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# Water Quality-Based Double-Gates Control Strategy for Combined Sewer Overflows Pollution Control

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**Abstract:** The combined sewer overflows (CSO) pollution has caused many serious environmental problems, which has aroused a worldwide concern. Traditional interception-storage measures, which exhibit the disadvantages of the larger storage tank volume and the low concentration, cannot efficiently control the CSO pollution. To solve this problem, a water quality-based double-gate control strategy based on the pollution based real-time control (PBRTC) rule was proposed, and the chemical oxygen demand (COD) concentration was taken as the control index. A case study was carried out in Fuzhou, China as an example, in which the hydraulic and water quality model were constructed to evaluate two schemes. According to the results, compared to the traditional scheme, the double-gate scheme can not only reduce the storage tank volume by 1515 $m^3$, but also increase the average COD interception rate by 1.84 times, thus ensuring the effective and stable operation of the facility. Furthermore, the traditional scheme and the double-gate scheme were evaluated under design rainfall beyond the design return period, which confirmed the high performance of the double-gate scheme in controlling CSO pollution.

**Keywords:** combined sewer overflows pollution; hydraulic and water quality model; pollution based real-time control; double-gate strategy based on water quality

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## 1. Introduction

In recent years, owing to the rapid process of urbanization and the frequent occurrence of extreme storm weather, combined sewer overflows (CSO) pollution has gained intense attention all around the world. This type of combined drainage system is employed as the main drainage method in most urban areas. Unfortunately, various pollutants can be carried into the water body when this combined drainage system overflows during heavy storm events, which will lead to serious water pollution problems, such as the deterioration of water quality, eutrophication, and abnormal growth of aquatic organisms [1–3]. Moreover, the CSO can result in other kinds of pollution to the river as well. For example, the research of the Suzhou industrial park showed that the overflow of stormwater was the source of heavy metal pollution [4]. Therefore, the ever-increasing CSO pollution need to be urgently addressed by the improvement of the stormwater management standards and wastewater treatment plant (WWTP) [5,6]. In order to minimize the impact of combined sewer overflows pollution, many cities have taken measures to build or expand the interception and storage facilities. However, most measures are expensive and ineffective, and the interception of stormwater mixed into the sewage system may lead to a reduction of pollutants concentration in the WWTP, greatly reducing the efficiency of biochemical treatment processes [7,8]. Therefore, in order to effectively ensure the safety of the urban water environment, it is necessary to put forward corresponding strategies to solve the urban combined sewer overflows pollution problems.

With the development of computer technology and the Internet, many cases of real-time control (RTC) technology have been introduced into the urban drainage system to solve the problem of large cost and decentralized management [9–11]. For example, Parolari et al. (2018) [12] used a water level control method based on the steady-state probability density function to control the discharge of a stormwater retention pond. The results showed that this technology can not only increase the water storage capacity and hydraulic retention time but also reduce the increase in peak flow and pollutants caused by urbanization [12]. Kroll and his colleagues utilized a water level based RTC control technique in Flanders, Belgium, and the results showed that the application of RTC can reduce the total overflow by 20%–50% [13]. However, RTC technology based on flow rate or water level exhibits a low correlation between pollution flow and concentration, which cannot achieve the desired results [14,15]. Thus, many scholars put forward the concept of pollution based real-time control (PBRTC) rule and corresponding intelligent water dispatching to realize the accurate analysis of pollutant concentration variation of combined sewer overflow. The PBRTC rules can transmit real-time data of water quality of CSO through sensors by optimizing online regulation rules and accurately monitoring the mixed-flow pollution process curve. Then, the controller is used to simulate the rainfall forecast, flow rate and water quality, optimize and generate control rules, thus achieving a better performance of real-time scheduling. With the development of water quality sensors and modeling tools, more and more attention has been paid to this control strategy, which is more effective than RTC based on flow or water level [16,17]. Ly et al. (2019) [16] compared the treatment effect of water-quality based RTC strategy QBR using the mass-volume (MV) curve with that of hydraulics-based RTC (HBR) in small scale wastewater networks (HBR). The results showed that the QBR was able to provide CSO load reduction from 3% to 43% compared with HBR for more than one-third of storm events [16,17]. Weinreich et al. (1997) [18] used the newly developed PBRTC simulation tool to reduce the total phosphorus ($P_{tot}$) and $NH_4^+$-N load of the urban drainage system by 48% and 51%, respectively [18]. In general, it has been proved to be a feasible strategy to optimize and control urban storage facilities by PBRTC rules. However, in current practical application, the PBRTC rules are mainly used for improving the original intercepting-storage facilities by installing the corresponding intelligent control components. These methods rarely make use of the digital drainage model to acquire the systematic construction plan during the design and construction process, thus limiting the application of PBRTC rules to some extent [11,19]. Therefore, in order to systematically control urban combined sewer overflows pollution, it is critical to select appropriate PBRTC rules to optimize the current digital drainage model, which would finally make most use of the roles of the digital drainage model and PBRTC in urban drainage system. Currently, there are successful cases of coupling RTC technology and drainage models. For example, Campisano A. et al. (2016) used the flow rate based RTC technology and drainage model, which can reduce CSO volume [20]. However, water level or flow rate based RTC technology have poor correlation with pollutants in the stormwater, which obtain the undesirable results in some study. Therefore, coupling the PBRTC rule and drainage models have been tried out. For example, Sharior et al. (2019) compared the total suspended solid (TSS) based RTC with water level based RTC, which can obtain a 40% reduction in the occurrence of CSO [17]. Nevertheless, TSS is not the only pollutant in the stormwater. It is very meaningful to explore the effect of the use of PBRTC based on other pollutants. As a result, the combination of PBRTC rule based on chemical oxygen demand (COD) value and digital drainage model was used in our study.

In this study, the stormwater pipe network system in Fuzhou is used as an example. By using InfoWorks ICM and ArcGIS, the two-dimensional drainage model is established, validated, and calibrated, which is used to optimize the traditional interception-regulation scheme and evaluate its chemical oxygen demand (COD) interception capacity and overflow COD concentration. Based on the PBRTC control rules, a double-gate scheme based on water quality was proposed, which used the COD as the control index and combined the local pollutant control specifications to confirm the specific COD value, and its intercepting capacity and overflow situation were simulated and evaluated. Under the same designed rainfall, the traditional scheme was compared with the double-gate scheme, including the facility size, COD interception rate, and COD concentration over 50 mg/L overflow volume. Furthermore, the operation performance of the double-gate scheme and the traditional scheme beyond current design condition, including the interception COD rate, the average COD interception concentration, and the over-standard volume of the overflow stormwater were further studied.

## 2. Materials and Methods

### *2.1. Study Area*

The study area is located in the western suburb of Fuzhou City, Fujian Province, China, between Liangcuo road and Honggan road, covering an area of about 0.89 km$^2$ (Figure 1). The whole area is low-lying, part of the main roads in the region are arc-shaped, and the ground elevation is from 6.0 to 123.4 m, which means that the fluctuation is big and flood is easy to occur in this area. The annual distribution of local precipitation is very uneven, and the precipitation is concentrated from April to September, accounting for 70% to 80% of the whole year.

