A STUDY OF VARIABLES CHARACTERIZING DRAINAGE PATTERNS IN RIVER NETWORKS

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ABSTRACT:
In GIS and in terrain analysis, drainage systems are important components. Due to local topography and subsurface geology, a drainage system achieves a particular drainage pattern based on the form and texture of its network of stream channels and tributaries. Drainage pattern recognition helps to provide a qualitative description of the terrain for analysis and classification and is useful for terrain modelling and visualization and applications in environment. Much research has been done on the description of drainage patterns in geography and hydrology. However automatic drainage pattern recognition in river networks is not well developed. This paper introduces a method based on geometric quantitative indicators to recognize drainage patterns in a river network automatically. Experiment results are presented and discussed.

1. INTRODUCTION
Drainage system is the pattern formed by streams, rivers and lakes in a drainage basin. As an indivisible part of the land, drainage system is an important component in GIS and in terrain analysis. In a drainage system, streams or rivers always connect together to form networks. In current GIS systems, river networks are stored as line segments with their geographical coordinates and topological relationships. Inside a network, different patterns can be observed and related to other geographical factors. In a drainage basin, a number of factors such as topography, soil type, bedrock type, climate and vegetation cover influence input, output and transport of sediment and water (Charlton, 2008). These factors also influence the nature of the pattern of water bodies (Tiwdale, 2004). As a consequence, drainage pattern can reflect geographical characteristics of a river network to a certain extent.

There are several types of drainage pattern. At present, much research has been done on the description of drainage patterns in geography and hydrology (e.g. Howard, 1967; Lambert, 1998; Twidale, 2004; Pidwirny, 2006). However, automatic drainage pattern recognition in river networks is not well developed. In this paper, several geometric indicators for the characterization of drainage patterns are presented and discussed on experiments. In GIS, such classification can be useful for terrain analysis or for generalization. At present, many researchers have started to pay attention to geographic features of river networks during the generalization process (Ai et al., 2007; Buttenfield et al., 2010; Stanislawski, 2009, 2011).

The paper is organized as follows. Section 2 briefly reviews related works in drainage pattern. In section 3, several geometric indicators are presented to recognize drainage patterns in a river network. In section 4, the method is tested in an experimental area, and the validity of indicators is discussed. Finally, conclusions and research perspectives are presented.

2. RELATED WORK
With the passage of time, a drainage system achieves a particular drainage pattern where its network of stream channels and tributaries is determined by local geologic factors. Drainage patterns are classified on the basis of their form and texture according to slope and structure. Their shape or pattern develops in response to the local topography and subsurface geology.

River segments inside a river network can be organised in five types of drainage pattern (Figure 1). Dendritic pattern (Figure 1a) is the most common form of river system. In a dendritic river system, tributaries of a main river join together in a shape analogous to the twigs of a tree (Lambert, 1998). Parallel patterns (Ritter, 2003) form where there is a pronounced slope to the surface. Tributary streams tend to stretch out in a parallel-like fashion following the slope of the surface (Figure 1b). In a trellis pattern (Figure 1c), the main river flows along a strike valley and smaller tributaries feed into it from the steep slopes on the sides of mountains. These tributaries enter the main river at right angles, causing a trellis-like appearance of the river system. The rectangular pattern (Figure 1d) is found in regions that have undergone faulting. Movements of the surface due to faulting offset the direction of the stream. As a result, the tributary streams make sharp bends and enter the main stream at high angles. Reticulate drainage patterns (Figure 1e) usually occur on floodplains and deltas where rivers often interlace with each other forming a net (Simon and Gerald, 2004).

Some experimental works have been done about morphological dependencies of river channel patterns, such as straight, meandering and braid pattern. Schumm and Kahn (1972) obtained an experimental relationship between slope and sinuosity for a fluvial channel, which can show threshold changes between pattern types. Here, sinuosity is a ratio of channel length to valley length. Results show that braided pattern appears on steep low-sinuosity channels. Schumm (1977)

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improved his model and pointed out that pattern adjustments, measured as sinuosity variations, are closely related to the type, size, and amount of sediment load. Although these works (e.g. Knighton, 1998; Lewin, 2001) about morphological dependencies apply to river channel pattern rather than river network, some of the indicators referred above can be considered in this paper.

