Two-dimensional Hydrodynamics and Water Environment Simulation: A Case Study in the Guanlan River Basin in China

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Abstract: As an important resource and environmental carrier, urban rivers are related to the survival of the city and restrict the development of the city. However, situations caused by environmental degradation, water pollution occurs in urban rivers. Therefore, comprehensive treatment of urban water pollution has become a necessity. This study establishes a two-dimensional Hydrodynamics and Water Environment (HWE) model based on MIKE21 FM, and then the simulation effect of the proposed HWE model is verified by comparison with the measured data. With Shenzhen city's Guanlan River as a case study, the results indicate that (1) the water level and water quality of the proposed HWE model have a good fit; (2) the flow velocity of the main stream in the Guanlan River shows a gradual increase trend from the upstream to the downstream, that is, the average flow velocity values of the upstream, middle, downstream reaches are 0.034 $m\cdot s^{-1}$, 0.041$m\cdot s^{-1}$, and 0.183 $m\cdot s^{-1}$; and (3) the temporal and spatial distribution of the water quality parameters in the Guanlan River shows that the flow of river water has a diluting effect on the sewage discharged from the sewage treatment plant. These findings are helpful to the analysis of urban river's hydrodynamics and water environment characteristics.

1 INTRODUCTION

Urban rivers are an integral part of human life, and the ecological foundation of the urban environment (Zhang et al., 2017). However, urban rivers are facing problems such as water degradation, water pollution, and the gradual decline of the aquatic ecological environment due to anthropogenic factors as consequence of rapid economic development and global climate change (Ge et al., 2020; Niu et al., 2021; Zhang et al., 2021). Therefore, the comprehensive management for the rivers is of significance for the urban development with the purpose of the harmony between human beings and water resources.

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). Generally, there exists certain errors between the results of mathematical statistics and the real results due to the complexity of the actual situation, and the method lacks an analysis of the mechanism. With the development of computer technology, mathematical model methods have gradually been applied to the field of water resources, and this method can make up for the deficiencies of mathematical statistics in mechanism research (Huang et al., 2015; Shchepetkin et al., 2005). Correspondingly, numerical simulation software has also been widely applied, and commonly used simulation software includes EFDC, ROMS, MIKE, HEC-RAS 2D, Iber 2D, Flood Modeller 2D, and PCSWMM 2D etc. (Chen et al., 2003; Pinos et al., 2019; Yuan et al., 2006).

Research on river water environment mostly focuses on the source and migration process of water quality elements, which is the research foundation for comprehensive treatment of water environment in rivers (Zuo & Li, 2013). Cui et al. (2021) analyzed the characteristics of temporal and spatial changes in river water quality with the help of logarithmic power

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function universal index formula. Wang et al. (2021) analyzed the influence of environmental changes on system attributes by establishing 14 Ecopath models composed of 28 functional groups along a subtropical urban river. Zhang et al. (2020) selected Chemical Oxygen Demand (COD), Total Phosphorus (TP) and Ammonia nitrogen content index (NH_3-N) as characteristic indexes to simulate the hydrodynamic and water quality of the Shunyi section of Chaobai river based on MIKE21 model. However, the research on joint analysis of the two-dimensional hydrodynamic and water environment of urban rivers by considering the impact of sewage treatment plants still have room for exploration, which are necessary for comprehensive management of urban river environment. Therefore, the aim of this paper is to establish a coupling model of hydrodynamics and water environment based on MIKE21 FM, and then analyze the hydrodynamic characteristics and pollutant migration law, which serves to find the key influencing factors for the comprehensive management of urban rivers.

2 STUDY AREA AND METHODOLOGY

2.1 Study Area

The Guanlan River Basin (22.58°-22.76°N, 113.96°-114.16°E) was selected as the study area (Figure 1), which is in the north-central part of Shenzhen city, south-central Guangdong province, southeastern China. The Guanlan River, one of the five major rivers in Shenzhen with a catchment area of more than 100 km^2, is the upstream section of the Shima River in the Dongjiang water system. It originated in Jigongtou, Niuzui Reservoir in the Cerebral Shell Mountain (385.4 masl). The mainstream passes through Longhua New District from south to north, enters the territory of Dongguan City below Qiping, Guanlan Street, and merges into Dongjiang River at the junction of Dongguan and Huizhou. The Guanlan River Basin referred to in this article includes the Guanlan River sub-basin and other tributaries of the Shima River system located in Shenzhen, with a total area of 247.3 km^2.

