Simulation of Point Source Pollution Transport Process in the Lower Yellow River during Non-Flood Season

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Abstract. The water body in Yellow river has poor ability to dilute and degrade pollutants during non-flood season due to less upstream inflow, which leads to pollution during non-flood season more serious than flood season. In order to evaluate the transport process of point source pollutants in the lower reaches of the Yellow River during non-flood season, a plain two-dimensional water quality mathematical model was established to simulate the horizontal and vertical propagation range of pollutants such as COD and petroleum below the outfall. Analysis of the migration regulation of pollutants in the river was performed. The results indicated that in the case without external pollution, the influence range of the emission of point source pollution during non-flood season is a certain range downstream of the sewage outlet. The concentration of pollutants at the outlet side is greater than that the other side until the distribution of pollutants across the section tends to be consistent, which provides technical support for assessing the impact of point source pollution on water environment during non-flood season.

Keywords. Non-flood season, lower Yellow River, water quality model, point source pollution.

1. Introduction
Water quality model was widely applied in the simulation, prediction, and assistant decision-making of water quality, which plays an important role in analyzing water pollution and controlling water environment [1]. The distribution of pollutants in water body is influenced by physical, chemical, and ecological processes, which results in complex migration and transformation process including transport, mixing, adsorption, desorption, precipitation, resuspension, and biodegradation, etc. [2].

Water quality model describes the regulation and relationship between physical, chemical, biological, ecological, and other aspects of the water quality components that participate in the water cycle [3]. Up to now, water quality model has developed from single variable to multi variables, from point source pollution to non-point source pollution, and from zero-dimensional model to one-dimensional, two-dimensional, and three-dimensional models gradually [4-5]. The physical meaning of the dispersion and diffusion of pollutants in water is simple, and easy to understand and establish model. However, the relationship between pollutants and other media, and the biodegradation of pollutants are still in the stage of laboratory research. The reason is that dispersion coefficient related to hydraulic conditions, comprehensive degradation coefficient related to biodegradation, and source and sink terms related to other media are difficult to be determined quantitatively, which is also the main factor restricting the development of water quality model [6-8].
As far as the Yellow River, the complex boundary conditions, hydrodynamic conditions and the high sediment concentration of river increase the difficulty in applying the water quality model. Moreover, the existing water quality models are still in the exploratory stage, which is inadequate to be applied in reality. In this study, the research ranged from 10km above the Yellow River Bridge to 10km below the Yellow River Bridge in Luoyang city, which focused on the impact of Jili sewage outlet on the water environment quality. The non-flood season was selected due to the pollutants migration and transformation is most unfavorable. Meanwhile, affected by the operation of Xiaolangdi reservoir, the sediment concentration in the river is low, so the influence of sediment is neglected in the model.

2 Methodology

2.1 Water Quality Model and Solution [9]

\[
\frac{\partial c}{\partial t} + \frac{\partial}{\partial x}((Hu) \bar{u}) + \frac{\partial}{\partial y}((HV) \bar{v}) = 0
\]  

\[
\frac{\partial (Hu)}{\partial t} + \bar{u} \frac{\partial (Hu)}{\partial x} + \bar{v} \frac{\partial (Hu)}{\partial y} = fHV - gH \frac{\partial c}{\partial y} + \frac{1}{\rho} \tau_{xw} + \frac{1}{\rho} \tau_{yb} + \frac{\partial}{\partial x}(HV \frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(HV \frac{\partial u}{\partial y})
\]  

\[
\frac{\partial c}{\partial t} + \bar{u} \frac{\partial (Hc)}{\partial x} + \bar{v} \frac{\partial (Hc)}{\partial y} = \frac{\partial}{\partial x}(D_x \frac{\partial c}{\partial x}) + \frac{\partial}{\partial y}(D_y \frac{\partial c}{\partial y}) - kHc + w
\]

where \(\bar{u}\) and \(\bar{v}\) are the vertical average velocity in the x and y direction, respectively, \(\tau_{xw}\) and \(\tau_{yw}\) are the wind stress along x and y direction, respectively, \(\tau_{xb}\) and \(\tau_{yb}\) are the bed shear stress along x and y direction, respectively; \(\rho g \bar{u} \sqrt{u^2 + \bar{v}^2}\) is the Kirschner force, \(H\) is the water depth, \(z\) is the water level, \(h\) is the distance from the base level to the bed surface, \(H = z + h\); \(C\) is the Cheshire coefficient, \(C = \frac{H}{n}\); \(n\) is Manning's coefficient, \(c\) is the vertical average concentration of pollutants, \(k\) is the degradation coefficient, \(W\) is the source term, \(D_x\) is the longitudinal dispersion coefficient, and \(D_y\) is the horizontal dispersion coefficient.

