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RIVER NETWORK PATTERNS AND THEIR EVOLUTIONARY PRECONDITIONS

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ABSTRACT

As a common phenomenon on land surfaces, river networks play an important role in fluvial geomorphological research. Various river network patterns were formed in different evolutionary modes triggered by local environmental conditions. To reveal the natural laws of these patterns and their evolutionary mechanisms, three typical river network patterns (TRNPs), named Plume, Nervation, and Dentritic, respectively, were classified in satellite images. The statistics of these TRNP's Horton ratios and shape parameters were also given. A transition of Horton ratios from divergence to convergence in different scales was detected, showing that Horton's law is not applicable universally. The convergence indicated that Horton ratios are environmental conditions invariant for large river networks. However, the difference in Horton ratios between small river networks is enormous, suggesting that Horton ratios can be used as indices of small river networks. Analysis of environmental conditions that relate to TRNP is also included in this paper.

Keywords: river network pattern, Horton's law, bifurcation ratio, length ratio, area ratio, environmental conditions

1. INTRODUCTION

Various river networks are generated by erosion and sedimentation of water flows. Fluvial landforms consisting of river networks cover most of the Earth. Thus research on networks is an important theme of geomorphology. A river network pattern is the combination style of all tributaries in a river network. Under the influence of geological structures and environmental conditions, river network patterns are generally found in impressive arrangements and are self-similar in different scales.

Horton (1945) devised stream-ordering rules known as Horton–Strahler rules, which can be expressed as follows: In a drainage network the channels without tributaries are designated as first-order streams down to their first confluence. A second-order stream is formed below the confluence of two first-order channels. Third-order streams are created when two second-order channels join, and so on. Horton–Strahler rules also state that streams of different orders can not create a stream of even larger order. For example, a fourth-order stream will not upgrade to a fifth-order stream when a second-order stream flows in.

Horton's law (as set forth below), derived from the Horton–Strahler rules, is regarded as the central principle of river network research. Numerous investigations (Ciccacci et al., 1992; Kinner and Moody, 2005) show that the linear rule of Horton's law is approximately valid in many natural river networks. Further, a relatively narrow range of Horton ratios (as set forth below) has been discovered. Some artificial river networks based on a random walk model, such as the one generated by Shreve (1966), also nearly obey that rule in a similar manner. Thus some scholars believe that Horton's law is a description of the most probable status of random river networks. Since the late 20th century fractal theory has become increasingly popular in river network research, and has provided new interpretations of Horton's law, initiating another field of river network research.

However, arguments about the physical significance of Horton's law still persist. Particularly, Horton ratios seem to be invariant with stream orders and network structures, which might suggest that there is no difference between river networks and between streams of different orders. For instance, Kirchner (1993) argued that Horton ratios could not reflect the difference among river network structures. According to abundant statistical data, this paper indicates that the invariance of Horton ratios is mainly found in drainage networks of large Horton orders. The influence of environmental conditions on network evolution could still be revealed by Horton ratios for drainage networks of small Horton orders.

2. METHODS

The free software GoogleEarth was adopted as the main data source. It provides global satellite images at varying resolutions, which can be changed by adjusting the "eye altitude" parameter. In this study "eye altitude" was fixed when doing sample analysis. Some places overlaid by high-resolution images were also avoided in sampling. Thus we can make sure that all data were collected in the same resolution. In the sampling zone the river networks were divided according to Horton–Strahler rules and basin boundaries of different orders were outlined manually. Then the boundaries could be exported as kml data files so that further analysis could be conducted.

Horton's law is the basis of quantitative river network analysis in geomorphology. In Horton–Strahler ordering rules, if a river network contains streams of order ω= 1, 2, . . . , Ω, which means that the highest stream order is Ω, then the river network order is Ω for this network. And for streams of order ω, their number (N_ω), mean length (L_ω), and mean area (A_ω) can be introduced to define the following parameters:

$$N_\omega = R_B^{\Omega-\omega}, \tag{1}$$

$$L_\omega = L_1 R_L^{\omega-1}, \tag{2}$$

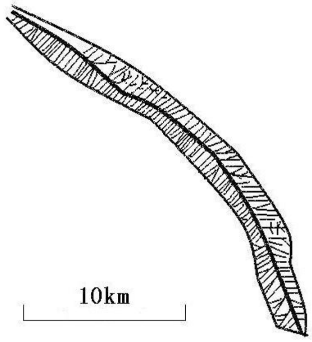
$$A_\omega = A_1 R_A^{\omega-1}, \tag{3}$$

where R_B, R_L, and R_A are termed the bifurcation ratio, the length ratio, and the area ratio respectively. Horton's law states that all three ratios are invariant with stream orders.

