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Rainwater utilization one-dimensional water quality model simulation analysis

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ABSTRACT

At present, our country existing storm flood calculation method can't meet the requirements, the design of modern city drainage and flood control calculation therefore, how to effectively use of rain flood resources and selection can reflect the characteristics of city of area of rain flood to Yu Hongli amount become urgent need further in-depth study of the problem, this paper takes Baoan District Guanlan River Watershed in Shenzhen city as an example, from the perspective of utilization of city of area of river of rain flood simulation and rain flood resources, utilization of water power model as the basis, the establishment of the one-dimensional water quality model through the research on the change of water quality, and through the actual water level, flow, water quality data to the model calibration and verification, the water level calculation research the establishment of the model, and the concentration of the measured water level, concentration of basically the same, show that the reasonable selection of parameters of model, the model is accurate and adequate representation can provide the necessary basis for the research on rain water resources utilization.

KEYWORDS

One-dimensional water quality model; Rainwater utilization; Guanlan river.

RESEARCH BACKGROUND

In recent years, China's urbanization process accelerated markedly. At this stage China has entered into off-line of high-speed urbanization, the emergence of unsynchronized material civilization and ecological civilization construction in the highly developed urbanization has produced incompatible contradictions. The contradictions mainly exhibited in two aspects. On one hand, the urbanization increases water demand of the city which exacerbates water shortages in the city; on the other hand, the Urban Rainwater disaster becomes more serious due to the change of urban surface runoff characteristics. Therefore, the implementation of urban rainwater resources utilization not only can ease the contradiction of urban water supply and demand which can effectively reduce the urban flood pressure, but also can improve the urban ecological environment. The practice of urban rainwater utilization has been proved to be effectively. Currently, urban storm water model mainly contains two types which are hydrological model and hydrodynamic model. Hydrology model uses the way of system analysis to take the catchment area as a black box or gray box system, establishing a relationship of input and output. Hydrodynamic model is based on the microscopic laws of physics (continuity and momentum equations) to simulate the convergence process slopes.

Guanlan River Diversion Project was one of the major local water sources of Shenzhen. However, due to the deterioration of water quality in Guanlan River, Guanlan River Diversion Project has been deactivated since late 2002, resulting in a waste of engineering and water resources. In order to improve the water quality of Guanlan River, so far the Guanlan River basin is beginning to take a series of water environment improvement project which will make some improvement in water quality after it has been completed. In order to make full use of local resources, this study analyzed Guanlan River as a test area which can not only benefit the social and economic development, improve the water environment, but also provide valuable theoretical basis for the development of the river rainwater utilization.

This study focused on the water quality by setting Guanlan River in Bao'an District of Shenzhen as the pilot area to establish a relationship between rain floods dynamic processes and water quality based on the hydrodynamic model. It established a one-dimensional water quality model, and made the simulation and verification of the model.

OVERVIEW OF THE RIVER BASIN

Guanlan River basin is located in north-central of Shenzhen City, and it is the upstream segment of the Shima River of Dongjiang River water system. It is developed from Danaoke Mountain. Guanlan River flows across Phuket, Pinghu Street (Junzi Bu River), Longhua Street, Mission Street, and Guangming Farm from south to north, and it entered to the Dongguan district in Guanlan Street. And in the junction area, the catchment area is 189.3km^2 (excluding Pinghu independent tributary). Guanlan River is one of the largest five rivers in Shenzhen City, its length is 22.56km, and the rivers average gradient is 2.12 ‰. Guanlan River belongs to the upstream of Dongjiang tributary-Shima River. The water development and distribution exhibited as a fan. There are 12 watershed tributaries, 7 two and three tributaries in Guanlan River. Among them, 5 tributaries directly flow into the territory of Dongguan which are Niuhu Rever, Junzibu River, Shanxia River, Egonglin River and Gumu River, all of the tributaries flow into Yan Tian water, another tributary of Shima River.

In recent years, the river water pollution of Guanlan River Basin becomes serious. The town area of the main tributaries flowed cross are all contaminated, and the overall quality of the water in the river is deteriorated. According to the results of water quality test of three river section which are Zhu town, Fangmapu and Qiping, the indicators of chemical oxygen demand, ammonia nitrogen contents, total phosphorus contents are seriously overweighed, indicating that the water quality is serious deteriorated even worse than the Class V standards of surface water.