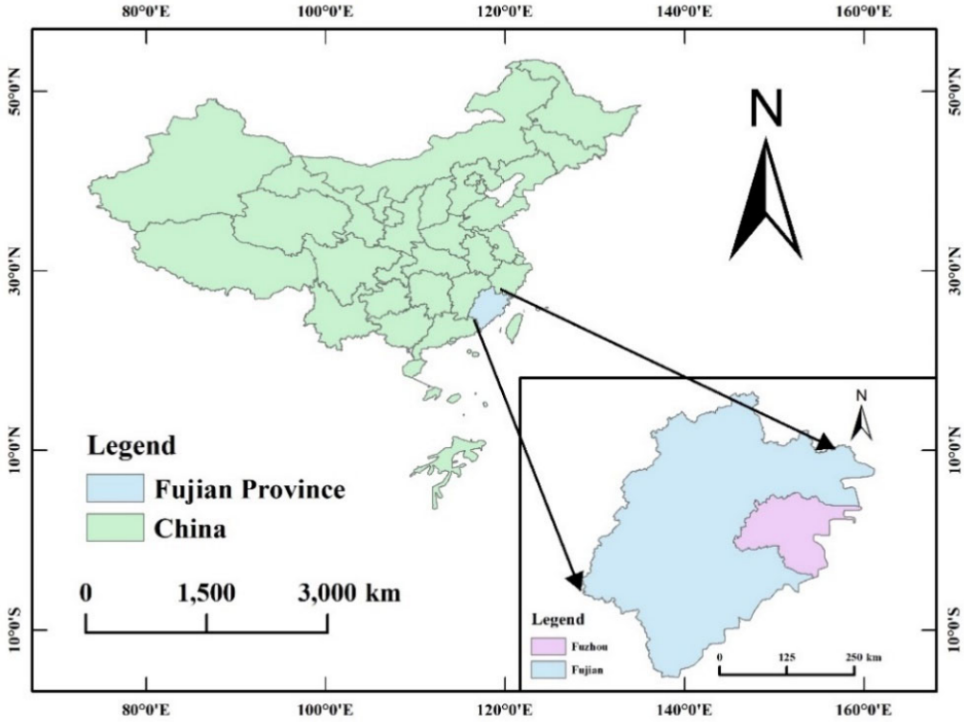


**Figure 1.** The location of this study area.

In addition, the drainage system of the region is a separate drainage system, and the stormwater is collected mainly by the branch roads. The ends of the regional stormwater pipes are connected to the MEITING canal, and the collected stormwater is then conveyed to Min River by the MEITING Canal. The mixed connection of the stormwater system is serious in the region, and the amount of water in MEITING canal is large in dry weather. More details about the study area can be seen in the previous study [21].

In this paper, InfoWorks 9.0 and ArcGIS 10.2 were used to generalize and divide the area of the pipe network and catchment. The study area is divided into 301 sub-catchment areas, and there are 268 nodes in this study area (Figure 2a). In addition, according to the actual land utilization (Figure 2b) in the region combined with the model of the underlying surface classification. The underlying surfaces of the area are divided into four types: roof, green space, road, and mountain. The Fixed model was used for road and roof, and the Horton model was used for green land and mountain. For the confluence model, stormwater management model (SWMM) sub-model is used for different types of underlying surfaces.

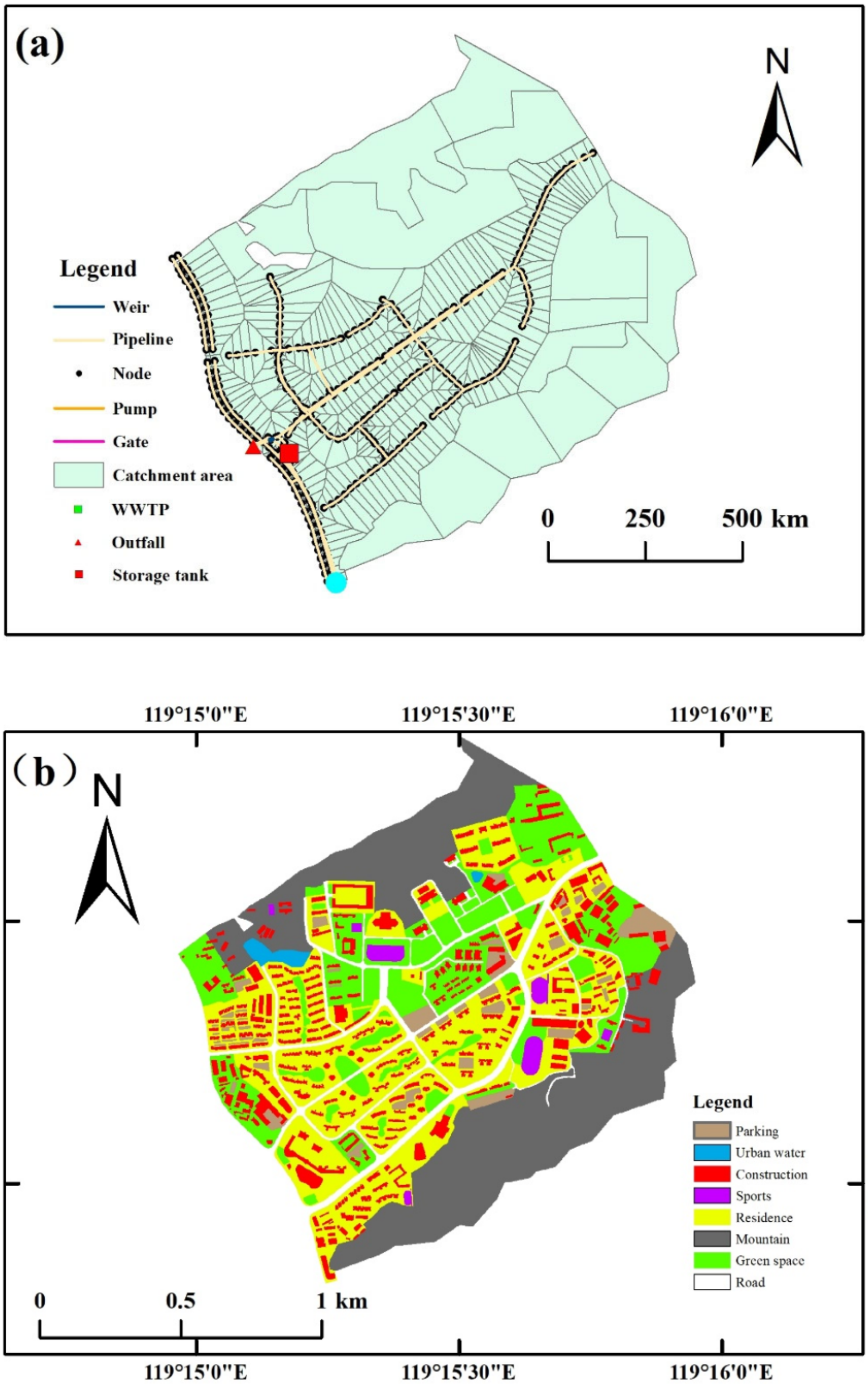


**Figure 2.** The detail information of study area: (**a**) pipe network system; (**b**) land utilization information.

### 2.2. *Hydraulic and Water Quality Model*

Before the hydraulic and water quality model were constructed, a series of investigation was carried out, such as pipe network survey, rain gauge installation, and field flow rate measurement and water quality sampling. Rainfall data were measured by the SL3-1A rain gauge (Meteorological Instrument Factory co., LTD., Shanghai, China), which was installed in the study area. The flow rate was measured by volume method or flow-area method and COD was tested according to the water quality sampling.

