Adaptive river network extraction method using local characteristics of water system

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Abstract: River network extraction is the basis of hydrological analysis and related issues. The accuracy of river extraction directly affects the accuracy of watershed related research. The key to extracting the river network by using hydrological analysis method is to determine the drainage area threshold. At present, there are existing methods for determining the drainage area threshold, which have problems such as inaccurate extraction with a single threshold and difficulty in obtaining data with multi-threshold. In view of this, based on DEM data of Jiuyuangou watershed in the Loess Plateau, combined hydrological analysis and digital terrain analysis methods, based on the principle of river network extraction from slope runoff, and taking into full consideration the hydrological characteristics of the terrain of the watershed, this paper proposes a threshold determination method based on multi-threshold constraints of local characteristics of the water system and compares the river network accuracy between the river network extracted by the threshold determined by this method and the single t value determination method and the river network extracted by the threshold determined by the river network density method. The results show that among the two river network quantitative indicators including average branch ratio and average length ratio, the corresponding values of the extracted river network by the threshold determined by the multi-threshold constraint method are 4.94 and 9.90, which are the least different from the real river network (4.36 and 9.60),

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and the other two methods are quite different. The research results show that the river network extracted by the threshold determined by the multi-threshold constraint method can more realistically express the characteristics of the water system, and requires less data, which provides a new idea for determining the optimal the drainage area threshold for the DEM water system.
Key Words: DEM; River Network Extraction; Flow Accumulation; Adaptive; Multi-threshold Constraint

1 Introduction

River network is a water network system composed of all rivers, lakes and other water bodies in the basin. It is a basic element reflecting the characteristics of the basin and plays a very important role in geoscience research. In recent years, extracting river network based on DEM (Digital Elevation Model) data has become the basis of hydrological research. Methods for extracting river network include moving window method, valley line search method, and slope runoff simulation method. Among these methods, determining the drainage area threshold is the key. The drainage area threshold, also known as the critical support area (CSA) of a river, is generally defined as the minimum drainage area required to support the permanent existence of a river(Quinn et al., 1991; Xiong et al., 2003), which determines the density and morphological characteristics of the water system, and directly affects the division of river network convergence area(Sha et al., 2016; Sun et al., 2013). In the application of these methods to extract river network, the determination of the drainage area threshold is highly subjective and uncertain(Zhang et al., 2019), which brings great challenges to the application of various methods. Many scholars have done a lot of research on how to determine the optimal drainage area threshold. (Tarboton et al., 2001) first applied the topographic water system drop in the study area as the basis for determining the drainage area threshold. This method can extract the main river network well, but the tributaries is seriously lacking(Yu et al., 2013). In order to overcome this defect, (Vogt et al., 2003) introduced more features, including climate, vegetation cover, topographic form, soil and lithology, and divided the landscape landform in the basin according to these features, and obtained different drainage area threshold for different zones. This method improves the disadvantage of inaccurate tributaries extraction to a certain extent, but the more characteristic data required by the method also brings difficulties to the application of the method. Different local characteristics of the water system have brought obstacles to the determination of the drainage area threshold. In order to improve the optimal threshold determination method and thereby improve the accuracy of the extracted river network, and use as little feature data as possible, many scholars have conducted further research. (Lin Wen-Tzu et al., 2006) track the flow path from the source to the water outlet, and set the optimal drainage area threshold by analyzing the simulated channel length and the actual channel length. However, this method is affected by the deviation of the length of the intermediate water system, which leads to the inaccuracy of the drainage area threshold. In order to determine the drainage area threshold simply and efficiently, (Kong et al., 2005, Yang et al., 2009) plotted the relationship curves of river source density (or river network density), river slope and drainage area threshold, and regarded the threshold corresponding to the curve inflection point as the optimal drainage area threshold. Whereas the artificial determination of the inflection point did not significantly improve the subjective problem in the threshold determination process. So as to avoid the subjective problem of setting the threshold, (Yang et al., 2011, Li et al., 2012) fitted the regression equations of the drainage area threshold with the fractal dimension of the river network and the average bifurcation ratio of the valley floor to realize the fast and accurate determination of the drainage area threshold. The objective parameters required by this method are affected by different fractal dimensions in different regions of the watershed, and there is a problem that the regression equations in some regions are not rigorous enough. In order to fully consider the watershed topography and hydrological characteristics, (Han Ling et al., 2020) Based on the ROC curve to analyze the influence of the cumulative accumulation on the channel to determine the drainage area threshold. Yet, different starting points of different channels have different flow accumulation. This method does not set different thresholds for different channels.

