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Simulation Study on the Impact of Water Flow Regulation Based on the MIKE 21 Model in a River Water Environment

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Abstract: Inadequate hydrodynamics can cause deterioration of the water environment within rivers. Regulating water conservancy projects can effectively improve the state of the water environment of rivers and promote sustainable regional development. The river plain in Zhejiang Province, China, suffers from severe hydrodynamic deficiencies, which have a significant impact on the state of the regional water environment. To investigate the changing state of the water environment of the river plain under water conservancy project control, in this study we constructed a two-dimensional hydrodynamic–water quality model based on the AD and ECOLAB modules in MIKE 21 software 2014 Edition. Combined with conservative tracers, the changes in the water displacement rate, flow rate, and water environment quality of the river plain were simulated under different regulation schemes over 7 days. A quantitative analysis of the effects of improving the state of the water environment in the river plain was carried out using a cluster analysis and a cloud model. (1) The water replacement rate of the outer river reached 90% after 3 days and approached 100% after 7 days. The water replacement rates of the inner pond were 51.2, 49.6, and 55.8%. This indicated that the engineering control measures effectively improved the replacement capacity of the river. (2) The contents of DO and BOD_5 in the river have increased from class V to above class 3. The overall water quality is in the range of classes 2 to 3, and in some parts it can reach class 1. This indicates that the regulatory plan played a certain role in improving the river water environment. (3) The water pollution in the study area showed a fluctuating and decreasing trend over 7 days. There was a positive correlation between the flow velocity, water replacement rate, DO, and BOD_5.

Keywords: water environment; river plains; water quality; MIKE 21; cloud model

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1. Introduction

Water resources play a controlling role in the evolution of the human environment and socioeconomic development [1]. As the major carriers of the water supply for production, living, and ecology, rivers play a vital role in the circular development of regional ecosystems and the natural environment [2,3]. River plains are highly susceptible to the influence of external water due to their low water circulation rates and poor exchange capacity [4]. Constructing flood control and drainage projects on natural rivers to regulate the hydrodynamics and improve the overall flow rate has become an effective engineering measure to improve the water environment in small catchments [5]. Hydrodynamic regulation through water conservancy projects can not only effectively solve the problems of the uneven distribution of regional water resources and insufficient hydrodynamic power of rivers but can also restore the ecology of rivers, slow down the degradation of wetlands, and improve the ecological environment of the water [6]. Although water conservancy projects have facilitated the use of water for regional production and living, they also change the original river structure and have extremely complex impacts on the water ecology of rivers. Therefore, it is of great significance to research the impacts of hydrodynamic regulation on the water environment of rivers and to accurately reveal the laws of hydrodynamic changes under engineering regulations to promote the sustainable development of rivers.

Hydrodynamics and water quality are two characteristics that can characterize river water [7,8]. Exploring the effects of hydrodynamic conditions on water quality in typical river channels and uncovering the coupling relationship between hydrodynamics and water quality is a research hotspot in the field of regional hydrodynamic regulation at home and abroad [9,10]. Developing coupled hydrodynamic water quality models is an important approach to the study of regional water ecology [11]. Two-dimensional and three-dimensional models take into account the flow velocity of the water and have high computational efficiency and simulation accuracy [12]. These models have significant advantages in terms of their ability to reflect the mutual transformation and influence between the quantity and quality of regional rivers, and they have been widely used in the research on the water quality and quantity in reservoirs, lakes, and basins [13].

In studying water circulation and self-purification, researchers have found that faster water flow rates can effectively increase the atmospheric reoxygenation of rivers, which increases the amount of dissolved oxygen and boosts the oxidation and decomposition of water pollutants. Accelerated flow rates improve the overall water capacity and replacement cycle of rivers, and they accelerate the dilution of water pollutants [14,15]. In addition, there is a close relationship between the flow rate of river water and the dilution of organic pollutants. Based on a regression analysis, Wright studied the BOD_5 degradation rates in 36 reaches of 23 rivers in the United States and found a significant correlation between the BOD_5 degradation coefficient of the water and the flow rate. Researchers have also found that organic matter degrades more rapidly in turbulent water than in laminar flow [16,17]. The existing studies have been fruitful but some aspects could still be improved. The studies are dominated by single simulations using model software and lack simultaneous monitoring based on field prototypes, and they are unable to grasp the spatial distribution of water in rivers and the water transmission routes. The current analysis of the effects of water diversion and regulation on improving the water environment of rivers indicates the lack of a unified evaluation index system that could be used to systematically study the sensitivity of different water quality indicators and the law of change.

Accordingly, this paper takes the Shenzhuangyang polder area as the research object. According to the arrangement of the regional sluice pump project, a two-dimensional coupled hydrodynamic–water quality model was built based on MIKE 21 software to simulate the evolution of the water environment after 7 days of drainage, and the water displacement effect was analyzed using a tracer. The model clarifies the effect of enhancing the hydrodynamics of the river plain and involves the dynamic simulation and monitoring of the state of the water environment. A cluster analysis was applied to discuss the changes in water quality characteristics under each water drainage scenario. A cloud model was introduced to quantitatively assess the quality of the water environment after the diversion. The study accurately revealed the laws between the hydrodynamic characteristics of the river plain and the diffusion and transport of pollutants under engineering regulation. The model further improved the technical methods of hydrodynamic regulation to improve the water environment of the river. This research provides a theoretical basis and scientific guidance for the hydraulic regulation and ecological water restoration of natural rivers in the engineering context.

2. Materials and Methods

2.1. Scope of the Study

The Shenzhuangyang polder area is located in the northeast of Nanxun District, Huzhou City (between 120°25′ to 120°28′ east in longitude and 30°49′ to 30°51′ north in latitude), in the Hangjiahu Plain in northern Zhejiang Province (Figure 1). The river is dense, creating a distinct water plain, and the topography is flat, with an average altitude of less than 5 m. The average annual temperature in the region is 15.6 °C, with 1142.1 mm of rainfall, 837 mm of water surface evaporation, a 403 mm average multi-year runoff depth, and 204 million m^3 of average multi-year runoff. The annual rainfall is concentrated between April and September, accounting for more than 71.2% of the yearly amount. With a total polder area of around 0.98 km^2, the study area has an average water depth of about 2.5 m and the maximum water depth can reach 3.2 m. This is a typical representative of the Lougang weir fields in southern China, where the slow flow of water in the lake over a long time has led to a severe lack of hydrodynamics and a poor water environment in the river, presenting a challenge in terms of meeting the everyday needs for regional water resource allocation and environmental protection. In recent years, the Shenzhuangyang polder area has been supplemented with active water through multiple points of water replenishment at the inlet, effectively improving the regional water environment.

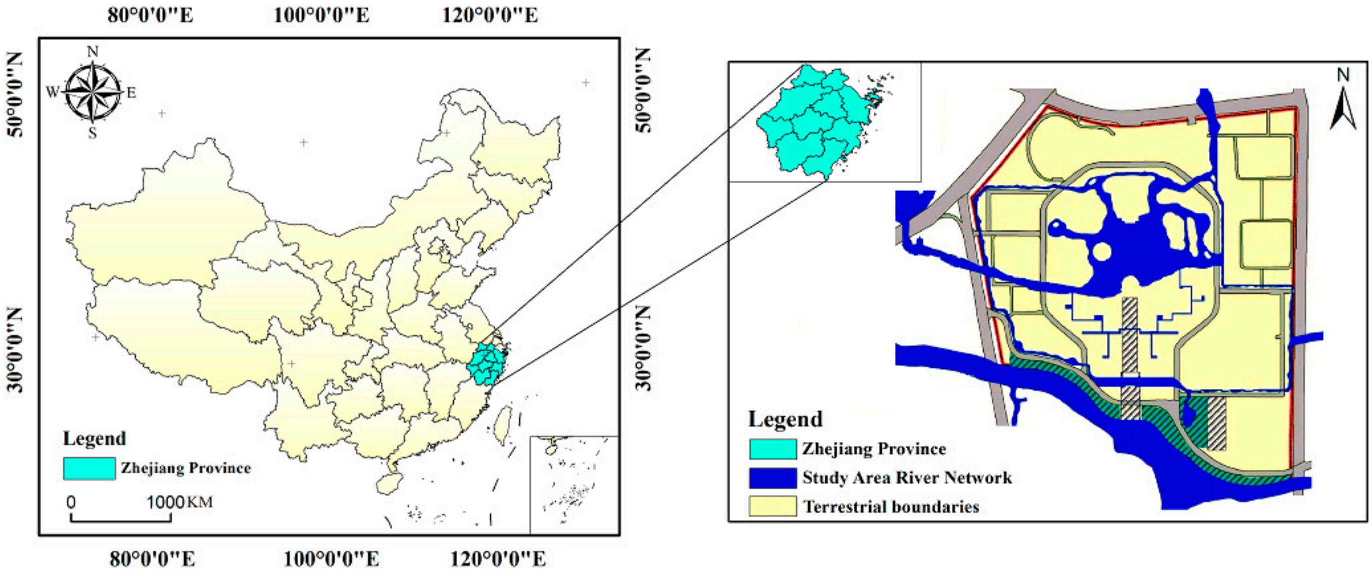


Figure 1. Schematic diagram of the study area.