### 2.2.1. Hydraulic Model Validation and Calibration

The hydraulic model is the foundation of the water quality model and plays an exceedingly important role in the whole modeling process, which must be validated and calibrated before using. In this study, the measured rainfall on 18 September 2018, and 15 October 2018, are selected to validate and calibrate the hydraulic model, respectively. For hydraulic model validation and calibration, Nash Coefficient is a good test parameter to measure the fitting degree of the model, the specific formula is as follows:

$$\mathrm{NSE} = 1 - \frac{\sum_1^n \left(\mathrm{Q_i} - \mathrm{Q_i'}\right)^2}{\sum_1^n \left(\mathrm{Q_i} - \overline{\mathrm{Q}}\right)^2} \tag{1}$$

where $\mathrm{Q_i}$ and $\mathrm{Q_i}'$ are the measured and calculated flows or water quality values at time step. $i$ and $n$ are the total number of time steps. $\overline{Q}$ is the average values of calculated flows or water quality values. Generally speaking, the NSE coefficient is close to 1, and the better the fitting degree is. It is generally considered that the hydraulic model can exhibit good performance when NSE value is more than 0.7 [22]. The results of hydraulic model validation and calibration are as follows (Figure 3a,b), the NSE coefficients of the hydraulic model are 0.89 and 0.82, respectively, which can be used for coupling of water quality model.

### 2.2.2. Water Quality Model Calibration

The evaluation of water quality model is similar to the evaluation of the hydraulic model, in which the NSE coefficient can reflect the fitting degree of the model. It is generally considered that NSE is greater than 0.6, which confirmed the good performance of the water quality model [23]. In this study, 15 October 2018 rainfall was used to calibrate the water quality index COD with 0.63 of the NSE coefficient, indicating that the water quality model could be used for further water analysis. More details about the hydraulic parameter derived from the calibration process can be seen in Table 1 and the water quality parameter derived from the calibration process can be seen in Table 2. Furthermore, because the purpose of our paper is not to explore the parameters of calibration process, the parameters of calibration process were only listed according to some literature [21,24,25].

**Table 1.** Hydraulic parameter derived from the calibration process.

| Underlying Surface | Confluence Model | Confluence Parameter | Runoff Model | Runoff Parameter | Initial Loss (m) |
|---|---|---|---|---|---|
| Green space | SWMM | 0.2 | Horton | 1 | 0.005 |
| Roof | SWMM | 0.014 | Fixed | 0.2 | 0.001 |
| Road | SWMM | 0.014 | Fixed | 0.2 | 0.001 |
| Mountain | SWMM | 0.2 | Horton | 0.6 | 0 |

**Table 2.** Water quality parameter derived from calibration process.

| Category | Parameter | Confidence Interval |
|---|---|---|
| Rainfall erosion factor | $C_1$ | $3.01 \times 10^8$–$3.23 \times 10^8$ |
| | $C_2$ | 2.010–2.130 |
| | $C_3$ | 22.47–23.99 |
| Pollution efficiency factor | $A_1$ | 2.01–2.34 |
| | $A_2$ | 0.000 |
| | $A_3$ | −0.412–−0.437 |
| | $A_4$ | 0.000 |
| Surface accumulation factor | $P_s$ | 67–72 |
| Decay factor | $K_1$ | 0.08–0.14 |

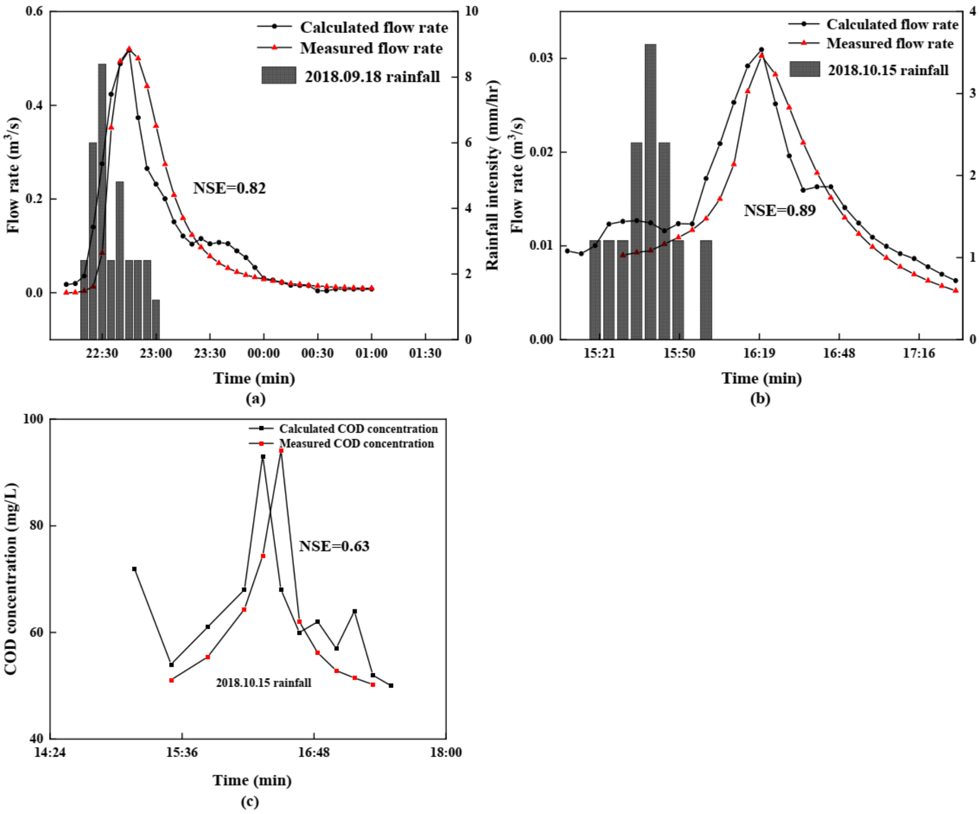


**Figure 3.** Model validation and calibration: (**a**) hydraulic model validation; (**b**) hydraulic model calibration; (**c**) water quality calibration.

### 2.3. The Calculation of Storage Tank Volume

According to Technical Code for Urban Stormwater Regulation and Storage Engineering (GB 51174-2017), the volume of the storage tank can be determined as followed:

$$V = 10DF\psi\beta \tag{2}$$

where $V$ is an effective volume of the storage tank (m$^3$); $D$ is storage capacity (mm); $F$ is catchment area (hm$^2$); $\psi$ is the runoff coefficient; $\beta$ is the safety coefficient. The storage volume $D$ can range from 4 to 8 mm according to the regulation, and 6 mm is determined according to the specific conditions of Fuzhou. Catchment area $F$ has been completed, and the study area exhibits the maximum catchment area of 104.7 ha. The runoff coefficient $\psi$ was estimated to be 0.61 based on the modeling results. According to the experience, the value of $\beta$ varies from 1.1 to 1.5, which is corresponding to the storage volume from 4215 to 5748 m$^3$.

### 2.4. The Calculation of Interception Ratio

The determination of the interception ratio is one of the important parameters in the design of intercepting weir. According to the code for outdoor drainage, the calculation of the interception ratio shall be as follows:

$$Q_j = (1 + n_0) \times Q_{dr} \tag{3}$$

where $Q_j$ is the interception flow rate of stormwater and sewage (L/s); $n_0$ is the interception ratio; $Q_{dr}$ is the flow rate of sewage in the dry weather. The interception ratio should be determined according to the water quality, water volume, environmental capacity of discharge water body, hydrology, climate, economy, and drainage area, which should range from 2 to 5. According to the results of sewage in dry weather, the discharge of sewage in dry weather is 0.2465 $m^3/s$. Therefore, the intercepting capacity of the intercepting pipe should maintain from 0.7395 to 1.479 $m^3/s$.

