Research on the Water Diversion Ratio Characteristics of the Plain River Network——A Case Study of the Channel in Zhangjiagang

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Abstract. This study combined numerical simulation with field observation, and this study took the classical bifurcated river of Zhangjiagang as an example and built a two-dimensional hydrodynamic model of the river course upon it. In addition, this project studied the influencing factors and the mechanism of the flow diversion ratio in the plain river network and established a formula to estimate the flow diversion ratios in plain river networks with ridge regression. The results show that: (1) the water diversion ratio in plain rivers has a positive correlation with the roughness, the ratio of the width of the tributary to that of the main channel and the water level differences. The water diversion ratio has a negative correlation with the mainstream discharge. (2) The mainstream discharge and the ratio of the width of a tributary to that of the main channel are two dominant factors of the flow diversion ratio. (3) By establishing an equation for the water diversion ratio, the water diversion ratio in the plain river network can be predicted.

1. Introduction

The bifurcated channel is a common river type in natural rivers [1]. The object of this paper is the Y-type river as the basic form and typical representative of the bifurcated channel [2]. The Y-type River is the most common form of bifurcated river. The separated discharge characteristics of a bifurcated river are customarily expressed by the WDR (water diversion ratio), the size and variation of which will affect the rise and fall of each branch to change the channel and decide the layout of flood control [3].

Generally, factors such as water depth, discharge, wetted cross-section, branch width, flow rate, flow direction, roughness and branch gradient are all related to the water diversion ratio [4, 5]. At present, research on the water diversion ratio is mainly carried out from three aspects [6-8]: laboratory experiments, field observations and formula derivations. Ramamurthy et al. [9] pointed out that the water diversion ratio of a right-angle open channel is related to the mainstream Froude number and the upstream to downstream vertical water depth ratio, and he derived the theoretical relationships among the three. From the field observation aspect, after analyzing the observation data of the east-west diversion ratio of the Ganjiang East-West River, Tang Limo et al. [5] Concluded that the water diversion ratio of the East-West River is mainly affected by four factors: discharge, water level, wetted area and hydraulic gradient. Hu Chunhong et al. [10] Established the multifactor comprehensive relationships of the WDR by using multiple regression and predicted the water diversion ratio of the...
lower Yellow River compound channel based on theseparated discharge ratio and the six factors of the width, depth, area, velocity, roughness and configuration of the floodplain and main channel. Previous studies focused on indoor flat bottom flume experiments or analyzed the drainage basins where the topographic relief is large, such as the Yellow River, Ganjiang River and so on. However, the above conclusions are not applicable to the plain river network regions where the terrain is low, the water flow is slow and most of the river channels are artificial.

In this study, a two-dimensional hydrodynamic model was established by EFDC, taking a typical Y-type bifurcated river in the plain of the Taihu lake basin located in Zhangjiagang as an example. Univariate regression and multiple regression were used to explore the correlation between the water diversion ratio and the roughness, the width ratio of water passage, the flow rate of the mainstream and the water level difference. On this basis, ridge regression was used to establish the prediction equation for the WDR in a plain river network. The results can be used to predict the WDR in plain river networks to provide a scientific reference for carrying out further regulation and engineering of plain river networks, such as water resource scheduling, water quantity & water quality modeling and ecological drainage.

2. Research area and methods

2.1. Overview of the research area
Zhangjiagang (31° 43'12" ~ 32° 02' N, 120° 21'57" ~ 120° 52' E) is located in the Taihu lake basin where the whole terrain is flat and has many river networks, the direction of rivers reciprocates uncertainly. There are 6, 033 channels with a total length of 4, 477.3km. It is a typical plain river networks area. The research object is seen in FIG. 1.