2.2. Hydraulic Engineering Layout of the Study Area

The river in the study area is divided into two parts: the outer channel and the central pond. The outer channel is connected to the central pond through two channels on the east and west sides and two on the north side. Generally, water in the central pond is not allowed to exchange with water in the outer channel through the east and west channels. Therefore, the water exchange in the central pond relies entirely on the two channels on the north side. In order to extract the water flow rate, replacement rate, and water quality data at each part of the river efficiently in real time, one monitoring point was set up in each of the four directions of the outer circle river (east, west, south, and north), as well as four monitoring points in the central reservoir, for a total of eight monitoring points to achieve overall monitoring and data extraction. The location of each hydraulic project and the specific monitoring points are shown in Figure 2.

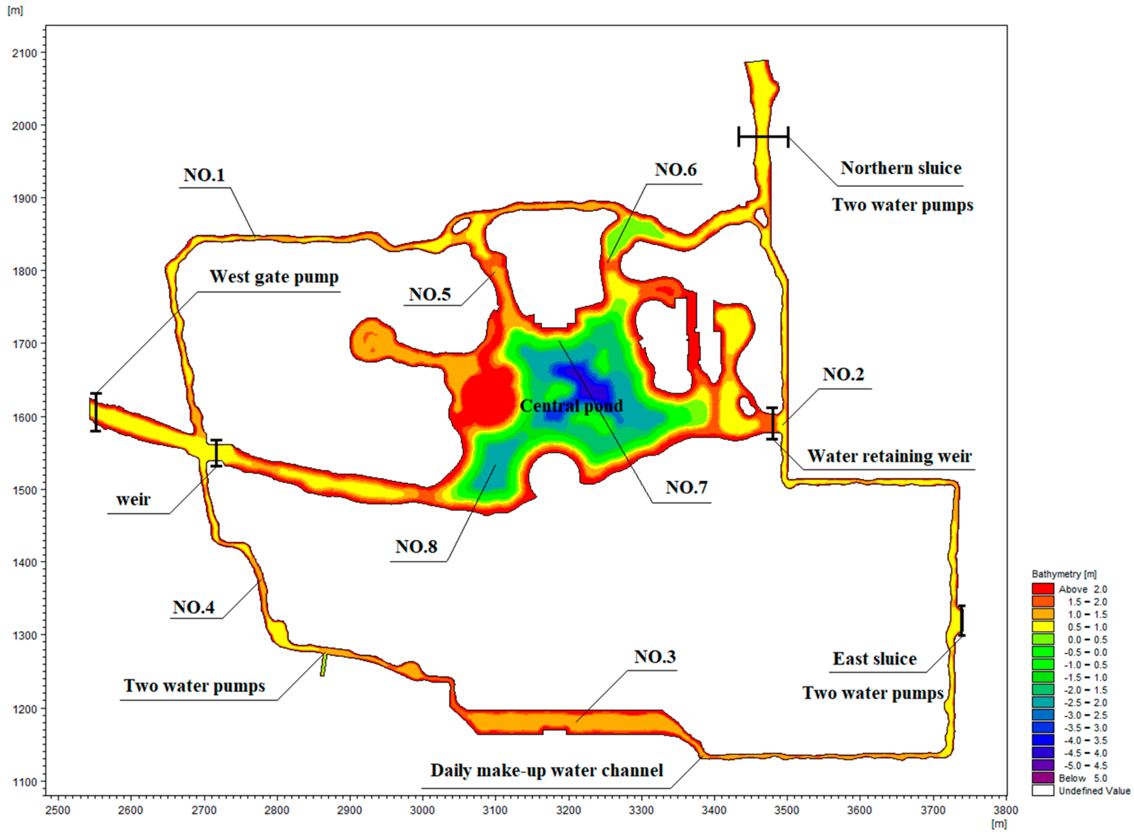


Figure 2. Schematic layout and monitoring points for hydraulic engineering in the study area.

2.3. On-Site Monitoring and Data Collection

Accurate hydrodynamic data monitoring and water quality data detection were necessary to ensure the study's accuracy. For on-site flow velocity monitoring, in this study we chose the Boyida HXH03-1S ultrasonic Doppler flow meter from Jiangsu Province, China. An EXO multi-parameter water quality analyzer (YSI), SH-24 intelligent dual-temperature zone disintegrator, and SH-3900A multi-parameter water quality analyzer (Sheng Aohua, Suzhou, China) were chosen as the chemical analysis and testing devices for the water samples. Each indicator was measured in three parallel groups to assure laboratory quality control, and the average value was used as the final result if the error of the three groups' measurements was less than 0.01 mg/L. The outcomes were revised if the inaccuracy was more obvious.

2.4. Hydrodynamic–Water Quality Modelling

2.4.1. Model Principles

MIKE 21, a two-dimensional numerical simulation model based on hydrodynamics and water quality research, mainly includes hydrodynamics (HD), advection–diffusion (AD), and water quality (ECOLAB) modules [18]. In this study we used a coupled module of the AD and ECOLAB functions. The control equation for the water quality model is as follows [19]:

$$\frac{\partial}{\partial t}(hc) + \frac{\partial}{\partial x}(uhc) + \frac{\partial}{\partial x}(vxc) = \frac{\partial}{\partial x}\left(h \cdot D_x \cdot \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(h \cdot D_y \cdot \frac{\partial c}{\partial y}\right) + S_c + P_c \quad (1)$$

In the equation, c represents the composite concentration of the substance (mg/L); u and v represent the water flow velocity in the x and y directions (m/s), respectively; h represents the water depth (m); D_x and D_y represent the diffusion coefficients of the substance in the x and y directions (m^2/s), respectively; S_c represents the source–sink term; and P_c represents the reaction equation of the substance in the ECOLAB module.

The water dynamics module includes a continuity equation and momentum equation, which are expressed as below [20].

The continuity equation for the water flow is as follows:

$$\frac{\partial H_0}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} = 0 \quad (2)$$

The equations of momentum in the x and y directions are as follows:

$$\frac{\partial \rho u}{\partial t} + \frac{\partial(\rho u u)}{\partial x} + \frac{\partial(\rho u v)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\mu_x \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_y \frac{\partial u}{\partial y}\right) \quad (3)$$

$$\frac{\partial \rho v}{\partial t} + \frac{\partial(\rho v u)}{\partial x} + \frac{\partial(\rho v v)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\mu_x \frac{\partial \mathrm{v}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_y \frac{\partial v}{\partial y}\right) \quad (4)$$

where H is the water depth (m); t is the time; x and y are the horizontal and lateral directions (m), respectively; v and u are the velocity of y lateral and x horizontal directions (m/s), respectively; ρ is the mass density of water (kg/m^3); p is the local atmospheric pressure (Pa); and μ_x and μ_y are the vortex viscosities in two horizontal directions.

2.4.2. Coupled Hydrodynamic–Water Quality Model

The coupled hydrodynamic–water quality model is a mathematical model that describes the flow and water quality changes in a river by studying the processes of pollutant influx, diffusion, and deposition in flowing water [21]. It is also the most direct method for quantitatively describing and dynamically simulating the coupling of river hydrodynamics and water quality. The advantages of the MIKE 21 coupled hydrodynamic–water quality model are that the one-way transfer calculation on the MIKE platform reduces the problem of differences in spatial scale matching, which improves the computational efficiency, and the two-dimensional model also has a small vertical transformation range, which makes the model calculations more accurate. The specific coupling process is shown in Figure 3.

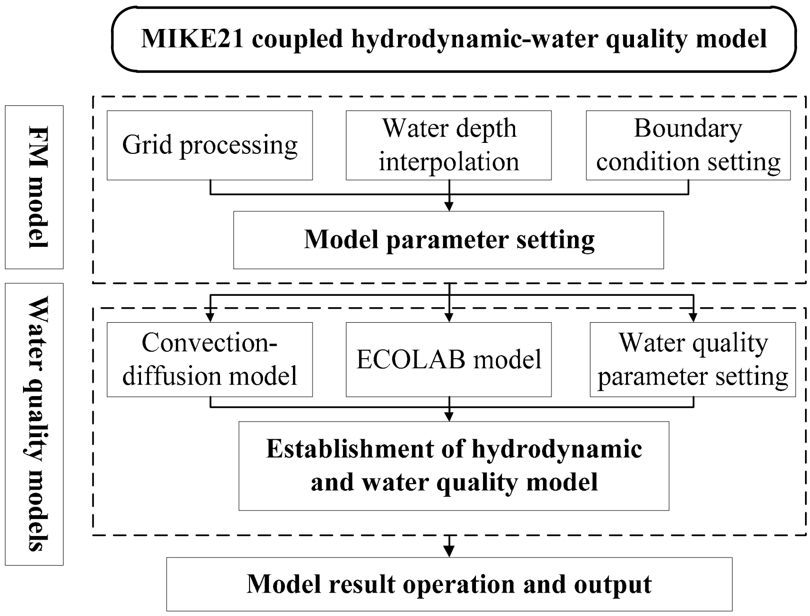


Figure 3. MIKE 21 coupled hydrodynamic–water quality mechanism.