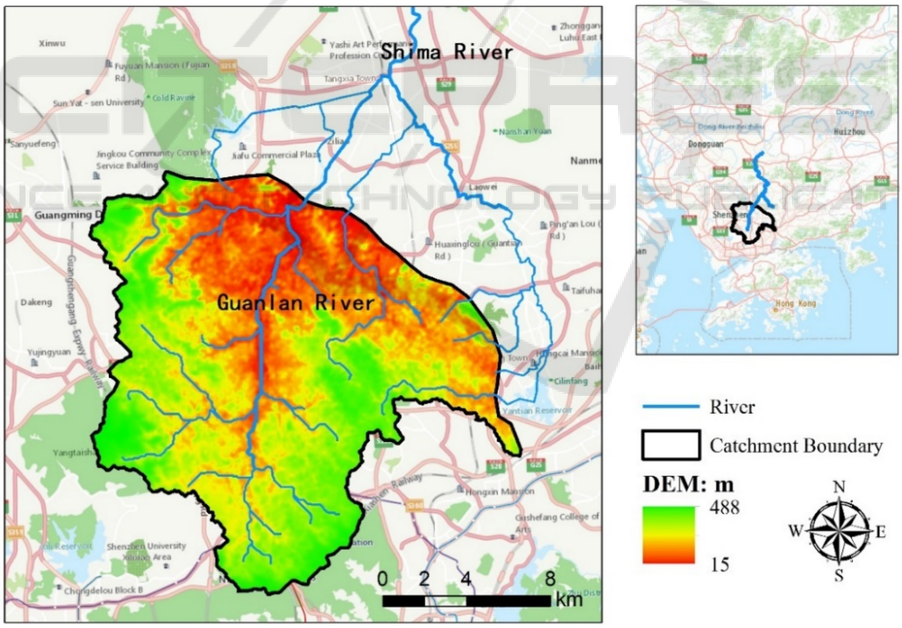


Figure 1: A schematic diagram of the study area.

The underlying surface of the Guanlan River Basin is divided into six categories: green space, water body, roof, bare soil and pavement. The area of green land (including mountains) is 104.25 km^2, water area is 11.25 km^2, roof area is 40.17 km^2, road area is 38.39 km^2, bare soil area is 2.64 km^2, paving area is 50.55 km^2, and the above-mentioned area is 247.3 km^2 in total.

2.2 Database

The data involved in this study mainly include the measured water quality data of the Guanlan River's main stream (GRMS) from January 1st to June 1st, 2019, and the current water environment monitoring data acquired during the project period. The main water quality indicators include COD, NH_3-N and TP. The 13 amphibious boundaries (only 6 have flow sequence data, among which Niuzui River and Minzhi River merge into Yousong River, and Dashuikeng River merges into Baihua River) and 13 point-source hydrodynamic boundaries are shown in Figure 2.

