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Quantitative Characterization of Channel Morphology and Main Controlling Factor of Shallow Water Delta—A Case from Ganjiang Delta, Jiangxi, China

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Abstract: (1) This paper selects the modern delta formed by the Ganjiang tributary in Poyang Lake. By performing high density statistical analysis of distribution channel parameters in the area using satellite images and geographic information processing software (LucaSpaceViewer 4.5.2, ArcGIS Pro 3.0.2, Global Mapper v23.1), including length, width, bifurcation angle, bifurcation frequency, and channel sinuosity, the distribution characteristics of delta distribution channels are derived and quantitatively characterized. (2) Classification and evaluation of these characteristics are carried out using factor and cluster analysis, ultimately identifying controlling factors affecting the morphology and distribution of the distribution channels. By statistically analyzing the geometric and bifurcation data of the channels, factor and cluster analysis for data reduction and classification, the channel is finally divided into three categories: Type I channels have relatively high channel length, width, sinuosity, bending amplitude, and a lower bifurcation (or confluence) growth rate; Type II channels are characterized by low channel length, moderate channel width, low sinuosity, low bending amplitude, and a high bifurcation (or confluence) growth rate; Type III channels are defined by moderate channel length, low width, high sinuosity, high bending amplitude, and low bifurcation (or confluence) frequency. (3) After excluding the influence of other factors, it was found that the main controlling factor for the morphology of the Ganjiang Delta channel is flow velocity, which is influenced by changes in the terrain slope. Flow velocity directly affects channel sinuosity, bending amplitude, and bifurcation (or confluence) frequency, and indirectly affects channel length and width.

Keywords: Poyang lake; Ganjiang delta; channel distribution; quantitative characterization; factor and cluster analysis

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1. Introduction

The shallow water delta is a type of delta dominated by river processes, typically developing in large open-flow depressional basins with shallow water, abundant supply, stable or gently sloping landforms, and slow overall subsidence. It can be divided into two types: channel delta and sandbar delta [1–6]. As one of the main types of sedimentary reservoirs in oil and gas basins, shallow water deltas have become an important object of oil and gas exploration and a hot topic in sedimentary research in recent years. Significant research has been carried out on (1) the sedimentary characteristics of shallow water deltas: Shallow water deltas deposited above the wave base, with some typical characteristics such as underwater distributary channel and distributary channel sandstone as the skeleton sand body, widely distributed frontal sheet sands, prodeltas in shallow water, discontinuous vertical sequence, and not the typical Gilbert three-layer type of the progradational configuration [7–10]; (2) sediment models of shallow water deltas: according to the different evolution of distributary action, when the water body is very shallow, the deltaic progradation is easy to form branching distributary channel type shallow water deltas, and distributary channels and natural levees are extremely developed. When the water body is relatively deep, the distributary channel will accumulate mouth bar or distributary bar at the channel branch, and the distributary channel sand body is connected to form the polygonal front sand body [10–13]; and (3) sediment characteristics of shallow water deltas: the distributary sand body is extremely developed, and sheet sands at the outer edge of the mouth bar, including natural levee, crevasse splay, overbank discontinuous sand and so on, can become the connected reservoir. In the contiguous distributary sand-bar delta, the sandstone body has good connectivity and a large distribution area, and most of the structural reservoirs are formed. The delta distribution channel makes it easy to develop lithologic reservoirs because of its isolated sand bodies, small distribution area and poor connectivity [9,10,14,15]. However, relatively little research has been done so far on modern shallow water delta deposition.

Modern deposition, as an important data source for sedimentology, plays a crucial role in guiding the overall study of shallow water deltas. With the application of satellite imagery in modern sedimentary research, it has played an important role [16,17]. For example, Yin (2012) used satellite imagery to describe modern sedimentation in the Dongting Lake and Poyang Lake estuaries, analyzing sand body development characteristics [18]. Sun (2015) used satellite images to statistically analyze changes in parameters such as bifurcation angles, bifurcation frequency, curvature, and width of river channels [19]. Coffey (2017) measured delta and tributary river network bifurcation angles and summarized patterns of delta distribution channel bifurcation angle variation [20].

Previous research on the morphology of river channel distribution has focused on quantitative characterization of specific channel types or summarizing or describing channel patterns based on spatial distribution. However, there is a lack of systematic statistics on river channel parameters, objective classifications, and in-depth studies on factors influencing river morphology. These gaps pose challenges for detailed descriptions of delta sand bodies and reservoir prediction.

Modern sediment surveys are the most basic and effective methods for understanding sediment characteristics and establishing sediment models, which have long been a focus of sedimentologists and have played a critical role in the development of sedimentology. Gilbert proposed the three-layer structure of deltas based on observations of modern lacustrine basin sediments [21], while Miall developed the modeling and structural analysis method through studies of modern river sediments [22], which became a milestone in sedimentological research. Therefore, this paper uses the modern river channels of the Ganjiang Delta on the southern side of Poyang Lake as an example, systematically measuring satellite images to quantitatively characterize the morphological characteristics of Ganjiang river channels, objectively classifying them, and summarizing the main controlling factors. Quantitative analysis of these parameters will be used to classify and summarize control factors. This research aims to provide data and a theoretical basis for the study of modern delta river sedimentation and the prediction of ancient delta reservoirs.

2. Geologic Background

The Ganjiang Delta in Poyang Lake is located in northeast Nanchang, Jiangxi Province, China. It is an inland lake basin formed under the continuous expansion of the ancient Ganjiang River, influenced by neotectonic movements and rising flood levels of the Yangtze River [17]. Located on the south bank of Poyang Lake, the Ganjiang River Delta is the largest and most developed delta in the Poyang Lake region [23], with an area of about 1600 km^2 [24]. The channel type is either a meander river with low curvature, or a straight river [16]. Ganjiang is the largest tributary flowing into Poyang Lake, with its watershed accounting for 50% of Poyang Lake's total drainage area. This delta features extensive plains, a rich channel network, and numerous lakes and marshlands.

Poyang Lake is heavily affected by the climate. In the rainy season, the surface area of the lake can reach 4225 km^2, while in the dry season, the surface area of the lake is only

244 km^2, and the difference in water level can reach 9.09 m [25]. The delta plain starts from the middle branch of Ganjiang River to the lake. During the rainy season, parts of the delta plain are submerged by lake water. During the dry season, as Poyang's water level drops, submerged delta plains are exposed again. According to whether the delta plain is affected by lake inundation or not, the delta plain is divided into the upper delta plain and the lower delta plain (Figure 1). The delta front and pre-delta are developed in the part that is underwater all year round. The Ganjiang River Delta is a typical river-dominated delta, with a length of about 70 km and its formation is mainly affected by changes in the terrain and lake water level [16].

