Experimental and numerical study of wastewater pollution in Yuhui channel, Jiashan city

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Abstract. Due to the development of economics and society in China, the huge amount of wastewater becomes a serious problem in most of the Chinese cities. Therefore, the construction of wastewater treatment plant draws much more attentions than before. The discharge from the wastewater treatment plant is then considered as a point source in most of the important rivers and channels in China. In this study, a typical wastewater treatment plant extension project is introduced as a case study, a filed monitoring experiment is designed and executed to observe required data, then, a two-dimensional model is established to simulate the water quality downstream of the wastewater treatment plant, COD\textsubscript{Cr} is considered as a typical pollutant during the simulation. The simulation results indicate that different discharge conditions will lead to different COD\textsubscript{Cr} concentration downstream of the wastewater treatment plant, and an emergency plan should be prepared to minimize the risk of the pollution in the channel under unusual and accident conditions.

1. Introduction

Jiashan city locates in northern Zhejiang province, China. The historical data indicated that Jiashan city was a relatively water resources abundant region especially in wet season\cite{1,2,3}, however, due to the severe pollution, the water quality of the rivers and channels in Jiashan city was getting worse during last decades. Recently, the regional water quality has been improved due to the water protection activity in Zhejiang. Nowadays, with the development of local economics, several new wastewater treatment plants have been constructed, therefore, the wastewater pollution becomes a key consideration in the local area. In this study, an extension project of a local wastewater treatment plant is introduced as a case study to show the environmental effects from the wastewater treatment plant, the extension project will increase the capability of the wastewater treatment plant from 15000m\textsuperscript{3}/d to 50000m\textsuperscript{3}/d. COD\textsubscript{Cr} (Chemical Oxygen Demand, Cr refers to dichromate oxidizability) is considered as the typical pollutant\cite{4,5,6}, a two-dimensional model is utilized to simulate the distribution of COD\textsubscript{Cr} in Yuhui channel of Jiashan city, and a field monitoring experiment is designed and executed to collect the essential data.
2. Methodology

2.1. Model configuration

In this study, an extension project of wastewater treatment plant is considered as a case study, which is close to Yuhui channel as shown in Figure 1. The discharge of the wastewater treatment plant is considered as a main point source in the local area. Yuhui channel is a 7.5km long, 50~120m wide channel, the averaged water depth of this channel is 3.8~4.2m approximately. A two-dimensional model based on DELFT3D software is established in this study in order to simulate the wastewater pollution from the extension project of the wastewater treatment plant, basic equations of this two-dimensional model are given as[6,7,8]:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + f, \tag{1}
\]

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + f, \tag{2}
\]

\[
\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left( \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right) + S, \tag{3}
\]

\[
\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left( \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right) + S, \tag{4}
\]

Where \(x, y\) (m) are the Cartesian coordinates; \(u, v\) (m/s) are the horizontal velocity in \(x\) and \(y\) direction; \(p\) (kg/m \(^3\)) is the pressure; \(\rho\) (kg/m \(^3\)) is the density, \(f\) (m/s \(^2\)) is the body force, \(C\) (mg/L) is the pollutant concentration, \(S\) (mg/L s) is the source term \([7,9]\). In total 12762 grids with 8~12m length and 3~7.5m width are configured in the model. The model setup is shown in Figure 2(b).

2.2. Field monitoring experiment

Since the historical data of Yuhui channel is insufficient, a field monitoring experiment is designed and executed in order to collect up-to-data information of this channel, which can be used in model verification and become the background values during the simulation. The 2-day-long (Wet season. from May 16\(^{th}\), 2017 to May 17\(^{th}\), 2017, sunny and cloudy) experiment measures both the water velocity and water quality of Yuhui channel. Three monitoring locations including upstream, downstream and verification location are distributed in Yuhui channel accordingly, which are also shown in Figure 2(a). The gates in the branches shown in Figure 2(a) ensure that the wastewater treatment plant is the main discharge source in the local area, the pollutant from these branches will not affect the water quality of Yuhui channel. The water level and velocity are taken every 0.5 hour and the water quality samples are taken every 4 hours each day.
2.3. Model verification