The water quality model consists of hydrodynamic model and water quality model based on the hydrodynamic model. Equation (1) is the continuous equation, equations (2-3) are momentum equations in x and y directions respectively, and equation (4) is convection diffusion equation of pollutants. The influence of surface wind stress is not considered, so \(\tau_{xw} = \tau_{yw} = 0\). The finite volume method (method omitted) was applied to solve the equations.

2.2 Initial Conditions and Boundary Conditions

2.2.1 Initial Conditions. \(U(x,y,0) = 0\), \(V(x,y,0) = 0\), \(C(x,y,0) = C_0(x,y)\), where \(C_0(x,y)\) is the background
concentration of various pollutants in the simulation.

2.2.2. Boundary Conditions. Fixed boundary:

\[
\frac{\partial U}{\partial n} = \frac{\partial V}{\partial n} = 0, \frac{\partial C}{\partial n} = 0
\]  

(5)

Inflow boundary:

\[
Q = Q_0(t), C = C(t)
\]  

(6)

Outflow boundary:

\[
Z = Z_0(t), \frac{\partial C}{\partial n} = 0
\]  

(7)

Source strength boundary:

\[
Q_w (m^3/d) \text{ And the actual measured pollutant concentration } c (mg/l), \text{ the dry weight of pollutants from various pollution sources is calculated (kg / day) and } w \text{ is the input value of source strength intensity.}
\]

2.3. Key Technology Processing

The dispersion coefficient is calculated by the following equations.

\[
D_x = \alpha_x u', D_y = \alpha_y u'
\]  

(8)

where \( u' = \sqrt{ghl}, I = \frac{u^2}{RC^2}, \) \( \alpha_x \) and \( \alpha_y \) are empirical coefficients of 4 and 0.5 respectively. The degradation coefficient are \( K_{cod} = 0.020/\text{day}, \) and \( K_{petroleum} = 0.015/\text{day}, \) respectively (see Research Institute of water resources protection of the Yellow River).

3. Case Analysis

3.1. Overview of the Study Area

Jili District of Luoyang city is located on the left bank of the lower reaches of the Yellow River with many chemical enterprises. The production and domestic sewage are discharged into the lower reaches of the Yellow River through the Erdao River on the left bank, and it can cause pollution of the local river section downstream of the sewage outlet if the point source pollution discharge exceeds the discharge standard during non-flood season. The plane two-dimensional water quality model was established to simulate the impact of discharging point source pollution. The selection of river section calculated is mainly focused on the impact range of sewage on the upstream and downstream, i.e., the calculated river section can cover the impact area of pollutants. The river section is 1km upstream and 10km downstream of outlet. The main stream of the Yellow River fluctuates strongly with the wide surface and shallow depth. The two sides of the river are controlled by the diversion engineering, so it belongs to the typical wide shallow section. Furthermore, the prediction period is the dry season, and the discharged water is almost clear water with less sediment content, and the impact of sediment on pollutants in water body is not obvious due to the operation of Xiaolangdi Reservoir in the upstream. The water environment quality standard is the grade III in Environmental quality standards for surface water (GB3838-2002), and the water quality is mainly affected by the Xiaolangdi Reservoir in the upper reaches together with the sewage outlets and agricultural non-point source pollution along the Yellow River. Due to the limited self-purification capacity of water body, the impact of sewage discharge on the water quality of the Yellow River during the non-flood season is stronger than that during the flood season under the same sewage discharge condition. Therefore, the non-flood season is selected as the most unfavorable condition to study the impact of sewage discharge on the water environment quality of the Yellow River and the discharge amount during non-flood season is taken as
300 m$^3$/s.

3.2. Calculation Conditions

The topography of the study river section is based on the measured section data after the flood season in 2018, and the elevation of grid nodes is interpolated. According to the measured bed sediment composition from Xiaolangdi to Huayuankou in the downstream of Yellow River, the roughness coefficient is taken as 0.016.

