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Research Article

A New Model for the Regulation Width of Waterway Based on Hydraulic Geometry Relation

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Based on the results of the width of channel regulation on the field observations and indoor experiments, a new model of the width of channel regulation on hydraulic geometry relation was proposed and its coefficients were determined in theory in terms of the principle of dimensional analysis and multiple linear regression method in this paper. Considering the action of channel width, average flow velocity, average water depth and the slope of bed river, the median grain size D_{50} was introduced. Through field data were verified well, and flow gradient formulas and hydraulic formulas results were compared with more consistent ones, and it was shown that this model could better reflect relatively stable riverbed. Moreover, the established expression not only was simple and explicit, but also better laid a good theoretical basis for waterway project design. Last, taking the waterway regulation project which was from Shaoguan to Qingyuan for calculation, the results showed that new calculation method was feasible and it could be a useful reference for the design of waterway regulation.

1. Introduction

Regulation width is closely correlated with the remediation level; it is corresponding to the width of the river. It not only determines the length of regulating structures, but also directly affects the quality and the investment of the regulation project. Therefore, the regulation width, related to the number of projects and results, is one of the important parameters for the overall design of waterway project. Currently, the regulation width is still determined by virtue of experience and the use of fine reach simulation method. There is an urgent demand for a high accuracy and applicability of the method to determine the regulation width.

In order to explore the hydraulic geometry relation in equilibrium state of river, many domestic and foreign scholars had carried out in-depth researches and extensive applications on it and obtained a lot of achievements (Deng and Singh [1], 1999; Dingman [2], 2007; De Rose et al. [3], 2008; Turowski et al. [4], 2008; Navratil and Albert [5], 2010; Huang et al. [6], 2011; Jung et al. [7], 2013). The study results showed that most of the hydraulic geometry relations were focused on the discharge, flow velocity, water depth, channel width, and slope of bed river and few of them took into account the median grain size D_{50}.

The adjustment of shock river is affected by many factors; sediment grain size plays a significant role in the process. Based on the results of Gilbert [8] (1914), ignoring the effect of the ratio between width and depth, Lane [9, 10] (1955) put forward $GD_{50} \sim QJ$. He believed that if the change of amount and composition of bed load could be compensated by the change of discharge and slope of bed river, the river will keep balance. Li and Simons [11] (1982) also believed that if the river carried a large number of fine particles wash load, the presence of them will have some impact on the sediment carrying capacity. They amended the formula of Lane and got another correlation $GD_{50}/C_P \sim Q$. Bray [12] (1973) attempted to build a formula reflecting the impact of bed sediment composition and discharge on the slope. He obtained the correlation $J \sim Q_2^{-0.344} D_{50}^{0.586}$ by analyzing the data of gravel river in Canada. According to the 25 stable shoal data from the Wye

River in England, Hey [13] (1982) obtained the relationship among the slope of bed river, discharge, median grain size and sediment transport rate and got the formula $J = 1.02Q_{\Pi}^{-0.52}D_{50}^{1.10}G_b^{0.11}$. Hey [14] (1982) compared to the data from the 66 stable reachs of three gravel rivers in England, and then received a better formula $J = 0.679Q_{\Pi}^{-0.53}G_b^{0.13}D_{50}^{0.97}$.

By taking into account the composition of the riverbank and riverbed, some scholars attempted to analyze the hydraulic geometry relation connected with the sediment particle size. Schumm [15] (1960) related the shape of the cross-section to the percentage of silt-clay content (M) measured from the channel perimeter and found that $B/H = 225M^{-1.08}$. Bray [16] (1982) further analyzed the composition of bed material and obtained $B/h \sim Q_2^{0.2}D_{50}^{-0.045}$ by introducing discharge and median grain size as influencing factors. In the case where composition of the material in the riverbed is not too thin, Yu [17] (1982) obtained a formula $B^{0.8}/h = 10.5(m/\sqrt{D_{50}})^{0.40}$ by taking into account the incipient velocity of material on riverbank and riverbed, which according to more than 60 domestic and foreign plain rivers.

