Skeleton Line Extraction Method in the Areas with Dense Junctions Considering Stroke Features

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Keywords: Areas with Dense Junctions, Skeleton Line, Stroke Features, Long-edge Adaptive Node Densification and Type III Triangles Aggregation.

Abstract: Polygon skeleton line extraction is a key and difficult problem in map generalization. Aiming at the problem that the traditional method is difficult to maintain the main structure and extension characteristics when dealing with areas with dense junctions, a method for extracting skeleton lines in areas with dense junctions considering stroke features is proposed in this study. Firstly, a long-edge adaptive node densification algorithm is put forward to construct boundary-constrained Delaunay triangulation for extracting the initial skeleton line. Then, Type III triangles are automatically identified as the basic unit. According to the local width feature, Type III triangles aggregation is achieved to obtain the areas with dense junctions. Finally, we define the connecting arc and evaluate their importance. The stroke is iteratively constructed according to the importance of the arc, and the good continuity feature of the stroke is used to optimize the skeleton line. The actual water system data of Jiangsu Province are used to verify the results. The experimental results show that the proposed method can better identify the areas with dense junctions, and the extracted skeleton line is naturally smooth and well connected, which accurately reflects the main structure of the area.

1 INTRODUCTION

Ai (2002) believe that the extraction of skeleton lines is a key step to realize the comprehensive operation of maps such as polygon dimensionality reduction and split melting. The extraction of skeleton lines takes into account the shape features of polygons and summarizes the main body structure and extension characteristics of polygons. It shall meet the human visual cognition while conforming to the drawing specifications. Therefore, how to accurately and reasonably determine the skeleton line has always been a difficult point of research (Ai, 2010). There are three common methods for extracting skeleton lines: round skeleton line (LEE, 1982), straight skeleton line (Das et al, 2010) and skeleton line based on Delaunay triangulation (Cao et al.2015; Sintunata et al., 2016). Delaunay triangulation with "circular rule" or "maximum/minimum angle rule" has become a method of skeleton line extraction widely used by researchers (Ware, 1997), and the research in this paper also falls within this scope.

DeLucia et al. (1987) first proposed a skeleton line extraction method based on boundary constrained Delaunay triangulation (CDT) ; Zou et al. (2001) used this method to construct a polygonal skeleton and proved the effectiveness of this method . Li et al. (2006) attempted to apply this method to extract the main skeleton line of the polygon and achieved good results. However, in the course of research, some scholars have also found some problems, e.g., Penninga et al. (2005) pointed out that the skeleton line extracted based on Delaunay triangulation has at least the following three aspects: (1) at the branch connection point, skeleton lines present "saw tooth"; (2) tiny bumps on the boundary result in the formation of redundant "spike" skeleton lines; (3) fewer boundary nodes cause the end split line to be elongated and offset. Accordingly, Jones et al. (1995), Uitermark et al. (1999) and Penninga et al. (2005) proposed to use the branch skeleton line direction, boundary simplification, densification boundary nodes and other methods to modify the proposed skeleton line, which have better solved the above problem. However, these methods are only applicable to simple polygons with regular shapes and flattened boundaries. Haunert et al. (2008) have studied a large number of road data and found that when dealing with polygons with irregular shapes or complex branching convergence features, existing methods are difficult to maintain the main

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structure and extension characteristics at this place. Li et al. (2018) made a preliminary exploration of the skeleton line extraction in the areas with many junctions, but the method relies on the skeleton line direction and the branch gathering distance characteristics, so that it is still unable to handle complex area with dense junctions.

On this bases, according to the existing research, a method of extracting the skeleton line of the areas with dense junctions considering the stroke features is proposed to optimize the extraction effect of the skeleton line of the complex branch convergence.

