Flow-length difference as a measure of topographic roughness/incision

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Abstract—**A new surface roughness/incision measure is introduced based on the difference between the upstream flow length for each cell of a digital elevation model (DEM) along the topographic surface and its projection onto a horizontal plane. The upstream flow lengths along topographic surface can be calculated in ArcGIS software using the Flow Length tool with the inverse of cosine of local slope as weight. The projected horizontal flow length is derived using the same tool with the default weight of unity for each cell. The result of applying this index to the Oregon Cascade region, where big contrast in surface incision exists, shows that it not only reproduces the overall visual contrast in the spatial pattern of dissection, but also corresponds very well with the true degree of incision and reveals details. In contrast, the local relief and standard deviation of slopes, two other indices traditionally used to describe the degree to which the earth surface is incised by exogenic agents, do not always correspond to the true location of incision and lack the details. With more high resolution DEM data becoming available, this new roughness/incision measure can be used to quantify and reveal more detailed dissection pattern on Earth at various spatial scales.**

INTRODUCTION

The degree to which land surface is incised by exogenic agents is an important attribute that can provide insights into how landform evolved and what controlling factors and processes were involved. Previous studies have used various measures to describe the degree of land surface roughness or incision, including fractal dimension [1], stand deviation of a de-trended surface [2], eigenvector ratios of unit vectors constructed perpendicular to each cell in the DEM [3], local relief [4], standard deviation of slopes within a moving window [5], among others. While such measures provide a reasonable description of the land surface dissection or roughness, they are essentially statistical measures in nature and do not directly relate to the fluvial erosion processes. In addition, most of them are time consuming to construct, with perhaps the exception of local relief (*LR*), which is the difference between maximum and minimum elevations within a moving window (or focal range) [4], and standard deviation of slopes (*SDS*) within a moving window [5]. Here we propose to use the flow-length difference as a new measure of topographic roughness/incision. This new measure is simple and can be derived for every cell of the DEM based on flow lengths.

FLOW-LENGTH DIFFERENCE MEASURE

The rationale for this new flow-length difference (*FLD*) is the following: for areas of the land surface that is highly incised (thus with deeper valleys and steeper slopes), the flow length along the 3D topographic surface will be longer than its projection onto a 2D horizontal plane; for areas with little or no incision, these two lengths will be nearly identical. Thus the difference between these two lengths provides a measure of the degree of land surface roughness/incision by exogenic agents such as water erosion.

The implementation of *FLD* in ArcGIS is very simple. The horizontal flow length of every cell in the DEM can be calculated using the Flow Length tool with the default weight of 1 for every cell [3]. The 3D flow length along topographic surface can be calculated using the same tool, but with inverse of cosine of local slope as the weight:

$$s_i = h_i / \cos(\alpha_i) \qquad (1)$$

where s_i is the 3D flow length along topographic surface at the *i*-th cell; h_i is the projected horizontal flow length at the *i*-th cell; α_i is the local slope at the *i*-th cell. This is schematically shown in Figure 1.

The new *FLD* measure is expressed as:

$$FLD = \Sigma s_i - \Sigma h_i \qquad (2)$$

We choose difference instead of ratio because we want to avoid potential problem of dividing by zero at ridge cells, where the upstream flow lengths are zero. This is also in line with the

Local Relief measure (a difference). The summation is conducted along the flow path from a target cell to a drainage divide. The *FLD* can be calculated for every cell in the DEM.

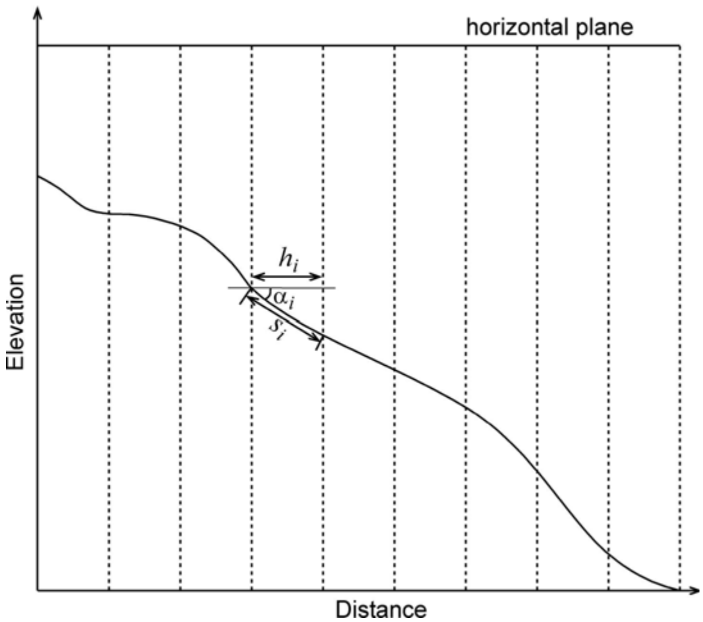

Figure 1. Schematic diagram showing a profile along a flow path. s_i is the 3D flow length along topographic surface at the *i*-th cell; h_i is the projected horizontal flow length at the *i*-th cell; α_i is the local slope at the *i*-th cell. (distances between each vertical dotted lines are either the same as cell size or 1.41 times the cell size)

