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Dimensional Analysis of Hydrological Response of Sluice Gate Operations in Water Diversion Canals

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Abstract: The hydrodynamics characteristics of artificial water diversion canals with long-distance and inter-basin multi-stage sluice gate regulations are prone to sudden increases and decreases, and sluice gate discharge differs from that of natural rivers. Research on the change characteristics of hydrological elements in artificial canals under the control of sluice gates is lacking, as are scientifically accurate calculations of sluice gate discharge. Therefore, addressing these gaps in long-distance artificial water transfer is of great importance. In this study, real-time operation data of 61 sluice gates, pertaining to the period from May 2019 to July 2021, including data on water levels, flow discharge, velocity, and sluice gate openings in the main canal of the Middle Route of the South-to-North Water Diversion Project of China, were analyzed. The discharge coefficient of each sluice gate was calculated by the dimensional analysis method, and the unit-width discharge was modeled as a function of gate opening (e), gravity acceleration (g), and energy difference (H). Through logarithmic transformation of the Buckingham Pi theorem-derived equation, a linear regression model was used. Data within the relative opening orifice flow regime were selected for fitting, yielding the discharge coefficients and stage–discharge relationships. The results demonstrate that during the study period, the water level, discharge, and velocity of the main canal showed an increasing trend year by year. The dimensional analysis results indicate that the stage–discharge response relationship followed a power function ($Q \propto (\frac{H}{e})^{constant}$) and that there was a good linear relationship between $lg^{(\frac{H}{e})}$ and $lg^{(\frac{K}{e})}$ ($R^2 > 0.95$, $K = (q^2/g)^{1/3}$). By integrating geometric, operational, and hydraulic parameters, the proposed method provides a practical tool and a scientific reference for analyzing sluice gates' regulation and hydrological response characteristics, optimizing water allocation, enhancing ecological management, and improving operational safety in long-distance inter-basin water diversion projects.

Keywords: sluice gate-controlled mode; discharge coefficient; stage–discharge response relationship; the South-to-North Water Diversion Project of China

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1. Introduction

Ensuring adequate water resources is an important basic foundation for the health and development of human society and ecosystems [1]. With the comprehensive influence of climate change, rapid population growth, rapid industrialization, and urbanization in recent decades, the conflict between the supply and demand of water resources has become increasingly prominent, which has become a global problem threatening the high-quality

development and sustainable development of human society [2,3]. Many hydraulic engineering projects have been built to alleviate and improve the water consumption demands for human life, industrial production, agricultural irrigation, and the ecological environment [4]. These projects have played an important role in water resource regulation, water environment improvement, and river and lake recovery. Inter-basin water diversion projects are an important part of these projects. This kind of project connects rivers and lakes across basins through long-distance water canals and effectively optimizes regional water resource allocation through multi-stage sluice gates. It serves as an important engineering means to solve the uneven temporal and spatial distribution of global water resources [5,6]. As the largest inter-basin water diversion project in the world so far, the Middle Route of the South-to-North Water Diversion of China (MRSNWDPC) has played an important role in optimizing water resource allocation, ensuring the safety of people's drinking water, reviving the ecological environment of rivers and lakes, and boosting the north–south economic cycle since December 2014. It has effectively alleviated the water shortage in the Henan, Hebei, Beijing, and Tianjin provinces and directly benefitted more than 108 million people [7–9]. Despite the remarkable social, economic, and ecological benefits of the inter-basin water diversion project, the regional hydrological regime, the temporal and spatial impact of the water environment, and the security of water quality in the context of inter-basin water diversion projects are still sources of concern and controversy [10]. Previous studies have shown that hydrological elements, such as the water level, discharge, and velocity of river-type water bodies, are prone to sudden increases or decreases under sluice gate regulations. Different water quality indexes have been transformed into measurements of sediment, dissolution, suspension, and biological phase, and compared with natural rivers. The water quality transformation mechanism under sluice gate regulations is particularly complicated, which may cause new water environment problems [11–13]. In addition, the ecological algal control method, using sluice gate regulations to adjust the velocity, has become an efficient and important means of engineering water quality protection and has been studied widely [10]. Unlike natural rivers, artificial canals exhibit abrupt hydrodynamic fluctuations due to gate-regulated flow, complicating discharge prediction and ecological management. Analyzing the relationship between sluice gate regulations and hydrological response under the multi-stage sluice gate regulations of long-distance inter-basin water diversion projects is of great scientific significance, as the findings could help to optimize water distribution and ensure water quality safety.

Domestic and foreign scholars have conducted relevant studies on the water environmental effect of sluice gate regulations in hydraulic engineering construction. Domingues et al. [14] found that dam construction had a strong disturbance effect on the regional water environment, which caused a significant decrease in nutrients. Yu et al. [15] used two-dimensional longitudinal and transverse average hydrodynamic and water quality models to simulate the spatial–temporal characteristics of organic matter migration and diffusion caused by the stratification of sluice dams. Dou et al. [13,16,17] proposed a research method for multi-stage water quality transformation under different "water-suspension-bottom-mud-organism" operation modes in sluice gate-controlled reach and studied the driving mechanism and quantitative contributions of sluice gate operations to the multi-stage water quality response. Chen et al. [18] constructed a coupled mathematical hydrology–hydrodynamics–water quality model and applied it to a sluice gate-controlled river network. Taking the heavily polluted sluice gate-controlled river in the Huai River Basin in China as their research object, Li and Zuo [19] built a one-dimensional hydrodynamic and water quality model of multi-sluice dams based on MIKE11 and proposed a sluice gate–dam regulations strategy for a heavily polluted river. In previous studies, before dam construction, monitoring data were used for qualitative comparative analysis. A nu-

merical simulation model was used to analyze the influence of dam and sluice gate operations on regional water quality and water ecology [20]. However, few studies have been conducted on the relationship between sluice gate-controlled regulations and the hydrological response of inter-basin water diversion projects under multi-stage sluice gate-controlled regulations. Water quantity is regulated by sluice gates along the main canal of the MRSNWDPC according to the actual water usage and demand [21]. Therefore, analyzing and calculating the discharge of each sluice gate is of great practical and scientific significance.

There are two methods widely used to calculate the discharge through sluice gates: the traditional hydraulic method and the dimensional analysis method [22]. The traditional hydraulic method is based on the energy equation used to calculate the discharge coefficient and submerged coefficient. It is usually supplemented by in situ observation calibration or table lookups. Then, the empirical formula is modified according to practical engineering applications [23]. The discharge calculated by the energy equation is nonlinear, and the parameter calibration is complicated [24,25]. Rajaratnam and Subramanya [26] proposed diagrams for the free discharge coefficient and submerged discharge coefficient. Based on Henry's test, Swamee [27] determined a calculation formula for the free discharge coefficient. Ferro [28] applied the dimensional analysis method and self-similarity theory to derive the stage–discharge response relationship of free flow; this method was also applied to submerged flow. Bijankhan et al. [29] verified the applicability of the sluice gate free flow formula derived by Ferro. Ferro [30] also derived the stage–discharge relationship from the momentum balance equation, and the results showed that discharge was calculated by the momentum coefficient. Shayan and Farhoudi [31] used the energy equation and momentum equation to explore the flow characteristics under the free flow and submerged flow and deduced the relationship between the discharge coefficient of the sluice gate and the relative opening and relative tailwater depth. Dimension analysis was used to ascertain the relationships among discharge, gate opening, and water depth upstream and downstream. Previous studies have shown that the fitting process of the dimensionality analysis method is relatively simple, and the discharge calculation results are more accurate [23]. Guo et al. [24] established an empirical coefficient model and dimensional analysis model for different discharge patterns of orifice flow, and the results showed that the dimensional analysis model was better than those of the empirical coefficient model. Cui et al. [23] derived the dimensionless relationship of arc gates based on dimensional analysis, and the results showed that dimensional analysis was simpler and more accurate. Bijankhan et al. [32] used the traditional energy formula and dimensional analysis method to fit the sluice gate discharge and found that the dimensional analysis method had higher calculation accuracy.

