Research on the Influence of Different Working Conditions of Wastewater Treatment Plants on Water Quality of Guanlan River Main Stream

Tao Zhou[1,2,3], Xiaoqi Zhang[1,2,3], Shuai Xie[1,2,3], and Yongqiang Wang[1,2,3,*]
[1]*Changjiang River Scientific Research Institute, Changjiang Water Resources Commission of the Ministry of Water Resources of China, Wuhan 430010, China*
[2]*Hubei Key Laboratory of Water Resources & Eco-Environmental Sciences, Changjiang River Scientific Research Institute, Wuhan 430010, China*
[3]*Research Center on the Yangtze River Economic Belt Protection and Development Strategy, Hubei Wuhan 430010, China*

Keywords: Guanlan River, Working conditions of overflow and water supplement, Water quality simulation calculation, Water pollution control

Abstract: The operation condition of wastewater treatment plants has great influence on river water quality. Different simulated working conditions of overflow and water supplement in Guanlan River Basin were established in this study according to the sewage treatment capacity of decentralized sewage treatment facilities in the basin and water purification capacity of water purification engineering for Guanlan estuary storage pond. A hydrodynamic and environment mathematical model for Guanlan River mainstream was developed, using pollution indicators like COD, NH3-N and TP concentrations to quantitatively analyze the water quantity and quality of the basin under different working conditions overflow and water supplement and to simulate the water quality changes in the main under the different operating conditions. The calculation results show that: (1) If there were only one overflow point and the overflow volume does not exceed 30,000 m3/d, the water quality of Qiping Section can meet the assessment requirements; (2) If overflow occurs at both overflow points, the water quality of Qiping Section meets the assessment requirements only when the overflow volume downstream the Guanlan plant does not exceed 20,000 m3/d and the overflow volume upstream the terminal gate does not exceed 15,000 m3/d; (3) The concentrations of COD, NH3-N and TP along the main stream are obviously lower under all working conditions of water supplement. This research is expected to provide scientific basis for water pollution control of Guanlan River Basin.

1 INTRODUCTION

In city regions of China, rivers are exposed to heavy pollution due to the large proportion of impermeable areas, complex production activities and diverse pollution sources. With the continuous improvement of wastewater collection and interception systems in city regions and the higher construction standard raised for wastewater treatment plants over the years, the pollution sources have been well controlled, and the influence of different operating conditions of wastewater treatment system on river water quality has become increasingly prominent. So, it is urgent to study the effect of different operating conditions of urban wastewater treatment plants on river water quality, so as to provide data support for further improvement of urban river water quality.

Hydrodynamics is the basis for studying the evolution of river flow. The two main methods commonly adopted for researching on hydrodynamics are mathematical statistics and mathematical model simulation (Sun et al., 2017; Huang et al., 2015; Shchepetkin & Mcwilliams, 2005). With the development of computer technology, mathematical model methods have gradually been applied to different disciplines. Numerical simulation software has also been widely applied, and commonly used simulation software includes EFDC, ROMS, FVCOM, MIKE, etc. (Chen et al., 2003; Yuan & Xu, 2006; Zuo & Li, 2013). Numerical model methods have also been widely used in water quality simulation of rivers and lakes (Jorgensen et al., 2005; Huang et al., 2010; Beletsky et al., 2006).

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However, previous studies mainly focus on the investigation of point-source and non-point source pollution in cities (Cheng et al., 2017), based on which empirical equations were used for some estimates that later became the input conditions of hydrodynamic models. Wang et al. (2014) estimated the loads of NH_3-N, COD, TN and TP in the annual rainfall runoff pollution in Neijiang City by studying the rainfall event mean concentrations in different underlying surfaces of Neijiang City; Yang et al. (2021) and Yang et al. (2015) estimated the loads of pollutants such as SS and COD of urban non-point source pollutants in Beijing by the event mean concentration statistics method. Chen et al. (2020) selected Shenzhen Guanlan River Basin as the research object, and built an evaluation model of urban non-point source pollution in the basin through field investigation and a study on surface accumulation samples. According to the pollution status of Guanlan River, the causes of water pollution and the local watershed planning, Zhang et al. (2018) put forward new water pollution control measures and built a flow and water quality coupling model to quantitatively analyze the water environment improvement effect of those measures. With the continuous improvement of the construction of urban wastewater treatment system and the increasing influence of different operating conditions of wastewater treatment plants on the water quality of rivers in cities, more and more studies show that working conditions of wastewater treatment system have an important impact on river water quality (Jia et al., 2021; Cho et al., 2020; Xiang et al., 2018; Xiong et al., 2017). However, the above researches did not consider the working conditions of wastewater treatment systems in detail. The lack of consideration of working conditions of wastewater treatment systems in previous studies limits the accurate simulation of urban river water quality, or makes it hard to provide comprehensive support for developing urban water pollution control schemes. Different from the above researches, this paper focuses on the simulation of different working conditions of wastewater treatment system so as to quantitatively analyze the influence of different working conditions of wastewater treatment system on river water quality.

In response to the insufficient consideration of different operating conditions of wastewater treatment system in previous studies, different working conditions of overflow and water supplement in Guanlan River Basin were established according to the current decentralized wastewater treatment facilities in the basin and the actual operating conditions of water purification engineering for Guanlan estuary storage pond. A hydrodynamic and hydrographic environment mathematical model for Guanlan River main stream was built, using pollution indicators like COD, NH_3-N and TP concentrations to quantitatively analyze the water quantity and quality of the basin under different working conditions overflow and water supplement, and to simulate the water quality changes in Guanlan River main stream under different operating conditions. The model is expected to provide scientific basis for water pollution control of Guanlan River Basin.

