Two-dimensional Model for Outfall Water Quality Forecasting of Sewage Treatment Plant

Xiaomin Liu
Water Conservancy and Civil Engineering College of Inner Mongolia Agricultural University, Hohhot 010018, Inner Mongolia, China

Haiyan Liu *
Beijing Information Technology College, Department of Computer Engineering, Beijing 100018, Beijing, China

Zheng Wan
Water Conservancy and Civil Engineering College of Inner Mongolia Agricultural University, Hohhot 010018, Inner Mongolia, China

Jianguo Liu
College of Energy and Power Engineering Inner Mongolia University of Technology, Hohhot 010051, Inner Mongolia, China

Xiaoxu Liu
Inner Mongolia Water Industry Investment (Group) Limited Company, Hohhot 010020, Inner Mongolia, China

*Corresponding author (E-mail: lhy_lj@sina.com)

Abstract
Taken Yuanbaoshan district sewage treatment plant in Chifeng city of Inner Mongolia as research subject, this article analyzes the water quality change rules of Laohahe River (receiving water). Plane 2-dimensional mathematical model MIKE21 developed by Danish Hydraulic Institute (DHI) has been chosen to analyze and calculate COD and NH3-N pollution factor through Flow Model software, to analyze pollution situation and influencing characteristics of into-river sewage in left bank of Laohahe River. The research results show that water quality under boundary conditions of different flow and water level has obvious changes in time and space. The impact of discharged sewage on water quality of Laohahe River during rain seasons (25% assurance rate) and normal seasons (50% assurance rate) is little with influenced range less than 100m for rain seasons and less than 300m for normal seasons while the impact during dry seasons (75% and 90% assurance rate) is huge with about 1000m influenced range from outfall to downstream, mostly of ammonia nitrogen. The application of 2-D model realizes to forecast the impact of into-river sewage on river water quality and provides an effective technical support for water quality management.

Key words: Water Quality Mathematical Model, Water Quality, Laoha River

1. INTRODUCTION
Per regulation of "Into-river Sewage Outfall Supervision and Management Method" (22nd Order by Ministry of Water Resources), prior to set up into-river outfall in the water area, application request and submission of demonstration report on this should be carried out by construction project. The content of the report should include the impact of into-river sewage on water quality and water function zone. Due to the uncertainty of factors such as discharge condition, receiving waters and development and utilization of water resources by a third party, the influence of into-river outfall differs a lot. Generally, there’s certain difficulty to access direct data of water quality change forecasting through field tests and laboratory tests as constraint by factors like manpower, financial resources and time etc. Therefore, usually a mathematical model will be adopted to monitor the change rules of water quality in sewage river sections.

Mathematical model will decrease the research spending and shorten the research duration also it has the advantages of fast speed and no-scale-effect. With widespread application of the computer, the role and status of numerical experiments and mathematical model in scientific research and engineering design increased constantly, using plane 2-diminonal water mathematical model for river water quality analysis will become future trend for water quality control. The plane 2-D flow mathematical model MIKE21 by DHI has been chosen in this study. This model adopts alternating direction implicit scheme (ADI) for solution and the equation matrix uses double sweep for solution, providing the format has second order accuracy.

The combination of high-efficiency calculation engine and advanced graphical user interface makes MIKE21 an indispensable tool in the world, which has been applied successfully in Australia, Denmark and many other countries and regions(Xu,2010; Xu,2010). China has successfully applied MIKE21 model in
Huangpu river water flow and water quality model (Xu and Yin, 2010; Xu and Yin, 2013), the Yangtze river water dynamics (Lin and Lu and Jiao, 2008; Cui, 2002) and Taihu lake eutrophication etc. This model has been applied extensively in the field of sewage impact on river water quality in area of chongqing, Nanhu lake and Mudanjiang etc (Wang and Chen, 2001; Huang, 2004; Wang and Chen and Wu, 2004; Ma and Yin and Sun, 2015). However application of this model in the field of water quality in Inner Mongolia is infrequent and also in the field of into-river sewage impact on river basin water pollution is rare (Wang and Zhao and Wu, 2008; Liu and Liu and Jiang, 2007; Li and Ye, 2011).

Taken Yuanbaoshan sewage treatment plant in Chifeng city of Inner Mongolia as research subject, the water quality of Yuanbaoshan plant sewage, which discharged into Laohahe River (receiving waters) running through Yuanbaoshan district of Chifeng city, exceeds the water quality requirement of Liao-Inner-Mongolia buffer zone of Laohahe River. MIKE21 Flow Model software (HD module and ECO module) developed by DHI will be applied, taking COD and NH3-N as pollution factors, to verify that the sewage discharged into and diluted by Laohahe River meets water quality requirement of buffer zone, to analyze and forecast the influence range of into-river sewage under Lao Hahe left bank near shore hydrological conditions, so to provide effective measures and technical support for future water quality simulation and prediction of into-river sewage outfall as well as river basin water quality control.

