Advances in the mapping of flow networks from digital elevation data

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[Paper submitted for presentation at the World Water and Environmental Resources Congress, May 20-24,2001, Orlando, Florida.]

Abstract

Digital elevation models (DEMs) are a useful data source for the automatic delineation of flow paths, sub watersheds and flow networks for hydrologic modeling. Digital representation of the flow network is central to distributed hydrologic models because it encodes the model element linkages through which flow is routed to the outlet. The scale (drainage density) of the flow network, used controls the scale of hillslope and channel model elements. Although field mapping is acknowledged as the most accurate way to determine channel networks and drainage density, it is often impractical, especially for large watersheds, and DEM derived flow networks then provide a useful surrogate for channel or valley networks. There are a variety of approaches to delineating flow networks, using different algorithms such as single (drainage to a single neighboring cell) and multiple (partitioning of flow between multiple neighboring cells) flow direction methods for the computation of contributing area and local identification of upwards curvature. The scale of the delineated network is sometimes controlled by a support area threshold, which may impose an arbitrary and spatially constant drainage density. This paper examines methods for the delineation of flow networks using grid DEMs. We examine the question of objective estimation of drainage density and describe a method based on terrain curvature that can accommodate spatially variable drainage density. The methods presented have been incorporated as a component of the TMDL Toolkit software developed to support hydrologic and water quality modeling and available from http://www.engineering.usu.edu/dtarb/.

Introduction

Terrain analysis based on digital elevation models is being increasingly used in hydrology (e.g. Wilson and Gallant, 2000). This is driven by the increasing availability of digital elevation data, nationally from the USGS (2001a; 2001b) and worldwide with space based data soon to be available from the NASA TOPSAR shuttle mission. This is also driven by the increasing computer power available in personal computers with the capability to rapidly download and process digital elevation model (DEM) data and use topographic attributes extracted from DEMs in hydrologic models. This paper focuses on the drainage network, which is an important topographic attribute that is commonly extracted and mapped from DEM data. We review and compare methods for drainage network extraction.

Hydrologic processes are fundamentally different on hillslopes and in channels. In channels flow is concentrated. Width is a function of discharge according to hydraulic geometry (e.g. Leopold et al., 1964). At the landscape scale a channel is represented as a line with no width. The drainage area, A, (e.g. in m^2) contributing to each point in a channel may be quantified. On hillslopes flow is dispersed. The "area" draining to a point is zero because the width of a flow path to a point disappears. On hillslopes flow and drainage area need to be characterized per unit width (e.g. $m^3/s/m = m^2/s$ for flow). The specific catchment area, *a*, is defined as the upslope drainage area per unit contour width, *b*, ($a = A/b$) (Moore et al., 1991) and has units of length (e.g. $m^2/m = m$). Figure 1 illustrates these concepts.

