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Geomorphology 29 (1999) 339–353

GEOMORPHOLOGY

An analysis of an arctic channel network using a digital elevation model

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Received 12 January 1998; accepted 15 December 1998

Abstract

Drainage basins possess spatial patterns of similarity that can be characterized by universal qualities in the fractal dimension and the cumulative area distribution. Features called water tracks often drain hillslopes in basins with permafrost and impose significant control on the hydrologic response of watersheds. We analyzed the arrangement of channel networks and water tracks in Imnavait Creek in Northern Alaska to determine if basins with permafrost possess the same universal characteristics as basins without permafrost. Using digital elevation models (DEMs), we explored the hillslope/channel scaling regimes, the spatial distribution of mass through the cumulative area distribution, and the fractal characteristics of channel networks in the Kuparuk River basin in Northern Alaska. Fractal analysis, slope–area analysis, and field mapping suggest that water tracks are positioned on the hillslopes where channels should occur. Fully-developed channel networks, however, possess certain universal characteristics in aggregation patterns that are manifested in a common cumulative area distribution. Imnavait Creek possesses those universal characteristics only above the scale of the hillslope water track, or when the drainage areas reach the main channels in the valley bottom. Our interpretation is that a rudimentary channel network formed on the hillslopes, but never developed into a mature channel network because permafrost is limiting erosion. Consequently, the undissected hillslopes are extensive. Given the dependence of permafrost on a cold climate, a warming climate and subsequent degradation of permafrost may have significant impacts on the erosional development of channel networks in the Arctic.

Keywords: drainage network; permafrost; arctic; fractal; Alaska

1. Introduction

Mature networks of fluvial channel possess patterns of spatial similarity across a wide range of scales. The purpose of this paper is to determine if drainage features in a basin with permafrost also exhibit patterns of similarity in spatial arrangement. Permafrost influences the form and hydrologic response of drainage basins in Arctic environments (McNamara, 1997; McNamara et al., 1997, 1998). Further, McNamara (1997) suggested that significant differences exist in the scaling of rainfall generated stream flow between Arctic and temperate regions, which can be attributed to the influence that permafrost has on the generation of runoff. Because

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PII: S0169-555X(99)00017-3

fundamental differences exist between hydrologic response in basins with and without permafrost, it is likely that differences exist in the spatial organization of the form of the drainage basin.

The advent of digital elevation models (DEMs) has led to a surge of research concerning the scaling of landscape form from which has emerged a suite of descriptive parameters that relate patterns across scales. These include the fractal dimension (Mandelbrot, 1982; Tarboton et al., 1988), and the cumulative area distribution (Rodriquez-Iturbe et al., 1992a). Perhaps the most significant result from this research has been the quantitative affirmation on the commonality of drainage basins from all geologic and environmental conditions. Apparent universalities in these parameters suggest that networks of fluvial channels evolve to a state of self-organized criticality (SOC) in which energy expenditure is minimized during the transfer of precipitation to runoff (Rodriquez-Iturbe et al., 1994). SOC means that dissipative, spatially extended, dynamical systems (rivers) naturally evolve to critical states (states that lack intrinsic spatial or temporal scales) despite the initial conditions (self-organized) (Bak et al., 1987, 1988). This similarity among basins occurs because of similar aggregation and convergence patterns of drainage features that arise as a network of channels evolves to that critical state.

The fractal dimension and the cumulative area distribution for a network of fluvial channels are closely related to a third important concept called slope–area scaling which describes the boundaries to which these universal qualities apply. Because these universal qualities appear in basins that have evolved to that self-organized critical state, deviations from these universal qualities in the fractal dimension, the cumulative area distribution, and slope–area scaling may hold information concerning the evolutionary state of a channel network.

Headwater basins in the Kuparuk River drainage in northern Alaska, a region completely underlain by permafrost, possess unusual drainage features called hillslope water tracks (Hastings et al., 1989; Walker et al., 1989) (Fig. 1). Water tracks are essentially linear zones of enhanced soil moisture in poorly defined depressions that overlying frozen ground and convey flow downslope perpendicular to the elevation contours. They often do not have incised channels, but are the dominant pathways for water removal from hillslopes in many Arctic watersheds. These features are typically spaced tens of meters apart and may or may not connect to channels in the valley-bottom. If water tracks are viewed as part of the channel network, the network appears feathered with numerous linear channels flowing directly into a main valley-bottom basin. If water tracks are excluded from the channel network, the network appears under-developed with vast, undissected hillslopes connected by single channels that occupy major valley-bottoms. An interesting and practical geomorphologic question is this: Where do these water tracks fit in the arrangement of paths of flow within a basin? Are water tracks part of the fluvial channel network with an arrangement similar to mature networks? Paths of flow on hillslopes possess different aggregation and convergence patterns, and transfer mass and energy differently than do channels. Thus, determining the role of water tracks in the arrangement of the paths of flow within a basin is an important problem for constructing hydrologic models of basins that contain water tracks.

We investigated the position of water tracks in the arrangement of channel networks in an Arctic basin by generating channel networks from DEMs that include and exclude hillslope water tracks, and comparing the characteristics of those networks to those of mature channel networks. The comparisons include relationships between local slope and drainage area (Tarboton et al., 1992; Montgomery and Foufoulo-Georgiou, 1993; Ijjasz-Vasquez and Bras, 1995), the spatial distribution of mass in the basin from cumulative area distributions (Rodriguez-Iturbe et al., 1992a), and the fractal dimension of channel networks (Tarboton et al., 1988, 1990; La Barbera

Fig. 1. (a) The Upper Kuparuk River basin looking southwest. The dark green lines on the hillslopes are water tracks. Some water tracks contain segments of incised channels, but they are usually only distinguishable by vegetation and soil moisture differences. Imnavait Creek has similar, but less photogenic water tracks. (b) Water tracks in a small drainage in the Sagavanirktok River basin. Water tracks stand out after a light fall snow because the shrubby vegetation looses snow quicker than the surrounding tundra.

(a)

(b)

and Rosso, 1989, 1990; Claps and Oliveto, 1996). Our comparisons reveal two important features of water tracks. First, water tracks exist at a critical geomorphologic threshold that represents a transition from hillslope to valley or channel processes. Second, water tracks do not possess arrangement properties that are characteristic of mature channel networks. These features may arise because permafrost has inhibited erosion and migration of channels on the hillslopes.

2. Background

Significant advances in recent years in fluvial geomorphology have led to the development of a new theory of the evolution of drainage basins wherein chance and the rules of optimum expenditure of energy control the structure of channel networks (Rodriguez-Iturbe et al., 1992a,b, 1994). Three topics that have been fundamental in these advances include slope–area scaling, the fractal nature of channel networks, and the cumulative area distribution.