Most of the above threshold determination methods are based on the use of topography and statistics to determine a drainage area threshold to extract river network around the entire watershed. The extraction results have inaccuracy problems. While, the entire watershed is divided according to characteristics such as climate and vegetation cover, and the thresholds of different area to extract river network will require more characteristic data to support it. Therefore, using a single data to extract local features and determining the drainage area threshold in different local areas based on local features will likely take into account the different local distributions and can use a single data source to extract more accurate river network.

2 Research Method

2.1 Method Overview

The drainage area threshold is not only related to terrain, climate, vegetation, geological characteristics, etc, but also to spatial changes. This also determines that the spatial distributions of the drainage area threshold is uneven and will change due to different underlying surfaces(Li et al., 2006) Most of the existing methods for determining the drainage area threshold adopt a single threshold for the entire study area. The single threshold is feasible when the underlying area of the study area is relatively uniform and the watershed space area is not large. However, when the basin area is large, the spatial impact of the threshold on the basin will be reflected. If the entire basin uses a threshold to extract the river network, although the overall effect is good and the main river network can be extracted, but many local details will be ignored and the tributaries cannot be well expressed. Therefore, dividing large watersheds and setting different drainage area thresholds for each sub-watershed are expected to improve water extraction results. Whereas, the existing methods for dividing large watersheds are mostly based on characteristic data such as climate, vegetation cover, topographical morphology, and soil. The difficulty in obtaining data has led to the inability to widely use the method. In view of this, this paper proposes an adaptive river network extraction method using local features of the water system. The main contributions of this method are:(1) Taking full account of the spatial variability of watershed terrain, the entire watershed is appropriately divided into multiple sub-watersheds, and different drainage area thresholds are set to extract the river network.(2) The experimental data only needs the basin DEM data, which is more convenient to obtain.(3) The threshold determination method is introduced into the mean of change-point analysis method in statistics combined with the t value method, which is not affected by human subjective factors.

2.2 Method Design

2.2.1 DEM Pre-procession

（1）Depression Fill

The depression is the local lowest point, and the flow direction of this point cannot be determined. Therefore, in the process of extracting the river network, the depression must be treated. The most common way is to use depression filling treatment. The basic principle is to search each grid point in the data, find grid points that are smaller than the surrounding points, and treat them as depressions. The surrounding points are regarded as depression outlets, and then increase the elevation inside the depression to the outlet of the depression.

（2）FlowDirection Calculation

The flow direction has single flow direction and multiple flow directions. Among them, the D8 algorithm is the most widely used in the single flow direction calculation method, the flow direction is calculated by the maximum distance weight difference, which is the current calculation method adopted by mainstream GIS software. The D8 method sets only eight possible flows in the grid of each unit, clockwise from east to northeast, and can be expressed by 1, 2, 4, 8, 16, 32, 64, 128, water flows into eight adjacent grids, as shown in Figure 1. On a 3 × 3 DEM grid, calculate the distance weight drop between the center grid and the adjacent grid, and take the maximum value as the outflow grid of the center grid. This direction is the flow direction of the center grid, as shown in Figure 2.

