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Errors in river lengths derived from raster digital elevation models

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Abstract

Length of river reaches is one of the most important characteristics of stream networks when applying hydrological or environmental simulation models. A common method of obtaining estimates of river lengths is based on deriving flow directions, accumulated area and drainage lines from raster digital elevation models (DEM). This method leads to length estimates with variable accuracy, which depends on DEM horizontal resolution, flatness of terrain, DEM vertical accuracy, the algorithm used to obtain flow directions and the way by which distances are calculated over raster structures. We applied an automatic river length extraction method for eight river reaches in the River Uruguay Basin (206 000 km^2), in Southern Brazil, and compared its results to the lengths obtained from drainage vector lines digitalized over satellite images. Our results show that relative errors can be higher than 30% in flat regions with relatively low DEM resolution. Preprocessing of DEM by the method known as stream burning greatly improves results, reducing errors to the range 1.9–7.4%. Further improved estimates were obtained by applying optimized values for the length of orthogonal and diagonal steps called distance transforms, reducing the errors to the range −2.0–3.3%.

Keywords: Drainage networks; River length; Flow direction; Stream burning; Distance transforms

1. Introduction

Flow of water over the landscape surface is a fundamental geomorphologic process that is intimately tied to its form. Natural drainage networks are primary elements of the terrain surface that integrate remote regions through the flow of water, sediments and chemical constituents. Rivers also play important roles as ecological corridors, through which species migrate.

One of the most important characteristics of a river is its length, which can be measured by physically wandering along its course using a GPS receiver, or by calculating distances along lines extracted from maps or derived from remote-sensing data. While the first method is obviously infeasible in most cases, the second is strongly dependent on quality of map data (Mueller, 1979) and may be excessively time consuming.

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Currently, the most common approach of extracting river network characteristics consists of automatic analysis of matrices representing terrain altitudes, or Digital Elevation Models (DEM), produced by remote sensing.

There are a large number of applications characterizing terrain surface form and drainage networks using DEMs. The literature on this specific point alone is large, Pike (1993) identifying over 100-refereed articles. Although the expression DEM is used inconsistently in the literature (Burrough and McDonnel, 1998; Weibel and Heller, 1991), it is strictly defined here consistent with the terms of Burrough and McDonnel (1998) as a *regular gridded matrix representation of the continuous variation of relief over space*. Several authors (Mark, 1979; Werner, 1988; Wolf, 1991) have attempted to place network quantification within a wider context of topographic form. In particular, the problem of scale of both spatial extent and resolution related with automatic extraction of drainage network is still unsolved.

In hydrological sciences, the automatic derivation of drainage network over a DEM has provided practical tools, as described by several authors (Burrough and McDonnel, 1998; Fekete et al., 2001; Jenson and Domingue, 1988; Liang and Mackay, 2000; Moore et al., 1991; Olivera et al., 2002; Verdin and Verdin, 1999). In recent years, several methods were developed to automatically extract useful information from DEMs for particular hydrological models. This is the case of the HEC-HMS rainfall-runoff model (Olivera, 2001), SWAT (Olivera et al., 2006), HL-RMS (Reed, 2003), TOPMODEL (Quinn et al., 1991), and others (O'Donnell et al., 1999; Paz et al., 2006; Turcotte et al., 2001).

Given a DEM in a raster structure, algorithms such as the well-known D8 (deterministic eight-neighbor) algorithms are used to derive flow directions (Jenson and Domingue, 1988), i.e. the direction water flows out of each pixel. Upstream drainage areas can then be calculated summing areas of all upstream pixels for every pixel (Jenson and Domingue, 1988). By showing only pixels with accumulated drainage area higher than a pre-defined threshold, a good approximation of the drainage network can be obtained. Distance along a given flow path can then be measured pixel by pixel, considering whether the neighboring pixels are diagonal or orthogonal neighbors and computing a distance equal to the pixel side or 1.414 times pixel side, respectively, which roughly corresponds to stream length, as pointed out by Fairfield and Leymarie (1991).

Errors in river lengths calculated by this way are due to a variety of causes, including horizontal DEM resolution, vertical DEM accuracy and occurrence of large flat areas. Several authors have addressed the influence of DEM resolution and accuracy over its derived products (Fekete et al., 2001; Holmes et al., 2000; Oksanen and Sarjakoski, 2005; Raaflaub and Collins, 2006; Walker and Willgoose, 1999; Wolock and Price, 1994; Zhang and Montgomery, 1994). Besides these two factors, the difficulty in automatically defining flow directions in large flat areas is a major challenge in extracting drainage networks and river lengths from DEM. Vector information, such as digitized lines representing river network, often referred as blue lines, have been used in postprocessing techniques in order to overcome this difficulty. The most common of these techniques is known as stream burning, and the use of the resulting DEM leads to the extraction of more correct raster drainage lines and river lengths (Callow et al., 2007; Graham et al., 1999; Kenny and Matthews, 2005; Mayorga et al., 2005; Olivera and Raina, 2003; Saunders, 1999; Turcotte et al., 2001).

Although using the stream-burning procedure significantly reduces inaccuracy, systematic errors may still be present in river lengths. These errors are independent of DEM resolution and correctness, and are related to the way in which distances are measured along raster lines, as pointed out by De Smith (2004). In this paper, we discuss several errors that may occur when deriving river lengths from raster elevation data, and test the distance operators proposed by De Smith (2004) and Butt and Maragos (1998) to correct systematic errors that can appear even in the cases where DEMs conditioned by stream burning are used. Relatively long river reaches in the Uruguay River basin, located in South America, are used for a case study. This basin has a drainage area of about 206 000 km^2, and the selected rivers are markedly distinct in terms of slope, sinuosity, drainage area, width and length. Extracted river lengths are compared with lengths measured over the available vector river drainage network.

2. Flow directions and river networks derived from raster DEMs

Perhaps the most widely used algorithm for calculating flow directions is the D8 algorithm. This