2.1. Slope-area scaling

Slope–area scaling of the form:

$$S \sim A^{-\theta} \tag{1}$$

where S is channel slope, A is drainage area, and θ is a scaling exponent typically between 0.2 and 0.6 has long been recognized in fluvial geomorphology (Flint, 1974). Recent studies have investigated this relationship in terms of the scaling characteristics and aggregation patterns of channel networks (Gupta and Waymire, 1989; Willgoose et al., 1991; Tarboton et al., 1991, 1992). Eq. 1 can not hold ad infinum as it implies an infinite slope as the drainage area approaches zero. A change in the scaling regime exists at the lower bound to Eq. 1 where the channel network gives way to the hillslopes. Thus, the channel head represents an important threshold in the manner in which mass and energy are transported. Montgomery and Foufoula-Georgiou (1993) discuss two general approaches for identifying channel heads in DEMs, constant threshold and slope-dependent threshold. Both involve selecting upslope drainage areas below which channels will not occur, called the support area of the channel.

Tarboton et al. (1992) proposed a method of constant threshold based on the concept that a transition occurs in processes that dominate erosion at the channel head. Above the channel head diffusive processes dominate erosion, whereas below the channel head concentrated advective processes dominate erosion. They argued that this transition coincides with a transition from convergent to divergent topography. They derived the relation between process transition and topographic transition by recognizing the implicit relation between S and A in functions that are typically used to model sediment flux. This concept combined with criterion for hillslope stability proposed by Smith and Bretherton (1972) yields:

$$A\frac{\partial F}{\partial S}\frac{\mathrm{d}S}{\mathrm{d}A} = F - A\frac{\partial F}{\partial A} \tag{2}$$

where F is the sediment flux, A is upslope drainage area, and S is local slope. If the right side of Eq. 2 is negative, small perturbations grow into channels. If the right side of Eq. 2 is positive, the hillslope remains unchanneled. The only way for the left side of Eq. 2 to be negative is in the $\mathrm{d}S/\mathrm{d}A$ term. Therefore, a slope reversal in a plot of local slope against drainage area should occur at the threshold drainage area between unchanneled to channeled regions. That threshold drainage area should equal the average drainage area required before channels can form, or the channel support area.

Montgomery and Dietrich (1992) showed that support areas for channels are not constant within a basin, but depend on local slope. They reported empirical relationships between slope (S) and threshold area (A_{th}) of the form $A_{\mathrm{th}} = CS^{-\eta}$, where C and η are empirically determined constants. Consequently, Montgomery and Foufoulo-Georgiou (1993) argued that it is not appropriate to assign one drainage area to represent the initiation threshold for all channels in a basin. They suggested that the slope reversal on slope–area plots described by Tarboton et al. (1992) does not represent where channels will occur, but rather represents the transition from convex to concave landscapes, or the transition from hillslopes to unchanneled valleys, and that channels will initiate in the valleys somewhere downslope depending on the slope. Ijjasz-Vasquez and Bras (1995) proposed a method to derive slope-dependent channel support areas entirely from plots of slope–area. They identified four distinct scaling regimes in slope–area plots, as opposed to two identified by Tarboton et al. (1992). Each of the approaches described above recognizes that the relation between slope and area possesses information on the erosional processes operating at various scales.

2.2. The fractal nature of channel networks

Several studies have shown that channel networks possess characteristics of fractals (Mandelbrot, 1982; Tarboton et al., 1988, 1990; La Barbera and Rosso, 1989, 1990; Beer and Borgas, 1993; Nikora, 1994; Claps and Oliveto, 1996). The term 'fractal' implies that an object or pattern has self-similar or self-affine properties. Self-similar means that parts of an object are identical to the whole, and self-affine means that parts of an object resemble systematically squashed or stretched versions of the whole. Thus, fractal channel networks possess similarity patterns that transcend geologic controls. Ideal fractals display similarity across an infinite range of scales, which is rarely seen in nature. Consequently, the ranges of fractality can be used to decipher characteristic scales and thresholds at which physical processes operate.

The fractal dimension (D) describes how a measure, say length L, changes with a scale transformation, say ruler size r:

$$L \sim r^{D}. \tag{3}$$

Solving for D yields:

$$D \sim \log(L)/\log(r). \tag{4}$$

Thus, the fractal dimension represents the ratio between the log-value of a measure and the scale at which it was measured, and L scales with r by the scaling exponent D.

In conventional Euclidean geometry, D is either one, two, or three. For example, the measured length of a finite straight line, $D=1$, is independent of the actual size of the ruler, and is simply the number of steps the ruler must take times the measure of the ruler. As the ruler decreases in size, the number of steps increases linearly and the measured length remains the same.

The measured length of a self-similar curve changes with the size of the ruler. As the size of the ruler decreases, the measured length L increases non-linearly with r. The exponent D then takes on non-integer values, hence the term 'fractal'. The fractal dimension can be viewed as the dimension in which the measure is independent of the size of the ruler. Its deviation from the conventional dimension is an indicator of complexity (De Cola and Lam, 1993).

Several empirical relationships in fluvial geomorphology have the form of Eq. 3. Perhaps the most famous, based on the attentions of Mandelbrot (1982), is the relationship between the mainstream length (L) and drainage basin area (A):

$$L = aA^{m} \tag{5}$$

where a and m are empirical parameters. Hack (1957) reported a value of $m=0.6$ in the Shenandoah Valley. Gray (1961) compiled the measures of 47 rivers and determined that m is approximately 0.568. Dimensional analysis of Eq. 5 suggests that m should equal 0.5. Mandelbrot (1982) suggested that the anomalous value of m result from the fractal nature of rivers. He suggested that the fractal dimension of a river channel is $D=2\times m=1.1$ to 1.2, and further suggested that the branching channel network is space-filling and takes on the dimension of a plane, $D=2$.

Several direct and indirect methods have emerged to calculate the fractal dimension of channel networks. A computationally simple technique is functional box counting (Mandelbrot, 1982; Feder, 1988; Tarboton et al., 1988; Rosso et al., 1991). A grid is imposed on the channel network with four quadrants of size r. The number of boxes N required to cover the network is calculated. Then, each quadrant is itself divided into quadrants and again the number of boxes required to cover the network is computed. This continues down to the resolution of the grid, and the fractal dimension is the slope of the plot of log N against log r, or:

$$D = \log(N)/\log(r) \tag{6}$$

which is identical to Eq. 4.