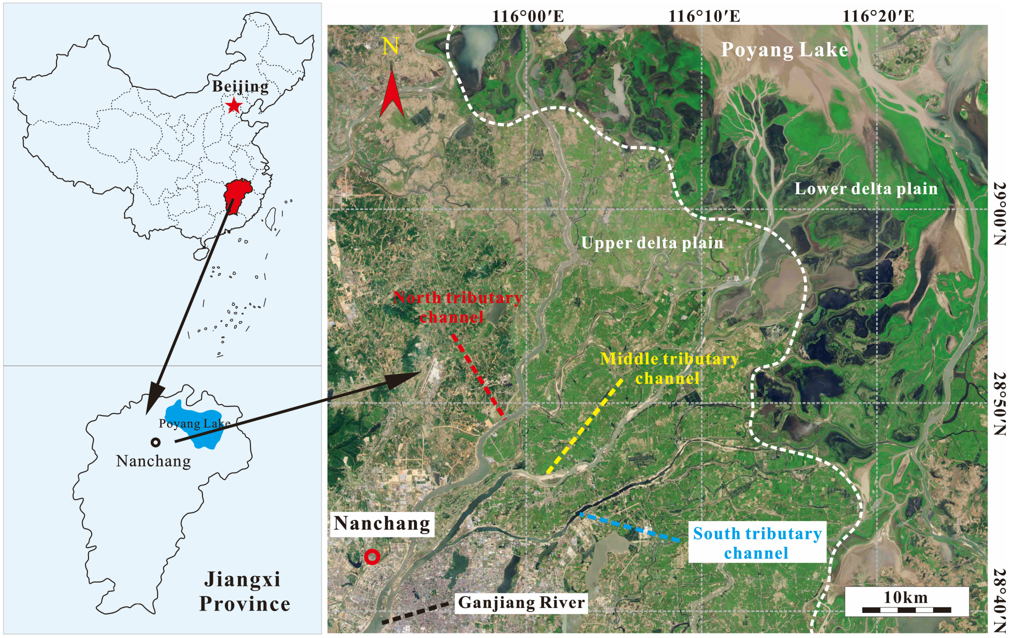

Figure 1. Geographical Location of the Ganjiang Delta.

The delta is further divided into the upper delta plain, lower delta plain, delta front, and prodelta. The upper delta plain is relatively long, spanning about 40 km~50 km, and remains above the water surface for extended periods. The lower delta plain is shorter, about 10 km~20 km, and lies between mean high and low water levels. During flood seasons, the lower delta plain is submerged in the waters of Poyang Lake, and during the dry season, as the water level recedes, this lower plain is exposed above the lake surface [26].

3. Materials and Methods

The study method of this paper mainly includes two parts: statistical data methods and data processing methods. Data statistical methods are mainly used to measure or calculate the shape parameters of the channel, such as the actual length, straight length, channel width, bending degree, bending amplitude, branching angle and channel deflection angle. In the data processing part, factors and cluster analysis are used to reduce and classify the collected channel morphology parameters.

3.1. Data Statistical Methods

This paper focuses on the delta formed by the middle tributary of Ganjiang River in Poyang Lake, covering the distribution channels from the delta plain to the lakeshore. To eliminate the influence of other factors, channels affected by confluences and human activities were excluded from the analysis, ensuring that the measured channels are effective, contemporaneous sedimentary channels within the same hydrodynamic system. Using Google Earth, high-resolution satellite images were obtained, and study channels were numbered (Figure 2) for factor extraction. The bifurcating (deflection) angle of the river is measured by LucaSpaceViewer 4.5.2, the length and width of the river is measured by the surface distance obtained by ArcGIS Pro 3.0.2, and the elevation data is read by the topographic map in the Global Mapper v23.1. The planar geometric parameters of the distribution channel are measured and quantitatively characterized by the high density measurement method of systematic sampling, which provides data support for subsequent numerical analysis. The highest resolution of satellite images is 0.5 m.

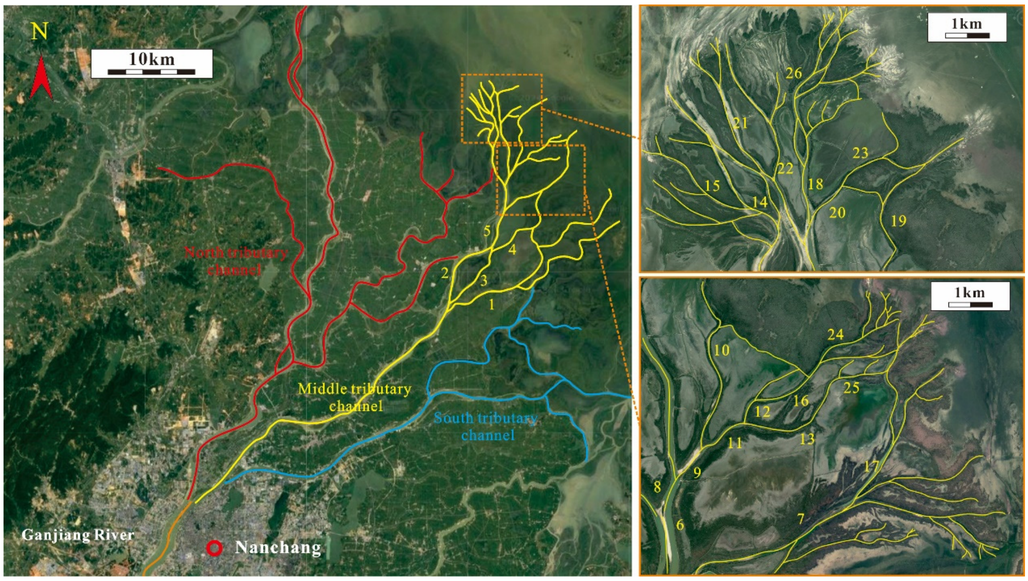

Figure 2. Chart of Channel Distribution and Numbering in Ganjiang Delta.

(1) Measurement method of channel width. In measuring channel width, the measurement line is perpendicular to the flow direction at the measurement point. About 100 m after the bifurcation, the width tends to stabilize; therefore, this study uses the width of the water body at 100 m from the bifurcation as the width of the post-bifurcation channel (Figure 3a). Satellite images reveal clear channel boundaries, with a maximum measured width of approximately 650.0 m and a measurement error of 1.0 m~5.0 m.

(2) Method for calculating channel sinuosity. Although the conventional channel sinuosity coefficient effectively indicates the degree of channel meandering, it does not provide a precise and intuitive measure of the bending amplitude. Therefore, this study also quantifies the channel's bending amplitude. Channel sinuosity is represented by the sinuosity coefficient, defined as the ratio of the actual length of the channel segment from the first bifurcation to the next bifurcation (or lake inlet) to the straight line length of that segment (Figure 3a). The bending amplitude is the ratio of the maximum distance between the channel segment from the first bifurcation to the next bifurcation (or lake inlet) and the straight line length of the segment (Figure 3a).

