AUTOMATED CONSTRUCTION OF STRUCTURED DENDRITIC RIVER NETWORKS

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ABSTRACT

The automated map generalization is always a challenging work in Geographical Information System (GIS). Regarded as terrain skeleton, drainage system should be considered in research on automated map generalization in the first place. Further, as the most important component of drainage system, generalization of rivers properly becomes a focal point. On land, rivers always connect together in networks, and most of these networks form tree structures. As a set of line features, river networks are generalized from large scale to small scale by two main steps: selective omission and selected rivers simplification. Before these steps, the structured dendritic river networks should be constructed. This paper puts forward an improved method of average direction based on angle of river network connections to detect the river flow and the main stream, and then create a data structure to store the topology relations of tributaries in the river networks. Eventually, the paper gives a comparative analysis with existed methods on river flow detecting and topology relation building.

KEYWORDS

Map generalization, dendritic river network, average direction, river flow, main stream.

INTRODUCTION

Generalization has a long history in cartography as an art of creating maps for different scales and purposes. Cartographic generalization is an intricate process whereby information is selected and represented on a map at a certain scale, not necessarily preserving all geographical or other cartographic details. With the development of computer science, automated generalization is the goal for which cartographers and geographers are always seeking after cartography entering digital era, and generalization of maps in digital environments is also called digital map generalization for short (Li 2007). Some existent applications, e.g. Google Map, Microsoft Bing Map, have already implemented multi-scale map representation by building different scale maps in spatial database which is the most common method in present GIS. But, there are still some advantages of automated map generalization that cannot be replaced: (1) It helps to realize continuous zoom in GIS. This is also called dynamic generalization (Mackaness and Glover 1999), which can transform a map from source scale to a small scale and continually display a temporary map of any smaller scale on computer screen dynamically. (2) It helps to build Multi-Representation Databases (MRDB) which contains several geographic datasets defined at different scales covering the same area (Kilpelainen 2000). These datasets updating is a time-consuming and costly work to acquire and update map data at different scales. Once automated map generalization works, it just needs to update the large-scale dataset and the small-scale datasets can be generalized automatically. So, according to above advantages, automated map generalization is always an important issue and major challenge in the research of cartography and GIS.

Drainage system is the pattern formed by the streams, rivers, and lakes in a particular drainage basin. Regarded as skeleton of terrain, drainage system should be considered in research on automated map generalization in the first place. Further, as the most important component of drainage system, generalization of rivers properly becomes a focal point. There are several reasons: (1) rivers are an important part of the land, and needs to be represented in maps of any kind; (2) rivers are fundamental concepts used for various analyses in geo-science. For instance, geologists can get original slope and original structure from drainage patterns. A river is a natural watercourse, usually freshwater, flowing towards an ocean, a lake, or another river. In a few cases, a river simply flows into the ground or dries up completely before reaching another body of water. So, on land, rivers always connect together forming networks. River networks are the object of this research for generalization. As a set of line features, river networks are generalized from large scale to small scale by two main steps: selective omission and selected rivers simplification (Li 2007).

However, before these two main steps, river networks should be structuralized. This paper puts forward an improved method of average direction based on angle of river network connections to detect the river flow and the main stream, and then create a data structure to store the topology relations of tributaries in the river networks. The remainder of the paper is organised as follow. Section 2 briefly reviews related works in river flow and main stream detection. In section 3, the methodology of river representation on average direction is introduced. Section 4 develops an experiment with the region of Hong Kong in map scale 1:50,000, and gives a comparative analysis with existed methods on river flow detecting and topology relation building. Finally, section 5 draws the conclusions and some research perspectives.

RELATED WORK

Dendritic river systems (from Greek δενδρίτης, dendrites, "of or pertaining to a tree") are the most common forms of river system. In a dendritic system, there are many contributing streams (analogous to the twigs of a tree), which join together into the main river (the branches and the trunk of the tree, respectively). They develop where the river channel follows the slope of the terrain (Lambert, 1998). In an idea fluvial system (see Figure 1), Schumm (1977) conceptualized it to consist of three zones: production zone, transfer zone, and deposition zone. The reference is made to sediment process. The dendritic river pattern usually occurs in the production zone where alluvial river has a capability of automatic regulation. One problem which should be noticed is that the confluence flow in river channel has some effects of automatic regulation and follows the principle of the minimum resistance. In fact, the forming of the angles of the confluence flows in river channel for tributary and main stream are not random, they should ensure that water and sediments in tributary and main currents can be drained freely.