In summary, the complex operation of multi-stage sluice gates has a significant impact on the hydrological regime of the main canal. Understanding the hydrological response to sluice gate operations is not only essential for ensuring the efficient operation of the water diversion project but also for maintaining ecological balance along the route. Previous studies have mainly focused on the impact of sluice gates on water quality and quantity from a hydrodynamic or hydrological cycle perspective, but few studies have been conducted on the relationship between sluice gate-controlled regulation and the hydrological response of inter-basin water diversion projects under multi-stage sluice gate-controlled regulation. In this study, the real-time operational data of 61 sluice gates along the main canal of the MRSNWDPC from May 2019 to July 2021, including water levels (front water level and back water level), discharge, velocity, and sluice gate openings, were used to analyze the variation laws of hydrological elements. We also fitted the discharge coefficients of sluice gates based on the dimensional analysis method. The main aims of this

study were as follows: (1) We aimed to calculate 61 sluice gates' annual average values of hydrological elements and analyze their interannual variations. (2) Based on the dimensional analysis method, we fitted the discharge coefficients of sluice gates and subsequently obtained the formula for sluice gate discharge. Compared with traditional hydraulic approaches that rely on iterative energy equation calibrations or empirical coefficients, this study introduces a dimensional analysis framework that reduces complex flow dynamics to data-driven fitting curves, offering superior adaptability to the MRSNWDPC's cascaded sluice gate configurations. This study addresses a critical gap in understanding how multi-stage sluice gates practically operate in long-distance inter-basin water diversion projects and influence hydrological responses. It provides an academic reference for clarifying the response characteristics of the hydrological regime and sluice gate-controlled mode of inter-basin water diversion projects and multi-stage sluice gate-controlled regulation, implementing scientific dam and sluice gate operation, and strengthening the optimal allocation of water resources.

2. Materials and Methods

2.1. Study Area and Data Collection

The Middle Route of the South-to-North Water Diversion Project of China (MRSNWDPC, 32°40′–39°58′ N, 111°42′–116°16′ E), with a total length of 1432 km, starts from the Danjiangkou Reservoir and ends at Tuancheng Lake, Beijing, the capital of China, spanning three climatic zones. Along this route, there is a long water diversion distance, large discharge, many cross-buildings, complex structures, and no regulating reservoir [10,33,34]. The section from Taocha (TC) to Beijuma (BJM) is 1197 km (TC hosts the first sluice gate of the main canal of the MRSNWDPC, and BJM hosts the last sluice gate in the open canal section). The Beijing and Tianjin provinces are culverts, with distances of 80 km in Beijing and 155 km in Tianjin. Sixty-four sluice gates and ninety-seven water diversion outlets are placed along the main canal of the MRSNWDPC. Sluice gates are the most important control structures of the inter-basin water diversion project, which control the water level and discharge [35]. This study analyzed the real-time operation data of 61 sluice gates. Each sluice gate was numbered for convenience (#1, #2…, up until #61). Thirty-seven sluice gates can be found in Henan province (#1, #2…, and #37, respectively), and twenty-four can be found in Hebei province (#38, #39…, and #61, respectively). More detailed information about the sluice gates is shown in Figure 1 and Supplementary Materials (Table S1).

In hydraulics, the ratio of the sluice gate opening e to the water head H_0 in front of the sluice gate is defined as the relative opening e/H_0, and the discharge regime is related to the relative opening e/H_0. For broad-crested weirs, when the relative opening is greater than 0.65, the discharge regime is defined as weir flow; otherwise, it is orifice flow [36]. The main canal of the MRSNWDPC comprises broad-crested weirs [37]. Under weir flow, the sluice gate has little effect on discharge regulation; therefore, this study only analyzed the stage–discharge response relationship under orifice flow.

The real-time operation data of 61 sluice gates, including data on water levels, discharge, velocity, and sluice gate openings, used in this study were monitored by the Construction and Administration Bureau of the Middle Route of the South-to-North Water Diversion Project of China. The main processing methods were as follows: (1) The annual average value of water level, discharge, and velocity of each sluice gate was calculated, which was used to analyze the interannual variation in hydrological elements. (2) The real-time operation data of the sluice gate were processed as daily average data, and the measurements of relative openings less than or equal to 0.65 were selected to fit the sluice gate discharge coefficients. Data and statistical analyses were performed using the R software (version 4.0.5, RStudio) and Microsoft Excel 2010 (USA, Microsoft).

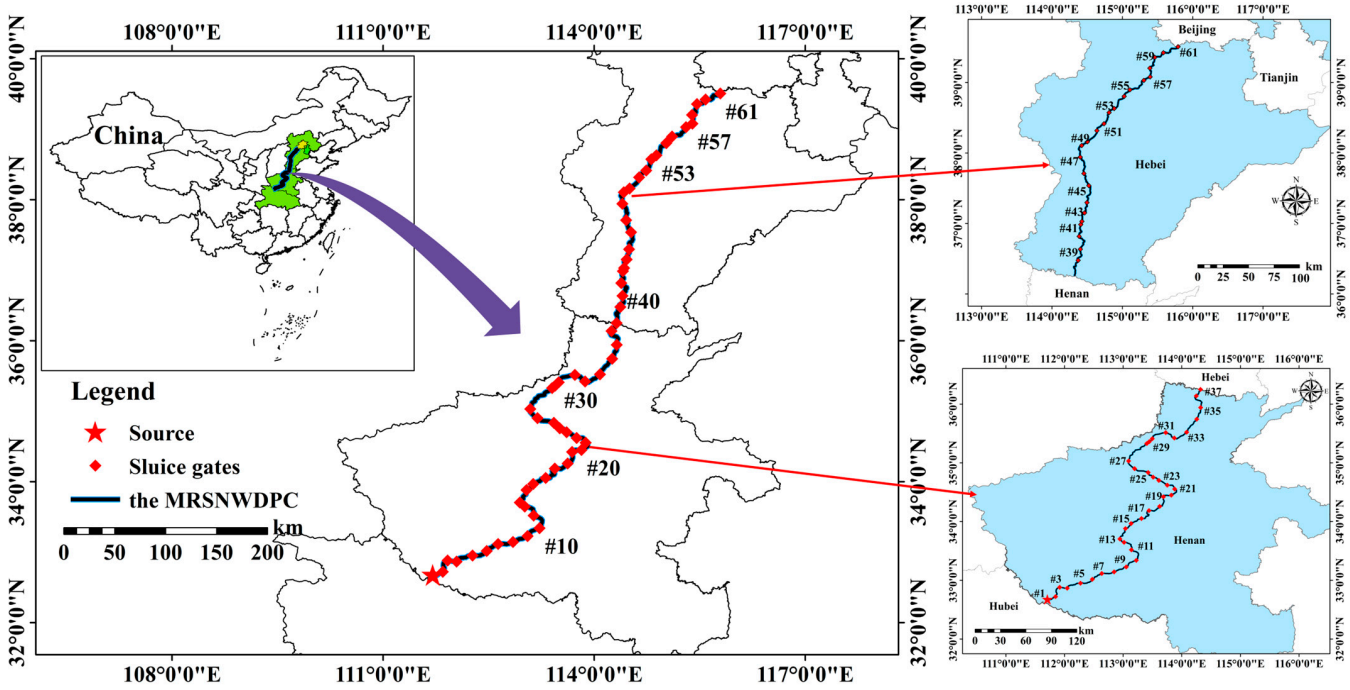


Figure 1. Location of the sluice gates of the main canal of the MRSNWDPC (the study area).