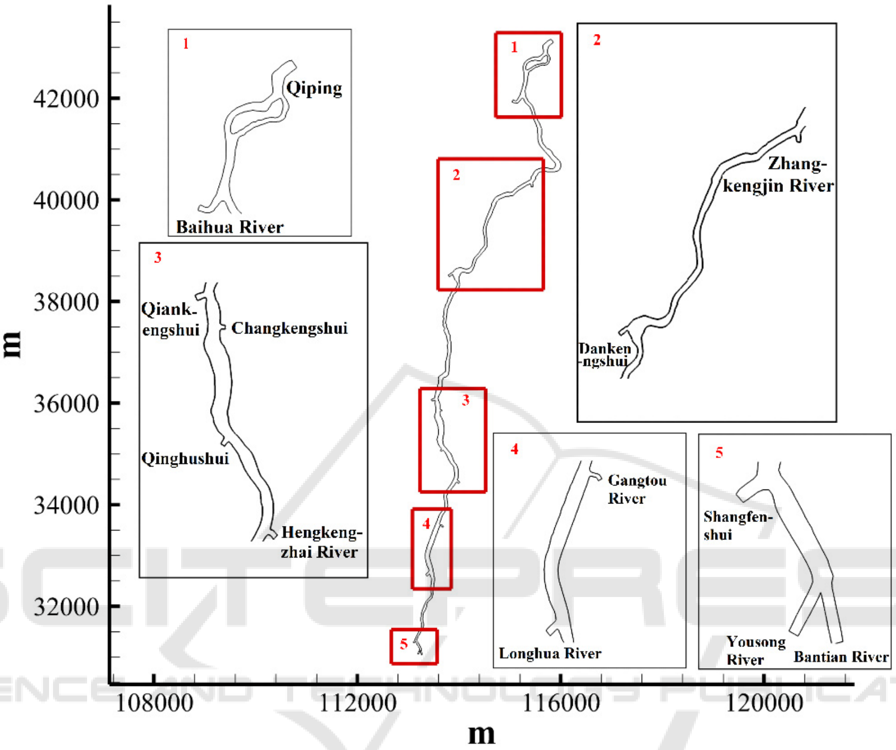


Figure 2: Generalized diagram of model hydrodynamic boundary.

2.3 Model Governing Equation

The GRMS is a relatively smooth river with a slope of 1.2‰. The vertical mixing of the water body is relatively uniform, and the uneven distribution of the spatial plane is relatively significant. Therefore, a flat two-dimensional mathematical equation with average water depth is used to describe the water quality movement characteristics of the GRMS from the perspective of reflecting the overall change characteristics of water quality in the study area. The mathematical model of the water environment in the GRMS based on the MIKE21 model is established.

The hydrodynamic control equation of MIKE21 FM module can be expressed as:

(1) Continuity equation

$$\frac{\partial h}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}=hS \tag{1}$$

(2) Momentum equation

$$\frac{\partial hu}{\partial t}+\frac{\partial hu^2}{\partial x}+\frac{\partial huv}{\partial y}=fvh-gh\frac{\partial \eta}{\partial x}-\frac{h}{\rho_0}\frac{\partial P_a}{\partial x}-\frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial x}+\frac{\tau_{sx}}{\rho_0}-\frac{\tau_{bx}}{\rho_0}$$
$$-\frac{1}{\rho_0}\left(\frac{\partial s_{xx}}{\partial x}+\frac{\partial s_{xy}}{\partial y}\right)+\frac{\partial}{\partial x}(hT_{xx})+\frac{\partial}{\partial y}(hT_{xy})+hu_sS \tag{2}$$

$$\frac{\partial hv}{\partial t}+\frac{\partial huv}{\partial x}+\frac{\partial hv^2}{\partial y}=-fuh-gh\frac{\partial \eta}{\partial y}-\frac{h}{\rho_0}\frac{\partial P_a}{\partial y}-\frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial y}+\frac{\tau_{sy}}{\rho_0}-\frac{\tau_{by}}{\rho_0}$$
$$-\frac{1}{\rho_0}\left(\frac{\partial s_{yx}}{\partial x}+\frac{\partial s_{yy}}{\partial y}\right)+\frac{\partial}{\partial x}(hT_{xy})+\frac{\partial}{\partial y}(hT_{yy})+hu_sS \tag{3}$$

The MIKE21 FM water quality module adopts the convection-diffusion equation, and the governing equation is:

$$\frac{\partial(hc)}{\partial t}+\frac{\partial(uhc)}{\partial x}+\frac{\partial(vhc)}{\partial y}=\frac{\partial}{\partial x}(hE_x\frac{\partial c)}{\partial x})+\frac{\partial}{\partial y}(hE_y\frac{\partial c)}{\partial y})-khc+S \tag{4}$$

