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A New Open Channel Flow Correction Method Based on Different Boundary Combinations in Hydraulic Modeling

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Abstract: In open-channel water transfer projects, hydrodynamic modeling has been one of the tools commonly used by the scheduling staff to perceive the changes in the water condition of the channel. The reliability of the flow monitoring data has not been guaranteed due to restrictions in the flow monitoring method. Flow monitoring errors directly reduce the accuracy of hydrodynamic modeling calculations, making it impossible to accurately grasp the real-time changes in the internal water conditions of the channel. In this paper, by utilizing the characteristics of the hydrodynamic model itself, which can be solved discretely with multiple boundary conditions, the method of correcting the boundary anomaly data is proposed by changing the combination of hydrodynamic boundaries. This solves the problem of the inaccuracy of hydrodynamic model calculations due to errors in the monitoring data and improves the accuracy of the hydrodynamic model calculations. In the actual operation process, it is found that the method proposed in this paper solves the problem of hydrodynamic model misalignment caused by flow observation errors by correcting the flow during the flow adjustment period, which greatly improves the calculation accuracy of the hydrodynamic model. Secondly, for a stable flow period, the method proposed in this paper can quickly capture and correct the local monitoring of abnormal data and improve the overall hydrodynamic simulation accuracy.

Keywords: flow correction; hydrodynamic modeling; hydrodynamic boundary conditions; flow anomaly; hydrodynamic model misalignment

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1. Introduction

As an important engineering measure to alleviate the uneven spatial distribution of water resources, the open channel water transfer project has an important role in the optimal allocation of water resources in the region and in alleviating water resource conflicts. The main task of the water transfer project is to transfer water from an area with more water to an area with less water, so the change in the water conditions inside the channel during transportation is a point of greater concern [1,2]. With the increasing demand for watershed digitization and channel water condition change perception, hydrodynamic modeling has been widely used with channel algorithms to obtain more real-time and fine water flow dynamic information [3]. However, there are many uncertainties in the process of hydrodynamic modeling to simulate water condition changes, and the error mainly comes from the water condition monitoring of the channel. Water-condition-monitoring data are a tool used in water transfer engineering to carry out scientific research and dispatch decision-making [4]. In recent years, with the improvement of the informatization level, the distribution of water condition monitoring stations along the project has become more and more intensive, and the quality of monitoring data has also improved. However, in the monitoring process, subjective and objective reasons, such as data recording error, detection equipment failure, and data transmission loss, will still cause monitoring data abnormalities [5]. This abnormal data will greatly reduce the simulation accuracy of the hydrodynamic model, leading to the dispatcher's insensitivity to the water regime change in the channel and the inability to accurately obtain the channel water regime change. Therefore, improving the quality of monitoring data is of great significance in improving the simulation accuracy of the hydrodynamic model.

Flow monitoring, as an important part of water information monitoring, is of great significance for hydraulic control, hydraulic characterization, and accurate simulation of hydrodynamics in channels [6–8]. Compared with water level monitoring, flow monitoring is more affected by flow disturbances, so the accuracy of water level monitoring is higher than that of flow monitoring [9,10]. Therefore, the purpose of this paper is to use the boundary combination of the hydrodynamic model to modify the flow process of the channel pool as much as possible by using the hydrodynamic model itself. The hydrological method and the water balance method are usually used to correct the channel flow [9,11]. The hydrological method is used to calculate the confluence, and the confluence results are used to correct the overflow section of the channel, which is not sufficient in terms of accuracy and time scale to meet the real-time sensing needs of the river. The water balance method is used to correct the river flow. By default, the flow of a downstream section is considered accurate. This method utilizes the information in that section to recursively push upstream, taking into account factors such as upstream and downstream boundary strips, river topography, and model parameters. However, this method poses challenges in identifying the source of errors, leading to increased model instability. Furthermore, the results of the extrapolation are not reliable enough [12].

2. Related Work

A hydrodynamic model can be approximated and generalized as a systematic project that consists of a number of input parameters with numerous uncertainties in the modeling process, which makes it difficult to accurately simulate a natural river or water transfer project using a one-dimensional hydrodynamic model. These parameters can be broadly categorized into external and internal parameters. The external parameters include the boundary data of the hydrodynamic model, the inner boundary data, the diversion and inflow data, etc. The internal parameters include the topographic data of the river channel, channel roughness, channel leakage coefficients, backwater area due to changes in cross-section, flow coefficients of the control gates, etc. These two types of parameters work together in the hydrodynamic model, so improving the simulation accuracy of the hydrodynamic model is transformed into a process of model external parameter correction and internal parameter optimization. Generally, the external parameters are derived from monitoring data, and the errors mainly come from the damage of monitoring equipment, unscientific monitoring methods, human input errors, etc. The internal parameters are mainly solved inversely using measured data, and this inverse process is usually dominated by optimization algorithms and data assimilation [13,14], followed by the optimal solution. The accuracy of the internal parameters usually needs to be ensured before external parameter corrections are made; therefore, the internal parameters of the hydrodynamic model need to be determined first. The water transfer project will generate significant water level and flow data. These data can be used to improve the accuracy of the hydrodynamic model by internally adjusting parameters such as the roughness of the channel, flow coefficients of the control gate, leakage coefficient of the channel, and other relevant factors. Validating the model against high-quality water data ensures that the hydrodynamic model accurately simulates the system under normal conditions. The above method can avoid the influence of the internal parameters of the hydrodynamic model on the correction of the external parameters, which ensures the higher effect of the hydrodynamic model on the correction of the abnormal data and also improves the overall perception of the dispatchers on the channel.

The hydrodynamic model can be approximated as a systematic engineering model, which is composed of many input parameters that have many uncertainties in the modeling process, and these parameters can be roughly divided into external parameters and internal parameters. These parameters can be roughly categorized into external parameters and internal parameters. External parameters include the boundary data of the hydrodynamic model, the inner boundary data, and the data on water diversion and water inflow, etc.; internal parameters include the topographic data of the river channel, the roughness of the channel, and the data of overflow at the control gate, etc. These two types of parameters work together in the hydrodynamic model, so improving the simulation accuracy of the hydrodynamic model is transformed into a process of model external parameter correction and internal parameter optimization. Generally, the external parameters come from monitoring data, and the errors mainly come from damage to monitoring equipment, unscientific monitoring methods, human input errors, etc. The internal parameters mainly utilize the measured data. The internal parameters are mainly solved inversely using measured data, and this inverse process is usually dominated by optimization algorithms, data assimilation, and then the optimal solution. In the process of external parameter correction to ensure the accuracy of the internal parameters, the method is to use the above-mentioned method to optimize the internal parameters, find the optimal solution of the internal parameters, and bring them into the model to obtain an accurate hydrodynamic model. In this paper, the monitoring data without abnormal data are used to rate the internal parameters of the model, and the hydrodynamic model is used to correct the external data so as to achieve the effect of correcting the monitoring data of the water transfer system and then to ensure a higher hydrodynamic model simulation effect.

