eltner et al. (2015) provide a summary for researchers wanting to apply the SfM method. They summarize the state of the art of published research on SfM photogrammetry applications in geomorphometry. In addition, they give an overview of terms 15 and fields of application, and they identify key future challenges, with a specific focus also on the errors associated with such a technique.

2.2 Research and innovative techniques

A fundamental operation in geomorphometry is the extraction of parameters from DEMs to understand the underlying process. How these parameters and objects are evaluated and identified still presents a challenge, and there is still room for 20 improvement. Papers included here, extend our knowledge about fluvial dynamics and incision, or stage dependent patterns in rivers. A further collection of work focuses on sediment, erosion and connectivity at the hillslope or watershed scale.

Hergarten et al. (2016) develop and explore an extension of the chi-transformation (χ) to small catchment sizes. They solve the limitation of the χ technique for different watershed sizes, extending the stream power equation to headwater areas dominated by debris flows. In addition, the authors introduce an alternative optimization scheme to linearize the chi-elevation 25 relation.

Brown and Pasternack (2016) demonstrate a relatively new method of analysis for stage dependent patterns in rivers named geomorphic covariance structures (GCSs). Using meter-scale resolution DEMs, their approach aims to understand if and how the covariance of bed elevation and flow-dependent channel top width are organized in a partially confined, incising gravel-cobbled bed river with multiple spatial scales of anthropogenic and natural landform heterogeneity across a range of discharges.

30 Trevisani and Cavalli (2016) propose a flow-oriented directional measure of roughness based on geostatistics that keeps into account surface gravity-driven flow directions. Their approach shows the potential impact of considering directionality in the calculation of roughness indices. In addition, they demonstrate how the use of flow-directional roughness can improve the geomorphometric modelling of sediment connectivity, and the interpretation of landscape morphology.



Sklar et al. (2016) propose a novel way to quantify the three-dimensional geometry of catchments. The authors develop an empirical algorithm for generating synthetic source-area power distributions, parameterized with data from natural catchments. Their model can be used to explore the effects of topography on the distribution on fluxes of water, sediment, isotopes and other landscape products passing through catchment outlets.

5 Bigelow et al., (2016) focus on erosion and sedimentation, and the identification of sediment sources and sinks across landscapes from a practitioners' point of view. Their approach demonstrates a modern analysis of important geomorphic processes affected by land use that can be easily applied by agencies to solve common problems in watersheds, improving the integration between science and environmental management.

10 Grieve et al. (2016) present software for the automatic extraction and processing of relevant topographic parameters to rapidly generate non-dimensional erosion rate and relief data. This application allows identification of whether landscapes are in topographic steady state, and to identify clear signals of an erosional gradient or evidence for a landscape decaying following uplift.

2.3 Research and innovative applications

In this section, the collected papers expand the applications of geomorphometry to a larger spatial and temporal domain, 15 investigating past tectonic history, or past interactions between ice sheets and climate in glacial systems. Other researchers show the effectiveness of multitemporal datasets at the hillslope or catchment scale to give new insights about sediment dynamics and seasonal pattern of erosion processes. Finally, two more papers push the frontier of which processes may be examined by SfM for quantitative analysis in the glaciological field.

20 Andreani and Gloaguen (2016) present a study that uses geomorphic indexes to classify the landscape into different regions in order to unravel its tectonic history. These observations/interpretations allow for a better understanding of the recent evolution of the diffuse triple junction between the North American, Caribbean, and Cocos plates in northern Central America.

Wickert (2016) offers a general method to compute past river flow paths, drainage basin geometries, and river discharges at 25 the continental-scale. By integrating numerical modelling (i.e. ice sheet, isostatic adjustment and climate) with field data including geomorphology his work builds new insights into past glacial systems and climate–ice-sheet interactions.

25 In Loyer et al. (2016), terrestrial Laser Scanning (TLS) is used as a monitoring tool at the catchment scale to analyze the coupling between sediment dynamics and torrent responses in terms of debris flow events. Similarly, Bechet et al. (2015) provide a novel example of how high-resolution time-lapse DEM collection can give insights into processes, in particular for understanding the seasonal pattern of erosion processes for black marls badland-type slopes.

The work by Piermattei et al. (2015) demonstrates the advantages and potential of SfM to calculate the geodetic mass balance 30 of glacier in the Ortles-Cevedale Group, Eastern Italian Alps. In addition, they investigated the feasibility of using the image-based approach for the detection of the surface displacement rate of an active rock glacier. Westoby et al. (2015) analyze the surface evolution of an Antarctic blue-ice moraine using multi-temporal DEMs from TLS and SfM. The authors' results provide an additional understanding of inter-annual development of moraine systems.



3 Future challenges

The availability of DEMs at multiple scales in terms of resolution and spatial and temporal coverage offers great opportunities for the investigation of Earth-surface processes. Geomorphometry has become inter-disciplinary, with focus on new techniques in digital terrain production but also analyses, independent of the subject, and/or field. This special issue showcases potentially 5 exciting developments and tools (e.g. synthetic DEMs, neural networks) that are the building blocks for the next step-change in the field. In reading and compiling these contributions we hope that you, the scientific community, will be inspired to seek out collaborations and share your ideas across subject-boundaries, between technique developers and users, enabling us as a community to fully exploit the wealth of knowledge inherent in our digital landscape.

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