(3) Measurement of Bifurcation and Deflection Angles. The bifurcation angle is defined as the angle α between the two distributary channels (Figure 3a), which aids in the precise description of the delta's distributary channel morphology. The deflection angle of the bifurcation is the angle [20] between the angle bisector of the bifurcation angle (β) and the flow direction at the channel bifurcation point (Figure 3b).

(4) Statistical method of channel bifurcation (or confluence) frequency. In this paper, an arc-shaped cross section with a 5 km spacing is used, with the first bifurcation point of the upper plain channel of the delta as the origin. Bifurcation and confluence events of delta distribution channels are then recorded (Figure 4). Channel bifurcation (or confluence) frequency refers to the number of bifurcations (or confluences) that occur per unit distance.

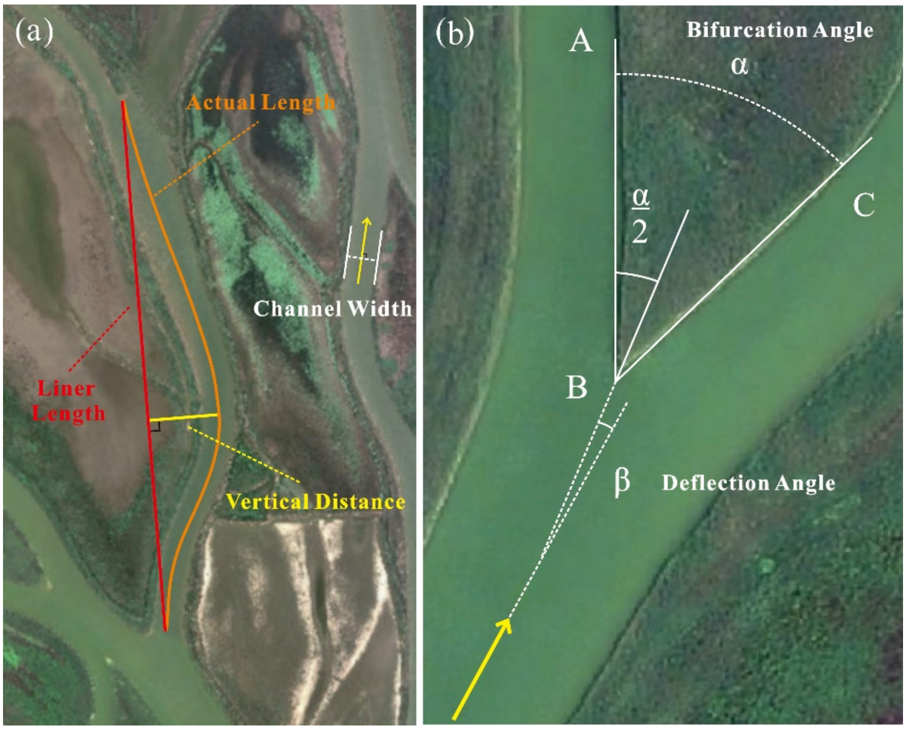

Figure 3. Quantitative statistical method for distribution channel morphology parameters. (**a**) Quantitative statistical method of channel liner length, actual length and channel width; (**b**) Quantitative statistical method of bifurcation Angle and bifurcation deflection Angle.

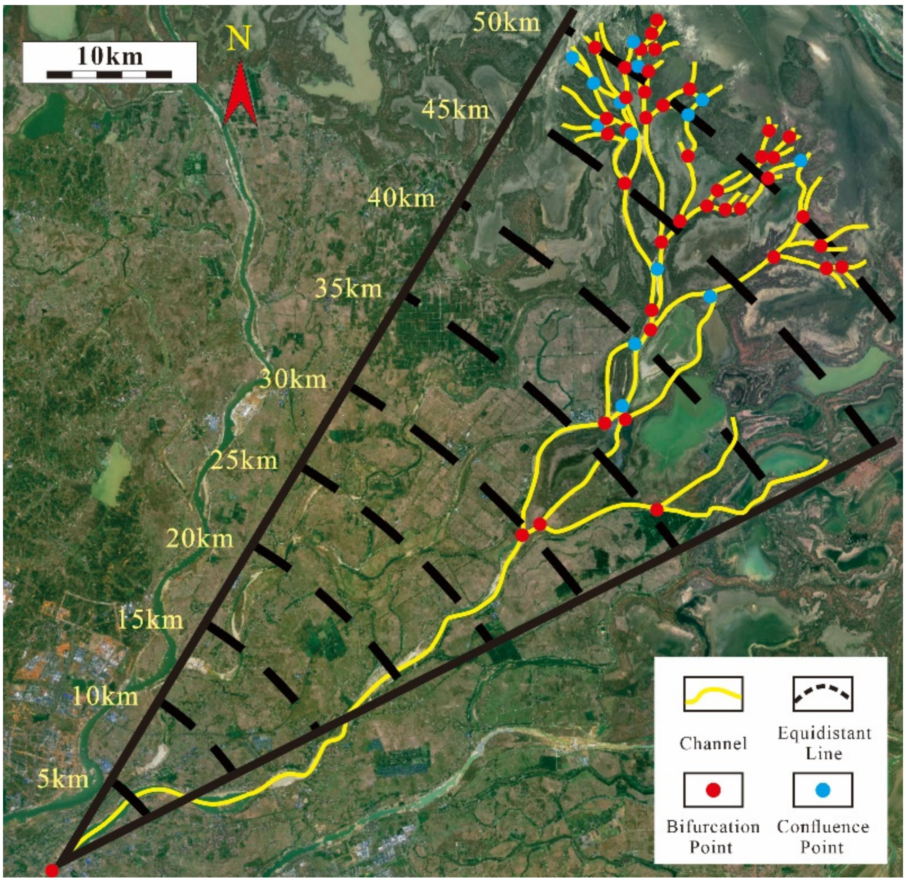

Figure 4. Statistical method for bifurcation frequency (confluence) of distribution channels.

3.2. Data Processing Methods

3.2.1. Factor Analysis

Since each river channel has a variety of morphological parameters, it is impossible to determine the characterization of various parameters on the overall morphological characteristics of the channel, so it is necessary to screen out parameter types that have a clear characterization of the morphological characteristics of the river channel. In this paper, factor analysis is used to reduce the dimension of channel morphology parameters, so as to screen out the main parameter types of channel morphology.

Factor analysis is a data simplification technique that extracts common factors from variable groups. It explores the basic structure of observed data by studying the internal dependence relationship between variables and uses a few factors to reflect the primary information of many original variables [27,28]. Factor analysis has the following advantages: (1) The number of factors is much smaller than that of the original variables; (2) factors are not a simple choice of original variables but a new synthesis; (3) there is no linear relationship between factors; and (4) factors can be interpreted clearly, maximizing the role of professional analysis [27].