2.2. Dimensional Analysis Method

Dimensional analysis was selected for three primary reasons: (1) Operational efficiency: It reduces complex flow dynamics to a linear relationship between discharge (Q), gate opening (e), and hydraulic head (H), avoiding iterative energy equation calibrations required for traditional methods. (2) Adaptability: Unlike traditional hydraulic models that require iterative energy equation solutions or site-specific empirical coefficients, the dimensional analysis method simplifies the discharge calibration by leveraging dimensionless groups. It accounts for site-specific geometric (N, B) and operational (e/H_0) parameters, validated here for broad-crested weirs. (3) Error mitigation: This method reduces computational complexity and enhances accuracy in dynamic flow regimes, where multi-stage sluice operations introduce turbulent fluctuations and geometric variations absent in single-gate studies, achieving a low mean absolute percentage error and outperforming regression-based approaches in non-stationary flow regimes. The proposed framework and schematic of a typical sluice gate can be found in Figures 2 and 3.

Based on exponential dimension analysis, Shahrokhnia and Javan [38] derived the hydraulic relationship of arc gates.

Assuming the submerged flow, the unit-width discharge q was a function of the gate opening e (m), the gravity acceleration g (m/s), the energy difference H (m), and the viscosity coefficient μ. The functional relationship can be written as follows:

$$q = f(e, g, H, \mu) \tag{1}$$

$$H = H_0 - H_t \tag{2}$$

The relationship is expressed as a monomial (a product of variables raised to constant exponents), which is a common form in dimensional analysis to simplify complex flow dynamics, where H_0 is the head in front of the sluice gate, m, and H_t is the head behind the sluice gate, m.

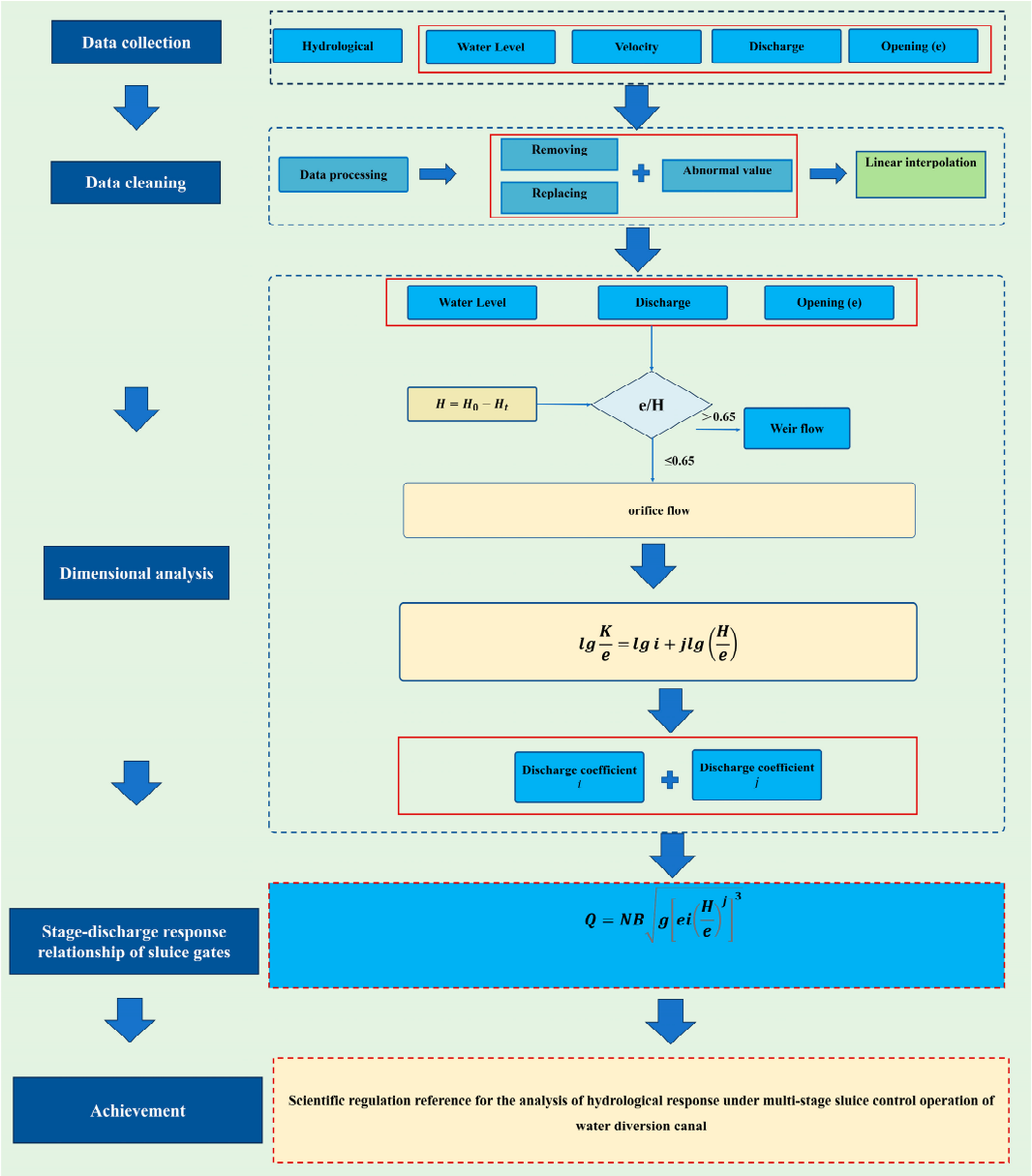


Figure 2. The proposed dimensional analysis-based methodology framework of this study.