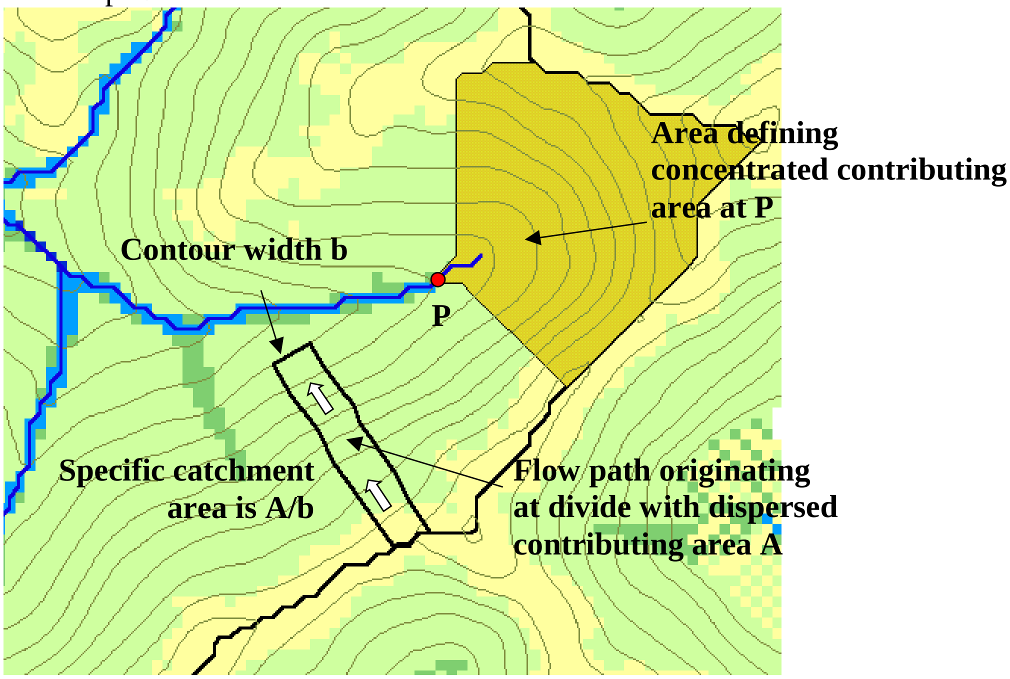

Figure 1. Definitions of concentrated and dispersed contributing area and specific catchment area.

The research literature has not always been clear on the distinction between hillslopes and channels. For example, Band, (1993) wrote "*any definition of a finite channel network is arbitrary and entirely scale dependent*". However Montgomery and Dietrich (1992) wrote "*landscape dissection into distinct valleys is limited by a threshold of channelization that sets a finite scale to the landscape*". In this paper we take the position that there is a finite scale that is an attribute of the landscape and that quantifies its texture, and we use the quantity drainage density, to quantify this scale. Drainage density is defined (Horton, 1932; 1945) as the total length of channels divided by area and measures the degree to which a landscape is dissected by channels. Smith (1950) showed that drainage density was related to topographic texture as quantified by the number of contour crenulations per unit contour length. We will illustrate that drainage density and topographic texture is different for different landscapes and present methods for drainage network delineation that are sensitive to these differences. We do however acknowledge that topographic generalization associated with the support scale (grid size) of digital elevation model data can affect the scale of extracted drainage networks especially if grid sizes approach hillslope lengths. Topographic texture and drainage density may vary spatially and in this paper we introduce methods for drainage network extraction that respect this variability.

The differences between processes on hillslopes and in channels make this work important. Model elements in hydrologic and water quality models are sometimes delineated based on area draining directly to a channel segment with hillslope or overland flow length an important parameter used to quantify for example hydrologic response time or erosion and sediment delivery (e.g. hillslope length in the USLE methodology (Wischmeyer and Smith, 1978)). Geographic information system (GIS) based methods are being used increasingly to delineate channels and watersheds and automatically extract these parameters for use in hydrologic models. We feel that it is important in applying these GIS methods to objectively identify the scale associated with the terrain and extract and map drainage networks and watersheds at the correct scale, so that these model input parameters are estimated correctly. The goal of this paper is to present ways to objectively characterize the distinction between hillslopes and channels, and to describe methods for delineating drainage networks from digital elevation models that respect this distinction.

Our method for channel network delineation automatically respects spatial variability in drainage density through the identification of locally curved grid cells. The grid of local curvature is then used as a weight grid in a drainage area accumulation function with a support threshold to delineate the channel network and watersheds. The support threshold is chosen objectively using the constant drop property for Strahler streams. In what follows we review the standard methodology for working with DEMs in hydrology, involving the computation of flow directions, drainage areas and methods for channel network delineation. We then describe our method and illustrate its application in different texture landscapes.

Digital elevation model methods

In this paper we use grid digital elevation model data. Grid DEMs consist of a matrix data structure with the topographic elevation of each grid cell stored in a matrix node. Grid DEMs are distinct from other DEM representations such as triangular irregular network (TIN) and contour-based data storage structures. Grid DEMs are readily available and simple to use and hence have seen widespread application to the analysis of hydrologic problems (Moore et al., 1991). However they do suffer from some drawbacks that arise from their gridded nature. The methods and software discussed in this paper are directly applicable to grid DEMs. Some of the principles involved may be useful with other DEM data structures, but we have not implemented any of the methods for other data structures.