The analysis includes R-type factor analysis of variable correlation and Q-type factor analysis of sample correlation. Analysis variables are selected to calculate R-type and Q-type factor loading matrices. Later, a planar graph is drawn with the Q-type factor loads F0 and F1 of the sample, and the correlation coefficient matrix of the original variables is calculated. After selecting the analysis variables, their R-type factor loads are projected onto the graph. After factor rotation, a scatter chart of variables and samples is generated, and the factor score is calculated [28]. Accordingly, correlation statistics and analysis between variables and samples are performed, and then the objective classification results of samples are explored [29,30].

Assuming n samples with all variables (m) for each sample, the matrix is:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \tag{1}$$

where $x_{ij} \geq 0$ (i = 1, 2, . . ., m; j = 1, 2, . . ., n), with at least one nonzero point in each row and column. According to:

$$z_{ij} = \frac{x_{ij}\frac{x_i x_j}{T}}{\sqrt{x_i x_j}} \tag{2}$$

x_i and x_j can express as:

$$x_i = \sum_{j=1}^{n} x_{ij} (i = 1, 2, \ldots, m) \tag{3}$$

$$x_j = \sum_{i=1}^{m} x_{ij} (j = 1, 2, \ldots, n) \tag{4}$$

From Equation (2), we obtain Equation (5) [29]:

$$T = \sum_{i=1}^{m}\sum_{j=1}^{n} x_{ij} = \sum_{i=1}^{m} x_i \tag{5}$$

Based on the eigenvalues of the variance-covariance matrix ($\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_m$), the corresponding unit eigenvectors (u_1, u_2, . . ., u_p) are calculated using the first P eigenvalues

(λ_1, λ_2, . . ., λ_p), whose cumulative percentage of eigenvalues is ≥80%, to obtain the R-type factor loading matrix as follows:

$$U = \begin{bmatrix} u_{11}\sqrt{\lambda_1} & \cdots & u_{1p}\sqrt{\lambda_p} \\ \vdots & \ddots & \vdots \\ u_{m1}\sqrt{\lambda_1} & \cdots & u_{mp}\sqrt{\lambda_p} \end{bmatrix} \quad (6)$$

Scatter data analysis based on the matrix is the so-called R-type factor analysis, which indicates the degree of correlation between variables.

The contribution rate of the selected elements was calculated according to the R-type factor loading matrix of the variable analysis. The elements that had a significant impact on sample analysis were screened at the same time. Q-type factor analysis shows the relationship between samples according to the scatter plot of the Q-type factor load matrix on the factor plane. Sample classification was based on the correlation coefficient (C_{ij}) from the Q factor analysis. The correlation coefficient is the angle cosine obtained after data normalization:

$$C_{ij} = \frac{\sum_{t=1}^{n}(x_{ti} - \overline{x}_i)(x_{tj} - \overline{x}_j)}{\sqrt{\sum_{t=1}^{n}(x_{ti} - \overline{x}_i)^2}\sqrt{\sum_{t=1}^{n}(x_{tj} - \overline{x}_j)^2}} \quad (7)$$

3.2.2. Cluster Analysis

Cluster analysis is performed on the dimensionality-reduced dataset by factor analysis to facilitate the subsequent assessment of the main control factors. When performing cluster analysis, it is necessary to quantify and evaluate cluster results. Clustering effectiveness can be assessed using the similarity coefficient. The similarity coefficient between the clustered data y_i and the original signal s_j is defined by Equation (8) [31]:

$$\xi_{ij} = \frac{\left|\sum_{K=1}^{l} y_i(k)s_j(k)\right|}{\sqrt{\sum_{K=1}^{L} y_i^2(k)\sum_{k=1}^{L} s_j^2(k)}} \quad (8)$$

If ξ_{ij} = 1, it indicates that the separated signal y_i differs from the original signal s_j only in amplitude, meaning the separated signal is very pure. If ξ_{ij} = 0, it indicates that the separated signal y_i is completely different from the original signal s_j, and the signal has not been separated. Therefore, the closer the value of ξ_{ij} is to 1, the better the separation effect. To ensure the validity of the separation results, this paper classifies the data using ξ_{ij} = 0.90 as the threshold.

4. Results

In this paper, detailed quantitative parameters of the morphology of the middle tributary channel of the Ganjiang River are obtained by measuring and calculating satellite images. After analyzing the data with factor and cluster analysis methods, river channel types are objectively classified.

4.1. Geometric Parameters of Distribution Channel Morphology

Based on the channel parameters of the Ganjiang Delta tributaries of Poyang Lake (Table 1), it can be seen that the actual channel length in this region ranges from 784.43 m~8017.71 m, and the average length is 2782.04 m. The actual length decreases rapidly as the distance from origin of the channel. The linear length is 746.48 m~7566.27 m, and the mean is 2611.00 m, which has a law of variation similar to the actual length of the channel. The channel width is 30.69 m~462.51 m, and the average width is 122.41 m, which has the same negative correlation with the distance from origin of the channel. Channel curvature is less than 1.20, ranging from 1.00 to 1.19, with an average of 1.05, which decreases slightly as the channel expands. The bending range of the channel is 0.01~0.28, and the mean value is 0.11, which is consistent with the bending degree of the channel. The channel bifurcation angle ranges from 34.14°~94.66°, with an average of 58.37°. The channel bifurcation deflection angle ranges from 2.04°~33.05°, with an average of 9.52°. The bifurcation angle and the bifurcation deflection angle of the channel vary greatly with the channel extension, but there is no obvious law of change.

Table 1. Geometric parameters of the Ganjiang Delta distribution channel morphology.

Channel Number	Distance from Origin (km)	Data of Channel			Data of Channel Bending		Data of Channel Bifurcation	
		Actual Length	Linear Length	Channel Width	Bending Degree	Bending Amplitude	Bifurcation Angle	Deflection Angle
		(m)					(°)	
1	29.63	8017.71	7566.27	93.66	1.06	0.10	76.28	9.27
2	30.56	7554.41	6619.13	228.81	1.14	0.25	54.87	2.77
3	30.64	7404.03	6892.26	184.38	1.07	0.11	58.86	6.24
4	37.51	3888.78	3608.89	90.38	1.08	0.12	55.19	5.32
5	38.08	4066.25	3940.47	307.63	1.03	0.09	46.81	8.81
6	41.47	2768.75	2663.21	462.51	1.04	0.11	61.43	7.73
7	41.62	6349.57	6118.41	171.67	1.04	0.08	28.93	10.58
8	43.47	1275.97	1271.65	257.74	1.00	0.02	70.66	3.07
9	44.66	966.67	965.43	194.18	1.00	0.01	52.31	8.35
10	45.61	3187.23	2983.01	66.31	1.07	0.17	43.52	4.35
11	45.62	1459.21	1407.39	82.33	1.04	0.10	74.07	3.32
12	46.94	784.43	746.48	67.31	1.05	0.14	49.43	8.22
13	46.97	3506.01	2952.78	37.18	1.19	0.28	75.02	24.31
14	47.18	856.97	842.83	111.12	1.02	0.09	62.83	6.58
15	47.19	2738.29	2630.25	63.51	1.04	0.09	64.93	8.01
16	47.63	2307.21	2174.95	64.31	1.06	0.15	58.23	9.82
17	47.71	2020.91	2004.21	94.07	1.01	0.03	46.87	2.04
18	47.96	1459.05	1436.46	148.97	1.02	0.07	54.48	5.66
19	48.01	2043.18	1748.91	49.92	1.17	0.21	31.75	14.02
20	48.06	979.66	972.02	33.44	1.01	0.03	94.66	33.05
21	48.09	2491.32	2422.14	83.57	1.03	0.09	34.14	2.55
22	48.12	1653.11	1597.69	83.37	1.03	0.12	71.96	8.98
23	49.03	1419.07	1351.41	30.69	1.05	0.11	42.32	5.79
24	49.71	1462.75	1350.81	47.02	1.08	0.15	77.38	8.02
25	49.74	774.97	752.31	29.85	1.03	0.11	72.43	30.43
26	50.17	897.47	866.58	98.77	1.04	0.10	58.19	10.12

