Geomorphology 241 (2015) 243–254

Contents lists available at ScienceDirect

Geomorphology

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

Influence of DEM resolution on drainage network extraction: A multifractal analysis

A.B. Ariza-Villaverde *, F.J. Jiménez-Hornero, E. Gutiérrez de Ravé

Department of Graphic Engineering and Geomatic, University of Cordoba, Gregor Mendel Building (3rd floor), Campus Rabanales, 14071 Córdoba, Spain

ARTICLE INFO

Article history:
Received 11 August 2014
Received in revised form 23 March 2015
Accepted 27 March 2015
Available online 18 April 2015

Keywords:
Drainage network geometry
DEM resolution
D8 algorithm
Multifractal analysis
Flow accumulation threshold
Terrain attributes

ABSTRACT

Different hydrological algorithms have been developed to automatically extract drainage networks from digital elevation models (DEMs). D8 is the most widely used algorithm to delineate drainage networks and catchments from a DEM. This algorithm has certain advantages such as simplicity, the provision of a reasonable representation for convergent flow conditions and consistency among flow patterns, calculated contributing areas and the spatial representation of subcatchments. However, it has limitations in selecting suitable flow accumulation threshold values to determine the pixels that belong to drainage networks. Although the effects of DEM resolution on some terrain attributes, stream characterisation and watershed delineation have been studied, analyses of the influence of DEM resolution on flow accumulation threshold values have been limited. Recently, multifractal analyses have been successfully used to find appropriate flow accumulation threshold values. The application of this type of analysis to evaluate the relationship between DEM resolution and flow accumulation threshold value needs to be explored. Therefore, this study tested three DEM resolutions for four drainage basins with different levels of drainage network distribution by comparing the Rényi spectra of the drainage networks that were obtained with the D8 algorithm against those determined by photogrammetric restitution. According to the results, DEM resolution influences the selected flow accumulation threshold value and the simulated network morphology. The suitable flow accumulation threshold value increases as the DEM resolution increases and shows greater variability for basins with lower drainage densities. The links between DEM resolution and terrain attributes were also examined.

1. Introduction

A digital elevation model (DEM) is a numerical representation of the Earth's surface that contains the terrain height (Felicísimo, 1994). A DEM can be defined by means of i) contours with *x*, *y* coordinate pairs along each contour line of a specified elevation, ii) a triangulated irregular network made up of irregularly distributed nodes and lines with three-dimensional coordinates (*x*, *y*, and *z*) and iii) a two-dimensional array of numbers that represents the spatial distribution of elevations on a regular grid. The main advantage of the third definition is its computational efficiency and lower storage requirements (Walker and Willgoose, 1999). Thus, raster DEMs have been broadly applied to modelling certain features of the surface hydrology such as catchments (O'Callaghan and Mark, 1984; Jones, 2002), drainage networks (O'Callaghan and Mark, 1984; Turcotte et al., 2001), channel heads (Montgomery and Dietrich, 1988; Julian et al., 2012) and wetness indices (Beven and Kirkby, 1979; Vaze et al, 2010). A DEM reproduces real hydrological features with accuracy and computational efficiency that are determined by its resolution, vertical and horizontal precision and terrain attributes (Moore and Grayson, 1991; Quinn et al., 1991; Wolock and Price, 1994; Deng et al., 2007; Wu et al., 2008a, 2008b; Dehvari and Heck, 2013).

Several studies have verified the link between simulated hydrological features and DEM resolution. Zhang and Montgomery (1994) explored the effects of grid size on landscape representation and hydrologic simulations. The lower the DEM resolution (i.e., large grid size), the higher the mean topographic index because of increasing contributing area and lower slopes. Similarly, Sørensen and Seibert (2007) studied the effects of DEM resolution on the calculation of topographic wetness and established notable differences between different grid resolutions. Kenward et al. (2000) analysed the effects of the vertical precision of DEMs on the accuracy of hydrology predictions, pointing to the reduced spatial coherence in images with lower vertical precision, and concluded that topography plays a fundamental role in hydrologic and geomorphologic modelling. This statement has been confirmed by Falorni et al. (2005) based on the strong influence of relief on the vertical accuracy of DEMs and derived terrain attributes. Regarding the effects on DEM resolutions, McMaster (2002) explored the effects of DEM resolution on