2 OVERVIEW OF STUDY AREA

2.1 Natural Conditions

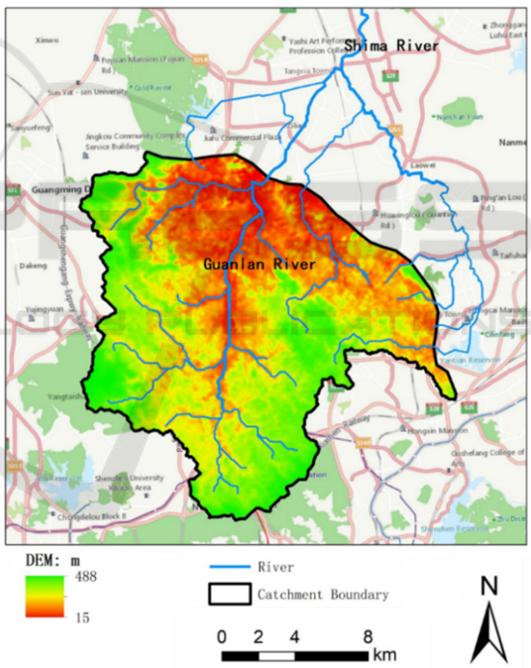


Figure 1: Geographical location of Guanlan River Basin.

Located in the north-central part of Shenzhen, Guanlan River Basin is the upstream section of Shima River in Dongjiang River system (Figure 1). The river basin originates from Jigongtou region of Niuzui Reservoir in Danaoke Mountain, Minzhi Sub-district. Its main stream passes through Longhua New District from south to north, and then enters Dongguan City through Qiping Village, Guanlan Sub-district. The rainwater catchment area above the junction between

Shenzhen and Dongguan is 196.4 km^2, and the river length is 14.2 km (excluding the main source, Yousong River). Then, the Guanlan River leaves Shenzhen, merges into other tributaries and forms Shima River in Tangxia Town, Dongguan City, and further merges into Dong River at the boundary of Dongguan and Huizhou. Apart from Guanlan River, Shima River system contains additionally five independent tributaries in Shenzhen, i.e., Niuhu River, Junzibu River, Shanxia River, Egongling River and Mugu River, all of which join Shima River in Dongguan City.

Guanlan River Basin involves 31 rivers of different sizes, serving as drainage channels for floods from Guanlan River Basin and urban rainwater, and playing a role of flood control and urban drainage together with reservoirs, drainage pumping stations and rainwater drainage culvert systems in the basin. There are 6 independent rivers, i.e., Guanlan River, Junzibu River, Niuhu River, Shanxia River, Egongling River and Mugu River and 14 first-class tributaries of Guanlan River Basin, of which only Guanlan River has a catchment area larger than 100 km^2.

2.2 Current Problems

The recently expanded wastewater treatment plants in Guanlan River Basin will gradually be put into operation, and then the source clean-up and rain-wastewater diversion works will be further promoted and optimized, which can significantly lower the risk of wastewater overflow in Guanlan River Basin. Before the completion of the annual construction target, however, the following problems may still exist in the water quality compliance of Guanlan River Basin:

(1) Insufficient wastewater treatment capacity in the basin

The daily average water discharge of Guanlan River is about 10^6 m^3/d according to the hydrological monitoring results at Qiping Section in November 2018. The total treatment capacity of the in-service water purification plants and decentralized wastewater treatment plants has reached 1.18×10^6 m^3/d by now. Limited by factors such as changes in peak of incoming water, sludge disposal and equipment maintenance, however, the actual daily treatment capacity of wastewater treatment facilities in the basin may fluctuate from 8×10^5 to 10^6 m^3, which means there is a possible risk of wastewater overflow.

The existing wastewater treatment plants in the basin are estimated to be standard raised and capacity expanded by 2019. By that time new plants (e.g. Minzhi plant) are anticipated to be completed and put into operation, and expected to raise the designed wastewater treatment capacity in the basin to 1.33×10^6 m^3/d, which is higher than the drainage volume of the basin in November 2018 (dry season), and basically meets the needs of wastewater treatment during the dry season. Nevertheless, it is still possible that a single-day or instantaneous wastewater inflow exceeds the designed treatment capacity when considering the social and economic development, maintenance and shutdown of wastewater plants and other factors.

(2) Defective interception box culvert system

The existing box culverts of the Guanlan River main stream were built on a basis of 7 mm initial and small rainwater. The intercepting pipes along the river of tributaries are built with the interception ratio was set 2-5. The initial and small rainwater system, however, was not separated from the wastewater system. As a result, the box culvert is prone to siltation and overflow. In addition, the interception capacity of the main stream does not match that of tributaries, making the tributary box culvert easy to overflow.

(3) Low operation efficiency of storage ponds

Currently there are 2# (Longhua) storage pond (volume of 25,900m^3), 3# (Guanlan) storage pond (volume of 220,000m^3) and 4# (estuary) storage ponds (volume of 220,000m^3) in Guanlan River Basin. However, the design objectives of each storage pond are not clear, resulting in low efficiency of initial rainwater storage. There is a lack of effective system linkage between the dispatching scheme of storage ponds, interception box culverts and wastewater plants.

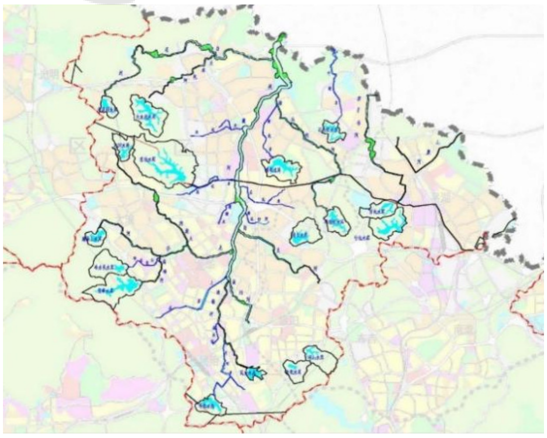


Figure 2: River system distribution of Guanlan River Basin.