The hydrodynamic model uses the four-point difference method to discretize the Saint-Venant equations and is finally solved using the catch-up method [15]. In the process of solving, different combinations of boundaries will appear, and current scholars tend to use flow-level or water-level flow as the upstream and downstream boundaries of the model, so as to guarantee the stability and accuracy of the model computation as much as possible, and it is not easy to cause the accumulation of errors. However, as mentioned above, in the open channel, the error of flow monitoring is larger than that of water level monitoring, and the error of flow monitoring is very accidental, so in the process of combining the boundary of flow or ater level, the model is easily affected by the error of flow, which leads to the instability or imbalance of the model calculation. If the whole hydrodynamic process uses the water level as the upstream and downstream boundaries of hydrodynamics, in the process of its discrete difference, if the initial value is set unreasonably, it will lead to the instability of hydrodynamic model calculations, and in order to ensure the stability and accuracy of the hydrodynamic model calculations, it is still necessary to search for the optimal level-flow relationship of the channel. Therefore, this paper uses the hydrodynamic model to test the original boundary; if the error is large, then change the boundary combination, using different boundary combinations to calculate the hydrodynamic elements, and then correct the flow process in the nullah, thereby improving the calculation accuracy of the hydrodynamic model [16,17].

Most of the methods for flow correction are focused on neural network methods as of now [18,19]. Neural network modeling is used to extract the relationship between the data to predict the future trend of the data, but this approach However, this method only considers the relationship between the data and does not consider the mechanism of the process inside the river, so the water level-flow relationship inside the channel cannot be fully reflected in the calculation process. In addition, the neural network model needs to collect a large amount of water data as a training set in order to accomplish a better flow correction and then carry out the complex parameterization process to ensure that the prediction model achieves better accuracy.

The method proposed in this paper plays a crucial role in data corrections within open-channel water regulation projects. This holds particularly true for projects involving serial lock groups, where the abundance of regulatory locks introduces a potential for errors if data from any individual lock deviates from the norm. These incremental errors can undermine the accuracy of hydrodynamic results downstream in the canal pool, emphasizing the importance of correcting this observed data for maintaining optimal water regulation. Our approach addresses this issue by altering the boundary combinations of hydrodynamic models. Leveraging the characteristic of hydrodynamic models that allows for solutions for a variety of boundary combinations, anomalous data within the measured sequences can be corrected, thus reducing the impact of unusual data on the entire system. Unlike the complexities inherent in parameter tuning for neural network models, our method simply requires ensuring that the parameters for the hydrodynamic model are rational. This simplifies not only data collection but also significantly alleviates the challenges associated with parameter adjustment.

The rest of this paper is organized as follows: Firstly, Section 2 introduces the related technologies involved in this study. Section 3 is mainly about the model construction, the results of the model calculation, and the analysis of the results. Section 4 is the conclusion of the model.

3. Methodology

3.1. Study Area

The Middle Route of the South-to-North Water Diversion Project (MRRSNWDP) is a water diversion project from the Danjiangkou Reservoir in the middle and upper reaches of the Hanjiang River. It goes north through Henan and Hebei provinces, connecting the Haihe River, the Yellow River, the Huaihe River, and the Yangtze River. The self-flowing water transports the 'South Water' to the Tuancheng Lake in Beijing and the Outer Ring River in Tianjin. The project is 1432 km long, with a total of 64 control gates, 97 water outlet gates, one pumping station, and many types of buildings such as inverted siphons, crossings, and pressureless culverts along the route. It has been eight years since the MRRSNWDP was officially opened to the public on 12 December 2014, with more than 2000 days of safe water transfer and a cumulative total of more than 50 billion cubic meters of water transferred to the north, which has already benefited 85 million people along the route [20,21].

The MRRSNWDP primarily serves as a long-distance open-channel water diversion project aimed at water supply. It encounters variable water diversion situations in its daily operations due to fluctuating downstream water demand requirements. Such changes lead to periods displaying pronounced water diversion fluctuations, while others exhibit minimal changes. These variances impose different impacts on the channel in different situations. For instance, the water diversion outlet of the MRRSNWDP is generally stationed upstream of the downstream control gate. Any diversion disturbances imply perturbations in the flow pattern of the downstream control gate. Such alterations inevitably induce abnormal water levels and flow fluctuations, posing a string of adverse effects on monitoring. During the course of water diversion disturbances, inaccurate flow monitoring is a common issue. Therefore, this study focuses on the White River and Caodun River control gates of the MRRSNWDP as specific research examples to ensure the proposed method holds high applicability and robustness in the open channel water diversion project. Water diversion conditions are bifurcated into the flow adjustment period and the flow stabilization period. Under both conditions, the flow dynamic correction method delineated in this study is engaged to rectify the flow of the first channel pool (between the White River and Dongzhao control gates) in hydrodynamic modeling. The flow of the subsequent channel pool is then corrected via the water balance equation, all based on the corrected flow. Figure 1 illustrates the study area.

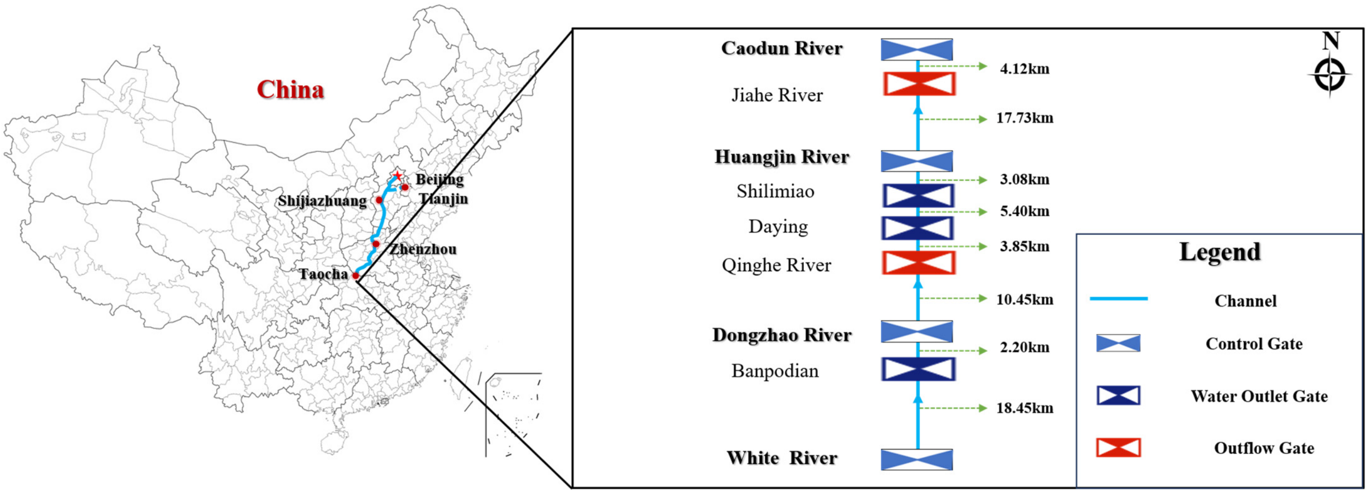


Figure 1. Study area.

3.2. One-Dimensional Hydrodynamic Model

A one-dimensional hydrodynamic simulation model is constructed based on the Saint Vebant system of equations, which consists of continuity equations and momentum equations, and the form of the equations is shown in the following equation [22]:

$$\begin{cases} B\frac{\partial Z}{\partial t} + \frac{\partial Q}{\partial x} = q \\ \frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(a\frac{Q^2}{A}\right) + gA\frac{\partial Z}{\partial x} + gAS_f = 0 \end{cases} \quad (1)$$

where B is the surface width of the overwater section, m; Z is the water level, m; t is the time, s; Q is the flow rate, m^3/s; x is the longitudinal distance of the channel along the main flow direction, m; q is the side inflow, m^3/s; α is the momentum correction coefficient; A is the area of the overwater, m^2; g is the acceleration of gravity, m/s^2; S_f is the friction ratio drop.

