Global River Slope (GloRS): a New Geospatial Dataset for Riverine Modeling and Analysis

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Introduction

• Rivers’ longitudinal gradient (i.e. slope) is a key parameter in fluvial hydrology, hydraulics, and geomorphology.
• Riverine slope affects a multitude of fluvial variables such as flow velocity and sediment transport.
• Limitations in the availability and accuracy of river slope data constrain the fidelity of fluvial modeling, particularly at large scales.
• Traditional slope calculation algorithms cannot accurately predict river slopes as these algorithms are based on cell-by-cell calculation, which is only suitable for hilllopes and steep streams.
• The Global River Slope (GloRS; Cohen et al. 2018) dataset calculation, validation and analysis is presented herein.

Methodology

• GloRS is based on a simple principle of calculating slope from elevation depression over the length of a river segment. Slope for a given river segment length is 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.
• Calculated using global-scale stream network and DEM through an automated GIS procedure with new stream conditioning and grid upsampling procedures.
• GloRS v1.0 (Cohen et al. 2018) and v1.1:
  • 15 arc-sec resolution (~460 x 460 m) SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS) DEM and stream-network were used.
  • 1 arc-min etopo DEM was used for high (>60°) latitudes.
  • Stream segments were split to limit their length to a maximum of 50km.
• Upscaling:
  • Upscaling a river slope layer to coarser spatial resolution is warranted for large-scale fluvial 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, leading to overestimation of river slope as both the main channel and its tributaries are averaged.
• An upsampling procedure was developed and used to upscale GloRS from 15 arc-sec to 6 arc-min:
  • GloRS v1.0 - Extracts the minimum slope value of the underlying high-resolution layer.
  • GloRS v1.1 - Extract the slope value of the grid-cell with the maximum contributing area value in the underlying high-resolution layer.

Validation

• Two datasets were used to evaluate the accuracy of GloRS observed slope values obtained from literature sources, and the National Hydrography Dataset Plus Version 2 (NHDPlusV2) stream network.
• A total of 34 river slope observations were collected (Fig. 1; from: Hinton et al. (2016), Williams and Rosgen (1989), Graf (1984), Knott and Lipscomb (1985), Jones and Sloss (1979)).
• Upscaling product (6 arc-min) resulted in similar correlation as the fine resolution products (15 arc-sec).
• An adjustment equation was used to improve GloRS values in low-slope locations (Fig. 2a):
  \[ S_{adj} = 5S_{0} + 0.111 \]
  where \( S_{0} \) is adjusted, and \( S_{adj} \) is original values.
• GloRS corresponded well to observed slope values with large biases (~1 order of magnitude) in 3 (out of 34) sites (Fig. 2b).
• NHDPlus resulted in a weaker correlation, higher RMSE and greater difference in mean from observed slope compared to GloRS in 25 observation points (excluding 9 non-contiguous U.S. sites) (Table 1).

Distribution Analysis

Average continental river slope (Fig. 3) range by a factor of nearly 6 between the continents, with Australia having the lowest average (0.0006) and Asia the highest (0.0035). Low river slope averages in Australia are expected given the absence of a significant continental mountain range, attributable to its generally older basement geology. South America is particularly interesting as it includes both very high river slope values, concentrated along the narrow Andes, and extensive areas of relatively low-sloping rivers (primarily within the Amazon Basin) (Fig. 1), resulting in the greatest variability in river slope (Fig. 3). The continents show relatively similar coefficient of variance, except for Oceania whose river-slope values are dominated by small mountainous Islands (primarily Papua and New Zealand); while average river-slope is high, variability within the islands is small.

Of the world’s 30 largest river basins, three Asian rivers (Indus, Ganges-Brahmaputra, and Yangtze) have the highest average slope (Fig. 4a). These rivers are among the world’s most tectonically active basins. Fig. 4b demonstrates that there is no direct link between basin size and its average river slope.

High within-basin variability in river slope is associated with rivers draining continental mountain ranges (Fig. 5). Central Asian basins yield the highest variability followed by South American basins. The most homogeneous basins are clustered in northeast Europe (e.g.Volga and Don Basins). Basins with high CV (Fig. 5) require large rivers draining mountain chains and developing extensive floodplains. Typically, these rivers are those draining into the passive margin side of large continental plates.

Controlling Factors

An exploratory exercise was conducted to investigate the potential influence of different factors on river slope by testing the correlation between basin-averaged river slope as the dependent variable (n=234) and basin-statistics (mean, max, STD, and range) of lithology, discharge, sediment flux, precipitation and terrain parameters.

Basin-averaged river slope explains 67% of the variability in basin-average river slope. This is an expected outcome given that rivers draining steep terrain have high slopes. This suggests that 37% of the variability in basin-averaged river slope is explained by other factors. A semi-empirical regression model based on the above analysis and our general assertions about the underlying drivers and mechanisms that may control river slope is proposed (Fig. 6):

\[ R_{s} = (0.012 + 0.0567R_{d})^{0.74} \times Q_{s}^{0.19}T^{0.18} \]

where \( R_{s} \) (m/m) is river slope, \( T_{s} \) is terrain slope (m/m), \( Q_{s} \) is discharge (m³/s), \( S_{s} \) is sediment flux (kg/s) and \( T \) is temperature (°C).

Conclusions

• A new Global River Slope (GloRS) geospatial dataset was developed based on automation of a simple GIS approach of calculating elevation depression for each river segment.
• The calculation is based on (relatively) high-resolution DEM and stream network and upscaled to a coarser resolution for use in global hydrology and geomorphic models.
• Good correspondence is achieved with observed values after applying a value-scaled adjustment equation.
• Continental and basin-scale distribution analysis highlight interesting new insights about the distribution of river slope and its links to topographic and geologic characteristics.
• We found that 67% of the variability in river slope is explained by average basin topography and an additional 10% was explained by its climatic, hydrological and geomorphic characteristics.