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GEO 4393C
5/8/18

Automation of Drainage Basin Analysis Using GIS

Introduction

As water resources have become politicized and over allocated, management of watersheds has become increasingly important. Geomorphological characteristics of watersheds provide scientists and policy makers the information necessary to make informed decisions about the management of watersheds. Historically, this analysis was done using topographic maps, however GIS analysis of the morphology of watersheds has been shown to be accurate and is more viable than other methods of analysis (Goudie 2013; Chandrashekar et al. 2015). The methods used to conduct this morphological research, however, are spread across various tools and the process of creating the data and executing the tools is tedious and time consuming. The objective of this research is to create a script tool that automates this process and calculates the parameters of interest, taking as input a watershed boundary vector, a streamlines vector, and a DEM, from the USGS datasets.

Background

ArcMAP contains tools to delineate any basin or sub-basin from a DEM, as well as the tools to calculate the same metrics as the tool created from this research. The script tool from this reserch fills a unique niche in that it uses USGS defined watersheds as input. The USGS maintains a database of over 1000 watershed basins, and these basins are the starting point for land management (USGS 2018). By using USGS watershed files as input, this tool can make use of the homogenous structure (units, fields, etc.) of the thousands of watershed files to calculate useful geomorphic characteristics for any given USGS watershed. The geomorphic characteristics of interest are described below.

Area: “a variable specifying the amount of land area contained within a drainage divide” (Goudie 2013). The area of the drainage basin is commonly used as a qualitative substitute for the amount of water or sediment that can be generated from a basin. The area is often used to compare basins of the same order of magnitude to one another (Strahler 1957).

Length: the maximum length of the basin, on its own, may only be useful for determining the scale of units to be used for analysis of sub-streams in the basin (Strahler 1957). However, it is necessary for several of the other morphometric calculations and therefore will be calculated and reported.

Relief Ratio: defined as the relief of the basin (difference between highest and lowest elevation within the basin) divided by the longest length of the basin parallel to the direction of flow (Schumm 1956). The relief ratio is dimensionless, which allows one to compare the relative relief between any two basins, regardless of size (Schumm 1956). It is a quantitative measure of the steepness of a drainage basin and qualitatively, a measure of potential erosion within the basin (Aparna et al. 2015).

Elongation Ratio: defined by Schumm (1956) as “the ratio between the diameter of a circle with the same area as the basin and the maximum length of the basin.” Again, this is a dimensionless measure that can be used to compare the shape of basins to one another.

Orientation: the orientation is simply the azimuth of the long axis of the basin. The orientation may be important for basins in regions that receive rainfall events from a particular direction. The orientation of the basin may also be indicative of underlying geologic controls, especially if several adjacent basins have similar orientations (Macka 2003).

Shape Index: According to Horton (1945) the “shape of the watershed is equal to the square of the length of the watershed divided by the area of the watershed, L^2/A.” It is an index that can be used to compare the rate of water and sediment yield between basins (Chandrashekar et al. 2015).

Drainage Density: is defined as the cumulative length of all stream channels in a drainage basin, divided by the drainage basin area, and is a fundamental measure of landscape dissection (Goudie 2013).

Basin Ruggedness Number: defined as the product of basin relief and drainage density, the ruggedness number describes the "complexity of the topography and the roughness of the terrain" (Goudie 2013). It is a dimensionless index which can be used to compare different basins.

Standard Deviation of Elevation: a raster depicting the standard deviation of elevation is one measure of topographic roughness (Ascione 2008). This method of analyzing roughness has been shown to perform as well as both simpler and more complex methods (Berti, Corsini, and Daehne 2013).

Methods

The usefulness of this tool relies on the extent and the structure of the files in the USGS National Hydrography Dataset (NHD). The NHD contains every watershed and sub-watershed in the US, as well as every stream segment for each watershed (USGS 2018). Furthermore, the structure of the watersheds is homogenous. That is to say that the fields in the attribute tables are the same for every file. Coupled with a DEM, the NHD provides a starting point for geomorphic analysis of any USGS defined watershed in the country. The script tool is to be tested by comparing values created from the script to values calculated using the ArcMAP GUI, on the same input files. The flowchart in Figure 1 depicts the steps taken to extract and calculate geomorphic characteristics from NHD files. Below are the steps performed by the script in the form of pseudocode.