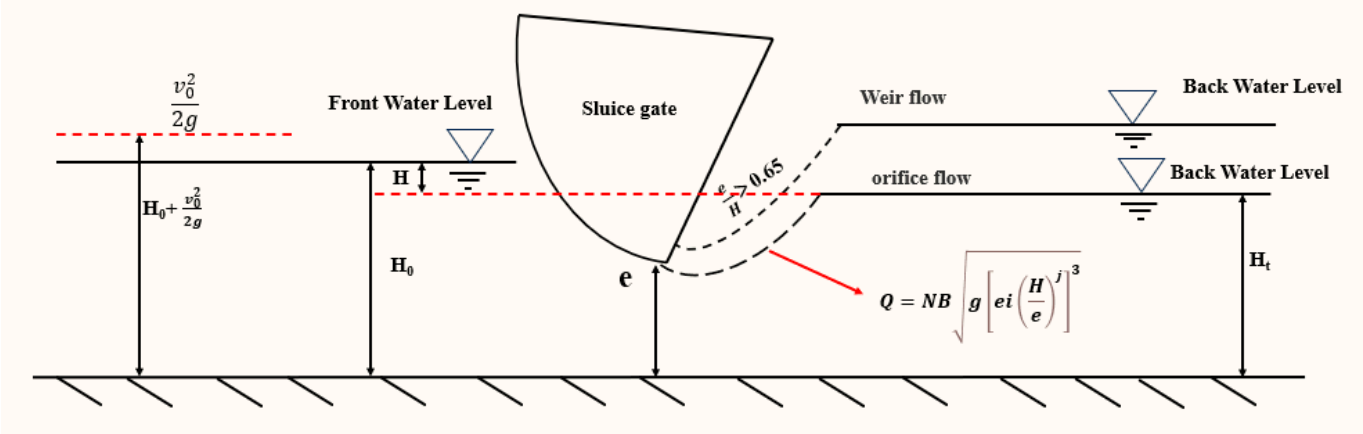


Figure 3. Schematic of a typical sluice gate with the mathematical variables involved.

It is assumed that the sluice gate discharge has the following form:

$$q = m\left(e^a g^b H^c \mu^d\right) \tag{3}$$

By assuming this form, we can use dimensional consistency (matching units on both sides) to solve for the exponents, reducing the problem to fitting constants rather than solving the full Navier–Stokes equations. In the above, a, b, c, d, and m are constants.

For the sluice gate of the main canal of the MRSNWDPC, the unit-width discharge can be written as follows:

$$q = \frac{Q}{NB} \tag{4}$$

This normalization is critical for generalizing the discharge formula across sluice gates with different numbers of holes or hole widths. It allows the analysis to focus on dimensionless ratios rather than absolute geometric parameters, enhancing the model's applicability to various gate designs. In the above, q is the discharge through the sluice gate, m^3/s; N is the number of holes in the sluice gate; and B is the width of the single-hole, m.

The viscosity term μ^d becomes negligible for turbulent flows (dominated by inertia, not viscosity), so $d = 0$. Through non-dimensionalizing Equation (3) using the Buckingham Pi theorem, Equation (5) can be obtained by dimensional analysis as follows:

$$\left(\frac{q^2}{g}\right)^{\frac{1}{3}} = m^{\frac{2}{3}} e \left(\frac{H}{e}\right)^{\frac{2c}{3}} \tag{5}$$

Using $K = \left(q^2/g\right)^{1/3}$, $i = m^{\frac{2}{3}}$, and $j = 2c/3$ as variable substitutions, the dimensionless relationship can be obtained as follows:

$$\frac{K}{e} = i\left(\frac{H}{e}\right)^j \tag{6}$$

To fit the parameters, a logarithmic transformation of Equation (6) can be performed to obtain Equation (7) as follows:

$$lg\frac{K}{e} = lgi + jlg\left(\frac{H}{e}\right) \tag{7}$$

By using $y = lg\frac{K}{e}$, $x = lg\frac{H}{e}$, $a = j$, and $b = lgi$ as variable substitutions, Equation (8) can be written as follows:

$$y = b + ax \tag{8}$$

If i and j are calculated, the discharge formula for each sluice gate can be written as follows:

$$Q = NB\sqrt{g\left[ei\left(\frac{H}{e}\right)^j\right]^3} \tag{9}$$

3. Results

3.1. Interannual Variation Characteristics of Hydrologic Elements

The data pertaining to the annual average water levels of each sluice gate of the main canal of the MRSNWDPC for the years 2019, 2020, and 2021 are shown in Figure 4. The average annual front water levels in Henan province were 122.21 m, 122.40 m, and 122.42 m, respectively, and the average annual back water levels were 121.15 m, 121.47 m, and 121.50 m, respectively. In Hebei province, the average annual front water levels were 74.92 m, 74.96 m, and 75.11 m, respectively, and the average annual back water levels were

74.18 m, 74.34 m, and 74.56 m, respectively. Figure 4 shows the average water levels of the main canal of the MRSNWDPC from 2019 to 2021, demonstrating an increasing trend year by year. As shown in Figure 5, the average annual discharge rates in Henan province were 187.1 m^3/s, 226.1 m^3/s, and 230.9 m^3/s, respectively, and the rates of velocity were 0.78 m/s, 0.89 m/s, and 0.90 m/s, respectively. In addition, the average annual discharge rates in Hebei province were 102.4 m^3/s, 113.2 m^3/s, and 120.1 m^3/s, and the velocity rates were 0.75 m/s, 0.75 m/s, and 0.77 m/s. The discharge differences between the Henan and Hebei provinces were 84.7 m^3/s, 113.0 m^3/s, and 110.8 m^3/s, and the velocity differences were 0.03 m/s, 0.14 m/s, and 0.13 m/s. From 2019 to 2021, the average annual discharge and velocity showed upward trends year by year.

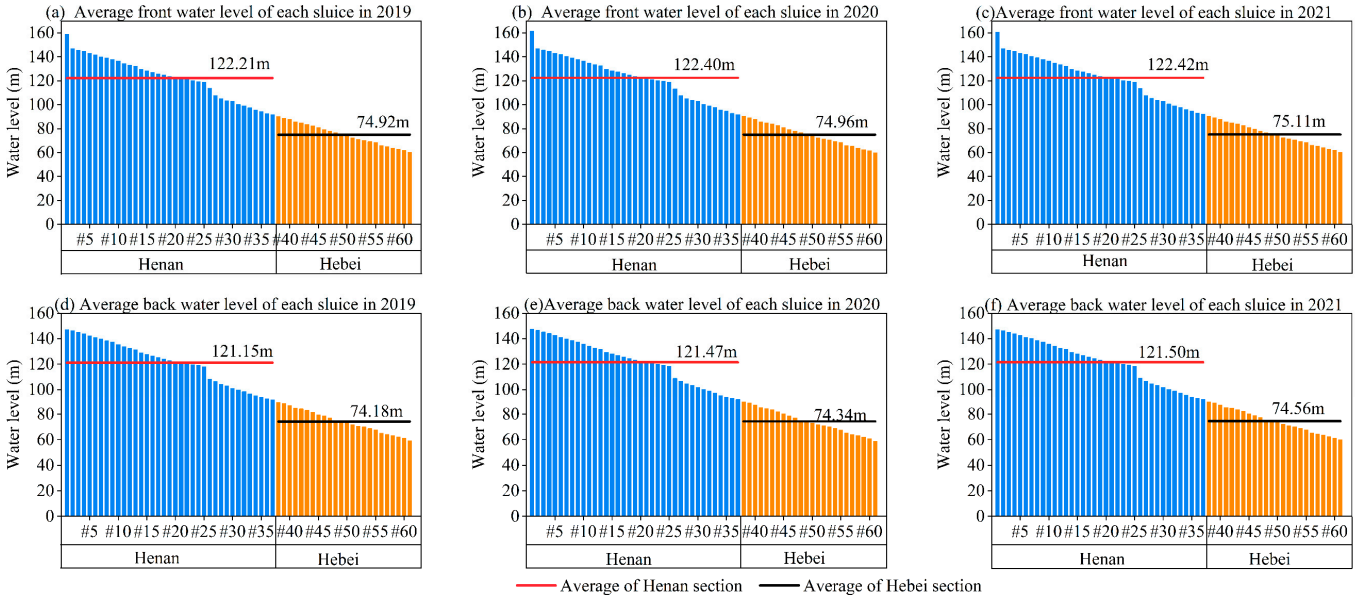


Figure 4. Annual average water level of each sluice gate of the main canal of the MRSNWDPC.