To tackle the above problems and assure the continuously up-to-standard water quality of Guanlan River, it is urgent to establish a flow and water quality model for Guanlan River main stream based on the current situation of plants, networks, rivers, stations and ponds in the basin, to calculate and analyze the water quality changes in the main stream of Guanlan River, so as to provide a basis for wastewater control and making dispatching plans for water quantity and quality in Shenzhen Guanlan River Basin.

3 GUANLAN RIVER MAIN STREAM FLOW AND WATER QUALITY MODELING

Guanlan River is considered as a relatively smooth river as its gradient of the main stream is 1.2‰. The water bodies are mixed vertically and evenly and are distributed unevenly in the spatial plane. For this reason, the depth-averaged two-dimensional mathematical equation was adopted to describe the movement characteristics of water flow and quality in the main stream of Guanlan River in order better to reveal the overall change characteristics of water flow and quality in the study area and meet the actual demand. Through analysis, this study tends to build a mathematical model for Guanlan River main stream water environment based on MIKE21.

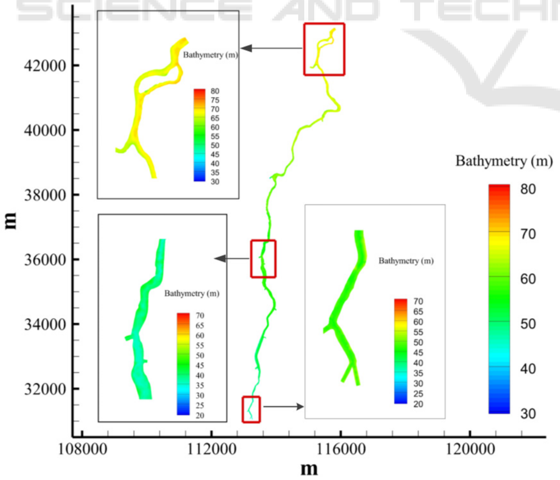


Figure 3: Underwater topographic map.

3.1 Calculation Area and Underwater Topography

There are 14 first-class tributaries and 5 independent tributaries (directly entering Dongguan) in the basin. The length of the main stream is about 17 km. See Figure 2 for the river system. Through field investigation and monitoring data analysis, the calculation area of Guanlan River main stream model includes all areas of Guanlan River main stream. The underwater topography after generalization of the model is shown in Figure 3. Due to the irregular boundary shape of Guanlan River, it is suggested to adopt unstructured grid (triangular grid) for division and enhance the calculation stability of the mathematical model. The x represents the east direction, the y represents the north direction, and the coordinate value is the length. The model involves 2750 nodes and 3835 computational grids (Figure 4).

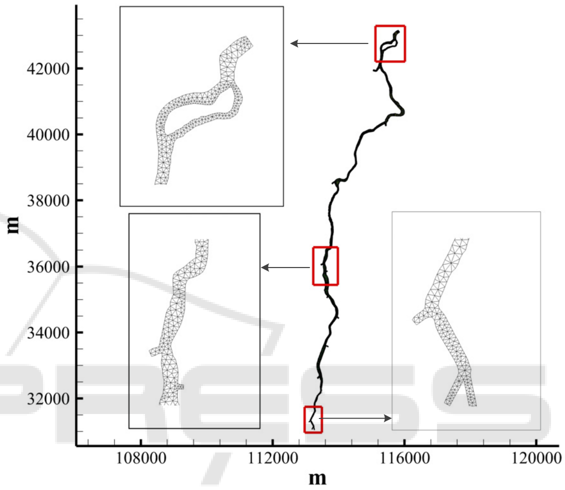


Figure 4: Grid division chart.

3.2 Calibration and Verification of Model Parameters

3.2.1 Hydrodynamic Parameters

1) Calibration of hydrodynamic parameters
According to the field investigation and the study results in similar areas, the initial roughness of Guanlan River main stream n is assumed as 0.033 for calculation, and the eddy viscosity coefficient is determined according to Smagorinsky equation.

2) Verification of hydrodynamic parameters
The measured daily hydrology and other basic data of Guanlan River main stream were used as the input of the constructed model for simulation calculation. The model was verified by the water level data of Qiping Section at the exit of Guanlan River main stream. The comparison between the calculated water level process (from January 1, 2019 to May 31, 2019) of Qiping Section at the exit of Guanlan River main stream and the measured water level change process is shown in Figure 5.

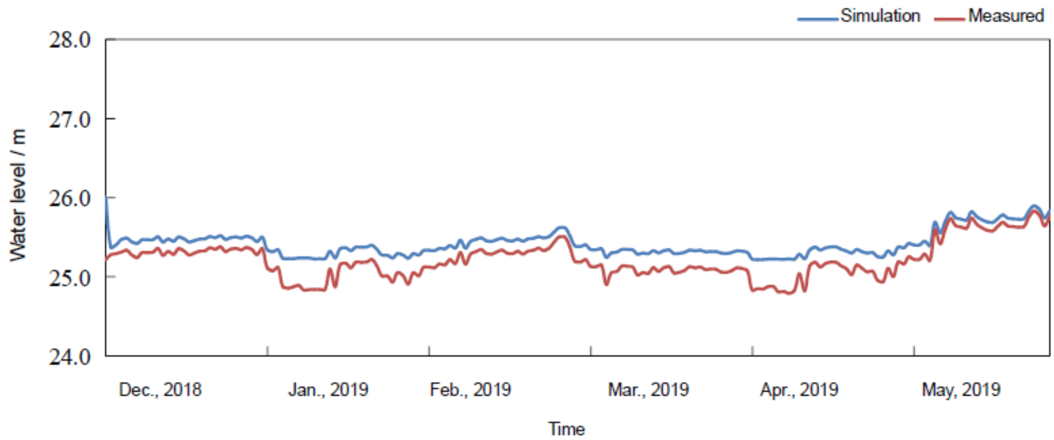


Figure 5: Comparison between the simulated and measured water levels in Qiping Section