1. Open csv file and write column headers to match metrics, Create empty list to store metrics,
2. Get linear unit name from WBD file using Describe function. The script works with either meters or feet as the projected unit, but calculations and conversions depend on which unit is selected.
3. Get watershed Name and HUCiD using search cursor on WBD file, append to list.
    a. *the 'HUC' field in the WBD files of the NHD is labeled as HUC2, HUC4, HUC8 etc. therefore the ListFields method is first used to create a list of fields from the WBD file and a for loop with the wildcard HUC* is used to get the specific HUCiD as a variable to pass to the search cursor.
4. Using search cursor on WBD, get area in Km^2 and Acres from table fields, and SHAPE@AREA token to get area in projected units. Append to list.
5. Run minimum bounding geometry tool on WBD file. Use search cursor on output polygon to determine the long axis of the basin and the orientation of the long axis. Append long axis and orientation to list.
6. Run Get Raster Properties tool on the DEM file with parameters as MAXIMUM and then MINUMUM. Subtract minimum from maximum to get relief. Append relief to list.
    a. *the DEMs from the USGS national map are in units of feet. If the linear unit as determined in step 2 is also feet, pass relief to step 7. If linear unit is meters, multiply relief by 0.3048 to convert to meters before passing relief to step 7.
7. Calculate relief ratio as (relief)/(long axis) using relief from step 6 and long axis from step 5.
    a. Relief ratio is reported as either feet per mile or meters per kilometer. If linear unit from step 2 is feet, divide relief ratio by 5280, if linear unit is meters, divide relief ratio by 1000. Append the corrected relief ratio to list.
8. Calculate shape index as $(\text{long axis})^2/(\text{area})$ using long axis from step 5 and area in projected units from step 4. Append shape index to list.

9. Calculate drainage density as either km/km^2 or mi/mi^2. Using search cursor on NHD streams file with SHAPE@LENGTH token and for-loop counter, calculate the sum length of all streams in the watershed. Convert to miles or kilometers based on linear unit from step 2. Divide by area (projected units) taken from step 4. Append drainage density to list.
10. Calculate ruggedness number as (relief)*(drainage density) using relief from step 6 and drainage density from step 10. Append ruggedness number to list.
11. Write list of metrics to csv file and close file.
12. Using focal statistics on DEM file, create Mean elevation raster.
13. Using focal statistics on DEM file, create Range elevation raster.
14. Calculate standard deviation raster as ((mean raster)-(DEM)) / (range raster)
15. Save standard deviation raster.