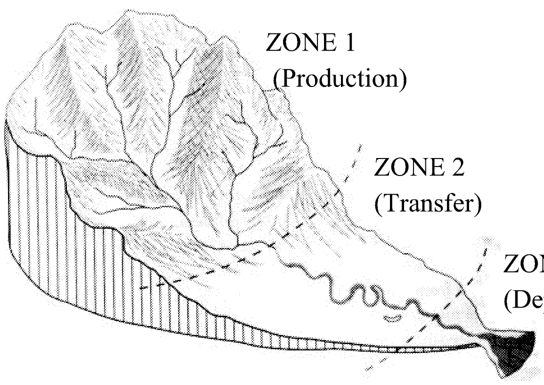


Figure 1 Idealized fluvial system (Schumm, 1977, diagram modified from Charlton, 2008)

In order to build a hierarchical (tree) structure of a river system automatically, inference of the flow direction and main stream in river networks is a necessary process. Although in many maps, each river has it name and should be treated as an entity, rivers in many other maps have no name, especially in large scale maps in which many small streams have no name. Usually, information about river networks only consists of the connectivity of channels, lacking any explicit information about the flow direction of the network. Many researches of river networks assume that the flow direction is already known (e.g. Smart 1970; Coffman and Turner 1971), but it is necessary to detect the river flow direction and main stream of a river network automatically.

There are many researches on detecting the river flow direction of a river network with additional information from a digital elevation model (e.g. O'Callaghan and Mark 1984; Fairfield and Leymarie 1991; Alves *et al.* 1992). Such an approach may be feasible in steep terrain with significant elevation, but it cannot work in flat terrain. Instead of using elevation information, a method based on the angles at which river segments connect in river networks has been put forward. Serres and Roy (1990) have found a set of inference rules (see Table 1) that match closely with dendritic river networks, and it is true for about 88% of the junctions in tree-like river networks empirically. Pavia and Egenhofer (2000) have presented an algorithm to find first the main branches of a network, from which it then infers the destination, based on the topology of channels and the angles at which river channels connect at junctions.

Table 1 Decision table for network junctions based solely on angles (Serres and Roy 1990)

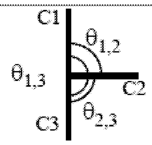
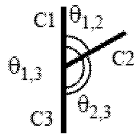
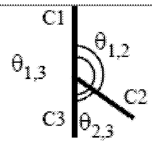
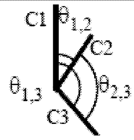
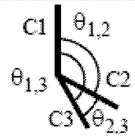
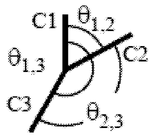
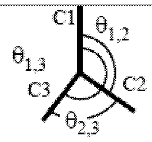
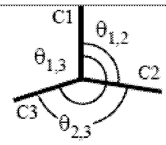
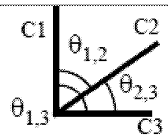
	1	2	3	4	5
Case					
$\theta_{1,3}$	= 180°	= 180°	= 180°	< 180°	< 180°
$\theta_{1,2}$	= 90°	< 90°	> 90°	≤ 90°	≥ 90°
$\theta_{2,3}$	= 90°	> 90°	< 90°	≥ 90°	≤ 90°
Downstream channel	C1 or C3	C3	C1	C3	C1

Table 1 - (Continued)

	6	7	8	9
Case				
$\theta_{1,3}$	> 180°	> 180°	> 180°	< 180°
$\theta_{1,2}$	≤ 90°	≥ 90°	≥ 90°	< 90°
$\theta_{2,3}$	≥ 90°	≤ 90°	≥ 90°	< 90°
Downstream channel	C3	C1	C3 **if** $\theta_{1,2} < \theta_{2,3}$ C1 **if** $\theta_{2,3} < \theta_{1,2}$	C3 **if** $\theta_{1,2} < \theta_{2,3}$ C1 **if** $\theta_{2,3} < \theta_{1,2}$

But, the angles at which river channels connect as junctions should be formed by three or more straight line segments, and river channels in map are always not a straight line but consisted by many points. Some researches (e.g. Serres and Roy 1990; Pavia and Egenhofer 2000) just take the start and end points of a river channel in a map as a straight line. It might cause irrational angles which would lead to inconsistent river flows and illogical main stream. So, this paper raises an improved method of average direction based on angle of river network connections to represent a river, and finishes some contrastive analysis on the influence to river flow direction and main stream based on different methods of representing a river channel with a straight line segment.