（3）FlowAccumulation Calculation

According to the obtained water flow direction data, calculate the range of the upstream catchment area of each grid unit. That is determine the number of specific upstream grid units that cumulatively point to the grid unit, as shown in Figure 3.

2.2.2 Main river network Extraction and Dividing

Tarboton proposed a criterion to help extract the appropriate valley density of the gully network(Tarboton et al., 2001), referred to as the t criterion, as a method to determine the drainage area threshold. The criterion is established by the difference index of the average drop of different levels of river network under multiple thresholds. The calculation formula is:

$$\mathrm{t} = \frac{\bar{a}-\bar{b}}{\sqrt{\frac{(n_a-1)S_a^2+(n_b-1)s_b^2}{n_a+n_b-2}}\sqrt{\frac{1}{n_a}+\frac{1}{n_b}}} \qquad (1)$$

Among them, $\bar{a}$、$\bar{b}$ represent the mean of two different levels of river network, s_a^2 and s_b^2 represent the mean square error of different levels of river network, n_a and n_b represent the number of samples of different levels of river network. The larger the value of t, the greater the difference in the mean value of the water drop, and the larger the catchment area needs to be. When the absolute value of t is less than 2, it is statistically significant that the difference between the two samples is small, so the minimum cumulative watershed confluence corresponding to the absolute value of t is less than 2 as the threshold.

This paper first determines the threshold value of the entire area according to the t criterion, extracts the main river network and divides the watershed. The advantages and disadvantages of watershed division directly affect the final effect of the multi-threshold constraint method. This is the first step of the multi-threshold constraint but also the most important step. If the divided area is too large, the details in the watershed cannot be extracted well. If the area is too small, the fine and cut trenches will be mistakenly included in the river network, resulting in the existence of pseudo-channels. When dividing the watershed, it is necessary to judge the true flow direction of the river network, remove the false watershed, and reasonably divide the watershed into small areas of relatively uniform size. It is worth noting that the division of the watershed refers to the division of the flow accumulation, not the division of DEM. Through practice, it is found that if the DEM data is segmented, it is necessary to recalculate the fill, the flow direction and the flow accumulation. The extracted river network will be disconnected at the junction of the respective watersheds, which is not in line with the actual phenomenon. This is because the segmented DEM is independent data, and does not link the overall situation. Recalculating the fill, flow direction, and flow accumulation can only obtain the river network information in each sub-basin.

2.2.3 River network Extraction

Experiments have found that for the sub-watersheds after division, the river network extracted using the threshold determined by the t criterion can better represent the main watershed, but there are serious problems of lack of tributaries, resulting in a situation that does not match the real river network. To this end, this paper introduces the mean of change-point analysis method to further accurately select the threshold, and then improve the extraction of the local river network.

As a mathematical statistical analysis method for processing nonlinear data, the mean of change-point analysis method is especially effective for the test with exactly one change point(Xiang et al., 2000), and is widely used in the research of the determination of suitable analysis windows in digital terrain analysis(Han et al., 2012; Hu et al., 2017). The calculation idea is as follows: with sample sequence Ao:

（1）Make j=2,3,4,…,M，divide the sample into two segments for each j：$M_1,M_2,\ldots,M_{j-1}$ and $M_j,M_{j+1},\ldots,M_N$. Calculate the $\overline{x_{11}}$ and $\overline{x_{12}}$ and statistics of each sample:

$$S_j = \sum_{t=1}^{j-1}(X_t - \overline{X_{J1}})^2 + \sum_{t=j}^{M}(X_t - \overline{X_{J2}})^2 \quad （2）$$

（2）Calculate the statistics of the overall sample:

$$\bar{X} = \sum_{t=1}^{M} X_t / M \quad （3）$$

$$S = \sum_{t=j}^{M}(X_t - \bar{X})^2 \quad （4）$$

The principle of the mean of change-point analysis method is that the gap between the statistic S of the original sample and the statistic S_j after the sample division will become larger due to the existence of the change point, so that the samples gradually tend to be gentle.