4.2. Factor and Cluster Analysis

The R-type factor loading matrix of the variable analysis documents a high contribution rate of actual length, linear length, channel width, bending amplitude, and bending degree (Figure 5), indicating a significant impact on the factor analysis results. Therefore, actual length, linear length, channel width, bending amplitude, and bending degree were selected for Q-type factor analysis to constrain the contribution rate of eigenvalues. According to the Q-type factor loading matrix (Figure 6), the scatter plot established on the factor plane is used to analyze the relationship between data and factors.

The variance contribution rate for the first eigenvalue is 52.09%, and the cumulative contribution rate for the second eigenvalue is 85.33% (Table 2). The eigenvalues are directly proportional to the amount of information recorded. The classification effect of samples and variables was maximized for a cumulative contribution rate of >80% [26,29]. The data documents that the first two eigenvalues contain the most information about the sample and its elemental composition.

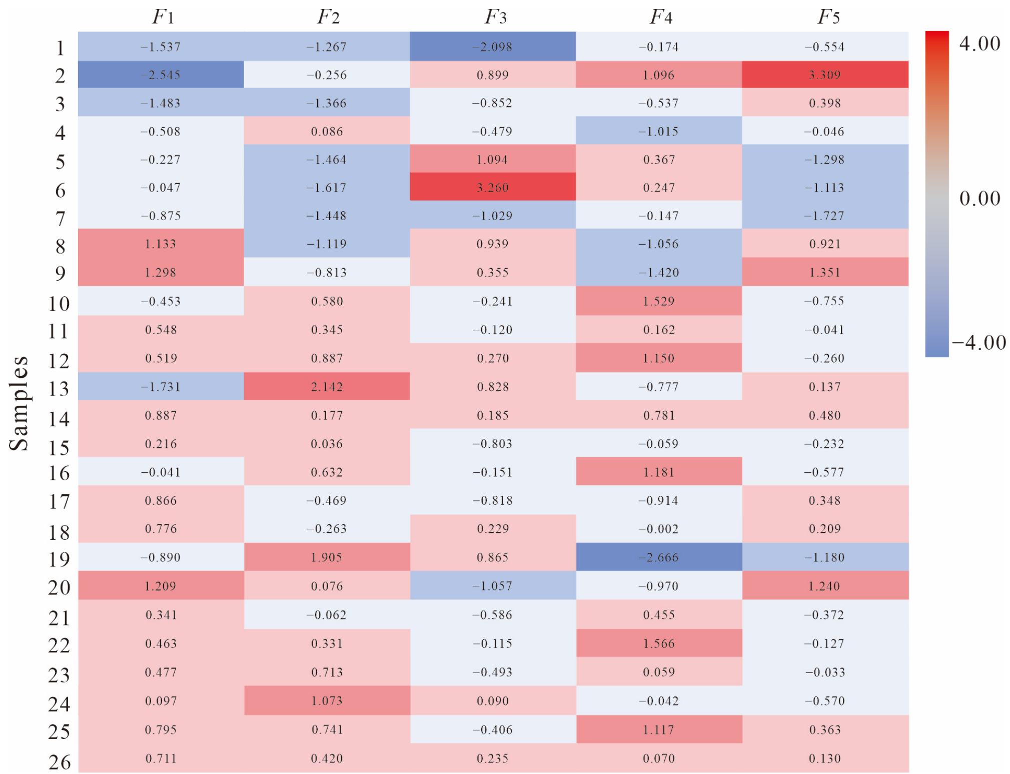

Figure 5. R-type factor load matrix heatmap.

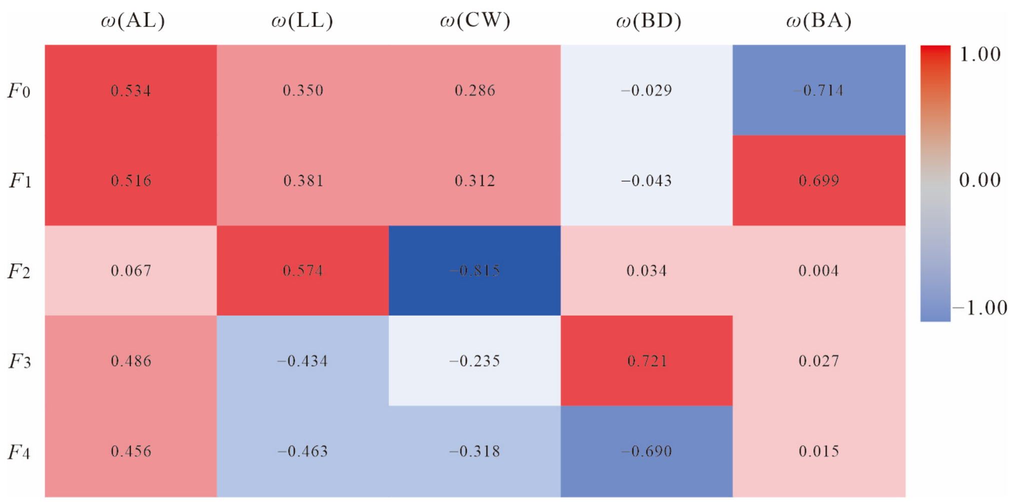

Figure 6. Q-type coefficient score matrix heatmap. (AL: Actual Length; LL: Linear Length; CW: Channel Width; BA: Bending Amplitude; BD: Bending Degree).

Table 2. Contribution rates for factor analysis eigenvalues.