Pits are removed from DEMs using the standard flooding approach described by Jenson and Domingue (1988). This fills depressions by increasing elevations within depressions to their lowest outflow point. Flow directions are assigned using the D8 (eight directions method) which assigns flow from each grid cell to one of its eight neighbors, either adjacent or diagonal, in the direction with steepest downward slope. The D8 method was introduced by O'Callaghan and Mark (1984) and has been widely used (Marks et al., 1984; Band, 1986; Jenson and Domingue, 1988; Mark, 1988). Multiple flow direction methods have also been suggested (Quinn et al., 1991; Tarboton, 1997). These proportion flow from a grid cell between more than one downstream grid cell, and by doing this avoid some of the biases associated with grid directions, resulting in better estimates of drainage area, especially on hillslopes. In this work the focus is drainage networks, where we do not admit splitting, braiding or dispersing of the network so we use the D8 method, although drainage area computed by a multiple flow direction method may be used as a threshold field to define sources in the channel delineation algorithm. In flat areas, where the steepest downwards slope is zero, we use the method of Garbrecht and Martz (1997) that assigns flow directions by forcing flow away from higher terrain and towards lower terrain. With flow directions assigned the drainage area contributing to each grid cell is computed by counting the number of grid cells that drain through each grid cell and multiplying by grid cell area. The earliest method (O'Callaghan and Mark, 1984) for delineating drainage networks uses a support area threshold applied to the grid of drainage area's. Channels and channel start points are mapped as those grid cells where the support threshold is exceeded. This procedure has been widely used. A significant question with this method is what support area threshold to use. Figure 2 illustrates this issue where drainage networks with two different support area thresholds are depicted. Tarboton et al. (1991) suggested methods based on the relationship between slope and contributing area, and the constant stream drop property to objectively decide upon a support area threshold. However a drawback is that the drainage density of the network extracted is still spatially uniform. Figure 3 shows the functional dependence between drainage density and support area threshold for some study areas.

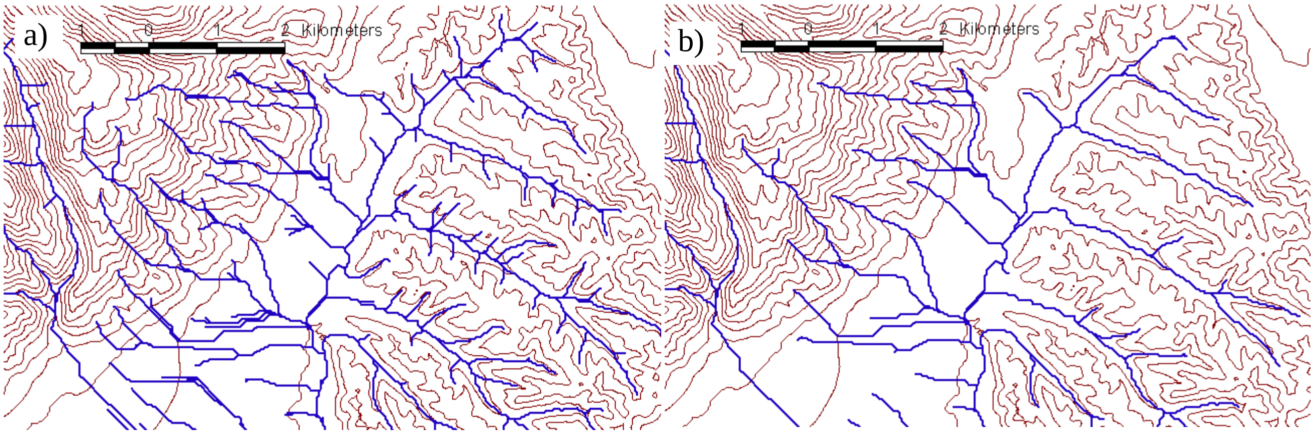

Figure 2. Mawheraiti River, New Zealand. 40 m contours, DEM with 30 m grid size based on Contours supplied by Land Information, New Zealand. Drainage networks delineated with a) 100 gridcell, b) 300 grid cell threshold.