2.5. Model Parameter Setting

2.5.1. Hydrodynamic Model Parameter Settings

The parameter settings for the hydrodynamic model were established based on the investigation of the current situation of the study area, including the topography, distribution of pollution sources, cross-sectional flow and size of the river, bed slope, and pollutant load. At the same time, the river was generalized, and digital characteristics of the river and cross-sections were extracted to form the river data and cross-sectional data. In addition to the river topography and initial and boundary conditions, the model also required the settings of solution formats, dry and wet depth, riverbed roughness, and diffusion coefficients [22]. The specific parameter settings are listed in Table 1.

Table 1. Model parameter settings.

Hydrodynamic Parameters	Value Basis	Value	Unit
CFL	Hydrodynamic calculation accuracy	0.9	–
Wet and dry boundaries	$H_{dry} < H_{flood} < H_{wet}$	$H_{dry} = 0.005$, $H_{flood} = 0.05$, $H_{wet} = 0.1$	m
Eddy viscosity coefficient	Smagorinsky coefficient	0.28	m^2/s
Manning coefficient	Field survey + model verification	32	$m^{1/3}/s$
Rainfall evaporation	Daily and net evaporation of river water	−11.075	mm/d

2.5.2. Parameter Settings for Water Quality Model

The parameters for the water quality model are the main factors that reflect the simulated quality of the river water environment in the study area. Due to the problem of water quality deterioration caused by low flow velocity and insufficient dissolved oxygen in the study area, the component concentration output of the convection–diffusion module was selected. Dissolved oxygen (DO) was used as the basis for studying the water's self-purification capacity and can effectively reflect the strength of its self-purification ability or the degree of pollution [23]. The 5-day biochemical oxygen demand (BOD_5) represents the dissolved oxygen consumed by microbial metabolism. The ECOLAB module outputs DO and BOD_5 as two fundamental indicators reflecting the river water quality, which can effectively reflect the degree of pollution.

The initial daily water level of the river in the study area was set to 2.5 m, and the initial concentration of tracer components in the river water was 0. Due to severe deterioration in the polder area in recent years, some water is categorized as class V (Table 2). Therefore, considering the worst-case scenario, the initial concentrations of DO and BOD_5 were set according to class V water standards at 2.0 and 10.0 mg/L, respectively. The data in Table 2 were provided by the "Environmental Quality Standards for Surface Water" (GB 3838-2002) [24].

Table 2. Classification and parameter values of surface water quality indicators (mg/L).

Water Quality Indicators	Class 1	Class 2	Class 3	Class 4	Class 5
BOD_5 ($\leq$)	3	3	4	6	10
DO ($\geq$)	7.5	6	5	3	2

The restricted water level of the pump gates in the western, northern, and eastern regions was set to 2.5 m, and the component concentration at the inlet was set to 1. The DO and BOD_5 concentrations were set to 5.54 and 3.46 mg/L, respectively, based on measured data from the local hydrological station. The DO and BOD_5 concentrations of river water beyond the outlet were considered the outlet control conditions and were set to 5.0 and 4.0 mg/L, respectively.

2.6. Design of Drainage and Sewage Disposal Program

The design of the drainage and sewage disposal program in this study was based on a coupled hydrodynamic–water quality model. By scientifically scheduling the functions of the water conservancy facilities after the transformation of the river, disturbances were imposed on the river to increase the hydrodynamics and accelerate the water renewal rate, thereby improving the purification capacity of the water and achieving the goal of reasonably improving the water environment of the river while satisfying the scheduling rules. The specific scheduling program is shown in Table 3.

Table 3. River hydrodynamic regulation program.

Program	Schedule
1	Western pump gate diversion (1.24 m^3/s), northern pump gate drainage (control gate water level 2.5 m)
2	Western pump gate diversion (1.24 m^3/s), eastern pump gate drainage (control gate water level 2.5 m)
3	Western pump gate diversion (1.24 m^3/s), northern + eastern pump gate drainage (control gate water level 2.5 m)

3. Results

3.1. Determining Model Rate

The river bed roughness is a critically important factor affecting the accuracy of hydraulic models and is reflected in the model as the Manning coefficient. Appropriate calibration is necessary to explore the impact of roughness on the model. Monitoring point 2 was selected as the model validation point for the study. Based on the measured topography of the river in the study area, the measured river depth data from November 1 to 1 December 2021 were used for model verification, combined with multiple adjustments. The findings show that the overall trend of the simulated water level is nearly identical to the real level when the roughness is 0.031. The maximum error occurs early in the model's operation, which is consistent with the theory of strong dependence on the initial water depth early in the simulation. The simulation results are shown in Figure 4.

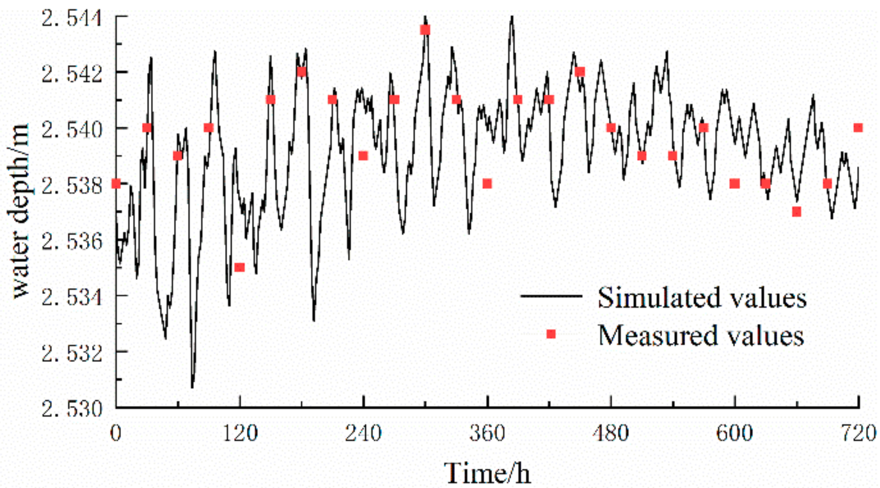


Figure 4. Comparison of simulated and measured water depths at monitoring point 2.

The coefficient of determination (R^2) is an indicator used to assess the goodness of fit of a regression model; the closer to 1, the more accurate the model. In this study, the fit of the measured and simulated values was plotted on the basis of removing specific values, and R^2 reached 0.91304, which meets the accuracy requirement of the model [25]. As a result, the model has high reliability and can satisfy the requirements for accurate model operation. The fitting results are shown in Figure 5.

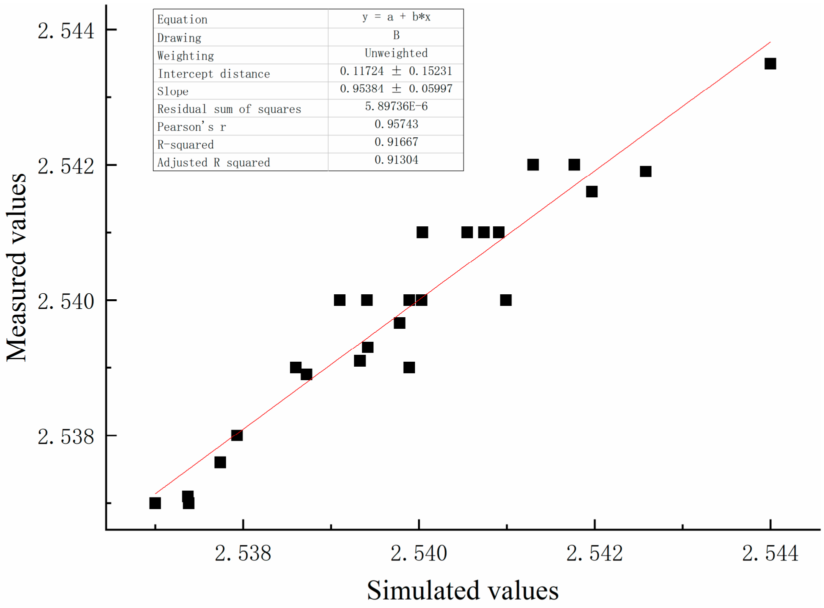


Figure 5. Fitting of measured to simulated values.