Eigenvalue Variance	Eigenvalue	Contribution Rate	Cumulative Contribution Rate
		(%)	
λ_1	65.114	52.09	52.09
λ_2	41.549	33.24	85.33
λ_3	16.545	13.24	98.57
λ_4	1.777	1.42	99.99
λ_5	0.014	0.01	100.00

Using factor reduction analysis, five types of channel parameters—actual length, straight line length, channel width, bending degree, and bending amplitude—were selected to represent 85.33% of the morphological characteristics of the middle distributary of the Ganjiang River (Table 2). These factors are sufficient to accurately characterize channel morphology and can serve as a reliable basis for classifying channel types. Clustering analysis based on similarity coefficients and using a similarity threshold of 0.90 divided these factors into three types (Figure 7).

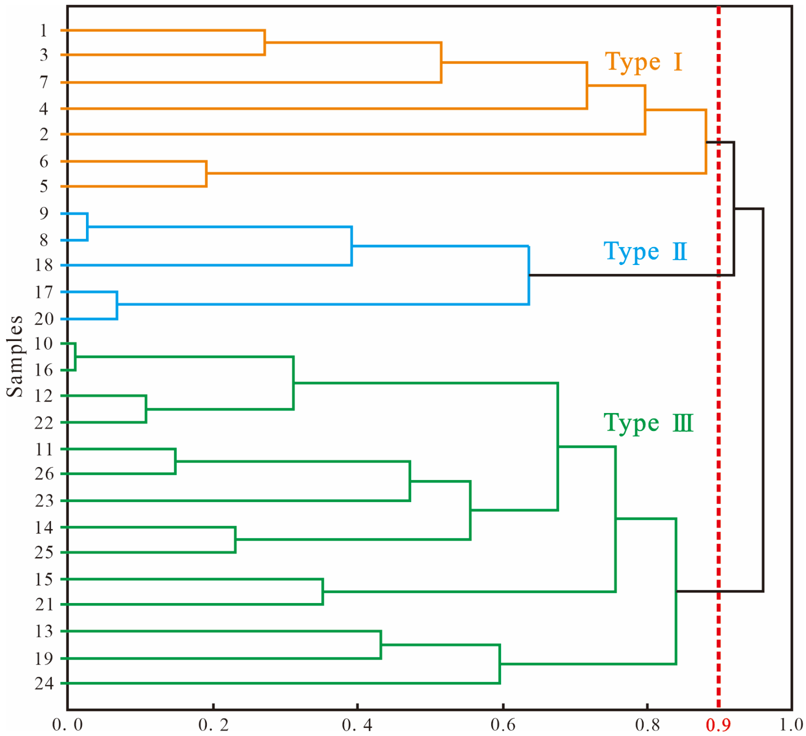

Figure 7. Channel parameter similarity coefficient classification dendrogram.

5. Discussion

Based on the analysis of channel morphology parameters of the Ganjiang River Delta, the following three problems are discussed: (1) variation of channel morphology parameters; (2) classification and distribution of channel morphology; (3) main controlling factors of channel morphology.

5.1. Variation of Channel Morphology Parameters

Based on the analysis of delta morphological parameters of the middle tributary of the Ganjiang River, the following rules are obtained: The middle tributary of the Ganjiang River has relatively few bifurcations in the upper delta plain, resulting in longer individual channels with larger widths. As the river extends into the lower delta plain, the frequency of bifurcation increases, and both the actual length and straight line length of the channels rapidly decrease (Figure 8a). Good data correlation shows that channel length is mainly related to distance from origin. Due to the division of the flow at the bifurcations, the flow volume decreases, causing the channel width to decrease rapidly as the river expands (Figure 8b). The weaker correlation in this case is likely due to the influence of channel confluence and regional geological conditions on channel width.

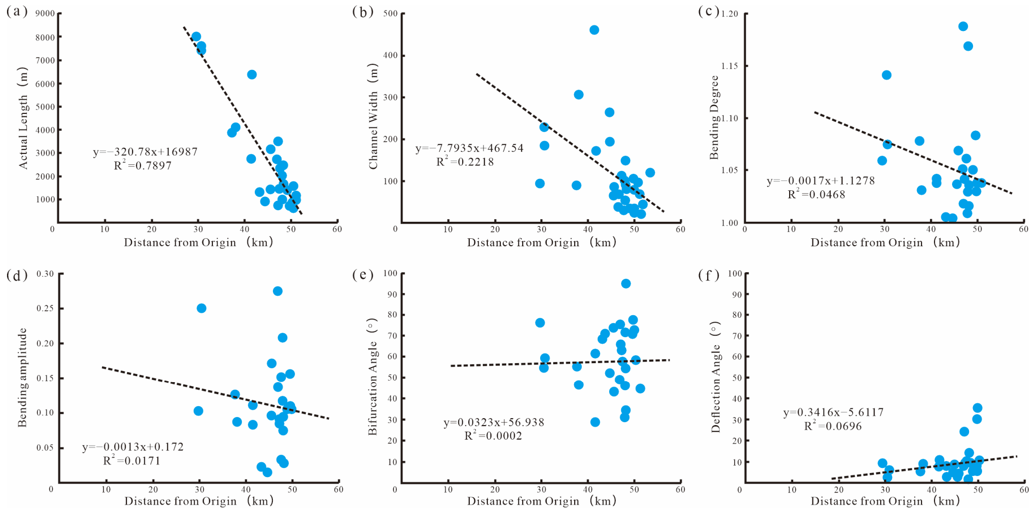

Figure 8. Distribution channel morphology geometric data variation chart. (**a**) actual length; (**b**) channel width; (**c**) bending degree; (**d**) bending amplitude; (**e**) bifurcation angle; (**f**) deflection angle versus distance from origin.

The bending degree of the channel in the study area is less than 1.20, indicating that these are low sinuosity channels. In addition, the degree of bending decreases significantly as the river expands (Figure 8c). The bending amplitude shows a similar trend (Figure 8d). There are no significant changes in the bifurcation angles or deflection angles of the channels as they extend (Figure 8e,f). The poor correlation among sinuosity coefficient, bifurcation, and distance from origin indicates that these factors are not directly affected by the change in distance from origin (Figure 8c–f).

In the Ganjiang River delta, as the river progresses, the number of distribution channels gradually increases from the first bifurcation point, spreading in a fan-shaped pattern. The vertical distance from the first bifurcation point to the terminal lakeshore is 56 km, during which the number of distributary channels increases from 1 to 56 at the lakeshore, with the delta expanding in a fan shape with a spread angle of 28° (Figure 3). The channel bifurcation frequency shows an upward trend (Figure 9a), rising from 0.58 times/km in the upper delta plain to 3.50 times/km in the lower delta plain, although the frequency increase rate decreases significantly. The channel confluence frequency is significantly lower than that of bifurcation, increasing from 0.60 times/km in the upper delta plain to 1.40 times/km in the lower delta plain, with a relatively low growth rate (Figure 9b).

