Geomorphology 250 (2015) 236–248

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Downstream hydraulic geometry relationships: Gathering reference reach-scale width values from LiDAR

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ARTICLE INFO

Article history:
Received 20 December 2014
Received in revised form 2 September 2015
Accepted 4 September 2015
Available online 9 September 2015

Keywords:
LiDAR
DTM
Feature extraction
Downstream hydraulic geometry relationship

ABSTRACT

This paper examines the ability of LiDAR topography to provide reach-scale width values for the analysis of downstream hydraulic geometry relationships along some streams in the Dolomites (northern Italy). Multiple reach-scale dimensions can provide representative geometries and statistics characterising the longitudinal variability in the channel, improving the understanding of geomorphic processes across networks. Starting from the minimum curvature derived from a LiDAR DTM, the proposed algorithm uses a statistical approach for the identification of the scale of analysis, and for the automatic characterisation of reach-scale bankfull widths. The downstream adjustment in channel morphology is then related to flow parameters (drainage area and stream power). With the correct planning of a LiDAR survey, uncertainties in the procedure are principally due to the resolution of the DTM. The outputs are in general comparable in quality to field survey measurements, and the procedure allows the quick comparison among different watersheds. The proposed automatic approach could improve knowledge about river systems with highly variable widths, and about systems in areas covered by vegetation or inaccessible to field surveys. With proven effectiveness, this research could offer an interesting starting point for the analysis of differences between watersheds, and to improve knowledge about downstream channel adjustment in relation, for example, to scale and landscape forcing (e.g. sediment transport, tectonics, lithology, climate, geomorphology, and anthropic pressure).

1. Introduction

1.1. Background and aims of research

Natural rivers develop channels in a broad range of forms (Knighton, 1987). As a consequence, the flow width (w) and the morphological characteristics of a stream are critical parameters in a wide range of hydrologic applications. Detailed topographic data are therefore a fundamental requirement (Biron et al., 2013; Cavalli et al., 2008; Charlton et al., 2003; Heritage and Hetherington, 2007; Hilldale and Raff, 2008; Jones et al., 2007; Lane et al., 2003; Tarolli, 2014).

Analysing bankfull widths at a reach-scale can provide representative geometry and statistics characterising longitudinal variability in a channel (Wohl et al., 2004; Stewardson, 2005; Harman et al., 2008; Xia et al., 2014). Flow width generally changes depending on the bankfull discharge, as the conditions forming the shape and morphology of a channel with recurrence intervals ranging between one and two years (Wolman and Leopold, 1957). The reach-scale flow width and discharge (Q) are related through a power law relationship (e.g., Wolman and Leopold, 1957; Emmett, 1975; Andrews, 1980; Carling, 1988; Finnegan et al., 2005; Wohl and David, 2008):

$$w = aQ^{b} \tag{1}$$

where a and b are empirically derived constants.

Channel geometry also reflects the capacity of the stream to transport sediment (Vianello and D'Agostino, 2007), thus widths may also be related to the stream power, which defines the rate of energy expenditure per unit length of the channel (Bagnold, 1966; Brummer and Montgomery, 2003; Finnegan et al., 2005). Analysing the stream power in relation to the sediment grain sizes also allows identification of thresholds for the adjustment of flow width in response to changes in discharge (Wohl, 2004). The empirical parameters of the downstream hydraulic geometry relationships are normally estimated by regression, using values surveyed at multiple cross-sections having two or more discharges. The comparison between watersheds is made through field work by researchers, but it is limited to specific field-surveyed case studies. Although some countries have numerous investigated sites (i.e. Faustini et al., 2009), in Italy, hydraulic relationships are available only for few areas in the Dolomites (i.e. Lenzi, 2001; D'Agostino and Vianello, 2005; Vianello and D'Agostino, 2007; Comiti et al., 2007; Wilcox et al., 2011) and some rivers in central Italy (i.e.

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http://dx.doi.org/10.1016/j.geomorph.2015.09.002
0169-555X/

Orlandini and Rosso, 1998; Whittaker et al., 2007a, 2007b; Yanites and Tucker, 2010). LiDAR datasets, on the other hand, are nowadays widely available, including for public download (e.g. the NSF-EAR-funded data facility OpenTopography, or the LiDAR geoportal for the Alpine region Trentino Alto Adige in Italy). Questions still need to be asked, such as why rivers with similar drainage areas have different widths. Some field-related works underlined how the nature of channels affects this, but urbanisation (e.g. Hession et al., 2003), geology and climate should also be considered. The availability of a large number of downstream relationships would allow investigation of the differences between watersheds at multiple scales, and in areas subject to various landscape forcings, such as sediment transport, tectonics, lithology, climate, geomorphology, and anthropic pressure. Clearly, although it is theoretically possible to measure bankfull width manually, it becomes impractical if hundreds or thousands of river width values must be obtained. During the past two decades, advances in remote-sensing technology have allowed the fast, precise and effective acquisition of topographic information with high quality (see Tarolli, 2014 for a full review), and the field of fluvial geomorphology has seen increased application of high resolution surveying technologies to characterise river bathymetry and floodplain topography (Heritage et al., 2009; Milan et al., 2011; Marcus, 2012; Sofia et al., 2014a, 2014b). Different data-driven methods have been proposed for channel geometry (Pavelsky and Smith, 2008; McKean et al., 2009; Johansen et al., 2011; Biron et al., 2013; Fisher et al., 2013; Güneralp et al., 2014; Bangen et al., 2014); however, an automated method for continuously extracting reach-scale width values from raster-based imagery would provide valuable insight into many hydrologic studies (Pavelsky and Smith, 2008). Limits related to channel sizes compared to data resolution have been noted (e.g. McKean et al., 2009), and automation should be further analysed, especially concerning: 1) small channels or channels with great variability in width; 2) analysis of channels in complex landscapes or covered by vegetation; and 3) the choice of the scale of analysis.