However, most of the researches on hydraulic geometry relations cannot introduce median grain size as an important factor. The main reason for that is, compared to other influencing factors, D_{50} might not be the best one to reveal the influence of hydraulic geometry relation. Actually, in the progress of section modeling, the composition of riverbank has a great impact on the hydraulic geometry relation. Recently, some scholars have studied and analyzed the effect of median grain size D_{50} (Chen and Lee [18], 1996; Dade [19], 2000; Rengers and Wohl [20], 2007; Song et al. [21], 2009; Ali et al. [22], 2012; Navratil et al. [23], 2013). Rengers and Wohl [20] (2007) found that the most significant predictor of grain size is site location because local channel width appears to strongly influence the factors of grain size. Ali et al. [22] (2012) evaluated the dependency of U_{mean} on discharge (Q), D_{50}, and S by regression analysis, and he found that the mean flow velocities were strongly dependent on grain size and discharge.

According to the previous study, the author thought that there were some problems that we need to pay attention to in the study of hydraulic geometry relation: (1) the factors are not comprehensive; (2) the relationship between regulation depth and regulation width is not enough; (3) the research to complex rivers is not enough.

In the paper, median grain size D_{50} was introduced as an important influencing factor in deriving the formula. The author utilized dimensional analysis method, the principle of dimensional analysis, and multiple linear regression method to establish a new model of the width of channel regulation on hydraulic geometry relation. Afterwards, he verified the new method with the measured data.

2. Methodology Description

2.1. Introduction of Common Formulas. Based on the previous study, many regulation width formulas had been proposed. Many common formulas such as Flow-slope formula, Hydraulic formula, Hydraulic Geometry Relation formula, Guangdong Waterway Bureau formula, and Hydraulic Research Institute formula had been widely used in special and local rivers. In the paper, these formulas would be introduced as follows.

Flow-slope formula:

$$B = \xi\left(\frac{Q^{0.5}}{J^{0.2}}\right), \tag{1}$$

where B is the regulation width (m); Q is the discharge of regulation depth (m^3/s); J is the slope of regulation reach; ξ is a coefficient of stable river width; it can be taken as 0.75 to 1.7.

Hydraulic Research Institute formula:

$$B_2 = KB_1\left(\frac{H_1}{\eta H'}\right)^y, \tag{2}$$

where B_2 is the regulation width (m); B_1 is the width before regulation (m); H_1 is the average water depth of cross-section before regulation (m); H' is the design water depth of the channel (m).

Hydraulic formula:

$$B = \xi^{10/11}n^{6/11}\left(\frac{Q^{6/11}}{J^{3/11}}\right), \tag{3}$$

where B is the regulation width (m); Q is the regulation discharge (m^3/s); J is the average slope of regulation reach; n is the roughness; ξ is the hydraulic geometry coefficient.

Hydraulic Geometry Relation formula:

$$B = (\xi H)^2, \tag{4}$$

where B is the channel width before regulation (m); H is the average water depth before regulation (m); ξ is the hydraulic geometry coefficient.

Guangdong Waterway Bureau formula:

$$B_2 = 0.8B_1\left(\frac{H_1}{H_2}\right)^{1.25}, \tag{5}$$

where B_2 is the regulation width (m); B_1 is the width before regulation (m); H_1 is the average water depth of cross-section before regulation (m); $H_2 = \eta t$, $\eta = (B_2/b)/(1.31B_2/b - 0.6)$, b is the bottom width of channel (m).

Flow-slope formula was derived according to the measured data in the central Asia rivers. From the formula it can be seen that, in the same conditions of incoming water and sediment, if the slope of bed river increases, the regulation width will become smaller. Hydraulic Research Institute formula was derived based on the successful experience of waterway regulation. Hydraulic formula was obtained on combination of the flow continuity equation, Chezy formula, and resistance formula. It assumed that the flow was steady and uniform, and it could not take into account the interaction between water flow and riverbed. But it could be a reference to the rivers of low sediment and uneasy deformation. Hydraulic Geometry Relation formula was based on the functional relation between river morphology and river hydrodynamic factors of stable reaches. It was an experimental formula of ratio between width and water depth

Table 1: The main influencing factors.