2 RELATED WORKS

2.1 Existing Extraction Method of Skeleton Line

Li et al. (2018) proposed a method for extracting skeleton lines from narrow long map-spot branch convergence area. The basic idea is to introduce a constrained Delaunay triangulation, identify the branch convergence area based on the degree of node correlation, and eliminate the jitter on the skeleton line of the branch convergence area under the direction and distance constraints. The specific steps are shown as below:

Step 1: Construct a constrained Delaunay triangulation to divide the narrow long map-spot. According to the number of adjacent triangles in the inner triangle of the polygon, the triangles in the Delaunay triangulation can be subdivided into three categories:

Type I triangle: There is one and only one adjacent triangle. As shown by ΔABC in Figure 1(a), the vertex A is the end point of the skeleton line.

Type II triangle: There are two adjacent triangles. As shown by ΔABC in Figure 1(b), the advancement direction of the skeleton line in the Type II triangle is unique.

Type III triangle: There are three adjacent triangles. As shown by ΔABC in Figure 1(c), the three extension directions occur at point O.

Step 2: Extract the central axis from the three types of triangles as follows for connection to form a skeleton line, wherein the common edges of two adjacent triangles are called adjacent edges:

Type I triangle: Connect the midpoint of the unique adjacent edge with its corresponding vertex, as shown by segment AD in Figure 1 (a);

Type II triangle: Connect the midpoints of two adjacent edges, as shown by segment DF in Figure 1(b);

Type III triangle: Connect the center of gravity and the midpoint of the three sides, as shown by segments OD, OF, OH in Figure 1 (c).

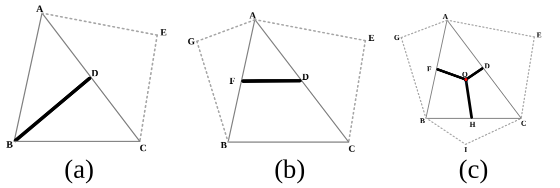


Figure 1: Triangle classification. (a) Type I triangle, (b) Type II triangle, (c) Type III triangle.

Step 3: Since the area where the Type III triangle is located is a branch convergence area, the branch aggregation area can be identified by the location of Type III triangle;

Step 4: Calculate the direction of the three related skeleton line branches in the branch convergence area. If there is a branch skeleton line with the same direction, it is preferentially connected as a straight line, and the remaining branch skeleton lines extend to the straight line in their respective directions; If there is no arbitrary two skeleton lines in the same direction, the Euclidean distance between the nodes is used as a measure of similarity, the branch nodes are aggregated to the geometric centre of the range, and the branch skeleton lines are connected to the aggregation nodes in respective directions.

2.2 Defects in the Existing Method of Extracting Skeleton Lines

In the existing method, each trigeminal region is used as a processing unit, and by setting a direction threshold and a branch node distance threshold, the skeleton line of simple junctions aggregation area can be obtained well. However, when the junctions is complicatedly converged, the existing method is difficult to precisely strip single branch convergence area, leading to no accurate extracted skeleton line. In addition, the shape of the skeleton line in the junctions is complicated, and each branch convergence area is used as a unit for processing, unable to consider the overall characteristics of the area formed by the mutual association between the branches, resulting in the destruction of the overall structure of the area.

3 METHODOLOGY

In this paper, a method for extracting skeleton line in the areas with dense junctions considering stroke features is proposed, including three key steps as follows. (1) Long-edge adaptive node densification: Create Delaunay triangulation with polygon boundary constraints for long-edge adaptive densification; (2) Areas with dense junctions identification: Identify the branch structure and aggregate the qualified branches; (3) The skeleton line extraction in the Areas with dense junctions: According to the good continuity characteristics of the stroke, the skeleton line is optimized, leading to more in line with humans cognitive law.

