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Classification of drainage network types in the arid and semi-arid regions of Arizona and California

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ABSTRACT

The present study aims to classify channel network types in arid and semi-arid regions and to determine whether pinnate networks occur in these areas by using scaling invariance measures. The average slope of the preexisting topographic surface is also studied to identify whether the slope affects the development of drainage networks in such arid and semi-arid regions. Twenty channels in the states of Arizona and California, USA, were analyzed. In this study, the measures used to classify drainage networks and to obtain the Hurst exponent are the drainage area increments, the channel course irregularity, and the tributary junction angles. The average slope of the preexisting surfaces is calculated from sub-watershed areas that are small and topographic curvatures that are close to zero. For all channels, the Hurst exponent is less than 0.91 which indicates that networks seem to be self-affine instead of self-similar. These channels present pinnate or parallel networks although the associated preexisting slope is below 3%. Such observations suggest that the preexisting slope does not have a significant influence on the development of pinnate networks in these arid and semi-arid regions.

1. Introduction and review

The occurrence of drainage networks in different regions depends on local physiographic and climatic characteristics which produce specific attributes that define the network structure and impact the basin's hydrologic response (Berger and Entekhabi, 2001). Classification systems have been developed to distinguish various channel network types including dendritic, parallel, and pinnate networks (Zernitz, 1932; Parvis, 1950; Howard, 1967; Phillips and Schumm, 1987; Mejia and Niemann, 2008). A dendritic network is a drainage network that appears tree-like with broad basin shapes along with relatively meandering stream courses and moderately acute tributary junction angles. A parallel network has narrower basin shapes and straighter stream courses. It is characterized by small tributaries which tend to join the major channels with nearly orthogonal junction angles and larger tributaries with more acute junction angles. A pinnate network has a feather-like pattern with very straight stream courses, and small tributaries merging with the main stream channel at acute junction angles. While dendritic and parallel networks were considered basic patterns (Howard, 1967), a pinnate network has often been considered as a modification of the dendritic pattern (Zernitz, 1932; Howard, 1967) or a modification of the parallel pattern (Phillips and Schumm, 1987). Fig. 1 illustrates examples of a dendritic network (Fig. 1a), a parallel network (Fig. 1b), and a pinnate network (Fig. 1c) from Tennessee, Colorado, and Arizona, respectively.

Several studies have focused on refining drainage network classifications by developing quantitative or numerical models. Morisawa (1963) investigated the orientations of first-order Strahler (1952) streams, which are headwater streams with no tributaries to determine river network types. It was observed that a uniform distribution of flow directions occurs in dendritic networks while a single direction dominates in parallel networks (Morisawa, 1963). Several authors identified that dendritic networks have channels oriented in many directions, and that the distribution of flow directions is nearly uniform (Zernitz, 1932; Parvis, 1950; Howard, 1967). Werner and Smart (1973) suggested methods for network classification using topologic path lengths and the number of links between the source and the outlet of a network. Argialas et al. (1988) examined third-order channel

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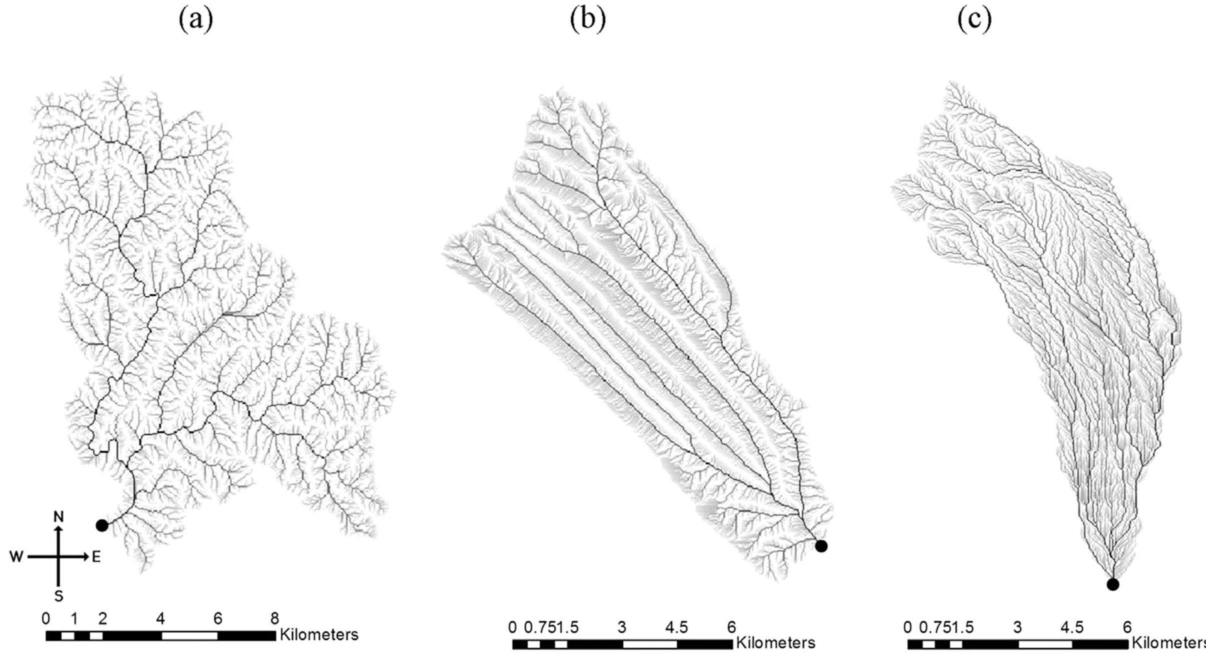