### 2.5. The Calculation COD Interception Rate

The COD interception rate is the important parameter, which can reflect the permance of the performance of interception facilities, such as intercepting pipe, storage tank and other relevant facilities. The calculation of the COD interception rate can be as follow:

$$\text{COD interception rate} = \frac{Q_s \times C_{CODs}}{Q_i \times C_{CODi}} \tag{4}$$

where $Q_i$ is the flow rate of upstream stormwater (L); $C_{CODi}$ is the COD concentration of upstream stormwater (mg/L); $Q_s$ is the flow rate of stormwater, which were intercepted into the storage tank (L); $C_{CODS}$ is the COD concentration of stormwater, which were intercepted into the storage tank (mg/L).

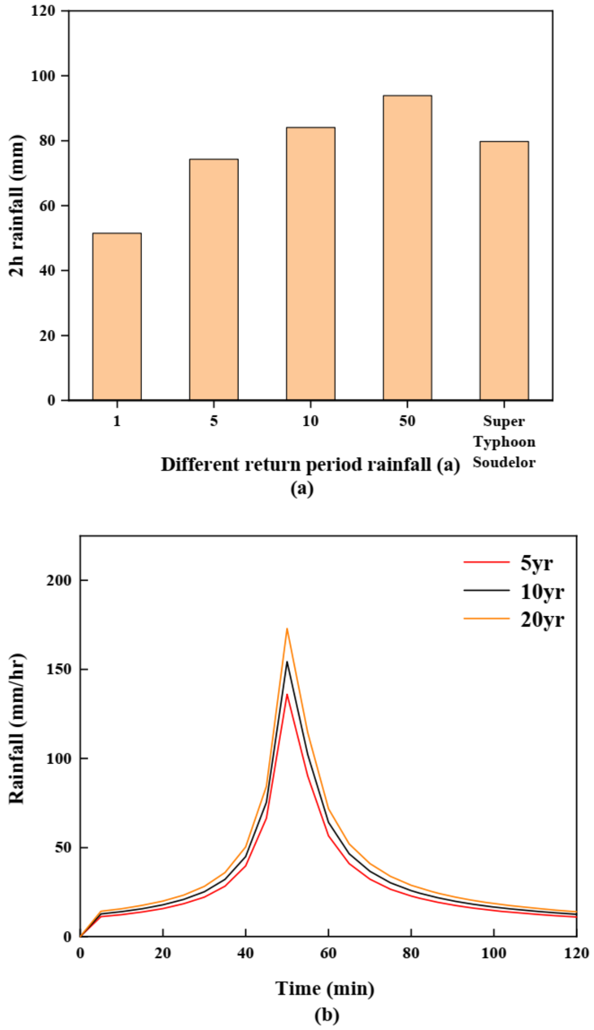
### 2.6. Design Rainfall

Both design rainfall event and observation rainfall can be used as the rainfall of the model construction [26]. However, owing to the difficulty of the field monitoring rainfall, which can be used in the research, the design rainfall events were selected as the main approach. According to previous studies, rainfall in China matches the Chicago rainfall pattern, therefore, the designed rainfall intensity should be calculated according to the rainfall characteristic in each area [27,28]. The designed rainfall intensity in Fuzhou area can be calculated according to the following formula:

$$i = \frac{2462.415(1 + 0.633\lg P)}{(t + 11.951)^{0.724}} \tag{5}$$

where i is rainfall intensity (mm/hr); P is the rainfall return period (a); t is the rainfall duration (h). According to Chinese national design standards, storm drains in big cities should be designed to range from two to five years return period. Comparing with previous study by Wei et al., (2019), it is found that the operational results of the model are more accurate under the conditions of the Super Typhoon Soudelor event on 9 August 2015, which was used for hydraulic model calibration [21]. In addition, when comparing the rainfall of 2 h in the designed rainfall return period $P$ = 1, 3, 5, 10, the designed rainfall of $P$ = 5 is equivalent to that of Typhoon Sudiro (Figure 4a), therefore, in this study, the stormwater pipe, canal, and intercepting weir are designed according to $P$ = 5.

Owing to the possibilities of storage tank, high COD concentration stormwater was failed to collect, and combined sewer overflow [29,30], which can easily appear under higher return period have existed, the performance of double-gate scheme must be assessed. Furthermore, the advantages of the double-gate scheme are required to further study, the design rainfalls of 6, 7, 8, 9, 10 and 20 years were selected to evaluate the double-gate scheme. The rainfall duration is 2 h, the concrete rainfall intensity can be found in Figure 4b.



(a)

(b)

**Figure 4.** Information about rainfall in this study: (**a**) the comparison of different rainfall; (**b**) rainfall intensity of different return period rainfall.

## 3. Results

### 3.1. Simulation Analysis of Outfall

The water quality and volume of the study area outfall are simulated by the hydraulic and water quality model. The specific discharge and COD concentration of the outfall can be seen in Figure 5. As shown in Figure 5, the stormwater begins at 17:55, and then the COD concentration quickly reaches the peak value of 380.7 mg/L, which is 5 times than that in dry weather. When the discharge flow rate reaches 1.24 $m^3/s$, the COD concentration drops rapidly, and decreases below 50 mg/L at 17:55. Then, the discharge flow rate reaches the peak value gradually and the COD concentration continues to decrease. The concentration of COD is over 50 mg/L at 19:17 until the end of rainfall. Generally, there are two periods existing in the stormwater interception. One is that when COD concentration is over 50 mg/L, the stormwater interception can effectively reduce the combined sewer overflows pollution. The other period happens from 17:55 to 19:17, in which the sewage exhibits the character of high-flow and low concentration. The sewage in this period can be discharged into the water body nearby, thus reducing the operation load and treatment cost of the WWTP.

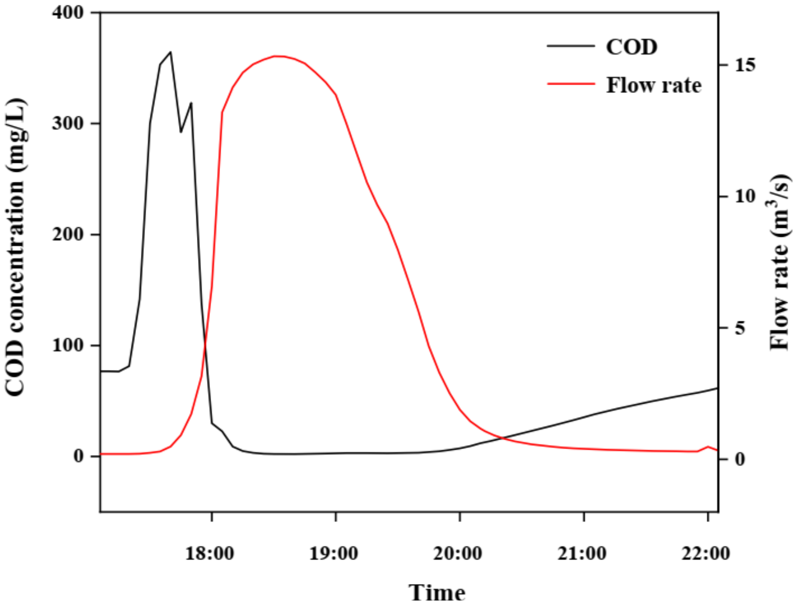


**Figure 5.** Discharge flow rate and chemical oxygen demand (COD) concentration of the simulation outfall.

## 3.2. *Traditional Interception Weir-Regulation Scheme*

### 3.2.1. The Optimization of the Interception Ratio and Intercepting Sewer

Theoretically, when selecting the interception ratio, the local rainfall intensity and design return period should be taken into account, and the quality and volume of sewage should be calculated. Thus, according to the interception volume obtained from the interception ratio, the overflow volume is calculated. The water quality of the water body is predicted using the environmental impact assessment water quality model and judged by the predicted results. If the value is not reasonable, it should be re-selected and calculated, but there are many factors to be considered in the actual process, such as the local environmental capacity requirements, hydrological conditions, economic conditions, and etc. Therefore, it is necessary to use the drainage model, which can quantitatively analyze the interception ratio and then compare the interception ratio according to the sewer network, the WWTP load, and the initial stormwater collection. Therefore, this study uses the drainage model that has been validated and calibrated to determine the interception ratio.

