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A Method for Estimating the Hydrodynamic Values of Anastomosing Rivers: The Expression of Channel Morphological Parameters

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Abstract: An anastomosing river is a stable multiple-channel system separated by inter-channel wetlands, and there are serious difficulties in observing the hydrodynamics of such river patterns in situ. Therefore, there are few reports on the hydrodynamic data of such rivers, for example, the upper Columbia and Pearl Rivers. In order to obtain the hydrodynamic parameter values at flow cross-sections of anastomosing rivers, without having to observe hydraulic radius, this study proposes a method called the Expression of Channel Morphological Parameters (ECMP) for hydrodynamic estimation. The calculation formula of the ECMP method is based on the shape factor (width–depth ratio), scale factor (mean depth), and gradient factor of the channel cross-sections of anastomosing rivers below a given water level as independent variables. This method can be used to calculate the mean velocity, discharge, specific stream power, and gross stream power of the flow cross-section at different water levels, only requiring the measurements of channel morphological parameters such as the mean depth, width–depth ratio, and gradient at the channel cross-section below the corresponding water level. The applicability of the ECMP method was verified using measured hydrological data. The results showed that the ECMP method is a practical estimation method with higher accuracy that is convenient for calculating the hydrodynamic parameters of anastomosing rivers. It can also be used to reconstruct ancient anastomosing rivers using the channel morphological parameters revealed from the fill sediments in ancient channels.

Keywords: anastomosing river; hydrodynamic parameters; calculation method; shape factor; scale factor; gradient factor

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1. Introduction

An anastomosing river is a stable multiple-channel system separated by inter-channel wetlands [1,2]. It has an important river pattern, with meandering, braided, straight, and anabranched rivers. The developing geomorphic areas are mainly alluvial plains, river deltas, and intermountain basins, and the suitable climate environment is mainly a humid and semi-humid climate zone, with occasional arid and semi-arid regions [2–5]. The study of anastomosing rivers began in the 1970s, making it the shortest-lived and least-studied river pattern among all known river patterns. Compared with the relatively in-depth research on other river patterns, the anastomosing river pattern requires further research on some aspects, especially of fluvial dynamics.

So far, research on anastomosing rivers has mainly focused on the fields of fluvial geomorphology and sedimentology. A series of in-depth studies have been conducted on the channel morphology, formation and evolution, as well as the sedimentary characteristics of anastomosing rivers (e.g., [6–20]). The evolutionary rules of anastomosing rivers in different climatic zones, and the distribution and transformation of anastomosing river patterns with other river patterns against different geomorphic backgrounds, have also been explored (e.g., [21–27]). The majority of the riverbed materials in these anastomosing rivers are reported to be sandy sediments, while a smaller number are silty or muddy sediments; the latter are mainly abandoned or swampy anastomosing channels with very slow flow velocities. Recently, some researchers have begun preliminary research on anastomosing rivers with riverbed materials consisting of gravel sediments [28,29]. In contrast, there are few studies on the hydrodynamics of anastomosing rivers [15–17] due to the insufficient observation of their hydrological and hydrodynamic parameters. Therefore, fluvial geomorphologists mainly compare the dynamic differences between different anastomosing rivers or between anastomosing river patterns, as well as other river patterns based on river channel gradients. The hydrodynamic parameters of rivers, such as flow velocity and stream power, are key parameters for revealing the hydrodynamic characteristics of rivers. However, there are few reports on these parameters of anastomosing rivers worldwide, despite their widespread distribution.

In order to study the formation and evolution mechanism of anastomosing rivers, the differences between different anastomosing rivers, or those between anastomosing rivers and other river patterns, it is necessary to understand the hydrodynamic characteristics of anastomosing rivers at different water levels, especially the bankfull stage. Manning's equation is usually the basic formula used to calculate river hydrodynamics [30–34]. However, for the water flow in multiple channels of an anastomosing river, the hydraulic radius in Manning's formula is more difficult to obtain compared to other river patterns due to the diversity of the hydraulic radius, especially during the bankfull stage, due to it being a chance encounter that only occurs once every few years. Therefore, it is time-consuming and labor-intensive to directly observe the hydraulic radius of the water flow in different channels of an anastomosing river under different water-level conditions. How to obtain the hydrodynamic parameters of anastomosing rivers without the direct observation of hydraulic radius remains a challenge.

The objectives of this work are: (1) to construct approximate calculation formulas by replacing the hydraulic radius in classical formulas with the combination function of channel morphological parameters for estimating the typical hydrodynamic parameters of anastomosing rivers; (2) to verify the effectiveness of the constructed formulas using the relevant measured data of the anastomosing channels in the upper Columbia River, Canada. We call the constructed calculation formulas the Expression of Channel Morphological Parameters (ECMP) method. We hope this method can play a role in the approximate calculation of the hydrodynamic parameters of anastomosing rivers and aid in revealing the hydrodynamic mechanism of the evolution of these rivers.

2. Background and Methodology

2.1. Background

Hydrodynamic research on alluvial rivers often involves parameters such as velocity, discharge, stream power, etc., which are primarily obtained based on long-term hydrological data observations at fixed cross-sections of the rivers. For alluvial river patterns with a single channel, the observation of hydrological data is relatively convenient. Conversely, it is extremely inconvenient to carry out long-term hydrological observations at fixed hydrological stations in anastomosing rivers due to the presence of multiple channels (2–5 or more) and extensive inter-channel wetlands at cross-sections (Figure 1). This is likely why reported hydrodynamic data are lacking for many anastomosing rivers around the world, with only a few exceptions (e.g., [15,17]). This impedes further research on hydrodynamic characteristics and mechanisms in the formation and evolution of anastomosing rivers.

The inconvenience of the real-time observation of hydrological data of anastomosing rivers mainly manifests in the following aspects. Firstly, there is an inconvenience regarding the observation time. Bankfull discharge commonly occurs only once every few years. Therefore, it is expected that some key hydrological parameters, such as the hydraulic radius of the bankfull flow for an anastomosing river, are fully observed, which requires years of waiting and timely on-site observations. Otherwise, one risks not only prolonging the waiting period, but also missing the moment when the bankfull flow occurs. Secondly, the increase in observation times for multiple channels of an anastomosing river leads to further inconvenience. When seeking to obtain relatively complete hydrodynamic parameters, compared to a single-channel river pattern, an anastomosing river requires several times the number of hydrological parameter observations due to the presence of multiple channels. Thirdly, in addition to other hydrological parameters, frequent measurements of the wetted perimeter of the water flow in each channel of an anastomosing river are required due to changes in water level, which also lead to great inconvenience. Among the geometric parameters of a water flow cross-section, a more difficult parameter to observe is the wetted perimeter, which is a key parameter for calculating the hydraulic radius. Therefore, it is necessary to construct a method based on more easily observable channel morphology parameters at certain water levels in order to estimate the corresponding hydrodynamic parameters for each channel of an anastomosing river.