The main causes of serious deterioration of water quality include three aspects. The first cause is the characteristics of Rain Source of the river basin and the total amount of emissions compared to the natural river runoff is large. As a large number production and life sewage directly flowed into the river basin; currently, the average amount of daily sewage is 370,000 m^3/d, and there are three sewage treatment plants in the area (Huawei sewage treatment plants, Longhua sewage treatment plant and Guanlan sewage treatment plant), and the designed total scale is 250,000 m^3/d, and another emergency water treatment of Guanlan River is 400,000 m^3/d. However, the actual collection of sewage treatment is only about 52,000 m^3/d, and about 318,000 m^3/d sewage direct flow into river without treatment. The second cause is that the pollution source in the watershed basin is very serious, and it is not under effective control. Thus, the pollution source on the surface runoff into the river with the rain which one of the main sources of the river. The third cause is that long-term contamination of river sediment is not cleared and the organic matter and heavy metal content were exceeded which exacerbated the deterioration of water quality.

The catchment area of Guanlan River is 46.6km^2, the tributary in the basin is rich, and there are abundant available resources of rainwater. Currently, Guanlan River is under project of contamination interception. There are Longhua sewage treatment plant in the basin which can discharged waste water after standard treatment, making the source of pollution simple and the water quality stable. There is water intake point of Qiankeng Reservoir in the main tributary of Guanlan River, and Dahe Sluices is located at 300m downstream of the water intake point of the reservoir which can prevent and store flood and make effective use of rainwater resources. At the upstream Dahe Sluices of Guanlan River, there are two tributaries, Gangtou River and Longhua River flowed into Guanlan River; at the Shangfen Water point, there are Yousong River and Bantian River flowed into Guanlan River. Thus, according to the principle of efficient use of existing water facilities, Dahe Sluice was selected as the lower boundary range calculating; according to the confluence with the river basin water quality and taking the terrain processing and convergence calculation simple into consideration, the flow and water quality concentration of Gangtou River and Longhua River regarded are taken as gathered items processed. There are two tributaries flowed into Guanlan River on the section of Shangfen. In order to simplify the processing of two tributaries import, reducing the workload of field data survey and calculation, the Shangfen section was selected as the up border to calculate the range. Thus, the upper boundary for calculation is Shangfen water section, the lower boundary for calculation is Dahe Sluice, and the total river length for calculation is 4km.

ESTABLISHMENT OF ONE-DIMENSIONAL WATER QUALITY MODEL

One-dimensional water quality model is to apply water environment simulation to quantitative description the migration and transformation of pollutants in the water planning mathematical equations, and to build relationships before rainwater and water quality. It can establish water quality model to quantitative the simulation and prediction of water quality.

One-dimensional flow, water quality concentration model equations

Continuity equation $\frac{\partial Z}{\partial t}+\frac{1}{B}\frac{\partial Q}{\partial x}=\frac{q}{B}$ **(1)**

Momentum equation $\frac{\partial Q}{\partial t}+(gA-\frac{BQ^2}{A^2})\frac{\partial Z}{\partial x}+\frac{2Q}{A}\frac{\partial Q}{\partial x}=\frac{Q^2}{A^2}\frac{\partial A}{\partial x}\Big|_z-\frac{gQ|Q|}{Ac^2R}$ **(2)**

In the formula， Q、Z、A、B、R refer to the flow, water level, over the water area, width, and hydraulic radius over the water in the cross-section, respectively； q referes to lateral inflow； g refers to acceleration due to gravity ; c refers to Chezy ; x、t refer to the spatial and temporal coordinates, respectively.

Basic water quality convection-diffusion equation

$$\frac{\partial(AS)}{\partial t}+\frac{\partial(QS)}{\partial x}-\frac{\partial}{\partial x}(AE_X\frac{\partial S}{\partial x})+S_c-S_m=0 \quad \textbf{(3)}$$

In the formula, S refers to substance concentration of delivery ; E_x refers to longitudinal dispersion coefficient ; S_c refers to decay items related to transporting substance concentration, $S_c=k_dAS$, K_d refers to attenuation factor; S_m refers to external source or sink terms.