Peckham approached the drainage network delineation problem from the perspective of a grid network tree. A grid flow network may be constructed by considering each grid cell with unit drainage area as the source of a first order stream. The Strahler (1952) stream ordering system is then used to "order" the entire network. Source streams are designated first order; the confluence of two (or more) first order streams is the beginning of a second order stream; the confluence of two (or more) second order streams produces a third order stream and so on. When a stream of a given order receives a tributary of lower order, its order does not change. A Strahler stream is defined as an entire set of sequential stream segments with the same order. Figure 4 illustrates a grid network, where line thickness and color is related to grid network order. Peckham then suggested pruning this network by discarding streams

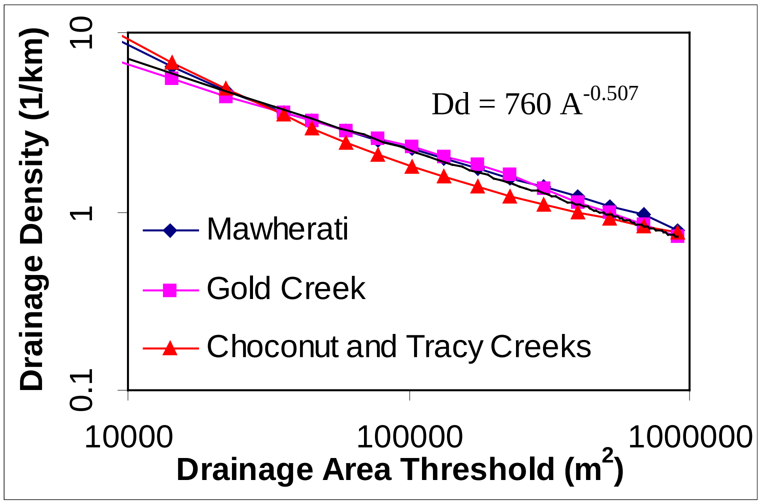

Figure 3. Drainage density (total channel length divided by drainage area) as a function of drainage area support threshold used to define channels for the three study watersheds.

with order below a specified threshold. For example in figure 4 the red flow network is delineated by pruning streams of order three and lower. Application of this method still requires selection of the order threshold with which to prune the grid network.

Montgomery and Dietrich suggested based on field analysis of channel heads a channelization threshold of the form

$a\ S^{\alpha} > C$

For their field areas they suggested α=2 and C = 200 m. This algorithm does provide a mechanism for spatially variable drainage density, with higher drainage density where slopes are steeper. Our experience with this algorithm has been that it results in "feathering" of the drainage network in steeper areas while omitting drainage networks in less steep valleys. Figure 5 illustrates a drainage network delineated using this approach.

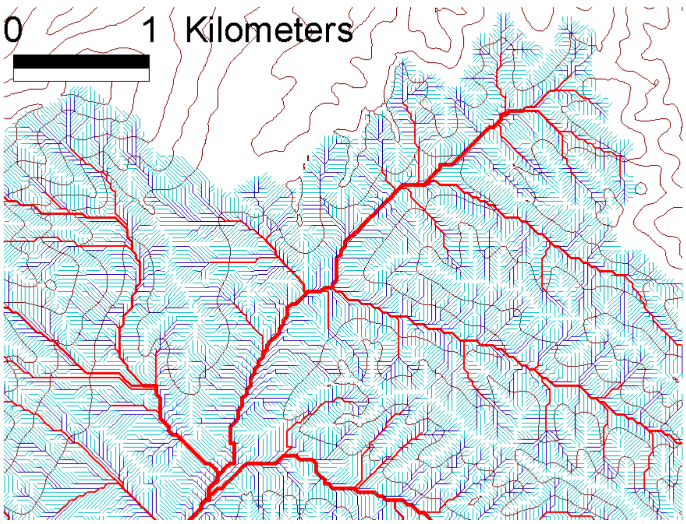

Figure 4. Grid network for the Mawheraiti River.