* Corresponding author. Tel.: +34 957 212126; fax: +34 957 218455.
E-mail addresses: g82arvia@uco.es (A.B. Ariza-Villaverde), fjhornero@uco.es (F.J. Jiménez-Hornero), eduardo@uco.es (E. Gutiérrez de Ravé).
URL: http://orcid.org/0000-0003-4498-8797 (F.J. Jiménez-Hornero).

http://dx.doi.org/10.1016/j.geomorph.2015.03.040
0169-555X/

the positional accuracy of derived hydrologic networks by using two hydrological algorithms: D8 (O'Callaghan and Mark, 1984) and D8-LAT (Tarboton, 1997). Chaubey et al. (2005) also described the influence of DEM resolution on watersheds, stream network delineation and sub-basin classification by using the SWAT model (Soil and Water Assessment Tool), which is a river basin scale model to quantify the impact of land management practices in large, complex watersheds. Accordingly, the accuracy of the simulation of hydrological processes also depends on the algorithms that are used to extract hydrologic features from DEMs. The first approach developed to extract river networks was the D8 algorithm, which uses a neighbourhood of eight cells as possible flow directions. However, the results of applying this method are sometimes non-realistic (Turcotte et al., 2001) due to the determination of the flow in only one of the eight possible directions, the presence of flat areas and pits and the lack of information on lake locations. The multiple flow direction method (MFD) was suggested by Freeman (1991) to overcome the limitations of D8. This approach does improve the D8 model in some aspects, but it requires additional computational time to calculate a greater density of flow connections (Gallant and Wilson, 1996), and the flow from a pixel is dispersed to all of the neighbouring pixels that have lower elevations. Lea (1992) developed an algorithm that calculates the flow direction through the aspect associated with each cell. It has the advantage of specifying flow direction continuously and without dispersion. Costa-Cabral and Burges (1994) developed the DEMON (Digital Elevation Model Network) algorithm to improve the modelling proposed by Lea (1992). Both plane flow methods are deterministic and resolve flow directions. However, as Tarboton (1997) stated, they are susceptible to problems that arise from the approximation involved in fitting a plane through four points. Tarboton (1997) and Orlandini et al. (2003) have proposed the D8-LAD and the D8-LTD methods, respectively, to overcome some of the limitations of the D8 algorithm, such as the effects of grid artefacts (i.e., pits and flats areas), high dispersion and significant computational costs. However, both methods have shortcomings. The removal of the unimodal link between flow directions and the difficulty in calculating the catchment boundary due to the multiple flow directions from a cell (Orlandini et al., 2003) are the main drawbacks of the D8-LAD algorithm. On the other hand, users have to specify the dampening factor for the D8-LTD model. To improve this algorithm, Paik (2008) proposed a global search method, GD8, and argued that there is no analytical justification to fix the dampening factor to 1, as Orlandini et al. (2003) recommended. Orlandini and Moretti (2009) replied to Paik (2008) and affirmed that the analytical background does exist and is easily illustrated by considering a portion of a sloping plane. Later, Orlandini et al. (2014) demonstrated the validity of their method to determine slope lines in grid digital elevation models, which is the key factor for obtaining the smallest transverse deviations.

As described above, recent alternatives to the D8 method exhibit drawbacks that limit their application. As a consequence, the D8 algorithm is the most commonly used (Tribe, 1992; Martz and Garbrecht, 1998; Saunders, 1999; Jones, 2002). Its popularity stems from its simplicity and reasonable representation for convergent flow conditions (Freeman, 1991), and it preserves the consistency between the flow patterns, calculated contributing area and spatial delineation of sub-catchments (Martz and Garbrecht, 1992). The D8 method is widely used in GIS packages, for example ESRI's ArcGIS software, and is frequently used to study different hydrological processes (Cai et al., 2012; Gericke and Venohr, 2012; Babbar-Sebens et al., 2013; López-Vicente et al., 2013; Rodriguez et al., 2013).