where xy represent the Cartesian coordinate system, t is the time, u and v are the velocity components in the x and y directions, respectively, h is the total water depth, S is the source term, d is the still water depth, η is the water level, P_a is the local atmospheric pressure, ρ is the density of water, ρ_0 is the reference water density, $f=2\Omega\sin\phi$ is the Coriolis coefficient (Ω is the angular rate of the earth's rotation and ϕ is the geographic latitude), s_{xx}, s_{xy}, s_{yx}, s_{yy} are the radiation stress component, fu, fv are the acceleration caused by the rotation of the earth, τ_{sx}, τ_{sy} are the surface wind stress, τ_{bx}, τ_{by} are the bottom friction stress, c is the concentration of pollutants, E_x, E_y are respectively sum of turbulent diffusion coefficient and dispersion coefficient in x and y directions, T_{xx}, T_{xy}, T_{yx}, T_{yy} are the horizontal viscous stress, k is the attenuation coefficient.

3 GENERALIZATION OF THE HWE MODEL

The calculation area in this study includes all areas of the GRMS. Due to the irregular shape of the boundary of the GRMS, the model should be divided by the unstructured grid (triangular grid) processing method, and the calculation stability of the mathematical model should be ensured. x represents the east direction, y represents the north direction, the unit of coordinate value is meters. The model has a total of 2750 nodes and 3835 calculation grids, which is shown in Figure 3.

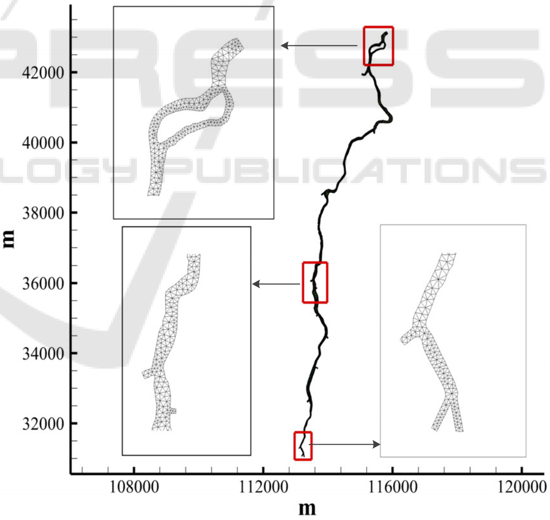


Figure 3: Meshing diagram.

4 CALIBRATION AND VERIFICATION FOR PARAMETERS OF THE HWE MODEL

4.1 Hydrodynamic Parameters

The roughness of the GRMS is n=0.033 as the initial roughness for calculation, and the eddy viscosity coefficient is determined according to the Smagorinsky formula. The measured daily hydrology and other basic data of the GRMS are the input data for the model, and the calculated output of the model is compared with the monitoring data of the water level at the outlet section of the GRMS. The comparison results of the simulated and measured water level of the Qiping section in the GRMS from January 1, 2019 to May 31, 2019 are shown in Figure 4.

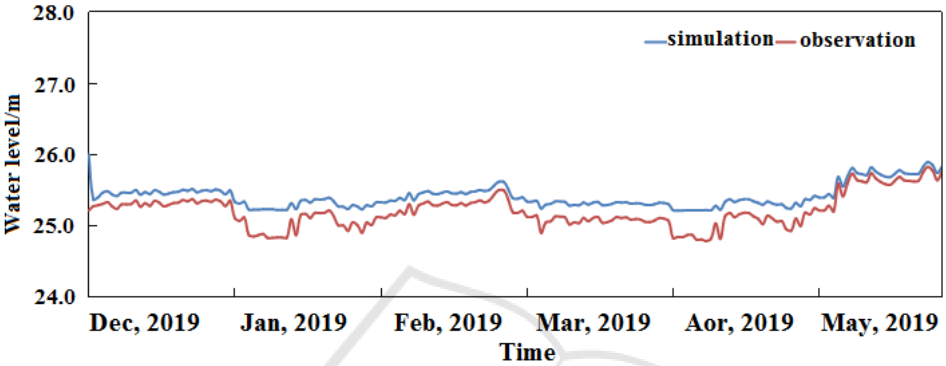
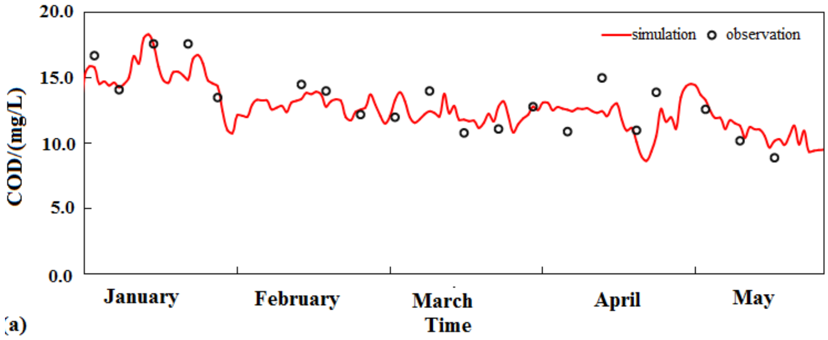