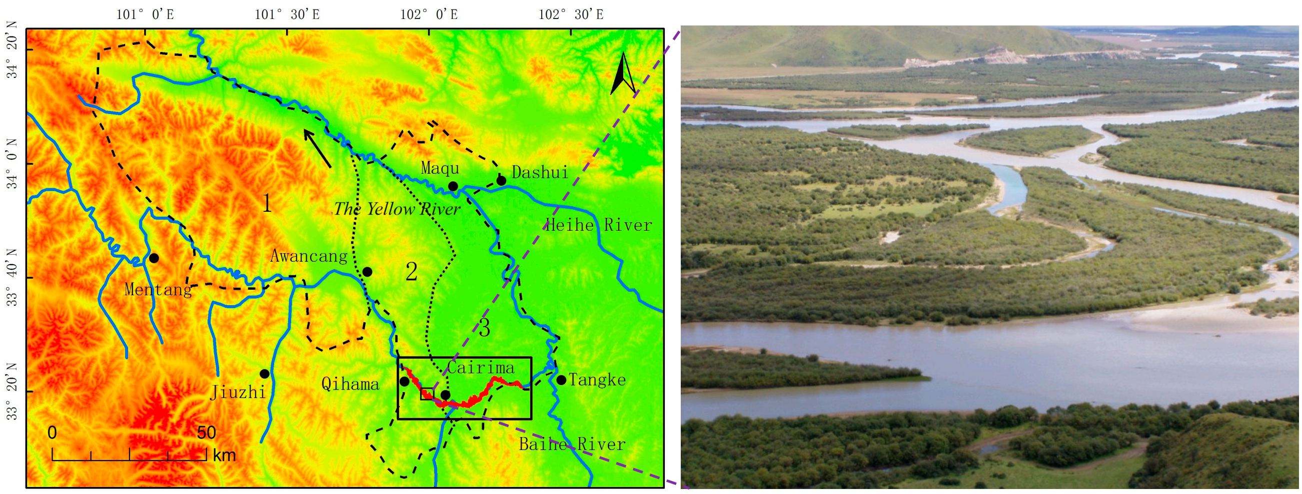

Figure 1. Anastomosing multiple-channel system in Maqu reach of the upper Yellow River, China. (The channel marked in red in the rectangular box shows an anastomosing pattern, with more than 5 channels in cross-sections. The blue lines represent the main stream and its tributaries of the Yellow River, as well as the black arrow indicates the direction of water flow. The closed dash line shows the boundary of the Maqu County in Gansu Provence of China. The areas marked by 1, 2, and 3 are mountainous, hilly, and valley plain regions, respectively.) (The picture was taken by the author of this article while the index map was modified after Liu and Wang [28]).

2.2. Methodology

The study of river dynamics mainly focuses on the following parameters: (1) The water surface gradient, also known as the energy slope, which can qualitatively reflect the changes in water flow potential energy. (2) The average velocity of a cross-sectional area, which characterizes the flow characteristics of the water. (3) The discharge, which indicates the flow flux at a unit of time. (4) The stream power, in both gross and specific forms, which reflects the energy consumption parameters of the river flow in relation to promoting the movement of sediment within the riverbed. Manning's equation (Formula (1)) is the most basic calculation formula for hydrodynamics such as flow velocity, while the equation of flow continuity ($Q = UWD$) is the basic calculation formula for water discharge:

$$U = \frac{1}{n} r^{2/3} S^{1/2} \tag{1}$$

where Q represents water discharge (m^3/s), U represents the average velocity in a flow cross-section (m/s), W signifies the width of the water surface (m), D denotes the water depth (m), n represents the Manning's roughness coefficient (dimensionless), r stands for the hydraulic radius (m), and S denotes the gradient of the water surface (dimensionless).

The equations and related variables presented above are analytical formulas established for single-channel rivers. When anastomosing rivers with multiple channels, the velocity observation and corresponding hydrological calculations can be particularly complex and time-consuming. To avoid the huge workload caused by fluid characteristics observations, and to obtain these hydrodynamic parameters more conveniently, some independent variables in the above formulas may be replaced by more intuitive and easily measurable river channel morphological parameters.

The channel morphology or flow cross-section shape in a river system is the long-term response to the hydrodynamic force at the corresponding water level. Conversely, the value of the hydrodynamic parameters at the corresponding water level can be inferred using the relevant morphological parameters of these sections. If the above hypothesis is true, this study would constitute a highly necessary and significant attempt to establish more convenient expression formulas, with channel morphological parameters serving as independent variables, for hydrodynamic calculations in anastomosing rivers.

River flow velocity is one of the key indicators for assessing the magnitude of fluid dynamics. According to Manning's equation (Formula (2)), it is evident that the average velocity of water flow is primarily influenced by the hydraulic radius and water surface gradient. Additionally, it is also influenced by the boundary material conditions, which can be characterized by the Manning's roughness coefficient n. Given a specific cross-section of a river course, the boundary material composition and shoreline vegetation status are determined, allowing for a rough determination of the n value.

Usually, the average velocity of a river's flow changes with the change in water level. Therefore, the change in water level brings obvious uncertainty to the comparison between different river flows. For a given cross-section of a particular river course, the average velocity at the bankfull discharge remains relatively stable over a short period of time, making it suitable for comparing the hydrodynamic forces of different river courses under bankfull discharge conditions. Therefore, the average velocity at the bankfull discharge is typically used as a significant indicator of river dynamics in fluvial geomorphology.

Assuming that the cross-section of a river channel is rectangular (Figure 2a), the width of the channel w_{bf} is equal to the width of the water surface, w. If the depth of the channel and the water flow are d_c and d, respectively, the width–depth ratio of the water flow is $R_r = w/d$, and the width of the water flow w can be expressed as $R_r d$.