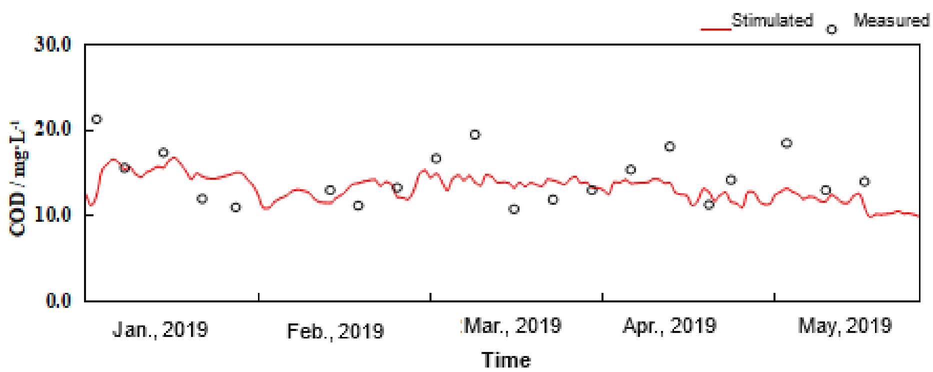
3.2.2 Water Quality Parameters

1) Calibration of water quality parameters

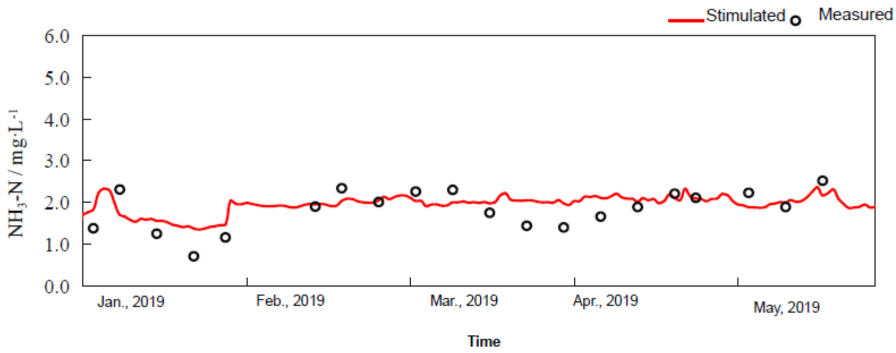
From the monitored water quality data from January 1, 2019 to May 31, 2019, combined with the study results in similar areas, it can be concluded that the comprehensive degradation coefficients of COD, NH_3-N and TP in Guanlan River are 8.0 e^{-8}/s, 1.0 e^{-8}/s and 1.0 e^{-8}/s, respectively.

2) Verification of water quality parameters

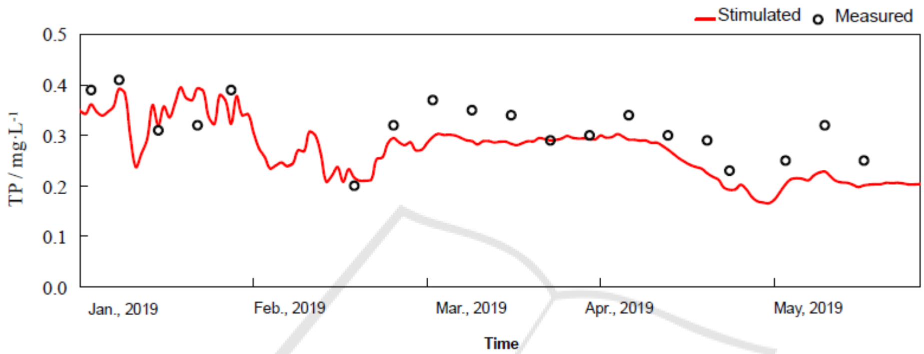
Available data indicates that overflow occurred all the time except for 4 days in the first 21 days in March, 2019. During the rainfall period, the facilities in Guanlan River Basin are unable to fully receive the mixed flow of rain and wastewater at peak, and the wastewater interception system may overflow to the river channel, resulting in the deterioration of the water quality of main streams and tributaries and the unstable daily water quality monitoring data of each tributary estuary. This makes it difficult to calibrate the water quality model. The measured daily hydrology and other basic data of Guanlan River main stream were used as the input of the constructed model for simulation calculation, and the main monitoring data of Guanlan River were used for verification. The water quality data of four monitoring points, i.e., Qinghu Bridge, Meiguan Expressway, Fangmapu and Qiping Section along Guanlan River and 11 first-class rivers of Guanlan River from January 1, 2019 to May 31, 2019 were simulated and calculated by the model. See Figure 6 for comparison between the simulated process of main water quality (COD, NH_3-N, TP) and the measured water quality change process (e.g., Qiping Section of the main stream). The water quality process of Guanlan River (COD, NH_3-N and TP) simulated by the water quality model is well consistent with the measured values, demonstrating the constructed water quality model well reflects the migration and diffusion law of pollutants in Guanlan River. Therefore, the model can be used for water environment simulation and analysis in lake regions along Guanlan River main stream.



(a) Comparison between the simulated and measured COD concentrations in Qiping Section of main stream



(b) Comparison between the simulated and measured values of NH_3-N concentration in Qiping Section of main stream



(c) Comparison between the simulated and measured TP concentrations in Qiping Section of main stream

Figure 6: Comparison between the simulated and measured water quality of Qiping Section of main stream.

