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Original Research

Study on Hydraulic Regulation of a Tidal Plain River Network Based on Gate-Pump Joint Operation

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Abstract

Tidal plain river networks are often characterized by weak hydrodynamic conditions and limited self-purification capacity. In this study, a one-dimensional hydrodynamic-water quality model for the Haishu District of Ningbo City, China, was constructed using the self-developed software, the Drainage Water Modeling System (DWMS). To expand the spatial reach of water diversion, enhance river network fluidity, and improve water quality, this study systematically investigates the water diversion effects under different gate-pump joint operation modes using the verified model and introducing the concept of conservative substance. The simulation results show that, for tidal plain river networks with pollution sources along the rivers, the "pre-discharge then diversion" mode is the optimal operational scheme compared with the "simultaneous diversion and discharge" mode. This approach can increase the water renewal efficiency at the terminal river reach by 13% to 20%.

Keywords: hydrodynamic-water quality model, conservative substance, joint operation, water exchange rate

Introduction

Water diversion projects can effectively dilute pollutants, enhance hydrodynamic conditions, and improve the self-purification capacity of water bodies by introducing clean water from external sources [1-4]. The practice of improving river water quality through water diversion began in Japan. In 1964, to address pollution in the Sumida River, clean water was discharged from the Tone and Arakawa Rivers at a rate of 16.6 m³/s, equivalent to three to five times the original discharge of the Sumida River [5]. Subsequently, in 1975, Japan initiated large-scale inter-basin water diversion projects to improve water quality in ten rivers, including Nakagawa River, Shinmachi River, and Kagawar River, marking a significant milestone in the application of this approach [6]. Successful examples from other countries include the diversion from the Mississippi River to Lake Pontchartrain in the United States [7, 8] and the project

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benefiting Moses Lake in Washington [9], both of which demonstrated significant positive effects.

In China, Shanghai pioneered water resource scheduling to improve water quality in the 1980s [10]. Following this precedent, other cities including Nanjing [11, 12], Hangzhou [13], Kunming [14], and Suzhou [15, 16] conducted extensive experimental studies and practical applications, achieving notable improvements in water quality [17-21].

To enhance the water environment of the urban river network, Liu et al. [22] developed a hydrodynamic mathematical model for the urban area of Changzhou, Jiangsu Province, China, using InfoWorks ICM and proposed constructing four active overflow weirs to create a three-level water level difference, thereby optimizing flow distribution and increasing flow velocity. For typical tidal river networks, Chen et al. [23] analyzed flow velocity variations under different water diversion schemes, using the Qingsong area in Qingpu District, Shanghai, China, as a case study. To improve water fluidity, they proposed a water diversion strategy characterized by 'north diversion and east drainage, with natural drainage in the southwest'.

The effectiveness of water diversion depends on multiple factors, including flow velocity, the relative position to the freshwater inlet, the quantity and quality of both the diverted and receiving water, and the circulation pattern of the flow field. Thus, a high instantaneous flow velocity does not necessarily ensure an effective improvement in water quality [24]. Previous studies on urban water diversion scheduling have primarily focused on optimizing the diversion volume, the spatial distribution of water sources, and the pathways of diversion to enhance flow conditions [25-29]. For instance, Zhou et al. [30] used a coupled hydrodynamic-water quality model to assess the enhancement of water quality in the Waihai area of Dianchi Lake under various water diversion scenarios. These scenarios involved differing diversion volumes, inflow/outflow locations, and seasonal allocation patterns. The study identified increasing the volume of water diversion as the most effective measure for improving water quality. Similarly, Zhang et al. [31] presented a case study on water quality improvement in Xihu Lake through diversion and water distribution, in which the diversion discharge was determined and rationally allocated to four different locations. Some researchers analyzed the response of water quality improvements – specifically for chemical oxygen demand (COD), total phosphorus (TP), and ammonia nitrogen (NH_3-N) – to variations in the diversion flow rate, and found that the improvement rates for COD, TP, and NH_3-N increased with rising flow rate, but eventually plateaued upon reaching specific saturation thresholds [32].

However, previous studies have predominantly focused on large-scale water transfers [33-35] or single-gate operations [23]. There is a distinct lack of research addressing the combined scenario of low diversion discharge, tidal backwater effects, and in situ pollution in urban tidal plains. In such contexts, conventional continuous diversion strategies often fail because limited inflow cannot overcome tidal resistance to flush pollutants effectively. Therefore, optimizing the operation of gates and pumps is a crucial strategy for enhancing hydrodynamic conditions and increasing the water renewal efficiency under these compound constraints [36, 37].

