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Analyzing high resolution topography for advancing the understanding of mass and energy transfer through landscapes: A review

Paola Passalacqua [a,b,*], Patrick Belmont [c], Dennis M. Staley [d], Jeffrey D. Simley [d], J Ramon Arrowsmith [e], Collin A. Bode [f], Christopher Crosby [g], Stephen B. DeLong [h], Nancy F. Glenn [i], Sara A. Kelly [c], Dimitri Lague [j], Harish Sangireddy [a,b], Keelin Schaffrath [c], David G. Tarboton [k], Thad Wasklewicz [l], Joseph M. Wheaton [c]

[a] *Department of Civil, Architectural, and Environmental Engineering, The University of Texas at Austin, 301 E. Dean Keeton St., STOP C1700, Austin, TX 78712-2100, USA*
[b] *Center for Research in Water Resources, The University of Texas at Austin, 301 E. Dean Keeton St., STOP C1700, Austin, TX 78712-2100, USA*
[c] *Department of Watershed Sciences, Utah State University, 5210 Old Main Hill, NR 350, Logan, UT 84322-5210, USA*
[d] *U.S. Geological Survey, Denver CO, USA*
[e] *School of Earth and Space Exploration, Arizona State University, 1151 S. Forest Ave., Tempe, AZ 85281, USA*
[f] *Department of Integrative Biology, University of California Berkeley, Valley Life Sciences Bldg 3140, Berkeley, CA 94720-3140, USA*
[g] *UNAVCO, 6350 Nautilus Drive, Boulder, CO 80301-5394, USA*
[h] *U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025-3561, USA*
[i] *Department of Geosciences, Boise State University, 1910 University Drive, Boise, ID 83725-1535, USA*
[j] *Géosciences Rennes, Université Rennes 1, UMR6118 CNRS, Campus de Beaulieu, 35042 Rennes Cedex, France*
[k] *Department of Civil and Environmental Engineering, Utah State University, 4110 Old Main Hill, Logan, UT 84322-5210, USA*
[l] *Department of Geography, A-204 Brewster Hall, East Carolina University, Greenville, NC 27858, USA*

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ABSTRACT

The study of mass and energy transfer across landscapes has recently evolved to comprehensive considerations acknowledging the role of biota and humans as geomorphic agents, as well as the importance of small-scale landscape features. A contributing and supporting factor to this evolution is the emergence over the last two decades of technologies able to acquire high resolution topography (HRT) (meter and sub-meter resolution) data. Landscape features can now be captured at an appropriately fine spatial resolution at which surface processes operate; this has revolutionized the way we study Earth-surface processes. The wealth of information contained in HRT also presents considerable challenges. For example, selection of the most appropriate type of HRT data for a given application is not trivial. No definitive approach exists for identifying and filtering erroneous or unwanted data, yet inappropriate filtering can create artifacts or eliminate/distort critical features. Estimates of errors and uncertainty are often poorly defined and typically fail to represent the spatial heterogeneity of the dataset, which may introduce bias or error for many analyses. For ease of use, gridded products are typically preferred rather than the more information-rich point cloud representations. Thus many users take advantage of only a fraction of the available data, which has furthermore been subjected to a series of operations often not known or investigated by the user. Lastly, standard HRT analysis work-flows are yet to be established for many popular HRT operations, which has contributed to the limited use of point cloud data.

In this review, we identify key research questions relevant to the Earth-surface processes community within the theme of mass and energy transfer across landscapes and offer guidance on how to identify the most appropriate topographic data type for the analysis of interest. We describe the operations commonly performed from raw data to raster products and we identify key considerations and suggest appropriate work-flows for each, pointing to useful resources and available tools. Future research directions should stimulate further development of tools that take advantage of the wealth of information contained in the HRT data and address the present and upcoming research needs such as the ability to filter out unwanted data, compute spatially variable estimates of uncertainty and perform multi-scale analyses. While we focus primarily on HRT applications for mass and energy transfer, we envision this review to be relevant beyond the Earth-surface processes community for a much broader range of applications involving the analysis of HRT.

* Corresponding author at: Department of Civil, Architectural, and Environmental Engineering, The University of Texas at Austin, 301 E. Dean Keeton St., STOP C1700, Austin, TX 78712-2100, USA.
E-mail address: paola@austin.utexas.edu (P. Passalacqua).