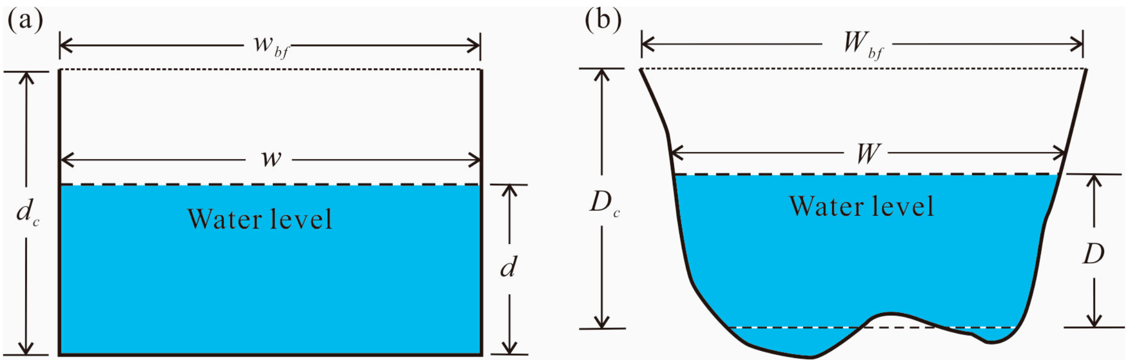

Figure 2. Schematic diagram of morphological parameters at (**a**) assumed rectangular and (**b**) natural irregular cross-sections of single channel of an anastomosing river. The depth, width, and hydraulic radius of water flow are based on the cross-sectional shape of water flow, while the mean depth and width–depth ratio of channel are based on the cross-sectional shape of a channel below the water surface.

Similarly, in the case of an irregular channel cross-section, as shown by the cross-sectional shapes of many natural river channels (Figure 2b), the mean depths D and D_c are adopted for the water flow and channel cross-sections, respectively. For the water flow, when it does not reach the bankfull stage, its wetted perimeter (x, unit: m) is $(2 + R)D$. Then, its hydraulic radius r (unit: m) can be expressed by Formula (2).

$$r = \frac{A}{x} = \frac{RD^2}{(2+R)D} = D\frac{R}{2+R} \tag{2}$$

At the bankfull stage, the water flow cross-section is equal to the channel cross-section. At this point, the water depth D matches the channel depth D_c, the water flow cross-section area A corresponds to the channel cross-section area A_c, and the water flow width–depth ratio R matches the channel width–depth ratio R_c (=W_{bf}/D_c). Hence, the calculation formula for the hydraulic radius (R_c) at the bankfull discharge can be phrased as Formula (3).

$$r_\mathrm{c} = \frac{A_\mathrm{c}}{x} = \frac{R_c {D_c}^2}{(2+R_c)D_c} = D_c\frac{R_c}{2+R_c} \tag{3}$$

Formulas (2) and (3) comprise two types of independent variables: water or channel depth (D or D_c), and water or channel width–depth ratio (R or R_c). Among them, the width–depth ratio reflects the morphological factor of a cross-section, which serves as a significant measurement index for assessing the river's cross-channel morphological characteristics and diagnosing the channel patterns [1–4,30]. The water or channel depth (D or D_c) serves as a scaling factor that indicates the size (scale) of a river flow or channel.

This formula can be interpreted as follows: the hydraulic radius of any river that can be approximated as having a rectangular cross-section is equal to the ratio of water depth times the width–depth ratio of the water flow cross-section divided by the sum of that ratio and an additional value of 2. However, for U-shaped (not rectangular) river channels, the formula for calculating the hydraulic radius remains the same, except that the average water depth is used instead. As shown in Figure 3, when the channel width–depth ratio is less than 60, the hydraulic radius of the channel significantly increases with the increase in the channel width–depth ratio, but is always less than D. When the channel width-to-depth ratio is greater than 60, the hydraulic radius of the river gradually approaches D with the increase in the channel width-to-depth ratio. When the ratio of the width-to-depth is very large (>120), the ratio ($R/(2 + R)$ or $R_c/(2 + R_c)$) in Equations (2) or (3) tends toward D during the process of gradual increase; then, the maximum hydraulic radius is infinitely close to the asymptote limited by the water depth D, that is, the hydraulic radius can be approximately regarded as equal to the depth. The calculated relation points between the channel width–depth ratio and hydraulic radius, represented by the combination of channel depth and width–depth ratio at the channel cross-sections in the anastomosing reach of the Colombian River, basically fall, as expected, within the theoretical curve range (Figure 3).

The width–depth ratio of the channel cross-sections in anastomosing rivers is commonly less than 40, which serves as a necessary condition for identifying the anastomosing river pattern [1,13]. As shown in Figure 3, the hydraulic radius of a channel with a width–depth ratio less than 40, particularly one with a width–depth ratio less than 25, is not solely dependent on the water depth but is also significantly affected by the width–depth ratio of the channel cross-section. For example, when the width–depth ratio (R) of the channel is 7.3, the hydraulic radius r is 0.78 times the water depth. When R is 25.2, r is 0.93 times the water depth. When R is 40, r is 0.95 times the water depth. Qian et al. [31] used the water depth instead of the hydraulic radius in their work, which is applicable to braided rivers with a high width-to-depth ratio. However, replacing the hydraulic radius with the depth of water for all anastomosing channels and straight channels with similar gradients is inaccurate due to their small width–depth ratio (<40).

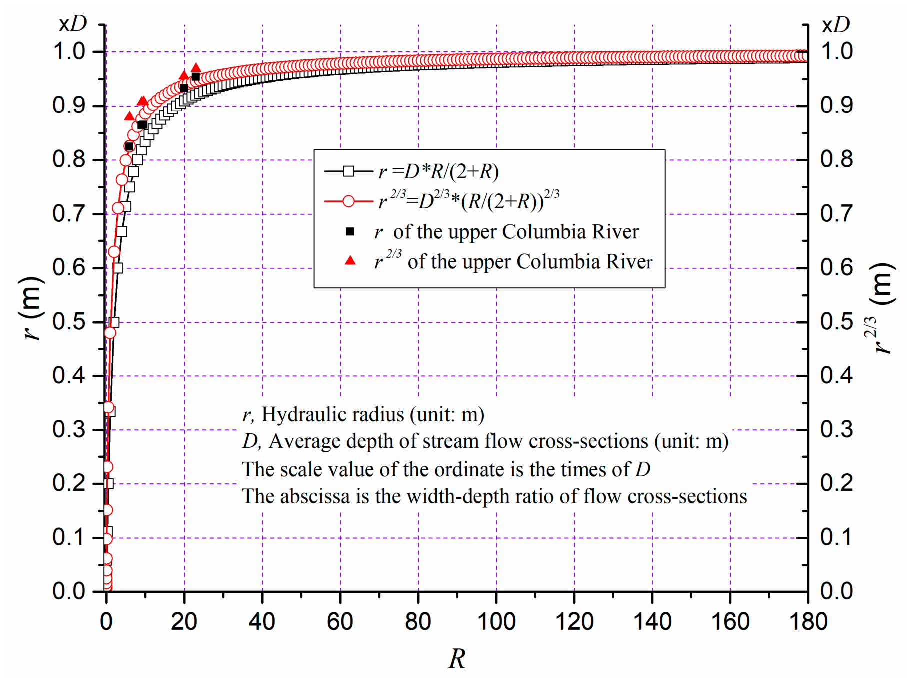

Figure 3. Relationship among hydraulic radius, mean channel depth, and width–depth ratio at channel cross-sections below given water levels (D represents the mean depth and R represents the width–depth ratio of channel cross-sections below given water levels. The observed value of D and R of the Columbia River was quoted from the literature [17]).