The flow accumulation threshold value is a parameter of the D8 algorithm whose suitable determination allows the selection of DEM cells that represent drainage networks. Tarboton et al. (1988), Montgomery and Dietrich (1992) and Orlandini et al. (2011) have suggested that the threshold value may strongly depend on DEM resolution. The quality of generated drainage networks is influenced by DEM resolution (McMaster, 2002; Chaubey et al., 2005) because it affects the basin slope and, as a consequence, the upslope contributing area (Thieken et al., 1999; Walker and Willgoose, 1999; McMaster, 2002; Wu et al., 2008a, 2008b). Thus, the flow accumulation threshold value needs to be modified according to the resolution of the DEM.

Ariza-Villaverde et al. (2013) determined the appropriate threshold value to a high accuracy by means of a multifractal analysis for a DEM resolution of 10 m. Different multifractal methods have been successfully applied to the study of river network morphology (Rinaldo et al., 1993; De Bartolo et al., 2000, 2004, 2006a, b) and to analyse different variables such as the influence of lithological and tectonic morphologies on rivers (Gaudio et al., 2006; Dombrádi et al., 2007). The multifractal theory implies that the complex and heterogeneous behaviour of a self-similar measure (i.e., statistically similar on any scale) can be represented as a combination of interwoven fractal sets with corresponding scaling exponents. The advantages of the multifractal approach are that its parameters are independent over a range of scales and that no assumption is required about the data following any specific distribution. Two main classes of multifractal algorithm can be distinguished: fixed-size algorithms (FSA) and fixed-mass algorithms (FMA), which were introduced by Badii and Politi (1984a, b, 1985). The first class is suitable for multifractal objects in which the original region is initially divided into several pieces; each piece is sub-divided at each step into other pieces, the size of which is reduced by a constant factor. The approaches include the box-counting method (Russel et al., 1980), the sandbox method (Tél et al., 1989; Vicsek, 1990; Vicsek et al., 1990) and the generalised correlation integral method (Pawelzik and Schuster, 1987), which have been applied to the study of river networks (Rinaldo et al., 1992, 1993; Rigon et al., 1993; De Bartolo et al., 1995, 2000, 2004, 2006a). The FMA algorithms are appropriate if the measure of each piece is reduced by a constant factor (Mach et al., 1995). In this method, the quantity that is held fixed is no longer the size of the covering boxes, but the measure inside the box. De Bartolo et al. (2006b) applied the fixed-mass algorithm to the analysis of river networks and braided channels with very good results. In general, FSA are advantageous for their computational aspects (Gaudio et al., 2004). However, some of these algorithms pose challenges with regard to the right side of the spectrum, i.e., for negative moment orders, and also for the analysis of border effects when networks are analysed by emphasising regions that have few data points (De Bartolo et al, 2000). To solve these problems, the sandbox method and the generalised correlation integral method have proven to be able to reconstruct the complete multifractal spectrum (left and right sides) and to solve the border effects, whereas the box-counting method fails in the case of negative moment orders.

Multifractal parameters known as information, capacity and correlation dimensions have been suggested as suitable to describe drainage network morphology (Saa et al., 2007; Ariza-Villaverde et al., 2013). Thus, the influence of DEM resolution on the D8 algorithm threshold flow accumulation value is explored here by using the Sandbox multifractal method. The accuracy of the obtained drainage networks will be checked by comparing them against the accuracy of photogrammetric restitution.

2. Study area

Four river basins located in the north of the province of Cordoba, Andalusia, southern Spain, were selected for this study (Fig. 1). The basins have different degrees of drainage density. The basins' locations can be found on sheet number 922 of the 1:50,000 territorial division national maps published by the National Geographic Institute of Spain. The corresponding DEMs with 5, 10 and 25 m resolutions were obtained from photogrammetric flights in 2010 and generated by automatic correlation (scale 1:25.000). In addition, the drainage networks in the study area from photogrammetric restitution provided by the Department of Agriculture, Fisheries and Environment, Government of Andalusia, were used to check the results from the D8 algorithm.

The study basins present maximum and minimum heights of 154 and 584 m, respectively, and an average slope of 30%. The main types of soil that are prevalent in the study basins are regosol, lithosol and