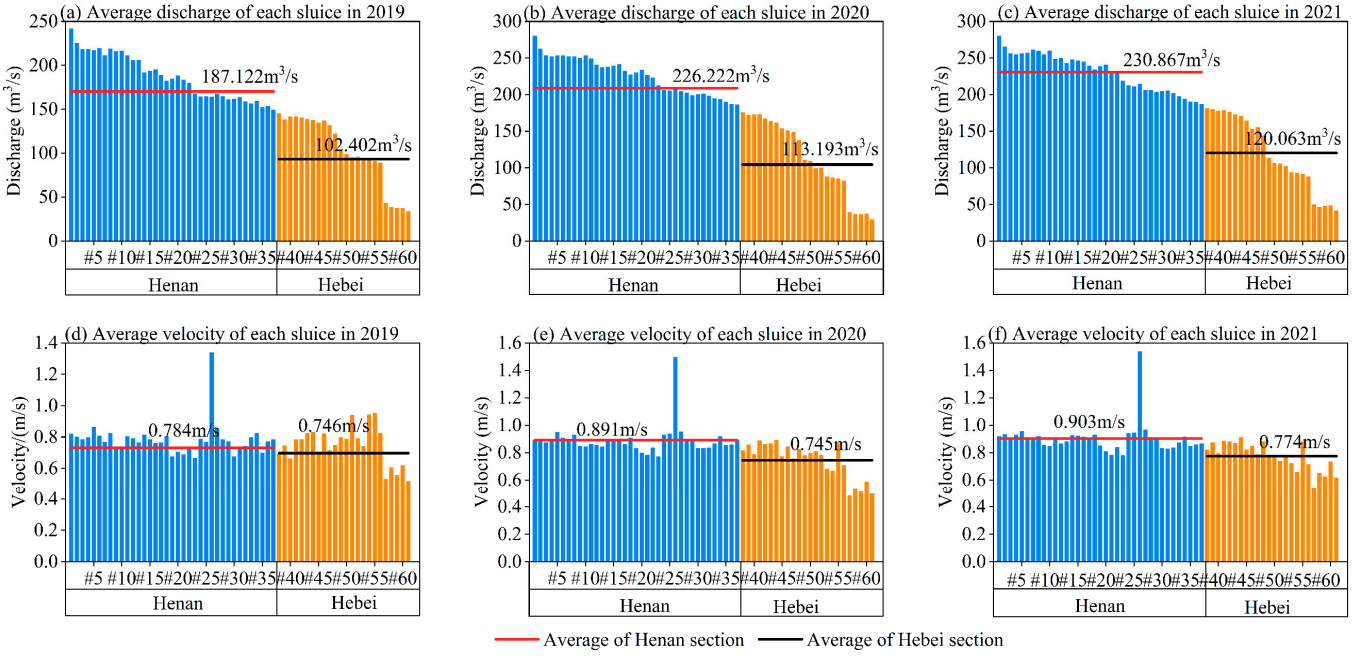


Figure 5. Annual average discharge and velocity rates of each sluice gate of the main canal of the MRSNWDPC.

Upon analyzing the interannual variation in hydrologic elements from 2019 to 2021, the water levels, discharge, and velocity showed increasing trends year by year, and the values for Henan province were all greater than those for Hebei province. From 2019 to 2021, the water diversion generally showed an increasing trend year by year. These trends in hydrological elements are directly related to the sluice gate operations in the MRSNWDPC. The increasing water diversion volume, which is regulated by the sluice gates, leads to observed changes. This result helps us understand how sluice gate-controlled water diversion affects the hydrological regime of the main canal, which is a key aspect of our research purpose.

3.2. Discharge Coefficient Fitting of Sluice Gates

Based on the dimensional analysis method, the discharge coefficients of the sluice gates were fitted. With $\lg(\frac{H}{e})$ as the horizontal coordinate and $\lg(\frac{K}{e}$ as the vertical coordinate, the data points were plotted for linear fitting. The hydrological regime of #26 (CH) directly affects the stability and safety of water diversion. #57 (XHS) is the source for Tianjin province, so the hydrological regime and water environment changes are very significant for people's domestic drinking water, water for industrial production, and water for agricultural irrigation. Due to the word count restrictions placed on this article, this paper only shows the fitting results of #8, #26, and #57. The other sluice gate fitting results are shown in the Supplementary Materials (Tables S2 and S3).

The fitting results of discharge coefficients of #8, #26, and #57 are shown in Figures 4 and 5, and the results indicate a linear relationship. The shaded parts shown in Figures 4b and 5b represent relative openings greater than 0.65. During this period, the sluice gate opening increased. When the bottom edge of the sluice gate left the water surface, the front water level was equal to the back water level, and the flow regime was weir flow. The formula for sluice gate discharge fitting based on the dimensional analysis was not suitable for calculating the discharge.

For #8, we needed to fit the sluice gate discharge coefficient with time as the node segment. Figure 6 shows sluice gate #8's fitting results regarding the discharge coefficient from 28 May 2019 to 17 April 2020. The determination coefficient (R^2) was 0.948. Figure 4c shows the fitting results from 18 April 2020 to 20 July 2021. The determination coefficient (R^2) was 0.945. Figure 7 shows the fitting results regarding the discharge coefficients of #26 and #5, respectively, with determination coefficients (R^2) of 0.995 and 0.997, respectively. The fitting results show that $\lg(\frac{H}{e})$ and $\lg(\frac{K}{e})$ had a good linear relationship, and the dimensional analysis method was more reliable in fitting the discharge coefficients.

Based on the dimensional analysis method, the discharge coefficients of 61 sluice gates along the main canal of the MRSNWDPC were fitted. More detailed information about the discharge coefficient fitting results is shown in the Supplementary Materials (Figures S1–S5). This paper only shows the results of #8, #26, and #57 (as shown in Table 1). Table 1 shows that the dimensional analysis conducted to fit the discharge coefficients was relatively reliable. The R^2 values for #26 and #57 were greater than 0.99, but that of #8 was less than 0.95. By analyzing the fitting results of the discharge coefficients of 61 sluice gates, we found that the R^2 of 56 sluice gates was greater than 0.95. The dimensionality analysis method was suitable for fitting the discharge coefficients of the main canal of the MRSNWDPC, and the fitting result was ideal. The overall fitting results for Henan and Hebei provinces were analyzed. All the R^2 values of the 37 sluice gates in Henan province were greater than 0.93, but the R^2 values of the 23 sluice gates in Hebei province were greater than 0.97, except for #39, which had a value of 0.896. Based on the dimensional analysis method, the discharge formula of each sluice gate was obtained. The average error, relative error, root mean square error, and relative root mean square error were used

to evaluate the overall calculation accuracy of discharge in Henan and Hebei provinces. As shown in Table 2, the results show that the overall fitting results for Hebei province were better than those for Henan province, further proving the effectiveness and reliability of the dimensional analysis method.