Horton (1933, 1945) recognized the self-similar nature of river networks decades before fractal concepts were introduced, and formulated a set of similarity numbers that collectively became known as Horton's laws of drainage network composition. When a channel network is ordered according to Horton (1945) or Strahler (1952), the following ratios can be calculated:

$$R_b = \frac{N_{w-1}}{N_w} \tag{7}$$

$$R_l = \frac{L_w}{L_{w-1}} \tag{8}$$

$$R_a = \frac{A_w}{A_{w-1}} \tag{9}$$

where R_b, R_l, and R_a are the bifurcation ratio, length ratio, and area ratio, respectively; N_w, L_w, and A_w are the number of streams, the mean length of streams, and the drainage area of order w. When Horton's laws hold true, R_b, R_l, and R_a plotted against stream order produce straight lines. Hence, Horton's numbers are geometric scaling laws. Tarboton et al. (1988) and La Barbera and Rosso (1989) recognized the connection between Horton's numbers and the self-similarity embodied in Eq. 4, and independently derived the fractal dimension in terms of Horton's numbers as:

$$D = \log(R_b)/\log(R_l), \text{if } R_b > R_l. \tag{10}$$

Tarboton et al. (1988) used several methods including functional box counting and Hortonian analysis to determine that the fractal dimension of mature networks should be two because rivers drain entire basins (space filling), as Mandelbrot (1982) suggested. La Barbera and Rosso (1989) used Eq. 10, however, and estimated values for D around 1.6 to 1.7. Tarboton et al. (1990) reasoned that this was because Eq. 10 does not account for the fractal nature of individual stream reaches, which is most commonly around 1.1, and suggested that by multiplying the two fractal dimensions, the true fractal dimension of two is revealed. La Barbera and Rosso (1990) countered that $D = 2$ is a limiting case, and that the fractal dimension of channel networks varies between two and unity, depending on the landscape. Claps and Oliveto (1996) determined that D is typically around 1.7, similar to La Barbera and Rosso (1989, 1990).

Phillips (1993) stated that Horton's laws only apply if they hold true for all scales, which is rare and suggested that using Horton's laws to calculate the fractal dimension of a channel network is prone to error. He used Eq. 10 to calculate the fractal dimension of fifty third order drainage basins and over a third had D values greater than two, which is physically impossible. In addition, Phillips (1993) argued that a fractal dimension of two for channel networks is unrealistic in nature. If the network does indeed drain the entire basin, the fractal dimension should be two. A finite lower limit, however, exists to channel networks called the drainage density (Montgomery and Dietrich, 1988, 1992). The suggestion by Mandelbrot (1982) that a channel network must penetrate everywhere in order to drain a basin does not distinguish between hillslope paths of flow and incised channels. The drainage density represents a lower boundary to the range of scales for which channel networks can exhibit fractal characteristics, and the fractal dimension of a channel network should be somewhat less than two. Tarboton et al. (1992) proposed that this lower boundary corresponds to the shift in scaling regimes on slope–area plots discussed previously.

La Barbera and Rosso (1989) and Phillips (1993) contend that the fractal dimension reflects the degree to which the network is constrained by geologic factors, where $D = 2$ implies an unconstrained basin. Fractal dimensions less than two imply that the channel network is geologically constrained. Thus, we can infer the controls of the landscape on the evolution of the channel network.

2.3. The cumulative area distribution

Rodriguez-Iturbe et al. (1992a) showed that the probability that any point in a fluvial channel network has a drainage area, A, greater than the drainage area at any other point in the basin, a, scales according to:

$$P[A > a] \propto a^{\beta} \tag{11}$$

where the exponent, β, is consistently near -0.43. Eq. 11 is called a cumulative area distribution, and measures the degree to which paths of flow converge. Moglen and Bras (1994) showed that a distinct change in the value of β occurs between the hillslope and channel regimes in a basin. In the hillslope regime, the cumulative area distribution is convex in log–log space (linear in arithmetic space) which implies minimal convergence of paths of flow. In the channel regime, drainage areas increase non-linearly as channels converge (linear with a slope of β in log–log space). The apparent universality of $\beta = -0.43$ for fluvial channels likely results from a common underlying principle governing the aggregation patterns of fluvial networks. Thus, a β value of -0.43 can be considered an indicator of a mature fluvial channel network that occurs at a threshold drainage area between the hillslope and channel regimes.

Optimal channel networks (OCNs), developed under the principle that channel networks arrange themselves to minimize the expenditure of energy possess the same exponents in Eq. 11 as do the real networks, and also exhibit fractal characteristics identical to natural channel networks (Marani et al., 1991; Rinaldo et al., 1992; Rodriguez-Iturbe et al., 1992a; Rigon et al., 1993). Thus, Rodriguez-Iturbe et al. (1992a) suggested that the universal values of β arise from the fractal nature of channel networks. de Vries et al. (1994) derived a relation between the exponent β and the topological fractal dimension D_t of ideal channel networks. They showed that $\beta = 1 - (1/D_t)$. Assuming that $D_t = 1.8$, a common value for mature channel networks, results in $\beta = -0.44$, which is remarkably close to the empirical values reported by Rodriguez-Iturbe et al. (1992a).

The apparent universality of β, its relation to fractality of the drainage basin, and the favorable comparison to OCNs suggest that fluvial channel networks evolve to a common state of self-organizing criticality (Rinaldo et al., 1993). Rinaldo et al. (1992) and Rigon et al. (1993) suggested that SOC in river basins is maintained by the interplay of hydrologic processes operating at different scales. Thus, the scaling of hydrologic response is somehow linked to the fractal characteristics of a drainage basin. These are significant advances towards establishing long needed theoretical connections between the spatial variability of hydrologic processes and landscape form for which hydrologists often work with unjustified empiricisms.

3. Study area

Imnavait Creek (68°37′N, 149°17′W) drains 2.2 km^2 in the headwaters of the Kuparuk River in Northern foothills of the Brooks Range in Arctic Alaska (Fig. 2). The entire region is underlain by

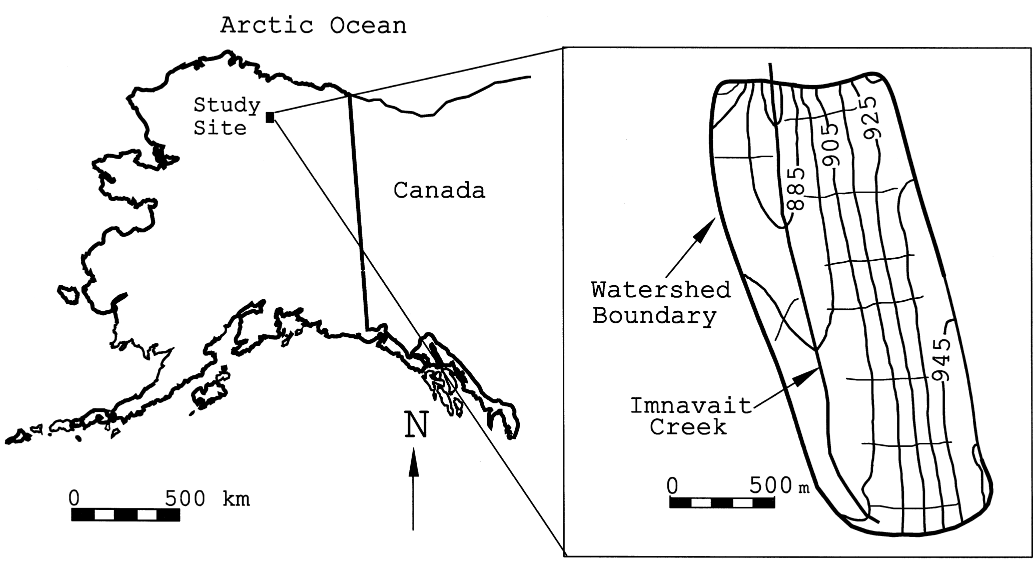

Fig. 2. Location map of Imnavait Creek. The approximate locations of some of the larger water tracks are shown as thin lines perpendicular to the contours.

continuous permafrost, has a continuous snow cover for 7–9 months each year, and is tree-less. Permafrost effectively isolates surface water from the deep sub-surface, and all subsurface flow occurs in the active layer, a thin layer that undergoes freezing and thawing. Soils thaw to depths around 40–50 cm, with maximum depths of thaw near 100 cm in some locations.