Based on the investigation, the average flow rate in dry weather is 0.2465 $m^3/s$, and the intercepting flow rate in wet weather ranges from 0.7395 to 1.479 $m^3/s$. According to the hydraulic calculation with the interception ratio of 3, the suitable value of intercepting pipe diameter can be found in Table 3. The details about other important parameters such as roughness coefficient, slope, and upper and lower pipe elevation can be seen in Table 4.

**Table 3.** Calculated flow rate of different pipe diameter.

| **Pipe Diameter (mm)** | 600 | 800 | 1000 | 1200 |
|---|---|---|---|---|
| **Calculated Flow Rate ($m^3$/s)** | 0.251 | 0.540 | 0.980 | 1.593 |

**Table 4.** Other important parameters in design of the intercepting pipe.

| **Parameters** | **Roughness Coefficient** | **Slope** | **Upper Pipe Elevation (m)** | **Lower Pipe Elevation (m)** |
|---|---|---|---|---|
| Value | 1.5 | 0.00167 | 2.9 | 2.805 |

Therefore, according to the traditional hydraulic calculation, the diameter of the intercepting pipe is 1000 mm, and the other three kinds of pipes are selected to simulate and compare the intercepting effect (Figure 6). After the simulation, the flow rate of the 1000 mm diameter pipe increases rapidly, which the actual flow rate can reach from 3.37 to 3.43 $m^3/s$ and the actual interception ratio can reach 12.7, which is more than 2 times the maximum interception ratio $n = 5$. In order to avoid the damage of storage facilities caused by too large intercepting flow in wet weather, the intercepting pipe DN600 is selected by simulation, and the actual flow can reach from 1.04 to 1.08 $m^3/s$ and the actual interception ratio can reach $n_0 = 3.34$.

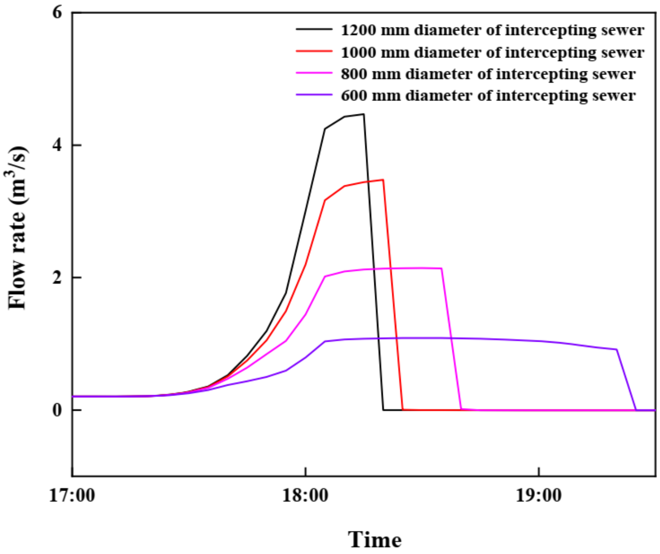


**Figure 6.** The optimization of pipe diameter.

### 3.2.2. The Optimization of Storage Tank Volume

According to Equation (2), the volume range of the storage tank is from 4217 to 5748 $m^3$. In order to analyze the operation effect of the storage facility of the project, the factor of safety β is 1.1 and 1.5, respectively. The volume of the storage tank is 4215 $m^3$ and 5748 $m^3$, respectively. The simulation results show that the inflow of volume of 4215 $m^3$ and 5748 $m^3$ storage tank stops at 19:00 and 19:21, respectively (Figure 7). However, the concentration of COD reaches peak value at 17:55 and drops to below 50 mg/L after 18:40. This part of stormwater belongs to the low concentration stormwater and can be directly discharged into the water body, which can reduce the volume of the storage tank and the operating load of WWTP. According to the simulation results, considering the factors of safety, economy, and environmental protection, the volume of the storage tank is selected as 4215 $m^3$.

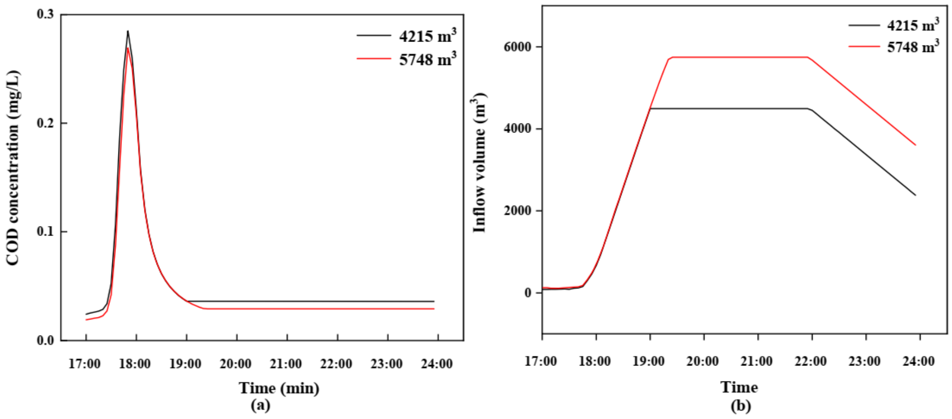


**Figure 7.** The optimization of storage tank volume: (**a**) The simulation of different storage tank volume on COD interception rate; (**b**) The simulation of different storage tank volume.

### 3.2.3. Analysis of Combined Sewer Overflows Pollution

According to the traditional interception-storage design, the operation flow is shown in Figure 8. With the rainfall, the water level of the intercepting weir increases gradually. When the water level reaches the requirement of the opening of the water-level based gate, the intercepting pipe will be filled with water. As the rainfall continues, the storage tank fills up, and the gates close. When the downstream municipal WWTP has a surplus capacity, the sewage pump will be used to drain the high concentration of stormwater in the storage tank.