Type	Main influencing factors
Characteristic factors of the flow	Average water depth (H)
	Average flow velocity (V)
Characteristic factors of the bed river	Median grain size (D_{50})
	Channel width (B)
	Slope of bed river (J)

established by mathematical statistics method. Guangdong Waterway Bureau formula was derived according to the successful experience of Beijiang River, Hanjiang River, and Dongjiang River waterway regulation. Owing to the different conditions of water and sediment, and Beijiang River, Hanjiang River and Dongjiang River were mountainous rivers, whether this formula could be used in plain rivers remained to verify further.

Compared to the Flow-slope formula, Hydraulic formula, Hydraulic Geometry Relation formula, Guangdong Waterway Bureau formula, and Hydraulic Research Institute formula are not widely used in the waterway regulation. Flow-slope formula and Hydraulic formula are frequently used to determine the regulation width in the engineering.

2.2. Derivation of the New Equation

2.2.1. The Main Influencing Factors. Many hydraulic geometry relations appeared in the previous studies, but most of them were based on channel width, average water depth, average flow velocity, and slope of bed river. There is little research by taking into account the median grain size (D_{50}). In the paper, the author will attempt to establish a hydraulic geometry relation by introducing the median grain size.

The main influencing factors of hydraulic geometry relation can be seen in Table 1.

2.2.2. The Basic Relations. The relation between hydraulic geometry relation and the main factors can be expressed as the following general function:

$$F\left(H, B, J, D_{50}, V\right) = 0, \tag{6}$$

where F is the relation of the function.

Using the method of dimensional analysis can get the dimensional relation of the factors which are shown in (6):

$$F\left(\frac{B}{H}, J, \frac{1000D_{50}}{H}, \frac{V}{\sqrt{gH}}\right) = 0. \tag{7}$$

Then the formula of hydraulic geometry relation can be written into the following dimensionless form:

$$\frac{B}{H} = a_0 J^{a_1}\left(\frac{1000D_{50}}{H}\right)^{a_2} F_r^{a_3}, \tag{8}$$

where F_r is the Froude number; a_0, a_1, a_2, and a_3 are the coefficients.

2.2.3. Determination of Physical Parameters. Take the natural logarithm to (8); then get it:

$$\ln\frac{B}{H} = \ln a_0 + a_1 \ln J + a_2 \ln\frac{1000D_{50}}{H} + a_3 \ln F_r. \tag{9}$$

According to Ni et al. [24, 25] (2010), the least square method combination of enumeration can be used to determine the coefficients. Concrete steps are as follows.

(1) The establishment of objective function

$$f = \sum_{i=1}^{n}\left(\ln a_0 + a_1 \ln J_i + a_2 \ln\frac{1000D_{50_i}}{H_i} + a_3 \ln\frac{V_i}{\sqrt{gH_i}} - \ln\frac{B_i}{H_i}\right)^2, \tag{10}$$

where J_i, D_{50_i}, H_i, V_i, and B_i represent the ith layer slope of bed river, median grain size, water depth, flow velocity, and channel width respectively; n is the total number of the layers considered.

(2) When the objective function reaches the minimum, the following conditions are satisfied:

$$\begin{aligned}
\frac{\partial f}{\partial a_0} &= 0 \Longrightarrow \frac{2}{a_0}\sum_{i=1}^{n}\left(\ln a_0 + a_1 \ln J_i + a_2 \ln\frac{1000D_{50_i}}{H_i} + a_3 \ln\frac{V_i}{\sqrt{gH_i}}\right) \\
&= \frac{2}{a_0}\sum_{i=1}^{n}\ln\frac{B_i}{H_i}, \\
\frac{\partial f}{\partial a_1} &= 0 \Longrightarrow 2\sum_{i=1}^{n}\ln J_i \times \left(\ln a_0 + a_1 \ln J_i + a_2 \ln\frac{1000D_{50_i}}{H_i} + a_3 \ln\frac{V_i}{\sqrt{gH_i}}\right) \\
&= 2\sum_{i=1}^{n}\ln J_i \times \ln\frac{B_i}{H_i}, \\
\frac{\partial f}{\partial a_2} &= 0 \Longrightarrow 2\sum_{i=1}^{n}\ln\frac{1000D_{50_i}}{H_i} \times \left(\ln a_0 + a_1 \ln J_i + a_2 \ln\frac{1000D_{50_i}}{H_i} + a_3 \ln\frac{V_i}{\sqrt{gH_i}}\right) \\
&= 2\sum_{i=1}^{n}\ln\frac{1000D_{50_i}}{H_i} \times \ln\frac{B_i}{H_i},
\end{aligned}$$

Table 2: The range of influencing factors.