Over 130 water tracks on the hillslopes have been identified from aerial photographs in the Imnavait Creek watershed. Many of these, however, can only be detected from aerial photography and are indistinguishable from the surrounding hillslopes in the field. Approximately 10 to 15 large water tracks are easily identifiable in the field based on differences from the surrounding hillslopes in vegetation, soil moisture, and topography (Fig. 2).

The creek occupies a north–northwest trending glacial valley which was formed during the Sagavanirktok glaciation (Middle Pleistocene) (Hamilton, 1986). The elevation of the basin ranges between 844 and 960 m with an average of 904 m. Expansive, relatively undissected valley walls with fairly consistent slopes extend the length of the basin, with ridgelines that are approximately 1 km apart. The dominant vegetation in the Imnavait basin is tussock sedge tundra covering the hillslopes (Walker et al., 1989). An organic layer typically near 10 cm thick, but up to 50 cm thick in the valley bottom, overlies glacial till (Hinzman et al., 1991). The creek is essentially a chain of small ponds, called beads, which formed where the stream has eroded and melted massive deposits of ground-ice. The stream bottom rarely cuts through to mineral soil but maintains itself in the organic layer.

4. Data structure and analysis

North Pacific Aerial Surveys from Anchorage, Alaska, provided digitized elevation contours at 5 m intervals from aerial photographs of the Imnavait Creek basin. We kriged the contour data to produce a 10 m resolution DEM. From this DEM, we extracted paths of flow and performed slope–area scaling analysis, determined fractal dimensions, and constructed cumulative area distributions.

We wrote a series FORTRAN codes, called DRCHAN, to extract information from DEMs. DRCHAN uses a multiple flow direction routine similar to Quinn et al. (1991) to produce networks of flow. Several methods exist for extracting features of a drainage basin from DEMs (see for example, ; Mark, 1984; O'Callaghan and Mark, 1984; Band, 1986; Jenson and Domingue, 1988; Martz and de Jong, 1988; Morris and Heerdegen, 1988; Freeman, 1991; Fairfield and Leymarie, 1991; Chorowitz et al., 1992 and Meisels et al., 1995). A commonly used method for the extraction of the drainage network is the D8 method in which potential paths of flow are identified from each node by comparing the elevation of the node to the elevations of the surrounding nodes (O'Callaghan and Mark, 1984). A single path of flow then originates from each node directed toward its steepest neighbor.

Algorithms for multiple flow direction assign flow from a node to each of its downslope neighbors that are weighted according to slope to account for divergent flow (Freeman, 1991; Quinn et al., 1991). In both techniques, drainage areas at each node are calculated by summing the total number of nodes that contribute flow to that node. Studies comparing algorithms of single flow direction and multiple flow direction have shown that algorithms of multiple flow direction are superior for capturing the spatial variability of geomorphologic features (Moore, 1995; Wolock and McCabe, 1995). The latter study, however, showed that the choice of algorithm does not make a significant difference in hydrologic modeling.

After the initial identification of paths of flow, DRCHAN fills artificial depressions by a flooding routine until flow spills to the lowest surrounding point and completes all paths of flow to basin outlets at the domain boundaries. Each flow path from one node to another forms a flow segment, and the top coordinates, bottom coordinates, drainage area, and slope of each segment of flow are written to a file. A second algorithm arranges the segments of flow into a network of paths of flow by matching the bottom coordinates of a segment to the top coordinates of its downslope continuation until all nodes drain to an outlet at the edge of the DEM file. Each outlet is assigned a number, and every segment of flow is coded according to the outlet so individual basins can be isolated for analysis. The channel networks are then distinguished from hillslope paths of flow by assigning a channel support area below which channels can not occur.

Various methods have been devised to determine channel support areas (Jenson and Domingue, 1988; Morris and Heerdegen, 1988; Tarboton et al., 1991, 1992; Chorowitz et al., 1992, 1993; Montgomery and Foufoulo-Georgiou, 1993). Recently, new methods have been developed to recognize channel heads strictly from the DEM contours without inferring the physical processes involved in the formation of the channel head (Tribe, 1992; Meisels et al., 1995) These methods offer the advantage of removing the subjectivity in determining support areas for the channels. We used the slope–area scaling method of Tarboton et al. (1991, 1992) because it enables a comparison between process and form.

After the channel network is identified using DRCHAN, the network is characterized by the Horton/Strahler scheme of stream order (Strahler, 1952, 1957). Individual streams, defined as the reach between changes in Strahler order, are identified and the coordinates, slopes, lengths, stream orders, and stream magnitudes are stored. Similar details are recorded for stream links, defined as the reach between any two stream junctions. From this information, Horton's numbers can be determined. Additional algorithms calculate the probability distributions of local slope, area, and energy dissipation, and the fractal dimension of channel networks by functional box counting.

5. Results and discussion

We determined two critical drainage areas in the Imnavait Creek basin: the channel support area from slope–area scaling (A_{cr1}), and the threshold drainage area from the cumulative area distribution (A_{cr2}). A_{cr1} and A_{cr2} should be equal for a fully-developed channel network. The following discussion shows that A_{cr1} and A_{cr2} are not equal in Imnavait Creek, and argues that this inequality holds significant implications concerning the evolutionary state of channel networks. We show that water tracks in the Imnavait Creek basin occupy one of three distinct flow path regimes: (1) the hillslope regime at drainage areas less than 0.0031 km^2, (2) the water track regime above 0.0031 km^2, and (3) the fluvial channel regime above 0.015 km^2.