Preliminary Result

The study area is located in the Cascade Range in Oregon, between 121.31°W and 122.75°W and between 43.31°N and 45.26°N, and is roughly 117 km × 216 km. We chose this study area because it is characterized by contrast in dissection between the Western Cascades (west part) and the High Cascades (east part) related to the lithology and geologic and hydrologic history (see [6] and references therein). The DEM data was obtained from the National Elevation Dataset (NED[1]) and has a spatial resolution of 37.215 m.

Figure 2 shows the preliminary result of *FLD* obtained for the study area in comparison with Local Relief (*LR*) and Standard Deviation of Slope (*SDS*) for two representative sites of the study area. The *LR* and *SDS* are derived with Focal Statistics tool in ArcGIS [7] using elevation and slope as input, respectively. For both cases, a circular window with radius of 5 cells (or approximately 186 m) is used. The *FLD* is derived as described in previous section using Flow Length tool in ArcGIS and smoothed with Focal Statistics tool (focal mean) with a same 5-cell radius circular window to match the *LR* and *SDS* result for easy comparison. The only input required for Flow Length tool is a flow direction grid, which can be derived from original DEM using Flow Direction tool [7]. The upstream option of the Flow Length is used because it is desired to have high *FLD* values for the deeply incised valleys.

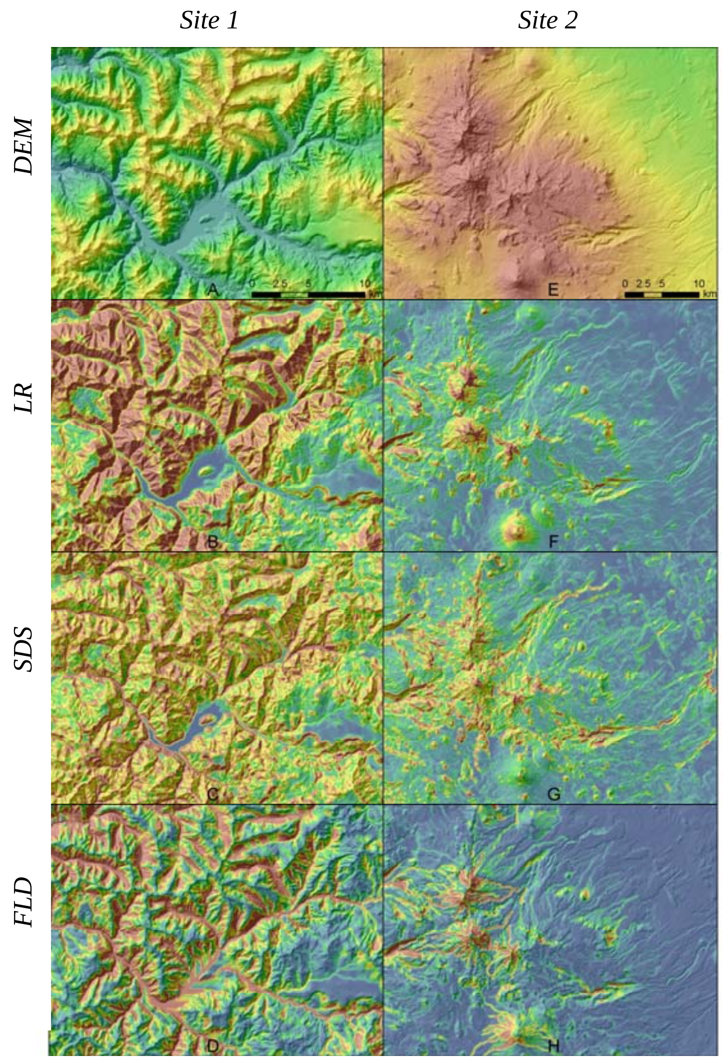

Figure 2. A, E: DEM with hillshade (resolution = 37.2 m); B, F: Local Relief (*LR*) with hillshade; C, G: Standard Deviation of Slope (SDS) with hillshade; D, H: Flow-Length Difference (*FLD*) with hillshade. Warm color indicates high value.