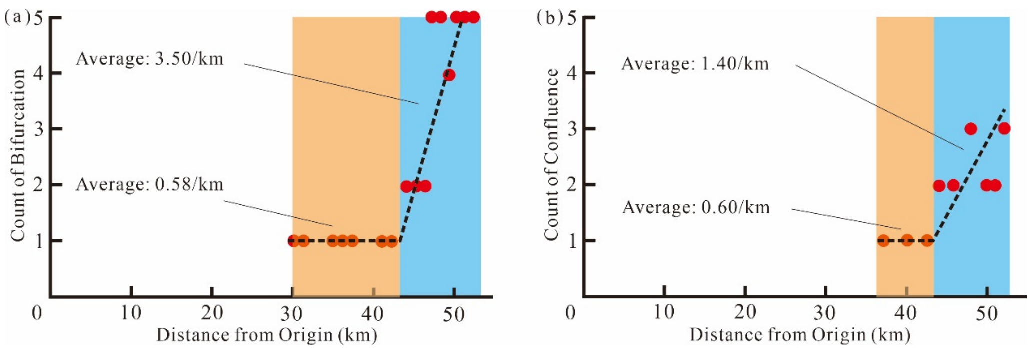

Figure 9. Channel Bifurcation Frequency and Confluence Frequency Variation Chart. Count of (**a**) bifurcation; (**b**) confluence versus distance from origin. (Orange area: Upper delta plain. Blue area: Lower delta plain. Dashed line: trend line of the value change. Solid line: indicator line of mean value).

5.2. Classification and Distribution of Channel Morphology

Since the actual length, linear length, channel width, bending amplitude and bending degree contain most of the information about river channels (Table 2), scatter mapping is performed to reflect the relationships and differences between different types of river channels.

The planar graph of the sample data was plotted using F0 and F1 from Q-type factor analysis. The R-type factor loading matrix (Figure 5) is projected onto the graph to obtain the scatter chart of the factor analysis (Figure 10).

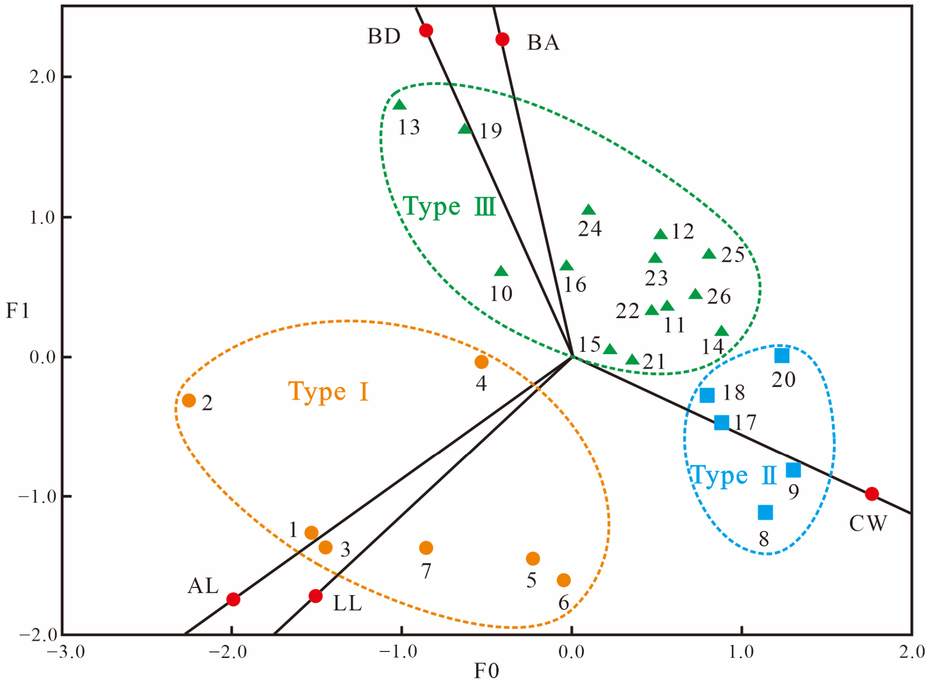

Figure 10. Factor, cluster analysis, and system tract partition diagram. (**AL**: Actual Length; **LL**: Linear Length; **CW**: Channel Width; **BA**: Bending Amplitude; **BD**: Bending Degree).

The type I channel has fewer bifurcations, and individual channels are long and continuous, so the actual length and straight line length are the main distinguishing features. There is no obvious difference between type II channel and type III channel in channel length, but type II channel has higher channel width because it is located in the upper part of the lower delta. Compared with type II, type III channel is mainly characterized by smaller channel width and larger channel sinuosity. These characteristics indicate the gradual development of channel morphology from fewer, longer and wider channels in the upper delta to shorter and finer channels widely distributed in the lower delta.

The five factors obtained by factor reduction—actual length, linear length, channel width, bending degree, and bending amplitude—were cross-analyzed. The results show that the overall classification of different channel types is well aligned with factor analysis (Figure 11), indicating that these five factors are closely related to factors influencing the morphological differences of delta channels.

The main characteristics of these three types of channel morphology are summarized as follows. Type I: Upper delta plain channels, characterized by longer lengths, greater widths, higher sinuosity, greater bending amplitude, and lower bifurcation (or confluence) growth rates; Type II: Upper part of the lower delta plain, marked by shorter lengths, moderate widths, lower sinuosity, lower bending amplitude, and higher bifurcation (or confluence) growth rates; Type III: Located at the forefront of the lower delta plain, where channels have narrower widths, higher sinuosity, greater bending amplitude, and lower bifurcation (or confluence) frequencies.

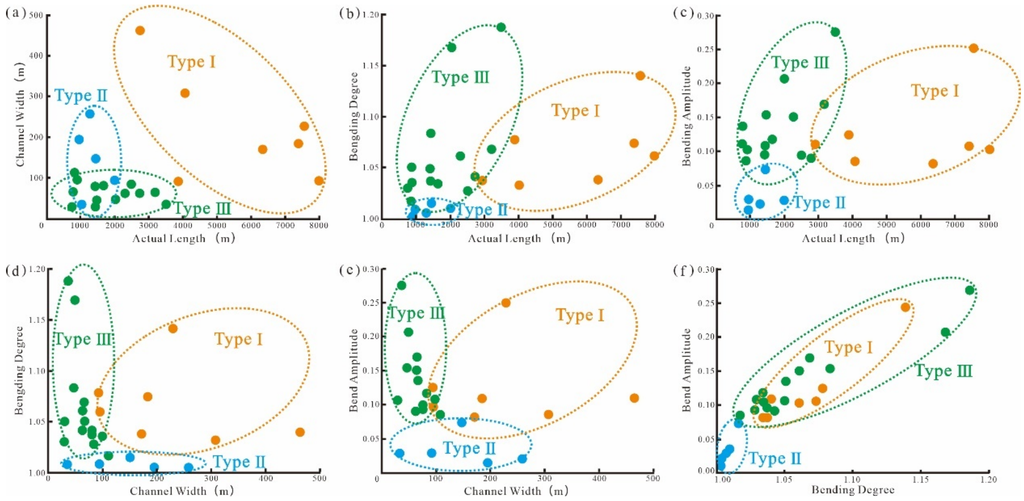

Figure 11. Plots of (**a**) Actual Length versus Channel Width, (**b**) Actual Length versus Bending Degree, (**c**) Actual Length versus Bending Amplitude, (**d**) Channel Width versus Bending Degree, (**e**) Channel Width versus Bending Amplitude, (**f**) Bending Degree versus Bending Amplitude.