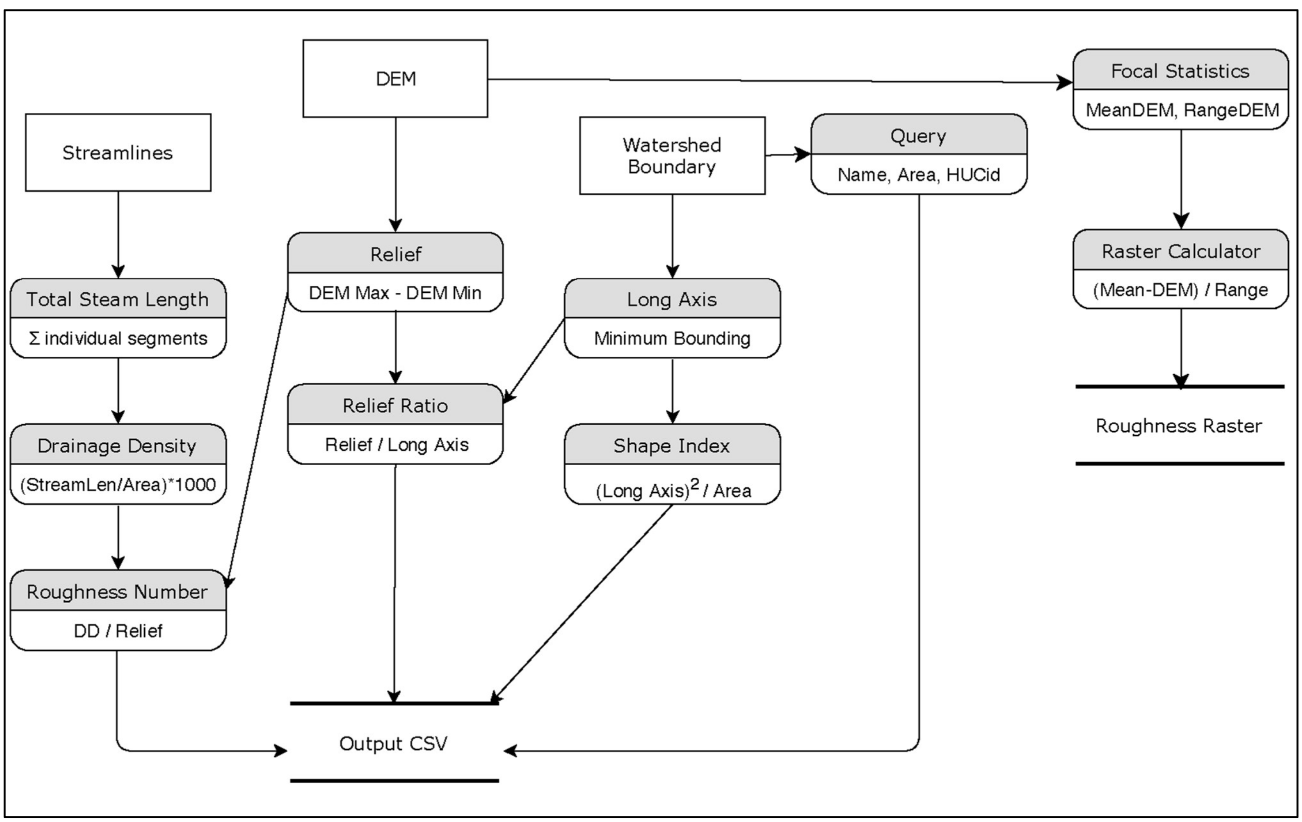

Figure 1. Flow diagram

Results and Findings

The tool was tested on the Guadalupe River basin of HUCiD 12100201. The metrics are located in table 1 below and the standard deviation raster is located below in figure 2. The calculated values of area in projected units, elongation, long axis, relief, relief ratio, shape index, drainage density and ruggedness number all match values calculated manually using ArcMAP GUI, and the queried values of Basin name, HUCiD, Linear unit name, area in Km^2, and area in acres all match values in the original USGS shapefiles. The tool was successful at streamlining the process of calculating geomorphic characteristics of a USGS defined watershed basin.

Table 1
Calculated and Queried Values

Metric	Value
Basin Name	Upper Guadalupe
HUCid	12100201
Linear Unit	Meter
Area Projected Units	3,710,179,721
Area Km^2	3710.7
Area Acres	916,932.71
Elongation (projected units)	0.467171616
Orientation (Azimuth)	96.74413642°
Long Axis (projected units)	147121.4798
Relief (feet)	139.9374491
Relief Ratio	0.951169396
Shape Index	5.833876373
Drainage Density	1.48455326
Ruggedness Number	207.7445963