Local slopes and drainage areas were calculated for every point in the Imnavait Creek DEM, then were sorted by drainage area and averaged in bins of 50 points to reduce scatter on plots of slope–area. The plot of slope–area for Imnavait Creek (Fig. 3) appears similar to those described by Ijjasz-Vasquez and Bras (1995) where dS/dA is positive in region one, becomes negative in region two, is less negative in region three, and returns to steeply negative in region four. A fifth region appears at the high drainage areas. According to the ideas of Tarboton et al. (1992), the channel support area, A_{cr1}, occurs at a drainage area of 0.0031 km^2. Ijjasz-Vasquez and Bras (1995), however, suggested that the transition between the hillslope and channel regimes begins in region 3 and is completed at the beginning of region 4, and that the transition between regions one and two represents the transition from hillslopes to unchanneled valleys. Region four begins near 0.009 km^2.

We mapped the locations of the heads of the eight largest water tracks in Imnavait Creek using a GPS accurate to 1 m then used DRCHAN to determine the drainage areas contributing to those points. The average contributing area was 0.0028 km^2, which is reasonably close to A_{cr1} determined from Fig. 3a. This favorable comparison suggests that water tracks originate at a critical geomorphologic threshold that represents a transition from hillslope to valley or channel processes.

A transition on the cumulative area distribution of the Imnavait Creek basin begins near 0.009 km^2, coincident with the beginning of region four on Fig. 3, and is completed near 0.015 km^2 (Fig. 4). Left of 0.009 km^2 the cumulative area distribution is convex in log–log space, as is characteristic of hillslopes. Beyond 0.015 km^2, the cumulative area distribution becomes linear in log–log space with a slope of -0.44, which is very close to what Rodriguez-Iturbe et al. (1992a) reported as universal for mature networks of fluvial channels. Therefore, the organization of paths of flow at drainage areas greater than 0.015 km^2 possess aggregation patterns similar to mature networks of fluvial channels. Fig. 5 shows, with the exception of a few large water tracks, the drainage area 0.015 km^2 does not occur until the transition from the main valley walls to the main valley bottom. This coincidence suggests that the

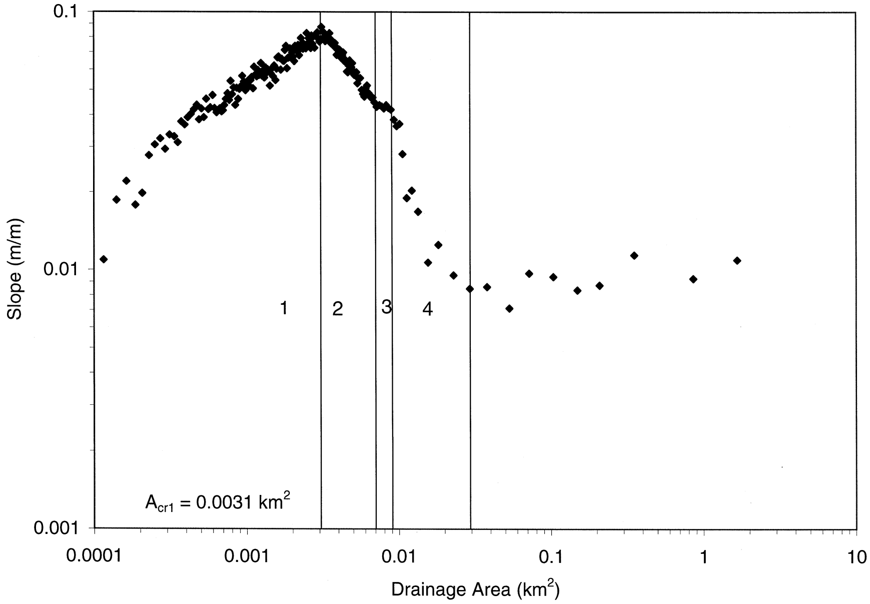

Fig. 3. Slope-area analysis of the Imnavait Creek basin from a 10 m resolution DEM. The four regions correspond to those described by Ijjasz-Vasquez and Bras (1995). The critical drainage area (A_{cr1}), below which channels should not occur, is 0.0031 km^2.

minimum scale of the network of fluvial channels occurs in the main valley bottom, and excludes the water tracks on the hillslopes.

The fractal dimension by functional box-counting of the Imnavait Creek network generated using $A_{cr1} = 0.0031$ km^2 is 1.69 (Fig. 6). Multiplying by 1.1 to

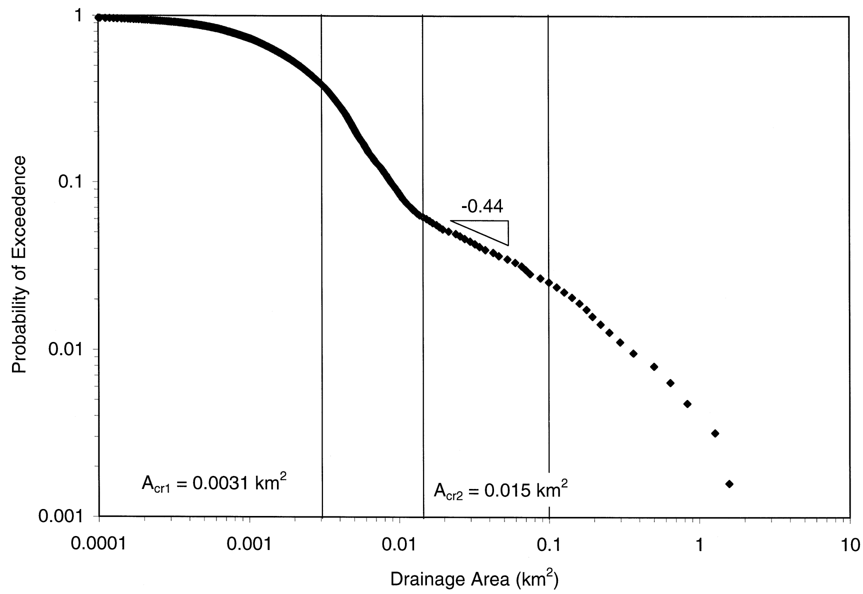

Fig. 4. The cumulative area distribution of Imnavait Creek. The second critical drainage area (A_{cr2}), identified as the drainage area where the slope equals -0.44, begins near 0.015 km^2. A_{cr1} is determined on Fig. 3.