![Fig. 1 location of the research object in Zhangjiagang](image)

2.2. Model design and operating conditions
The influencing factors that affect the WDR are the mainstream discharge Q, roughness n, ratio of branch width to channel width B, and water level difference Δz. The influence of single parameters on the WDR was explored, using the control variate method, keeping other parameters unchanged. The WDR was calculated by the formula [11]: 

\[ \xi = \frac{Q_1}{Q} \]

where \( \xi \) is the WDR of the bifurcated river, \( Q_1 \) is the branch discharge, and \( Q \) is the mainstream discharge. Initial values of the repeat parameter are...
Q=15 m$^3\cdot$s$^{-1}$, $n=0.05$, $B=0.63$, and $\Delta z=0.1$ m. The operating conditions for each parameter are set as follows:

Table 1 operating conditions

| Parameter | Parameter value | Other parameters values |
|-----------|----------------|-------------------------|
| $Q/m^3\cdot s^{-1}$ | 3, 5, 8, 10, 12.5, 15, 17.5, 20, 23, 25, 26.22, 30 | $N = 0.05$, $B = 0.63$, $\Delta z = 0.1$ |
| $n$ | 0.01, 0.02, 0.025, 0.03, 0.035, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.1 | $Q = 15$, $B = 0.63$, $\Delta z = 0.1$ |
| $B$ | 0.35, 0.49, 0.63, 0.80, 0.91, 1.00 | $Q = 15$, $n = 0.05$, $\Delta z = 0.1$ |
| $\Delta z/m$ | 0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45 | $Q = 15$, $n = 0.05$, $B = 0.63$ |

2.3. Data analysis

Univariate regression and multiple regression were used for correlation analysis with the significance level set to $\alpha = 0.05$. The ridge regression method was used to overcome multicollinearity. To unify dimensions, the degree of influence of each parameter on the WDR was explored after each parameter was standardized.

3. Results and discussion

3.1. Model construction and calibration

3.1.1. Analysis of field observation results. There are three monitoring sites in the research area, Zisheng Bridge, Songfeng Bridge and Mugu Bridge, as shown in Figure 1. Field sampling was conducted on October 26th, 2018, and October 27th, 2018. The monitoring frequency was 30 min, and the monitoring time was 8 h. The discharge data of each section were derived from the handheld ADV data measured at three monitoring sites. Acoustic Doppler Current Profilers were used to measure the sectional morphology of each monitoring point in the river. The branch angle of the river is 70° from the drainage diagram. The WDR time series were calculated according to field observation data as follows:

Fig. 2 partial field observation data
3.1.2. Model construction. The length of the mainstream Dongheng River (2442.00m) and the length of the branch Gudugang River (917.00m) were taken as the water boundary of the model. The grid was divided by Cartesian coordinates into a total of 22143 grids, with each grid having a side length of 2m. The sections of most models were generalized by trapezoidal form [12]. In this paper, the bottom elevation file of the model was established based on the monitoring data of the actual monitoring section, and the bottom elevation of the model was obtained by interpolation after importing the measured topographic data to simulate the river section as precisely as possible. The upstream inlet, tributary outlet and the downstream outlet of the main branch were set as the computational boundaries. The discharge was the boundary condition of the inlet, and the water level was the boundary condition of the two outlets. Both the discharge data and water level data were obtained from field observation. The simulation time was set to 10d with a time step of 0.4 s.

3.1.3. Model calibration. Model calibration is an important step in the establishment of a hydrodynamic model. The NSE Nash efficiency coefficient formula was used to evaluate the discharge fitting effect [13] (see formula (1), where \( Q_0^t \) is the measured value at time \( t \), \( Q_m^t \) is the simulated value at time \( t \), and \( Q_0 \) is the average monitoring discharge. The calculation result is \( NSE = 0.86 \). The Nash-Sutcliffe efficiency coefficient is between 0.75 and 1.00, indicating that the simulation results are good [14]. The measured value of the bifurcated river was compared with the simulated value, and the values derived from the three empirical formulas [3, 10, 15] (FIG. 3). The simulated value was the closest to the measured data in the simulation time, indicating that the model simulation was more accurate than the empirical formula method in predicting the branch WDR.

\[
E = 1 - \frac{\sum_{t=1}^{T}(Q_0^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_0^t - Q_0)^2}
\]

(1)

![Fig. 3 calibration results of braided river model](image_url)