Influencing factor	Range
Average flow velocity (m/s)	0.09~4.31
Average water depth (m)	0.15~25
Median grain size (mm)	0.02~200
Channel width (m)	2.8~1890
Slope of bed river (‰)	0.01~21.47

$$\frac{\partial f}{\partial a_3} = 0 \Longrightarrow 2\sum_{i=1}^{n} \ln \frac{V_i}{\sqrt{gH_i}} \times \left(\ln a_0 + a_1 \ln J_i + a_2 \ln \frac{1000D_{50_i}}{H_i} + a_3 \ln \frac{V_i}{\sqrt{gH_i}} \right),$$
$$= 2\sum_{i=1}^{n} \ln \frac{V_i}{\sqrt{gH_i}} \times \ln \frac{B_i}{H_i}, \tag{11}$$

where n is the total number of the layers for fitting. Solving (11) with the matrix method gives a_0, a_1, a_2, and a_3.

The measured data covers several types of rivers in Asia, North America, Europe, and Oceania. It includes 700 Chinese data, 42 Indian data, 98 Australian data, 350 American and Canadian data, and 210 English and Italian data, and the total of data is 1400. In the paper, 1000 data for the linear regression calculation of formula are selected randomly, and the others are used to verify the formula. The range of influencing factors of 1000 measured data is shown in Table 2.

The parameter value of each river in 1000 measured data is shown in Table 3.

Analyzing 1000 domestic and foreign measured data by multivariate linear regression analysis combination of the least square method, the values of coefficients can be obtained:

$$a_0 = 155.163, \qquad a_1 = -0.434,$$
$$a_2 = -0.175, \qquad a_3 = 1.069. \tag{12}$$

Then the regression equation of hydraulic geometry relation can be written as

$$\frac{B}{H} = 155.163 J^{-0.434} \left(\frac{1000D_{50}}{H} \right)^{-0.175} F_r^{1.069}, \tag{13}$$

where B is the channel width (m); H is the average water depth (m); J is the slope of bed river (‰); D_{50} is the median grain size (mm); F_r is the Froude number.

The multiple correlation coefficient (R) is 0.712; then the F-statistic can be obtained by $F = (R^2/M)/((1 - R^2)/(N - M - 1))$, where N is the number of observations, $N = 1000$; M is the number of independent variables, $M = 3$ [40]. According to the F tables it can be seen that $F_{0.05}(M, N - M - 1) \in (2.60, 2.68)$ while $P = 0.05$; then we can get

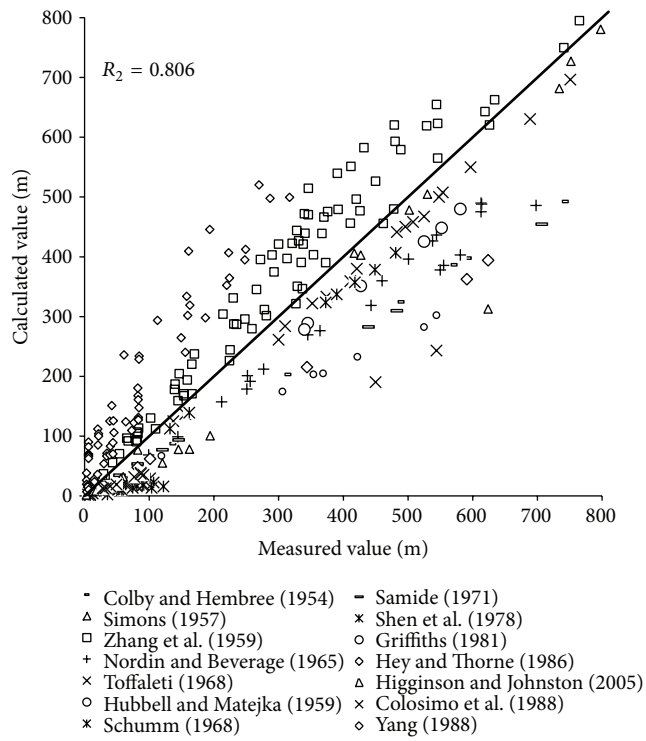

Figure 1: Verification diagram of (1).