3.2. Analysis of the Hydrodynamic Simulation Results

Under the initial conditions, the water gates in the west, north, and east of the river were closed. Only the southern canal was used to supply water to meet the daily production and living needs of residents in the polder. The calibrated model was then used to simulate the hydrodynamic conditions of the river under normal working conditions. The flow velocity changes at eight monitoring points in the river are shown in Figure 6.

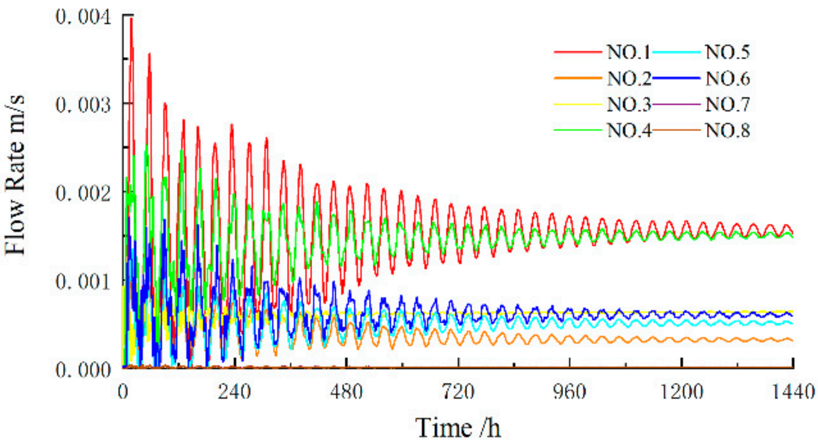


Figure 6. Flow velocity variation of the river monitoring points under normal operating conditions.

After starting the water supply from the southern canal, the flow velocity at various monitoring points in the river gradually stabilized within 24 h, with dynamic fluctuations observed at each point. Among them, the flow velocity at points 1 and 4 was the highest and remained stable at 0.0018 m/s. The flow velocity rates at points 2, 3, 5, and 6 ranged from 0.0003 to 0.0006 m/s. The minimum flow velocity was observed at points 7 and 8, at only 1.2×10^{-5} m/s. Therefore, it can be inferred that under normal operating conditions, the flow velocity is faster in the outer channels of the river than in the internal ponds but does not exceed 0.002 m/s. The flow velocity in the central pond is extremely slow, indicating a poor overall hydraulic condition of the river, which seriously affects the purification effect of the water.

Based on daily flow velocity monitoring at various points, simulations were conducted using regulation programs 1–3. The changes in flow velocity are shown in detail in Figure 7.

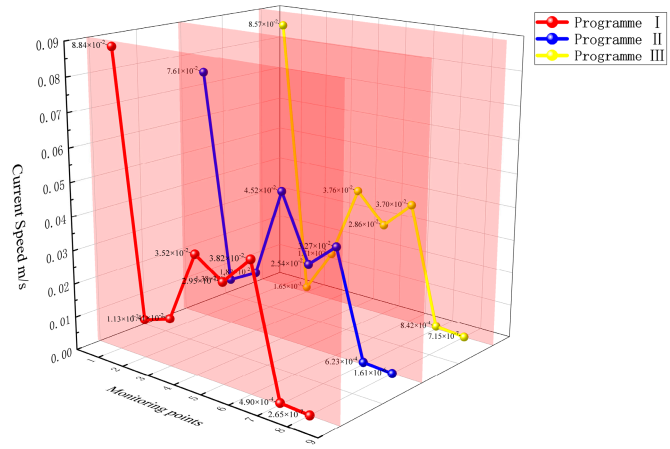


Figure 7. Flow velocity variations at river monitoring points under three regulation programs.

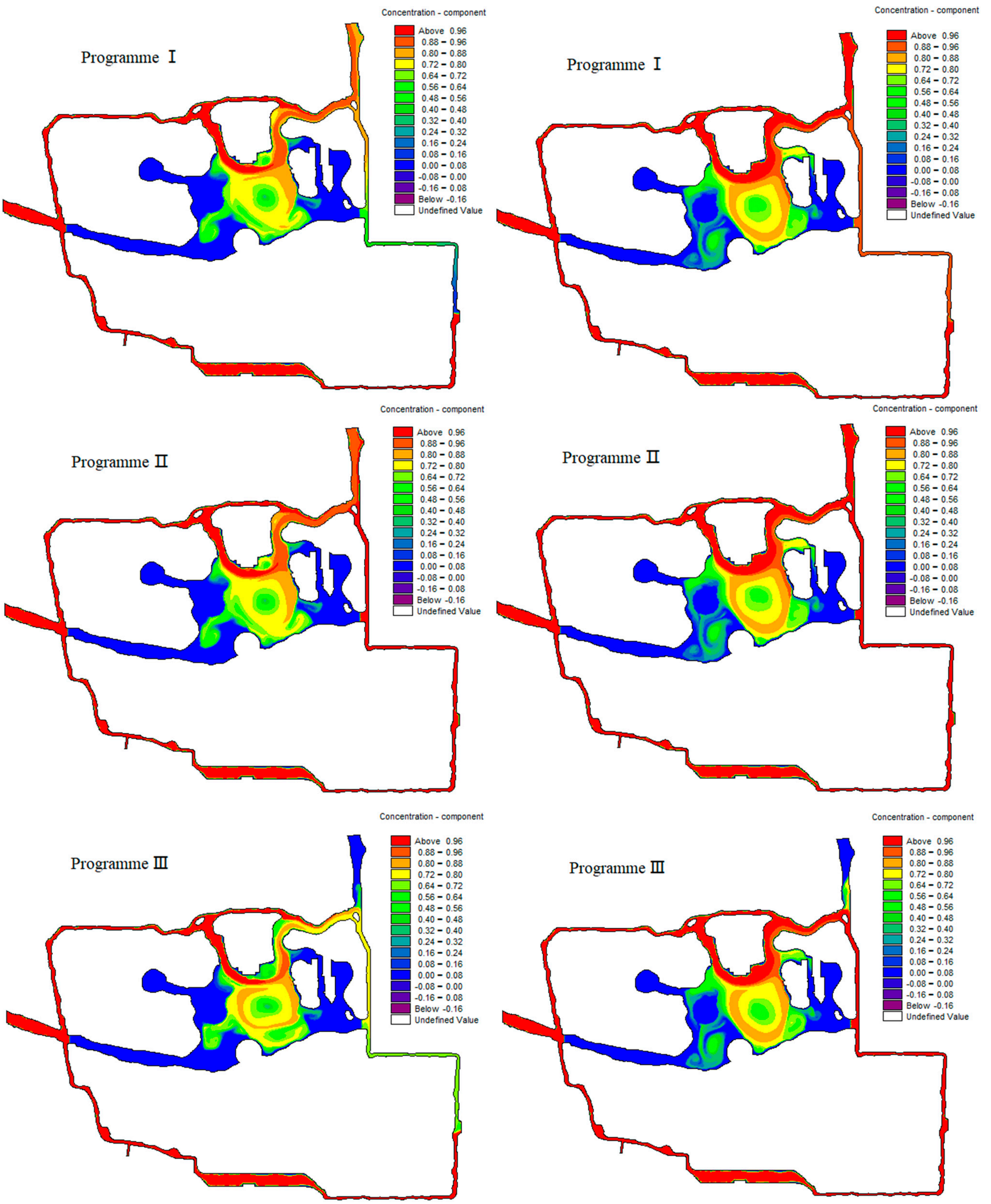
After the implementation of drainage regulation measures, the improvement in the hydraulic conditions of the river channels was significant. The flow velocity was generally better under programs 1 and 3 than under program 2, especially in driving the water in the outer channels of the river, with point 1 leading. The overall flow velocity range reached 0.07–0.09 m/s. However, the hydraulic drive of the central pond represented by point 8 was somewhat inadequate, with the water velocity still below 0.001 m/s.

3.3. Analysis of the Effect of Water Replacement

Based on the analysis of the flow velocity, an analysis of the water replacement effect in the river was conducted. A conservative tracer was used in the simulation study of the water replacement, and the degradation process of the tracer was not considered. The coefficients of the tracer were set to be the same as those of the convective diffusion module parameters. The initial tracer concentration in the river was set to 0 and the tracer concentration at the northern water gate was set to 1. The three programs simulated the water replacement situation for 7 days under continuous water intake and drainage (Figure 8).

The results show that after 72 h of continuous water intake and drainage, most of the water in the outer channels of the river in the study area was covered and updated, and the update degree was high. The water replacement rate in the channel between point 6 and the northern water gate exceeded 80%. In the central pond, the water replacement rate near points 5 and 6 also reached over 70%, and the newly replaced fresh water remained in a clockwise vortex in the pond. In addition to the central area, fresh water gradually replaced the other corners of the central pond. However, the replacement effect was poor, with a replacement rate of less than 32%.