METHOD OF SOLUTION

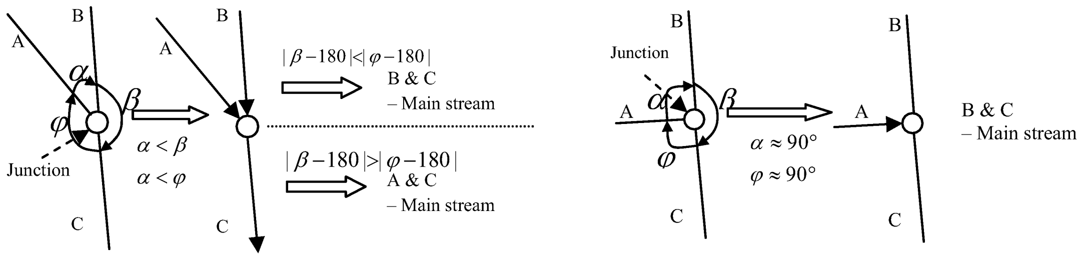
Dendritic River Flow Direction and Main Stream

According to the decision for network junctions based solely on angles of Serres and Roy (1990), there are 9 kinds of situation needed to consider (see Table 1). The junction geometry describes the information among the related channels. The primary geometric concern is the information about the angles at which the channels flow together. Two heuristics about the junction geometry are important (Pavia and Egenhofer 2000). One is acute-angle assumption, the other one is the 180° assumption.

The acute-angle assumption presumes that the two consecutive channels that enclose the most acute angle are the upstream channels, which are based on an inference mechanism about the channel flows that is based solely on angles at river junction.

The 180° assumption presumes that the predominant continuation of the flow direction is along the main channel. The upstream channel that forms an angle closest to 180° with the downstream channel is considered to be part of the main channel.

This paper has summarized the two assumptions into a simple method to infer the river flow direction and main stream.



(a) Situation 1 (b) Situation 2

Figure 2 Decision sketch for detecting flow direction and main stream

In Figure 2, river A, B and C connect as the junction. The angles α, β, φ are formed by river AB, BC, AC respectively. The angle α is the smallest angle among three angles in the Figure 2(a), so according to acute-angle assumption the river water flows from river A and B to C. In addition, the angle β is closer to 180° than other two angles, so the river B, C are main channel and river A is the tributary. In Figure 2(b), α and φ are almost close to 90°, so the river flows from A to the junction, and the river B and C are main stream. However, this method cannot determine the river flow of main stream, it needs other information.

River Tributary Representation

In the previous review, the research works in river flow detecting or main stream inference make use of the terminal points to represent a river. Actually, a river consists of many points with many twists and turns. Only representing a river by terminal points would cause some irrationality in river flow detecting and river topological relationship establishing. Here, we use three methods to represent a river by a line segment, and the contrastive analysis has been illustrated in the later section.

Supposing a river is a polyline consisting of N points, $Pt_i = (X_i, Y_i)\ \ i = 1, 2, ..., N$ is a point in the polyline. When $i = 1$ or $i = N$, the point is terminal point of the polyline. A line segment is consist of two points in these N points, so the line segment can be presented as $Ls = \{Pt_i, Pt_j\}\ i, j = 1, 2, ..., N$ and $i \neq j$.

Represented by terminal points

In this case, the line is consisted of the two terminal points Pt_1 and Pt_N, so the line can be described as:

$$\begin{aligned} & Ls = \{Pt_1, Pt_N\} \\ \Rightarrow\ & Ls = \{(X_1, Y_1), (X_N, Y_N)\} \end{aligned} \tag{1}$$

Represented by line segment close-by junction

In this case, the line segment close to the junction is used to represent a river.

$$\begin{aligned} & Ls = \{Pt_1, Pt_2\} \ \text{ if } Pt_1 \text{ is the junction} \\ \Rightarrow\ & Ls = \{(X_1, Y_1), (X_2, Y_2)\} \\ & or \\ & Ls = \{Pt_{N-1}, Pt_N\} \ \text{ if } Pt_N \text{ is the junction} \\ \Rightarrow\ & Ls = \{(X_{N-1}, Y_{N-1}), (X_N, Y_N)\} \end{aligned} \tag{2}$$

where there are two situations, one is the Pt_1 is the junction, another is Pt_N is the junction.