Model solution

(a) Unsteady implicit difference scheme for solving the water group

Unsteady flow equations adopts Preissmann four point weighted discrete implicit difference scheme, shown as Figure 1, F stands for flow Q and water level Z, thus, F in the river segment within the time-weighted average of the corresponding magnitude of the partial derivative can indicated as

$$\begin{cases} F=\frac{1}{2}(F_{j+1}^n+F_j^n) \\ \frac{\partial F}{\partial x}=\theta\frac{F_{j+1}^{n+1}-F_j^{n+1}}{\Delta x}+(1-\theta)(\frac{F_{j+1}^n-F_j^n}{\Delta x}) \\ \frac{\partial F}{\partial t}=\frac{F_{j+1}^{n+1}+F_j^{n+1}-F_{j+1}^n-F_j^n}{\Delta t} \end{cases} \quad \textbf{(4)}$$

In the formula, θ refers to weighting factor, which usually is 0.5~1.0.

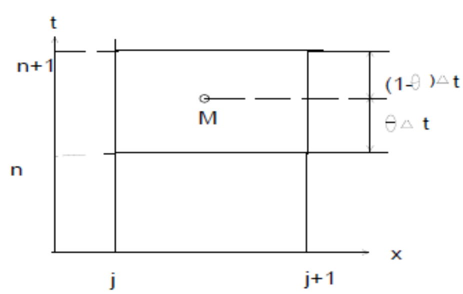

Figure 1: Difference scheme diagram

Hypothesis that there are m segments in the river, thus, there are (m-1) micro segments, the first segment is numbered as 1, the last segment is numbered as m. According to formula (4) Discrete format, the water flow from j segment, thus.

Continuity equation $-Q_j^{n+1}+Q_{j+1}^{n+1}+c_jZ_j^{n+1}+c_jZ_{j+1}^{n+1}=D_j$ **(5)**

Momentum equation $E_jQ_j^{n+1}+G_jQ_{j+1}^{n+1}-F_jZ_j^{n+1}+F_jZ_{j+1}^{n+1}=\phi_j$ **(6)**

In the formula, $c_j=\frac{B_{j+\frac{1}{2}}^n\Delta x_j}{2\Delta t\theta}$

$$D_j = \frac{q_{j+\frac{1}{2}} \Delta x_j}{\theta} - \frac{1-\theta}{\theta}(Q_{j+1}^n - Q_j^n) + c_j (Z_{j+1}^n + Z_j^n)$$

$$B_{j+\frac{1}{2}}^n = (B_j^n + B_{j+1}^n)/2$$

$$E_j = \frac{\Delta x_j}{2\theta \Delta t} - (\alpha u)_j^n + (\frac{g|u|}{2\theta c^2 R})_j^n \Delta x_j$$

$$G_j = \frac{\Delta x_j}{2\theta \Delta t} + (\alpha u)_{j+1}^n + (\frac{g|u|}{2\theta c^2 R})_{j+1}^n \Delta x_j$$

$$F_j = (gA)_{j+\frac{1}{2}}^n$$

$$\phi_j = \frac{\Delta x_j}{2\theta \Delta t}(Q_{j+1}^n + Q_j^n) - \frac{1-\theta}{\theta}\left[(\alpha u Q)_{j+1}^n - (\alpha u Q)_j^n\right] - \frac{1-\theta}{\theta}(gA)_{j+\frac{1}{2}}^n (Z_{j+1}^n - Z_j^n)$$

By Manning formula $c = \frac{1}{n} R^{1/6}$, thus $\frac{g|u|}{2\theta c^2 R} = \frac{gn^2|u|}{2\theta R^{4/3}}$

Convenient for writing, the superscript (n-1) was ignored superscript (*n*+1), any formula of micro segment in (5) and (6) can be write as:

$$-Q_j + Q_{j+1} + c_j Z_j + c_j Z_{j+1} = D_j \quad \textbf{(7)}$$

$$E_j Q_j + G_j Q_{j+1} - F_j Z_j + F_j Z_{j+1} = \Phi_j \quad \textbf{(8)}$$

In the formula, c_j、D_j、E_j、F_j、G_j、ϕ_j all calculated by initial value, thus, the equations are linear equations with constant coefficients. For every river with *m*-1 micro segments, there are 2(*m*-1+1) unknown values and they can list the 2 (m-1) equations. Combine with boundary conditions at both ends of the river, it can form Closed algebraic equations.