$F = 341.35 > F_{0.05}(M, N-M-1)$; it means that the regression equation and the measured data are in close relations.

To be convenient for the calculation, the formula can be simplified as

$$B = 45.76 J^{-0.434} (1000D_{50})^{-0.175} H^{0.64} V^{1.069}, \tag{14}$$

where V is average flow velocity (m/s) and others parameters are the same as those in (13).

Then, (14) is the formula of the regulation width based on hydraulic geometry relation.

3. Results and Comparison

In order to make the formula more persuasive, the 400 remaining data are used for the verification of the formulas. using (1), (3), and (14) to calculate the regulation width according to the 400 remaining data. Then comparison of the results with the measured value is done; the results are showed in Figures 1, 2, and 3. In the figures, x-axis is the measured value and y-axis is the calculated value.

From Figure 1 to Figure 3 it can be seen that the correlation coefficients of the three formulas are 0.806, 0.677, and 0.829, respectively. Based on the results it can be found that the calculated value by (1) and (14) are fitting better with the measured value compared with the values calculated by (3). If the results calculated by (1) and (14) are compared, it can be found that the scatter' distribution of (14) is better than that of (1).

The results of the comparison between the measured and the calculated can be seen in Table 4.

Table 3: The parameter value of each river.

No.	River	Source	V (m/s)	B (m)	H (m)	J (%)	D_{50} (mm)	Amount
1	Niobrara River	Colby and Hembree [26] (1954)	0.90	21.39	0.47	1.43	0.29	40
2	Punjab canal	Simons [27] (1957)	0.62	17.08	1.40	0.218	0.28	42
3	Yangtze River	Wuhan Hydropower College [28] (1959)	1.23	1135.68	9.93	1.7	0.36	290
4	Rio Grande River	Nordin and Beverage [29] (1965)	0.89	58.35	0.65	1.18	0.45	138
5	Mississippi River	Toffaleti [30] (1968)	1.14	659.09	9.47	0.059	0.36	77
6	Middle Loup River	Hubbell and Matejka [31] (1959)	0.75	44.44	0.33	1.31	0.35	30
7	Australia rivers	Schumm [32] (1968)	3.3	220	21	0.17	0.37	98
8	N. saskatchewan and Elbow River	Samide [33] (1971)	2.33	4.94	1.64	3.82	31.81	40
9	Missouri River	Shen et al. [34] (1978)	1.55	211.30	3.40	0.148	0.12	25
10	New zealand rivers	Griffiths [35] (1981)	1.52	42.93	1.50	2.57	52.35	60
11	United Kingdom rivers	Hey and Thorne [36] (1986)	1.95	24.74	1.42	4.75	62.61	45
12	Northern Ireland rivers	Higginson and Johnston [37] (1988)	1.70	19.19	1.54	3.42	43.83	49
13	Italy rivers	Colosimo et al. [38] (2005)	1.45	9.36	0.39	1.0	36.93	56
14	Yellow River	Yang [39] (1988)	1.76	559.06	2.12	0.22	0.09	410