Represented by average direction

In this case, the line segment points from the junction point to the centre point of the rest points except the junction. The line can be represented as:

$$
\begin{aligned}
&Ls = \{Pt_1, Pt_c\} \text{ if } Pt_1 \text{ is the junction} \\
&\Rightarrow Ls = \{(X_1, Y_1), (\frac{\sum_{i=2}^{N} X_i}{N-1}, \frac{\sum_{i=2}^{N} Y_i}{N-1})\} \\
&or \\
&Ls = \{Pt'_c, Pt_N\} \text{ if } Pt_N \text{ is the junction} \\
&\Rightarrow Ls = \{(\frac{\sum_{i=1}^{N-1} X_i}{N-1}, \frac{\sum_{i=1}^{N-1} Y_i}{N-1}), (X_N, Y_N)\}
\end{aligned} \quad (3)
$$

where Pt_c and Pt'_c are the centre points.

Dendritic River Network Topological Relationship

The dendritic river network has been defined as a threaded tree in which there are two fields: data field, indication field. A pseudo code of the tree is as follows.

```
RIVER
{
        Int        id;
        Point []   pts;
        Double     length;
        ......
        RIVER      OutTributary;
        RIVER      InTributary;
        RIVER      LowerRiver;
        RIVER      UpperRiver;
}
```

Among them, data field is used to store the related information about a river tributary, such as coordinate array, river id and length; indication field is used to refer to the tributaries, upper river, and lower river. Take the simulated river in Figure 3(a) as an example. Figure 3(b) illustrates the tree node structure and the threaded tree structure of the simulated river is shown in Figure 3(c).

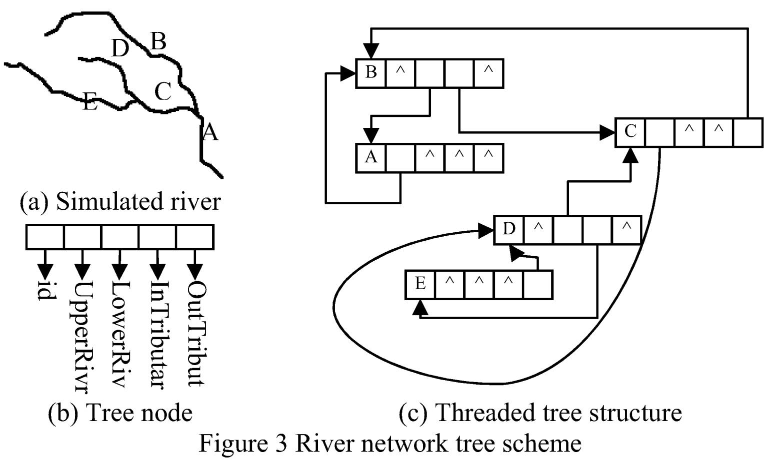


Figure 3 River network tree scheme

EXPERIMENT AND RESULTS
Experiment Data

The experiment region is Hong Kong and the data's map scale is 1:50,000. There are three kinds of hydrology data in a layer: rivers, catch-waters and isobaths. Catch-water is a kind of artificial channel, so this paper has eliminated them firstly. In addition, the isobaths also should be eliminated. In the Figure 4, the blue polylines are rivers, the bold red polylines are catch-waters, and the dashed polylines are isobaths.

The rivers in Hong Kong have a typical dendritic drainage pattern. Hong Kong stands on volcanic terra firma, with its landscape dominated by hills and mountains. A crest lining from the northeast to south west forms the backbone of Hong Kong. The highest peak is Ta Mo Shan, located in central New Territories at 957 meters above sea level. Only nearly 20% land are flat, and Kowloon peninsula and the north-western New Territories are mainly flat areas. Most of the streams flow from the hills and mountains into the South China Sea.