2.3. Data Sources

Two different types of hydrological parameters for flow cross-sections and channel morphological parameters of anastomosing rivers were used to validate the proposed method in this study. The hydrological and channel morphological parameters at the bankfull stage were cited from Reference [17], while those under the bankfull stage were measured by the Changjiang Water Resources Commission, Bureau of Hydrology, Ministry of Water Resources, China in 2017 and were documented in the Hydrological Data of the Changjiang River Basin [35]. All these data were observed by professionals according to relevant standards, and the accuracy meets the requirements.

3. Results

3.1. Mean Velocity of Water Flow in an Anstomosing Channel

Manning's equation can be used to solve the mean flow velocity at a flow cross-section under different water levels. In a given channel cross-section, both the water depth and the water surface width vary with changes in water level. The gradient of the water surface may vary, but this change is typically ignored. Since the hydraulic radius is constantly changing with the variations in water level, the average velocity U of the cross-section will also change with the changes in water depth (and water level). If the channel morphological parameters (D_m and R) are taken as independent variables to replace the hydraulic radius in the Manning's Equation (1), then the calculation formula for the mean flow velocity at different water depths in a channel can be obtained:

$$U = \frac{1}{n} r^{2/3} S^{1/2} = \frac{1}{n} \left(D_m \frac{R}{2+R} \right)^{2/3} S^{1/2} \tag{4}$$

The independent variables in Equation (4) are three factors related to the channel below a certain water level and its morphology, namely the average depth D_m of the water flow cross-section (a scale factor related to the channel below the water level), the width–depth ratio R of the flow cross-section (a shape factor related to the channel below the water level), and the water surface gradient S (approximately equal to the channel gradient S_c, a gradient factor related to the channel).

When the flow reaches the bankfull stage, the morphological parameters of the flow cross-section are equal to those of the corresponding channel cross-section. That is, the average depth and width–depth ratio of the water flow at the bankfull level are equal to the average depth D_{cm} and the width–depth ratio of the channel R_c, respectively, and the water surface gradient is equal to the channel gradient S_c. In this case, Formula (4) can have the following special cases:

$$U_{bf} = \frac{1}{n} {r_{bf}}^{2/3} {S_c}^{1/2} = \frac{1}{n} \left(D_{cm} \frac{R_c}{2 + R_c} \right)^{2/3} {S_c}^{1/2} \tag{5}$$

Clearly, the three independent variables (D_{cm}, R_c, and S_c) in Formula (5) represent the scale factor, shape factor, and gradient factor of the channel, respectively. In other words, the average flow velocity of the water flow in the bankfull state is entirely dependent on the shape, scale, and gradient of the channel. In anastomosing river systems, the mean velocity of the water flow among different channels will vary due to differences in at least one of the three morphological parameters of the channels: their shape, scale, and gradient.

3.2. Discharge of Water Flow in an Anastomosing Channel

The flow discharge refers to the total volume of water flowing through a cross-section per unit of time. According to the flow continuity equation, this is the product of the average velocity and the area of the cross-section. By substituting Equation (4) into the flow continuity equation, the following relationship can be derived:

$$Q = \frac{1}{n} \left(D_m \frac{R}{2 + R} \right)^{2/3} S^{1/2} R {D_m}^2 = \frac{1}{n} {D_m}^{8/3} R \left(\frac{R}{2 + R} \right)^{2/3} S^{1/2} \tag{6}$$

Equation (6) indicates that the river discharge can be expressed as a function of three factors—the shape, scale, and water surface gradient of the flow cross-section. When the river flow reaches the bankfull stage, Formula (6) can be transformed into a function relationship between the bankfull discharge and the channel-related parameters (independent variables).

The bankfull discharge is a crucial parameter in river flow dynamics, which is influenced by the channel's scale factor, shape factor, and gradient factor. Therefore, for the channels of ephemeral or abandoned anastomosing rivers, regardless of whether there is water flow passing through or the water reaches the bankfull level, the bankfull discharge can be calculated using Formula (7), avoiding the need to wait for years until a bankfull flow occurs for measurement.

$$Q_{bf} = \frac{1}{n} {D_{cm}}^{8/3} R_c \left(\frac{R_c}{2 + R_c} \right)^{2/3} {S_c}^{1/2} \tag{7}$$

3.3. Stream Power of Water Flow in an Anastomosing Channel

The formulas for gross stream power and specific stream power are the most commonly used formulas to calculate stream power. The core independent variables in the former are water discharge and channel gradient, while, in the latter, they are water discharge, channel gradient, and channel width at the bankfull state. By correlating the relative equations, a calculation formula for the gross (bankfull) stream power (Ω_{bf}) for an anastomosing channel can be obtained, expressed solely via channel morphological parameters.

$$\Omega_{bf} = \frac{1}{n} \gamma g {D_{cm}}^{8/3} R_c \left(\frac{R_c}{2 + R_c} \right)^{2/3} {S_c}^{3/2} \tag{8}$$

Clearly, the three independent variables, D_{cm}, R_c, and S_c, in Equation (8) represent the channel mean depth, channel width–depth ratio, and channel gradient, respectively. These are all channel morphological parameters, and their calculation is not restricted by whether there is water flow in the channel, whether the water flow reaches the bankfull stage, etc.