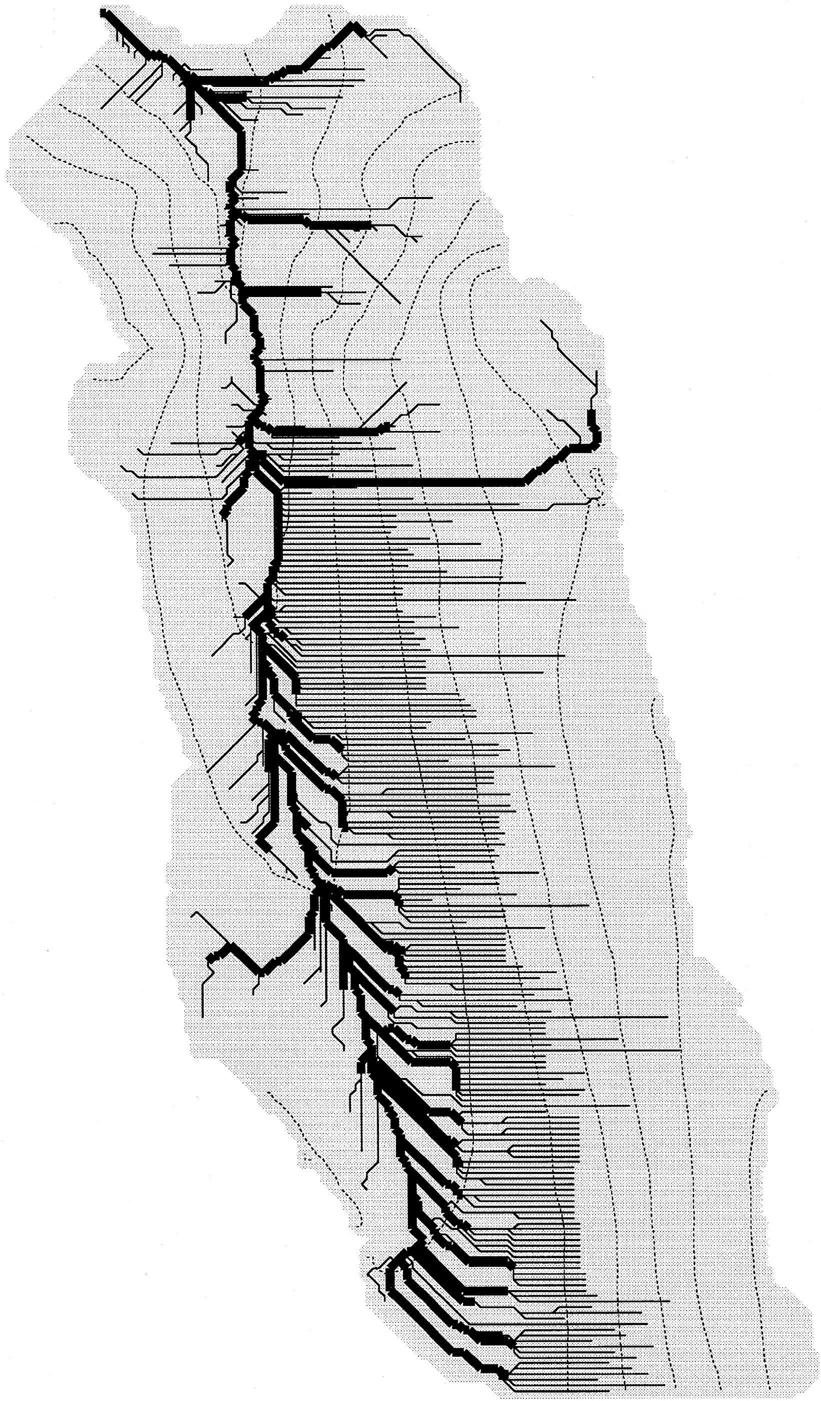

Fig. 5. Channel networks for Imnavait Creek. The network of thick black lines is the network generated using A_{cr2}. The network thin black lines is the network generated using A_{cr1}. The dashed lines are contour lines at 10 m intervals. Note that when A_{cr2} is used as a channel support area, most of the channels in the Imnavait Creek basin are in the broad valley bottom.

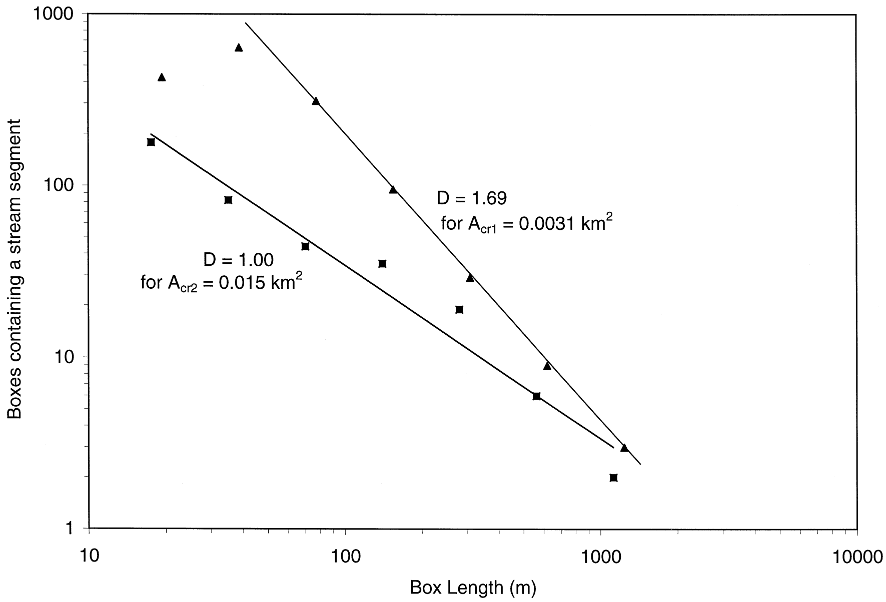

Fig. 6. Fractal dimensions by functional box counting for channel networks from Fig. 5.

take into account the sinuosity of the individual stream channels yields a fractal dimension of 1.86, which is close to what other researchers have reported as typical values for mature channel networks (La Barbera and Rosso, 1989; Claps and Oliveto, 1996). The log-linear fit on Fig. 6 breaks down at box sizes smaller than approximately 50 m, or 2500 m^2, which is reasonably close to the channel support area predicted by Fig. 3 and to average drainage area at the heads of water tracks. That the field-mapped water track support area coincides with the lower limit of fractality suggests that a change in the organization of paths of flow occurs at the water track scale.

The fractal evidence alone might suggest that the water tracks are part of the network of fluvial channels. Evidence from the cumulative area distribution, however, suggests that the water tracks do not belong to the same class of aggregation patterns as fluvial channels. If we use A_{cr2} as the channel support area, the fractal dimension by functional box counting of Imnavait Creek is 1.00 (Fig. 6). The dimension of 1.00 is the dimension of a straight, unbifurcated line lacking even the slightest sinuosity. This is a reasonable description of the main channel of Imnavait Creek. Thus, the fractal dimension of Imnavait Creek using A_{cr2} supports the suggestion that only the bottom channels in main valley act as 'normal' fluvial systems, and that water tracks on hillslopes are not part of the network of fluvial channels.

Two seemingly conflicting lines of evidence exist. First, fractal analysis and field mapping suggest that channels originate at the channel support area coincident with A_{cr1}. Second, the aggregation of the patterns of flow do not possess universal characteristics of mature channel networks until A_{cr2}, which is much greater than A_{cr1}, and the channel network above this area has a very low fractal dimension. According to Phillips (1993), a low fractal dimension implies that the channel network is severely constrained by the geology of the basin. A second reason may be that the basin has not had time to fully develop into a mature network. The Imnavait Creek basin, however, has been exposed for nearly 1 million years and can be considered an old basin. No bedrock controls occur in the basin to constrain the erosive development of the channel network. We suggest that permafrost may be the constraining variable.