Firstly, hydraulic model is verified by the field monitoring experimental data. During the verification, the boundary conditions used in the hydraulic model are based on the upstream velocity and downstream water level measured by the experiment. The water level comparison at the second monitoring location (Verification location in Figure 2(a)) is given as:

![Figure 2. Numerical model of Yuhui channel (a) Monitoring sections, (b) Simulation grids.](image)

![Figure 3. Water level comparison between experimental data and numerical model](image)

(a) May 16th (b) May 17th

Note: Water level refers to the Chinese national reference elevation (1985)
Secondly, water quality model is also verified based on the concentration of COD$_{Cr}$, the comparison location is similar with the location used in the verification of hydraulic model, and the comparison between measured and simulated COD$_{Cr}$ concentration is given as:

![Graph showing measured and simulated COD$_{Cr}$ concentration comparison.](image)

**Figure 4.** Comparison between measured and simulated COD$_{Cr}$ concentration.

As shown in Figure 3 and Figure 4, the hydraulic model and water quality model both show good agreement with experimental data, the maximum discrepancy in water level comparison is 6.6%, which appears at 10:00 on May 16$^{th}$. And the maximum discrepancy of COD$_{Cr}$ concentration is 2.5%, which appears at 13:30 on May 17$^{th}$. Based on the above comparisons, both the hydraulic model and water quality model are acceptable in simulating the water flow region and water quality of Yuhui channel.

3. Case study

3.1. Simulation cases

In total, seven different cases are simulated based on different conditions of the wastewater treatment plant. These seven cases are divided into three groups, namely current group, short term group, and long term group, the simulation cases are listed in Table 1.

| Group       | Case | Condition | Flow rate (m$^3$/d) | COD$_{Cr}$ (mg/L) | Standards              |
|-------------|------|-----------|---------------------|-------------------|------------------------|
| Current     | 1-1  | Current   | 15000               | 100               | GB18918-2002 (1B)      |
|             | 2-1  | Normal    | 35000               | 50                |                        |
| Short term  | 2-2  | Unusual   | 35000               | 150               | GB18918-2002 (1A)      |
|             | 2-3  | Accident  | 35000               | 400               |                        |
| Long term   | 3-1  | Normal    | 50000               | 50                | GB18918-2002 (1A)      |
|             | 3-2  | Unusual   | 50000               | 150               |                        |
|             | 3-3  | Accident  | 50000               | 400               |                        |

Note: The standard GB18918-2002 is the Discharge standard of pollutants for municipal wastewater treatment plant (P.R.China). The organic load entering the wastewater treatment plant is COD$_{Cr}$ = 500mg/L.

As shown in Table 1, the simulation cases in short term group and long term group have different pollutant concentrations, which are given by different operating conditions of the wastewater treatment plant extension project in the future. For example, case 2-1 and case 3-1 are the normal condition (90% treatment efficiency), case 2-2 and case 3-2 are the unusual condition (70% treatment efficiency), case 2-3 and case 3-3 are the accident condition (20% treatment efficiency).
3.2. Results and discussions

The constant background conditions of Yuhui channel for all the simulation cases are based on the historical data and the field monitoring experiment, which are given as:

1) Upstream condition: Flow rate $Q = 30.5$ m$^3$/s, water level $H = 0.9$m.
2) Concentration of $\text{COD}_{Cr} = 17.3$mg/L. Decay rate of $\text{COD}_{Cr} = 0.11$ d$^{-1}$.

All the cases are simulated for a month in order to obtain steady state and minimize the effects from the initial condition. The CPU time of all the simulations is quite similar, which is 5 hours approximately with both the hydraulic model and water quality model activated. The simulation results for all the cases show differences in $\text{COD}_{Cr}$ concentration due to the different wastewater discharge flow rate and different discharge $\text{COD}_{Cr}$ concentration. The simulation results for all the cases are shown in Figure 5.