The hydraulic gradient S_f of the channel can be calculated by the Manning-Strickler formula:

$$S_f = \frac{Q^2 n^2}{A^2 r^{4/3}}, \quad (2)$$

where r is the hydraulic radius, m.

The Saint-Venant equations represent a system of first-order, nonlinear, hyperbolic partial differential equations. As this system does not currently have an analytical solution, it is essential to rely on numerical methods for obtaining an approximate one. The main computational approach nowadays involves discretizing the Saint-Venant system using the Preissmann four-point weighted implicit difference format, which is recognized for its rapid convergence and high stability.

In the course of the four-point differential computation process, boundary conditions play a critical role in hydrodynamic modeling. Their function is primarily to lessen the number of unknowns, equating them with the number of equations to ensure the uniqueness of the numerical solution. Typically, these boundary conditions encompass the upstream and downstream boundaries. Moreover, these can be subdivided into four distinct combinations based on the upstream flow, downstream water level, upstream flow, downstream flow, upstream water level, downstream flow, or the upstream water level and downstream water level. Additionally, information about the remaining two unknown boundaries can be acquired by using the two known ones. This method provides a unique platform for utilizing the diverse characteristics of the data to select the suitable boundary combination, which in turn enables the correction of monitoring data via hydrodynamics itself.

3.3. Evaluation Indicators

In this paper, we use the correlation coefficient R^2, relative mean squared error (RMSE), and Nash-Sutcliffe efficiency coefficient (NSE) as three pairs of error metrics to evaluate the results of the model simulation, which are calculated as follows:

$$R^2 = \left(\frac{\sum_{t=1}^{T} \left(O_t - \overline{O}\right)\left(M_t - \overline{M}\right)}{\sqrt{\sum_{t=1}^{T}\left(O_t - \overline{O}\right)^2}\sqrt{\sum_{t=1}^{T}\left(M_t - \overline{M}\right)^2}} \right), \quad (3)$$

$$RMSE = \sqrt{\frac{1}{T}\sum_{t=1}^{T}(O_t - M_t)^2}, \quad (4)$$

$$NSE = 1 - \frac{\sum_{t=1}^{T}(O_t - M_t)^2}{\sum_{t=1}^{T}\left(O_t - \overline{O}\right)^2}, \quad (5)$$

where M_t is the simulated value and O_t is the measured value.

The selection of R^2, NSE, and RMSE as evaluative metrics for the computation capability of the model in this paper is justified by their aptitude to represent the relationship between the calculated and observed values. While R^2 and NSE provide some insights, they fail to indicate if there is a deviation between observed and calculated figures and cannot assure sufficient data fitting by the model. However, RMSE can capture the discrepancy between observed and calculated values and measure the fitting degree. Moreover, although NSE is commonly used to assess hydrological models, it may generate abnormally high data when the observed values are significantly low or near zero, leading to potential inaccuracies in evaluation results. R^2, on the other hand, does not share this issue. Therefore, employing these three measures as evaluative metrics for the model's computational outcomes can provide a more comprehensive display of the model's computational results and enhance the reliability of these results.

In this study, we address potential abnormalities in the monitoring data of water transfer projects by leveraging the solution characteristics of the hydrodynamic model. This approach aims to refine the precision of this model in a nullah pool context. Essentially, if a certain data type exhibits an anomalous value, we employ additional data in combination with the hydrodynamic model to remedy the abnormality. When an outlier appears at the flow boundary, we substitute the traditional upstream and downstream flow-level boundaries with a water-level boundary, followed by a correction of the flow boundary.

In instances where there is an obvious abnormality in the upstream water level data, such data is typically eliminated, and linear interpolation is applied for additional data. This method has little impact on the water level–flow relationship of the channel when there are fewer anomalies. However, when numerous anomalies are present, the water level and flow rate data may not appropriately reflect the channel's true water conditions. In this case, we incorporate the flow boundary combination into the hydrodynamic model, compute the water level data, and use it as an interpolation value to substitute the original anomalies. This strategy successfully circumvents the problems arising from linear interpolation.

Yet, in everyday monitoring processes, the accuracy of flow data monitoring is often inferior to that of water level data. Consequently, this study takes the hydrodynamic model's upper boundary flow data anomaly as the primary subject for research. The technological roadmap is detailed in Figure 2.