![Diagram of river network patterns](image)

Figure 1. Drainage network patterns (diagrams modified from Ritter, 2006)

At present, much research has been done on the definition, classification and description of drainage patterns in geography and hydrology. Many scholars work on predicting river channel pattern from in-channel characteristic, such as slope and discharge, but not drainage pattern. Indeed, drainage pattern is recognized as an important element in GIS but its classification has not been considered yet. Therefore, the next section studies the geometric and topologic characteristics of each type of river patterns and presents a classification method based on several geometric quantitative indicators in river network.

3. DRAINAGE PATTERN RECOGNITION

Based on the description of different drainage patterns, each pattern has its own characteristics, which can be reflected in some quantifiable variable related to some topological and geometrical aspects. Therefore, each pattern can be characterized by a combination of different variables. In this section, the method for drainage pattern recognition is introduced. First, terms describing river networks are defined then classification criteria are introduced and the different steps of the process are detailed.

3.1 Definition of Features in River Networks

A river network is composed of several connected river segments. End points of the river segments are the nodes. There are three types of node: the junction node connecting river segments, the source node corresponding to river springs and the outlet towards where the flow goes. A river network is located in a catchment. The catchment controlled by a tributary flowing into a main stream is called a sub-catchment. All these features are illustrated in Figure 2.

The river network forms a tree structure. The structure is built by assigning an order number to each tributary. Ordering starts by assigning order 1 to branchless tributaries. The order of a stream is always higher than the order of its tributaries so that the highest order is assigned to the segment connected to the outlet. Most relevant ordering schemes are the Horton-Strahler scheme based on (Horton, 1945) and modified by Strahler (1957) and the Shreve scheme (Shreve, 1966).

![Diagram of cut-edges](image)

Figure 2. Features in river network (modified from Li, 2007)

3.2 Drainage Pattern Recognition

In section 2, 5 types of drainage pattern were introduced. This work addresses the identification of the patterns based on geometric characteristics identified inside a network. According to the description given in section 2, Table 1 proposes a list of characteristics for each of them.

The reticulate pattern is specific as rivers form a cycle instead of a tree. Therefore, recognition of reticulate patterns is discussed in the next section while identification of other patterns based on geometric indicators is introduced in section 3.2.2.

![Table of drainage pattern characteristics](image)

Table 1. Drainage pattern characteristic

3.2.1 Reticulate Pattern Recognition: In graph theory, a cut-edge (also known as a bridge) is an edge whose removal produces a graph with more components than the original (Bondy and Murty, 2008). Equivalently, an edge is a bridge if and only if it is not contained in any cycle. The figure 3 illustrates the cut-edges in an undirected graph, where the dashed line is cut-edge and the solid line is edge contained in a cycle.

![Diagram of cut-edges in an undirected graph](image)

Figure 3. Cut-edges in an undirected graph
Considering the river network as an undirected graph, all cut-edges are found using a bridge-finding algorithm (Tarjan, 1974). Edges which are not identified as cut-edges are components of cycles and form reticulate patterns.

### 3.2.2 Dendritic, parallel, trellis, and rectangular pattern recognition

In this section, some geometric quantitative indicators are defined to recognize these patterns.

1. **Angle**: From the geometric characteristics of drainage patterns in Table 1, the most important variable is the angle formed by a tributary with its main stream at a junction node. The average angle of all angles in a catchment is one quantitative indicator.

2. **Sinuosity**: In order to distinguish rectangular patterns, the shape of a tributary is needed. In this pattern, tributary streams make shape bends almost to right angle.

Schumm (1977) set the sinuosity variable of a stream as the ratio of the channel length to the valley length. If the sinuosity ratio is equal to or is greater than 1.5, the channel is considered to be meandering (Ritter, 2003). Only using length value to calculate the sinuosity would lose the information about the river shape. Sometimes a stream seems almost straight, but it would have approximate sinuosity ratio with bending stream, as shown in Figure 4. In order to distinguish angular streams in rectangular patterns from other patterns, a different method is used to identify bended tributaries.