3.1 Long-edge Adaptive Node Densification

Boundary densification is one of the key steps in establishing a boundary-constrained Delaunay triangulation. In the dense area of the bifurcation, there will be a large number of complex areas with one side branch dense while no branch on the other side. If not densified, the constrained Delaunay extraction directly extracts the skeleton line, which will cause a large deviation in the identification of the branch convergence area. If the traditional overall densification method is used, it will lead to invalid branches in the normal end. Therefore, the long-edge adaptive densification is proposed to perform node densification on such complex areas in this paper. The specific steps are shown as below:

Step 1: Identify the obtuse triangle in the Type III triangle and set the minimum angle threshold Amin. If the minimum angle in an obtuse triangle is smaller than Amin, it is marked and put it into the triangle set S, as shown by the blue triangle in Figure 2 (a);

Step 2: Identify the longest edges of all the triangles in the set S, and find the Type II triangles adjacent to the longest edges with one edge as the boundary, as shown by the yellow triangle in Figure 2(b);

Step 3: Identify the longest edge of the above-mentioned Type II triangle and determine whether it is a boundary edge. If it is a boundary edge, it is marked as the local long edge to be densified, and the Type II triangle is marked as the triangle to be densified. The purple triangle is shown in Figurer 2(c);

Step 4: Set the densified step size to the smallest and shortest edge of Type III triangle set associated with Type II triangle to be densified;

Step 5: Densify by the densified step size, as shown in Figure 2(d).

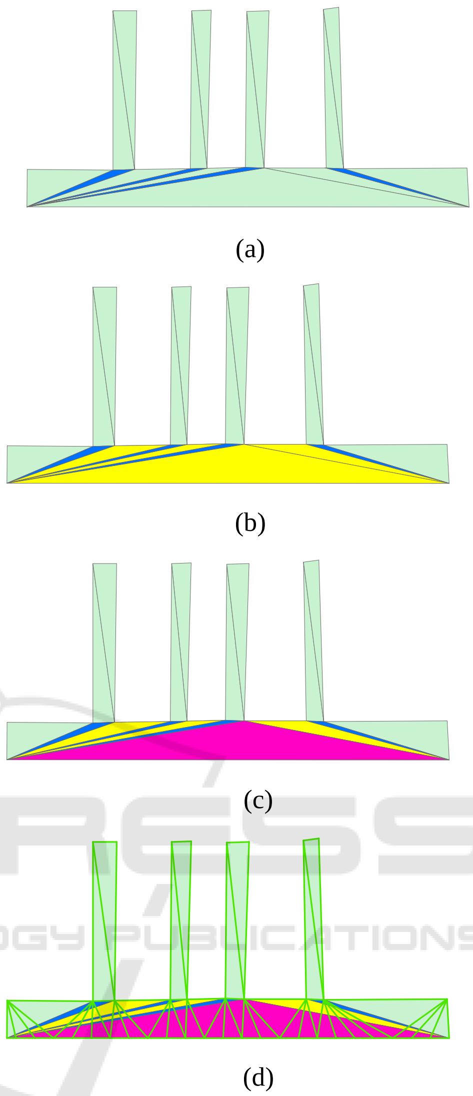


Figure 2: Long-edge adaptive densification. (a) Elongated Type III triangle, (b) Type II triangle with one edge as the boundary, (c) Local long edge to be densified, (d) Densify by densified step size.

3.2 Identification of Areas with Dense Junctions

3.2.1 Trident Identification

The first step in the identification of the areas with dense junctions is to identify the trident area in the polygon. The identification method is shown as follows. (1) After long-edge adaptive densification, construct a polygonal boundary constraint Delaunay triangulation and extract the initial skeleton line; (2) Construct a point and line topology for the initial skeleton line, and for any node of the skeleton line topologies, the number of arcs associated with the node is *ArcNum(Node)*; (3) When *ArcNum(Node)*=3 of a node, the node is a trident node, and the area is the trident area, as shown by the nodes A-P in Figure 3(a). It can be found that these trident nodes are the center points of Type III triangles.