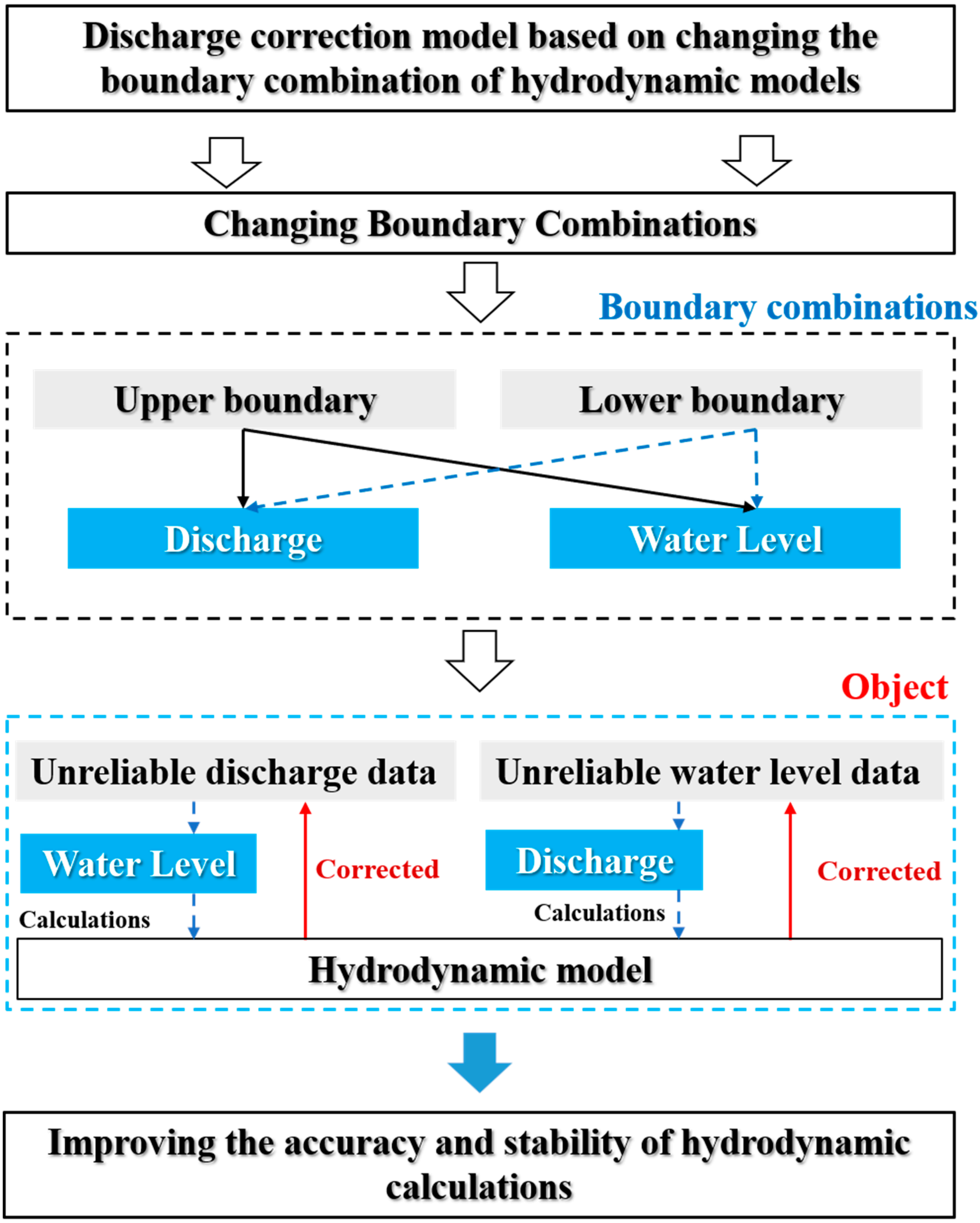


Figure 2. Technology roadmap.

To further validate that the corrected flow boundary aligns closely with the actual flow boundary, the study area is subdivided into the 'Correction Module' and the 'Validation Module'. The 'Correction Module' specifically addresses detecting anomalies in water data at the channel boundary and utilizes the method proposed in this paper to rectify such anomalies, with flow data anomalies serving as a primary example. In instances where the flow at the upstream boundary is abnormal, the upstream overflow flow Q_{ca} is derived using a boundary combination of water level in the 'Correction Module'. The upstream overflow flow is then discharged according to the water balance relationship to the overflow flow Q_n of the control gate at the downstream boundary of the 'Correction Module'. During this process, the control gate downstream of the correction area serves as the upstream boundary for the 'Validation Module'. This facilitates the building of a hydrodynamic model for the 'Validation Module', using the corrected Q_n as the post-corrected validation area. The adjusted Q_n is then used as the upstream boundary of the 'Validation Module', to carry out hydrodynamic calculations for the 'Validation Module'. To evaluate the impact of the flow correction, a comparison of the water level accuracy in the validation area before and after the gate is carried out, both pre- and post-flow rate correction. A schematic representation of these calculations is depicted in Figure 3.

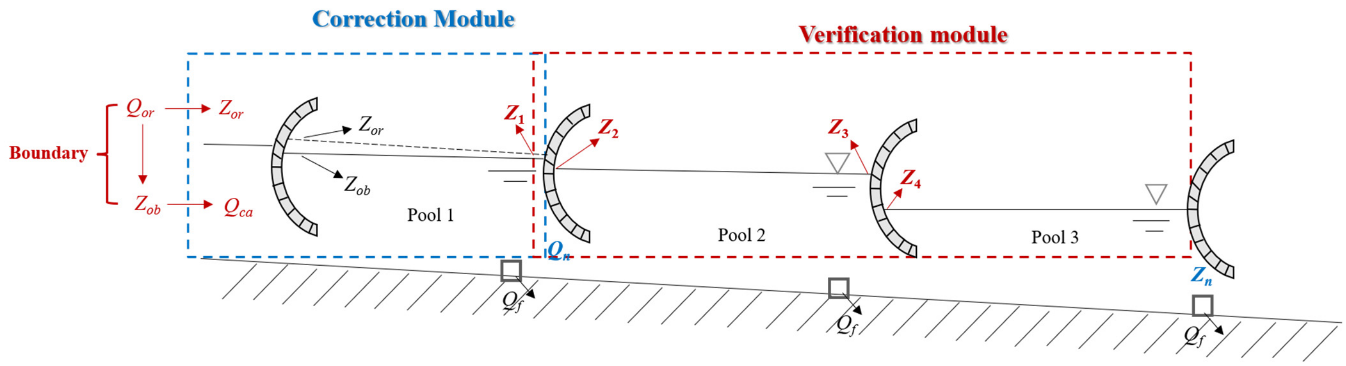


Figure 3. Calculation schematic figure.

4. Results and Discussion

4.1. Flow Adjustment Period Throttle Gate Overflow Correction Results

The flow adjustment process of the control gate is mostly affected by the water diversion change in the diversion port. In this paper, to select a typical case, the flow and water level data of a whole month in July 2018 in the study area are selected as the upper and lower boundaries of the hydrodynamic calculations, and the monitoring frequency of the data is 2 h/time. The combination of the upstream and downstream boundaries and the change in the water diversion of the half-slope diversion port are shown in Figure 4.

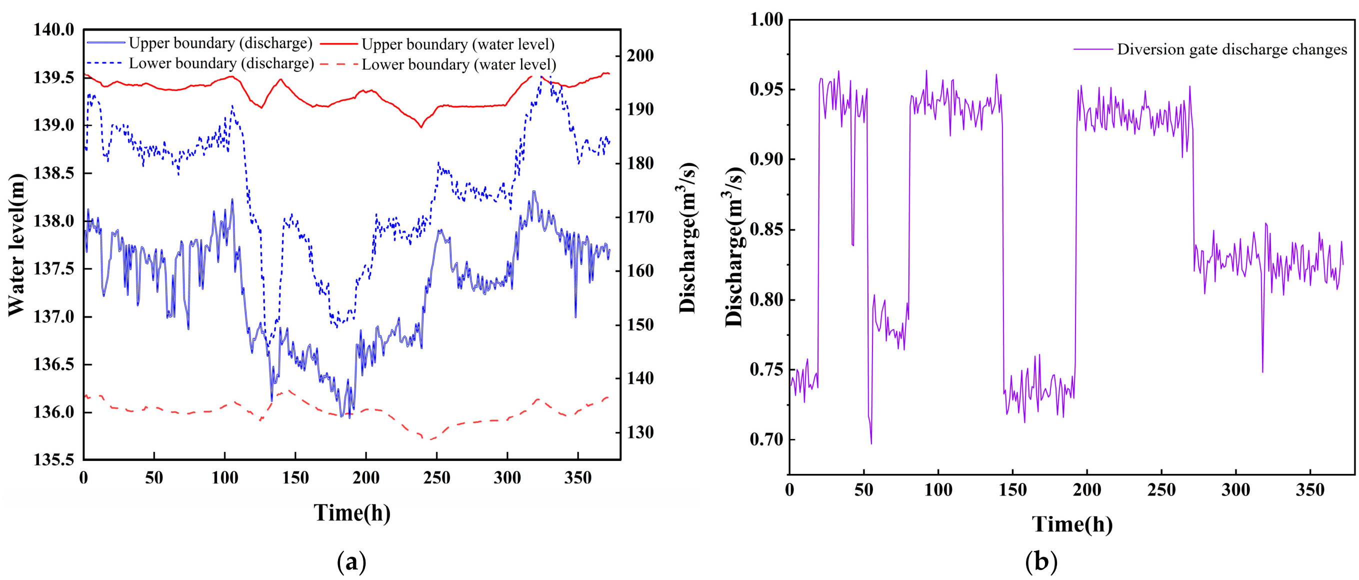
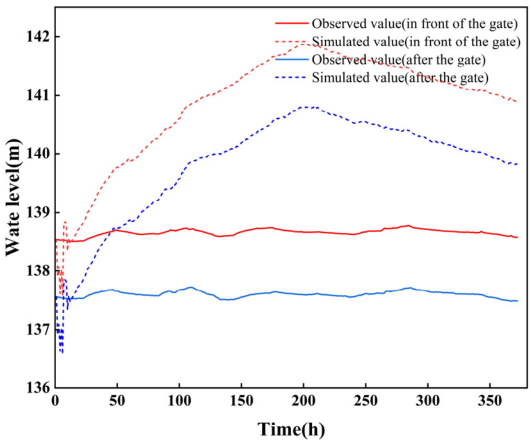