3.2. Influence of the functional connectivity parameters of the water body on the WDR

3.2.1. Influence of the mainstream discharge. FIG. 4 is the relationship between the branch WDR (\( \xi \)) and the mainstream discharge (\( Q \)). The relationship between \( Q \) and \( \xi \) was established by using the regression analysis:

\[
\xi = 0.452Q^{-0.252}(R^2 = 0.916, P < 0.001)
\]

(2)

Figure 4 shows that with an increase in \( Q \), \( \xi \) decreases gradually. When \( Q \) is between 8 m\(^3\) s\(^{-1}\) and 20 m\(^3\) s\(^{-1}\), \( \xi \) decreases from 0.28 to 0.2 with a decrease of 8% by the time \( Q \) reaches a critical flow of 20 m\(^3\) s\(^{-1}\). Between 20 m\(^3\) s\(^{-1}\) and 30 m\(^3\) s\(^{-1}\), however, WDR decreases by only 0.7%, and the increase in discharge has little effect on the WDR.
Based on the measured discharge on October 26th and 27th, 2018, this paper determined the variable parameter value of the studied Y-type river discharge as 8 \text{m}^3 \cdot \text{s}^{-1} to 30 \text{m}^3 \cdot \text{s}^{-1}. The change in discharge will lead to a change in water depth, flow rate, width of diversion section, etc., which will influence the characteristics of the branch WDR. When the other conditions remain unchanged, the mainstream discharge increases, the flow rate increases, and the centrifugal force required by the flow to overcome its inertia in order to veer increases correspondingly. It becomes difficult for the flow to enter the branch and the WDR consequently decreases. The sensitivity of the WDR to the flow change is different in different regions and even different river sections, and there are even some situations when more than one critical flow is generated [16-18]. Generally, when the mainstream discharge is less than the critical flow, the branch WDR decreases with the increase in the mainstream discharge. After the mainstream discharge reaches the critical flow, the increase in the discharge has little effect on the WDR. In a water diversion project, the hydrodynamic conditions of the whole river network are often improved by increasing the amount of water diversion. However, it should be noted that the increase in water diversion from the mainstream will lead to a decrease in the branch WDR, which may have the opposite effect on the branch hydrodynamic condition.

![Fig. 4](image-url)

**Fig. 4 relationship between the branch WDR and mainstream discharge**

3.2.2. *Influence of water level difference.* FIG. 5 shows the relationship between $\xi$ and the water level deflections $\Delta z$ (the difference between the water level of the branch and that of the mainstream). The relationship between $\Delta z$ and $\xi$ was established by using the regression analysis:

$$\xi = 0.718\Delta z + 0.14 (R^2 = 0.997, P < 0.001)$$

(3)

FIG. 5 shows that $\xi$ has a good linear relationship with the water level difference. When $\Delta z$ increases from 0 to 0.45m, $\xi$ increases from 0.136 to 0.46. With a decrease in the water level of the branch, $\Delta z$ increases, and $\xi$ increases accordingly.

Under the condition that the water level of the mainstream does not change, the water level difference increases, and the water level of the branch decreases. Under the action of gravity, the water flow tends to flow to the direction of lower water level, i.e., the branch direction, leading to an increase in the WDR. The linear relationship between the WDR and water level difference is found in other plain river network areas, such as the Jiangdu section [19] of the Yangtze River and Poyang Lake [20]. The water level difference is an important factor affecting the water distribution in a water diversion project. The greater the water level difference is, the greater the branch discharge will be, the faster the flow rate will be, and the stronger the branch water mobility will be, to achieve the goal of optimizing the internal river dynamic conditions. However, an excessive water level difference may lead to the sudden increase in the branch WDR and the rapid rise of water level, which will affect the river ecology. The influence of the water level difference on the WDR should be fully considered, and measures, such as joint operation...
of sluice and dam and ecological water replenishment, should be taken to reasonably arrange the discharge of the sluice and dam.