3.2.2 Trident Association

Whether the identified tridents can be aggregated needs to be judged by the connecting arc between the tridents, wherein the connecting arc segment is defined as below. If the first and end points of an arc segment are trident nodes, then the arc segment is a trident connecting arc. The specific steps for determining the associated relationship are shown as follows:

Step 1: Calculate the local approximate width W_{NODE} of the area where the trident is located: record twice the maximum value among the three edges of Type III triangle corresponding to the trident as the local approximate width W_{NODE} of the area where the trident is located, i.e., $W_{NODE}=Max(L_{30},L_{31},L_{32})\times 2$;

Step 2: Calculate the local approximate width W_{ARC} of the area where the connecting arc is located: calculate the local approximate widths W_{Ns} and W_{Ne} of the area where the first node N_s and the end node N_e of the connecting arc are located, and use the large value as the local approximate width W_{ARC} of the area where the connecting arc is located, i.e., $W_{ARC}=Max(W_{Ns},W_{Ne})$;

Step 3: Calculate the effective length L_v of the connecting arc segment: record the part of the connecting arc between the first and end nodes of the connecting arc segment with the internal length of Type III triangle as the effective length L_v of the connecting arc segment, as shown in Figure 3(b), and the effective length of the connecting arc between the first node F and the end node G is $L_v=L_{FG}-L_{32}-L'_{30}$;

Step 4: If the effective length L_v of the connecting arc between the two trident nodes is smaller than the local approximate width W_{ARC} of the area where the connecting arc is located, i.e., $ArcNum(N_s)=3$, $ArcNum(N_e)=3$ and $L_v<W_{ARC}$ are satisfied simultaneously, then the two tridents are associated with each other, and the connecting arc between them is marked Arc_{link}.

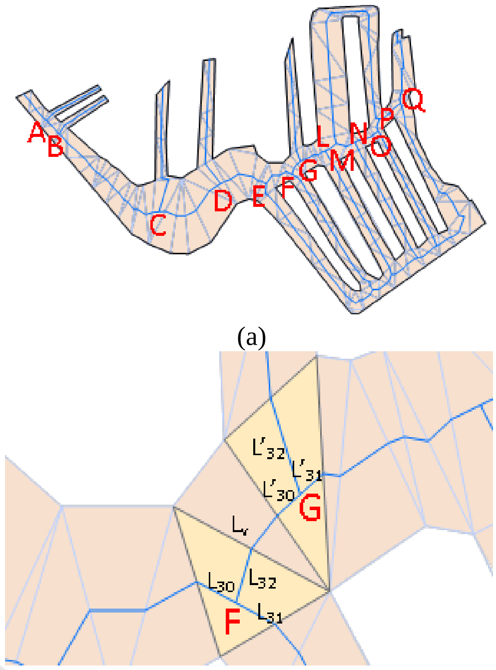


Figure 3: Trident association judgement. (a) Trident node, (b) Effective length Lv of connecting arc.

3.2.3 Trident Aggregation

Calculate the associated arc Arc_{link} for all trident nodes of the polygon to be placed in the set S (Arc_{link}). Select an Arc_{link} and use its first node N_s and end node N_e as tracking nodes to detect whether Arc_{link} also exists in the first node N_s and end node N_e (except Arc_{link} itself) and record to the neighboring association Arc_{link} set $NeighborArc_{link}(Arc_{link})$. After each Arc_{link} is detected, it is clustered and expanded to obtain the junctions aggregation result.

3.3 Skeleton Line Extraction in Areas with Dense Junctions

For any trident aggregation area, this paper takes into account the stroke feature to extract its internal skeleton line.
Accordingly, a stroke is first constructed with the connecting arc as a unit in this paper, and then the skeleton line of the trident region is extracted, leading to natural extension according to the stroke feature and obtain a skeleton line more in line with human cognition.

Table 1: The meaning and calculation method of connecting arc parameters.