As shown in Figure 5(a) to Figure 5(c), the comparison between case 1-1, 2-1 and 3-1 indicates that for different flow rate of the wastewater treatment plant, the concentration of $\text{COD}_{Cr}$ exhibits differently downstream of the wastewater treatment plant. However, due to the higher standard of the extension project, the concentration of $\text{COD}_{Cr}$ in case 2-1 and 3-1 do not show large discrepancy compared to case 1-1.

Figure 5(d) to Figure 5(i) compare the results of $\text{COD}_{Cr}$ for different operating conditions either in short term or long term simulations. From the concentration contours in Figure 5(d) to Figure 5(f) and Figure 5(g) to Figure 5(i), the normal treatment condition results in the best downstream $\text{COD}_{Cr}$ concentration, the unusual treatment condition gives a worse downstream $\text{COD}_{Cr}$ concentration, the accident treatment condition exhibits worst due to the fact that the accident treatment condition has the highest $\text{COD}_{Cr}$ discharge concentration. The simulated $\text{COD}_{Cr}$ concentrations of all the seven cases at different distances downstream of the wastewater treatment plant are given in Table 2.
Table 2. COD$_{Cr}$ concentration downstream of the wastewater treatment plant (mg/L).

| Distance L(m) | 1-1  | 2-1  | 2-2  | 2-3  | 3-1  | 3-2  | 3-3  |
|--------------|------|------|------|------|------|------|------|
| 500          | 17.7691 | 17.8491 | 18.9474 | 21.6931 | 18.0707 | 19.6121 | 23.4655 |
| 1000         | 17.7662 | 17.8459 | 18.9376 | 21.6669 | 18.0661 | 19.5983 | 23.4288 |
| 1500         | 17.7646 | 17.8439 | 18.9318 | 21.6516 | 18.0634 | 19.5903 | 23.4075 |
| 2000         | 17.7616 | 17.8404 | 18.9213 | 21.6234 | 18.0585 | 19.5755 | 23.3681 |

As shown in Table 2, COD$_{Cr}$ concentration downstream of the wastewater treatment plant reduced from L = 0 to L = 2000m in all the cases since the decay rate of COD$_{Cr}$ is 0.11. However, it is also observed that the concentration of COD$_{Cr}$ does not change too much from the initial location (L = 0) to L = 2000 although the COD$_{Cr}$ concentration keeps reducing in all the simulation cases. Due to the fact that the flow rate of Yuhui channel is 30.5m$^3$/s, which is almost 50 times greater than the wastewater discharge flow rate, therefore, the COD$_{Cr}$ concentration is highly affected by dilution in Yuhui channel rather than diffusion as well as degradation.

When comparing the simulation results of short term group (group 2) and long term group (group 3) in Table 1, Table 2 and Figure 5, the same tendency is observed in both groups, namely, higher COD$_{Cr}$ concentration of the wastewater discharge, worse water quality is obtained downstream of the wastewater treatment plant. Hence, the normal condition should be operated in order to ensure the water quality of Yuhui channel. Emergency plan should be prepared and initiated when unusual condition or accident condition happens.

4. Conclusions
In this study, a wastewater treatment plant extension project has been introduced as a case study in order to simulate the pollutant transportation in Yuhui channel. A field monitoring experiment is designed and executed in order to verify the numerical model and collect necessary data. The numerical model is then used to simulate different cases, which can be defined as recent group, short term group and long term group. Three conditions are also defined for short term group and long term group simulations, which are normal condition, unusual condition and accident condition. The simulation results indicate that the normal condition with 90% treatment efficiency will only increase the COD$_{Cr}$ concentration in Yuhui channel at most 5%, the unusual condition with 70% treatment efficiency and the accident condition with 20% treatment efficiency will lead to higher COD$_{Cr}$ concentration in Yuhui channel, thus, an emergency plan should be prepared for the wastewater treatment plant extension project in the future to minimize the effects from unusual and accident condition.

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