This paper introduces the concept of a conservative substance and constructs a hydrodynamic-water quality model for the river network in Haishu District, Ningbo City, China. The study examines the differences in flow velocity, water exchange rate, and other factors under both the current and optimized operation modes during unfavorable tidal conditions. Based on the results, an optimized joint operation mode for gates and pumps is proposed, providing a reference for practical engineering operations.

This study contributes to the literature by applying conservative substance tracing to quantitatively distinguish the renewal efficiency of different river reaches under complex tidal interactions, and proposing a sequential gate-pump joint operation strategy tailored for low-diversion scenarios, addressing the combined challenge of limited inflow, tidal backwater, and in situ pollution.

Materials and Methods

Study Area

The old town area of Haishu District, Ningbo City, China, encompasses approximately 10.4 km². Its core river network includes Cuibai River, Maiyu River, Beidou River, and City Moat, all of which are separated from surrounding rivers by control gates (Fig. 1). The Tujiayan pump station, with a water diversion capacity of 5 m³/s, diverts water from the Yaojiang River; this water is subsequently discharged back into the Yaojiang River and Fenghua River through the outer gates – Baofengqi gate and Chenglangyan gate.

Currently, the operation of gates and pumps within the study area lacks systematic coordination. Furthermore, the downstream section of the river network is tidal. During high-tide periods, the rising tidal level in the outer river exerts a strong backwater effect on the river network, which impedes the river network's outflow. Outflow gates either remain closed entirely or, when partially open, operate with minimal efficiency, thereby prolonging water retention within the river network. Consequently, pollutants in river reaches distant from the water diversion source are neither sufficiently diluted nor effectively transported. This leads to pollutant accumulation and elevated concentrations and severely diminishes the water body's self-purification capacity and thus limits water quality improvement.



Fig. 1. Rivers and water conservancy facilities in the study area.

Water quality monitoring data from January to December 2022 revealed widespread exceedances of ammonia nitrogen (NH_3-N) concentration standards across the four main rivers. The grade classification was evaluated according to the Environmental Quality Standards for Surface Water of China (GB 3838-2002). Over 40% of monitoring points were classified as below Grade V (inferior), 10% as Grade V, and 20% as Grade IV. Notably, Cuibai River, situated closest to the water source, exhibited significantly better water quality compared with Maiyu River, Beidou River, and City Moat, indicating a pronounced spatial decay of renewal and dilution capacity along the diversion pathway.

Additionally, numerous bottlenecks such as bridges and culverts along the river channels, coupled with unreasonable gate-pump operation, have led to localized backwater effects and insufficient water supply to the outflow gates. Therefore, optimizing the joint operation of gates and pumps is critical for enhancing hydrodynamic conditions, strengthening the self-purification capacity, and improving the overall urban water environment.

Model Setup

Hydrodynamic Model

(1) Saint-Venant Equations for Hydrodynamics

1) Continuity Equation

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q_L \tag{1}$$

2) Momentum Equation

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{\alpha Q^2}{A}\right)+gA\frac{\partial Z}{\partial x}+gA\frac{Q|Q|}{K^2}=q_L v_x \tag{2}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{\alpha Q^2}{A}\right)+gA\frac{\partial h}{\partial x}-gAS_0+gAS_f=q_L v_x \tag{3}$$

Where t is time (s), x is the displacement along the river direction (m), A is the cross-sectional flow area (m^2), Q is the discharge (m^3/s), Z is the water level (m), h is the water depth (m), $S_f=\frac{Q|Q|}{K^2}$ is friction slope, $S_0=\frac{\partial Z_d}{\partial_x}$ is the bottom slope, Z_d is the riverbed elevation (m), q_L is lateral inflow per unit length (m^3/s), v_x is flow velocity of lateral inflow along the flow direction (m/s), g is the acceleration of gravity (m/s^2), K is the flow modulus (m^3/s), and a is the momentum correction coefficient.

(2) Computational Approach

Considering factors such as river network confluences, gates, and pump stations, the river network is divided into reaches connected at branch points. A three-level coupled solution method – integrating branch points, reaches/hydraulic structures, and the overall river network – combined with a large sparse matrix solver is employed to efficiently solve the hydrodynamic equations.