According to the monitoring results of Erdao River at section of 50m before entering the Yellow River Estuary, the water quality factors with serious pollution were selected as the variables to predict the transport process of Erdao River in the lower Yellow River and its impact on the water environment quality of the river section. The average values of the current monitoring results of 1000 m downstream of the Yellow River and 2000 m downstream of the Yellow River are taken as the background values of the Yellow River water quality in the study area. The distribution of pollution sources is shown in figure 1, and the monitoring results of typical pollutants in each section are shown in table 1.

![Figure 1. Calculation area.](image)

### Table 1. Monitor results of typical pollutants in each section (Unit: mg/l).

| Section | Sampling location                                                                 | Attribute | Water quality factor | COD  | Petroleum |
|---------|----------------------------------------------------------------------------------|-----------|----------------------|------|-----------|
| W2      | Mengjin bridge on the Yellow River                                               | mean value| 16.2                 | 0.04 |           |
| W3      | 1000m downstream the discharge outlet of the Yellow River                         | mean value| 18.7                 | 0.06 |           |
| W4      | 2000m downstream the discharge outlet of the Yellow River                         | mean value| 18.1                 | 0.05 |           |

3.3. Result Analysis

3.3.1. COD Prediction and Analysis. The COD values at W3 and W4 sections were selected as the background values, and the interpolated node values were taken as the initial values. The designed Erdao River discharge is 0.3 m$^3$/s with concentration of 150 mg/l.

The results indicated that drainage of Erdao River has effects on the COD concentration in the river due to higher drainage COD concentration at Erdao River, especially the lower sections below the outlet (figure 2). The influence of the drainage discharge into the Yellow River on the flow field is not obvious due to less discharge at Erdao River (figure 3). In the area between the entrance of the study river and the upstream of Erdao River into the Yellow River, the concentration of COD is gradually decreasing due to dispersion and degradation, and the average concentration is about 15.8 mg/l in the
upstream area of the Yellow River. However, a pollution zone with higher concentration is formed at the downstream of the sewage outlet. The envelope with contour line of 20 mg/l has a width of 400 m and a length of 3500 m, which is the main impact area of sewage discharge. The external COD concentration of this area is less than 20 mg/l, which meets the grade III water quality standard (figure 4). The concentration of COD in the left bank near the outlet is higher than that in the right bank, and the farther away from the outlet, the concentration tends to be consistent in the cross section because of the influence of convection and diffusion.

Figure 2. Distribution of calculated COD concentration in studied river reach.

Figure 3. Distribution of COD concentration near sewage outlet.

Figure 4. Contour map of calculated COD concentration near sewage outlet.

3.3.2. Prediction and Analysis of Petroleum Pollution. The petroleum pollution values at W3 and W4 sections were selected as the background values, and the interpolated node values were taken as the
initial values (figure 5). The designed Erdao River discharge is 0.3 m$^3$/s with concentration of 2 mg/l (figure 6).

![Figure 5. Distribution calculated petroleum pollutants.](image)

![Figure 6. Distribution of process flow and petroleum pollutant concentration near sewage outlet.](image)

![Figure 7. Contour of calculated petroleum pollutant concentration near the sewage outlet.](image)

Petroleum pollution is treated as soluble pollutants. The results indicated that the migration process of petroleum pollution in the downstream of the sewage outlet is similar to that of COD concentration.
The pollution zone with 0.05 mg/l of sewage concentration is about 380 m wide and 3600 m long (figure 7).

4. Conclusion
(1) Two-dimensional water quality model can simulate the migration process of point source pollutants in water body during non-flood season.

(2) When pollutants enter the water body, the dispersion caused by velocity gradient and the diffusion caused by concentration gradient determine the migration speed of pollutants. The dispersion effect is greater than the diffusion, and pollutants migrate slower horizontally. The concentration of pollutants in the sewage bank side is greater than that of the other side until the concentration tends to be uniform in the cross section. The calculation results fit the general regulation.

(3) In this study, the calculation period is non-flood season with low sediment concentration. Therefore, the interaction between sediment and pollutants is neglected in the model. However, the sediment problem cannot be avoided when water quality model is established on the Yellow River, so relevant experimental research is needed.

(4) Lack of measured data to calibrate parameters and verify the model. The accuracy of the model is affected by the parameters of dispersion coefficient and comprehensive degradation coefficient.

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