(b) Implicit difference scheme for solving water quality equation

Water transport and diffusion equation is accordance with the first difference scheme, the convection term adopts upwind scheme, and the rest adopt the central difference scheme, then the node equations were constructed according to the water quality concentration equations for each node, and then turn to solve each section of water concentrations.

For formula (3), it adopts implicit difference upwind scheme to deal with its discrete. Take the difference along the flow as an example, in the formula the time items takes pre-difference, convection term takes upwind analysis, and the diffusion term use central difference scheme, them it obtained:

$$\begin{cases} \frac{\partial (AS)}{\partial t} = \frac{(AS)_i^{k+1} - (AS)_i^k}{\Delta t}, \\ \frac{\partial (QS)}{\partial x} = \frac{(QS)_i^{k+1} - (QS)_{i-1}^{k+1}}{\Delta x_{i-1}}, \\ \frac{\partial}{\partial x}(AE_x \frac{\partial S}{\partial x}) = \left[\frac{(AE_x)_i^{k+1} S_{i+1}^{k+1} - (AE_x)_i^{k+1} S_i^{k+1}}{\Delta x_i} \right. \\ \left. - \frac{(AE_x)_{i-1}^{k+1} S_i^{k+1} - (AE_x)_{i-1}^{k+1} S_{i-1}^{k+1}}{\Delta x_{i-1}} \right] \frac{1}{\Delta x_{i-1}}, \\ S_c - S_m = \overline{K}_{di-1}^{k+1} (AS)_i^{k+1} - \overline{S}_{mi-1}^{k+1} \end{cases} \quad \textbf{(9)}$$

For countercurrent, it can obtain a similar result, in the formula $\overline{K}_d$、 $\overline{S}$ refer to the value of river segment, superscripts k is the initial value of period, k+1is the last value of period, where there are periods at the end of the following values are written on the label is omitted. After finishing, discrete format in formula (9) can be simplified as:

$$a_iC_{i-1}+b_iC_i+c_iC_{i+1}=Z_i\ (i=1,\ \ldots,\ n\ ) \qquad \textbf{(10)}$$

In the formula, a_i, b_i, c_i are derived factor; C_i is the concentration at the end of I segment; n is the number of cross-section of the river.

For the general section (i=2, …, n-1):

$$\begin{cases} a_i = -\left[D_{11} + D_{21} + F_{c1}\right]\Delta t/V\,, \\ b_i = \left[D_{11} + D_{22} + D_{21} + D_{32} + F_{c2} - F_{d2}\right]\Delta t/V \\ +\left[\overline{K}_{k,i-1} + \overline{K}_{d,i}\right]\Delta t + 1\,, \\ c_i = -\left[D_{22} + D_{32} - F_{d3}\right]\Delta t/V, \\ z_i = \alpha_i S_i^k + \left[\overline{S}_{mi-1}\Delta x_{i-1} + \overline{S}_{mi}\Delta x_i\right]\Delta t/V \end{cases} \qquad \textbf{(11)}$$

For the first section (i=1):

$$\begin{cases} a_1 = 0, \\ b_1 = \left[D_{32} - F_{d2}\right]\Delta t/V_2 + \overline{K}_{d,1}\Delta t, \\ c_1 = -\left[D_{32} - F_{d3}\right]\Delta t/V_2\,, \\ z_1 = \alpha_1 S_1^k + r_{d2}\overline{S}_{m1}\Delta x_1 \bullet \Delta t/V_2 \end{cases} \qquad \textbf{(12)}$$

For the end section (i=n):

$$\begin{cases} a_n = -\left[D_{11} + F_{c1}\right]\Delta t/V_1, \\ b_n = \left[D_{11} + F_{c2}\right]\Delta t/V_1 + \overline{K}_{d,n-1}\Delta t, \\ c_n = 0, \\ z_n = \alpha_n S_n^k + \overline{S}_{m,n-1}\Delta x_{n-1} \bullet \Delta t/V_1 \end{cases} \qquad \textbf{(13)}$$