The results show that under the three programs, the greatest displacement rate in the central pond was located on the north side of the pond, reaching over 55%. This area is close to points 5 and 6, and the water displacement process is the most intense. Fresh water flows in from point 5, travels 180° counterclockwise in the pond, and out from point 6. The second highest displacement rate was in the clockwise vortex in the pond's center; from the inside out, it increased from 40 to 88%. The weakest displacement rate was located south of the pond and can be seen as a branch of the central vortex. The water displacement in this area rotates counterclockwise, and the water displacement rate from the inside out increased from 48 to 80%.



(**a**) (**b**)

Figure 8. River water replacement effect: status of the drainage system after (**a**) 72 h and (**b**) 168 h of water intake.

After 168 h of water diversion, the water replacement rate of the three programs in the river stabilized and the water replacement rate in the outer circle of the river reached more than 96%. In the central water pond, the water replacement range of the inlet and outlet channels and the areas near the inlet and outlet remained the highest at 88–96%. The replacement pattern in the center of the water pond still followed the original pattern, with the replacement range being maintained at 48–88%. With increasing water diversion times, the central vortex continuously expanded and the replacement rate gradually increased.

The simulated displacement rates at the eight monitoring points after 7 days are shown in Figure 9. Except for the slight difference in displacement rates at positions 2, 8, and 7, the water displacement effect at the other five points reached or approached 100%. Because the eastern water gate is slightly narrower than the northern water gate in the outer ring, point 2 showed a slightly better displacement rate at the eastern water gate under a single water outlet. At point 7, representing the central water pond, displacement rates of 51.2, 49.6, and 55.8% under the three programs after 168 h were recorded. Overall, the radar maps of water displacement in the central water pond under programs 1 and 3 were fuller than that under program 2, indicating a trend of eastern + northern > northern > eastern regarding the water displacement effect during the same period.

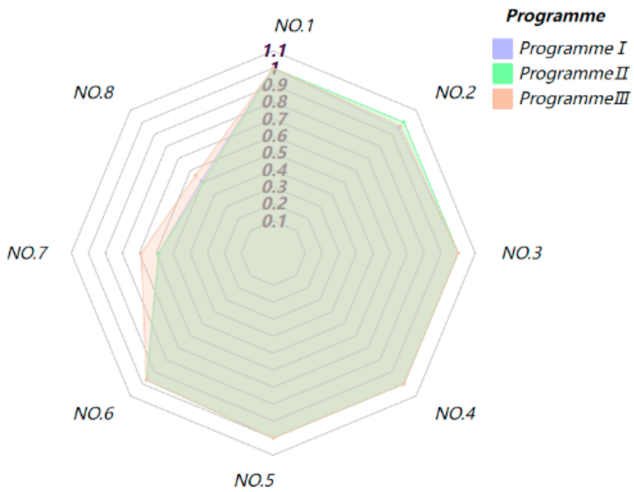


Figure 9. Radar map of water displacement rates at the monitoring sites.

3.4. Water Quality Simulation Analysis

Based on the simulation of water exchange capacity rates in the three water diversion and drainage programs for the river, the ECOLAB module was added to simulate the water quality changes in the river plain for 7 days, focusing on the two leading water quality indicators that contribute to the deterioration of the water environment. The initial water quality index of the river was set to class V and the inflow water quality was set to class 3.

3.4.1. Analysis of Water Quality Simulation Results

Based on the initial water quality classification of the river, the simulation results for scenarios 1 to 3 were compared and analyzed. Figure 10 shows the migration and distribution of water quality indicators one day after water diversion and drainage.

Figure 10 shows that 24 h after water diversion, the water quality changes in DO and BOD_5 contents in the inner and outer ring channels of the three scenarios followed the law of water replacement. The river channel showed a significant decrease in pollutant concentration in the outer ring and a driving phenomenon spreading from the outer ring to the center of the river channel. The difference between the three scenarios lies in the significant difference in water quality concentrations between the eastern and northern outlets.

Due to the unstable water quality in the study area after one day of drainage and replenishment and the central water not being fully replenished, it is not easy to reflect the overall water replenishment status of the river. Therefore, a comparative analysis of the water quality index migration and distribution cloud map after 7 days of drainage and replenishment is introduced.

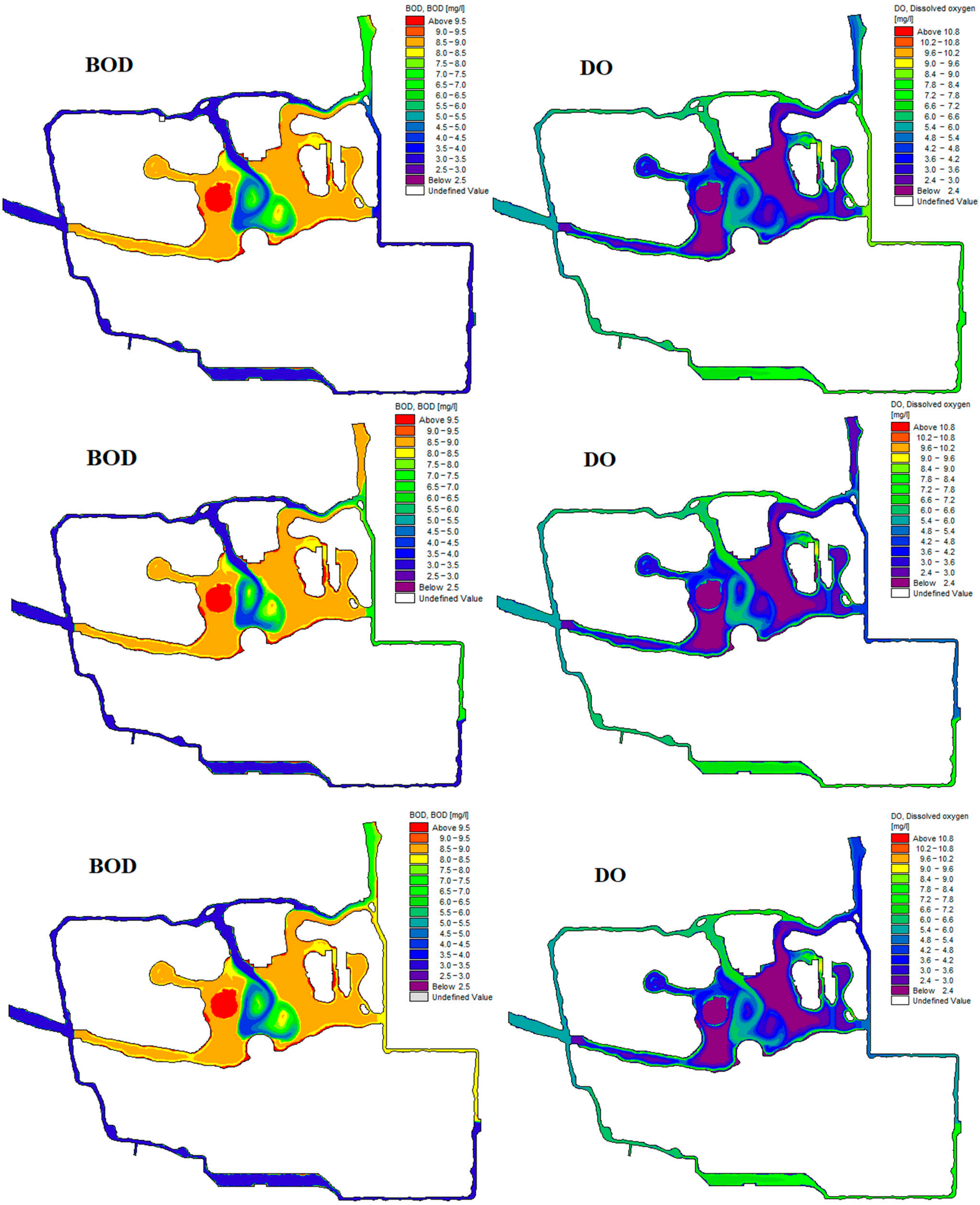


Figure 10. Water quality changes after 1 days of drainage diversion.

The Figure 11 indicate that 7 days after the water diversion and drainage programs were implemented, due to the increase in residence time of fresh water, the pollutants in the river had sufficient exchange and degradation durations and there was a significant improvement in water quality in both the inner and outer ring channels. Except for the part of the river center where water replacement was not carried out and the concentration of pollutants has decreased relatively less, the DO content in other parts reached class 3 water standards.