Parameter name	Meaning	Calculation method
Length	Length of connecting arc	*L=Distance(Ns,Ne)*
Approximate width	Local approximate width of connecting arc	$W_{NODE}=Max(L_{30},L_{31},L_{32})\times 2$
Connectivity	The number of other connecting arcs that intersect this connecting arc	$D(v_i)=\sum_{k=1}^{n} r(v_i,v_k)$ Where, $r(v_i,v_k)$ indicates the connectivity between nodes.
Proximity	The minimum number of connections from the connecting arc to all other connecting arcs, reflecting the possibility that other connecting arcs will be aggregated in this connecting arc	$C(v_i)=\frac{n-1}{\sum_{k=1}^{n} d(v_i,v_k)}$ Where, $d(v_i,v_k)$ indicates the shortest distance between two nodes.
Betweenness	Measure the extent of this connecting arc between other connecting arcs and whether the connecting arc acts as a "bridge"	$B(v_i)=\frac{1}{(n-1)(n-2)}\sum_{j.k\in n;j\neq k;k\neq i}\frac{m_{jk}(v_i)}{m_{jk}}$ Where, m_{jk} indicates the number of the shortest distance between two nodes; $m_{jk}(v_i)$ indicates the number of the shortest distance between two nodes passing the node v_i

3.3.1 Arc Importance Evaluation

The basic idea to determine the importance of connecting arcs in this paper is to use the length, connectivity, proximity and mediation of connecting arcs, weighted by CRITIC (Criteria Importance Though Intercrieria Correlation) method (Diakoulaki et al., 1995) to obtain the importance of connecting arcs. The meanings of the parameters of connecting arc segments are shown in Table 1.

3.3.2 Construct a Stroke Connection

Based on the importance of each connecting arc segment, the stroke connection of the areas with dense junctions is iteratively calculated, and the main steps are shown as follows:

Step 1: Identify the trident node with only the associated arc on one side, and select one as the stroke connection to track the starting node. Then, the connecting arc is taken as the tracking arc to get the node on the other side of the arc, which is used as a tracking node;

Step 2: The connecting arc of the tracking node is taken as the stroke connection candidate set R to calculate the importance of each connecting arc segment;

Step 3: Preferentially connect the arc segment of larger importance with the previous arc segment to form a stroke;

Step 4: According to the ideas of Steps 2 and 3, continue to track the calculation of the stroke connection until there is no connection arc of the tracking node, then the single stroke connection ends;

Step 5: Explore the branch connecting arc of the existing stroke connection until all the connecting arcs of intersecting dense areas have been calculated, then the stroke connection calculation ends, as shown by the thick blue line in Figure 4.

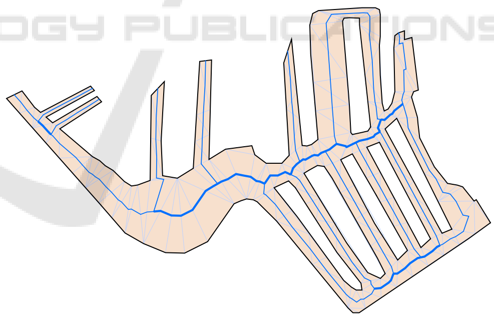


Figure 4: Junctions aggregation result.

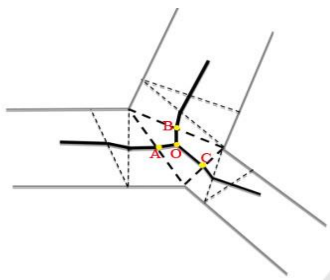
3.3.3 Skeleton Line Adjustment

The connecting arc Arc_{link}, as the basic unit of stroke connection in areas with dense junctions, consists of two trident nodes. For any of the trident nodes, the two arcs with the stroke connection are used as the reference arc. The midpoint of the two-point line on the edge of Type III triangle is used as the adjustment position of the trident node, and the three arc segments associated with the trident node are connected with the midpoint to complete the skeleton line adjustment of each trident region. As shown in

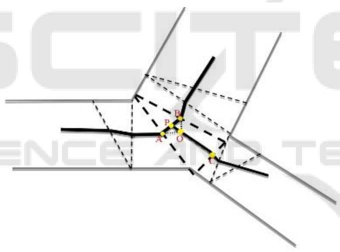
Table 2: Overall situation statistics of experimental surface element processing results.

