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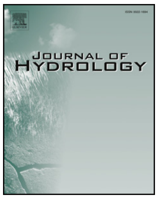

Research papers

Global river slope: A new geospatial dataset and global-scale analysis

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ABSTRACT

A rivers' longitudinal gradient (i.e. slope) is a key parameter in fluvial hydrology, hydraulics, and geomorphology. It affects a multitude of fluvial variables such as flow velocity and sediment transport. Limitations in river slope data, both its availability and accuracy, constrain the fidelity of fluvial modeling, particularly at larger or global scales. Traditional slope calculation algorithms cannot accurately predict river slopes as these are based on cell-by-cell calculation, which is only suitable for hillslopes and small mountainous streams. This paper presents a methodology for calculating global river slope and a procedure to upscale it for relatively coarse resolution, suitable for global scale modeling. The methodology is based on a simple principle of calculating slope from elevation depression over the length of a river segment, which is automated to allow global scale calculations. Version 1.0 of the Global River-Slope (GloRS) geospatial dataset is introduced and shown to be a step improvement over a previous product (NHDplus for the contiguous United States) and compares favorably to observed slope data collected from the literature. Statistical analysis of Earth's continents and large basins highlights interesting spatial trends. A semi-empirical regression analysis between basin-average river slope and other basin-scale parameters show that terrain slope accounts for 67% of the variability in basin-average river slope, with average discharge, sediment load and basin temperature contributing additional improvements to global predictions of 3%, 4%, and 3%, respectively.

1. Introduction

River slope gradient is a key parameter in hydrological and geomorphic modeling. Slope controls the gravitational related factors of water flow and sediment movement in fluvial systems (Du Boys, 1879; Meyer-Peter and Müller, 1948; Bagnold, 1966). In hydrologic and hydraulic applications, river slope is a key parameter controlling flow velocity (Manning, 1891). River slope, through its control on flow velocity, affects the shear stress exerted on sediment particles and thus their transport rates and mechanism (Meyer-Peter and Müller, 1948; Bagnold, 1966). Slope also controls the gravitational potential exerted on sediment and rock and thus their susceptibility to movement. As a result, the dominant sediment transport mechanism in steep mountainous streams is typically bedload transport while most sediment transported in lowland rivers is typically in suspension (about 90%; Meade et al., 1990; Bartram and Ballance, 1996). It is important to note that these differences in sediment transport mechanisms between headwater and lowland rivers are also driven by sediment size characteristics and local hydraulic and geomorphic processes (e.g. river evolution, floodplain erodibility; Mueller and Pitlick, 2013).

Slope calculation for a river reach is simple: dividing the elevation difference between the up and downslope points by the length of the reach. These parameters can be measured in the field for individual reaches or extracted from a Digital Elevation Model (DEM) and aerial imagery in a GIS system for long reaches and even entire river systems. Traditional automated slope calculation algorithms, on the other hand, are based on measuring the elevation difference between each grid cell in a DEM and one of its neighboring cells. In most slope algorithms, the adjacent grid-cell selection is based on steepest elevation decent (D8 algorithm; O'Callaghan and Mark, 1984). More directionality flexible algorithms have been developed over the years (e.g. Dinf; Tarboton, 1997). Several river slope calculation approaches were developed over the years based on calculating the distance between a river location and a downstream point or the basin outlet (e.g. Moore et al., 1991; Thieken et al., 1999; Walker and Willgoose, 1999; Olivera, 2001; Fekete et al., 2001; Reed, 2003; Mayorga et al., 2005; Lin et al., 2006). These approaches can be highly inaccurate when based on relatively coarse resolution DEMs, used in regional and global scale modeling, as grid-cells may represent both the river and surrounding landscape and may not capture small scale meandering.

Slope calculations are scale-dependent and are thus sensitive to the spatial resolution of the DEM (Gregory and Schumm, 1987; Snow and

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Slingerland, 1987; Knighton, 1999; Biedenharn et al., 2000; Montgomery and Brandon, 2002). This poses a challenge for calculating river slopes. Large rivers typically have a very low local topographic gradient (e.g. $\sim 1 \times 10^{-5}$ m/m for the lower Mississippi River; Nittrouer et al., 2008) while small rivers may be considerably narrower than the DEM grid-cell size. As a result, the vertical and horizontal resolution of the DEM is typically inadequate for accurate calculation of river slope using standard slope calculation algorithms. High-resolution DEMs (e.g. LiDAR-based) may provide sufficient resolution but are challenging to use for medium and large rivers as the channel width will be represented by a large number of grid cells, and thus different slope values, which will complicate large-scale modeling and analysis.