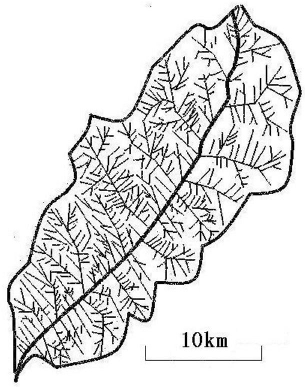
3. TYPICAL RIVER NETWORK PATTERNS

There is no apparent difference between river network patterns and structures among large river networks, while for the small ones, the difference between their network patterns could be vast, showing the divergence in evolutionary modes triggered by local environmental conditions. For example, the small river network patterns in Figure 1 all have their own distinctive features, whether in shape or in composition of tributaries. Many classifications of river network patterns have been provided by earlier researchers; the most common one is Howard's (1967), which divided patterns into Trellis, Parallel, Radial, etc. Although this classification is convenient, it sometimes divides river network patterns of similar evolution mechanisms into different categories, because some very local conditions like small mountains may intervene and distort the patterns. Also, this kind of classification lacks quantitative descriptions.

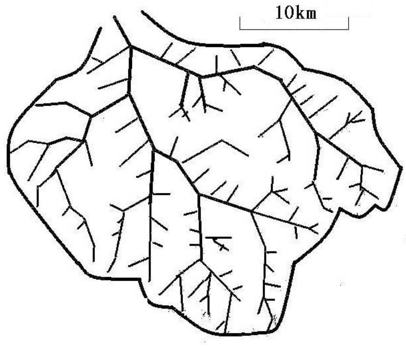
To reflect the essential divergence in evolutionary mechanisms, this study classified three typical river network patterns (see Figure 1) by texture: (a) Plume: large numbers of short tributaries line vertically along the main stream, forming a Plume-like structure; (b) Nervation: this network has a main stream and its parallel tributaries are arrayed like Nervations; (c) Dentritic: this shows continuous bifurcation upstream, similar to that of a tree. Based on this new classification, statistical analysis can be performed and distributions analyzed.



(a) Plume (a river in the Kubuqi desert)



(b) Nervation (The Yan river)

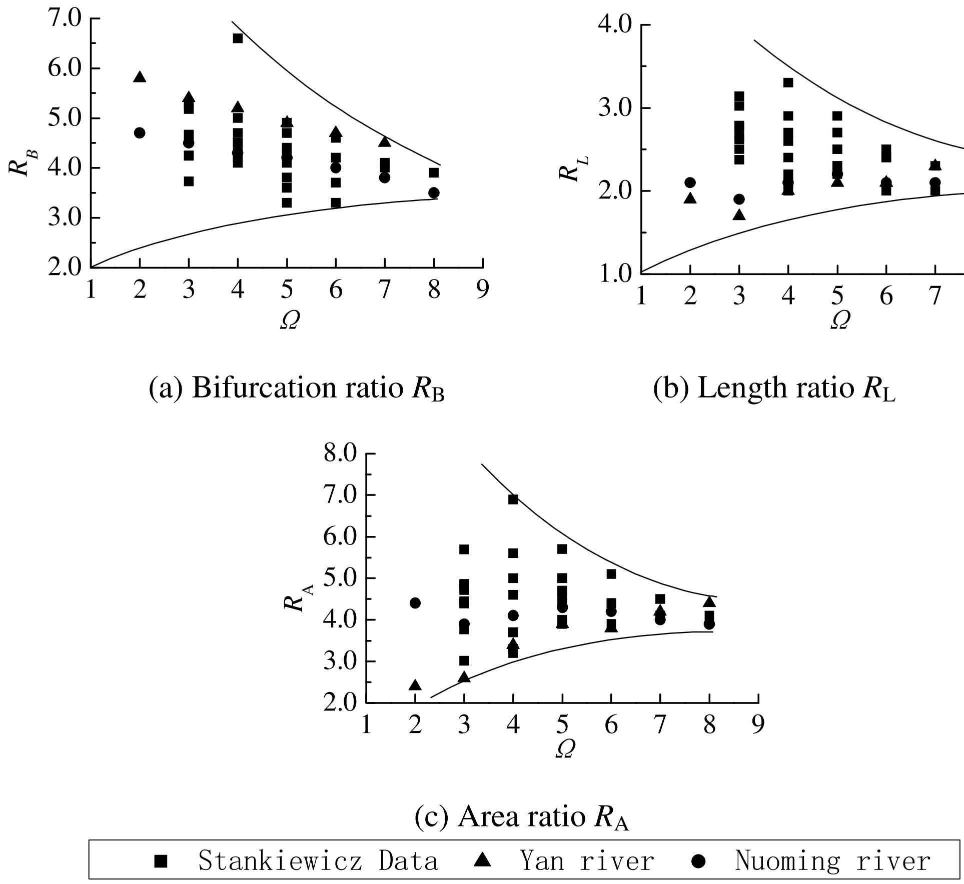


(c) Dentritic (The Noming river)