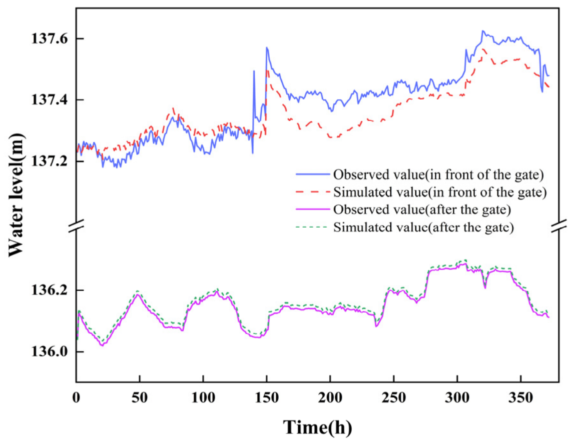
Figure 4. (**a**) Boundary combinations and (**b**) changes in diversion flows in channels.

From Figure 4, it can be found that in July, the half-slope diversion caused several diversion changes, this diversion of water on the water level and flow of the channel pool had a greater impact on the water level and flow, upstream and downstream of the water level and flow have occurred a large fluctuation in the same time can be found that the flow process downstream surprisingly greater than the upstream of the flow process, the center line of the project along the line of the process of the inlet is not available, the case also corroborated by the above description, in the process of flow adjustment, the monitoring of the channel also brought greater difficulty, resulting in monitoring inaccuracy.

In this paper, the hydrodynamic model of White River control gates and Caodun River control gates is constructed using the upstream flow of White River control gates and the water level in front of Caodun River control gates. The water level and flow information of Dongzhao River control gates and Huangjin River control gates in the channel are calculated, and the results are shown in Figure 5.



(**a**) Dongzhao River control gate



(**b**) Huangjin River control gate

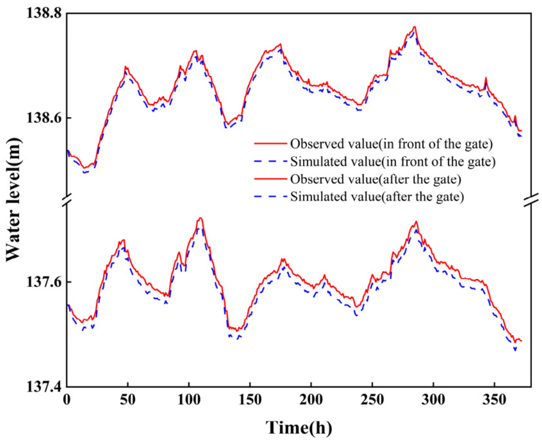
Figure 5. The flow adjustment period of hydrodynamic calculation results under the original boundary.

As can be seen from both Figure 5 and Table 1, the half-slope diversion is located upstream of the Dongzhao River's control gates and undergoes frequent diversion disturbances. The monitoring information of the channels may be biased, and the R^2, NSE, and RMSE of the Dongzhao River's pre-gate and post-gate levels are far away from the normal intervals. The R^2 of the pre-gate and post-gate water levels of the control gates of the Huangjin River is higher than 0.8, the NSE is also higher than 0.85, and the RMSE is lower than 0.2, and the simulation of the hydrodynamic model in the Huangjin River is greatly improved compared with that of the Dongzhao River.

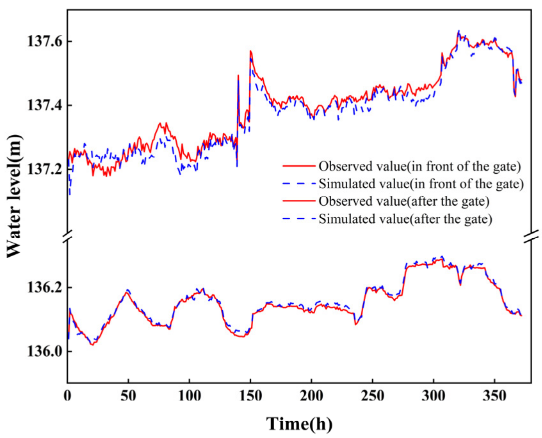
Table 1. R^2, NSE, and RMSE for hydrodynamic calculations in the original boundary case.

Name of the Control Gate			R^2	RMSE	NSE
Dongzhao River	Water level	In front of the gate	0.23	1.73	0.13
		After the gate	0.21	1.34	0.14
Huangjin River	Water level	In front of the gate	0.84	0.19	0.88
		After the gate	0.95	0.05	0.96

From the pre-gate and post-gate levels of the Dongzhao River control gate, it can be seen that the accuracy of the simulation results of the hydrodynamic model in this section is very low, so it needs to be considered that the boundary conditions of the hydrodynamic model are not set reasonably enough. In the process of water transfer, the accuracy of water level monitoring is often higher than that of flow monitoring, so the boundary conditions of hydrodynamics are set to the water level data, using the upstream and downstream water levels for hydrodynamic modeling, the St. Vernand equation for flow difference calculation, and the flow of the upper boundary in the use of water balance equations to internalize the flow of the downstream flow of the various control gates of the process. In this case, the flow process of the Dongzhao River is obtained by subtracting the diversion process of the half-slope diversion from the modified White River overflow process. The modified hydrodynamic simulation results are examined by constructing the hydrodynamic model of the Dongzhao River-Caodun River. The modified hydrodynamic simulation results are shown in Figure 6.



(**a**) Dongzhao River control gate



(**b**) Huangjin River control gate

Figure 6. Corrected pre- and post-gate levels of the Dongzhao River and the Huangjin River.