Figure 4: Comparison results of simulated and measured water level of Qiping section.

4.2 Water Quality Parameters

The comprehensive degradation coefficients of the main water quality indicators, COD, NH_3-N and TP, considered for the GRMS are $8.0e^{-8}$/s, $1.0e^{-8}$/s, $1.0e^{-8}$/s, respectively. The measured daily hydrology and water quality data of the Guanlan River's main stream are used as the input data for the HWQ model, and the simulation results are compared with the main monitoring data of the GRMS to verify the reliability of the model. The water quality results including the four monitoring points (i.e., the Qinghu Bridge, Meiguan Expressway, Fangmapu and Qiping Sections on the main stream of the Guanlan River) and the 11 first-class rivers entering the estuary from January 1, 2019 to May 31, 2019 are simulated by the HWQ model. The water quality (COD, NH_3-N and TP) process of the GRMS and the confluence of various rivers simulated by the model fits well with the measured values, indicating that the constructed water quality model can better reflect the migration and diffusion of pollutants in the main stream of the Guanlan River. The Gangtou River estuary section is selected to show the fitting effect of COD, NH_3-N and TP parameters (Figure 5).



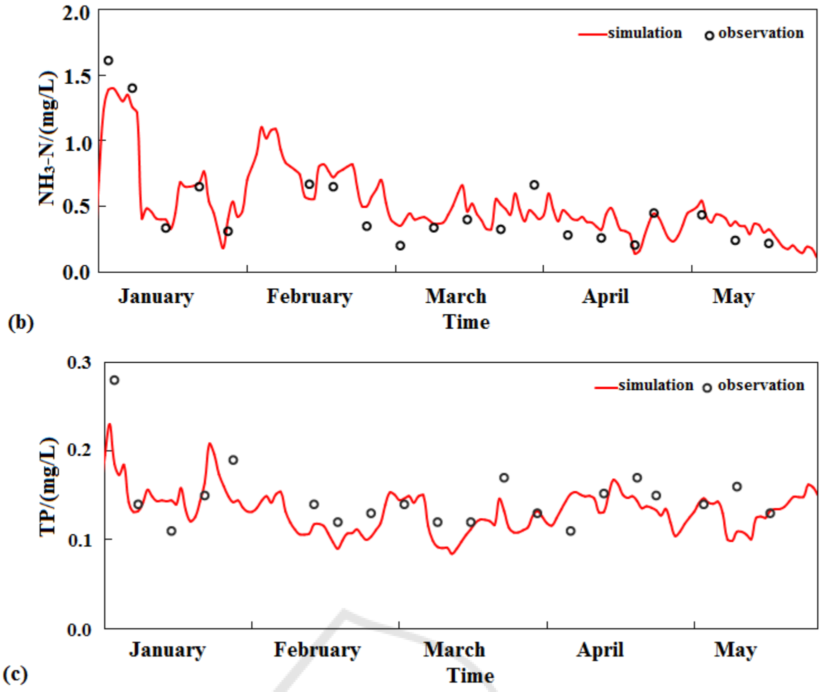


Figure 5: Comparison results of simulated and measured water quality of Gangtou River Estuary: (a) COD; (b) NH3-N; (c) TP.