Trident number	Number of areas with dense junctions	The case of areas with dense junctions containing connecting arc segments			
2286	124	Max	Min	Average	Total
		307	1	15.6	1939
	stroke connection number in the dense area	Stroke containing connecting arc			
	385	Max	Min	Average	Total
		66	1	3.1	1939

Figure 5, assuming that the arcs of OA and OB belong to the same stroke at the trident node O, the intermediate point P of AB is taken to connect AP, BP and OP to form a new skeleton line.



(a)



(b)

Figure 5: Skeleton line adjustment in trident area. (a) Before adjustment, (b) After adjustment.

4 EXPERIMENT AND ANALYSIS

4.1 Experimental Data and Environment

Relying on the WJ-III map workstation developed by China Institute of Surveying and Mapping, the method of extracting the skeleton line of the areas with dense junctions considering of stroke features proposed in this paper is embedded, and a complex water topographic map in Jiangsu with a scale of 1:10000 is taken as a case for reliability and superiority verification. The experimental data space range is 2.7×2.7 km2, the software system running environment is Windows 7 64-bit operating system, the CPU is Intel Core I7-3770, the main frequency is 3.2GHz, the memory is 16GB, and the solid state hard disk is 1024GB.

4.2 Reliability and Superiority Analysis

In order to verify the reliability and superiority of the proposed method, the method of this paper is compared with the skeleton line extraction method of Li et al. (2018). The overall situation of the processing area using the method of this paper is shown in Table 2.It can be seen from Table 2 that the junctions is densely distributed, and about 85% of the tridents meet the aggregation conditions.

4.2.1 Visual Cognition Analysis

The densely distributed areas of typical junctions in the experimental area are as shown in Figure 6.

It can be seen from Figure 6 that for complex areas with dense junctions, the method of Li et al. (2018) is subject to severe interference of the complex boundary and arrangement structure of the branch, unable to process the skeleton line jitter of this area, and the extracted skeleton line has a large degree of distortion, thus losing the overall structure of this region. In contrast, the method of this paper can better extract the main structure of this region and more accurately describe the skeleton line of the main structure. For the backbone area with larger connectivity within the rectangle A, the skeleton line extracted in this method can also summarize its extension characteristics well.