Fig. 1. Different channel network types: (a) Caney Fork Creek in Tennessee for a dendritic network, (b) Piceance Creek in Colorado for a parallel networks, and (c) Cunningham Wash trib. 1 in Arizona for a pinnate network.

networks to distinguish different network types. Argialas et al. (1988) calculated attributes of river networks and classified categories of the attributes. Ichoku and Chorowicz (1994) proposed a quantitative method that uses a digital elevation model (DEM) for the development of a classification system based on 16 features of channel networks. Ichoku and Chorowicz (1994) used a classification tree with empirical thresholds to determine network types. Jung et al. (2015) proposed a new approach for the river network classification based on tributary junction angles and secondary tributary lengths.

In a more recent study, Mejia and Niemann (2008) presented three measures derived from scaling invariance for the classification of five network types including dendritic, parallel, and pinnate. The measures focus on the drainage area increments along a channel, the stream course irregularities, and the tributary junction angles. Among the measures, the drainage area increment is the incremental accumulation of the area along mainstreams. The authors observed that dendritic networks characterized by self-similarity show horizontal regression lines when the drainage area increments and the channel course irregularity are plotted as a function of the Euclidean basin length. On the other hand, parallel and pinnate networks characterized by self-affinity exhibit steep slopes of these measures. Self-similarity means that the horizontal features of a small subbasin are statistically similar to a large basin's features when the small subbasin is isotropically rescaled, whereas one can expect self-affinity when the small subbasin is anisotropically rescaled. Mejia and Niemann (2008) determined that channel networks are classified as dendritic networks when the Hurst exponent H of the irregularity of stream courses is approximately zero and as parallel or pinnate networks when the Hurst exponent is less than ~0.91. The Hurst exponent is the self-affine parameter describing the degree of anisotropy. If H is equal to one, the anisotropy disappears and the networks indicate self-similarity. Parallel networks are distinguished from pinnate networks on the basis of the measure of the tributary junction angle. Channel networks are expected to be parallel when the average slope of the regression line created by the tributary junction angle measure as a function of the Euclidean basin length is > 0.01. On the other hand, channel networks are expected to be pinnate when the slope of the regression line derived from the tributary junction angle measure as a function of the basin length is < 0.01.

Several authors have sought to identify the conditions under which dendritic, parallel, pinnate, and related networks occur (Zernitz, 1932; Parvis, 1950; Howard, 1967). Dendritic networks are thought to occur when geological and topological conditions have little effect and the networks develop freely. Parallel networks are expected to develop mainly on more steeply sloping topographic surfaces, although parallel topographic features may be an important contributing factor in some cases. Parallel networks are also formed in response to lithologic or structural control. No clear conditions have been identified for the development of pinnate networks. Zernitz (1932) mentioned that large topographic slopes can generate pinnate networks, while Howard (1967) suggested that a combination of large slopes and easily erodible substrates can lead to the occurrence of pinnate networks.

Several experimental studies have been conducted to better understand the conditions which influence the development of channel networks. Mosley (1972) made a flume of 15.3 m by 9.2 m with artificial precipitation that was applied at a constant intensity for rill erosion. In this experimental study, dendritic patterns were observed in microrills at low surface slopes, while parallel patterns were present at large surface slopes. The large slopes are the initial slopes of the experiment. Another study with a flume of 2 m by 3 m was carried out to examine the impact of increasing initial surface slopes on the development of drainage networks, from dendritic to parallel and pinnate (Phillips and Schumm, 1987). They found the transition between dendritic and parallel networks to occur when the slope exceeds 3%. However, the occurrence of pinnate networks was not observed in their experiment. Jung et al. (2011) used 30 river basins in the states of Colorado, Tennessee, Utah, and Wyoming in the USA to examine the transition between dendritic and parallel networks based on the slope of the preexisting topographic surface; that is, the average slope of regions that are relatively unaffected by modern hillslope and fluvial processes. The