(3) Hydrodynamic Boundary Conditions

For model validation, the upstream boundary condition was defined using observed inflow discharge at the Tujiayan pump station, while measured tidal elevations from Chenglangyan Station were applied at the downstream boundary. Gate operation schedules were configured based on field monitoring records.

For scenario simulations, the upstream boundary discharge was set to the design capacity of the Tujiayan pump station (5 m^3/s). The operational status of the pump station and gates adhered to the specific scheduling rules of each scenario. A representative unfavorable tidal pattern from Chenglangyan Station served as the downstream boundary condition; the selection methodology for this typical tidal pattern is detailed below.

Hourly tidal elevation records collected at Chenglangyan Station across three consecutive years were statistically analyzed. Results indicated an annual mean high tide level of 1.53 m and an annual mean low tide level of -0.31 m.

To conservatively evaluate diversion scheduling performance, a representative unfavorable tidal pattern was selected as the typical boundary condition. This pattern features peak high-water levels marginally above the long-term annual mean high tide and trough low-water levels slightly above the annual mean low tide. After analysis, the hourly tidal series from 00:00 to 12:00 on November 4, 2022, was selected and appropriately extended to serve as the typical tidal pattern (Fig. 2).

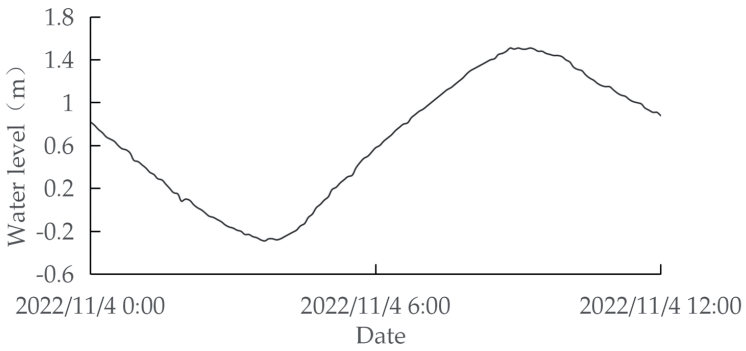


Fig. 2. The typical tidal pattern at Chenglangyan Station.

Water Quality Model

(1) One-Dimensional Convection-Diffusion Control Equation

$$\frac{\partial(AC)}{\partial t}+\frac{\partial(QC)}{\partial t}=\frac{\partial}{\partial x}\left(AE_x\frac{\partial C}{\partial x}\right)+S_c+S_k \quad (4)$$

Where A is the cross-sectional flow area (m^2), Q is the discharge (m^3/s), C is the pollutant concentration (mg/L), t is time (s), x is the displacement along the river direction (m), E_x is the longitudinal dispersion coefficient of pollutants (m^2/s), S_c represents external source/sink terms (positive for sources, negative for sinks) (mg/(L·s)), and S_k is the internal reaction term related to pollutant degradation (mg/(L·s)), defined as $S_k = KAC$, where K is the first-order degradation coefficient (d^{-1}).

(2) Discretization of the One-Dimensional Convection–Diffusion Equation

The convection–diffusion equation describes the migration, transformation, and diffusion of pollutants in water. The pollutant concentration in a river section can be obtained by solving the corresponding partial differential equation.

The finite difference method is employed to discretize the differential equation. The convection term is approximated using an implicit upwind scheme, the time term is discretized with forward differencing, and the diffusion term is treated with central differencing. Since the flow direction in the river network is variable, both downstream and upstream differences are considered in the formulation.

Model Validation

The hydrodynamic and water quality model was validated using synchronously monitored field data from May 27–28, 2022. A total of 12 monitoring points were established across the study area (locations shown in Fig. 3), where water level, discharge, and NH_3-N concentration were measured. Detailed records of the monitored variables at each point are provided in Table 1.