In the formula:

$$\begin{cases} V_1 = \Delta x_{i-1}\,(A_{i-1} + A_i)/2, V_2 = \Delta x_1\,(A_i + A_{i+1})/2, \\ V = V_1 + V_2, \qquad \alpha_i = A_i^k/A_i, \end{cases} \qquad \textbf{(14)}$$

$$\begin{cases} D_{11} = (AE_x)_{i-1}/\Delta x_{i-1}, \qquad D_{22} = (AE_x)_i/\Delta x_i, \\ D_{21} = (AE_x)_i/\Delta x_{i-1}, \qquad D_{32} = (AE_x)_{i+1}/\Delta x_i, \end{cases} \qquad \textbf{(15)}$$

$$\begin{cases} F_{C1} = (Q_{i-1} + Qa_{i-1})/2, \qquad F_{c2} = (Q_i + Qa_{i+1})/2, \\ F_{d2} = (Q_i - Qa_i)/2, \qquad F_{d3} = (Q_{i+1} - Qa_{i+1})/2, \end{cases} \tag{16}$$

$$\begin{cases} Q_w = (Q_{i-1} + Q_i)/2, \\ Q_e = (Q_i + Qa_i)/2 \end{cases} \tag{17}$$

In the above formula, the variables corresponding to the flow rate *Qa* is the absolute value of *Q*.

One-dimensional mathematical model for solving water quality as follows:

(1) On the basis of the flow calculation, by using equation (10) to (13), the river water quality concentrations of each section recursive equations is established;

(2) The use of recursive equations on the river to solve the water quality of the river concentration of each section.

(c) One-dimensional water quality model to calculate the boundary

The calculation range for the cross-sectional boundary is 32, the lower boundary is 1and the length of river calculated is about 4km, and 32 cross sections are calculated. Because the water intake at the upstream boundary distance of about 300 meters, in order to ensure the simulation results, the section interval set by the dense to sparse, 1 to 13 section spacing 50m, 13~15 sectional distance of 150m, 16 ~ 32 sectional distance of 200m, the average cross-section spacing of approximately 150m. Cross-sectional arrangement is shown in Figure 2.

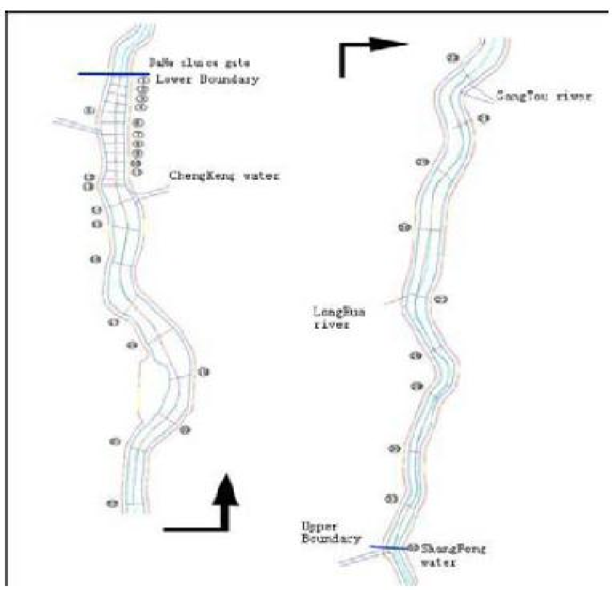

Figure 2: One-dimensional water quality model section arrangement diagram

ESTABLISH ONE-DIMENSIONAL FLOW RAINWATER UTILIZATION WATER QUALITY MODEL

Model validation

Test the section 19, section 1, and the water level of the water intake, flow, water quality data to test the model calibration and validation. Analog area can be shown in Figure 2 section 1-19. In the simulation, the chemical oxygen demand in the main pollutants river COD, NH3-N and Fe were set as water quality indicators.

Hydrodynamic boundary: the upstream boundary of section 19 adopted October 19, 2012 - the 20th measured flow hydrograph downstream control section of a border using the measured water level over the same period, the section 19 process with the measured water level line in Figure 3 and 4 of the section 1 are shown.