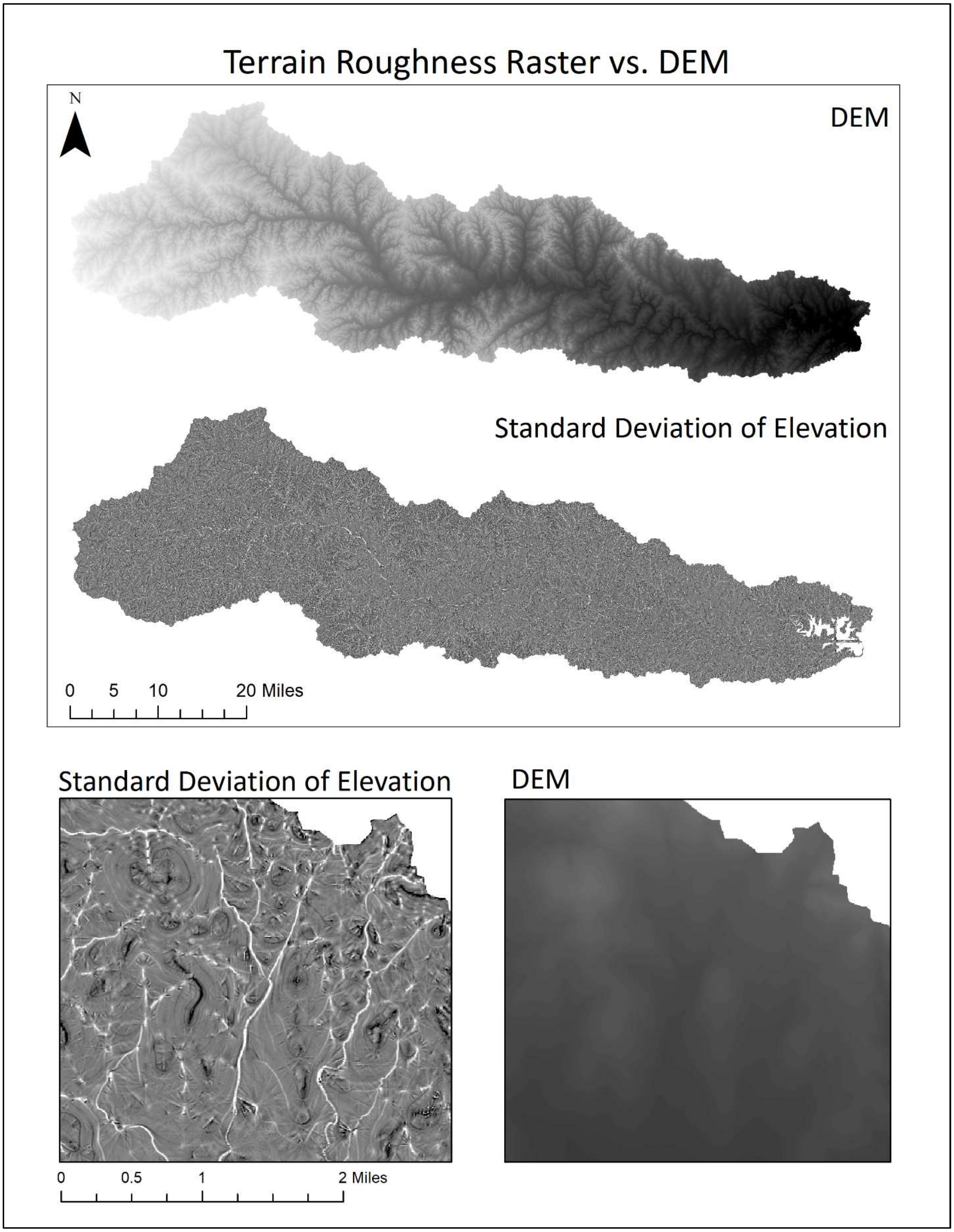

Figure 2. Visualization of Terrain Roughness with Standard Deviation of Elevation

Conclusion

The objective of this project was to create an ARCGIS script tool that streamlined the process of performing basic geomorphic analysis on USGS defined watershed basins. After testing the script tool against results obtained through the ArcMAP GUI, it was confirmed that the tool performs accurately. While the tool does achieve the project goals, it is not without limitations. One of the guiding principles of the project was that the tool should be simple to use, even for inexperienced ArcMAP users. The tool itself is simple to use, but it does require the user to project the NHD, WBD, and the DEM before using the tool. The projection of the DEM must be changed from default settings to avoid tiling image artifacts and the DEM must be clipped to the boundary of the WBD file. Each of these steps, while outside the bounds of the tool itself, raises the difficulty of the process and takes away from the simple, streamlined workflow that was the original goal of the tool. The next step in developing this tool further will be to increase the usability by taking the processes of projecting, clipping, and mosaicking, etc. and integrating them into the script. There are two other limitations of the tool that will also be addressed in future development. First, the tool is limited to a single watershed basin at a time. Geomorphologists often need to compare two or more basins to each other and several of the metrics calculated by the tool are indices that only make sense in comparison to other basins. Functionality to process multiple basins simultaneously will be attempted in future work. A final area in which the tool can be improved is in the range of geomorphic characteristics that the tool calculates. At present, the tool is limited to terrain analysis. With the addition of climatological data or stream discharge data, the number of useful geomorphic characteristics that can be calculated more than doubles. By adding functionality to interface with the USGS steam discharge network or with climate data from NOAA, geomorphic metrics such rainwater runoff and potential evapotranspiration could be added to the output table. At present the tool successfully calculates the metrics stated in the objectives, but there are several areas in which the functionality and usability can be increased in further development.

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