### 2. OVERVIEW OF THE RESEARCH ZONE

Yuanbaoshan district of Chifeng city (41°55′~42°25′, 119°03′~119°30′) is located in the eastern Inner Mongolia Autonomous Region, bordering with Liaoning and Hebei provinces. The area totals 952.14 km². Its geographical location is 25 km distant from Beijing and 238 km from Jinzhou port. It belongs to the Bo Hai economic circle and is the nearest sea route of Inner Mongolia Autonomous Region. Yuanbaoshan district sewage treatment plant (42°03′35″ and 119°19′41″) is located around 4 km in northern Ping Zhuang area with processing capacity of 18.25 million m³/a and Lao Ha He as the receiving waters. The discharged water quality is shown in Table 1.

<table>
<thead>
<tr>
<th>Item</th>
<th>COD</th>
<th>BOD5</th>
<th>SS</th>
<th>NH3-N</th>
<th>TN</th>
<th>TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pollutant quantity (t/a)</td>
<td>75</td>
<td>15</td>
<td>15</td>
<td>7.5</td>
<td>22.5</td>
<td>0.75</td>
</tr>
<tr>
<td>Upgraded water quality (mg/L)</td>
<td>50</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>15</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Laohahe River is originated in Guangtoushan of Qi Laotu Mountains in Pingquan city of Hebei province with total length of 425 km and basin area of 29710 km². The average runoff is 1.27 billion m³. The river runs from southwest to northeast through the area of Yuanbaoshan town then into Fengshuigou town. Yingjinriver, level 1 tributary of Laohahe River, originated from Qi Laotu mountain of northern mountains in Weichang Hebei province, runs from eastern edge of Changsheng village in Yuanbaoshan town to Namniao village then joining into Lao Ha He. The river length totals 207.2 km with basin area of 10652.16 km² and average runoff of 536.8 million m³. For reference, both banks of the two rivers are flat with fertile soil. Laohahe River runs through whole Yuanbaoshan district. Louzidianriver, one of the river tributaries, runs through Ping Zhuang town where Yuanbaoshan government seat. And Yin Jinriver, another level 1 tributary, flows through Yuanbaoshan industrial park. Chifeng hydrological station was set in Yin Jinriver while Taipingzhuang and Xinglongpo hydrological stations etc. set in Laohahe River. For intra-research-area river characteristics, please see Table 2.

<table>
<thead>
<tr>
<th>River system</th>
<th>River Name</th>
<th>River Level</th>
<th>Basin Area/(km²)</th>
<th>Length/(km)</th>
<th>Average Gradient</th>
<th>Drop</th>
<th>Average Flow(m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laohahe River</td>
<td>Main stream</td>
<td>582.54</td>
<td>74</td>
<td>1/1170</td>
<td>42.7</td>
<td>41.84</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Level 1 tributary</td>
<td>137.35</td>
<td>22</td>
<td>1/650</td>
<td>33.8</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Level 1 tributary</td>
<td>193.56</td>
<td>15.3</td>
<td>1/376</td>
<td>40.7</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Level 1 tributary</td>
<td>64.98</td>
<td>18.7</td>
<td>1/556</td>
<td>33.6</td>
<td>0.27</td>
<td></td>
</tr>
</tbody>
</table>

There are four existing sewage outfalls in Liao-Meng buffer zone of Laohahe River. The total annual discharge is 18.5 million m³, total annual COD emissions is 903.16 t/a and total annual ammonia nitrogen discharge is 80.122 t/a. With operation of each sewage treatment plants, the discharge amount arrives 6.5 million m³, COD emissions of 325 t/a, and ammonia nitrogen discharge of 20.5 t/a. In 2011, NH3-N and COD of Taipingzhuang section in upstream of sewage treatment plant outfall during flood season and non-flood season are classified exceeding V-type water, meaning pollution is serious. The water quality of downstream You
Yiqiao section is much better than upstream Taipingzhuang section with NH3–N classified as IV-type and COD as IV-type while water quality of Xinglongpo section in downstream of YouYiqiao section is better that upstream Taipingzhuang section with NH3–N classified as III-type and COD as III-type. Sewage discharged by Yuanbaoshan treatment plant into Laohahe River impacted the water quality a lot.

2.1. Model Simulation Scope and Network Division

Two-dimensional convection diffusion model will be taken with equations as follows:

\[
\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + S + f_x(c,t)
\]

Among which: \( \mu \) is velocity of \( x \) direction (m/s), \( v \) is velocity of \( y \) direction (m/s), \( D_x \) is longitudinal dispersion coefficient (m²/s) and \( D_y \) is horizontal dispersion coefficient (m²/s), \( C \) is the concentration (mg/L), \( S \) is source term and \( f_x(c,t) \) is reaction term.

The modeling scope will be 18km river, 11.3 km in upstream of sewage outfall and 6.7km in downstream. Two-dimensional hydrodynamic model will be used to establish the forecast grid as shown in figure 1 and FM grid will be taken with total grids of 2182.