The network of water tracks may be the imprint of a fully unconstrained network of channels that was initially laid down soon after deglaciation, but permafrost may have limited erosion in the basin and inhibited the water tracks from incising the hillslopes. Indeed, Howard (1990) suggested that an initial rudimentary drainage network is rapidly created on a new surface before a more regular, process controlled network is formed. We suggest that the water tracks form networks of paths of flow that efficiently drain the basins, yielding fractal dimensions close to those of networks of fluvial channels, but were 'frozen' in immaturity and never developed into mature patterns of aggregation. The consequence is large valleys with extensive, relatively undissected hillslopes.

6. Summary and conclusion

Water tracks begin at a drainage area that is coincident with the channel support area derived from slope–area scaling. The fractal dimension of the network of paths of flow in Imnavait Creek generated using a channel support area from slope–area scaling is similar to those reported in other regions for fully-developed networks of fluvial channels. This evidence alone suggests that water tracks function as part of the network of fluvial channels. Fully-developed channel networks, however, evolve to a self-organized critical state and possess certain universal characteristics (attractors) in aggregation which are manifested in a cumulative area distribution. The Imnavait Creek basin possesses those common features only above the scale of water tracks, or when the drainage areas reach the main channels of the bottom of the valley. Therefore, water tracks occupy a flow regime that is transitional between the purely hillslope paths of flow and the fluvial channels in the bottom of the valley.

Our interpretation of these results is that a rudimentary channel network was set on the hillslopes, but never developed into a mature network. Consequently, the undissected hillslopes are extensive. A low fractal dimension further suggests that the channel network is constrained. It may be that permafrost has restricted the development of channel network by restricting erosion.

The suggestion that permafrost is restricting the development of channel networks has significant implications for climate change studies in the Arctic. Hinzman and Kane (1992) showed that a warming climate will degrade permafrost, and speculated that the increased subsurface reservoir will have significant hydrologic consequences. These consequences will be further complicated if channels further incise and hillslopes erode. Essentially, the structure of the watershed will change which may lead to unpredictable consequences in hydrologic response. Field studies designed to investigate hillslope erosion, channel initiation, and channel migration are needed to test the idea that the erosional development of the channel networks in basins with permafrost are restricted.

Acknowledgements

This work was supported by the National Science Foundation grants OPP-9214927 and OPP-9318535.

References

Bak, P., Tang, C., Wiesenfeld, K., 1987. Self-organized criticality: an explanation of 1/f noise. Phys. Rev. Lett. 59, 381–385.

Bak, P., Tang, C., Wiesenfeld, K., 1988. Self-organized criticality. Phys. Rev. A 38 (1), 364–374.

Band, L.E., 1986. Topographic partition of watersheds with digital elevation models. Water Resour. Res. 22 (1), 15–24.

Beer, T., Borgas, M., 1993. Horton's laws and the fractal nature of streams. Water Resour. Res. 25 (5), 1475–1487.

Chorowitz, J., Ichoku, C., Riazanoff, S., Kim, Y.J., Cervelle, B., 1992. A combined algorithm for automated drainage network extraction. Water Resour. Res. 28 (5), 1293–1302.

Chorowitz, J., Ichoku, C., Riazanoff, S., Kim, Y.J., Cervelle, B., 1993. Reply to comment on 'A combined algorithm for automated drainage network extraction', by J. Garbrecht and L.W. Martz. Water Resour. Res. 29 (5), 537–539.

Claps, P., Oliveto, G., 1996. Reexamining the determination of the fractal dimension of river networks. Water Resour. Res. 32 (10), 3123–3135.

De Cola, L., Lam, N.S., 1993. Introduction to fractals in geography. In: Lam, N.S., De Cola, L. (Eds.), Fractals and Geography. Prentice-Hall, New York, pp. 3–22.

de Vries, H., Becker, T., Eckardt, B., 1994. Power law distribution of discharge in ideal networks. Water Resour. Res. 30 (12), 3541–3543.

Fairfield, J., Leymarie, P., 1991. Drainage networks from grid digital elevation models. Water Resour. Res. 27 (5), 709–717, Correction, Water Resour. Res., 27 (10) 2809 (1991).

Feder, J., 1988. Fractals. Plenum, New York.