Water quality boundary: upstream boundary section 19 adopted measured COD, NH3-N, Fe concentration of October 19, 2012 - the 20th; downstream water intakes at border control period measured using COD, NH3-N and Fe concentration average of 19.7 mg/l, 2.9mg/l, and 0.58 mg/l, respectively. Section 19 measured COD, NH3-N concentration process line as shown in Figure 5 and 6.

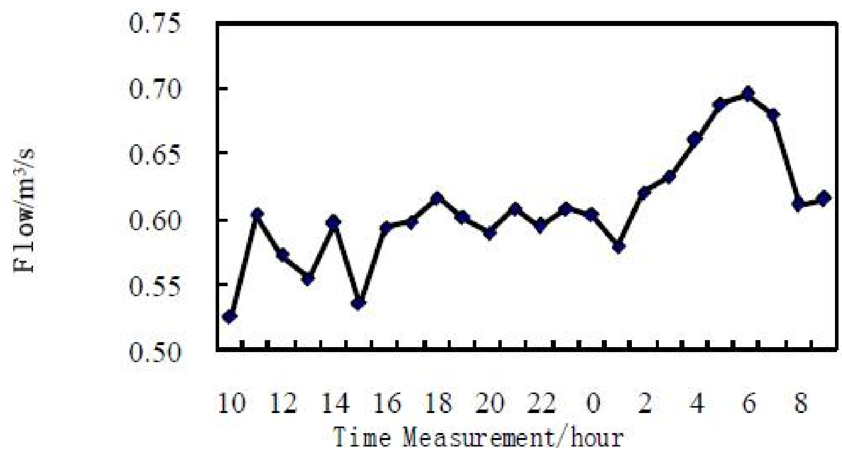

Figure 3: The measured flow value of section 19

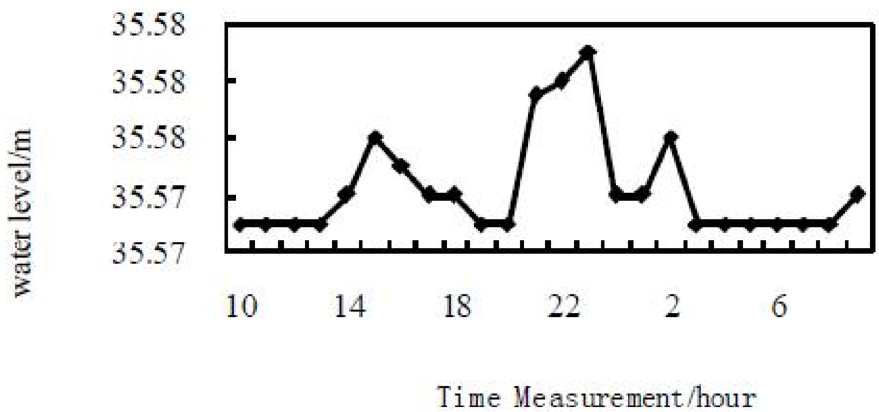

Figure 4: The measured water level value of section 1

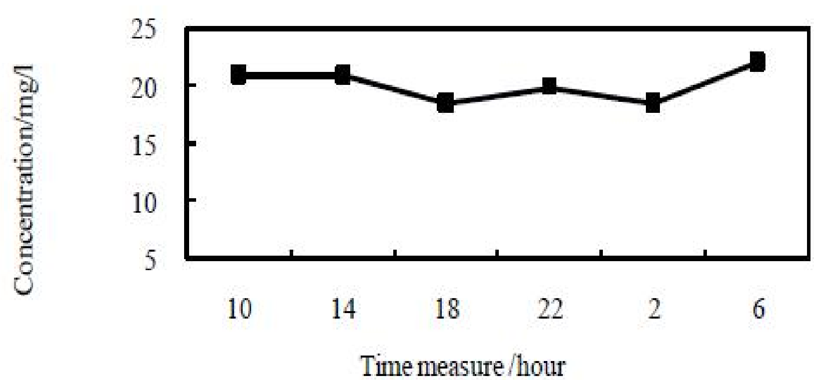

Figure 5: The measured COD concentration process of section 19

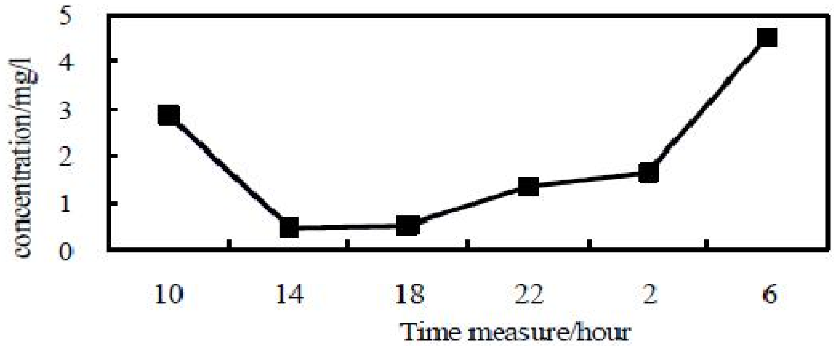

Figure 6: The measured NH_3-N concentration process of section 1