![Fig. 5 relationship between the branch WDR and water level difference](image)

3.3. Influence of the structural connectivity parameters of a water body on the WDR

3.3.1. Influence of roughness. FIG. 6 is the relationship between ξ and the river roughness (n). The relationship between n and ξ was established by using the regression analysis:

\[ ξ = 0.019 \ln(n) + 0.31 \quad (R^2 = 0.991, P < 0.001) \quad (4) \]

During simulation, the value of n ranges from 0.01 to 1 and ξ changes accordingly from 0.224 to 0.265. When n is between 0.01 and 0.025, ξ increases the fastest, from 0.224 to 0.238, increasing by 1.4%. When n ranges from 0.07 to 0.1, ξ increases at the slowest rate, from 0.261 to 0.265, with an increase of 0.4%. When the roughness is between 0.025 and 0.07, which is the actual roughness range of the plain river network, the WDR range is 0.238-0.261. In general, the WDR increases with an increase in roughness. The growth rate gradually slows, but the overall range of variation is not large, being only 4.1%.

The roughness range of plain river networks is approximately 0.025-0.07 [21]. In natural river channels, the roughness is minimized to 0.025 under the conditions that the channel is clean, straight and smooth without sand or beach. With an increase in plants, shoals and stones in the channel, the roughness gradually increases. In the case of multiple stagnated sections, clusters and shoals, the roughness of the plain river network reaches a maximum value of 0.07. Within the roughness value range of plain river networks, the WDR only changes by 2.3%, indicating that the roughness has little influence on the WDR. The influence of roughness on the WDR is mainly realized by blocking the flow to different degrees and consequently changing the discharge. Under the conditions of certain section shape and area of the river channel, the flow velocity clearly decreases with an increase in the roughness, the centrifugal force required for the flow to overcome its own inertia in order to veer will decrease correspondingly, and the flow is more likely to enter the branches, thus increasing the WDR. Chen Jieren et al. [22] studied the rump of Ganjiang River, showing that the branch WDR increased slightly in the area where there were more plants in the river resulting in higher roughness. However, the effect of water plants on roughness was less than 0.05; its effect on the WDR is less than 1% [23] and can be ignored. Ecological engineering is often used to purify water quality in plain river network regulation projects. According to the above conclusions, planting aquatic plants has a weak effect on improving the hydrodynamics of a branch and the purification effect mainly comes from the biological effect of the plants themselves. At the same time, because the roughness has little influence on the WDR, when predicting the WDR of a plain river network or establishing the model of a plain river network,
measurement of the roughness of major tributaries with large amounts of water is suggested, while for some tributaries with small amounts of water, the roughness can be deduced according to the empirical formula or referring to the data of previous years.

![Fig. 6 relationship between the branch WDR and roughness](image)

3.3.2. Influence of ratio of the width of the tributary to that of the main channel. FIG. 7 is the relationship between the branch WDR (ξ) and the ratio of the width of the tributary to that of the main channel (B). The relationship between ξ and B was established by using regression analysis:

$$\xi = 0.372B - 0.017 \quad (R^2 = 0.998, P < 0.001)$$

(5)

FIG. 7 shows that there is a good linear relationship between ξ and B when the main branch width remains unchanged. When B ranges from 0.34 to 0.63, the WDR increases from 0.122 to 0.219, increasing by 0.097. When B is between 0.63 and 0.91, ξ increases from 0.219 to 0.321 and increases by 0.102. In the range of 0.91 to 1, ξ increases by 0.03. In general, B has a great influence on the value of ξ. When B increases from 0.34 to 1, the value of ξ increases from 0.122 to 0.35, an increase of 22.8%.

With an increase in the branch width ratio, the branch width increases, the branch section increases, thus the water passing capacity increases, and the WDR increases significantly. In the plain river network area, the depth change caused by topographic scouring and silting is small, and the change in the cross section is mainly caused by the change in the width. The relevant research is consistent with the conclusion of this paper [24, 25]. In an experiment with a right-angle open channel flume in the laboratory that was conducted by Ramamurthy [26], three different cross water width ratios (0.22, 0.77 and 1) were set, keeping other conditions unchanged. It was found that the WDR was the largest when the cross water width ratio was 1. It can be seen that the greater the ratio of the width of the tributary to that of the main channel is, the stronger the water passing capacity is and the greater the branch WDR. In practical engineering, widening and landfilling the channel leads to a change in the channel width and directly affects the WDR. In the treatment of plain river network, consideration can be given to widening branch channels to increase the diversion volume, accelerate the water flow speed, and improve the dynamic conditions of the river.
3.4. Comprehensive influence equation of the WDR in a plain river network