Here we present an automated method for calculating river slope based on river segment length and elevation depression. The methodology is used to calculate the first Global River Slope layer (refer to herein as GloRS). The accuracy of GloRS is evaluated by comparing the calculated slope against reported slope values and an independent hydrography dataset. Employing GloRS offers a first set of river slope statistics at global and continental scales and within large river basins. In this paper, basin-averaged river slope values are used for an exploratory exercise, looking at potential causality or predictability of other basin-scale parameters (e.g. water and sediment discharge, lithology, temperature).

2. Methodology

2.1. River slope calculation

Our river slope methodology is following Hannon (2011), where slope for a given river segment length was calculated using the difference between its highest and the lowest elevation (derived from an underlying DEM), corresponding to its most upstream and downstream locations respectively. We apply this method to a global-scale stream-network and DEM to compile GloRS through an automated procedure (using a Python script).

The interval length of the stream-network's river segments influences the accuracy of river slope calculation and the resulting dataset spatial resolution. Longer segments yield coarser resolution while shorter segments are limited by the DEM vertical and horizontal resolution. Stream-network layers are typically split into feature segments at river confluences. Quite often many of these segments will be very long, primarily along the main stem of large rivers. The GloRS calculation script includes a feature-splitting procedure which splits river-network segments longer than a user-defined value (e.g. 50 km). It works by generating points at the user-defined distances along the stream-network (Fig. 1) which are then used to add new joints to the original stream-network line features. The user-defined splitting interval controls the maximum reach length. The stream-network will include many shorter features that originally existed between confluence points. The splitting procedure will therefore only affect segments longer than the user-defined length while retaining the 'natural' stream network segments which are shorter than the user-defined value.

Fig. 1. Illustration of the stream-network splitting procedure. Points are generated on top of the stream network line features at user-defined distances (e.g. 50 km), the point layer is used to split each feature.

Following the stream-network splitting, the minimum and maximum elevation of each segment are extracted from an underlying DEM. The segment lengths are calculated using a GIS tool. These values are added to the stream-network layer attribute table as new fields (columns). Elevation depression is calculated as the difference between the maximum and minimum elevations, for each river segment. River slope is then calculated by dividing the elevation depression attribute value by the river segment's length attribute value. The stream-network vector layer can then be converted to raster layer based on the slope attribute value, ensuring that the raster extent and spatial resolution are similar to the DEM used.

2.2. Upscaling

Using as high as possible resolution of the stream-network and DEM is advisable for the aforedescribed river slope calculation, as these will better capture river sinuosity and in-stream elevation. We will discuss the importance of these factors later. Upscaling a river slope layer to coarser spatial resolution is warranted for different applications, such as large-scale river modeling frameworks (e.g. WBMsed; Cohen et al., 2013, 2014). Standard GIS resolution-conversion tools average the cell values of the high-resolution grid-cells underlying a coarse-resolution grid-cell (Fig. 2) which will lead to overestimation of river slope. This is because a grid-cell in the upscaled raster layer is meant to represent the highest-order river reach within its spatial domain. Think, for example, of a 6 arc-min (~11 × 11 km) river layer. A grid-cell with such a resolution will cover, with the exception of few very large river reaches, not just the largest river in that domain but also many of its smaller tributaries. Averaging the values of all the fine-resolution grid-cells will, therefore, skew the resulting river slope in the upscaled layer as it will also capture (and give equal weight to) small river reaches which typically have higher slopes. To alleviate this problem, we develop an upscaling procedure that extracts the minimum value of the underlying high-resolution grid-cells and uses this value for the upscaled raster layer (Fig. 2). This approach assumes that the lowest slope value in the high-resolution layer represents the largest river reach within the coarse-resolution gird-cell domain. While this is a reasonable

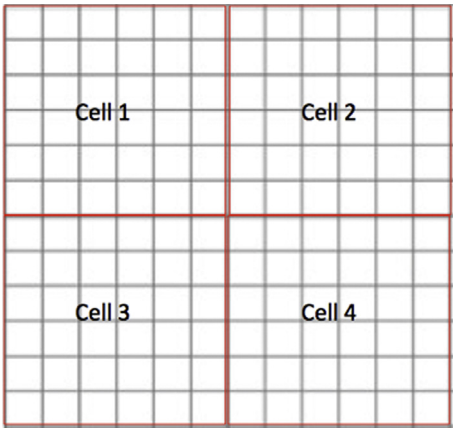

Fig. 2. Illustration of the upscaling 'neighborhood'. In a standard GIS conversion tools, the value of a coarse-resolution cell (red outline; Cell 1, 2, 3 and 4) will be calculated based on the average of all its underlying cells (gray outline). Our procedure extracts the minimum value of the underlying high-resolution cells and uses it as the value for the coarse-resolution cells. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)