The verification results of water intake measuring point level, COD, NH3-N, Fe concentration are shown in Figure 7 to 10. The change trends and magnitude of calculated water level and measured values are consistent. No matter the trend, phase or amplitude changes of COD, NH3-N and Fe concentration are exactly the same, the analog error is small, and the simulation of whole process works well. In summary, the water level and concentration calculated in the model are basically the same as measured, indicating that the parameter selected to calculate in the model is reasonably, the model has better accuracy and adequate representation, and it can simulate the flow and water quality under different conditions.

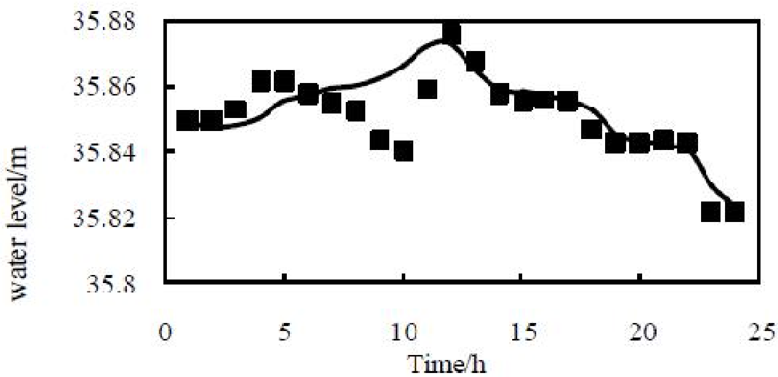

Figure 7: Comparison of the intake between the simulated and measured water levels

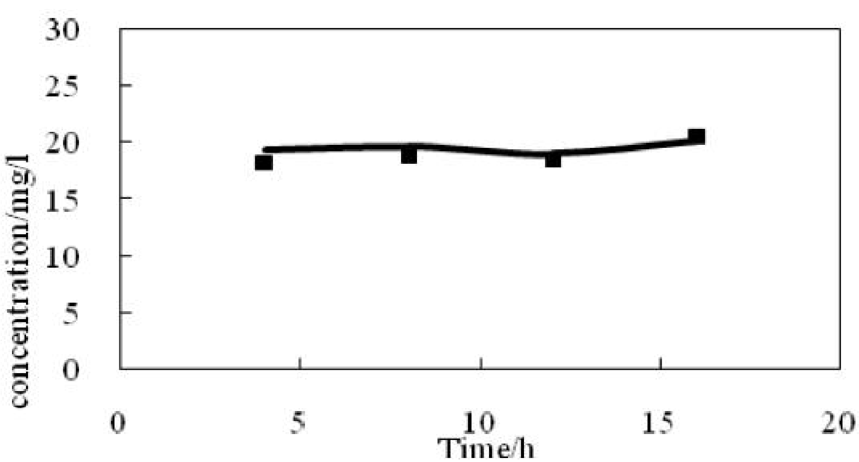

Figure 8: Comparison of the intake,s COD between the simulated and measured concentrations