4 ANALYSIS OF MAIN STREAM WATER QUALITY CHANGES UNDER DIFFERENT OVERFLOW CONDITIONS

4.1 Assumption of Different Overflow Conditions

According to the analysis of wastewater treatment capacity of Guanlan River, the daily wastewater treatment capacity of Guanlan River Basin wastewater treatment plant varies from 701,500–1,234,700 tons under the current conditions (January 1–July 31, 2019), while the daily wastewater treatment capacity of Guanlan River Basin wastewater treatment plant is 1,075,000 tons under the current conditions. It can be concluded that the wastewater treatment facilities basically meet the needs of basin wastewater treatment under the current conditions. Field investigation shows that there are mainly two overflow points in the main stream of Guanlan River, i.e., the overflow point downstream the Guanlan water purification plant and the terminal culvert gate overflow point. When the wastewater treatment plants in Guanlan River Basin reduce production or stop production, the wastewater to be treated will be transferred to the downstream through the main stream culvert. When it exceeds the box culvert capacity in the Guanlan estuary storage pond water purification project, the wastewater to be treated will continue to fill the box culvert, and the wastewater in culvert pipes will be forced to the vicinity of Guanlan water purification plant and overflow to the main stream of Guanlan River, as shown in Figure 7.

Table 1: Assumption of overflow conditions in Guanlan River main stream.

Operating conditions	Downstream the Guanlan water purification plant ($\times10^4$ m^3/d)	Terminal culvert gate ($\times10^4$ m^3/d)
Condition 1	3	2
Condition 2	2	1.5
Condition 3	3	3
Condition 4	3	0
Condition 5	10	0
Condition 6	18	0
Condition 7	16	0
Condition 8	14	0
Condition 9	0	15
Condition 10	0	14
Condition 11	0	13
Condition 12	0	19
Condition 13	0	18
Condition 14	0	16

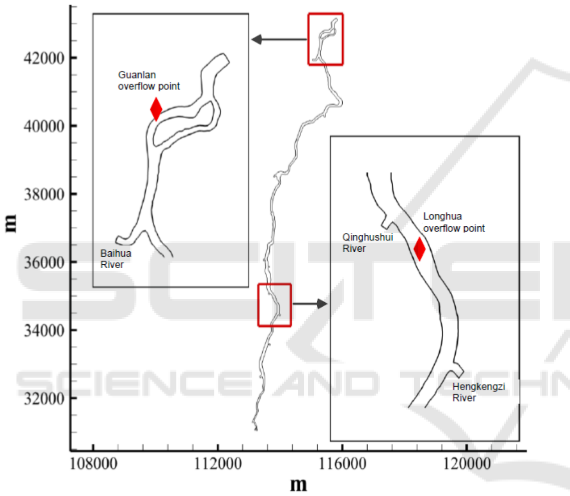
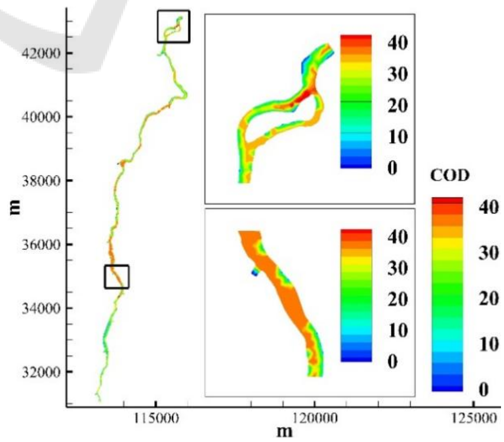


Figure 7: Location of overflow points of Guanlan River main stream.

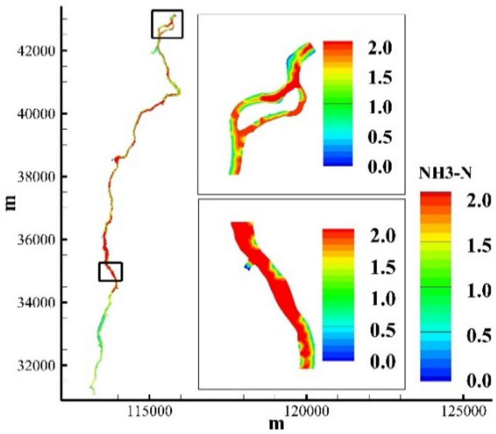
4.2 Analysis of Water Quality Changes in Qiping Section of Guanlan River under Different Overflow Quantities

Based on the hydrodynamic and water environment mathematical model built in Section 3, the flow and water quality changes in Guanlan River main stream under those 14 conditions (as shown in Table 1) were simulated, respectively. The water quality of Guanlan River main stream and Qiping Section under each condition was subsequently analyzed according to the simulation results. Conditions 1, 4 and 9 are used for specific explanation, while the calculation results of other conditions are shown in Table 2. Figures 8–10 show the pollutant distribution of Longhua and Qiping Sections under each condition.