Figure 1 Three typical river network patterns (TRNPs)

4. RESULTS

Figure 2 was plotted from data in this study and Stankiewicz's (2005) work, showing the relationship between Horton ratios and river network orders. With the increase of river network orders, all Horton ratios of different data groups become constant; this trend is not related to environmental conditions such as climate. This result suggests that there is a tendency of Horton ratios to converge with increase in river network order Ω: The bifurcation ratio, length ratio, and area ratio converge to 4, 2, and 4, respectively.



(a) Bifurcation ratio R_B

(b) Length ratio R_L

(c) Area ratio R_A

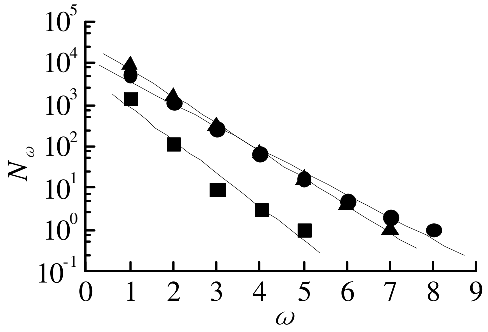
Figure 2 The transition of Horton ratios from divergence to convergence

Thus for a river network of order larger than 8, equations can be derived as below:

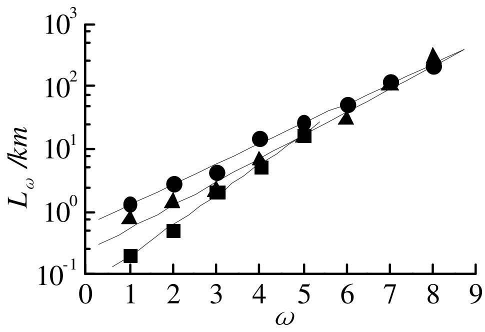
$$\begin{cases} N_\omega \approx 4^{\Omega-\omega}, & \omega \geq 8. \\ L_\omega \approx 2^{\omega-1} L_1, & \omega \geq 8. \\ A_\omega \approx 4^{\omega-1} A_1, & \omega \geq 8. \end{cases} \tag{4}$$

On the other hand, the Horton ratios of small drainage basins might be very different due to local soil, climate, or topography. This kind of divergence has profound significance because it revealed that small river networks follow different evolutionary mechanisms triggered by environmental conditions.

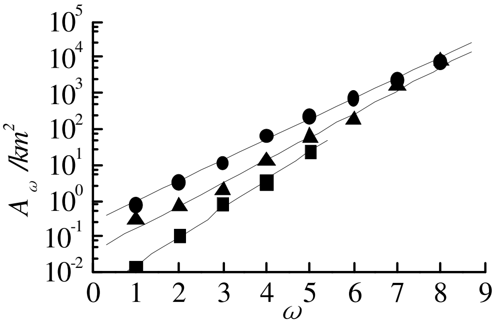
By sampling the main distribution zone of each typical river network pattern (Plume: Inner Mongolia; Nervation: Loess Plateau; Dentritic: Northeastern China), we obtain stream number, mean length, and mean area of each stream order ω(see Figure 3).