This paper first uses the t criterion to set a threshold for each sub-basin after division from small to large and calculates the corresponding t value. Then the mean of change-point analysis method is used to find the change point. The threshold corresponding to the change point is the optimal threshold of the sub-basin. According to this threshold, the minimum drainage area threshold is set, and the river network of the sub-basin is extracted. Finally, the river networks extracted from each sub-basin can be combined to form the final river network of the entire large watershed.

3 Research area Profile and Data Sources

3.1 Research Area Profile

This paper selects the Jiuyuangou watershed in the Loess Plateau as the experimental sample area. The Jiuyuangou watershed is affiliated to Suide County, Yulin City, Shaanxi Province, China, and is a first-level tributary on the left bank of the Wuding River. It lies within 110°15′—110°22′ east longitude and 37°29′—37°39′ north latitude. The watershed area is about 69.7km^2(Wang et al., 2016). The region is a typical landform type in the loess hilly and gully region of the Loess Plateau, with an altitude between 820-1180m above sea level and a ravine density of 5.34km/km^2(Huang et al., 2020).

3.2 Data Sources

The experimental basic geographic information data in this paper comes from China National Basic Geographic Information Center. The data uses D_Krasovsky_1940 custom coordinate system and the resolution is 5m. The specific data information is shown in Table 1:

The original DEM data is shown in Figure 4:

4 Results and Analysis

4.1 Drainage results of multi-threshold constraint method

Firstly, according to the formula (1), the t-value of the average difference of different levels of river network in the study area is calculated. The results are shown in Table 2. It is found that when the t value is less than 2, the corresponding threshold value is 60000, and the study area threshold is set to 60000 to extract the river network in the research area, as shown in Figure 5.

Secondly, the river network extracted above is divided into watersheds. Under the condition of satisfying the actual flow pattern, it is reasonably divided into 7 sub-basins in Figure 6, where the numbers 1-7 represent the code each sub-basin.

Then increase the threshold from small to large, set the initial value to 100, accumulate 10 in sequence, and calculate the t value corresponding to each threshold until the absolute value of t is less than 2, as shown in Table 3.

Then use the mean of change-point analysis method to find the change point in sub-basin code 1, as shown in Figure 7. When the threshold is 880, the difference between S and S_j is the largest, forming a change point. By analogy, the watershed change points of watershed codes 2-7 are calculated respectively, and the optimal thresholds of each sub-watershed are obtained. The results are shown in Table 4.

Finally, the river network extracted from each sub-basin according to the corresponding threshold in Table 4 is obtained. The effect is shown in Figure 8.

4.2 Drainage results of other methods

In order to verify the river network accuracy of the threshold extraction determined by the above multi-threshold constraint method through a comparison method, other methods need to be used to compare the river network accuracy. Since the key of this paper is to determine the threshold of the river, the threshold needs to be used as a variable, and the extraction method of the river network remains unchanged. Under the premise of the extraction method of the river network adopted in this paper-the principle of slope runoff extraction, a single t value determination method and river network density these two methods are used to extract the river network. Both of these methods meet the premise of the slope runoff principle, but the selection of the threshold is different.

4.2.1 Drainage results by single t value method

Increase the threshold from small to large, set the initial value to 100, accumulate 10 in sequence, and calculate the t value corresponding to each threshold until the absolute value of t is less than 2, as shown in Table 5.

Then use the mean of change-point analysis method to find the change point in the study area, as shown in Figure 9. The calculation results show that when the threshold is 1860, the difference between S and S_j is the largest, forming a change point. The threshold value of the optimal catchment area obtained by this single t value determination method is 1860, and the corresponding river network diagram is shown in Figure 11.

4.2.2 Drainage results of river network density method

River network density refers to the length of the river per unit area in the basin(Cheng et al., 1986). The unit is generally expressed in km/km^2. The mathematical expression is:

$$E = \frac{\sum C}{F} \tag{5}$$

Among them, E refers to the density of the river network, $\sum C$ refers to the total length of the river within the area of the F basin, and F is the total area of the basin.