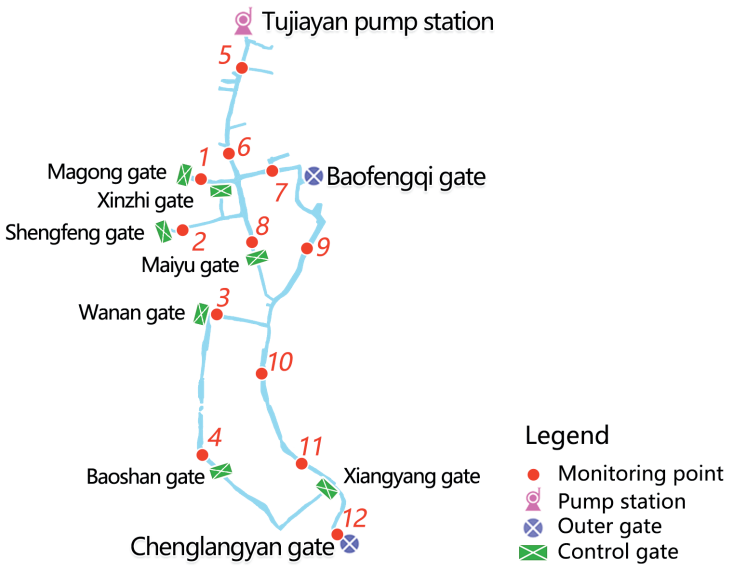


Fig. 3. River network and monitoring points in the study area.

Table 1. Monitoring items for each point in the study area.

Monitoring points	Monitoring items		
	Water level (m)	Discharge (m^3/s)	NH_3-N concentration (mg/L)
1#	√		√
2#	√		√
3#	√		√
4#	√		√
5#		√	√
6#			√
7#		√	√
8#	√	√	√
9#	√	√	√
10#		√	√
11#	√		√
12#		√	√

For model validation, monitoring point 8# was selected for water level validation due to its location in the primary controlled reach and the availability of synchronous water level and discharge observations. Points 7# and 11# were selected for NH_3-N validation because they represent the upstream and downstream parts of the regulated river network, respectively; these points allow for an effective assessment of the model's capability to simulate pollutant transport along the diversion pathway. Flow validation was conducted based on the outflow process at the Chenglangyan gate, which is the key downstream hydraulic control for the scenario simulations. In addition to graphical comparison, three statistical metrics were employed: the root mean square error (RMSE), mean absolute error (MAE), and the coefficient of determination (R^2).

As shown in Figs. 4 and 5, the simulated water levels are in good agreement with the observations.

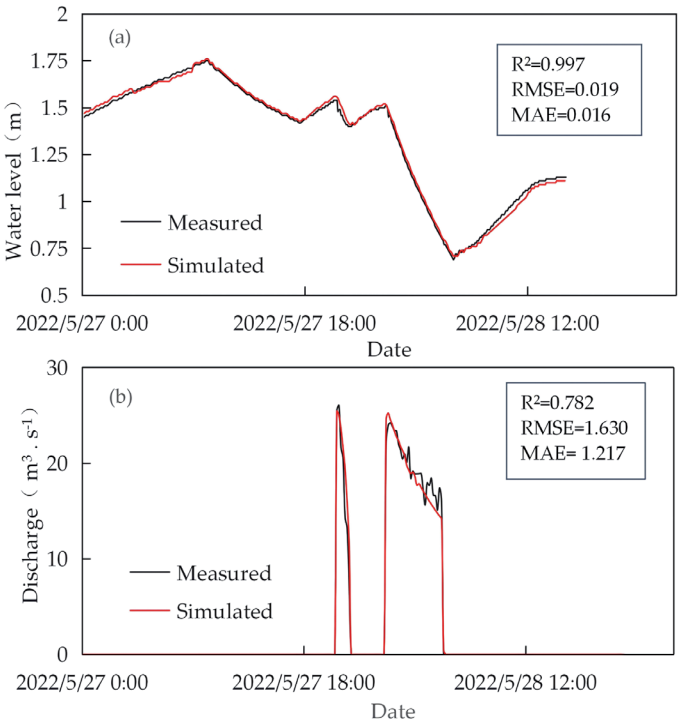


Fig. 4. Hydrodynamic validation results: a) water level at monitoring point 8#; b) discharge of the Chenglangyan gate.