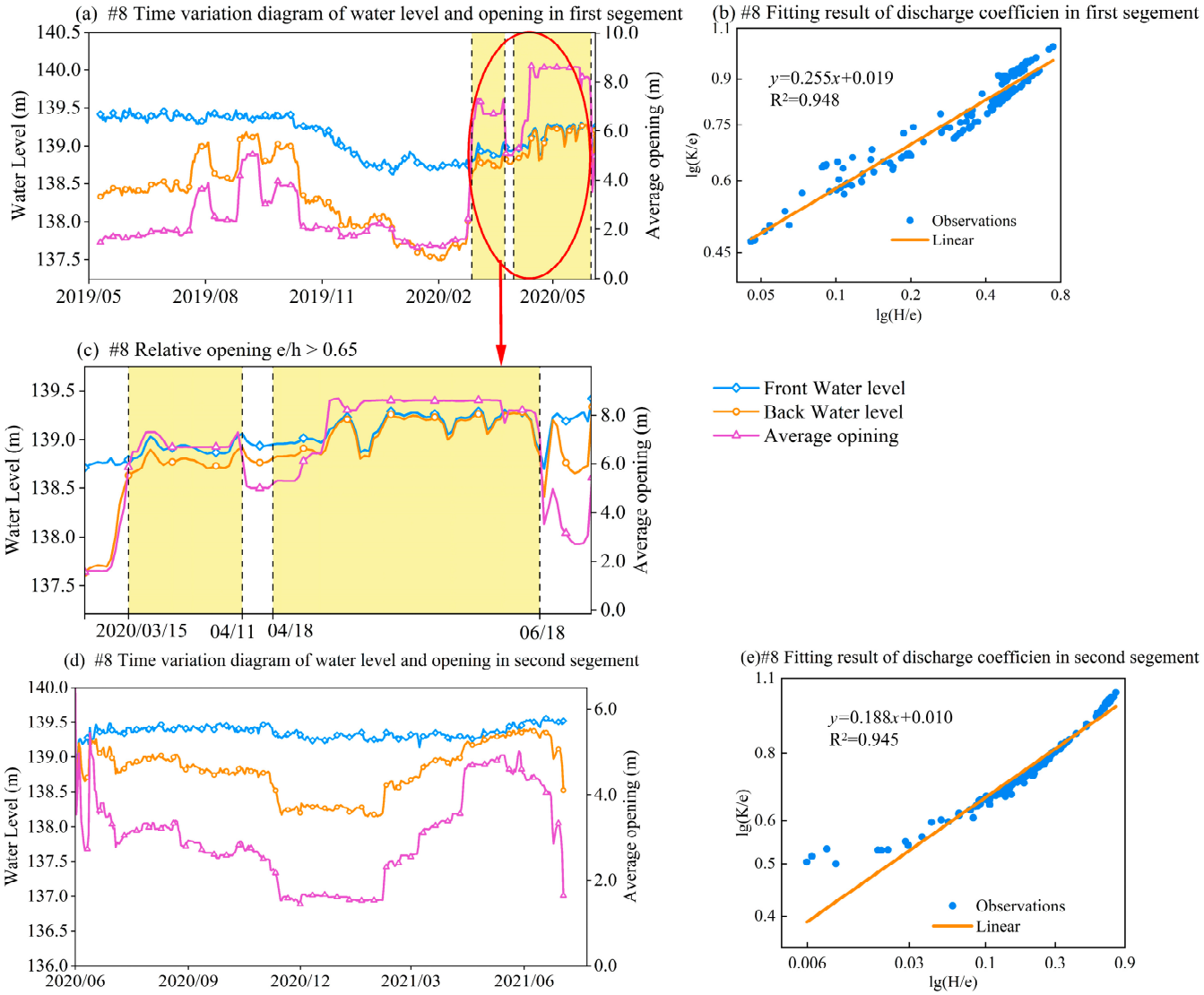


Figure 6. Fitting results regarding the discharge coefficient of sluice gate #8.

Table 1. Fitting results regarding the discharge coefficients of sluice gates #8, #26, and #57.

JZZ_ID	Discharge Coefficient *i*	Discharge Coefficient *j*	Linear Fitting Formula	R^2	Province
#8	1.045	0.255	$y = 0.255x + 0.019$	0.948	Henan
	1.002	0.188	$y = 0.188x + 0.001$	0.945	
#26	1.062	0.285	$y = 0.285x + 0.026$	0.995	Henan
#57	1.151	0.323	$y = 0.323x + 0.061$	0.997	Hebei

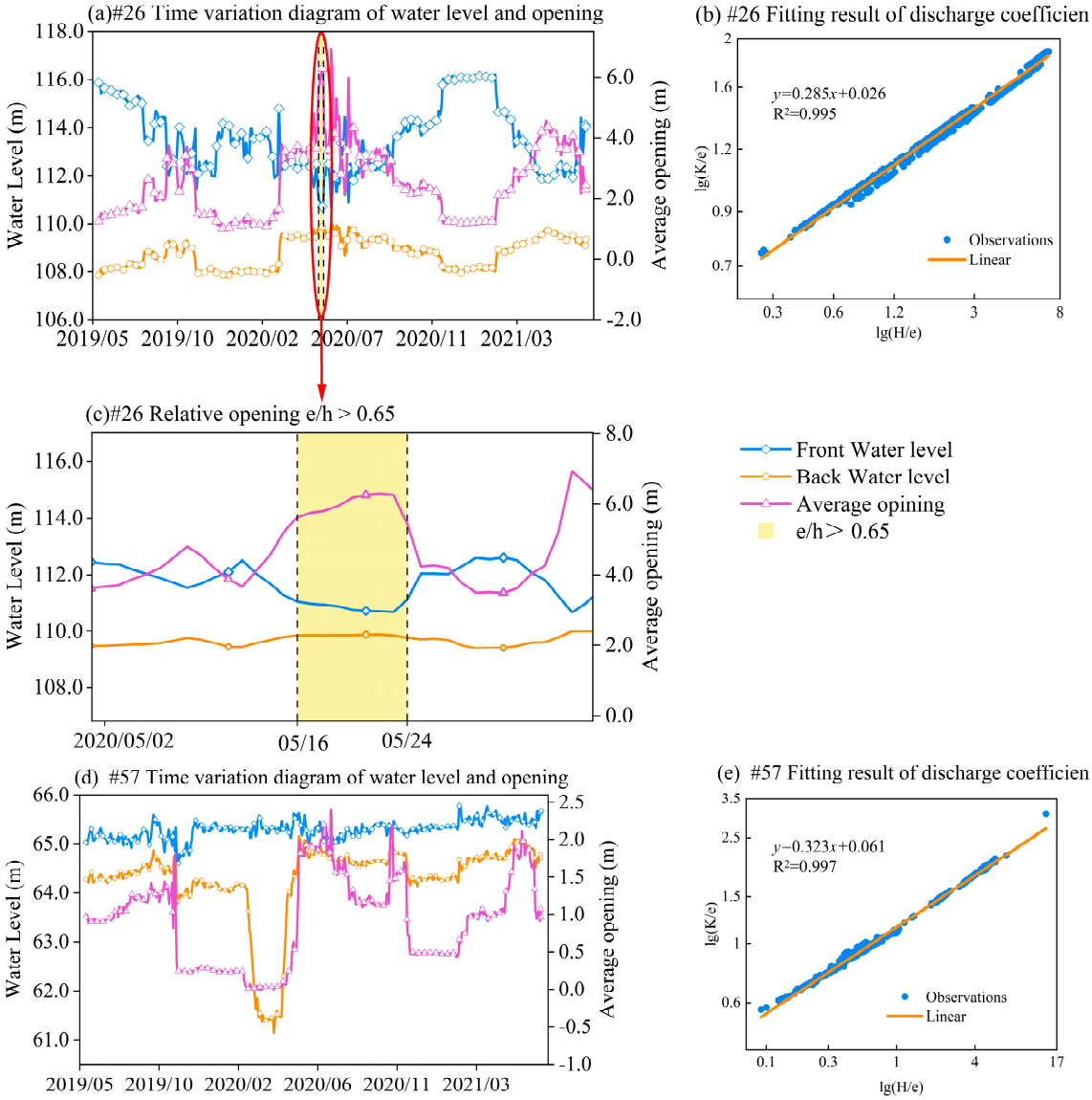


Figure 7. Fitting results regarding the discharge coefficients of sluice gates #26 and #57.