5 CHARACTERISTIC ANALYSIS OF HYDRODYNAMICS AND WATER ENVIRONMENT

The GRMS is divided into three areas: the upstream (S), the middle (Z) and the downstream (X). Each area selects four points, the monthly average value of which is used to analyse the regional characteristics (Figure 6).

5.1 Hydrodynamic Characteristics of the Main Streamin Guanlan River

As shown in Figure 7, the hydrodynamic characteristics and pollutant migration laws of the main stream in the Guanlan River from January 1, 2019 to May 31, 2019 were analyzed based on the simulation results derived by the proposed hydrodynamic and water environment model. The range of flow velocity of the GRMS is 0-0.354 $m \cdot s^{-1}$, and the average flow velocity is 0.086 $m \cdot s^{-1}$. The average flow velocity values of the upstream, middle, downstream reaches are 0.034 $m \cdot s^{-1}$, 0.041$m \cdot s^{-1}$, and 0.183 $m \cdot s^{-1}$. As the upstream slope of the GRMS is gentler than the middle and lower reaches, the upper reaches are obviously influenced by river retention. Furthermore, the middle and downstream flow velocity is relatively large due to the gravity of the water flow. Therefore, the flow velocity of the GRMS gradually increases from the upstream to the downstream.

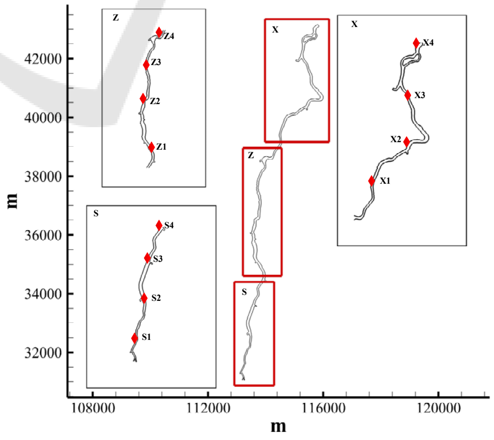


Figure 6: Schematic diagram of main points on the Guanlan River’s main stream.

5.2 Temporal and Spatial Distribution Characteristics of Water Environment in the Guanlan River's Main Stream

The sewage treatment plants are mainly distributed in the middle and lower reaches, and the three water quality indicators, COD, NH_3-N and TP are used to analyze the temporal and spatial distribution characteristics of water quality in the GRMS. In Figure 8(a), the average concentrations of COD in the upstream, midstream and downstream are 12.36 mg·L^{-1}, 12.92 mg·L^{-1} and 13.31 mg·L^{-1}, respectively. Figure 8(b) shows that the average concentrations of NH_3-N in the upstream, midstream and downstream are 0.80 mg·L^{-1}, 0.48 mg·L^{-1} and 0.46 mg·L^{-1}, respectively, while the average concentrations of TP in the upstream, midstream and downstream respectively are 0.15 mg·L^{-1}, 0.23 mg·L^{-1} and 0.24 mg·L^{-1}. The change trends of the water quality indicators in the upper, middle and downstream districts are due to the dilution effect of the sewage treatment plants along the way to the water body, which can be concluded from the results of Figure 8-9 as follows: (i) as shown in Figure 8, the dilution effect of the sewage treatment plants on NH_3-N from upstream to downstream is significant; (ii) take the simulation results of water quality in the downstream section as an example, the index values of COD and TP show a decreasing trend from the upper section to the lower section.