Supposing a river segment is composed of \( N \) points \( P_i \) with \( P_j \) and \( P_k \) the end points (Figure 4). There are \( N-1 \) vectors \( \overrightarrow{P_kP_{k+1}} (1 \leq k \leq N-1) \). A set of angles \( \Omega \) are formed by vectors:

\[
\Omega = \{ \overrightarrow{P_jP_{j+1}} \mid 2 \leq j \leq N-1 \}
\]

If the maximum value among these angles is close to \( 0^\circ \), it indicates that the river segment is almost straight; otherwise, if it is equal to or greater than \( 90^\circ \), it shows that the river segment has an obvious turning which is a bended tributary. So, the maximum value \( \max(\Omega) \) is used to indicate the river segment sinuosity level.

3. **Length ratio**: It is the ratio of tributaries to main stream is the third indicator. The difference between parallel and trellis pattern is length, the tributaries in parallel pattern are long relative to trellis patterns.

Long tributaries in parallel pattern and short tributaries in trellis pattern are relative conception in geography. The river absolute length cannot be used to distinguish different drainage patterns directly. This paper takes the length ratio of tributary to main stream as an indicator. The main stream is not a single river segment connected to the tributary but a series of consecutive segments with the same direction and same order (Figure 5).
average value $\beta$ of all river segment sinuosity in a catchment should be equal to or greater than 90°; otherwise, in parallel and trellis, $\beta$ should be smaller than 90°. The parameter average length ratio $\delta$ is used to divide parallel and trellis patterns. In parallel patterns, tributaries have long length so $\delta > 1$; otherwise, $\delta < 1$ indicates that most tributaries are shorter than main stream, which occurs in trellis pattern. Parallel and trellis patterns form in elongated catchments and are therefore characterized by high elongation $\gamma$. The different indicators are summarized in Table 3.

<table>
<thead>
<tr>
<th>Drainage Pattern</th>
<th>Average Angle ($\alpha$)</th>
<th>Average Sinuosity ($\beta$)</th>
<th>Average Length Ratio ($\delta$)</th>
<th>Catchment Elongation ($\gamma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dendritic</td>
<td>$\alpha &lt; 90^\circ$</td>
<td>-</td>
<td>$\delta &gt; 1$</td>
<td>$\gamma &lt; 1$ or $\gamma = 1$</td>
</tr>
<tr>
<td>Parallel</td>
<td>$\alpha &lt; 90^\circ$</td>
<td>$\beta &lt; 90^\circ$</td>
<td>$\delta &gt; 1$</td>
<td>$\gamma &gt; 1$</td>
</tr>
<tr>
<td>Trellis</td>
<td>$\alpha = 90^\circ$</td>
<td>$\beta &lt; 90^\circ$</td>
<td>$\delta &lt; 1$</td>
<td>$\gamma &gt; 1$</td>
</tr>
<tr>
<td>Rectangular</td>
<td>$\alpha = 90^\circ$</td>
<td>$\beta = 90^\circ$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3 List of quantitative indicators

4. RESULTS AND DISCUSSION

Experimental evaluation of indicators was done on the Russian river, California at a scale of 1:24,000 (Figure 7) from the Russian River Interactive Information System (RRIIS 1).

Algorithms were implemented in C++ using the Boost Graph Library (BGL2) to find cycles. The bolder the line, the greater the Horton-Shtrahler. Results are illustrated on several regions shown on Figure 7.

Figure 7. Russian river provided by RRIIS

4.1 Identification of reticulate networks

The cut-edge finding algorithm helps us to get the rivers which are not in reticulate part, then, the rest of the river channels are in the reticulate pattern. Figure 8 shows reticulate river networks from region $R_1$ of Figure 7.

Figure 8. Reticulate pattern in river networks, the solid lines are rivers, and the bold solid lines are reticulate part in the river network.

4.2 Identification of other networks

We select several sub-catchments from Russian river basin (Figure 9) and provide the quantifications of average angle, tributary shape and average length ratio and catchment elongation in Table 3. The sub-catchment (a), (b), (c), (d) and (e) are with the biggest Horton-Shtrahler order of 4, 4, 4, 3, and 3 respectively.

Figure 9. Sub-catchment from Russian river basin, (a), (b), (c), (d) and (e) from regions $R_2$, $R_3$, $R_4$, $R_5$, $R_6$ respectively.