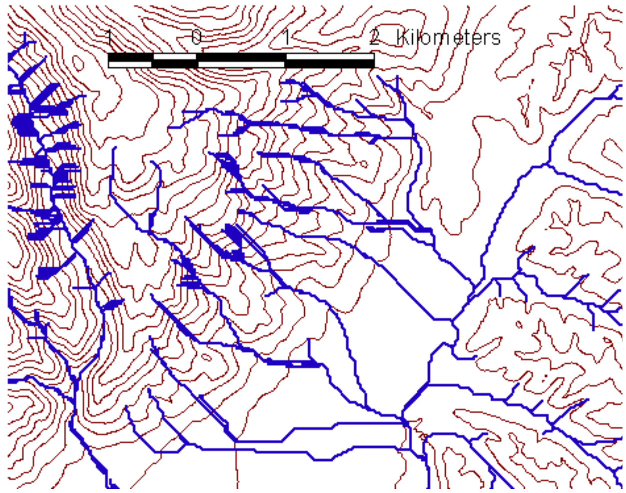

Figure 5. Channels mapped using $a\ S^2 > 200$ m is specific catchment area and S is slope.

Topographic texture

The previous section reviewed some of the common methods for delineation of drainage networks from digital elevation model data. All require the selection of some parameter that controls the form of network extracted and the resulting drainage density scale. It is the premise of this paper that the drainage density of extracted channel networks should be adjusted to match the natural texture of the topography, so that the drainage network provides a good approximation of the domain over which channel processes, which are distinct from hillslope processes occur. The previous figures 2 to 5 were all for the same study area in New Zealand. Figures 6 and 7 illustrate topography drawn to the same scale with the same contour interval for two other areas chosen to illustrate the difference in topographic texture. In each of these a drainage network with the same constant drainage area threshold has been mapped. This network appears too coarse in the case of figure 6 and about right in the case of figure 7 relative to the contour crenulations. In the next section we will describe an objective methods for the delineation of drainage networks based on curvature that provides an automatic way to adjust to the natural topographic texture.

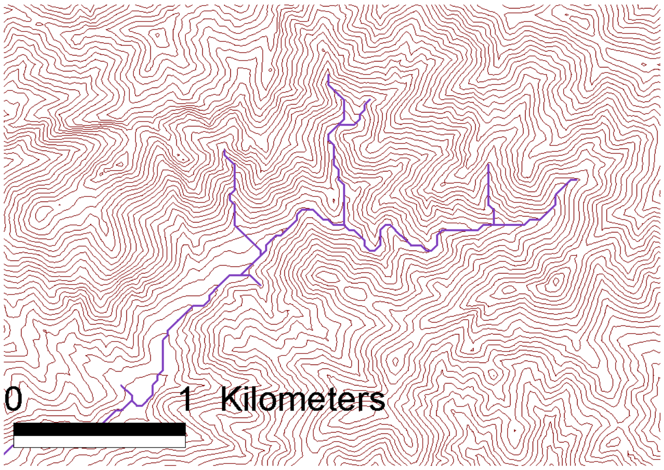

Figure 6. Gold Creek in the Sunland Quadrangle, Los Angeles County, California. 20 m contour interval. Channels mapped with drainage area threshold of 500 grid cells = 0.45 km^2.

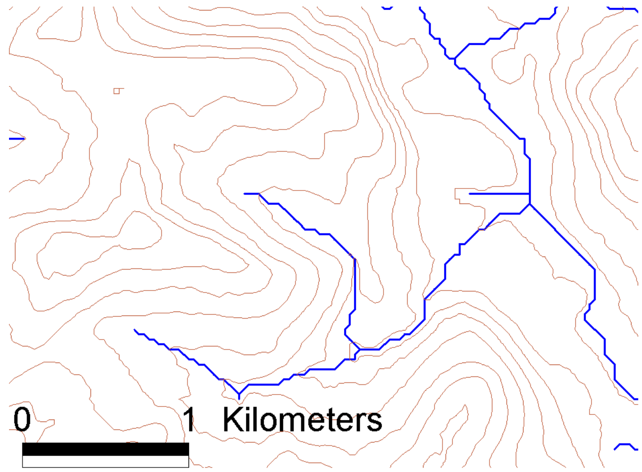

Figure 7. Choconut and Tracy Creek in the Endicott Quadrangle, Broome County, New York. 20 m contour interval. Channels mapped with drainage area threshold of 500 grid cells = 0.45 km^2.