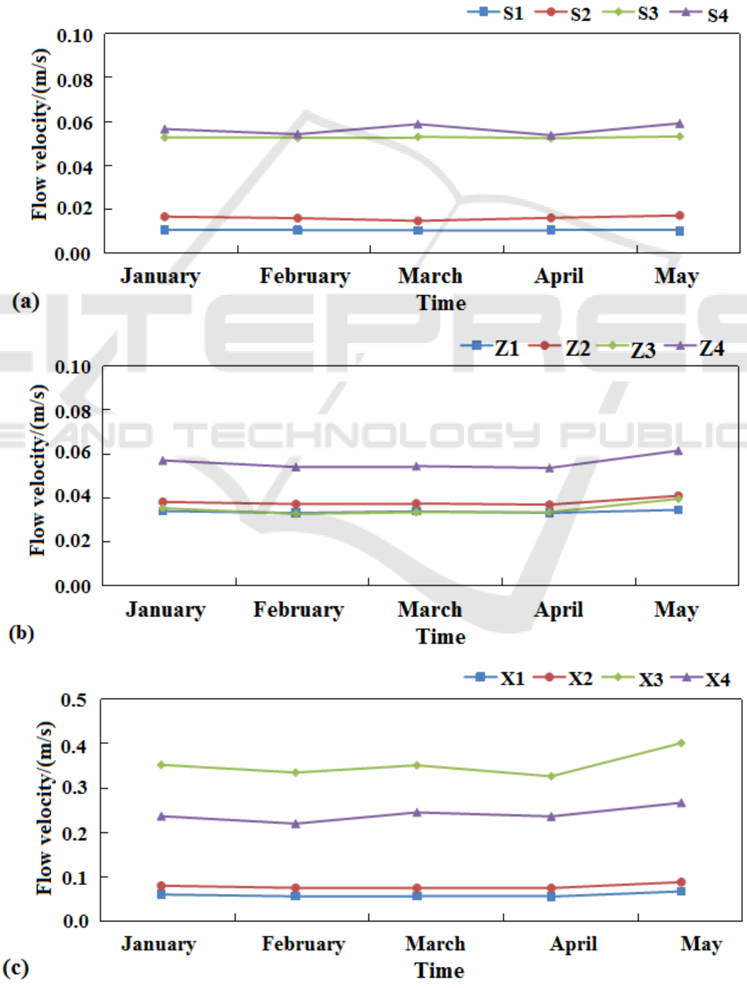


Figure 7: Changes in the flow velocity of the main stream of the Guanlan River: (a) upstream (S); (b) middle (Z); (c) downstream (X).