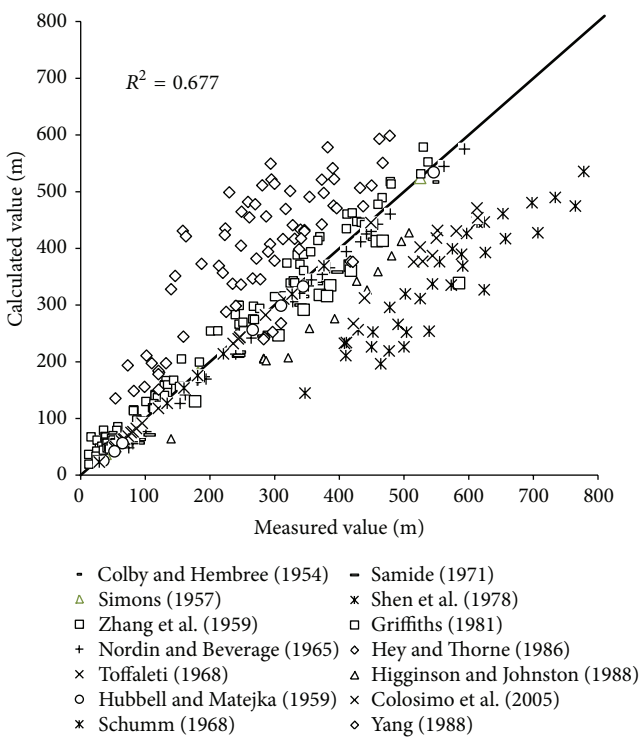

Figure 2: Verification diagram of (3).

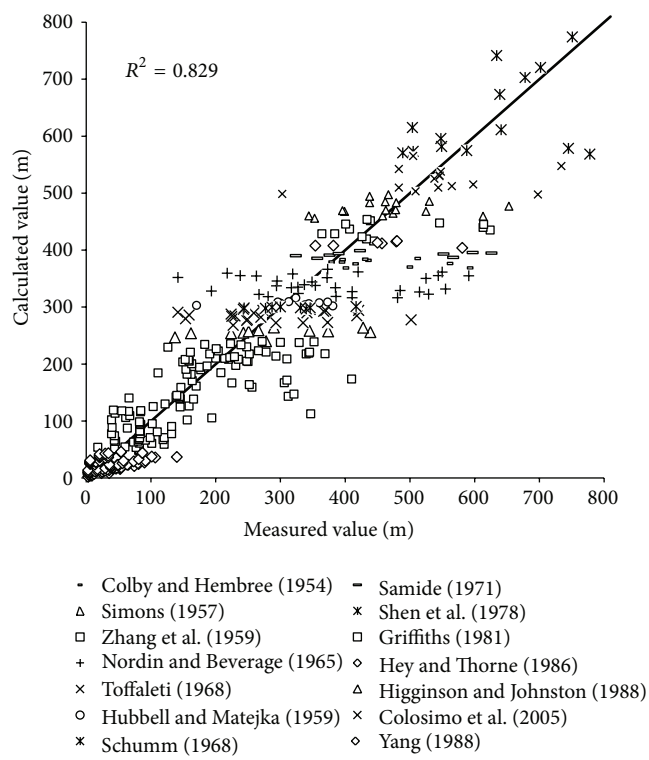

Figure 3: Verification diagram of (14).

From Table 4 it can be seen that the average errors by (1), (3), and (14) are 7.47%, 9.08%, and 7.11%, respectively. And the results show that $E_{10\%}$ and $E_{20\%}$ by (14) are the largest compared to (1) and (3). On the whole, the accuracy of (14) is the highest among the three. Also from the results it can be found that the average error by (14) is very close to that by (1). Therefore, which is better between (3) and (14) needs further analysis.

4. Applications

4.1. Engineering Situation. A long time ago, the reach from Shaoguan to Qingyuan was a perennial navigable river which was good for transportation and navigation. So many businessmen from different regions traded here; it could be an important place affecting the local economic development and people's life.