River network density is a macro factor describing the development of a river. The larger the value, the more fragmented the surface, the lower the stability of surface material, and the easier it is to form surface runoff. River network density is easy to find and is often used as a method to determine the optimal drainage area threshold of a watershed(Li et al., 2018)

The specific method is to increase the threshold from small to large, set the initial value to 100, accumulate 10 in sequenc, and calculate the density of the river network corresponding to each threshold. Some thresholds correspond to the density of the river network as shown in Table 6:

The relationship curve between the drainage area threshold and the river network density is shown in Figure 10:

Subsequently, the density of the river network corresponding to different thresholds is subtracted from each other. According to statistics, the first-order difference of a set of data (the difference between the two data before and after) is less than 10^{-6}, which can be regarded as the data tending to be stable. Based on this idea, the threshold value of the relationship between the drainage area threshold and the density of the river network tends to be stable at 1250. The optimal drainage area threshold value obtained from this river network density method is 1250, and the corresponding river network diagram is shown in Figure 11.

4.4 Drainage quality evaluation

Before evaluating the quality of the river network, a river network reference standard needs to be selected to compare and verify the accuracy of the river network extracted by the thresholds determined by the above three methods. By establishing mountain shadows in the study area in ArcGIS 10.2 and performing manual vectorization, a real reference river network is obtained, as shown in Figure 11.

Through intuitive visual observation, we can see that three methods for determining the threshold of the river network: the multi-threshold constraint method, the single t value determination method and the river network density method can extract the shape of the main river network in the study area, but the results of the treatment of tributaries are very different.

Compared with the real reference river network, the river network extracted by the single t value determination method with the threshold value of 1860 has too many tributaries missing, and it is not as good as the multi-threshold constraint method in the treatment of watershed details. And the classification of the river network is unreasonable, the rivers of all levels are showing a decreasing trend, and the treatment of tributaries is obviously less than the real reference river network. Therefore, in addition to the shape of the channel, the physical meaning it represents is actually not as good as the multi-threshold constraint method from the figure.

Compared with the real reference river network, the river network diagram extracted by the river network density method represented by the threshold value of 1250 is not accurate in local tributaries. The tributaries of sub-basin code 5 in the lower left area are somewhat sparse compared to real reference river network, and the tributaries in most other areas are sparse compared to real reference river network. Similarly, the classification of the river channel is not accurate enough, which is quite different from the classification of the real reference river network. In order to further proceed from the perspective of the data itself, the following will analyze the accuracy of the river network extracted by the three threshold determination methods: multi-threshold constraint method, single t value determination method, and river network density method through more rigorous two river network quantitative indicators.

4.4.1 Average branching ratio

The branching ratio refers to the ratio of the number of channels of a certain level to the number of channels of a higher level(Lu et al., 2016). Expressed as:

$$\mathrm{r_b} = \frac{n_x}{n_{x+1}} \tag{6}$$

Among them, r_b is the branching ratio, r_b is the number of river channels of level x, and n_{x+1} is the number of river channels of level x+1.

The average branching ratio refers to the cumulative total of the product of the branching ratio of adjacent channels in a river network and the total number of adjacent two-level channels divided by the cumulative total of adjacent two-level channels. Although the number of channels will change with the change of the threshold, the ratio of the number of channels at different levels is almost unchanged, and the average channel branching ratio will also tend to be stable, close to a constant. The channel branch ratio is often used to compare the branching capacity of the river network, and can be used as a quantitative evaluation index of the river network.