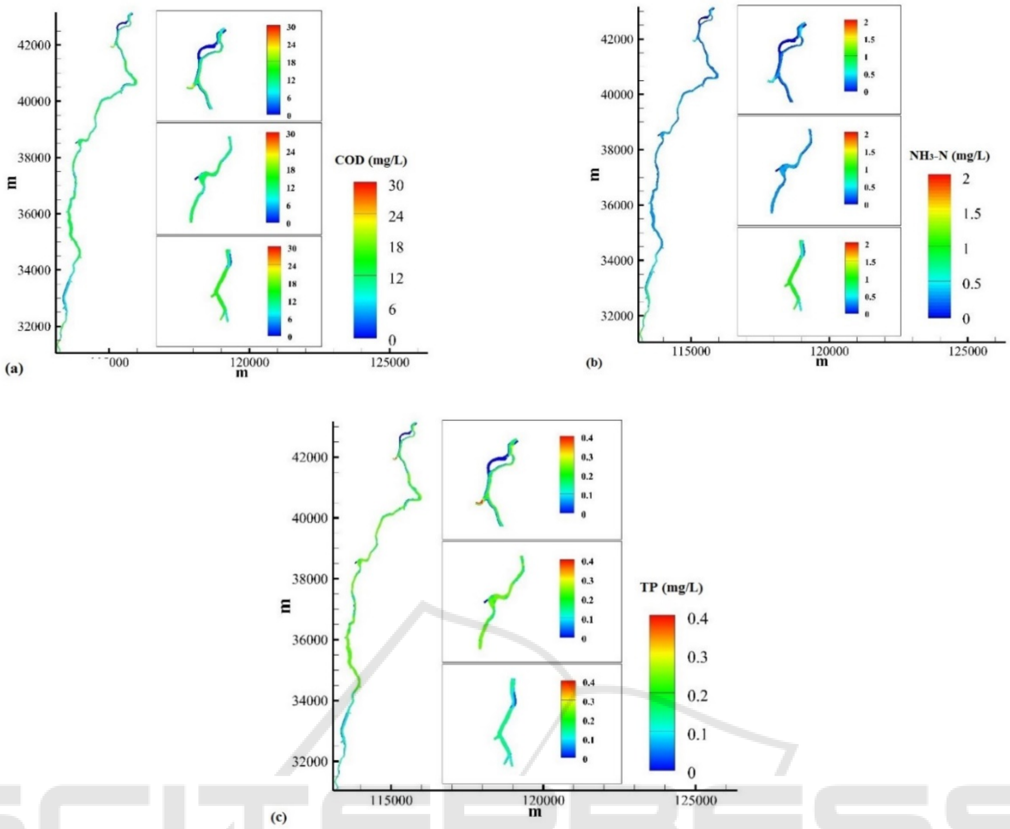


Figure 8: Distribution of water quality in Guanlan River's main stream: (a) COD; (b) NH3-N; (c) TP.

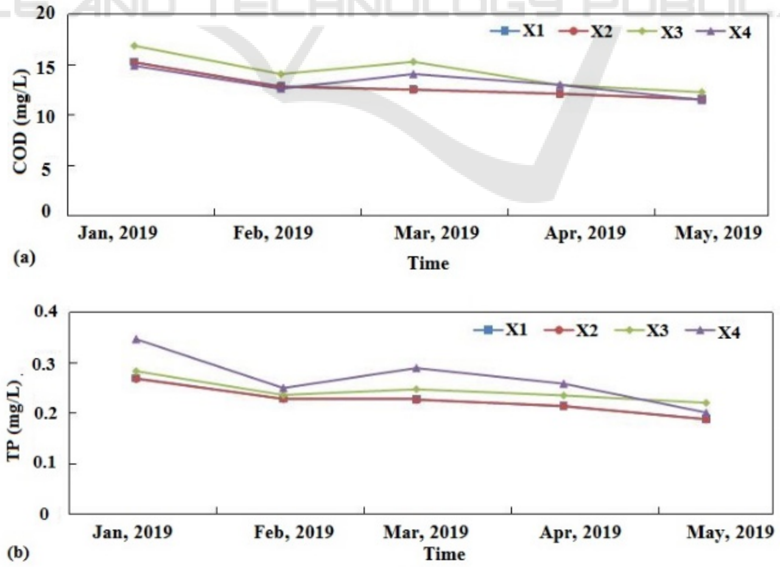


Figure 9: Changes of water quality in the downstream of the Guanlan River's main stream: (a) COD; (b) TP.

6 CONCLUSIONS

In this paper, combined with the characteristics of the Guanlan River project, a two-dimensional HWE model for the GRMS was constructed based on MIKE21 FM. Then, the measured water level and flow data of each section of the Guanlan River is used to calibrate and verify the rationality of the model establishment. The main conclusions are summarized as follows:

(1) The water level and water quality of the proposed HWE model have a good fit, which can be applied to the simulation analysis of the Guanlan River's hydrodynamic and water environment scenarios.

(2) As the upstream slope of the GRMS is gentler than the middle and lower reaches, the flow velocity of the GRMS shows a gradual increase trend from the upstream to the downstream, that is, the average flow velocity values of the upstream, middle, downstream reaches are $0.034\ m\cdot s^{-1}$, $0.041 m\cdot s^{-1}$, and $0.183\ m\cdot s^{-1}$.

(3) The change trends of the water quality indicators in the upper, middle and downstream districts are shown as follows: i) the average concentrations of COD in the upstream, midstream and downstream are $12.36\ mg\cdot L^{-1}$, $12.92\ mg\cdot L^{-1}$ and $13.31\ mg\cdot L^{-1}$, respectively; ii) the average concentrations of NH_3-N in the upstream, midstream and downstream are $0.80\ mg\cdot L^{-1}$, $0.48\ mg\cdot L^{-1}$ and $0.46\ mg\cdot L^{-1}$, respectively; iii) the average concentrations of TP in the upstream, midstream and downstream respectively are $0.15\ mg\cdot L^{-1}$, $0.23\ mg\cdot L^{-1}$ and $0.24\ mg\cdot L^{-1}$. Moreover, the sewage treatment plants along the way has a dilution effect on the water body (indictor values of COD, NH_3-N and TP) within a certain range.

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