The specific stream power (ω_{bf}) at the bankfull stage of an anastomosing river channel was expressed solely using channel morphological parameters and can be obtained as follows:

$$\omega_{bf} = \frac{\Omega_{bf}}{W_{bf}} = \frac{1}{n}\gamma g {D_{cm}}^{5/3}\left(\frac{R_c}{2+R_c}\right)^{2/3} {S_c}^{3/2} \tag{9}$$

The independent variable in Equation (9) is the same as that in Equation (8). Once the necessary channel morphological parameters are obtained through on-site measurements, this equation can be used to numerically calculate the specific stream power in anastomosing channels without measured hydrological data. However, specific stream power needs to be separately calculated for each channel in an anastomosing river system, due to the significant differences in specific stream power among different river channels with varying scales or shapes. In fact, the width-to-depth ratio and channel gradient are the main parameters distinguishing different river patterns, while the channel depth only serves as a scale factor for a river; the channel depth alone cannot determine the characteristics of diverse river patterns. Evidently, the specific stream power of anastomosing channels can also be expressed as a function of the channel shape factor, scale factor, and gradient factor.

If it is necessary to calculate the stream power when the water level is below the bankfull level, the mean water depth (D_m), width–depth ratio (R), and water surface slope (S) of the water flow can be used in place of the channel depth (D_{cm}), width–depth ratio (R_c), and channel gradient (S_c) in Formulas (8) and (9), respectively. This leads to Formulas (10) and (11), which can be used to calculate, respectively, the gross stream power (Ω) and specific stream power (ω) of the water flow at a certain water level in an anastomosing channel.

$$\Omega = \frac{1}{n}\gamma g {D_m}^{8/3} R\left(\frac{R}{2+R}\right)^{2/3} S^{3/2} \tag{10}$$

$$\omega = \frac{\Omega}{W} = \frac{1}{n}\gamma g {D_m}^{5/3}\left(\frac{R}{2+R}\right)^{2/3} S^{3/2} \tag{11}$$

3.4. Validation of the ECMP Method at the Bankfull Stage

The anastomosing river in the upper reaches of the Columbia River in Canada is one of the most representative rivers in the world in terms of sedimentological and geomorphological study. The observation of the river's dynamic parameters is relatively complete, which is rare for this river pattern. In order to verify the applicability of the ECMP method and its expression formulas under bankfull discharge conditions, the measured hydrodynamics parameters of the five active channels in the anastomosing river reach (Figure 4, Table 1) were selected as the comparison object to verify the calculated values of corresponding parameters, calculated according to the ECMP method. The measured data used for comparison were collected from the literature [17] and are shown in Table 1, and the corresponding hydrodynamic parameters, calculated according to the ECMP method, are shown in Table 2.

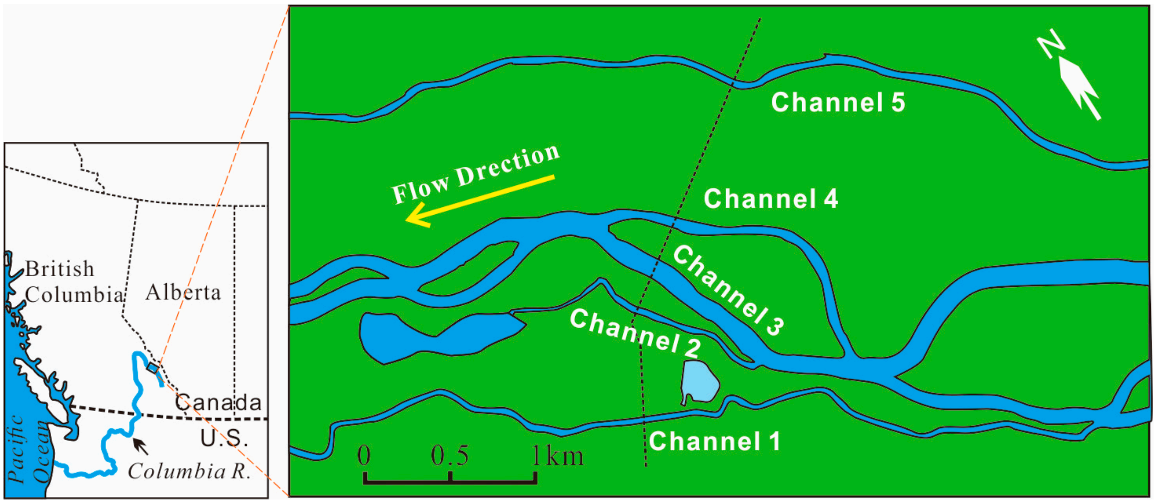

Figure 4. Location sketch of the anastomosing channels in the upper reach of the Columbia River in Canada (modified according to Figures 1 and 4 in Reference [17]).

Table 1. The measured values of the morphological and hydrodynamic parameters at near bankfull stage of the anastomosing channels in the upper Columbia River, Canada (collected from Reference [17]).

№	W	D_{max}	R_{min}	D	S	r	U_{bf}	Q_{bf}	ω	Ω
1	19.3	2.12	9.1	1.54	0.000078	1.40	0.32	9.5	0.38	7.3
2	24.8	1.08	23	0.65	0.000074	0.60	0.15	2.4	0.07	1.7
3	56.03	5.85	9.6	4.37	0.000068	4.10	0.79	193.5	2.3	128.9
4	20.7	1.04	19.9	0.75	0.000076	0.80	0.35	5.4	0.19	3.9
5	18.63	3.17	5.9	1.99	0.000074	1.80	0.40	14.8	0.58	10.8

Note: № means the number of the anastomosing channels; W represents the channel width (m); D_{max} represents the maximum channel depth (m); R_{min} represents the ratio of channel width to maximum depth (minimum width/depth ratio); D represents the average channel depth (m); S represents channel gradient (dimensionless); r is the hydraulic radius; U_{bf} represents the average velocity (m/s) of bankfull discharge. Q_{bf} is the discharge of bankfull stage (m^3/s); ω represents specific stream power (W/m^2); Ω represents the gross stream power (W/m, the value calculated by present author according to the measured data).

Table 2. The calculated values of hydrodynamic parameters using ECMP method under the bankfull stage of the anastomosing channels in the upper Columbia River, Canada.

№	n	R	r	U_{bf}	Q_{bf}	ω	Ω
1	0.035	12.5	1.33	0.305	9.1	0.36	6.9
2	0.041	38.2	0.62	0.152	2.5	0.07	1.8
3	0.027	12.8	3.78	0.741	181.5	2.16	120.9
4	0.021	27.6	0.70	0.327	5.1	0.18	3.8
5	0.032	9.4	1.64	0.374	13.9	0.54	10.1

Note: The Manning's roughness coefficient n for each river channel is calculated from Manning's equation based on measured flow velocity and gradient values; R represents the ratio of river width to average depth (average width–depth ratio, m/m); the meaning of other symbols is the same as in Table 1.