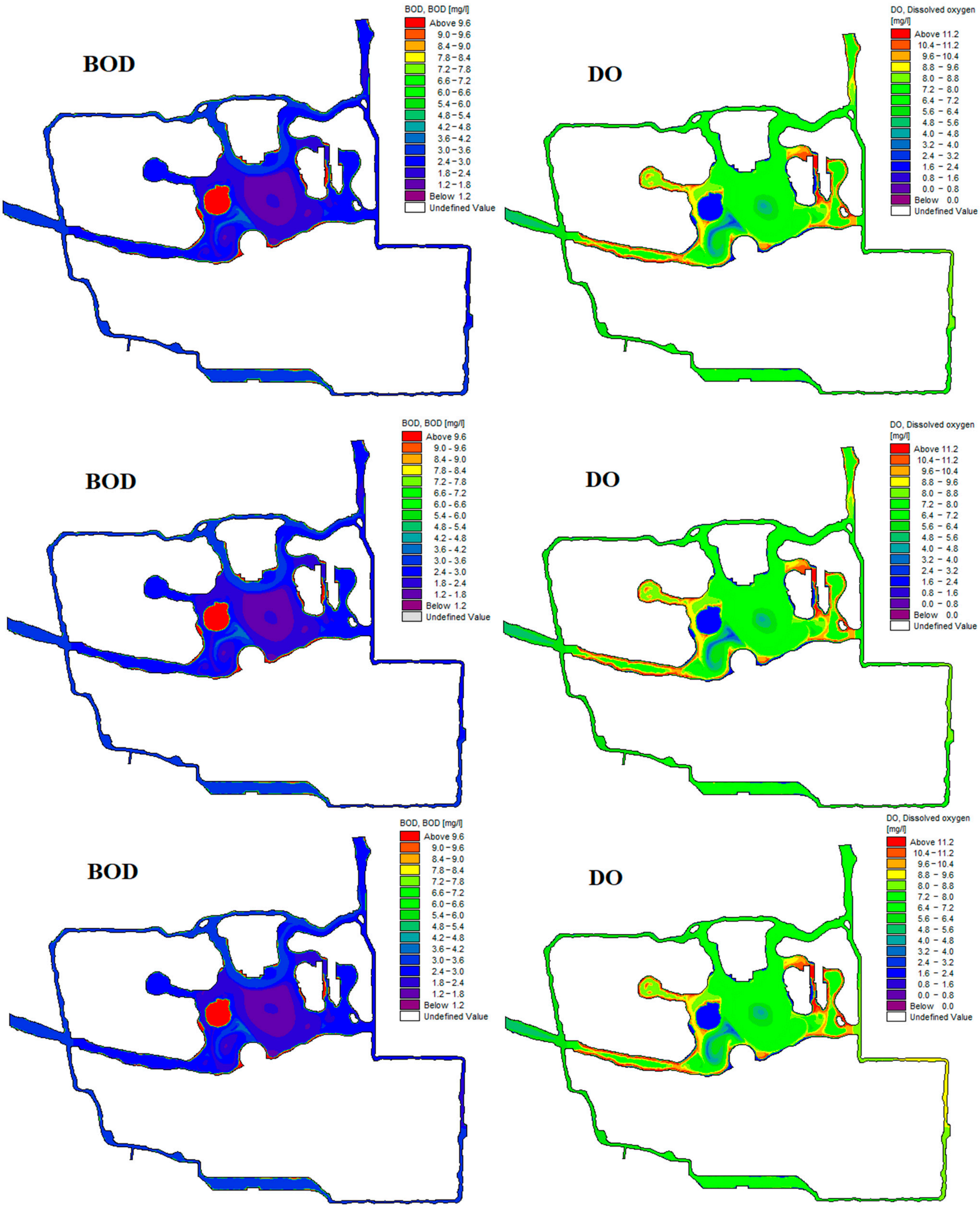


Figure 11. Water quality changes after 7 days of drainage diversion.

The DO concentrations in the outer ring channels were between 6.4 and 8.2 mg/L, reaching class 2 water standards. With an increased DO concentration and a corresponding increase in flow rate, the BOD_5 concentration gradually decreases, and decreases faster than the increase in DO. The average concentration of BOD_5 in the water reached class 3 water standards or above; the concentration in some water areas in the center pond was less than 1.8 mg/L and even reached class 1 water standards. The order of the water BOD_5 contents was program 1 > program 3 > program 2.

To quantitatively investigate the variations in water quality within the river of the study area over time, the 7-day spatiotemporal data for water quality changes at various monitoring points in the three programs were extracted, as shown in Figure 12.

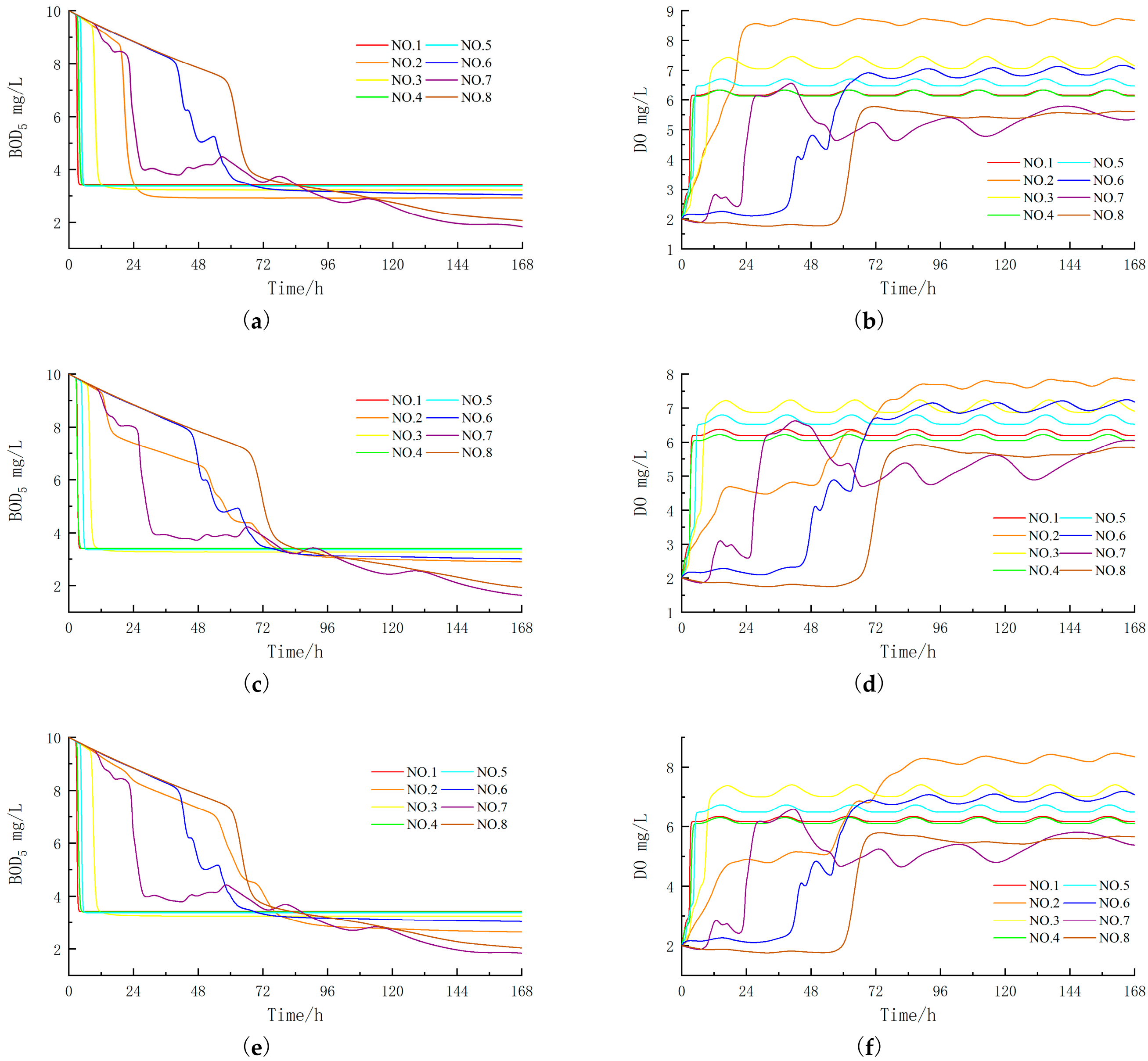


Figure 12. Water quality results at monitoring points after 7 days of drainage diversion: (**a**) BOD_5 content and (**b**) DO content at monitoring points of program I; (**c**) BOD_5 content and (**d**) DO content at monitoring points of program II; (**e**) BOD_5 content and (**f**) DO content at monitoring points of program III.

From Figure 12a,c,e, it can be seen that 7 days after introducing the diversion water, the BOD_5 and DO contents under the three programs decreased or increased to varying degrees. Except for the continuous decrease in BOD_5 at points 7 and 8, the values at other points fluctuated and stabilized to a certain extent. The fastest stabilization was achieved at points 1, 3, 4, and 5, which only took 5–12 h. Points 2 and 6 required 96 h to stabilize.