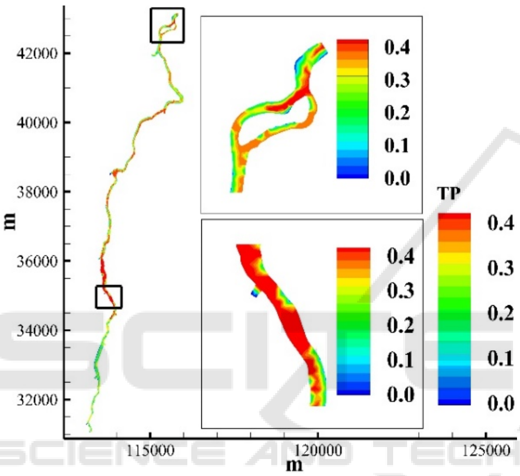
(1) Condition 1 represents all wastewater treatment plants whose effluent is discharged into the main stream of Guanlan River operate normally according to the designed capacity, and indicates the water quality changes in the section downstream the Guanlan water purification plant when overflow occurs, both at the overflow point downstream the Guanlan water purification plant and at the overflow point of the terminal culvert gate (Figure 8). Under Condition 1, COD, NH_3-N and TP concentrations in overflow point downstream the Guanlan water purification plant are 36.59 $mg \cdot L^{-1}$, 2.18 $mg \cdot L^{-1}$ and 0.40 $mg \cdot L^{-1}$, while COD, NH_3-N and TP concentrations in Qiping Section are 37.22 $mg \cdot L^{-1}$, 2.26 $mg \cdot L^{-1}$ and 0.41 $mg \cdot L^{-1}$. The water quality of Guanlan River main stream is Inferior-to-Class V.



a) COD distribution under Condition 1



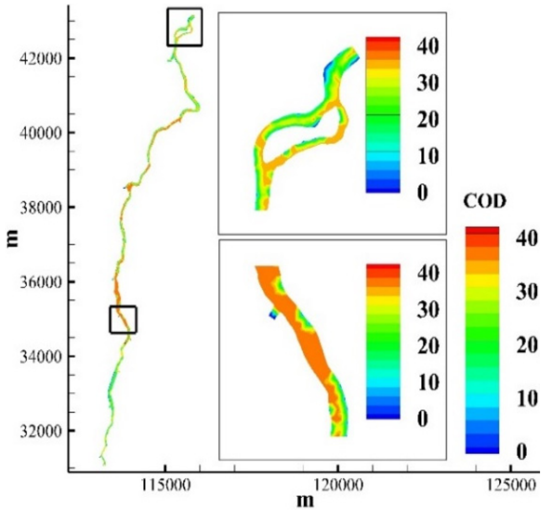
b) NH3-N distribution under Condition 1



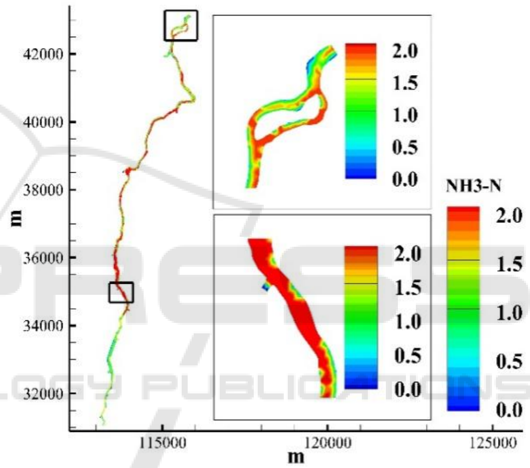
c) Figure 8c. TP distribution under Condition 1

Figure 8. Pollutant distribution under Condition 1.

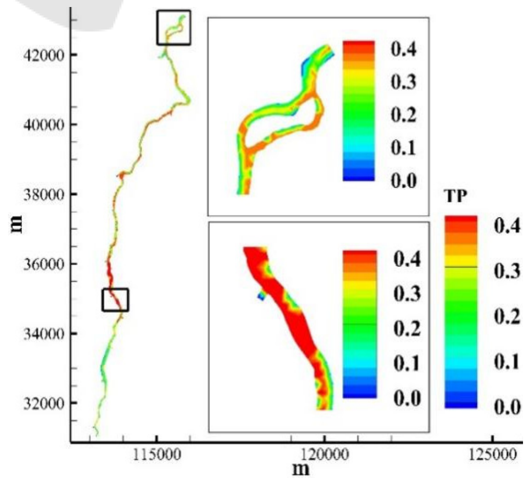
(3) Condition 9 represents all wastewater treatment plants whose effluent is discharged into the main stream of Guanlan River operate normally according to the designed capacity, and indicates the water quality changes in the section downstream the Guanlan water purification plant when overflow does not occur at the overflow point downstream the Guanlan water purification plant but occurs at the overflow point of the terminal culvert gate (Figure 10). Under Condition 9, COD, NH_3-N and TP concentrations at overflow point downstream the Guanlan water purification plant are 30.57 $mg \cdot L^{-1}$, 1.53 $mg \cdot L^{-1}$ and 0.31 $mg \cdot L^{-1}$. COD, NH_3-N and TP concentrations in Qiping Section are 39.72 $mg \cdot L^{-1}$, 2.43 $mg \cdot L^{-1}$ and 0.45 $mg \cdot L^{-1}$. The water quality of Guanlan River main stream is Inferior-to-Class V.