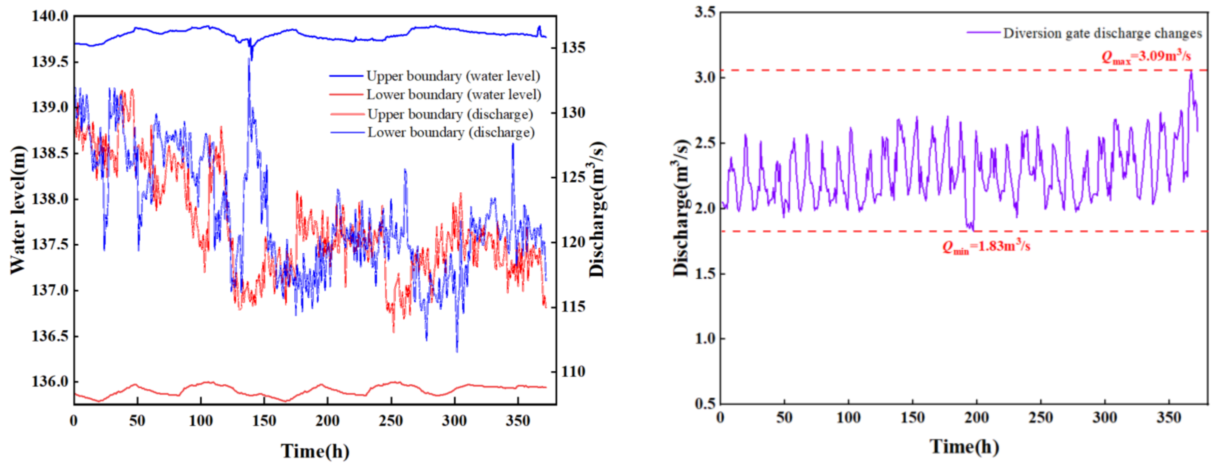
From Figure 6 and Table 2, it can be seen that the hydrodynamic simulation results of the pre-gate and post-gate levels of the Dongzhao River control gates and the Huangjin River control gates are much better than those before the flow rate is not corrected, and the corrected hydrodynamic results of R^2 are all higher than 0.9, the RMSE are all lower than 0.1 m, and the NSE are also all higher than 0.9, which indicates that the corrected flow rate can be better for the water-level-flow relationship within the channel.

Table 2. R^2, NSE, and RMSE for hydrodynamic calculations in the corrected boundary case.

Name of the Control Gate			R^2	RMSE	NSE
Dongzhao River	Water level	In front of the gate	0.95	0.05	0.97
		After the gate	0.93	0.06	0.95
Huangjin River	Water level	In front of the gate	0.91	0.09	0.90
		After the gate	0.97	0.02	0.99

4.2. Corrected Results of Throttle Gate Overflow during the Smooth Flow Period

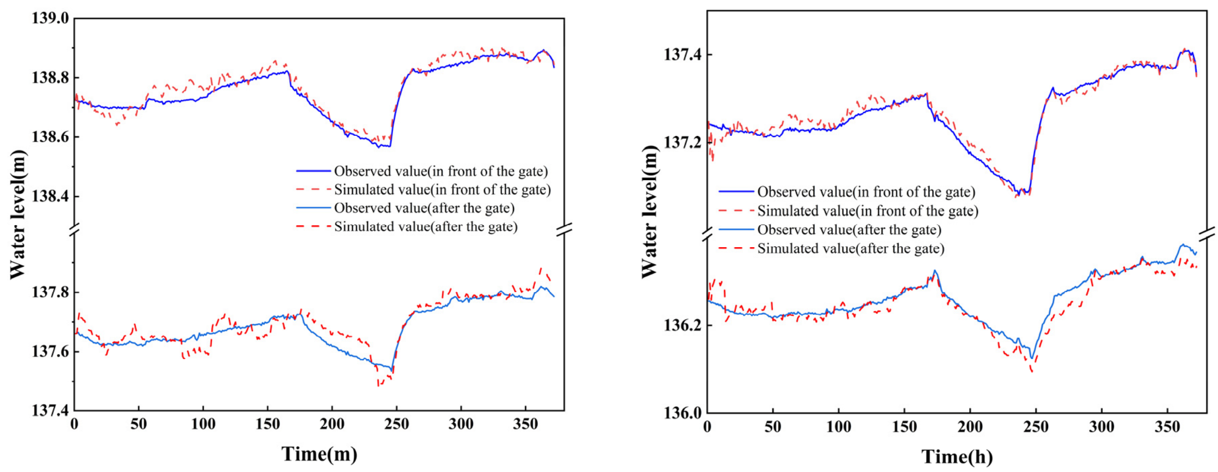
From the aforementioned analysis, it is evident that during the flow adjustment phase, flow monitoring tends to display bias, inevitably leading to less accurate hydrodynamic simulation outcomes. However, adjusting the boundary of the hydrodynamic model to correct the overflow at the throttle gate significantly improves the precision of the hydrodynamic simulation results. The decrease in accuracy is particularly noticeable at the throttle gate due to flow monitoring. To underscore the comprehensive adaptability and robustness of the method suggested in this study, tests are also conducted during the flow stabilization phase. This is to examine whether the water level-flow relationship of the channel can be enhanced by revising the boundary of the hydrodynamic model. To ensure the reproducibility of the experimental outcomes, the test region remains consistent, encompassing the White River and Caodun River control gates. This facilitates the verification of the water level relationship before and after the gates at the Dongzhao River and Huangjin River control gates. The water level and flow data from January 2018 for the White River Sectional Lock and Huangjin River Sectional Lock were adopted as the upstream and downstream boundaries for the hydrodynamic model. The boundary conditions and flow processes at the half-slope diversion are graphically represented in Figure 7.



(**a**) The boundary of the Smooth Flow Period (**b**) Diversion flows of the Smooth Flow Period

Figure 7. Boundary combinations and changes in diversion flows in channels.

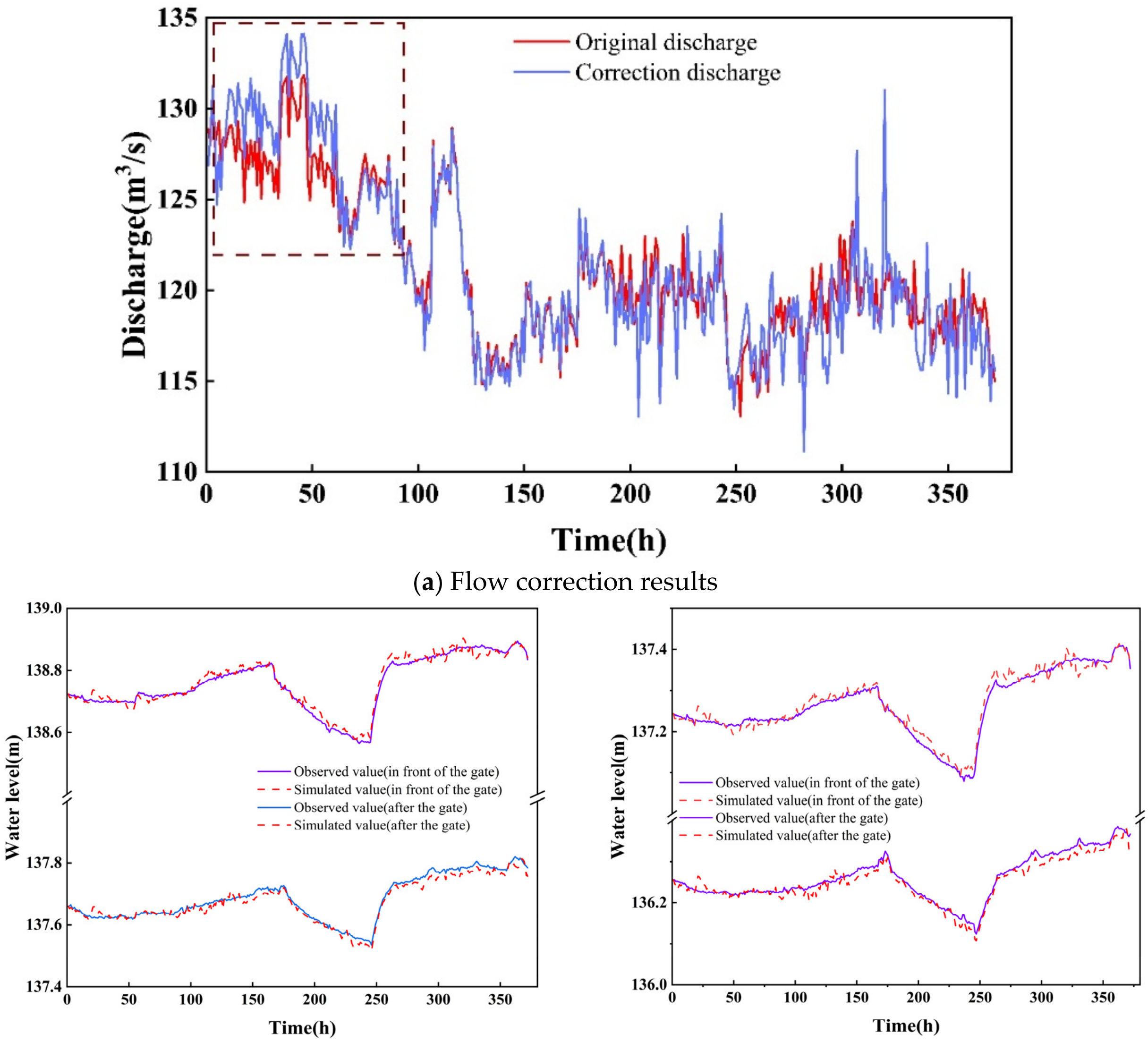
Compared with the water splitting situation at the half-slope diversion in Figure 4, the selected water splitting data in January 2018 appears to be smoother, stable, and oscillating around a certain mean value, and the maximum deviation is only 1.26 m^3/s, with no obvious water splitting changes. And in the case of upstream and downstream flow boundaries, there is no indication in Figure 4 that the flow downstream is higher than the flow upstream; in this case, it cannot be indicated that at this time the flow monitoring is inaccurate. To validate whether the proposed method in this study can improve the level-flow relationship of channels during the steady flow period, the conventional flow-level was used as the initial boundary combination for the hydrodynamic calculation of the Dongzhao River and Huangjin River.The simulation results before and after the gates of the Huangjin River are shown in Figure 8.