(a) Number N_ω



(b) Mean length L_ω

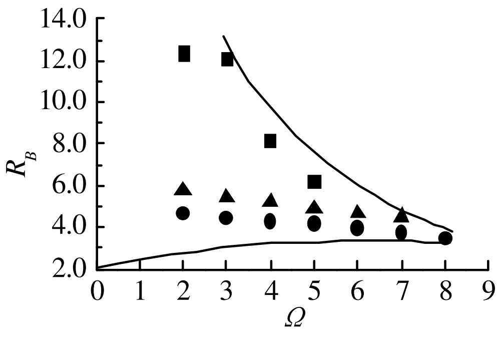


(c) Mean area A_ω

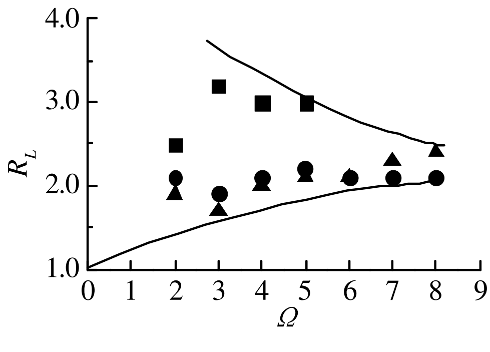
■ Plume ▲ Nervation ● Dentritic

Figure 3 Statistical data for typical river network patterns

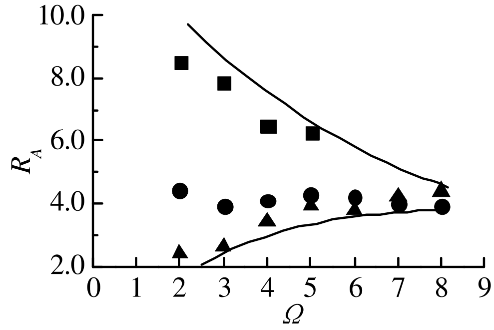
Horton ratios of every network order (see Figure 4) could be calculated from the data of Figure 3. The Horton ratios of typical network patterns all evidently converge with increase of network order, but each typical network pattern converges in its own fashion. The ratios of Dentritic networks have the greatest stability among all river network orders. This means that the self-similarity of Dentritic networks is the most remarkable in all scales; the Plume network is just the opposite.



(a) Bifurcation ratio R_B



(b) Length ratio R_L



(c) Area ratio R_A

Figure 4 Horton ratios of typical river network patterns

In addition to the structure, all three network patterns are totally different in basin shape. A diagram showing drainage area versus stream length is shown in Figure 5.

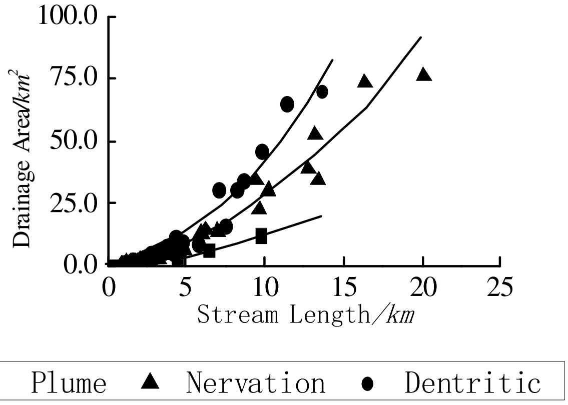


Figure 5 The relationship between stream length and drainage area of TRNPs

With the same channel length, the order of network patterns' drainage area is Dentritic > Nervation > Plume. That is, the Plume network has the narrowest shape, while the Dentritic network is widest, as seen in Figure 1.

5. EVOLUTIONARY PRECONDITIONS

The river network evolutionary preconditions include environmental factors such as climate, soil, and so on. Table 1 summarizes some of these factors by analyzing the distribution of TRNPs in China. Results indicate that the relationship between network patterns and annual precipitation is close.

Table 1 River network evolutionary preconditions

TRNP	Annual Precipitation (mm)	Surface material	Topography	Vegetation coverage (%)	Representative districts

Plume	50~200	Aeolian sand soil, Desert soil, etc.	Districts of very mild slope	0–10%	Some small drainage basins in Inner Mongolia
Nervation	200~800	Loess, Cinnamon soil, Chestnut soil, etc.	Mountain, Plateau	10%–40%	Loess Plateau, Mingjiang river, etc.
Dentritic	400–2000	Phaeozem, Chernozem, red soil, etc.	Mountain	>40%	Nengjiang river, Jialing river, Dongting lake network, etc.

6. CONCLUSIONS

1. To reflect the essential divergence in network evolutionary mechanisms triggered by local environmental conditions, this study classified three typical river network patterns (TRNPs) by textures: Plume, Nervation, and Dentritic networks.
2. The Horton ratios R_B, R_L, and R_A of all river networks converge to 4, 2, and 4 respectively (for network order $\Omega > 8$), despite location of the networks. This result indicates the convergence of river networks in macro-scale, that is, the environmental conditions are invariant.
3. The divergence of Horton ratios in micro-scale shows the influence of different evolutionary mechanisms. The transition from divergence to convergence indicates that Horton's law is not applicable universally.
4. The Horton ratios of Dentritic networks are of the greatest stability during all river network orders. This means that the Dentritic networks' self-similarity is the most remarkable. On the contrary, the Plume networks are just the opposite. The basin shape of Plume networks is the narrowest, while the shape of Dentritic networks is the widest.
5. The relationship between distribution of network patterns and of annual precipitation is close. In China the boundary between the Plume and Nervation patterns is around the 200 mm precipitation line, and the boundary between the Nervation and Dentritic patterns is around the 800 mm precipitation line. Networks evolve towards the Dentritic pattern in humid areas, and towards the Plume pattern in arid areas.

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