Flint, J.J., 1974. Stream gradient as a function of order, magnitude and discharge. Water Resour. Res. 10 (5), 969–973.
Freeman, T.G., 1991. Calculating catchment area with divergent flow based on a regular grid. Comput. Geosci. 17 (3), 413–422.
Gray, D.M., 1961. Interrelationships of watershed characteristics. J. Geophys. Res. 66 (4), 1215–1233.
Gupta, V.K., Waymire, E., 1989. Statistical self-similarity in river networks parameterized by elevation. Water Resour. Res. 25, 463–476.
Hack, J.T., 1957. Studies of longitudinal profiles in Virginia and Maryland. US Geol. Surv. Prof. Pap. 294B, 1.
Hamilton, T.D., 1986. Late Cenozoic glaciation of the Central Brooks Range. In: Hamilton, T.D., Reed, K.M., Thorson, R.M. (Eds.), Glaciation in Alaska: the Geologic Record. Alaska Geological Society, Anchorage, AK, pp. 9–49.
Hastings, S.J., Luchessa, S.A., Oechel, W.C., Tenhunen, J.D., 1989. Standing biomass and production in water drainages of the foothills of the Phillip Smith Mountains. Holarctic Ecology 12 (3), 304–311.
Hinzman, L.D., Kane, D.L., 1992. Potential response of an Arctic watershed during a period of global warming. J. Geophys. Res. 97 (3), 2811–2820.
Hinzman, L.D., Kane, D.L., Gieck, R.E., Everett, K.R., 1991. Hydrologic and thermal properties of the active layer in the Alaskan Arctic. Cold Regions Sci. Tech. 19, 95–110.
Horton, R.E., 1933. The role of infiltration in the hydrologic cycle. American Geophysical Union Transactions 14, 446–460.
Horton, R.E., 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. Geol. Soc. Am. Bull. 56, 275–370.
Howard, A.D., 1990. Theoretical model of optimal drainage networks. Water Resour. Res. 26 (9), 2107–2117.
Ijjasz-Vasquez, E., Bras, R.L., 1995. Scaling regimes of local slope versus contributing area in digital elevation models. Geomorphology, 12 (1995) 2990–311.
Jenson, S.K., Domingue, J.O., 1988. Extracting topographic structure from digital elevation data for geographic information system analysis. Photogramm. Eng. Remote Sens. 54 (11), 1593–1600.
La Barbera, P., Rosso, R., 1989. On the fractal dimension of stream networks. Water Resour. Res. 25 (4), 735–741.
La Barbera, P., Rosso, R., 1990. Reply to comment on 'On the fractal dimension of stream networks', by D.G. Tarboton, R.L. Bras, and I. Rodriguez-Iturbe. Water Resour. Res. 26 (9), 2245–2248.
Mandelbrot, B.B., 1982. The Fractal Geometry of Nature. Freeman, New York.
Marani, A., Rigon, R., Rinaldo, A., 1991. A note on fractal channel networks. Water Resour. Res. 27 (12), 3041–3049.
Mark, D.M., 1984. Automated detection of drainage networks from digital elevation models. Cartographica 21, 168–178.
Martz, L.W., de Jong, E., 1988. CATCH: a FORTRAN program for measuring catchment area from digital elevation models. Comput. Geosci. 14 (5), 627–640.
McNamara, J.P., 1997. A nested watershed study in the Kuparuk River basin, Arctic Alaska: Streamflow, scaling, and drainage basin structure. PhD dissertation, University of Alaska Fairbanks.
McNamara, J.P., Kane, D.L., Hinzman, L.D., 1997. Hydrograph separations in an Arctic watershed using mixing model and graphical techniques. Water Resour. Res. 33 (7), 1707–1719.
McNamara, J.P., Kane, D.L., Hinzman, L.D., 1998. An analysis of streamflow hydrology in the Kuparuk River basin: a nested watershed approach. J. Hydrol. 206, 39–57.
Meisels, A., Raizman, S., Karnieli, A., 1995. Skeletizing a DEM into a drainage network. Comput. Geosci. 21 (1), 187–196.
Moglen, G.E., Bras, R.L., 1994. The importance of spatially heterogeneous erosivity and the cumulative area distribution within a basin evolution model. Geomorphology 12, 173–185.
Montgomery, D.R., Dietrich, W.E., 1988. Where do channels begin? Nature 336 (6196), 232–234.
Montgomery, D.R., Dietrich, W.E., 1992. Channel initiation and the problem of landscape scale. Science 255, 826–830.
Montgomery, D.R., Foufoulo-Georgiou, E., 1993. Channel network representation using digital elevation models. Water Resour. Res. 29 (12), 3925–3934.
Moore, I.D., 1995. Hydrologic modelling and GIS. In: Goodchild, M.F., Steyaert, L.T., Parks, B.O., Crane, M.P., Johnston, C.A., Maidment, D.R., Glendinning, S. (Eds.), GIS and Environmental Modelling: Progress and Research Issues. GIS World, Fort Collins, CO.
Morris, D.G., Heerdegen, R.G., 1988. Automatically derived catchment boundaries and channel networks and their hydrological applications. Geomorphology 1, 131–141.
Nikora, V.I., 1994. On self-similarity and self-affinity of drainage basins. Water Resour. Res. 30 (1), 133–137.
O'Callaghan, J.F., Mark, D.M., 1984. The extraction of drainage networks from digital elevation data. Comput. Vision Graph. Image Processing 28, 323–344.
Phillips, J.D., 1993. Interpreting the fractal dimension of river networks. In: Lam, N.S., De Cola, L. (Eds.), Fractals and Geography. Prentice Hall, New York, pp. 142–157.
Quinn, P., Beven, K., Chevallier, P., Planchon, O., 1991. The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. Hydrol. Processes 5, 59–79.
Rigon, R., Rinaldo, A., Rodriguez-Iturbe, I., Bras, R.L., Ijjasz-Vasquez, E., 1993. Optimal channel networks: a framework for the study of river basin morphology. Water. Resour. Res. 29 (6), 1635–1646.
Rinaldo, A., Rodriguez-Iturbe, I., Rigon, R., Bras, R.L., Ijjasz-Vasquez, E., Marani, A., 1992. Minimum energy and fractal structures of drainage networks. Water Resour. Res. 28 (9), 2183–2195.
Rinaldo, A., Rodriguez-Iturbe, I., Rigon, R., Ijjasz-Vasquez, E., Bras, R.L., 1993. Self-organized fractal river networks. Phys. Rev. Lett. 70 (6), 822–825.
Rodriguez-Iturbe, I., Ijjasz-Vasquez, E., Bras, R.L., 1992a. Power law distributions of mass and energy in river basins. Water Resour. Res. 28 (4), 1089–1093.
Rodriguez-Iturbe, I., Rinaldo, A., Rigon, R., Bras, R.L., Marani, A., Ijjasz-Vasquez, E., 1992b. Energy dissipation, runoff, and

the three-dimensional structure of river basins. Water Resour. Res. 28 (4), 1095–1103.

Rodriguez-Iturbe, I., Marani, M., Rigon, R., Rinaldo, A., 1994. Self-organized river basin landscapes: fractal and multifractal characteristics. Water Resour. Res. 30 (12), 3531–3539.

Rosso, R., Bacchi, B., La Barbera, P., 1991. Fractal relation of mainstream length to catchment area in river networks. Water Resour. Res. 27 (3), 381–387.

Smith, T.R., Bretherton, F.P., 1972. Stability and the conservation of mass in drainage basin evolution. Water Resour. Res. 8 (6), 1506–1529.

Strahler, A.N., 1952. Hypsometric (area–altitude) analysis of erosional topography. Geol. Soc. Am. Bull. 63, 1117–1142.

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Transactions of the American Geophysical Union 38, 913–920.

Tarboton, D.G., Bras, R.L., Rodriguez-Iturbe, I., 1988. The fractal nature of river networks. Water Resour. Res. 24 (8), 1317–1322.

Tarboton, D.G., Bras, R.L., Rodriguez-Iturbe, I., 1990. Comment on 'On the fractal dimension of stream networks' by Paolo La Barbera and Renzo Rosso. Water Resour. Res. 26 (9), 2243–2244.

Tarboton, D.G., Bras, R.L., Rodriguez-Iturbe, I., 1991. On the extraction of channel networks from digital elevation data. Hydrol. Process. 5, 81–100.

Tarboton, D.G., Bras, R.L., Rodriguez-Iturbe, I., 1992. A physical basis for drainage density. Geomorphology 5, 59–76.

Tribe, A., 1992. Problems in automated recognition of valley features from digital elevation models and a new method toward their resolution. Earth Surface Processes and Landforms 17, 437–454.

Walker, M.D., Walker, D.A., Everett, K.R., 1989. Wetland Soils and Vegetation, Arctic Foothills, AK. US Department of the Interior Biological Report 89 (7).

Willgoose, G., Bras, R.L., Rodriguez-Iturbe, I., 1991. A physical explanation of an observed link area–slope relationship. Water Resour. Res. 27 (7), 1679–1702.

Wolock, D.M., McCabe, G.J. Jr., 1995. Comparison of single and multiple flow direction algorithms for computing topographic parameters in TOPMODEL. Water Resour. Res. 31 (5), 1315–1324.