(**a**) Dongzhao River control gate (**b**) Huangjin River control gate

Figure 8. The Smooth Flow Period of hydrodynamic calculation results under the original boundary.

Using the method of this paper, the boundary combination of hydrodynamics is changed, and the upstream and downstream hydrodynamic boundary combination of water levels is utilized to correct the overgate flow rate of the White River control gates. Then, the overgate flow rate of the Dongzhao River control gates is calculated through the method of water balance, and the overgate flow rate of the Dongzhao River is used to construct a hydrodynamic model of the Dongzhao River and Caodun River. This way, information about the water levels of the control gates of the Dongzhao River and Caodun River is computed. The corrected hydrodynamic calculation results are shown in Figure 9.



(**a**) Flow correction results

(**b**) Dongzhao River

(**c**) Huangjin River

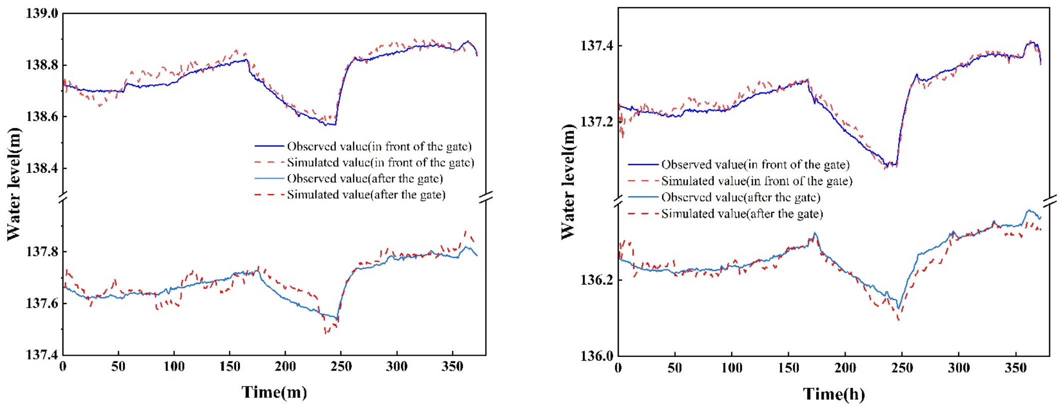
Figure 9. Corrected boundary inflow processes and pre- and post-gate levels of the Dongzhao and Huangjin Rivers.

By comparing Figures 8 and 9 and Table 3, it is found that the hydrodynamic model has little deviation in calculating the typical water level of the Dongzhao River and the Huangjin River control gate. The maximum deviation of the water level R^2 before and after the gate of the Dongzhao River is only 0.02, the maximum deviation of RMSE is only 0.02 m, and the maximum deviation of NSE is only 0.02 m. The maximum deviation of the water level R^2 before and after the Huangjin River gate is only 0.01, the maximum deviation of RMSE is only 0.01 m, and the maximum deviation of NSE is only 0.02 zm. The hydrodynamic calculation results of the Huangjin River are slightly better than the hydrodynamic calculation results of the Dongzhao River gate.

Table 3. Comparison of R^2, NSE, and RMSE for typical water levels at Dongzhao River and Huangjin River control gates under the corrected boundary and the original boundary.

Name of the Control Gate			R^2	RMSE	NSE
Dongzhao River	Original discharge	In front of the gate	0.94	0.05	0.94
		After the gate	0.95	0.06	0.92
	Corrected discharge	In front of the gate	0.95	0.04	0.94
		After the gate	0.97	0.03	0.95
Huangjin River	Original discharge	In front of the gate	0.96	0.03	0.94
		After the gate	0.97	0.02	0.95
	Corrected discharge	In front of the gate	0.97	0.03	0.96
		After the gate	0.97	0.03	0.95

To further verify the reliability of the model, we employed the method of dynamic box plots to monitor outliers under identical conditions. Using neural network interpolation, the computational results of the model, as shown in Figure 10, were derived.



(**a**) Dongzhao River control gate

(**b**) Huangjin River control gate

Figure 10. The neural network method is applied to calculate the water levels upstream and downstream of the Dongzhao and Huangjin River gates.

As indicated by Figure 10 and Table 4, the use of a neural network model for boundary data processing does not enhance the accuracy of the hydrodynamic model's computations. This paper, for comparative purposes, utilizes dynamic box plots to monitor and exclude outliers. The excluded data are then interpolated using a neural network model. The results show that the data interpolated with neural networking are nearly identical to the original flow data. This observation suggests that the anomalies in the boundary data are not due to global deviations but rather noncompliance with the water level-flow relationship in the channel pool. Thus, it is necessary to correct the upstream boundary data using the hydrodynamic model itself, which reflects the approach's advantages mentioned at the beginning of this article.

Table 4. Comparison of R^2, NSE, and RMSE of neural network methods for calculating typical water levels in the Dongzhao River and Jinjin River control gates.