1 http://www.russianriverwatershed.net
2 http://www.boost.org/doc/libs/1_48_0/libs/graph/doc/index.html
From Table 4, the catchment elongations of $S(a)$ and $S(c)$ are quantified as 0.87 and 1.7 respectively, so the $S(a)$ and $S(c)$ are not in elongate catchment and they are not in trellis and parallel pattern. The average sinuosity of $S(a)$ and $S(c)$ are 76.73° and 59.22°, meaning that the river segments in this two catchments are not bended and most likely do not form a rectangular drainage. In addition, the average angle of $S(a)$ and $S(c)$ are smaller than 90°, so they form a dendritic pattern. As to $S(d)$, it is in an elongated catchment because its elongation value is greater than 2, and average sinuosity is 59.12° showing that most stream channels are straight. But, the average angle of $S(d)$ is 49.79° which is much smaller than 90°, so $S(d)$ is in parallel pattern. The conditions of $S(b)$ and $S(e)$ are similar with $S(d)$ expect the average angle. The average angles of $S(b)$ and $S(e)$ are 81.14° and 85.43° respectively which are close to 90°, which explain that most tributaries in $S(b)$ and $S(e)$ join to main streams mostly at right angle. So they are in trellis pattern.

<table>
<thead>
<tr>
<th>Table 4 Information of sub-catchments in figure 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Angle</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>(a) 51.64°</td>
</tr>
<tr>
<td>(b) 81.14°</td>
</tr>
<tr>
<td>(c) 74.66°</td>
</tr>
<tr>
<td>(d) 49.79°</td>
</tr>
<tr>
<td>(e) 85.43°</td>
</tr>
</tbody>
</table>

Table 6 Number of drainage patterns

In table 6, taking order 2 to divide sub-catchments, there are 714 in total number. In this situation, most sub-catchments are made up of only less than 5 tributaries. The samples are too small to get an objective statistic of average value. And there are 118 sub-networks cannot be identified with threshold values of table 5. However, sub-catchment division under order 4 is too large. There are only 39 sub-catchment units. So, although 7 sub-networks have not been identified, the order 3 is a proper base to recognize the drainage patterns in Russian river. Some unclassified networks are shown in figure 10.

5. CONCLUSIONS

Drainage pattern is an important geographic factor for river basin. This paper pioneers automatic recognition of drainage patterns in river networks. Five patterns are classified: dendritic, parallel, trellis, rectangular and reticulate patterns. The method is based on geometric indicators, such as the average angle, average sinuosity, and catchment elongation to classify the patterns automatically. The method was applied on a case study, the Russian river basin, and the results were discussed.

The advantage of this work is that proposed geometric quantitative indicators are easy to obtain and calculate. Except the river network data itself, no other information about the terrain is needed. Validation of the results is based on assessments done on case studies. One limitation is that the qualitative description of the patterns relies on quantitative variables and depends on threshold values set by the users.

A first direction for further work may be to introduce fuzzy logic in the classification. Fuzzy logic can provide indication about the likelihood of a network to belong to a pattern.

<table>
<thead>
<tr>
<th>Order</th>
<th>2</th>
<th>3</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>113.12°</td>
<td>131.75°</td>
<td>90.22°</td>
</tr>
<tr>
<td>β</td>
<td>60.86°</td>
<td>65.24°</td>
<td>79.89°</td>
</tr>
<tr>
<td>γ</td>
<td>0.97</td>
<td>0.32</td>
<td>1.26</td>
</tr>
</tbody>
</table>

Figure 10. Unclassified sub-networks

Table 5 Threshold value of quantitative indicators

Table 6 shows the number of patterns in each order found of each type. 12 reticulate patterns were identified first.
Drainage patterns are identified for different sub-networks corresponding to sub-catchments of the main river catchment and can be computed for different orders. The patterns can be organized in a data structure providing a description of the drainage system for each order.

Another aspect is the addition of other parameters for further pattern descriptions. Drainage patterns such as radial and centripetal patterns have not been addressed in this paper. Their characterization needs information relating to spatial relationships between networks rather than geometric indicators. Therefore, on top of parameters related to network geometry, other topologic parameters can be considered.

6. REFERENCES