3.4.1. Prediction equation. The main factors that influence the WDR are Q, n, B and Δz, as determined by the above analysis. Using univariate regression and multiple regression combined with ridge regression, the multivariate prediction equation of the WDR in a plain river network is obtained. The process is as follows:

1. Select ξ as the dependent variable and Q, n, B, and Δz as independent variables on the basis of the single factor regression above, and for each variable transformation obtain: x1 = Q^{-0.252}, x2 = ln(n), x3 = B, x4 = Δz. The purpose of making ξ linear against x1, x2, x3 and x4 is to allow a multiple regression of x1, x2, x3 and x4.

2. Randomly select 80% of the simulated data for multiple regression. After multiple regression, there may be multicollinearity between the transformed x1, x2, x3 and x4, resulting in a P value for the roughness n of 0.479, which cannot undergo the test.

3. The other independent variables being in the condition of minimum P value, R^2 is large and can undergo the test, and ridge regression is selected. Take the ridge trace map into consideration and choose the ridge parameter k=0.6 to carry out ridge regression, thus obtaining the ridge regression equation as shown in equation (6).

4. Substitute the remaining 20% of the data into equation (6) for verification, and obtain the result of the comparison between the calculated value and the simulated value, as shown in FIG.8. The calculated value in the figure is close to the simulated value, reflecting that the regression effect of equation (6) is good. This equation overcomes multicollinearity and has a good fitting effect. This equation can be used to predict the WDR in a plain river network.

\[
ξ = 0.307Q^{-0.252} + 0.014\ln(n) + 0.252B + 0.490Δz - 0.088 \\
(\text{for } n\in(0.25,0.75), R^2 = 0.9007)
\]

![Fig. 8 comparison of the measured value and calculated value of the WDR](image-url)
3.4.2. Contribution model
Based on the qualitative discussion of the influence of each single factor on the WDR, a contribution value was created to evaluate the degree of influence of each factor on the WDR. To further explore the contribution of each factor to the WDR, the respective variables are first standardized to unify the dimensions. The ridge regression is then conducted using the process described above, and the equation is obtained as follows:

$$\xi = 0.157Q^{-0.252} - 0.042\ln(n) + 0.16B + 0.063\Delta z + 0.252(7)$$  

After the variables are standardized, their independent variable coefficients reflect their contribution to the WDR, which is consistent with the qualitative discussion results above. In equation (7), the coefficients of discharge and ratio of the width of the tributary to that of the main channel are 0.157 and 0.16 respectively, which are significantly greater than the coefficients of roughness and water level difference, indicating that the ratio of the width of the tributary to that of the main channel and the mainstream discharge are the main factors affecting the WDR. The degree of influence of each factor on the WDR is listed as follows: ratio of the width of the tributary to that of the main channel > mainstream discharge > water level difference > roughness. The reasons is that the amount of discharge is largely determined by the wetted area and flow velocity, which are directly related to the ratio of the width of the tributary to that of the main channel and the mainstream discharge.

Therefore, attention should be paid to the influence of the ratio of the width of the tributary to that of the main channel and the mainstream discharge when considering ecological drainage, improving river dynamic conditions and flood control layout.

4. Conclusion
1. In this study, a two-dimensional hydrodynamic model of the bifurcated channel at the entrance of Gudugang River was established based on the field observation data. The simulation results are good and the model can be used to study the WDR in a plain river network.
2. The WDR decreases with an increase in the main flow and increases with an increase in roughness, ratio of the width of the tributary to that of the main channel and water level difference.
3. The contribution value is used to evaluate the influence of various factors on the WDR. The order of the contribution value is ratio of the width of the tributary to that of the main channel > mainstream discharge > water level difference > roughness.
4. Ridge regression is used to obtain the comprehensive prediction equation for the WDR in a plain river network. It is proved that the fitting effect is good and can be used to predict the WDR of branch channels in a plain river network.

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