Curvature based drainage network delineation

Our procedures work by first identifying locally upwards curved grid cells. Upwards curved grid cells have been used by others to depict channel networks from digital elevation data (Band, 1986; Wilson and Gallant, 2000). However patterns of locally upwards curved grid cells are disconnected and not readily amenable to network analysis. We connect upwards curved grid cells by using them as a weighting field in a weighted drainage area computation. We then use a threshold in this weighted drainage area to map and delineate channels. The weighted support area threshold is chosen objectively using the constant drop property of channel networks (Broscoe, 1959). The smallest weighted support area threshold that produces a channel network where the mean stream drop in first order streams is not statistically different from the mean stream drop in higher order streams, is selected. Stream drop is defined as the difference in elevation between the beginning and end of Strahler streams. This constant drop method was used previously for support area thresholds, without the identification of upward curved grid cells and weighted drainage area accumulation by, Tarboton et al. (1991). The constant drop property is an empirical geomorphological attribute of properly graded drainage networks, that has a physical basis in terms of geomorphological laws governing drainage network evolution (Tarboton et al., 1992). By using the smallest weighted support area that produces networks consistent with this property we are extracting the highest resolution drainage network statistically consistent with geomorphological laws. A smaller weighted support area threshold would result in drainage networks with first order stream drops inconsistent with the rest of the drainage network. When such a network is mapped one observes that stream seem to extend up what appear to be smooth hillslopes. A weighted support area larger than required for consistency with the constant drop law results in a coarse drainage network that omits drainage paths from what contour examination would indicate to be valley forms.

Upwards curved grid cells are identified using algorithm due to Peuker and Douglas (1975) reported by Band (1986), illustrated in figure 8. This algorithm flags the pixel of highest elevation from each possible square of four adjacent grid cells. After one sweep of the matrix the unflagged grid cells represent drainage courses. Wilson and Galant (2000) suggest some alternative measures of curvature based on second derivatives of the surface. These could be used with a similar procedure.

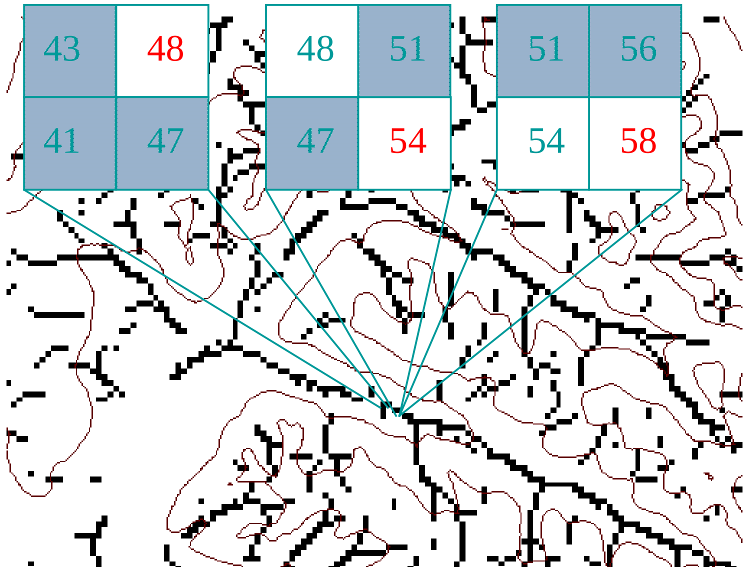

Figure 8. Peuker and Douglas (1975) method for identification of valley grid cells through a single sweep flagging (white) the highest grid cell in each set of four. The remaining unflagged (black) grid cells indicate valleys.