According to Makaske et al. [17], detailed observations were carried out of the stream flow velocity of five channel cross-sections in the anastomosing river reach (Figure 5) during the bankfull stage. Other hydrodynamic parameters, such as the discharge and stream power, were calculated using traditional calculation formulas, the observed velocity, and other relative values (Table 1).

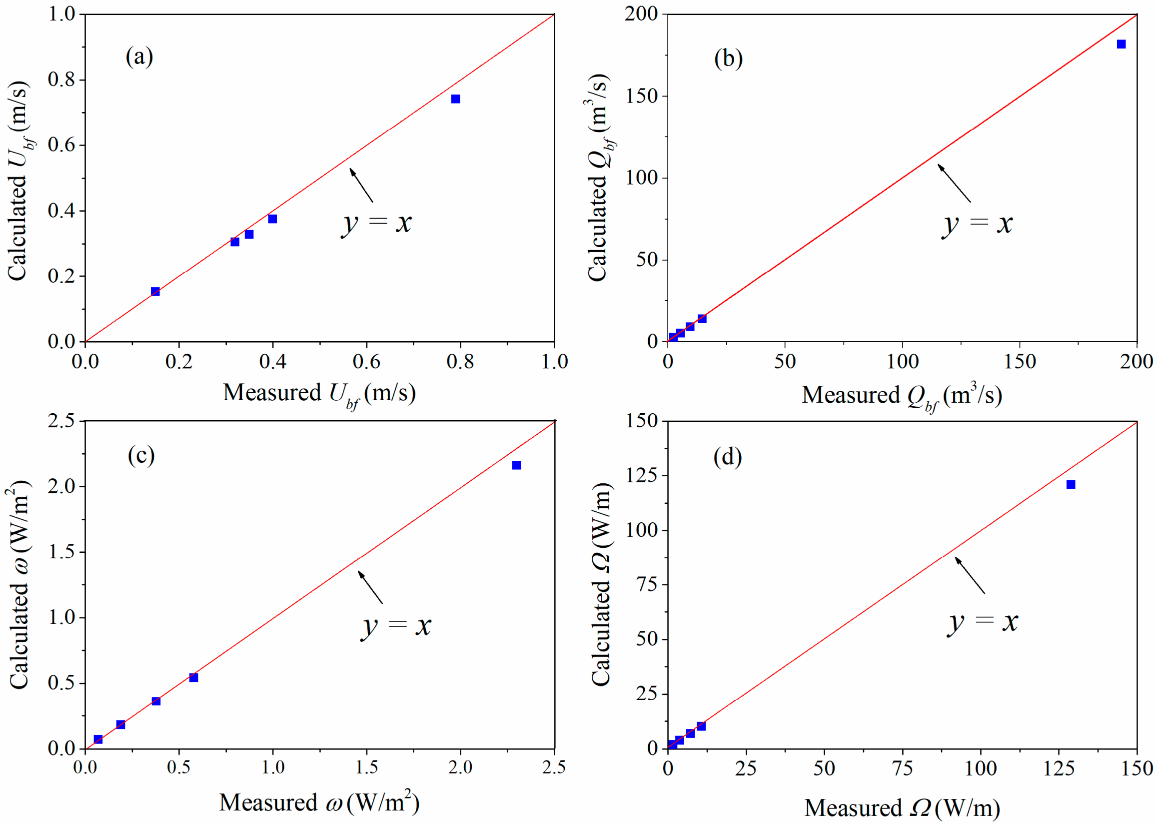

Figure 5. Comparison of measured values of hydrodynamic parameters reported by Makaske et al. [17] and calculated values using ECMP method under the bankfull stage at the cross-sections of the anastomosing channels in the upper Columbia River, Canada. (**a**) Mean velocity, (**b**) bankfull discharge, (**c**) specific stream power, and (**d**) gross stream power.

Based on the measured hydrological data [17], we supplemented the calculation of the total energy consumption rate for these five channels. Additionally, the traditional calculation method for the river width–depth ratio, which is calculated by dividing the river width by the average river depth, was corrected for its unreasonable calculation of the width–depth ratio by dividing the river width by the maximum river depth to obtain the minimum width–depth ratio. To verify the effectiveness of the ECMP method, it is necessary to know the Manning roughness coefficient n value for each channel. Here, the measured flow velocity, hydraulic radius, and river gradient values reported in the literature [17] were used to calculate n values using the Manning's equation (Formula (2)) (Table 2) to meet the roughness constant term in the ECMP calculation formula. Then, the ECMP formula was used to calculate the average flow velocity, discharge, specific stream power, and gross stream power for these five channels in the bankfull state (Table 2); scatter plots were then created with the corresponding measured hydrodynamic parameters (Figure 5). As shown in Figure 5, the calculated hydrodynamic parameter values using the ECMP method are very close to their corresponding measured values, with most of the scatter points distributed along the diagonal $y = x$. Although only a few scatter points deviate slightly from this line, the deviation is very small. This indicates that the calculated and measured hydrodynamic parameter values are very close and that the ECMP method performs well in calculations.

To further verify the effectiveness of the ECMP method, a difference evaluation was conducted between the calculated and measured values of hydrodynamic parameters, where the measured values of hydrodynamic parameters were used as the comparison object to determine the relative error of their corresponding calculated values. The relative error values of the mean velocity, discharge, specific stream power, and gross stream power are shown in Table 3, with relative error ranges of from −6.6% to 1.3%, from −6.2% to 4.2%, from −10.0% to 0%, and from −6.5% to 0%, respectively. The root mean square error (RMSE) for the mean flow velocity, discharge, specific stream power, and gross stream power of all five cross-sections at the bankfull stage are 0.03 m/s, 5.39 m^3/s, 0.07 W/m^2, and 3.6 W/m, respectively.

Table 3. Relative errors between the calculated and measured hydrodynamic parameter values of the anastomosing channels in the upper Columbia River, Canada (unit: %).

№	U_{bf}	Q_{bf}	ω	Ω
1	−4.7	−4.2	−5.3	−5.5
2	1.3	4.2	0.0	0.0
3	−6.2	−6.2	−6.1	−6.2
4	−6.6	−5.6	−10.0	−5.0
5	−6.5	−6.1	−6.9	−6.5

Note: The meaning of the symbols is the same as in Table 1.

3.5. Validation of the ECMP Method under the Bankfull Stage

The anastomosing channels in the middle reach of the Yangtze River have a typical anastomosing pattern (Figure 6) [16]. In terms of both the discharge and distribution area, this is one of the large-scale anastomosing rivers. Hydrological stations have been set up in the main channels, and daily hydrological data observations have been conducted for many years. This increases the convenience of verifying the ECMP method.