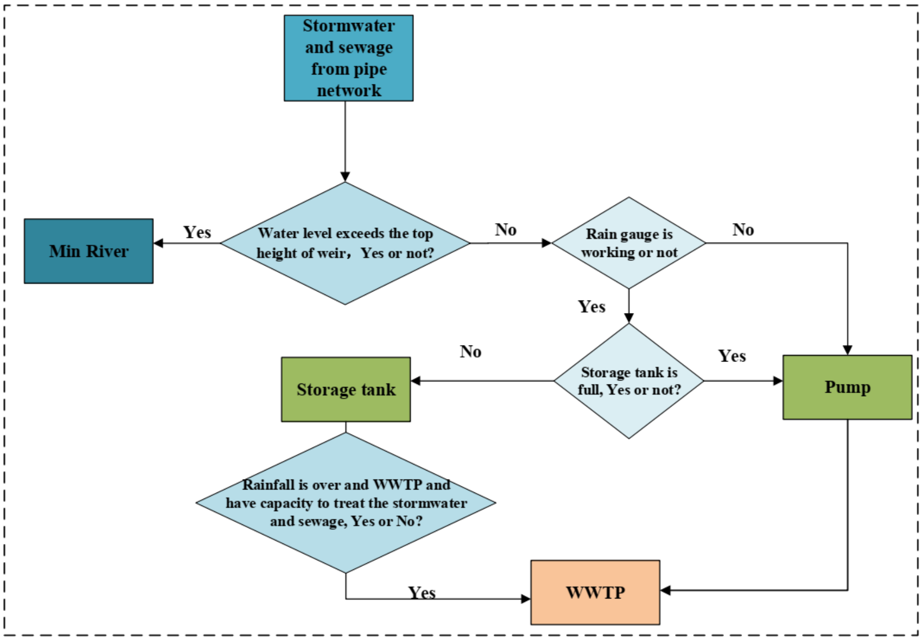


**Figure 8.** Working flow chart of traditional scheme.

After optimization, the traditional interception-storage tank capacity is shown in Figure 9. The influent COD concentration reaches peak value before 18:00. Although the intercepting pipe can intercept this part of the high concentration initial stormwater, a large part of the high concentration stormwater overflows into the water body, and the maximum concentration of COD in stormwater can reach 384.7 mg/L. In addition, the collected stormwater between 18:00 and 19:05 exhibits the COD concentration of less than 50 mg/L, which can be discharged into the water body, and the actual maximum flowrate of outfall can reach 15.23 $m^3/s$, which exceed the ability of intercepting pipe and storage tank. However, this stormwater is still collected by the traditional interception-regulation scheme, which results in the waste in the volume of the storage tank and the size of the WWTP.

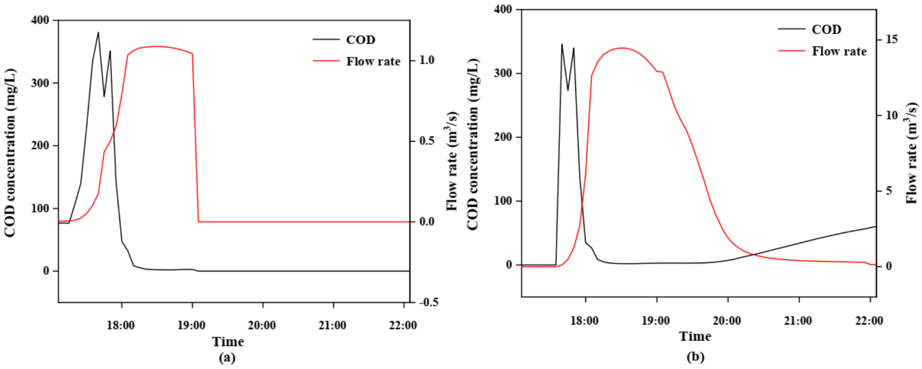


**Figure 9.** The simulation of traditional scheme: (**a**) COD interception of traditional scheme; (**b**) COD concentration of overflow of traditional scheme.

### *3.3. Double-Gate Storage Scheme Based on Water Quality*

#### 3.3.1. Workflow of Double-Gate Storage Scheme Based on Water Quality

After the traditional interception-storage tank simulation and the analysis of the pollution characteristics at the outfall, it can be found that the traditional interception-storage tank design cannot deal with the combined sewer overflows pollution problem under the designed rainfall conditions. In the outfall where the early stormwater erosion phenomenon is obvious [21], the traditional interception-storage tank design often neglects the variation of pollutants with the flow rate and focuses on the control of the flow rate, which leads to the unsatisfactory effect of the interception. Therefore, based on the above simulation, this section puts forward a water quality-based double-gate interception-storage strategy and formulate the corresponding RTC rules.

According to the study of Wei et al., (2019) [21], the COD concentration in this area has a good correlation with other water quality indexes and the early stormwater erosion phenomenon, so the COD concentration is selected as the index based on water quality control. On this basis, a double-gate storage scheme based on water quality was proposed. As shown in Figure 10, the schematic drawing of double-gate scheme was provided, which can help understand the difference of the traditional scheme and double-gate scheme. Firstly, the traditional overflow weir and inlet gate of the storage tank are transformed to the intelligent dispatching gate, which can be jointly controlled by the prediction and control analysis center. Secondly, the drainage model is installed at the remote terminal as the prediction and control analysis center. Thirdly, according to the concentration of COD monitored by the water quality sensor installed at the outfall, the influent of the outfall and the storage tank can be controlled in time according to the simulation results. At the same time, the system has the functions of sampling and rainfall monitoring, and the regulation is optimized gradually with the collection of water quality and rainfall data. According to the requirements of the A-class standard of discharge standard of pollutants for municipal wastewater treatment plant in China (GB 18918-2002), the concentration of COD in combined sewer overflows pollution is set to 50 mg/L.

In order to compare with the traditional interception-storage scheme, the facility arrangement and corresponding scale are unchanged in the scheme based on water quality, the length and height of the weir are still 3.3 m and 3 m, respectively. The diameter of the intercepting pipe is still 600 mm, the overflow weir is replaced by an intelligent dispatching gate of the same specification, which forms a double-gate dispatching system based on water quality with the inlet gate of the storage tank. The workflow of double-gate storage scheme based on water quality are described in Figure 11.

During the dry weather, the gate of the intercepting weir is closed, and during the dry weather, all the sewage is intercepted and diverted to the main municipal sewage pipe downstream. At the beginning of rainfall, the stormwater level of the intercepting weir gradually rises, the intercepting pipe water level rises with it, the inlet gate of the storage tank is opened inductively, the stormwater begins to enter the storage tank, and then the water quality sensing system begins to operate, when the COD concentration is less than 50 mg/L, the inlet gate of the storage tank is closed, and the interception weir gate is opened, and the low concentration stormwater is discharged into the receiving water body. At the later stage of rainfall, when the concentration of COD measured by water quality sensor is higher than 50 mg/L and the water level of the intercepting pipe is gradually reduced, the regulating gate of the intercepting weir is closed, and the sewage pump in the dry weather raised the excess sewage to WWTP downstream.