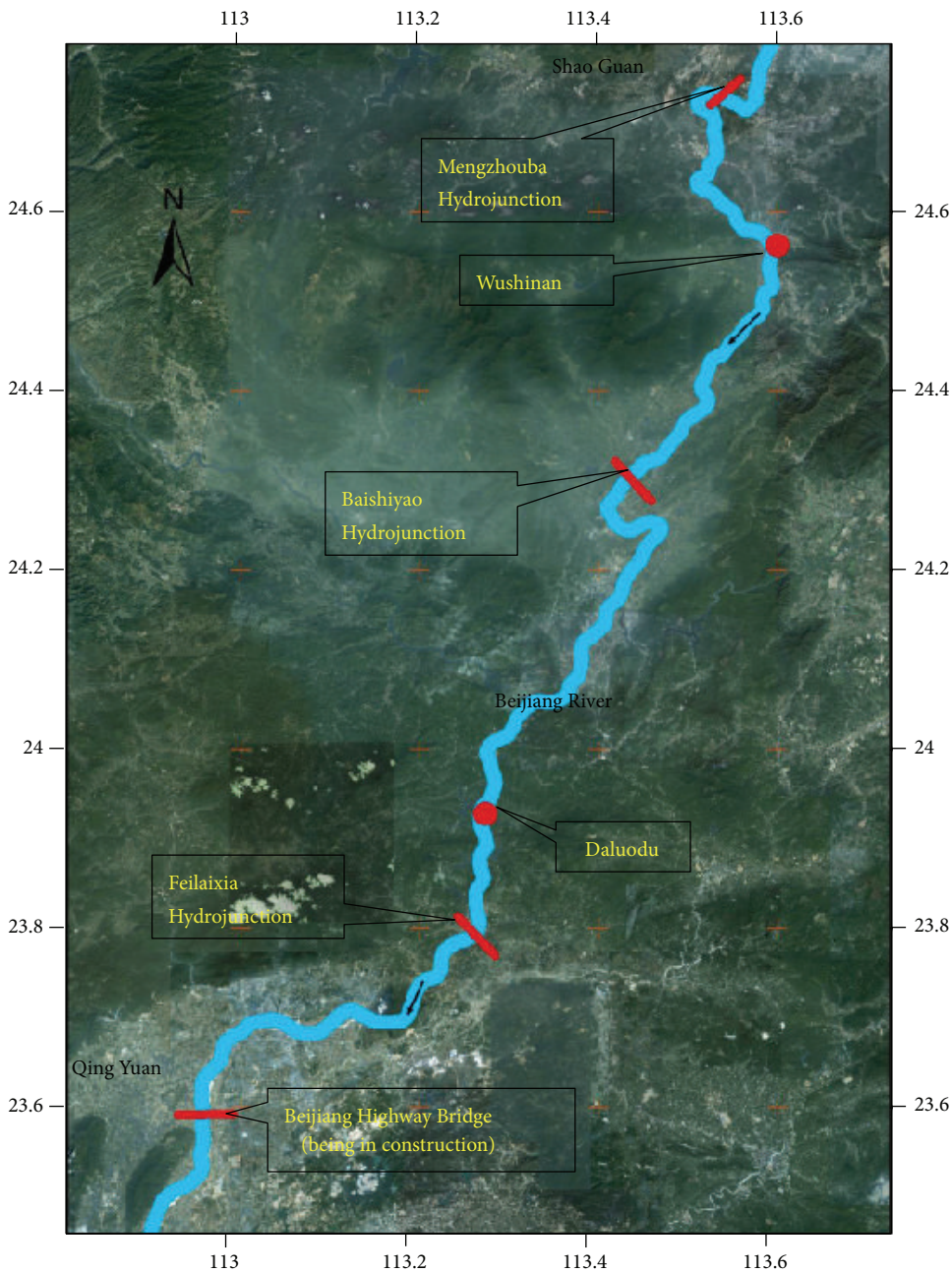

Figure 4: Location of each reach.

After 1990s, there had been built three large-scale projects, Mengzhouba Hydro-junction, Baishiyao Hydro-junction, and Feilaixia Hydro-junction, respectively. Then the navigable conditions of perennial backwater region were greatly improved. However, there were three reaches greatly influenced by the unstable flow while generating electricity. The three reaches, respectively, were Mengzhouba Hydro-junction to Wushinan Hydro-junction, Baishiyao Hydro-junction to Daluodu Hydro-junction, and Feilaixia Hydro-junction to Beijiang Highway Bridge. The location of each reach can be seen in Figure 4.

Because of the unstable flow, the riverbed evolution had been greatly influenced and the navigation condition was becoming worse than before. The phenomenon of ship jam always appeared.

Table 4: The results of comparison of the measured and the calculated.