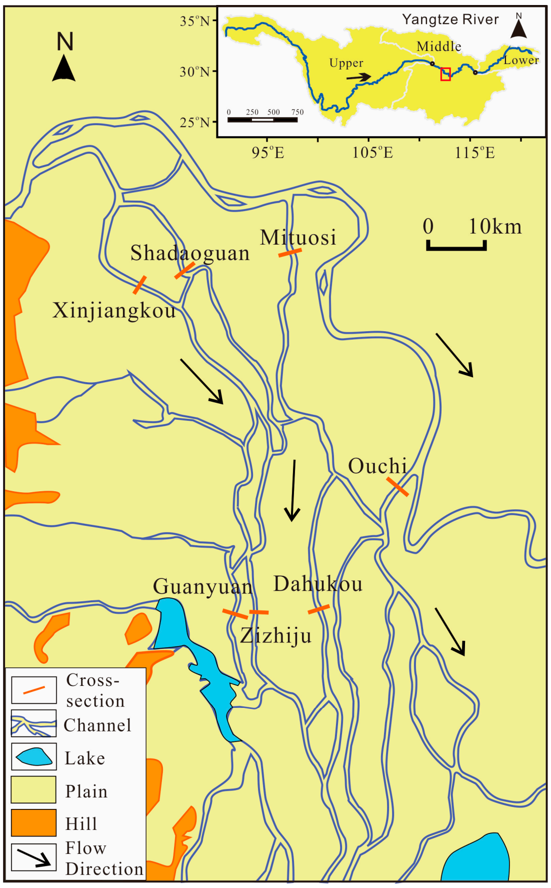

Figure 6. Location sketch of the seven gauging stations at the anastomosing channels in the middle Yangtze River, China.

Based on the daily mean measured hydrological data of the anastomosing channels on 7–8 October 2017 [35], the average gradient of the water surface was calculated using the water-level data and Manning's roughness coefficient was calculated using Manning's equation for the seven cross-sections located at the hydrological stations (Table 4). The mean flow velocity, discharge, specific stream power, and gross stream power at the cross-sections were calculated using the ECMP method (Table 4). A comparison between the calculated data and the corresponding observation data is shown in Figure 7. The hydrodynamic parameters calculated using the ECMP method are very close to the corresponding measured values, and these data points are mostly located on the diagonal $y = x$ or very close to the diagonal (Figure 7).

Table 4. The measured and calculated values of hydrodynamic parameters for the seven cross-sections of the anastomosing channels in the middle Yangtze River (the original observation data were collected from the Hydrological Data of Changjiang River Basin [35]).

Gauging Stations	n	S_c	U_m (m/s)	U_c (m/s)	Q_m (m^3/s)	Q_c (m^3/s)	ω_m (W/m^2)	ω_c (W/m^2)	Ω_m (W/m)	Ω_c (W/m)
Xinjiangkou	0.023	0.0000504	1.15	1.183	2340	2390.43	4.46	4.559	1155.8	1180.68
Shadaoguan	0.030	0.0000569	0.90	0.885	889	872.50	3.62	3.551	495.7	486.52
Mituosi	0.031	0.0000381	0.61	0.615	796	799.11	1.30	1.309	297.2	298.37
Ouchi	0.027	0.0000422	0.81	0.856	1110	1167.47	2.39	2.515	459.1	482.82
Guanyuan	0.029	0.0000622	0.78	0.778	647	643.00	2.43	2.419	394.4	391.94
Zizhiju	0.024	0.0000605	0.88	0.863	1150	1131.13	2.39	2.353	681.8	670.65
Dahukou	0.025	0.0000529	1.06	1.058	971	965.03	4.19	4.169	503.4	500.29

Note: The hydrological data were gauged on 7–10 October 2017. Due to the lack of measurements during this period, the data at Guanyuan Station were gauged on 23 October 2017. U, Q, ω, and Ω represent the mean flow velocity, mean discharge, specific power, and total power at the water flow cross-sections, respectively. The subscripts m and c of the parameter codes represent the measured and calculated values, respectively.

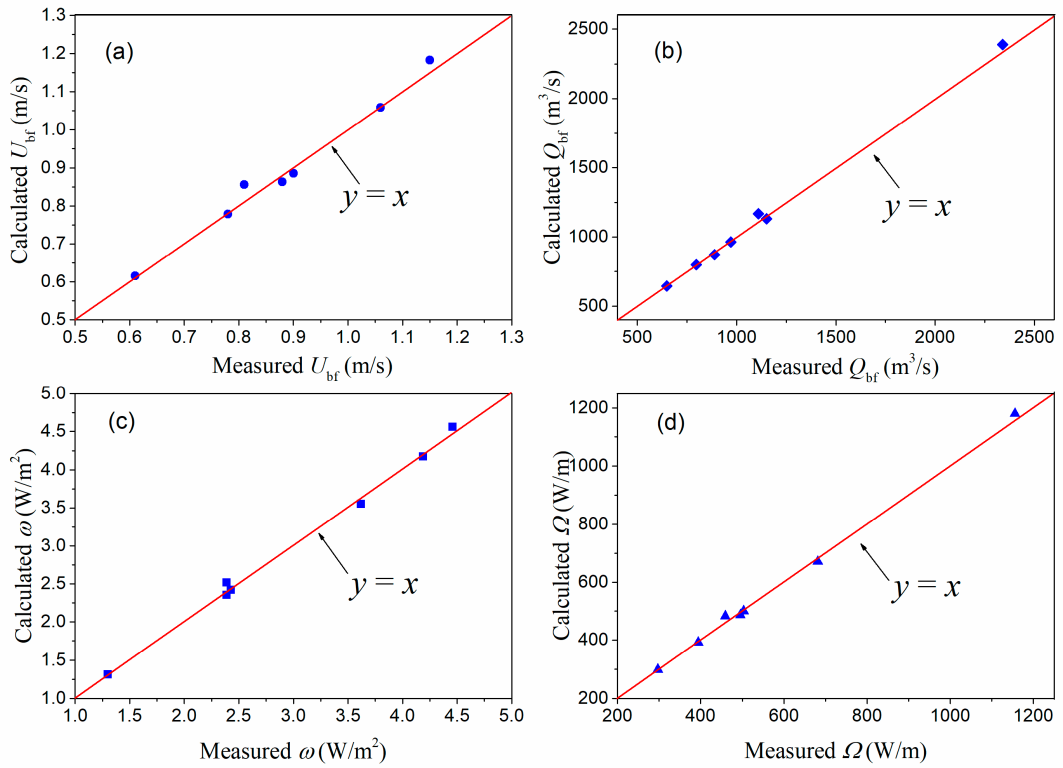

Figure 7. Comparison of the measured and calculated data at the seven cross-sections of the anastomosing channels in the middle Yangtze River (the water level during observation was lower than the bankfull stage). (**a**) Mean velocity, (**b**) discharge, (**c**) specific stream power, and (**d**) gross stream power.