From Figure 12b,d,f, it can be seen that the DO contents in the water under the three programs ultimately reached a dynamically stable state. Among all monitoring points, the fastest increase in DO content occurred at point 1, stabilizing at 5.0–6.3 mg/L 5 h after introducing the diversion water. Point 8 had the slowest increase in DO content, and it took 72 h to reach a relatively stable state.

The water quality changes at various monitoring points under the three programs are shown in Figure 13. Compared with the values of surface water quality indicators (Table 3), it can be seen that after 7 days of water diversion, the BOD_5 content at each point under the three programs met the requirements for class 3 water quality. The overall BOD_5 content range of the water was between class 2 and class 3, with the water at point 7 even reaching the class 1 quality standard.

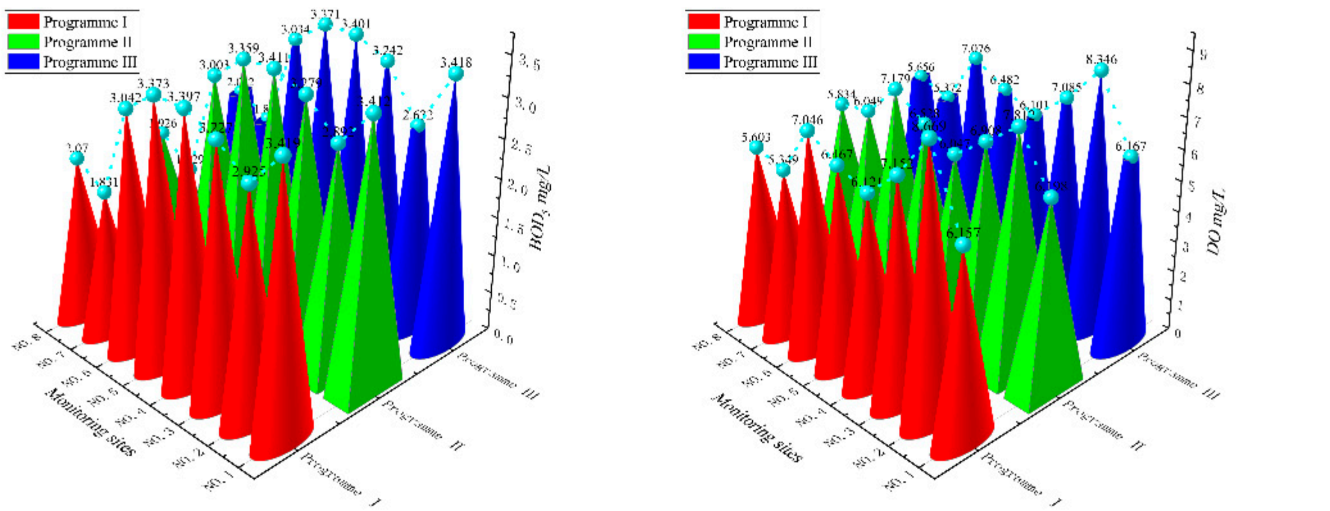


Figure 13. Final results for water quality changes at each monitoring site.

There is a distinct difference between the DO and BOD_5 content of the water. The lowest DO content is at points 7 and 8, which stabilized at 5.3–5.7 mg/L, meeting the class 3 water quality standard. The water at point 2 has the highest DO content, meeting the class 1 quality standard, while the DO content at the other points meets the class 2 standard.

3.4.2. Results of the Factor Cluster Analysis of Indicators

A cluster analysis is a process used to measure similarities and differences among indicator data. This study used a cluster analysis to analyze the water quality parameters, including the DO content, BOD_5 content, flow rate, and water replacement rate, at eight monitoring sites under three programs, to determine the impact of pollutant variables at each site.

From the heatmap and number of clusters in Figure 14, it can be seen that the indicator cluster analysis under the three programs is consistent with the overall cluster analysis. The velocity and displacement rate belong to the same category, indicating a close relationship between them, with the velocity affecting the state of the displacement rate. BOD_5 and DO are in the same category, indicating a mutual influence relationship between BOD_5, DO, velocity, and displacement.

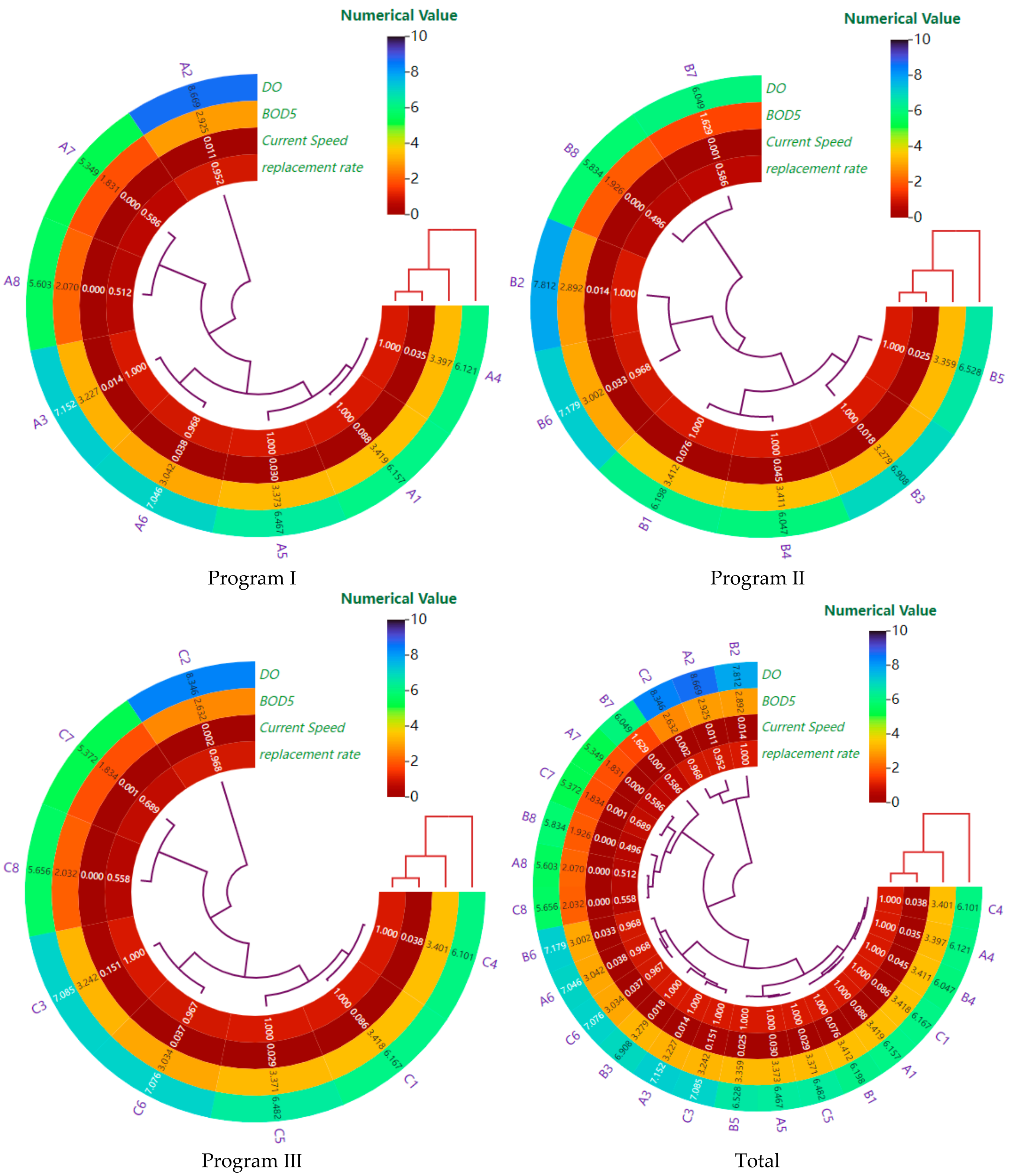


Figure 14. Indicator clustering heat map (A: program 1; B: program 2; C: program 3; A1: monitoring site 1 under program 1; and so on).

Regarding the classification relationship of verification points under the three programs, the overall classification state is consistent with programs 1 and 3. In comparison, program 2 deviates somewhat from the other two. Monitoring points 1 and 4, representing the northwest and southwest parts as initial points for replenishment, are in the same category under programs 1 and 3. Points 3, 5, 6, 7, and 8 belong to the central pond and southern replenishment canal area and are similar. Monitoring point 2, as the easternmost sampling verification point, is classified separately. In contrast, program 3 is only divided into two categories: one category including points 1, 2, 3, 4, 5, and 6; and one including points 7 and 8.