Name of the Control Gate			R^2	RMSE	NSE
Dongzhao River	Original discharge	In front of the gate	0.94	0.05	0.94
		After the gate	0.95	0.05	0.94
	Neural network	In front of the gate	0.95	0.04	0.94
		After the gate	0.95	0.04	0.94
Huangjin River	Original discharge	In front of the gate	0.96	0.03	0.94
		After the gate	0.96	0.03	0.94
	Neural network	In front of the gate	0.97	0.03	0.96
		After the gate	0.97	0.03	0.96

4.3. Discussion

During the flow adjustment period, the flow adjustments made it more difficult to accurately collect flow data, and as a result, there was an apparent problem of downstream flow being greater than upstream flow, in which the monitoring of channel flow could certainly be identified as problematic. Using the current monitoring flow data as the upstream boundary of the hydrodynamic model in the study area to calculate the pre-gate levels of the other control gates in the study area, it was found that the pre-gate and post-gate levels of the control gate nearest the downstream of the control gate at the upstream boundary (Dongzhao River control gate) were simulated to be out of calibration, and the validation deviated from the normal values; the hydrodynamic calculations of the Jinjin River control gate, which is downstream of the Dongzhao River control gate, showed results significantly superior to those of the Dongzhao River control gate, because the downstream flows were greater than the upstream flows. This is because the original hydrodynamic boundary uses the boundary combination of flow rate and water level, and the upstream boundary flow rate is now considered to be wrong, but the downstream water level is accurate, so in the process of differential calculation, the Huangjin River control gate is more affected by the downstream boundary than the upstream boundary, so in the process of calculation, the Huangjin River control gate does not have a hydrodynamic simulation misalignment, but due to the close proximity of the downstream boundary, the post-gate water level R^2 and NSE of the Huangjin River control gate are higher than 0.97, and the RMSE is only 0.02 m. Now the method of changing the boundary combination proposed in this paper is used to correct the boundary flow, and the corrected flow is used in hydrodynamic modeling. It is found that the corrected flow avoids hydrodynamic misalignment in the simulation process of the Dongzhao River and guarantees that the R^2 of the water levels before and after the gates are all greater than 0.3, that the NSE is greater than 0.95, and that the RMSE is all less than 0.06 m. Comparing the water level process of the Huangjin River In the process of comparing the water level of the Huangjin River control gate, the corrected flow rate also improves the accuracy compared to the uncorrected flow rate, and its pre-gate level R^2 and NSE are improved by 0.07 and 0.02, and the RMSE is reduced by 0.1 m, and the post-gate level R^2 and NSE are improved by 0.02 and 0.03, and the RMSE is reduced by 0.03 m, which is more significant to improve the effect.

In the flow smoothing period, since the diversion is more stable, there is no situation similar to the flow adjustment period where the downstream flow is greater than the upstream flow, so it is not possible to determine whether the current monitoring flow is in error or not. Therefore, the hydrodynamic calculations were performed according to the boundary combination of flow-water level, and it was found that there was no misalignment of the hydrodynamic calculation results in the Dongzhao River control gate, and the simulation results of its characteristic water level had R^2 and NSE higher than 0.92 and the RMSE lower than 0.06 m, which made the hydrodynamic results in the flow steady period better compared to the flow adjustment process. The simulation of the characteristic water level of the Huangjin River control gate is better than that of the Dongzhao River control gate, and its hydrodynamic calculation results of R^2 and NSE are higher than 0.94, and the RMSE is lower than 0.03 m. Correcting the original flow rate and then carrying out the hydrodynamic calculations, it is found that the corrected hydrodynamic results do not have a significant effect compared with the uncorrected ones, and the maximum deviation of the R^2 of the water level in front of the gate and the water level in back of the gate of Dongzhao River is only 0.02, and the maximum deviation of the RMSE is only 0.05. The maximum deviation of the pre-gate and post-gate water level R^2 of the Dongzhao River is only 0.01, the maximum deviation of RMSE is only 0.02 m, and the maximum deviation of NSE is only 0.02 m. However, as can be seen from Figure 8a, the flow rate is adjusted to be larger in the first 100 h by the change in the boundary combinations, and it can be found that the modified flow afterward is higher than the original one. The hydrodynamic simulation effect in the first 100 h leads to corrected hydrodynamic results that are closer to the measured values, and the simulation accuracy is better. It can be observed that by altering the boundaries of the hydrodynamic model, we can swiftly capture the abnormal values of the flow boundary data, thereby ensuring higher accuracy in model simulation.

Through the analysis of the above two operational scenarios, it is revealed that during the flow adjustment phase, modifying the boundary combination to correct the boundary of the overrate flow significantly enhances the simulation accuracy of the hydrodynamic model. This, in turn, bypasses the potential misalignment issues in the hydrodynamic model due to monitoring errors. During the period of steady flow, similar adjustments to the boundary combination, this time to correct the boundary of the overgate flow, can subtly increase the accuracy of the hydrodynamic model's predictions. Notably, throughout the study, changes were applied exclusively to the upstream boundary, while the downstream boundary consistently incorporated the water level boundary. From the resultant hydrodynamic simulations, it appears evident that enticing the downstream boundary enhances the hydrodynamic simulation outcomes, which aligns with this study's methodological approach. This approach has been validated under two water transfer conditions, offering relevant theoretical guidance for the real-time operation of MRRSNWDP.

The method proposed herein, however, necessitates a highly accurate hydrodynamic model. In practical terms, water regulation engineering typically encompasses a series of interconnected sluice gates. The approximate solution attained when the hydrodynamic model discretely solves the flow equation for the gates using an implicit difference format can lead to cumulative error, particularly in scenarios with a high quantity of sluice gates. This can pose challenges to ensuring the accuracy of the hydrodynamic model. Consequently, the efficiency of the approach proposed in this study might diminish when handling scenarios involving several in-pool gates.

5. Conclusions

In this study, the problem of unstable flow monitoring accuracy in water transfer projects is fully considered, and a method based on changing different boundary combinations in the hydrodynamic model is proposed to solve the problem of low accuracy in hydrodynamic simulation calculations. The method of this paper is applied to the MRRSNWDP and has achieved better results. The results show:

1. In the flow adjustment period, using the method proposed in this paper, the hydrodynamic model can be well avoided because of the inaccuracy of the monitoring data, which leads to the inaccuracy of the hydrodynamic model calculation. Comparing the hydrodynamic results of the corrected flow rate and the original flow rate, it can be found that the maximum R^2 can be improved by 0.72, the NSE can be improved by 0.84, and the RMSE can be reduced by 1.65 m.
2. In the process of flow stabilization, comparing the modified and original hydrodynamic results, it can be found that although the overall hydrodynamic simulation accuracy of the method proposed in this paper is not very significant, it is more accurate in capturing the location of the flow, which may be monitored abnormally, and making corrections to ensure that the local hydrodynamic simulation is better so that the results are more responsive to the water level-flow relationship of the channel. The results are more reflective of the water level-flow relationship of the channel.

Although the method proposed in this paper can make the R^2 and NSE of the hydrodynamic model simulation results greater than 0.9, the study area contains only three sectional gates, and as the number of sectional gates continues to increase, it is difficult to maintain the accuracy of the hydrodynamic model by changing the boundary of the hydrodynamic model due to the accumulation of errors in the internal and external data, so the subsequent study can introduce the data assimilation method to process the boundary data and internal parameters. Therefore, the subsequent research can introduce the data assimilation method to process the boundary data and internal parameters and continuously reduce the impact of simulation accuracy reduction due to the accumulation of errors in the tandem gate group, so as to realize the efficient and accurate calculation of the hydrodynamic model.

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