The relative error of the mean flow velocity below the bankfull stage is between –0.22% and 5.73%, while the discharge, specific stream power, and gross stream power are all between –1.86% and 5.18% (Table 5). This also indicates the higher accuracy of the ECMP method in calculating the hydrodynamic parameters at the cross-sections below the bankfull stage. The calculated RMSE shows that the errors of the mean velocity, discharge, specific stream power, and gross stream power calculated using the ECMP method at the seven cross-sections are 0.02 m/s, 30.56 m^3/s, 0.07 W/m, and 14.18 W/m^2. Compared to the actual values of the corresponding hydrodynamic parameters, such errors are also acceptable.

Table 5. Relative errors between the calculated and measured hydrodynamic parameters on the water flow cross-sections of the Jingjiang anastomosing channels in the middle Yangtze River (unit: %).

Gauging Stations	U	Q	ω	Ω
Xinjiangkou	2.89	2.16	2.16	2.16
Shadaoguan	−1.72	−1.86	−1.86	−1.86
Mituosi	0.80	0.39	0.39	0.39
Ouchi	5.73	5.18	5.18	5.18
Guanyuan	−0.22	−0.62	−0.62	−0.62
Zizhiju	−1.95	−1.64	−1.64	−1.64
Dahukou	−0.17	−0.61	−0.61	−0.61

4. Discussions

Due to the multiple channels and the common wetland environments, the in situ observation of hydrodynamic parameters in anastomosing rivers often faces challenges compared to other single-channel river systems. It is a challenging task to establish a rating curve between the water level and velocity via multiple observations and indirectly calculate the velocity of the bankfull water flow, which requires years of accumulated observations. Therefore, it is particularly necessary to construct independent variable parameters that are more easily observable to estimate the flow dynamics of anastomosing rivers.

The shape of a river channel is the result of the long-term shaping of the water flow. Therefore, there must be a potential functional relationship between the morphology of the river channels and their hydrodynamic forces. This research reveals the functional relationship between the hydraulic radius of different channels in an anastomosing river and the corresponding channel morphology parameters at corresponding water levels. The relationship between the typical morphological parameters of anastomosing channels is equivalent to replacing the hydraulic radius parameter in the Manning's formula. Based on this, an estimation ECMP method for the hydrodynamic parameters of anastomosing channels was obtained, one that does not depend on the presence of a water flow in the channel or on whether the water flow reaches the level of the bankfull stage.

In addition to the relevant independent variables, the ECMP method, like traditional hydrodynamic formulas, includes the constant term of the Manning's roughness coefficient n. If the mean flow velocity, hydraulic radius, and water surface gradient of a river are known, the value of n can be calculated using the Manning's formula. The n value used in this article is calculated based on the actual observation values of the two anastomosing river reaches [17,35]. For anastomosing rivers without observed hydrodynamic parameters, the roughness coefficient n value can be obtained by querying the relevant roughness coefficient table [30,36,37].

The results calculated using this method were validated using measured values from the anastomosing channels in the upper reaches of the Columbia River in Canada at the bankfull water level; these were further validated using measured values from the anastomosing channels in the middle reach of the Yangtze River at the below-bankfull level. The relative error of the various hydrodynamic parameters is generally between –6.9% and 5.73%, with only one set of data having a relatively larger error, which is still only –10%. Therefore, this method has a higher estimation accuracy and promising applications.

Although the RMSE of individual parameters with larger orders of magnitude is not ideal, such errors are similar to absolute errors and do not affect the prospects of this method as they are small relative errors.

The ECMP method greatly simplifies the observation content and numbers required to obtain relevant data on river hydrodynamics. That is, there is no need to measure the flow velocity and hydraulic radius values at the water flow cross-section; only the basic morphological parameters of the channel cross-sections below the water surface (mean depth, width–depth ratio, and slope) need to be observed. At present, the accuracy of observing the width of river channels or water flows using remote sensing technology can be precise to the submeter level (e.g., [38–40]). With the advancement of remote sensing observation technology, improvements in the observation accuracy of channel mean depth or mean water depth, to the submeter or even centimeter level, are expected in the future. If so, the channel morphological parameters of anastomosing rivers obtained using remote sensing technology can gradually meet the accuracy requirements of this method, thus eliminating the need for extensive field observations.

The establishment of the ECMP method not only brings great convenience to geomorphological and hydrodynamic research on modern anastomosing rivers, but can also be used to calculate the hydrodynamic parameter values of dried anastomosing rivers during their historical evolution period. It can even reconstruct the scale and morphological attributes of ancient anastomosing rivers based on a morphological analysis of the filling material in sedimentary strata (e.g., [11,20,21,41]), and estimate their paleo-hydrodynamic parameters. All of these provide possibilities for revealing the evolution mechanism of ancient anastomosing rivers.

5. Conclusions

Through the construction of the ECMP method and derivation of its core formula, as well as the verification of its feasibility, the following main conclusions can be drawn:

(1) The hydraulic radius at a flow cross-section of an anastomosing channel can be expressed as a function of the scale factor (mean depth) and shape factor (width–depth ratio) of the channel cross-section below the water level at the bankfull stage or under the bankfull stage.

(2) When the water flow has not reached the bankfull level, its hydrodynamic parameters (such as mean velocity, discharge, specific stream power, and gross stream power) can be expressed as different functions of the scale factor (mean depth), shape factor (width–depth ratio of the flow cross-section), and gradient factor (water surface gradient) of the flow cross-section.

(3) When the river flow rises to the bankfull stage, its river dynamic parameters (such as mean velocity, bankfull discharge, bankfull specific stream power, and bankfull gross stream power) can be expressed as different functions of the scale factor (average channel depth), shape factor (width–depth ratio of channel cross-section), and gradient factor (channel slope) of the channel cross-section.

(4) The validation results of the ECMP method indicate that this method has a relatively small level of error, making it a convenient method for estimating the hydrodynamic parameters of anastomosing rivers. It could have applications in the hydrodynamic reconstruction of ancient anastomosing rivers using the channel morphological parameters revealed from fill sediments in ancient channels.

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