a) COD distribution under Condition 4

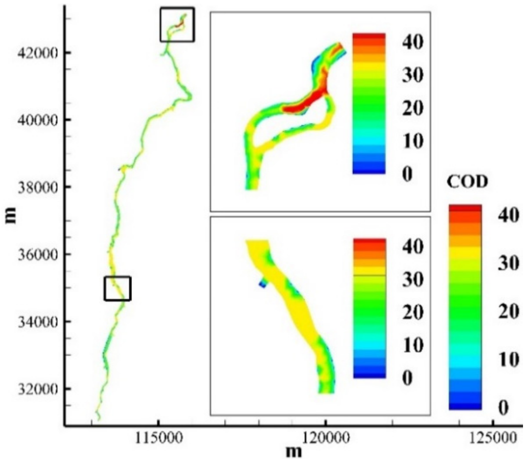


b) NH3-N distribution under Condition 4

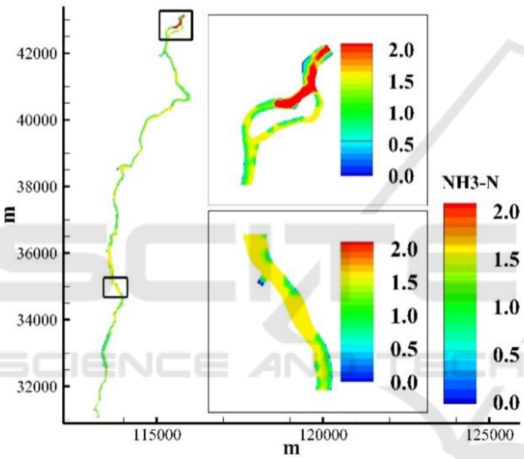


c) TP distribution under Condition 4

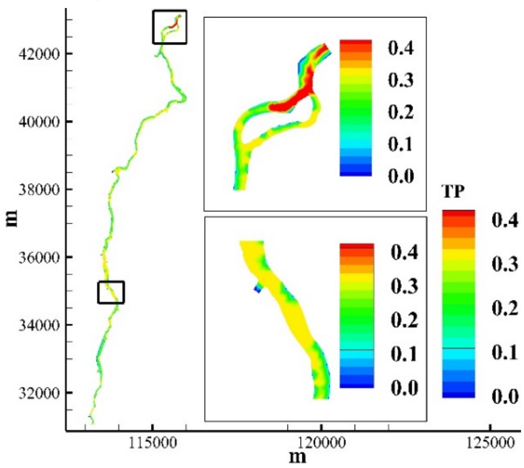
Figure 9: Pollutant distribution under Condition 4.



a) COD distribution under Condition 9



b) NH3-N distribution under Condition 9



c) TP distribution under Condition 9

Figure 10: Pollutant distribution under Condition 9

As shown in the table above, the calculation results show that: (1) If overflow only occurs at the overflow point downstream the Guanlan water purification plant and the overflow volume does not exceed 30,000 m^3/d, the water quality of Qiping Section can meet the assessment requirements; (2) If overflow only occurs at the overflow point upstream the terminal gate and the overflow volume does not exceed 30,000 m^3/d, the water quality of Qiping Section can meet the assessment requirements; (3) If overflow occurs at both overflow points, the water quality of Qiping Section meets the assessment requirements only when the overflow volume downstream the Guanlan plant does not exceed 20,000 m^3/d and the overflow volume upstream the terminal gate does not exceed 15,000 m^3/d.

5 ANALYSIS ON THE INFLUENCE OF THE GUANLAN STORAGE POND WATER PURIFICATION PROJECT ON WATER QUALITY OF THE MAIN STREAM

5.1 Working Conditions Setting of Water Supplement at Different Junction of Main and Tributaries

Referring to the water supplement planning of Longhua District, five working conditions of water supplement are assumed to analyze the influence of water supplement at the main stream/tributaries confluences in the middle and lower reaches of Guanlan River on the change of water quality in the main stream. See Table 3 for details.

Table 2: Analysis of water quality at the overflow points.

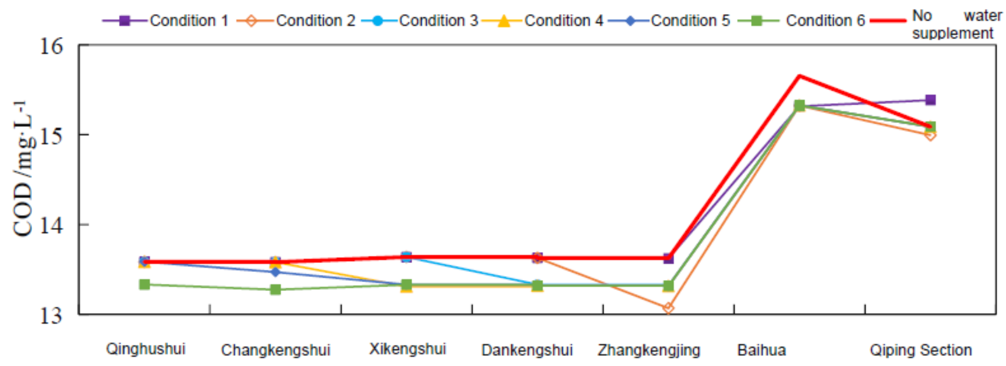
Water quality analysis	Overflow point downstream the Guanlan water purification plant				Qiping Section			
	COD	NH_3-N	TP	Water standard	COD	NH_3-N	TP	Water standard
Condition 1	36.59	2.18	0.40	Inferior-to-Class V	37.22	2.26	0.41	Inferior-to-Class V
Condition 2	34.62	1.96	0.37	Class V	36.20	2.00	0.39	Class V
Condition 3	36.59	2.18	0.40	Inferior-to-Class V	39.07	2.47	0.40	Inferior-to-Class V
Condition 4	40.44	2.72	0.46	Inferior-to-Class V	44.51	3.13	0.53	Inferior-to-Class V
Condition 5	50.28	4.30	0.67	Inferior-to-Class V	41.36	3.13	0.52	Inferior-to-Class V
Condition 6	46.02	3.69	0.59	Inferior-to-Class V	38.86	2.75	0.46	Inferior-to-Class V
Condition 7	42.31	3.05	0.49	Inferior-to-Class V	36.71	2.36	0.41	Inferior-to-Class V
Condition 8	38.53	2.39	0.43	Inferior-to-Class V	34.59	1.98	0.37	Class V
Condition 9	30.57	1.53	0.31	Class V	39.72	2.43	0.45	Inferior-to-Class V
Condition 10	30.57	1.53	0.31	Class V	37.89	2.23	0.42	Inferior-to-Class V
Condition 11	30.57	1.53	0.31	Class V	36.02	2.03	0.39	Inferior-to-Class V
Condition 12	30.57	1.53	0.31	Class V	46.74	3.30	0.56	Inferior-to-Class V
Condition 13	30.57	1.53	0.31	Class V	45.02	3.11	0.53	Inferior-to-Class V
Condition 14	30.57	1.53	0.31	Class V	41.50	2.73	0.48	Inferior-to-Class V