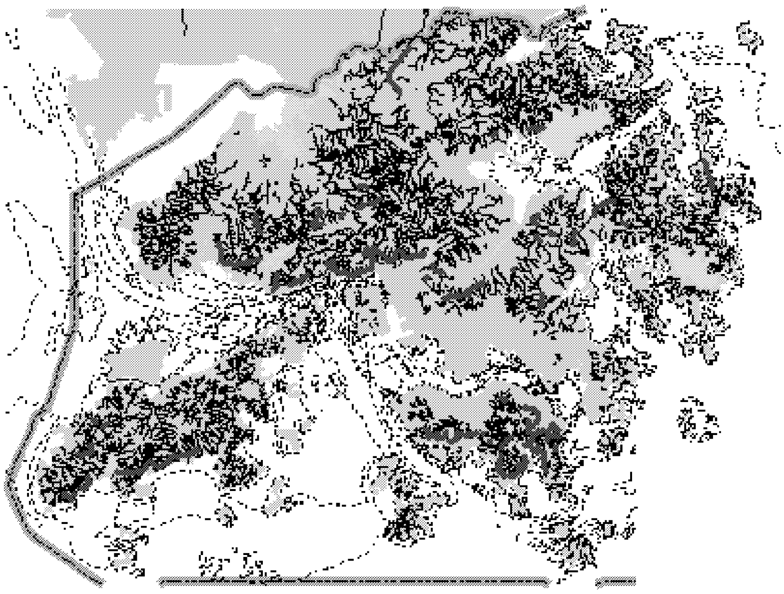


Figure 4 Experiment region and river data

Results and Discussions

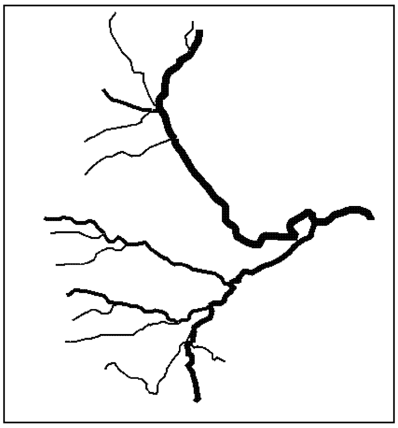
Due to the dendritic drainage pattern's characteristics, the river segments connecting at a junction only have one outlet, that is to say, only the situation that many rivers flow into another one river is correct theoretically. So, in this experiment, if a river separates into two or more branches, there is a flow direction conflict at this junction. The Table 2 shows the flow direction conflict result comparing with the three different represented methods in METHOD OF SOLUTION section.

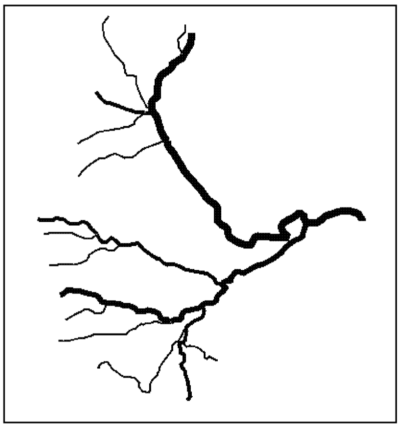
Table 2 Flow direction conflicts comparison

Represented Method	Internal Conflict	Edging Conflict	Total Conflict	Percent (%)
Terminal points	4	22	26	1.3% (26/1939)
Line segment close-by junction	18	43	61	3.1% (61/1939)
Average direction	4	12	16	0.8% (16/1939)

In the Table 1, internal conflict occurs inside the river network that means all the river segment connecting at the junction are not source or outfall. From the result, we can see that the represented method by average direction has the least conflicts in river flow direction, and by terminal points is also good. The method by line segment close-by junction performs poorly in the flow direction inference. There are 4 conflicts inside the river network, because there is a circuit in the river network which is not a typical dendritic river network. So, the average direction method improves the traditional methods in river flow direction.

As to the main stream, river segment represented by different methods can lead to different result. Figure 5 illustrates an example of different dendritic river networks built by the method of terminal points and average direction from the experiment region. From the Figure 5, the dendritic river network in (b) is more reasonable than (a), because the network in (b) is more balance than in (a). The average direction method also can help build a more correct river network, but the rationality is hard to be quantified.





(a) by terminal points (b) by average direction

Figure 5 Different dendritic river networks

CONCLUSIONS

This paper puts forward an improved method of average direction based on angle of river network connections to detect the river flow, and get the main stream of the river with principle of approximate 180^{0} , then create a data structure to store the topology relations of tributaries in the river networks. The conclusions are as follows:
(1) the average direction method improves the traditional methods (e.g. terminal points) in river flow direction in a certain extent;
(2) it can also be used to build a more reasonable dendritic river network, but the rationality is hard to be quantified, because there is no standard;
(3) this work is the fundamental of dendritic river network automated generalization, that is because with the correct river flow the outlet and source of the river network can be known and then the river network can be schemed as Horton scheme (Horton, 1945) in downstream routine; and following the main stream, the Horton scheme after upstream and the Shreve scheme (Shreve, 1966) also can be got. These two schemes have been considered the most relevant schemes for the multi-scale representation of river networks (Rusak Mazur and Caster, 1990);
(4) this work can be used in not only dendritic river pattern but also other tree like river patterns such as parallel, trellis, and rectangular patterns, but further work should be done to handler other non-tree like drainage patterns such as deranged and reticulate patterns.

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