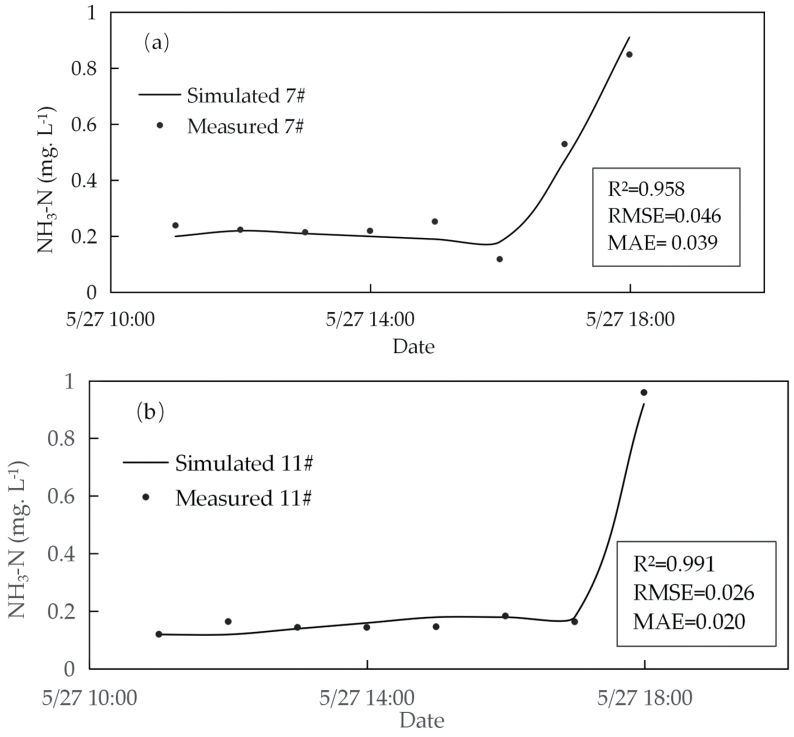


Fig. 5. Water quality validation results: a) NH_3-N concentration at monitoring point 7#; b) NH_3-N concentration at monitoring point 11#.

Similarly, the simulated gate discharge corresponds well with the measured outflow, and the simulated NH_3-N concentrations at both validation points closely match the monitored data.

In summary, the established model effectively captured the propagation of flow and pollutants following the diversion operation. Through validation, it was determined that Manning's roughness coefficient n ranges from 0.02 to 0.025, the gate discharge coefficient ranges from 0.3 to 0.35, the dispersion coefficient is 5 m^2/s, and the decay coefficient ranges from 0.04 to 0.07 d^{-1}.

Water Exchange Rate Calculation Method

Under fixed pollution loads and water diversion sources, the effectiveness of water quality improvement is primarily governed by hydrodynamic renewal and mixing. To accurately simulate the water diversion effect in each river reach, the concept of a conservative substance was introduced as a tracer in the water quality model. A conservative tracer does not decay, settle, or transform during transport; therefore, the decrease in its concentration directly reflects the proportion of original river water replaced by diverted water. This tracer-based water exchange rate is not identical to the reduction of conventional indicators such as NH_3-N or COD, because those indicators are additionally affected by external loads, degradation, sediment-water exchange, and biological processes. However, under identical loads and inflow concentrations, the tracer provides a robust and operationally interpretable indicator for comparing the relative renewal efficiency of different gate-pump operation modes. In the model, the initial concentration of the conservative substance was set uniformly to 1 mg/L, while the diversion water source was assigned a concentration of 0 mg/L, with a decay coefficient of zero. The water exchange rate is calculated as the ratio of the decrease in conservative substance concentration to its initial concentration:

$$\gamma = \frac{\Delta\rho}{\rho_0} \times 100\% \tag{5}$$

Where γ is the water exchange rate; $\Delta\rho$ is the decrease in conservative substance concentration (mg/L); ρ_0 is the initial concentration of the conservative substance (1 mg/L).

Results and Discussion

Design of Gate-Pump Joint Operation Modes

For tidal river reaches, downstream tidal effects restrict the ability to open gates for discharge during certain periods, limiting the water body's self-purification capacity. Consequently, water quality in river reaches distant from the water diversion source cannot be effectively improved. Therefore, based on fixed water diversion sources and pathways, this study explores optimized gate-pump joint operation.

The optimized operation aims to dynamically regulate the water level in the river network, artificially create and utilize favorable water level differences, enhance internal flow dynamics, improve overall water exchange efficiency, optimize the hydrodynamic conditions of the river network, promote pollutant dispersion and dilution, and ultimately enhance the overall water quality. Three joint operation modes are evaluated: Pre-discharge then diversion (PDD), First diversion then discharge (FDD), and Simultaneous diversion and discharge (SDD).