Table 2. Evaluation of calculation accuracy of sluice gate discharge formula.

Evaluation Indicators	Calibration	Verification	Province
Average error (m^3/s)	−0.42	1.06	Henan
Relative error (%)	4	4	
Root mean square error (m^3/s)	11.41	11.43	
Relative root mean square error (m^3/s)	0.06	0.07	
Average error (m^3/s)	0.03	1.29	Hebei
Relative error (%)	3	4	
Root mean square error (m^3/s)	4.44	5.54	
Relative root mean square error (m^3/s)	0.04	0.07	

3.3. Stage–Discharge Response Relationship of Sluice Gates

Figure 8 shows the stage–discharge response relationship of sluice gates #7, #26, and #57 under different sluice gate openings (0.1 m, 0.5 m, 1 m, 1.5 m, 2 m, and 2.5 m). When the sluice gate opening was constant, the stage–discharge response relationship was a power function. When the difference between front water level and back water level was constant, the discharge was proportional to the opening. When the sluice gate opening was constant,

the discharge was proportional to the difference between front water level and back water level. In addition, when the difference between the sluice gate opening and the water level was constant, the discharge was related to the number of gate holes.

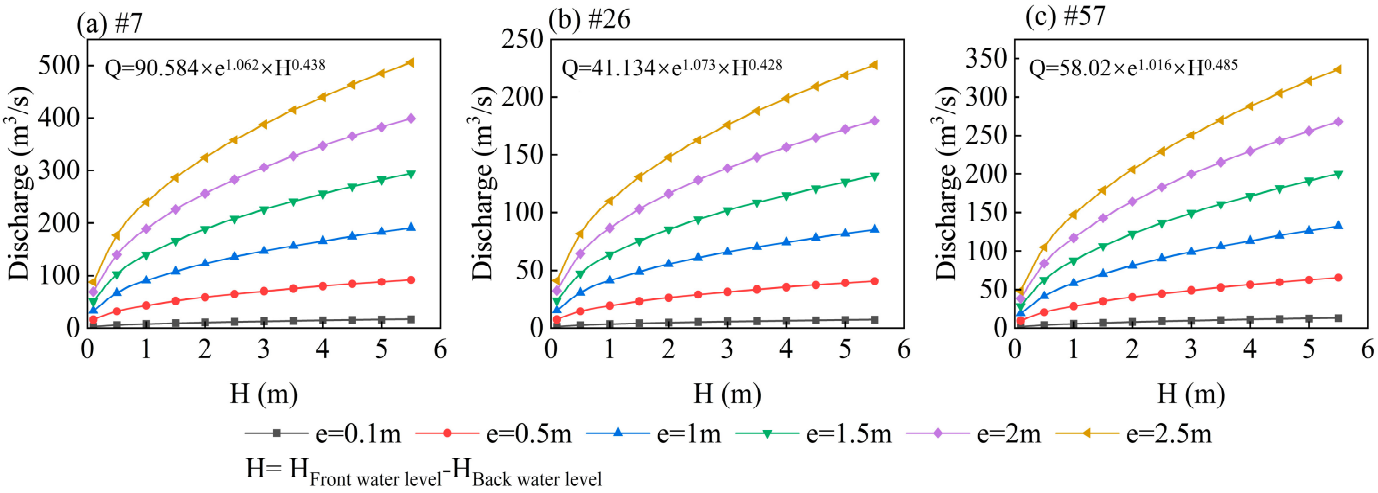


Figure 8. Stage–discharge response relationship of sluice gates #7, #26, and #57.

The main canal of the MRSNWDPC was divided into 60 ponds by 61 sluice gates, forming a highly coordinated "cascaded reservoir". Many data acquisition sensors, such as water level meters, flowmeters, and sluice gate opening meters, were set up to collect the data of each sluice gate in real time. The proposed methods and equations can calculate the required sluice gate opening based on the water level difference. In canal operation safety management, they can predict flow velocities and discharges. If a section of the canal is vulnerable to erosion due to high velocities, operators can use the equations to adjust the sluice gates to maintain a safe flow regime. In the actual operation process, the sluice gate opening was adjusted according to the measured data pertaining to the discharge and velocity of the main canal to ensure the quality and quantity of water distribution and the safety of the channel operation in order to provide a reliable guarantee for the residential water, the water used for industrial production, and the water used for agricultural irrigation water along the main canals.

4. Discussion

Without human intervention, changes in water level, discharge, and velocity in natural rivers are relatively stable. Due to artificial regulation, especially multi-stage sluice gates regulation, the hydrodynamic factors change frequently and violently, resulting in significant changes in water level, discharge, and velocity. Therefore, evaluating the hydrological situation sluice control mode response characteristics of inter-basin water diversion projects under long-distance multi-stage sluice gate regulation is necessary.

Based on our analysis of the real-time operation data of the main canal of the MRSNWDPC from May 2019 to July 2021, we found that the hydrologic features were obvious. The annual average water level, discharge, and velocity in Henan province were generally higher than in Hebei province from 2019 to 2021, and the hydrological elements showed an increasing trend year by year. When the dam heightening project of the Danjiangkou Reservoir was completed, the dam elevation increased from 162 m to 176.6 m, and the water level increased from 157 m to 170 m [39]. In 2017, the 164 m and 167 m water storage experiments of the dam were completed for the first time. In 2020, the main canal of the MRSNWDPC increased the water diversion volume and operated at 420 m^3/s for the first time from 29 April to 20 June, lasting 53 days. Nearly 1 billion m^3 of ecological

hydration was provided to 39 rivers along the route, and remarkable ecological benefits were achieved [40]. This indicates that the inflow in 2020 was relatively abundant. Overall, 9.054 billion m^3 (including 1.983 billion m^3 of ecological hydration) was transferred from Taocha in 2020–2021, achieving 112% of the annual water diversion plan [41]. The high-water storage and high-discharge water diversion changed the hydrological situation of reservoirs and canals, specifically causing changes in the water level and storage area and making the hydrodynamics more complicated [42]. Work centered around the diversion of large-flow water can make full use of flood resources in the flood season to effectively alleviate the water shortage in northern China and improve the ecological environment.