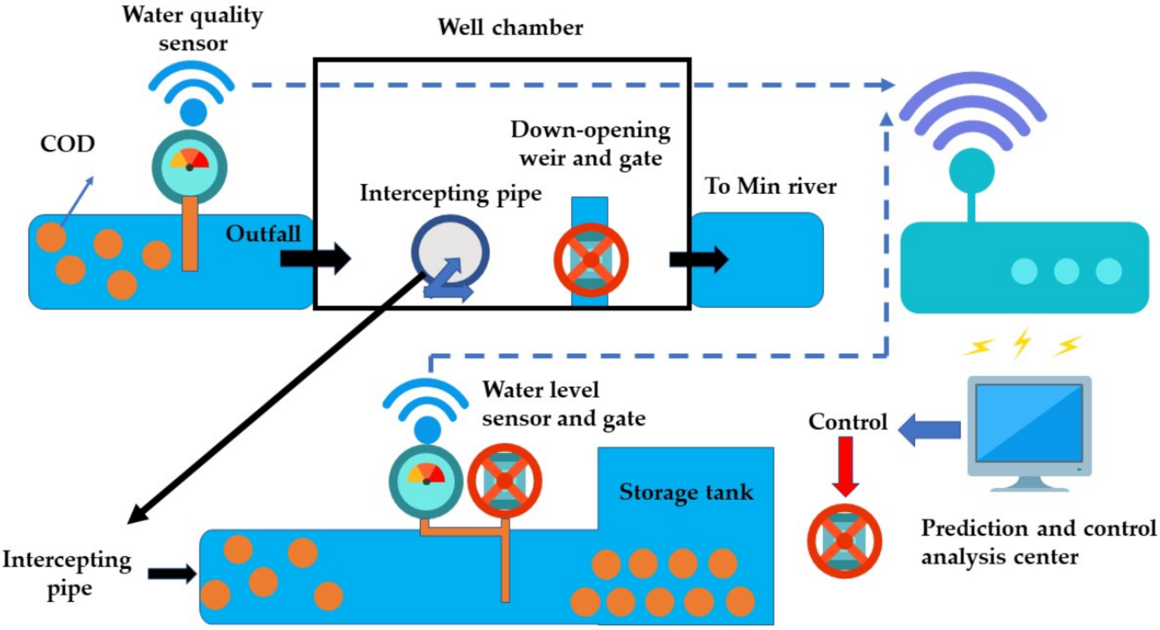


**Figure 10.** The schematic drawing of double-gate scheme.

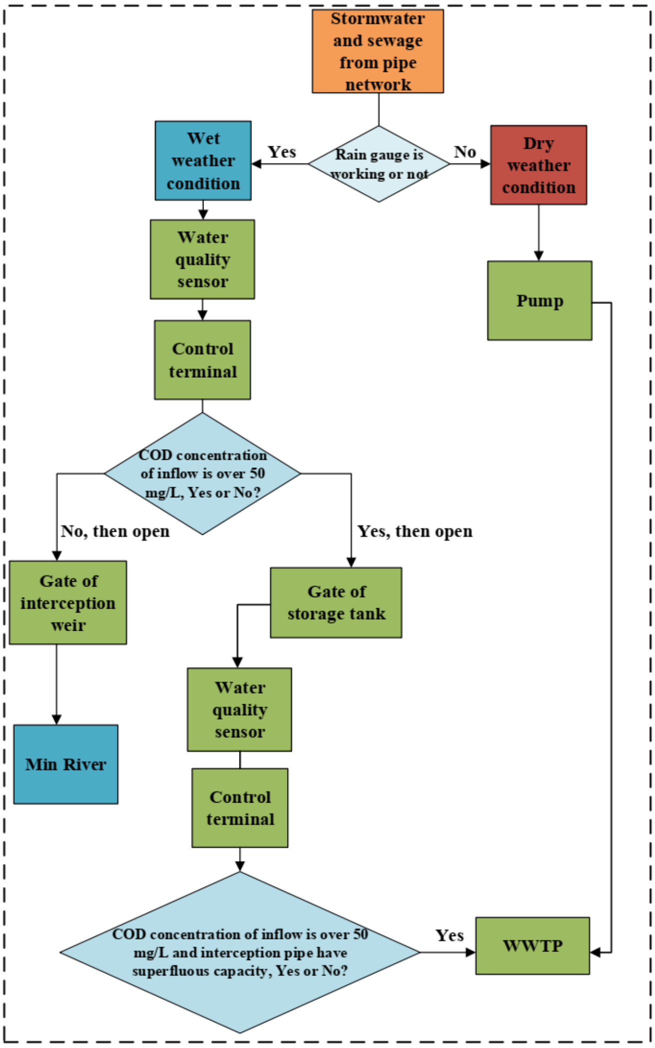


**Figure 11.** Working flow chart of double-gate scheme based on water quality.

### 3.3.2. Analysis of Combined Sewer Overflows Pollution of Double-Gate Storage Scheme Based on Water Quality

A total of 2643 $m^3$ water inflow was simulated, and then the volume of the storage tank was fitted out to be 2700 $m^3$. The storage tank volume of 1515 $m^3$ was reduced compared with the traditional optimization scheme. Comparing the influent flow rate of the storage tank with the COD pollution process curve (Figure 12a), it is found that when the COD concentration is reduced, the water quality-based double-gate storage system can immediately stop the interception, thus excluding the collection of low concentration combined sewage. As a result, the double-gate storage scheme based on water quality can significantly reduce the construction and operation costs of WWTP facilities.

At the same time, it can be found that the COD concentration in the whole interception process is higher and the average concentration of COD in the interception process is 181.9 mg/L, which is 138.1 mg/L higher than that in the traditional interception regulation and storage scheme, which is favorable for WWTP downstream. Comparing the interception curves of the two schemes, it is obvious that the PBRTC rules avoid the collection of a large number of low concentration stormwater. To sum up, the double-gate storage scheme based on water quality improves the concentration of the intercepting stormwater, which can increase the average COD interception rate compared to the traditional scheme by 1.84 times, and reduces the difficulty and cost of the treatment of the intercepting stormwater.

As shown in Figure 12b, the simulated curve of discharge and COD concentration of the overflow shows that the maximum concentration of COD is only 56.7 mg/L, which is about 328 mg/L lower than that of the traditional scheme, thus improving the pollution of outfall. According to the curve analysis, it is found that the discharge of COD exceeds the standard when the gate is opened, which is caused by the effect of the speed of the gate opening and closing. Therefore, the double-gate storage scheme based on water quality can significantly improve the pollution of outfall, which is of great significance in the developing countries where urban land is becoming increasingly scarce and low-carbon energy-saving is increasingly emphasized.

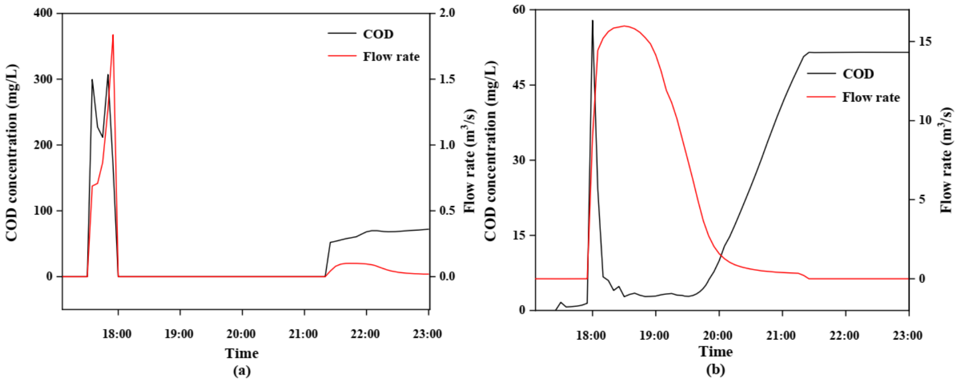


**Figure 12.** The simulation of double-gate scheme based on water quality: (**a**) COD interception of double-gate scheme based on water quality; (**b**) COD concentration of overflow of double-gate scheme based on water quality.

### 3.3.3. The Comparison of the Two Schemes

In order to better evaluate the effect of the traditional scheme and the double-gate scheme, the control effect of the end pollutant, the construction scale of the facility, and the pollutant concentration of the intercepting stormwater were discussed to evaluate the operation effect. First of all, when achieving the maximum effect of pollution control, the assessment section in practice often is set at the outfall to monitor the extent of pollutants over standard. Secondly, based on ensuring pollution control, the scale of construction should be reduced as far as possible, which can not only reduce the construction cost but also reduce the operating difficulty of the system. Finally, the cost of the downstream WWTP should be considered. When the concentration of pollutants in the intercepting pipe is too low and mixed with the original municipal sewage main pipe, the concentration of the WWTP influent will be too low, thus increasing the cost and difficulty of the sewage treatment. Therefore, the concentration of pollutants should be increased as much as possible.