Equations	$E_{10\%}$ (%)	$E_{20\%}$ (%)	Average error (%)
(1)	79%	88%	7.47%
(3)	65%	76%	9.08%
(14)	83%	93%	7.11%

Where $E_{10\%}$ represents the percentage of scatters which the error is less than 10% in the 400 measured data; $E_{20\%}$ represents the percentage of scatters which the error is less than 20% in the 400 measured data.

Table 5: Calculated results of regulation width.

Regulation depth	Reach	Equation (1)	Equation (2)	Equation (3)	Equation (4)	Equation (5)	Average value by (1) to (5)	Equation (14)
1.0	1#	99	121	94	58	118	98	91
	2#	93	116	149	100	227	137	134
	3#	144	202	224	133	302	201	198
1.2	1#	110	135	101	71	154	114	102
	2#	101	127	163	121	278	158	151
	3#	160	225	231	160	362	228	222
1.5	1#	127	153	109	93	178	132	117
	2#	115	142	181	157	313	182	174
	3#	177	244	248	205	403	255	256
Z		22.45%	13.43%	6.77%	28.39%	52.34%		4.95%

1# represents the reach from Mengzhouba Hydro-junction to Wushinan Hydro-junction; 2# represents the reach from Baishiyao Hydro-junction to Daluodu Hydro-junction; 3# represents the reach from Feilaixia Hydro-junction to Qingyuan Highway Bridge.
Z represents the average error compared to the average value calculated by (1) to (5).

4.2. Applications. Using (1), (2), (3), (4), (5), and (14) to calculate the regulation width with the measured data of the three reaches, in the paper, three cases have been considered when the regulation depths of the regulated reaches were 1.0 m, 1.2 m, and 1.5 m respectively. The results are shown in Table 5.

According to Table 5 and the comparison of the average value calculated by (1) to (5) with the results calculated by (14), it can be found that the error between the average value calculated by (1) to (5) and the results calculated by (14) is in the range of ±15 m. Compared to (1) to (5), the result calculated by (14) is closer to average value than that calculated by other equations. And the average error of the three reaches in different cases by (14) is 4.95%, the least among all the equations.

As have been analyzed above it can be seen that (14) has high accuracy and small error; it can be a useful and feasible method to calculate the regulation width in the waterway regulation. The key reason for that is introducing the median grain size as an influencing factor.

Owing to the unstable flow effected on the channel, it is an effective measure that use both low-water regulation and mean-water regulation to ensure the channel is reaching the standard (1.3 m $*$ 40 m $*$ 260 m) at small flow. Based on the standard, the regulation width can be obtained: (1) the reach from Mengzhouba Hydro-junction to Wushinan Hydro-junction: the low-water width is 100 meters and the mean-water width is 120 meters; (2) the reach from Baishiyao Hydro-junction to Daluodu Hydrojunction: the low-water width is 150 meters and the mean-water width is 180 meters; (3) the reach from Feilaixia Hydro-junction to Beijiang Highway Bridge: the low-water width is 200 meters and the mean-water width is 250 meters.

5. Conclusions

According to the present analysis and study, some conclusions can be drawn as follows.

(1) Equation (14) was established by dimensional analysis, the least square method, and multivariate linear regression analysis and verified by the 400 randomly measured data. With the results being compared with (1) and (3), can be found that the average error by (14) is the least. Based on the results it can be seen that (14) is simple in principle, practical in implementation, and reasonable in results and it can be a reliable basis to calculate the waterway regulation width.

(2) Based on the results of regulation width in waterway regulation it can be seen that the calculated value by (14) is the closest to the average value by the five common formulas. The key reason for that is introducing the median grain size D_{50} as an influencing factor in (14) and it is sensible to introduce the median grain size D_{50}.

(3) The results show that (14) can be widely used in different rivers because the measured data included various rivers which are in Asia, North America, Europe, and Oceania. There is little research on the median grain size D_{50} in Hydraulic Geometry relation and the research of regulation width of waterway remains to be an important topic with valuable engineering applications, so it is necessary to be verified further whether (14) is feasible to other local rivers.

Acknowledgments

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