Based on the dimensional analysis method, the discharge coefficients of 61 sluice gates were fitted. The fitting results show that $\lg(\frac{H}{e})$ and $\lg(\frac{K}{e})$ had a good linear relationship, and the fitting results were ideal. The advantage of dimensional analysis is that only two parameters need to be fitted, and the fitting process is relatively simple. Through the analysis of the fitting results of the discharge coefficients, fourteen sluice gates required piecewise fitting with time as the node, including ten in Henan province (#1, #8, #13, #15, #21, #23, #24, #27, #28, and #29) and four in Hebei province (#45, #58, #59, and #60). Henan province's values were greater than those of Hebei province. Wang et al. [25] used the dimensional analysis method to fit discharge coefficients without the segmentation phenomenon, which may be due to the maintenance of the sluice gates destroying the consistency of the data. Additionally, open canal water transmission is also affected by external wind and wave interference, data collection equipment, and other factors that may destroy the consistency of data [43]. The main canal of the MRSNWDPC diverts water from the Danjiangkou reservoir, and the water level and discharge are adjusted frequently along the way, which complicates sluice gate operation [44]. A previous study showed that the Froude number of orifice flow shrinkage sections was smaller, being close to one when the relative opening of each sluice gate was larger, which could be the reason for the large deviation between the calculated value and the measured value of the orifice flow when the relative opening was large [45].

According to the dimensional analysis method, the discharge coefficient was fitted, and subsequently, the stage–discharge response relationship of each sluice gate was obtained. When the sluice gate opening was constant, the stage–discharge response relationship was a power function. The accurate discharge equations derived from our dimensional analysis method are invaluable for the real-time operation of the MRSNWDPC. Controlling the sluice gate opening can help to meet the water consumption demands for domestic drinking, industrial production, and agricultural irrigation and ensure the safety and quality of the water being transmitted. One of the major contributions of our study is the establishment of a causal link between engineering interventions, hydrological dynamics, and ecological outcomes through robust sluice gate modeling for the management of complex flow dynamics. Studies have shown that in long-distance inter-basin water diversion projects, sluice gate regulation causes frequent changes in discharge and water levels, accelerating the life cycle of algae [46]. Although some studies have shown that the nutrients in the water body of the main canal of the MRSNWDPC are lower than in natural rivers, thus avoiding potential algae outbreaks [47], abnormal algae proliferation has still been detected [48,49]. The water quality safety of the main canal of the MRSNWDPC has been seriously affected. By adjusting the sluice gate openings, the algae can be controlled. When the water temperature fluctuates in the early warning interval, the upstream, midstream, and downstream discharge could be adjusted to be higher than 0.6 m/s, 0.5 m/s, and 0.6 m/s, respectively, which could effectively reduce the risk of algae growth [10]. To reduce the risk of algae proliferation, the discharge and velocity in the canal can be adjusted through the sluice gate openings. Additionally, during flood risk events or fast

water allocation requirement regulation cases, the water level and discharge in the canal change rapidly. Using our equations, operators can quickly determine the appropriate sluice gate adjustments to manage the incoming water volume, preventing flooding and protecting the safety of the canal and adjacent areas. Additionally, these equations can be integrated into the existing water management models of the project. This integration will allow for more accurate prediction of the system's response to different operational scenarios, enabling the development of more efficient and flexible operation strategies to balance water supply, energy consumption, and environmental impacts. Unlike single-gate or laboratory-scale analyses, our model integrates field data from a cascaded mega-long-distance canal system, revealing how dimensional analysis can efficiently characterize hydrological responses to multi-stage regulation.

Although the dimensional analysis method demonstrates broad applicability to gate-regulated flows, the discharge coefficients derived herein are context-dependent, reflecting the MRSNWDPC's unique operational (e.g., high-discharge pulses, ecological flow targets) and geometric (e.g., broad-crested weir geometry, 61-gate cascade) characteristics. Notably, the observed power-law stage-discharge relationship aligns with theoretical predictions for orifice flow, suggesting potential transferability to similar large-scale inter-basin projects. However, regional calibration is recommended for systems with distinct hydraulic roughness, gate configurations, or operational objectives (e.g., flood control vs. ecological flow management). Future work could leverage global datasets to refine coefficient frameworks, enhancing the method's utility across diverse climatic and infrastructural conditions, and couple hydrodynamic-ecological modeling to dissect the mechanistic pathways linking sluice gate operations to biodiversity and ecosystem resilience.

5. Conclusions

In this study, real-time operation data of the main canal of the MRSNWDPC from May 2019 to July 2021, including water level, discharge, velocity, and sluice gate opening, were used to analyze the interannual variations in hydrologic elements, and the discharge coefficients of 61 sluice gates were fitted by the dimensional analysis method, establishing a scientific framework for understanding and optimizing sluice gate operations in long-distance inter-basin water diversion projects. The main conclusions are as follows:

(1) From 2019 to 2021, driven by upstream dam operations and increased water diversion demands, the water level of the main canal of the MRSNWDPC showed an increasing trend year by year. The average annual front water levels were 122.21, 122.40, and 122.42 m, and the backwater levels were 121.15, 122.47, and 122.50 m, respectively, in Henan province. The average annual front water levels were 74.92, 74.96, and 75.11 m, and back water levels were 74.18, 74.34, and 74.56 m, respectively, in Hebei province.

(2) From 2019 to 2021, the flow discharge and velocity of the main canal of the MRSNWDPC showed increasing trend year by year. The average annual discharge rates in Henan province were 187.1 m^3/s, 226.1 m^3/s, and 230.9 m^3/s, and 102.4 m^3/s, 113.2 m^3/s, and 120.0 m^3/s in Hebei province, respectively. The annual average velocity rates in Henan province were 0.78 m/s, 0.89 m/s, and 0.90 m/s, and 0.75 m/s, 0.75 m/s, and 0.77 m/s in Hebei province, respectively.

(3) In sluice gate-controlled canals of the MRSNWDPC, flow discharge scales nonlinearly with gate opening and upstream/downstream water heads. The proposed dimensional analysis framework offers a novel approach to derive discharge coefficients for multi-stage sluice gates, overcoming the limitations of traditional hydraulic methods. It reduces complex flow dynamics to a two-parameter linear fit and verifies a power-law relationship with high accuracy ($R^2 > 0.95$ for 56 out of 61 sluice gates) and low prediction errors. This provides empirical evidence of hydrological responses to

sluice gate operations, enabling the rapid prediction of discharge and velocity under dynamic flow regimes.

Our study not only presents trends in water levels, discharge, and velocity but also provides a set of discharge equations with high accuracy. These equations offer a deeper understanding of the system behavior, enabling operators to predict the impact of sluice gate operations on the hydrological regime. By using these equations, we can optimize water resource allocation, ensuring a stable water supply for domestic, industrial, and agricultural use. This, in turn, improves the overall efficiency of the MRSNWDPC operation. Moreover, the insights gained from our study can be extended to similar long-distance water diversion projects worldwide, contributing to more sustainable water management practices.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w17111662/s1, Table S1: Location of the sluice gates of the main canal of the MRSNWDPC in this study; Table S2: Fitting result of the discharge coefficient of sluice gates in Henan province; Table S3: Fitting result of the discharge coefficient of sluice gates in Hebei province; Figure S1: Calibration results of discharge coefficient of the dimensional analysis method for sluice gates (#1–#13); Figure S2: Calibration results of discharge coefficient of the dimensional analysis method for sluice gates (#13–#24). Figure S3: Calibration results of discharge coefficient of the dimensional analysis method for sluice gates (#24–#35). Figure S4: Calibration results of discharge coefficient of dimensional analysis method for sluice gates (#36–#49). Figure S5: Calibration results of discharge coefficient of the dimensional analysis method for sluice gates (#50–#61).

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