According to formula (6), the average branching ratio of the multi-threshold constraint method is 4.94, and the specific calculation situation is shown in Table 7. By analogy, the average branch ratio of the river network in the study area is calculated by the single t value determination method and the river network density method. The average branch ratio of these three methods and the average branch ratio of the real reference river network are shown in Table 8. It was found that the difference between the multi-threshold constraint method, the single t value determination method, the river network density method and the real reference river network method were 0.58, 1.05, 1.01. The average branch ratio corresponding to the multi-threshold constraint method is the smallest difference from the real reference river network method and is closest to the real average branch ratio. The difference between the other two methods is more than 1, which is far from the true value. The single t value determination method has a greater difference.

4.4.2 Average length ratio

The average length ratio refers to the ratio of the average length of the tributaries of a certain level to the average length of tributaries of the lower level(Zhang et al., 2004), which is one of the most commonly used indicators for evaluating the shape of the river network. Since the number of river channels at each levels has different effects on the calculation of the average length, different weights need to be set. The calculation idea is as follows:

a: First, according to the attribute information, the total length of the river network at each levels is counted.

b: Secondly, divide the total length of tributaries by the number of rivers of the corresponding level to obtain the average length of tributaries of this level.

c: Then, the length ratios of the first-level tributaries and other high-level tributaries are calculated in sequence, and the arithmetic average of the length ratio of the first-level tributaries is obtained, and then multiplied by the weights corresponding to the first-level tributaries, and so on for the other levels.

d: Finally, the arithmetic average of the weighted length ratio of all levels of tributaries is added, and the result is the average length ratio of the entire river network.

The weight setting idea is: if the river network is k-level, the total length ratio between the tributaries of each levels is k(k-1)/2, and the length ratio of the first-level tributaries to other levels has k-1, so the weight of the first-level branch is 2/k, and the weight of the other-level branches is set by analogy.

According to Houghton's river network theorem, the average length ratio is calculated for the multi-threshold constraint method. The calculation process is shown in Table 9, and the result is 9.30. By analogy, the calculation of the average length ratio of the three methods is shown in Table 10. Compared with the average length ratio of the real river network, it is found that the single t value determination method and the river network density method are quite different. Although the average length ratio of the river network extracted by the multi-threshold constraint method is different from the real value, this difference is the smallest of the three methods. The difference between the three methods and the real reference river network are 1.99, 1.03, and 0.30. The average length ratio of the multi-threshold constraint method is the closest to the real value.

5 Conclusion

The determination of the drainage area threshold is the key to the extraction of river network using hydrological analysis methods. In the existing river network extraction methods, the determination of the drainage area threshold has problems such as inaccurate extraction of the river network with a single threshold and difficulty in obtaining data with multiple threshold. Aiming at the problem of how to determine the threshold of the watershed extraction watershed, based on the DEM data of the Jiuyuangou watershed in the Loess Plateau, a comprehensive t value determination method and mean of change-point analysis method, a multi-threshold constrained watershed area threshold based on the local characteristics of the river network is proposed. First, use the t criterion to calculate the drainage area threshold of the entire basin and extract the main river network information. Second, divide the watershed to obtain sub-basin information. Then, the mean of change-point analysis method is used to find the threshold of the sub-watershed, and the sub-watersheds are combined to form the final complete watershed. Finally, the average branch ratio and average length ratio are introduced to quantitatively evaluate the quality of the river network with the threshold determined by the multi-threshold constraint method, the single t-value determination method and the river network density method. The experimental results show that the multi-threshold constraint method proposed in this paper breaks the idea of one threshold corresponding to one watershed in the traditional method for determining the threshold value of the extraction watershed. Taking full account of the spatial variability of the watershed topography, the extracted river network has the smallest difference from the real reference river network, the highest accuracy and the closest to the true surface morphology, which provides a new choice for the determination of the drainage area threshold in hydrological analysis.

It is worth noting that the experimental area selected in this paper is located in the Loess Plateau. The proposed multi-threshold constraint method can theoretically be adapted to the extraction of river network in other geomorphic areas.The next study will compare the adaptability of the method to the extraction of river network in other geomorphic areas.

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