Table 3. Assumption of water supplement conditions at different main stream/tributaries confluences

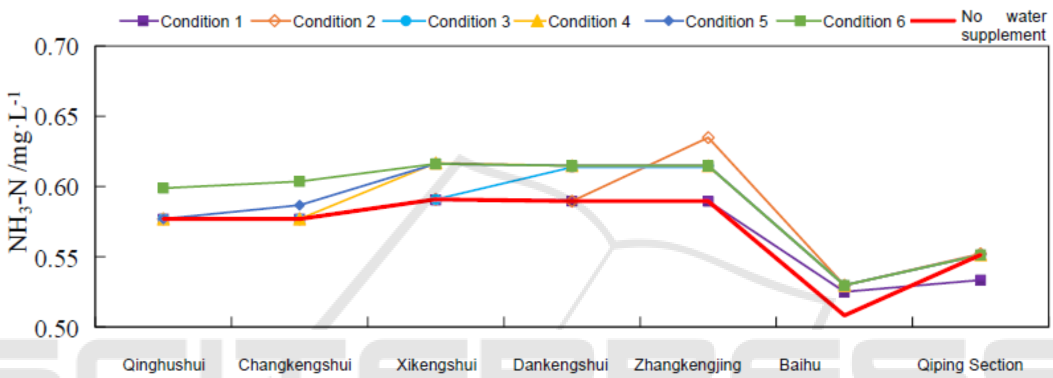
Condition	Additional point of main stream/tributary estuaries	Additional water volume ($\times 10^4$ m^3/d)
1	Baihuashui River	5
2	Zhangkengjing River	6
3	Dankengshui River	2
4	Xikengshui River	2
5	Changkengshui River	4
6	Qinghushui River	1

5.2 Analysis of Influence of Supplement Water on Main Stream Water Quality

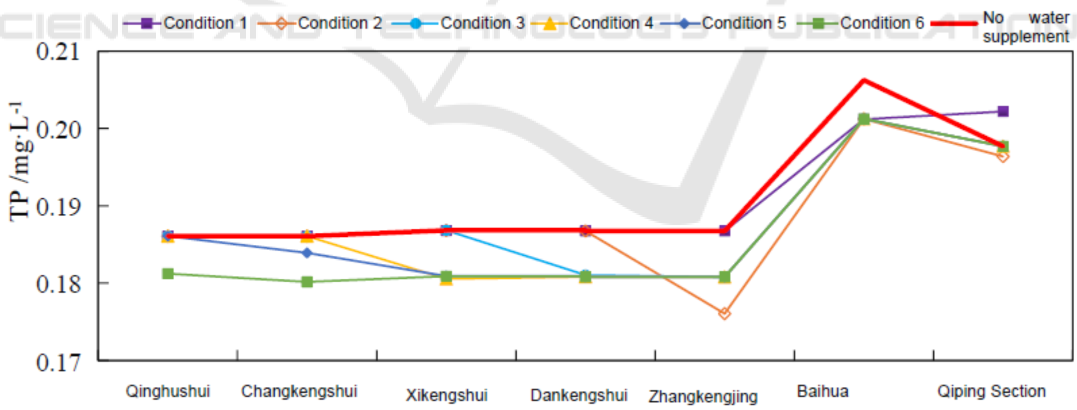
The results of numerical simulation analysis on the middle and lower reaches of Guanlan River show that the water quality along the main stream of Guanlan River has been greatly improved in comparison with the condition without water supplement, as shown in Figure 11, in which water supplement at the confluence of main stream/tributaries in the upper reaches of the basin (Condition 6) has the most significant effect on reducing COD and TP.



(a) COD changes along the middle and lower reaches of the main stream under each water supplement condition



(b) NH_3-N changes along the middle and lower reaches of the main stream under each water supplement condition



(c) TP changes along the middle and lower reaches of the main stream under each water supplement condition

Figure 11: Water quality changes along the middle and lower reaches of Guanlan River main stream under each water supplement condition.

6 CONCLUSIONS

In this study, a depth-averaged 2D mathematical equation was used to describe the characteristics of water quality in the main stream of Guanlan River, and a MIKE21-based mathematical model for water environment in the main stream of Guanlan River was built. According to the actual operating conditions of the decentralized wastewater treatment facilities in Guanlan River Basin and the Guanlan estuary storage pond water purification project, different overflow and water supplement condition were assumed. By using the mathematical model of hydrodynamic water environment, the influence of different working conditions overflows and water supplement on the water quality changes of Guanlan River was simulated and quantitatively analyzed.

When the main stream of Guanlan River overflows, the simulation results show that: (1) If overflow only occurs at the overflow point downstream the Guanlan water purification plant and the overflow volume does not exceed 30,000 m^3/d, the water quality of Qiping Section can meet the assessment requirements; (2) If overflow only occurs at the overflow point upstream the terminal gate and the overflow volume does not exceed 30,000 m^3/d, the water quality of Qiping Section can meet the assessment requirements; (3) If overflow occurs at both overflow points, the water quality of Qiping Section meets the assessment requirements only when the overflow volume downstream the Guanlan plant does not exceed 20,000 m^3/d and the overflow volume upstream the terminal gate does not exceed 15,000 m^3/d. In addition, the calculation results demonstrate that the concentrations of COD, NH_3-N and TP along the main stream are obviously lower under all working conditions of water supplement. The above conclusions are expected to provide a scientific basis for water pollution control of Guanlan River Basin.

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