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Contents

1. Introduction

One of the fundamental principles for understanding Earth-surface processes is *conservation* (Anderson and Anderson, 2010); the total rate of change of a quantity, such as mass or energy, within a control volume equals the rate of change of the quantity stored within the control volume plus the quantity net outflow across the control surface. Rates of change depend on sources and sinks of the quantity of interest and on spatial gradients in transport rates. Many problems of interest to geomorphologists and hydrologists can be cast in these terms (Kirkby, 1971). Development of a sediment budget of a watershed, for example, requires the identification of sediment sources and sinks, and the understanding of how sediment is transformed and transported from one point of the watershed to another.

The ability to predict water, sediment, and nutrient transfer, map natural hazards, perform a radiation balance, and understand biophysical feedbacks that control landscape form and function is of great value to Earth-surface scientists and natural resources managers. This ability relies on the understanding of how mass and energy are transferred through watersheds and landscapes. Contributions on this topic have populated the geomorphologic and hydrologic literature for over a century (Gilbert and Dutton, 1880; Davis, 1892; Gilbert, 1909; Gilbert and Murphy, 1914; Strahler, 1952; Culling, 1960; Kirkby, 1971; Smith and Bretherton, 1972; Willgoose et al., 1991a,b,c; Anderson, 1994; Howard, 1994; Tucker and Slingerland, 1994, 1997; Dietrich et al., 2003) which also account for the effect of biota and humans on landscapes. A large set of field observations and models, in fact, supports the knowledge that biological productivity directly and indirectly affects landscape evolution (e.g., Drever, 1994; Butler, 1995; Gabet, 2000; Lucas, 2001; Sidle et al., 2001; Bond et al., 2002; Yoo et al., 2005; Meysman et al., 2006; Phillips, 2009; Foufoula-Georgiou et al., 2010). Humans, long recognized as geomorphic agents (Marsh, 1869, 1882), have now significantly impacted landscapes and their ecosystems (Hooke, 1994, 2000; Foley et al., 2005; Ellis et al., 2006; Montgomery, 2007; Syvitski and Saito, 2007; Wilkinson and McElroy, 2007; Ellis, 2011; Sidle and Ziegler, 2012; Tarolli et al., 2014). Roads, for example, can play an important role in a watershed sediment budget as they constitute a significant source of sediment (Sidle and Ziegler, 2012) and disrupt ecosystem connectivity (Riitters and Wickham, 2003).

The evolution in mass and energy transfer studies is also reflected in mathematical modeling approaches. From the employment of classic mass and energy conservation laws (Eagleson, 1986; Lane, 1998; Trimble, 1999; Dietrich et al., 2003), recent years have also seen the development of *nonlocal* constitutive laws expressing the material flux at a point (e.g., sediment flux) as a function of the conditions in some neighborhood around this point in space and/or in time (e.g., Bradley et al., 2010; Foufoula-Georgiou et al., 2010; Ganti et al., 2010; Tucker and Bradley, 2010; Foufoula-Georgiou and Passalacqua, 2013; Furbish and Roering, 2013). The nonlocal approach allows incorporating the heterogeneity and complexity typical of geomorphic systems and the wide range of spatial and temporal scales that characterizes geomorphic processes.

Topographic gradients are a key factor in the transport of mass and energy. Whether computed at the location of interest or over a domain of influence as in nonlocal approaches, topographic attributes, such as slope, curvature, and roughness, play a fundamental role in the transport of mass and energy through landscapes. In the past, however, the representation of the Earth-surface was possible only at coarse spatial resolutions (i.e., ≥10 m). Data collected during the Shuttle Radar Topography Mission (SRTM data), for example, were a major breakthrough in the early 2000s, but are quite coarse (30 m resolution) compared to today's standards. SRTM data do not capture many of the small scale features and perturbations, both natural and anthropogenic, that combine to exhibit significant control over mass and energy transfer. This applies also to the U.S. Geological Survey's National Elevation Dataset that has traditionally only been available at 10 m and 30 m resolutions.

The explosion of availability of high resolution topography (HRT) over the last two decades is revolutionizing the way we study mass and energy transfer through landscapes. We define HRT as any topographic dataset, which in its raw form consists of location (x, y) and elevation (z) measurements that collectively compose a point cloud, and which have average spatial resolutions greater than or equal to one