Figure 9 presents a constant drop analysis where a t test has been used to evaluate the difference in mean stream drop between first and higher order streams. The 95% confidence level for t tests is essentially 2. Based on this test the curvature weighted support area threshold of 20 grid cells is selected for the Mawheraiti study area, because it is the smallest support area threshold where the absolute value of the t statistic is less than 2 indicating that the mean drop

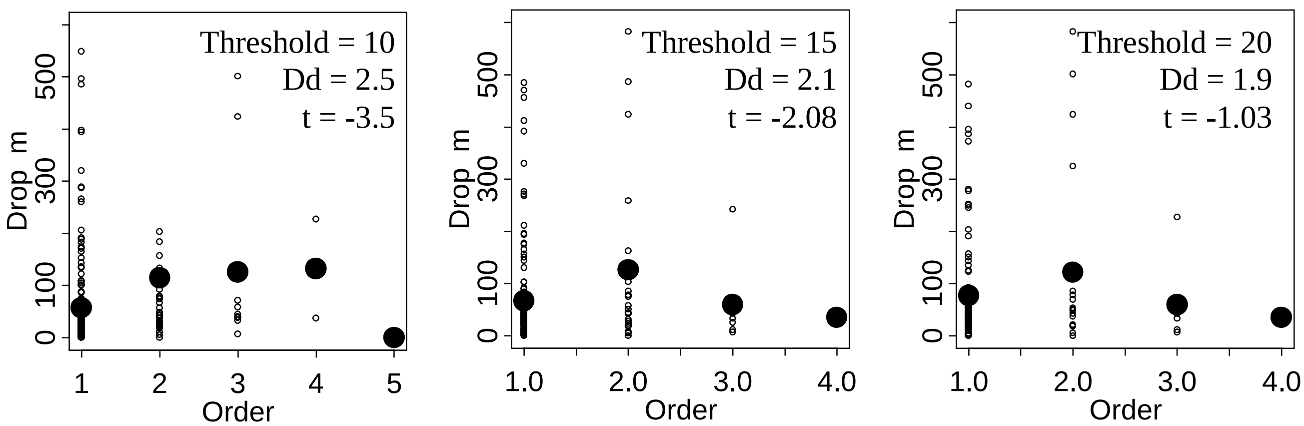

Figure 9. Stream drop test for Mawheraiti River. For each upward curved support area threshold the stream drop for each stream is plotted against Strahler stream order. The large circles indicate mean stream drop for each order The weighted support area threshold, drainage density (in km^{-1}) and t statistic for the difference in means between lowest order and all higher order streams is given.

between first order and higher order streams is not significantly different. The resulting channel network is shown in figure 10. Notice the adaptation of the procedure to the contour crenulations with lower drainage density relative to figure 1 in the flat areas, but comparable drainage density in the hilly areas. The Peuker Douglas procedure identified more upwards curved grid cells in the hilly areas where the contours are more crenulated than in the broad valley. The weighted accumulation of these resulted in higher drainage density in the hilly areas and fewer spurious looking drainage paths in the broad valleys. Figures 11 and 12 show channel networks for the other two study areas delineated automatically using this procedure. The t test resulted in different curvature weighted support area thresholds in the different areas.

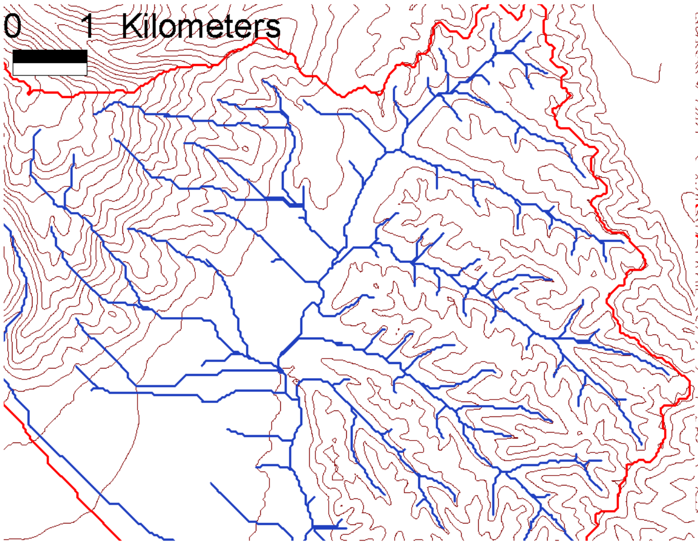

Figure 10. Mawheraiti River. 40 m contours. Drainage network delineated with upward curved weighted support area threshold of 20 grid cells.