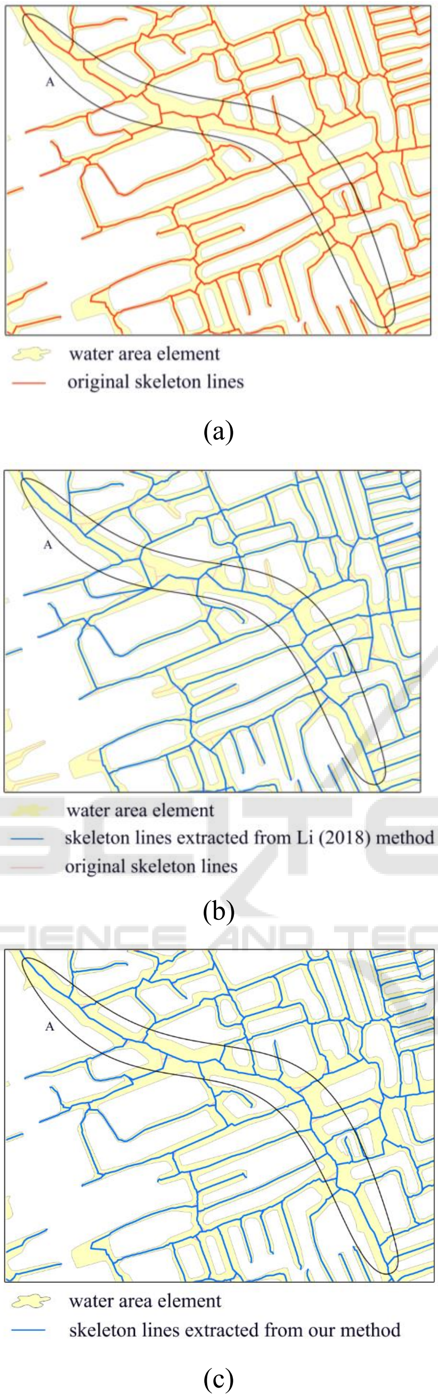


Figure 6: Comparison in extraction results of skeleton lines in complex areas with dense junctions. (a) Original skeleton line, (b) Extraction results of Li (2018), (c) Extraction results of this paper.

4.2.2 Network Function Analysis

The global efficiency commonly used in complex network theory is used to evaluate the network function of the results in this paper. The concept of dual graphs is introduced, where the nodes represent the connecting arcs between trident nodes, and the edges represent the relationship between the connecting arc segments and other connecting arc segments. It is formalized as $G = G(V, E)$, where *V* is the set of nodes and *E* is the set of edges. Then the "global efficiency" of the network *G* is calculated as below:

$$E = \frac{\sum_{\mathrm{i},\ \mathrm{j} \in G, \mathrm{i} \neq \mathrm{j}} \varepsilon_{\mathrm{ij}}}{N(N-1)} = \frac{\sum_{\mathrm{i},\ \mathrm{j} \in G, \mathrm{i} \neq \mathrm{j}} \frac{1}{\mathrm{d}_{\mathrm{ij}}}}{N(N-1)}$$

Where N is the total number of nodes, ε_{ij} is the efficiency between node *i* and node *j*, and d_{ij} is the minimum number of steps required by connecting node *i* and node *j*, i.e., the path length. The global efficiency range is [0, 1]. Meanwhile, the number of stroke connections formed by the arcs of the experimental area is counted, as shown in Table 3.

It can be found from Table 3 that in terms of global efficiency, the overall efficiency of the result in this paper is improved by 0.023 compared with the traditional method, which indicates that the method in this paper improves the smoothness of information dissemination in the network. Meanwhile, in the case of same number of arcs, the number of strokes constructed by the method in this paper is reduced by 72 compared with the traditional method, indicating that the network stroke access is better.

5 CONCLUSIONS

Aiming at the problem that the traditional method cannot accurately maintain the main structure and extension characteristics of the areas with dense junctions, a method of extracting the skeleton line of the areas with dense junctions considering the stroke feature is proposed in this paper. After verifying the topographic map of the actual water system in a certain area of Jiangsu, the main conclusions are shown as follows:

(1) Applicability: The method in this paper can better distinguish the areas with dense junctions and the areas with sparse junctions. For the identified 124 areas with dense junctions, the traditional method can only process 58% of the tridents, but this method can process all tridents.

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Table 3: Comparison in global efficiency and number of stroke connections.

Method	Number of arc segment	Stroke number	Global efficiency
Method of Li et al. (2018)	3617	1330	0.096
Method in this paper	3617	1258	0.119

(2) Superiority: Visual cognition analysis shows that for the complex areas with dense junctions, the skeleton line extracted by this method can better display the regional main structure and extension characteristics. The analysis of network function indicates that the skeleton line extracted by this method has better accessibility.

The stroke generation strategy has an important influence on the accuracy of the skeleton line extraction results by the method in this paper. The next research focus is to further refine the arc importance evaluation system and establish a more reasonable stroke generation strategy, so as to make the skeleton line extraction result more refined.

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