1 http://seamless.usgs.gov/

Overall the large scale contrast in dissection pattern in Oregon Cascades is captured by all of the three parameters. However, close-up views of highly incised areas show that high values of *LR* and *SDS* do not always correspond to deeply incised valleys (e.g., see Figures 3A, 3B, and 3C). In fact, some of the ridges have high *LR* and *SDS* values and valleys have low values, which is opposite of what they should be. In contrast, the *FLD* shows a better correspondence between high values and valleys and low values and ridges or flat areas (compare Figures 3B, 3C, and 3D). Close-up views of overall gently incised areas also demonstrate that *FLD* does a better job in revealing the details of incision around the volcanoes than *LR* and *SDS* (compare Figures 3F, 3G, and 3H). Whereas *LR* only shows high values around the peaks of the volcanoes and *SDS* shows a more diffusive pattern, *FLD* shows detailed incision pattern even in areas that are relatively flat and away from the volcano peaks.

We also applied *FLD* to a degraded global DEM (with 10km resolution, degraded from The Global Land One-km Base Elevation Project (GLOBE) data[2]). The result is shown in Figure 3. High *FLD* areas generally correspond to the major orogeny regions on Earth, e.g., the American Cordillera, the Alps, and the Himalayas. The tectonic activities and subsequent exogenic processes have created the surface incision and roughness that is readily revealed by the *FLD* measure.

Conclusion and Future Work

We have presented a new measure of surface roughness/ incision that is based on the difference of upstream flow length along topographic surface and its horizontal projection. Since this method considers the flow of water on the land surface, it is a better parameter for describing the degree to which the land surface is incised due to exogenic agents than other traditional statistical measures, such as local relief or standard deviation of slope. The result of *FLD* is easy to interpret because it is conceptually straightforward.

The other advantage of *FLD* over *LR* and *SDS* is that for *FLD* we do not have to worry about what radius of the moving circle to use (although the results presented here have been smoothed for better visualization and comparison with *LR*). In contrast, *LR* and *SDS* result depends heavily on the size of the window used.

The implied assumption of *FLD* is that the surface is carved by flowing fluid and the flow direction follows steepest descent, which can be derived from DEM. *FLD* will be able to measure the degree of incision and surface roughness created by the flowing fluid. As have been shown in this paper, *FLD* is better at revealing the details of the incision than at least two other traditional statistics-based measures. However, caution needs to be exercised if the implied assumption is not met. For example, for a perfect smooth cone shaped mountain with no incision, *FLD* will have high values.

Nonetheless, this new roughness/incision measure has great potential to be applied to reveal and quantify the dissection pattern on Earth at various spatial scales as more and more high resolution DEM data (such as Lidar data) become available.

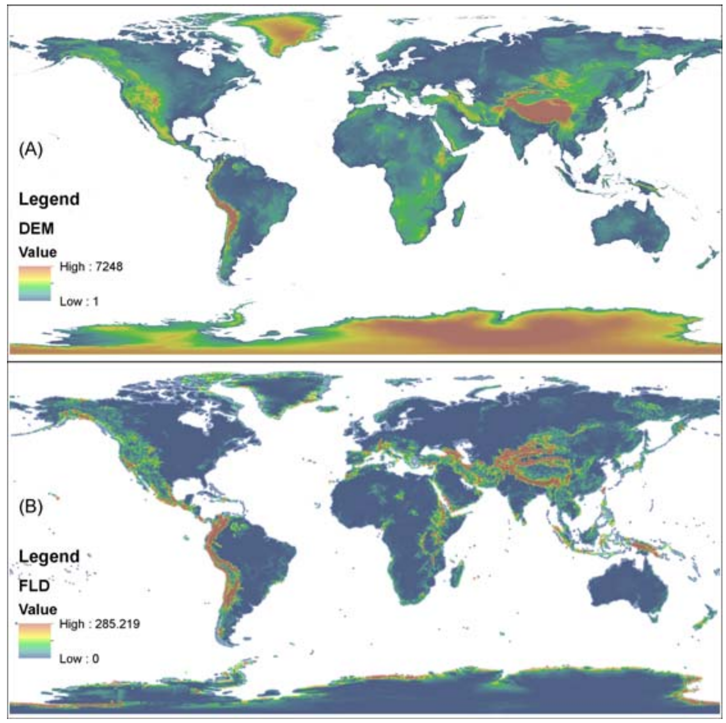

Figure 3. (A) Degraded Global DEM (10 km resolution). (B) FLD derived from DEM. Warm color indicates high value.

References

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