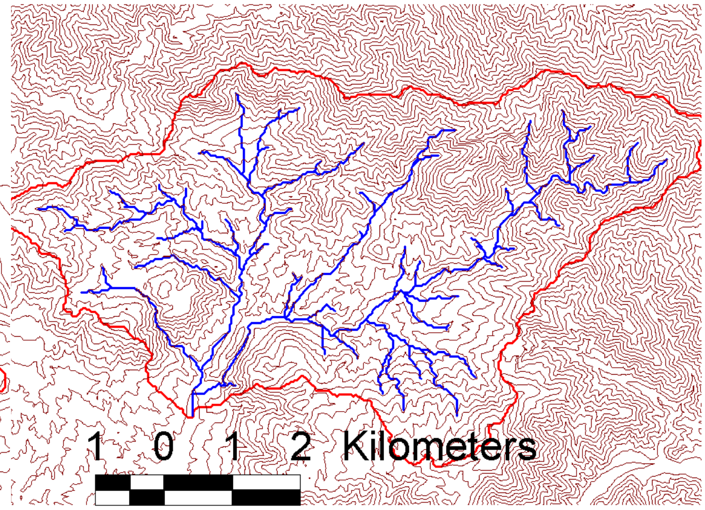

Figure 11. Gold Creek. 20 m contours. Drainage network delineated with weighted upward curved support area threshold of 44 grid cells determined from stream drop t test.

Implementation

The procedures presented have been programmed in C++ as a library of functions compiled into a component object model (COM) dynamic link library that is callable from other COM compliant systems such as Visual Basic and ESRI ArcGIS. The software accesses data in the ESRI grid data format directly using the GRIDIO application programmers interface that is part of ArcView. The software developed is part of the TMDL toolkit developed tosupport hydrologic and water quality modeling and is available from http://www.engineering.usu.edu/dtarb/.

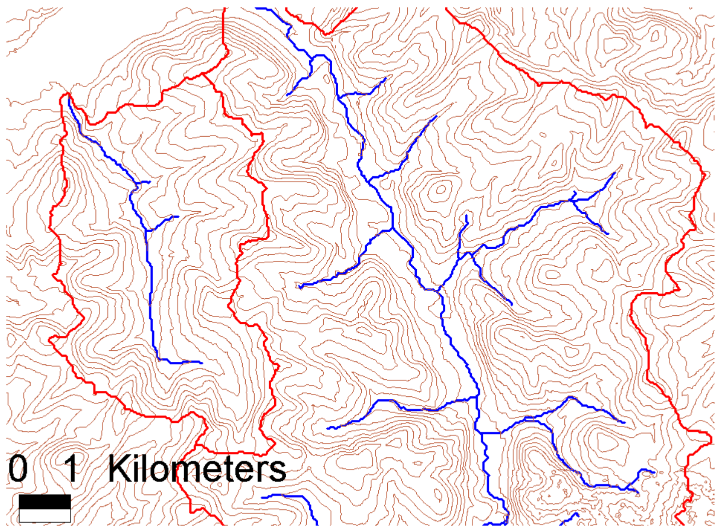

Figure 12. Choconut and Tracy Creeks. 20 m contours. Drainage network delineated with weighted upward curved support area threshold of 100 grid cells determined from stream drop t test.

Conclusions

This paper has introduced a method for the delineation of drainage networks based on the weighted accumulation of upwards curved grid cells. This method is adaptive to spatial variability in drainage density. The weighted support area threshold is chosen objectively using a t test to select the highest resolution drainage network with mean drop of first order streams not significantly different from the mean drop of higher order streams. In this way a drainage network consistent with geomorphology is delineated without the need to subjectively choose a support area threshold parameter.

Acknowledgements

We would like to thank Brian Smith and Darrel Brown for programming assistance. This work was supported by NASA under award #NAG5-7521, and the Idaho National Engineering and Environmental Laboratory.

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