Figure 1. Hydrodynamic - network division of water quality model

2.2. Calculation parameter calibration and validation of hydrodynamic model

The two-dimensional hydrodynamic model for river network is established per the terrain, survey and present engineering data to verify the hydrodynamic network parameters. And this model adopts Taipingzhuang hydrology data for calibration and validation. According to Taipingzhuang measured flow data, hydrologic analogy method was adopted to calculate upstream boundary flow data. And the downstream water level was obtained by the relations between water level and flow calculated with single cross section per downstream section flow.

The climate characteristics of Yuanbaoshan is 6-month frozen period, rainfall concentrated in June to August of each year, and basin evaporation capacity in late June and August is huge with occurrence of dry river. In order to choose reasonable model parameters, water level data from June 1, 2009 to June 15th in Taipingzhuang is taken for verification with results shown in figure 3. Through flow verification, rated roughness value \( n \) is about 0.032, which meets the model requirements.

2.3. Initial conditions and boundary conditions

Initial conditions of outfall: Lao Ha He bottom elevation in the outfall of sewage treatment plant is 483.86m and the outfall bottom elevation is 490m, which is above the water level of 487.71 m in fifty years. Therefore, there is no flood safety concern.

For different designed annual horizontal peak flow and average flow, corresponding parameters in Feasibility Report of Three-water-resource Water Supply Project in Ping Zhuang Town, Yuanbaoshan District, Chifeng City. Simulated water level adopted the water concentration changes of nearshore in left bank of Laohahe River after sewage entering into river under assurance rate of 25%, 50%, 75% and 90% respectively.

According to Feasibility Report of Sewage Treatment Plant Upgrading Project in Yuanbaoshan District Chifeng City, the design water quality of the sewage treatment plant reaches Level 1A standard in the Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant(GB18918-2002). For details, please see table 3.
Figure 2. Taipingzhuang Water Level Verification Figure

Table 3. Into-river Outfall Design Water Quality

<table>
<thead>
<tr>
<th>Index</th>
<th>BOD5 (mg/L)</th>
<th>COD (mg/L)</th>
<th>NH3-N (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>50</td>
<td>2</td>
</tr>
</tbody>
</table>

Boundary conditions: according to "Environmental Quality Standard for Surface Water" (GB3838-2002) (table 4) and water quality requirement of Liao-Meng buffer zone in Laohahe River where the sewage outfall located, downstream boundary conditions of the affected zone shall meet type-III water quality standard.

Table 4. Surface Water Quality Standards

<table>
<thead>
<tr>
<th>Water quality classification Testing factors</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH3-N≤</td>
<td>0.15</td>
<td>0.5</td>
<td>1.0</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>COD≤</td>
<td>15</td>
<td>15</td>
<td>20</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>BOD5≤</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>10</td>
</tr>
</tbody>
</table>

4. OUTFALL WATER QUALITY SIMULATION RESULT AND ANALYSIS

The water quality will be calculated per the sewage condition and hydrological design condition to predict the impact of discharged sewage by plant on offshore waters in left bank of Laohahe River.

Simulation for spread of COD and NH3-N of impact factors under assurance rate of 25%, 50%, 75% and 90% respectively has been carried out and part of the simulation results is shown in figure 3 and figure 4.
The figure 3 shows that COD under boundary conditions of different flow and water level has obvious changes in time and space. The impact of discharged sewage on water quality of Laohahe River during rain seasons (25% assurance rate) and normal seasons (50% assurance rate) is little due to large upstream runoff and flowing waters with influenced range less than 100m for rain seasons and less than 300m for normal seasons while the impact during dry seasons (75% and 90% assurance rate) is huge with influenced range from outfall to downstream about 1000m and decreasing pollutant concentration.
The figure 4 shows that NH3-N under boundary conditions of different flow and water level has changes in time and space similar to COD. The impact on water quality of Laohahe River during rain seasons and normal seasons is little while during dry seasons is large with maximum not exceeding 0.4% of control index. With water flowing down, ion diffuses and NH3-N metabolizes further by water self-purification ability and pollutants concentration decreases gradually then the required water quality achieved before accessing Xinglongpo hydrologic station.

According to the forecast results, even in the most adverse water conditions, into-river pollutants take through the effect of dilution, migration and assimilation, through the situation of river self-purification ability and pollutant diffusion spread effect, water quality in the downstream of Xinglongpo hydrologic station will improve to a certain extent and achieve the required standard in the downstream water function areas of DaBeihai section. As a result, water quality in the into-river outfall can meet the requirements of water function areas.

5. CONCLUSIONS

Water quality impact analysis was carried out on pollution factors of outfall in Laohahe River for Yuanbaoshan sewage treatment plant through water quality model to forecast the influence scope of sewage discharged by the outfall. The modeling results predicted accurately into-river pollution characteristics. Thus, the two-dimensional model MIKE21 can eliminate the interference of huge water flow change in north area during rain and dry seasons and has strong applicability to forecast outfall water quality, which could be applied in similar area to provide effective technical support for into-river outfall water quality simulation forecasting and water quality control management.

Acknowledgements

This work is supported by grants from the Chinese National Natural Science Foundation under contract (No.51409290).

REFERENCES