Three operational water level thresholds were defined based on long-term local regulation experience and empirical dispatching practices: the ecological water level (0.96 m), normal storage water level (1.30 m), and warning water level (1.66 m). These thresholds serve distinct functional roles: the ecological water level acts as the lower operational limit to prevent excessive dewatering and maintain habitat connectivity; the normal storage level represents the routine target for daily regulation; and the warning level functions as the upper bound for flood control and urban safety.

(1) Pre-discharge then diversion (PDD)

When the external river tide is predicted to enter a period of rapid ebb or approach the low tide level, the Chenglangyan gate is opened for pre-discharge to lower the water level to the ecological water level (0.96 m), after which the gate is closed. Subsequently, the Tujiayan pump station is activated for water diversion. When the river network water level rises to the warning water level (1.66 m) and the external tide level is lower than the river network water level, the Chenglangyan gate is reopened for discharge.

The PDD mode aims to discharge highly polluted water, lowering the initial water level to create storage capacity for subsequent high-quality water diversion and to increase the water level difference for that diversion. The diversion phase primarily raises the water level and stores cleaner water. Discharging at a high water level then utilizes the significant water level difference to efficiently exchange the mixed water body.

(2) First diversion then discharge (FDD)

The Tujiayan pump station is activated for water diversion. Once the river network water level reaches the warning water level (1.66 m) and the external tide level is lower than the river network water level, the Chenglangyan gate is opened for discharge. The gate is closed when the water level falls to the ecological water level (0.96 m).

The FDD mode rapidly builds up a high water level through diversion, accumulating substantial potential energy. Subsequently, when the gate opens, this energy is converted into a larger instantaneous flow rate to drive water exchange. A low water level threshold is implemented as a safeguard to prevent excessive drainage, thereby maintaining the ecological water level.

(3) Simultaneous diversion and discharge (SDD)

The Tujiayan pump station operates continuously for water diversion. When the river network water level exceeds the normal storage water level (1.30 m), the Chenglangyan gate is opened for discharge and is closed when the water level reaches the ecological water level (0.96 m).

The SDD mode aims to maintain the river network water level within a relatively stable range (0.96-1.30 m) through the real-time coordinated operation of gates and pumps. Throughout this process, it seeks to sustain a certain degree of water flow, with water diversion and discharge operating almost simultaneously.

Simulation and Analysis of Water Diversion Effects

One primary goal of water diversion projects is the dilution of pollutants through the introduction of cleaner water sources, which effectively replaces contaminated water. The water exchange rate quantifies how thoroughly this water replacement proceeds. The water exchange rate is analogous to the concept of water age, a fundamental environmental hydraulic parameter representing the residence time of water or solutes within a water body from entry to discharge [38-41]. It incorporates both hydrodynamic transport and mixing processes. Therefore, the water exchange rate serves as a more intuitive and operationally relevant indicator for evaluating the actual effectiveness of water diversion and regulation measures.

A 168-hour simulation period was selected in this study to conform to the weekly water exchange target specified for the water diversion project in Haishu old town. This duration also covers multiple complete tidal cycles and repeated gate-pump operation cycles, ensuring the simulation accurately reflects the actual periodic operational characteristics of the project.

Fig. 6 presents the calculated water exchange rates at the terminal river reaches of two key channels, namely Maiyu River and City Moat, over one operational cycle (one week) under the three joint gate-pump operation modes.

Maiyu River, located near the water diversion inlet, shows distinct water exchange rate patterns under the three modes. Both the PDD and FDD modes exhibit a relatively gradual increase in the water exchange rate during the early stage, followed by a steep rise after the gates are opened for discharge at higher water levels. In contrast, the SDD mode displays the most gradual increase, approximating a linear growth trend throughout the entire cycle.

City Moat, situated at the terminal section of the river network, shows an overall slower improvement in the water exchange rate compared with that in Maiyu River. The rising trends under the PDD and FDD modes are relatively similar, whereas the SDD mode exhibits a comparatively slower increase. By the end of the simulation period, the water exchange rate under the SDD mode remains lower than that achieved by the other two modes.