5.3. Main Controlling Factors of Channel Morphology

In general, the factors that affect the shape of channels usually have the following aspects: (1) Fluid velocity: Fluid characteristics significantly affect the sinuosity of distribution channels. Higher water flow rates tend to result in lower sinuosity, while slower flow rates can lead to more curved channels. (2) Sediment content: Sediment movement also affects the sinuosity of distribution channels. Large amounts of sediment can accumulate in the riverbed, altering the shape and bending of the channel. (3) Stability of riverbeds: Geological factors influence variation in channel sinuosity. For example, when distribution channels pass through different types of rocks or soils, their erosion resistance and stability may vary, affecting sinuosity. (4) Vegetation growth degree: vegetation moderates channel sinuosity by slowing water flow, reducing erosion, and stabilizing riverbanks through root systems, which helps maintain the shape and bending of distribution channels [32].

The middle distribution channel of the Ganjiang River is composed of channels deposited during the same period, and the different distribution channels originate from the same material source. Since all parameters were measured under the same hydrodynamic and ecological conditions, geological and vegetation cover conditions are assumed to be the same throughout the region. This indicates that the morphology of the distribution channels is mainly influenced by fluid properties. Given that the Ganjiang River basin is a shallow delta with slow flow rates and low sediment load, sediment content remains largely unchanged as the channel extends. Therefore, the main factor causing changes in fluid properties is flow velocity, and within the same hydrodynamic system, the key factor affecting channel flow velocity is topographical gradient.

In the same hydrodynamic system, the velocity of fluid flow is mainly controlled by topography. By measuring the elevation of the entire middle distributary of the Ganjiang River and calculating the gradient, it was found that the elevation difference from the bifurcation origin of the middle distributary of the Ganjiang River to the boundary between the upper and lower delta plains is 4.0 m, with a slope of 0.10 m/km (Figure 12). In this region, the flow rate is low, hydrodynamic forces are weak, and the river's erosive capacity is poor, making bifurcation less likely. As a result, channels in this region are longer, wider, and have higher sinuosity and bending, with a lower frequency of bifurcation (or confluence). As the channel extends into the lower delta plain, the topographic gradient increases to 0.66 m/km, resulting in a higher flow rate. Stronger hydrodynamic forces in this region cause channels to have lower sinuosity and bending than those in the upper delta plain. Stronger hydrodynamics also make channels more prone to bifurcation, significantly increasing the frequency of bifurcation (or confluence), while reducing the length and width of individual channels. As the river approaches the lake, the topography flattens again, with the gradient decreasing to 0.31 m/km. This results in channels that once again exhibit high sinuosity and bending, and the rate of bifurcation (or confluence) growth decreases significantly in this region.

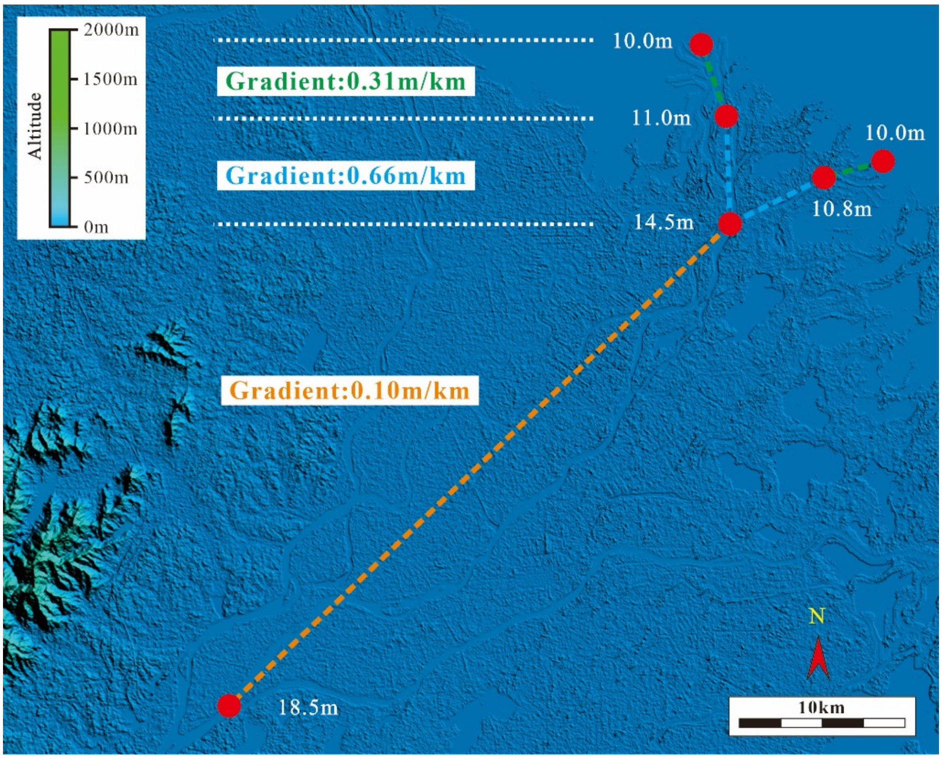

Figure 12. Elevation variation map of the middle distribution of Ganjiang River.

By comparison, it is found that the variation law of river channel data is basically consistent with the variation law of terrain slope. Therefore, it can be inferred that the main controlling factor of river channel morphology in the same hydrodynamic system is the flow velocity affected by terrain slope when the external conditions are basically the same.

6. Conclusions

The delta formed by the middle distributary of the Ganjiang River in Poyang Lake has a fan-shaped distribution and represents a meandering river delta. Based on statistical analysis of the internal channel geometry and bifurcation data, as well as dimensionality reduction and clustering analysis, the channels are classified into three types. Type I channels: characterized by longer lengths, greater widths, higher sinuosity, greater bending amplitude, and lower bifurcation (or confluence) growth rates; Type II channels: marked by shorter lengths, moderate widths, lower sinuosity, lower bending amplitude, and higher bifurcation (or confluence) growth rates; Type III channels: these feature moderate lengths, narrower widths, higher sinuosity, greater bending amplitude, and lower bifurcation (or confluence) frequencies. Fluid flow velocity, influenced by topographical gradient changes, is the primary factor controlling the morphology of the Ganjiang River delta channels. Flow velocity directly affects channel sinuosity, bending amplitude, and bifurcation (or confluence) frequency, and indirectly affects channel length and width.

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