The most recent literature includes pioneering approaches to the automated characterisation of landscape components: several authors have shown that physical processes or anthropogenic activities leave important signatures in the statistics of the morphological parameters derived from DTMs, and they have pointed out that by quantifying these signatures in detail, statistics or objective indexes can be used at different scales to automatically detect thresholds through which to identify processes, extract particular features, or characterize landscapes (e.g. Molloy and Stepinski, 2007; Thommeret et al., 2010; Passalacqua et al. 2012; Pelletier, 2013; Clubb et al., 2014; Sofia et al., 2014c, 2015; Chen et al. 2015; Tarolli et al. 2015; Prosdocimi et al., 2015). Following this line of research, this paper examines the ability of LiDAR topography to automatically provide reach-scale width values for the analysis of downstream hydraulic geometry relationships along some streams in the Dolomites, northern Italy. The approach provides reach-scale width data, rather than exact channel width at each location of the network. The automatically-captured downstream channel morphology is then related to flow parameters including drainage area and stream power.

1.2. Summary of equations and related literature

This section briefly summarises the main downstream hydraulic geometry relationships that are considered in the research. Flow width varies with bankfull discharge (Q_{bkf}), generally exhibiting a power law relationship:

$$w = \mathrm{d}{Q_{\mathrm{bkf}}}^{\mathrm{e}} \tag{2}$$

where d and e are empirically derived constants (Wolman and Leopold, 1957; Emmett, 1975; Andrews, 1980; Carling, 1988; Finnegan et al., 2005; Wohl and David, 2008).

The drainage area (A) is the morphometric variable most directly correlated to the peak discharge (Strahler, 1964). The link between Q_{bkf} and A is so clear that it enables Q_{bkf} to be estimated from A (Wolman and Leopold, 1957; Leopold et al., 1964; Emmett, 1975; Dunne, 1987; Leopold, 1994; Rice, 1998; Whiting et al., 1999; Brummer and Montgomery, 2003):

$$Q_{\mathrm{bkf}} = \mathrm{g}A^{\mathrm{h}} \tag{3}$$

where g and h are constants.

As a consequence, various researchers have found a direct proportionality in different environments for channel flow width and basin drainage area, which follows a power law similar to Eqs. (2) and (3) (Leopold and Maddock, 1953; Harman et al., 1999; Ibbitt, 1997; Rodriguez-Iturbe and Rinaldo, 1997; Knighton, 1998; Whiting et al., 1999; Dutnell, 2000; Montgomery and Gran, 2001; Brummer and Montgomery, 2003; Vianello and D'Agostino, 2007):

$$w = \mathrm{s}A^{\mathrm{t}} \tag{4}$$

where s and t are constants.

For many mountain streams, however, channel geometry reflects not only the downstream variation of bankfull discharge, but also the magnitude of bank erosion and the consequent changes in cross-section width (Vianello and D'Agostino, 2007). The main parameter responsible for the capacity to transport sediment, associated with the downstream coarsening of headwater channels, is the stream power (Ω) which defines the rate of energy expenditure per unit length of the channel (Bagnold, 1966; Brummer and Montgomery, 2003). Values of Ω, associated with the cross-sections at the bankfull condition, can be calculated from Q_{bkf} and local channel slope (S) (Bagnold, 1966; Richards, 1976; Ferguson and Lewin, 1981; Keller and Brookes, 1983; Ferguson et al., 1987; Van den Berg, 1995), according to the equation:

$$\Omega = \gamma Q_{\mathrm{bkf}} S \tag{5}$$

where γ is the specific weight of the water.

Using Eqs. (3) and (5), the stream power can be computed as a function of A.

S generally varies empirically as a function of A, in the form

$$S = \mathrm{m}A^{-\theta} \tag{6}$$

where m and θ are empirical constants representing the steepness and concavity of the river profile, respectively (Hack, 1957; Seidl and Dietrich, 1992; Montgomery and Foufoula-Georgiou, 1993; Montgomery, 2001; Stock, 2003; Brummer and Montgomery, 2003; Sklar and Dietrich, 2013).

Therefore, Ω can be re-written as:

$$\Omega = \gamma(\mathrm{gm})A^{(\mathrm{h}-\theta)}. \tag{7}$$

The erosive power of flowing water can also be evaluated based on the assumption that discharge is proportional to a specific catchment area (A_{s}), which is the catchment area draining across a unit width of contour ($\mathrm{m}^2\,\mathrm{m}^{-1}$), and the Stream Power Index (SPI) can be computed from digital topography according to the formulation

$$SPI = A_{\mathrm{s}} \tan\beta \tag{8}$$

where β is the slope gradient in degrees (Wilson and Gallant, 2001).