In summary, the SDD mode yields the least favorable outcome in terms of water quality

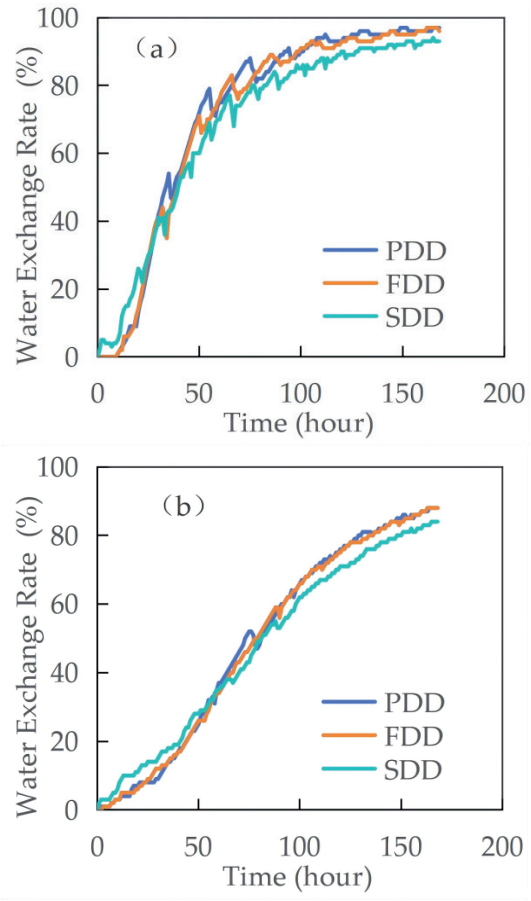


Fig. 6. Water diversion effects under different gate-pump joint operation modes: a) Maiyu River; b) City Moat.

improvement, particularly in the terminal reach where exchange efficiency is low. The PDD and FDD modes display comparable trajectories and final water exchange outcomes. These results underscore that the effectiveness of water diversion projects diminishes with increasing distance from the inlet, making water quality enhancement in terminal reaches a persistent challenge in such projects.

Comprehensive Multi-Index Analysis

To scientifically evaluate the comprehensive effectiveness of water diversion projects, current assessments are primarily based on indicators from two dimensions: water quality improvement and hydrodynamic enhancement. Water quality indicators typically focus on key pollutant concentrations, including chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), and total phosphorus (TP) [42]. Hydrodynamic indicators, on the other hand, encompass parameters that reflect flow dynamics and renewal capacity, such as target flow velocity and water exchange period [36, 43].

In this study, a comprehensive analysis of different gate-pump joint operation modes was conducted. Key performance indicators were measured at two representative locations: City Moat (near the Chenglangyan gate) and Maiyu River (near the water diversion source). The integrated results are summarized in Table 2, with the selected indicators defined as follows:

Average flow velocity: reflects the overall hydrodynamic intensity of the water body.

Duration of high flow velocity (>0.05 m/s): indicates the period during which the water body maintains effective pollutant transport capacity, which is critical for promoting pollutant dispersion. The value of 0.05 m/s is not a mandatory regulatory threshold; rather, it serves as a diagnostic threshold for weakly flowing urban plain river networks based on previous hydrodynamic regulation studies and local engineering practice.

Time to achieve 80% water exchange rate: a core indicator reflecting the water renewal efficiency at the terminal river reach; a shorter time corresponds to higher water renewal efficiency.

Based on the data presented in Table 2, a detailed comparative analysis of the three operation modes was conducted, leading to the following key findings and practical recommendations.

(1) Hydrodynamic Performance

Under the PDD and FDD modes, the average flow velocity and the duration of high flow velocity in the river network exhibit minimal differences. In contrast, under the SDD mode, frequent gate operations significantly enhance hydrodynamic conditions and produce markedly higher flow velocities. The average flow velocity in City Moat reaches 0.038 m/s, which is approximately 52–58% higher than that under the PDD (0.025 m/s) and FDD (0.024 m/s) modes. Similarly, in Maiyu River, the average velocity under the SDD mode (0.026 m/s) is about 44–53% higher than that under the PDD (0.018 m/s) and FDD (0.017 m/s) modes. The duration of high flow velocity follows the same trend:

Table 2. Key indicators under different gate-pump joint operation modes.

Scheduling Mode	Average flow velocity (m/s)		Duration of high flow velocity (h)		Time to achieve 80% water exchange rate (h)	
	Maiyu River	City Moat	Maiyu River	City Moat	Maiyu River	City Moat
PDD	0.018	0.025	17	18	66	129
FDD	0.017	0.024	13	18	80	134
SDD	0.026	0.038	35	45	83	148

the SDD mode yields the longest durations (45 h for City Moat and 35 h for Maiyu River). The duration under SDD is about 2.1 times that under PDD in Maiyu River and 2.5 times that in City Moat; compared with FDD, the ratios are about 2.7 and 2.5, respectively.