The storage tank volume of the double-gate storage scheme based on water quality is only 2700 m$^3$, comparing with the traditional storage scheme, and the 1515–3048 m$^3$ of storage tank volume is reduced. By comparing the average intercepting COD concentration of the two schemes, it is found that the effect of the double-gate scheme is much better than that of the traditional scheme.

The interception rate of COD in the two schemes is calculated to evaluate the control effect of the interception scheme on the total pollution. The comparison of COD interception rate and overflow volume of COD concentration over 50 mg/L between the two schemes can be found in Table 5. The traditional interception scheme exhibits the COD interception rate of 27.41%, while the double-gate scheme based on water quality has the COD interception rate of 50.63%. Although the double-gate storage scheme based on water quality has greatly improved the interception rate and decreased overflow volume of COD concentration over 50 mg/L, there are still pollutants discharged out from the outfall. The construction of an interceptive combined drainage system at the end of the drainage channel cannot completely eliminate the discharge of pollutants, which needs a comprehensive method. The combination of grey and green measures for regional environmental pollution control can better achieve the effect of pollution prevention and control [31].

**Table 5.** The comparison of two schemes.

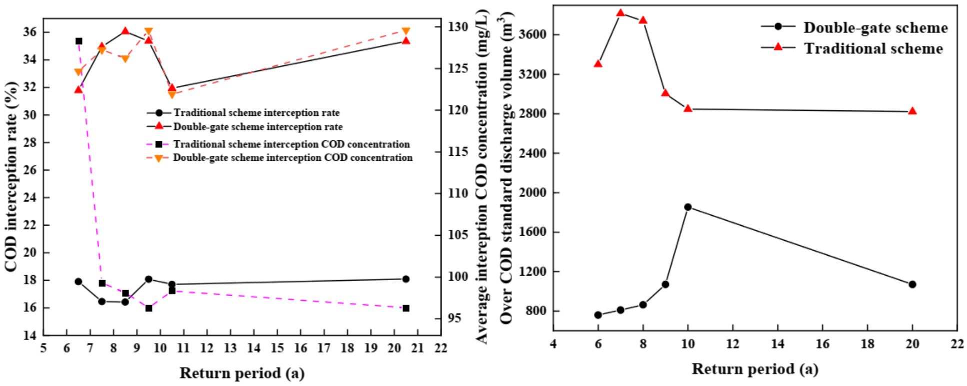
| Scheme | COD Interception Rate (%) | Overflow Volume of COD Concentration over 50 mg/L |
|---|---|---|
| Traditional scheme | 27.41 | 2163.17 |
| Double-gate storage based on water quality | 50.63 | 301 |

### *3.4. Analysis of Capacity of Double-Gate Storage Based on Water Quality and Traditional Scheme under Different Return Periods*

The performance of the double-gate scheme and the traditional scheme in different designs rainfall from two aspects, including the COD interception rate and average COD interception concentration, and the over-standard discharge of overflow were simulated.

From Figure 13a, it is easy to find that the COD interception rate of the double-gate scheme is higher than 30% under the designed rainfall. Under the rainfall of less than 10 years, the double-gate scheme shows a trend of increasing and then decreasing. Under the rainfall of 8 years return period, the COD interception rate can reach 36.06%. When the return period is larger than 10 years, the COD interception rate of the double-gate scheme increases with the increase of the return period. For the traditional scheme, the COD interception rate decreases first and then increases when the rainfall is less than 10 years, and the COD interception rate remains between 16.42% and 17.90%. The change of COD interception rate reduces when the rainfall is more than 10 years. On the other hand, the average COD interception concentration of the double-gate scheme varies little in the return period of 6–9 years, and the average COD interception concentration remains in the range of 124.66–129.57 mg/L. However, in the return period of more than 10 years, the average interception concentration shows a trend of gradually increase. In general, the traditional scheme shows a decreasing trend of average interception concentration with the increased return period, which may be related to the control rule of the traditional scheme. The traditional scheme takes the water level as the control index, and the water level increases rapidly with the increase of return period, the gate will be opened to intercept low concentration stormwater.

As can be seen in Figure 13b, the overflow volume of the double gate scheme increases at first and then decreases. The maximum overflow volume is only 1854.42 m$^3$, which is only half of the maximum overflow volume of the traditional scheme. The results show that the double-gate scheme has advantages in controlling over-standard overflow, which can reduce combined sewer overflows pollution.



(a)

(b)

**Figure 13.** The simulation of double-gate scheme based on water quality and traditional scheme under different return periods: (**a**) COD interception rate and average COD concentration interception rate; (**b**) Overflow volume of COD concentration over 50 mg/L.

## 4. Conclusions

In order to reduce the pollution caused by the overflow of stormwater and improve the concentration of intercepted stormwater, a two-dimensional drainage network model was established by using InfoWorks ICM and ArcGIS software, taking the drainage network of Fuzhou as an example. The results are as follows:

Using the validated and calibrated model, the diameter of the intercepting pipe of the traditional scheme was 600 mm and the volume of the storage tank was 4215 $m^3$. Simulation and optimization of interception rate and over-standard overflow volume control capacity of traditional scheme was evaluated. The results show that the COD interception rate of the traditional scheme is only 27.41%, and the over-standard volume of overflow reaches 2163.7 $m^3$.

Based on the rule of PBRTC, a double-gate control scheme based on COD concentration was proposed and its interception rate and over-standard overflow volume control capacity were evaluated. The results show that the COD interception rate can reach 50.63% and the over-standard overflow volume can reach 301 $m^3$. Although the double-gate scheme can effectively reduce over-standard overflow volume, some over-standard stormwater still entered the water body. Therefore, only relying on the end of the interception-storage measures cannot completely solve the problem of combined sewer overflows pollution, the future research needs the combination of gray-green measures to solve the problem. The two schemes were compared under the same rainfall event. The double-gate scheme has better performance than the traditional scheme. Firstly, the storage volume was reduced, and the double-gate scheme only needed a volume of 2700 $m^3$, which can effectively reduce the investment cost. Secondly, compared with the traditional scheme, the COD interception rate of the double-gate scheme was increased by 23.22%, and the volume of over-standard overflow was reduced by 1862.7 $m^3$.

The performance of the two schemes were also studied under rainfall in the beyond design standard return period. Firstly, from the aspect of COD interception rate, two schemes show different trends under design rainfall, which less than 10 years return period. The ranges of COD interception of the double-gate scheme and traditional scheme were 31.78%–36.05% and 16.42%–17.90%, respectively. When the return period of rainfall was larger than 10 years, the COD interception rate of the double-gate increased with the increase of rainfall return period and that of traditional scheme show a stable trend. For average COD interception concentration, the range of double-gate scheme was between 124.66–129.57 mg/L under design rainfall, which is less than 10 years return period, and it shows an increasing trend when rainfall return period increased. In contrast, the traditional scheme shows the decreasing trend when the rainfall return period increased. Secondly, for over-standard overflow volume, the maximum overflow volume of double-gate scheme is only 1854.42 m$^3$, which is only half of the maximum overflow volume of the traditional scheme. In conclusion, the double-gate scheme has a better performance than the traditional scheme under the design rainfall period or beyond the design rainfall period.

**Author Contributions:** Z.W. organized the framework of the article, experiments and wrote the paper. H.S., J.Z., and R.L. processed the experimental data and modified the article. X.H., and L.L. contributed to the collection and collation of experimental data and participated in the writing of the paper. H.L. organized experiments and provided ideas for improvement, B.D. was helpful in polishing language and improved text layout. G.F. conceptualization, methodology design, organized experiments writing—review & editing. All authors have read and agreed to the published version of the manuscript.

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