3.5. X-Conditional Cloud Model Evaluation Analysis

The cloud model is a mathematical model that describes the uncertainty transformation between qualitative concepts and their quantitative descriptions. The model's core purpose is to achieve mapping between qualitative and quantitative elements by constructing a cloud generator, which can effectively solve the problem of ambiguity and uncertainty in the evaluation process [26]. The X-conditional forward cloud model generates multiple cloud drops based on three numerical features, *Ex*, *En*, and *He*. Water droplets can form a cloud map to visualize the range of evaluation indicators. It is calculated as follows:

$$\begin{aligned} Ex &= \frac{X_{\min}+X_{\max}}{2} \\ En &= \frac{X_{\max}-X_{\min}}{2.355} \\ He &= k \times En \end{aligned} \tag{5}$$

In the formula, *Ex* is the point that best represents the qualitative concept and is the highest point on the cloud chart; *En* reflects the degree of dispersion and the fluctuation interval of the cloud droplets, which are represented on the chart as the span of the cloud shapes; He is a cohesive representation of all uncertain point degrees in the cloud space, reflected on the map as the thickness of the cloud shape.

Traditional single-factor evaluation methods could not be used to effectively perform a dual-index evaluation of DO and BOD_5 in this paper. Given the different simulation scenarios, specific indicators will perform better in one scenario and worse in others. Therefore, a comprehensive X-conditional cloud model evaluation method that can handle fuzzy factors has a certain level of objectivity.

It is assumed that the model has 10,000 water droplets. MATLAB's forward cloud model is used to generate two standard cloud models of the membership degree under two water quality indicators, as shown in Figure 15.

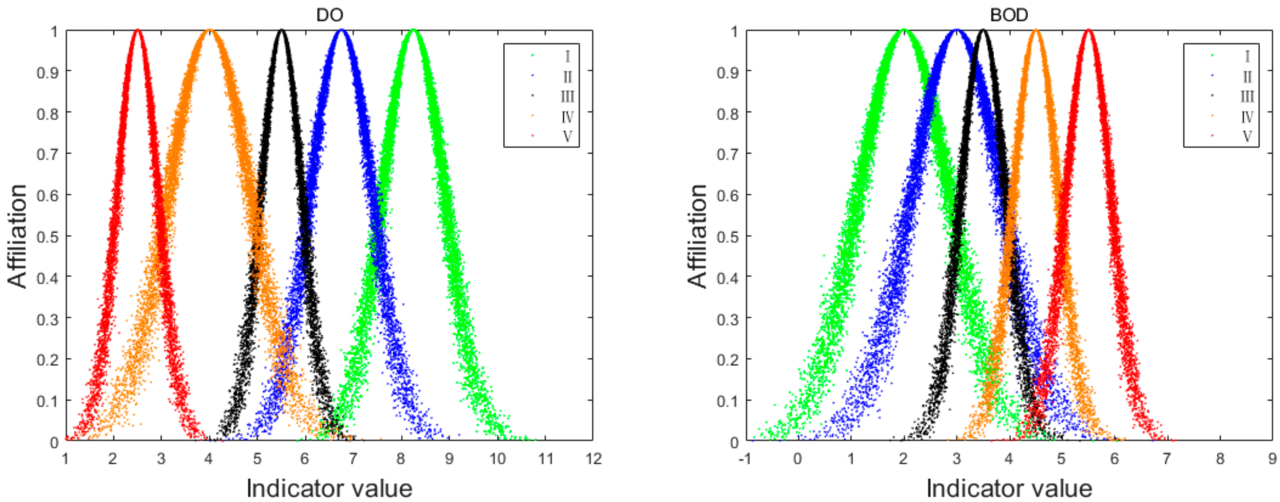


Figure 15. Cloud model of affiliation criteria for DO and BOD_5 indicators.

Since program 1 had the best overall water intake and discharge effects in the analysis, a radar chart was drawn to show the comprehensive evaluation results of the two water quality indicators for the program's eight monitoring points. The specific comprehensive evaluation results for determining water quality indicators are shown in Figure 16.

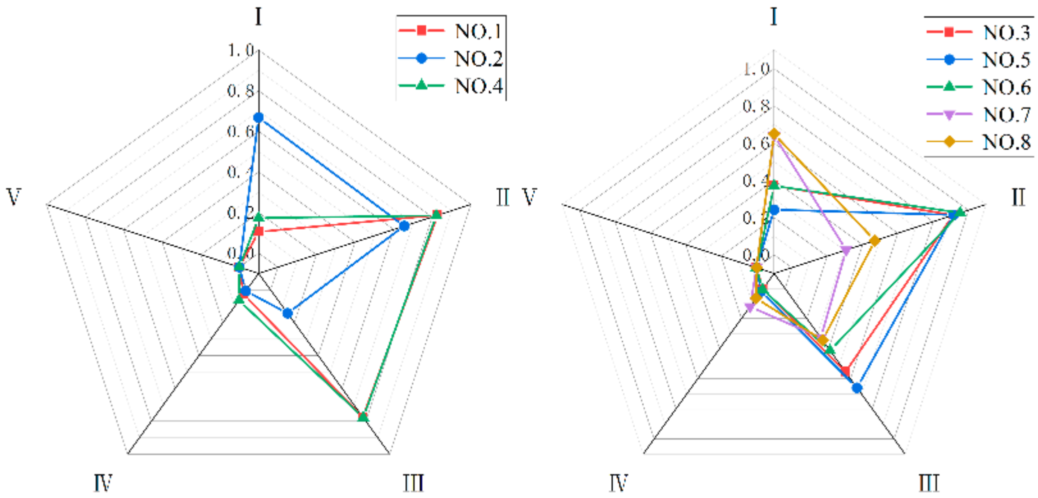


Figure 16. Results of the combined evaluation for water quality indicator determination.

It can be observed in the radar charts of water quality for the two types of monitoring stations that the water quality orders for the first and second types of monitoring points were ranked as 2 > 4 > 1 and 6 > 5 > 3 > 8 > 7, respectively. The highest certainty of water quality for the first type of station was at point 2, reaching 0.6923; the highest certainty for the second type was at point 6, reaching 0.9303; the highest certainty for the third type was at point 4, reaching 0.7827. The comparative analysis of water quality certainty validated the rationality of the research and the analysis results.

4. Discussion

In this paper, we examined the state of the water environment based on the water conservancy projects in the Shenzhuangyang polder area in Zhejiang Province, China. A coupled model of the water environment of the river using the MIKE 21 hydrodynamic and water quality model as a technical platform was established. Convective diffusion and the ECOLAB module were used to simulate the regulation programs, and a quantitative analysis and evaluation of BOD_5 and DO in the study area were carried out using a cluster analysis and cloud modeling. The MIKE 21 coupled hydrodynamic–water quality model showed high simulation accuracy. It is feasible to use engineering measures to relieve the pressure on the regional water environment and improve the water quality. This is verified by the research results of Zhang et al. and Pan et al. [27–29]. Compared with single hydrodynamic or water quality simulations, this study effectively took advantage of the small spatial matching difference of the MIKE coupled model. The tracer section was added to demonstrate the effect of water displacement and quantitatively discuss the dynamic changes in water flow velocity and water quality during one week. A set of research processes was formed to analyze the flow rate change of the river and evaluate the water environment status. This study makes a practical contribution to improving the regional water environment and promoting ecologically sustainable development. Taking into account the influence of anthropogenic factors on the water environment makes the results more representative. A study by Pant et al. on the impact of human activities on water quality in the Bagmati River during the COVID-19 pandemic can be used to verify the reliability of this study [30].

The MIKE 21 coupled hydrodynamic–water quality model overcomes the weaknesses of traditional hydrodynamic and water quality models with a single simulation function. However, the model is constrained by the need for more measured data. Further corrections should be made in response to the wind during the coupled simulation. Xing et al. demonstrated the importance of considering the contribution of wind to water quality changes [31]. Furthermore, due to the large area of water within the study area, the water quality data from the monitoring sites are only representative of a certain area. The next study should consider the use of GIS 10.7 and ENVI 5.3 software programs for the quantitative inversion of water quality data to produce spatial files and improve the accuracy of the simulation. A study by Milad et al. can provide a reference for water quality data inversion [32].

5. Conclusions

(1) In this study, a MIKE 21 coupled hydrodynamic–water quality model was constructed based on the AD and ECOLAB modules, and tracers were introduced to visualize the effects of changes in the water. After validation, the R^2 of the model reached 0.91304, which indicates high simulation accuracy and means the model could be used to simulate the state of the water environment of the river;

(2) The simulation results showed that the water displacement rate in the outer ring of the river reached over 90%, while the rates of the internal pond reached 51.2, 49.6, and 55.89%. The DO and BOD_5 in the river improved from class 5 to class 3, and the water quality dynamic process showed a fluctuating downward trend;

(3) In an analysis of the evaluation effect of the clustering and the cloud model on the drainage, the flow rate showed positive correlations with water displacement, DO, and BOD5. After regulation, the highest certainty value for class 1 reached 0.6923, the highest certainty value for class 2 was 0.9303, and the highest certainty value for class 3 was 0.7827. This shows that the hydraulic engineering control measure is more effective at improving the state of the water environment of the river.

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