(2) Water Exchange Efficiency

Regarding water exchange efficiency, the SDD mode performs the least effectively. Although it achieves a large discharge volume and effectively removes polluted water, the simultaneous process also flushes out a significant portion of the newly introduced clean water, thereby reducing the net renewal efficiency. Consequently, achieving an 80% water exchange rate requires the longest duration under the SDD mode: 148 hours in City Moat and 83 hours in Maiyu River. In contrast, the PDD mode achieves the same target in the shortest time, requiring only 129 hours and 66 hours at the respective locations. The performance of the FDD mode falls between the other two, needing 134 hours for City Moat and 80 hours for Maiyu River. Overall, compared with the SDD mode, the PDD mode improves the water renewal efficiency by 13% in City Moat and 20% in Maiyu River, which makes it the most efficient option for complete water renewal.

A notable spatial pattern emerged: regardless of the scheduling mode, the time required to achieve an 80% water exchange rate in City Moat is significantly longer (approximately 1.5 to 2 times) than that in Maiyu River near the water diversion source. This indicates that the distance from the diversion source directly impacts water exchange efficiency. This observation aligns with on-site monitoring results. This pattern reflects a combined distance-decay mechanism: as diverted water travels away from the inlet, part of the hydraulic energy is dissipated by channel friction and junction losses, and part of the clean water is retained or mixed in upstream branches. In addition, tidal backwater at the downstream boundary reduces the available discharge head during high-tide periods, while bridges, culverts, narrowed sections, and local bottlenecks weaken longitudinal transport and enhance stagnant or reciprocating flow. Consequently, terminal reaches receive less effective clean-water replacement than reaches close to the diversion source.

Therefore, under conditions of limited diversion capacity and with pollution sources present along the river channels, the PDD mode is recommended as the optimal strategy for routine operations. This approach involves first pre-discharging highly polluted water to a low level, then diverting clean water until a higher water level is reached before discharging again. This sequence enhances water mixing and promotes more efficient pollutant displacement.

Conclusions

A one-dimensional hydrodynamic-water quality model was developed for the Haishu District river network in Ningbo City, China, using the Drainage Water Modeling System (DWMS). Field monitoring data validated the model, demonstrating its capability to accurately simulate flow and pollutant transport under gate-pump joint operations.

By introducing the concept of a conservative substance, this study quantitatively evaluated the water renewal efficiency under three gate-pump joint operation modes. The core scientific finding is that for river networks constrained by low diversion discharge, tidal backwater effects, and in situ pollution, the PDD mode outperformed conventional SDD strategies. Specifically, compared with the SDD mode, the PDD mode enhanced the water renewal efficiency at the terminal river reach by 13% to 20%. This enhancement is attributed to the creation of a more favorable hydraulic gradient through staged water level manipulation, which mitigates the adverse effects of tidal obstruction.

From an engineering perspective, the findings provide actionable guidance for standardized operation rules. Under limited diversion capacity (5 m^3/s in this case), the PDD mode is recommended as the routine operation scheme. Practically, this translates to a simple rule-based protocol: initiate pre-discharge when the external tide recedes toward low tide, followed by staged refilling and flushing. This strategy effectively balances pollutant dilution with water resource conservation, thereby circumventing the inefficiencies inherent in continuous operation modes.

Although the validation results are satisfactory, this study has limitations. The use of a 1D model simplifies complex three-dimensional flow structures, such as transverse circulation and stagnant zones behind bridge piers, which may influence local mass transfer. Additionally, the simulation period of one week (168 h) captures the primary exchange cycle but may not fully represent long-term ecological responses, such as sediment resuspension or benthic feedback. The proposed operation rules are most applicable to similar plain river networks with mild slopes and strong tidal influences. Future research should integrate intelligent optimization algorithms, such as genetic algorithms and deep reinforcement learning, with hydrodynamic models to enable real-time, automated gate-pump scheduling that adapts to dynamic meteorological and tidal forecasts.

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AI Usage Disclosure Statement

During the preparation of this manuscript, the authors used Tencent Yuanbao (an AI assistant developed by Tencent based on the Hunyuan model) solely for checking spelling and basic grammar. All substantive content, including research design, data analysis, result interpretation, and manuscript drafting, was completed entirely by the authors. The authors take full responsibility for the content of this work.

Conflict of Interest

The authors declare no conflict of interest.

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