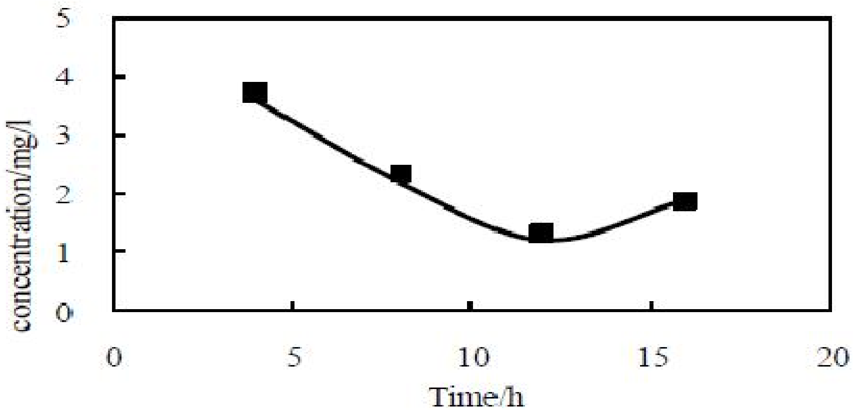

Figure 9: Comparison of the intake's NH_3-N between the simulated and measured concentrations

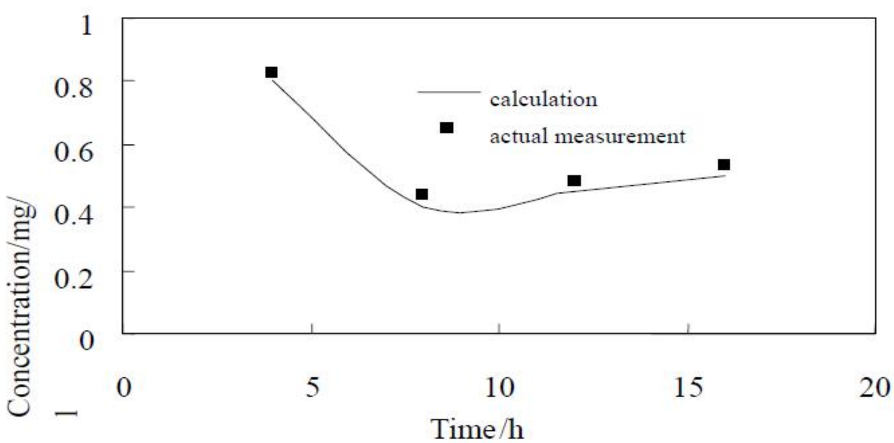

Figure 10: Comparison of the intake's Fe between the simulated and measured concentrations

Parameter calibration

According to the model validation and calibration results, the roughness of the section calculated is 0.032; COD attenuation coefficient is 0.08; NH3-N attenuation coefficient is 0.1; Fe attenuation coefficient is 0.12.

Longitudinal dispersion coefficient varies E_x changed with the water conditions changed due to the complexity of the flow changes. Range of variations of E_x is up to several orders of magnitude with a constant value calculation will bring large errors. Therefore, the different cross-sections take different values. For a certain micro-segment is:

$$E_x = 0.011\frac{V^2B^2}{hu_*} \tag{18}$$

In the formula, h is the average depth for section; $u_* = \sqrt{ghJ}$, is friction velocity, J is the hydraulic gradient ; V is the average velocity; B is water width flowing.

CONCLUSIONS

(1) This study established one-dimensional water quality model by analysis from the start of water amount and water quantity, the establishment of a one-dimensional water quality model, by

application Mathematical equation model of water environment, it can simulate and predict water quality quantitative.

(2) The model was calibrated and validated by measuring water level, flow, and water quality data. The results showed that the water level and concentration level calculated is consistent with the data measured. Thus, the water level and concentration calculated in the model are basically the same as measured, indicating that the parameter selected to calculate in the model is reasonably, the model has better accuracy and adequate representation, and it can simulate the flow and water quality under different conditions.

(3) The study found that the amount of rain water used have a great relationship with the upstream runoff water quality, so the upstream water quality management is the key of rainwater resource utilization which can be obtained by interception engineering and waste water management, protection of river runoff and water quality, increasement of Guanlan River rainwater resources, and can also obtained by increasement of the availability of local water resources.

(4) One-dimensional flow model of water quality established in the study can be used in the water environmental capacity measurement of Pearl River, pollutant emissions calculations and the development of regional total water pollutant control programs or control programs multiple applications. And it has good applicability and a certain degree of accuracy in the Pearl River Delta.

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