Risk Assessment of Sudden Water Pollution Accidents Based on the One-Dimensional Hydrodynamic Model for Weihe River Basin, China

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Abstract. The frequent water pollution incidents can lead to deterioration of water environment and increase risk of endangering people’s health. According to the characteristics of sudden water pollution accidents, a one-dimensional river-water pollution model was established in this study using hydrodynamic method. Then, taking the Weihe river basin as an example, the longest distance, size of longitudinal dissociation, and the risk range of contaminants were estimated via the model. Moreover, the changes of contaminant concentration risk in the different flow were assessed by the emergency measures of water diversion, which could achieve the purpose of improving water quality in a short time, and greatly reduce the risk of water pollution accidents. The results showed that, in the flow of $30\text{m}^3\text{s}^{-1}$ and $60\text{m}^3\text{s}^{-1}$ the maximum contaminant distance moved forward 34\% and 49\% than natural condition. Meanwhile, the maximum concentration was decreased by 30\% to 40\% and the total length section was approximately reduced by 25 to 45\%. These validations have showed the method is an ideal tool for making pollution accident emergency treatment. However, the parameters of the model should be adjusted for different watersheds. This study can provide the basis for the water pollution risk decision management.

Keywords. Sudden water pollution accidents; river basin; hydraulic model; emergency measures; risk assessment.

1. Introduction
Water is an important foundation for ensuring the survival and development of human beings and maintaining ecological balance. However, many parts of the world have been facing various problems of water resources such as water pollution, the deterioration of water environment and so on [1-4]. Sudden pollution accident is characterized by suddenness, instantaneous and serious harmfulness, so the emergency disposal is needed to deal with it [5, 6]. When the water pollution accidents occur, the water ecological environment of the polluted area will be affected in a short time [7, 8]. In recent years, water pollution incident frequently occurs in the major basins of the world, which can lead to the deterioration of water environment and the reduction or loss of the use value and function of water [9, 10]. Besides, it seriously threatens the water supply safety and increases the risk of endangering people’s health. Therefore, how to deal with the sudden water pollution accidents has become an urgent problem to be solved.
Many scholars have paid great attention to the water pollution issues and conducted quantitative researches on it. In addition, according to the characteristics of uncertainty and information incompleteness of sudden water pollution accidents, many meaningful studies on the river water pollution accidents also have been performed from different angles, such as the emergency measures and response system proposed based on different sensibility of the sudden pollution incidents [11, 12], contaminant spills in the truckee River [13], the migration and diffusion process of sudden dangerous chemicals in water pollution [14, 15], the warning and control strategy for sudden water pollution accidents [16-18], the simulation of pollution process [14, 19], and various researches on the measures of emergency management [20, 21]. At the same time, water multi-stage processing technique, GIS technology decision framework, two-dimensional water quality model [23, 24] and other approaches have also been used for the assessment of water pollution accident.

Although the above researches and measures of the emergency risk assessment on sudden water pollution accidents have been successfully carried out, there are some limitations. For example, the risk assessment, the emergency treatment methods and the simulations of sudden river water pollution accidents have not been thoroughly studied. So, in this study, taking Weihe River basin as a case, the concentration changes of the pollutants in time and space were quantitatively investigated by using one-dimensional hydraulic model and the water flow measures, so as to determine the risk degree of pollution hazards. The results can provide a basis for the decision makers to effectively carry out the prevention and emergency treatment for sudden water pollution accidents.

2. Methods

2.1. Methods

The emergency risk assessment model for the sudden water pollution accidents occurring in river basin was firstly established by hydrodynamic and water-quality methods. The main steps were shown as follows:

(1) Model establishment

Generally, after the discharge of pollutants into water body, the mixing process of the pollutants and water body can be divided into three stages. The first stage is three-dimensional mixing, that is, mixing in the vertical (depth direction), horizontal (width direction) and longitudinal (flow direction) directions. Then, the pollutants enter the two-dimensional mixing stage. The mixing distance is generally determined by the hydrological conditions of river. Finally, the mixing of pollutants and water moves along the direction of the river flow by one-dimensional law.

Assuming that river water flows in the form of plug flow, there are three major processes: molecular diffusion, turbulent diffusion and diffusion. So, the hydraulic model can be established as equation (1).

\[
\frac{\partial (AC)}{\partial t} + \frac{\partial (QC)}{\partial x} = \frac{1}{\partial x} \left[ (\varepsilon_m + \varepsilon_T + D_s)A \frac{\partial C}{\partial x} \right] + SA
\]

(1)

where \(C\) represents the concentration of pollutants in the control volume (mmg/L); \(Q\) is the flow through the control volume (m³/s); \(A\) represents the water area (m²); \(S\) is the degradation of pollutants per unit time and per unit volume (g/m³.s); \(\varepsilon_m\) is the molecular diffusion coefficient; \(\varepsilon_T\) is the turbulent diffusion coefficient; And \(D_s\) is the diffusion coefficient.

The flow exhibits a great impact on the diffusion and migration of pollutants. The average flow velocity of the river is exponentially related to the water level, which can be expressed as follows:

\[
Q = h \cdot l \cdot n
\]

(2)

\[
u = nh^2 J^2
\]

(3)
\[ A = h \cdot l \]  

where the velocity of the river section is \( u \) (m/s); \( h \) is the depth of the river (m); \( J \) is the hydraulic gradient; And \( l \) is the width of the river.

The concentration of pollutants varies with the change of river water level. Meanwhile, the molecular diffusion coefficient and turbulent diffusion coefficient are smaller than diffusion coefficient, and the magnitudes of them are \( 10^{-5} \text{ to } \ 10^{-4} \) and \( 10^{-2} \), respectively, which can be ignored under normal circumstances. So, the hydraulic model can be further expressed as follows:

\[
\frac{\partial C}{\partial t} + \left( h - \frac{D}{h} \right) \cdot \frac{\partial C}{\partial x} = D \cdot \frac{\partial^2 C}{\partial x^2} + \left( k_x - \frac{\partial h}{\partial x} - \frac{\partial h}{\partial t} \cdot h \right) C \tag{5}
\]

where \( k_x \) is the degradation coefficient of pollutants (\( d^4 \)).

(2) Model solving

As the dispersion effect is more obvious than the diffusion effect in small rivers, one-dimensional diffusion model can be used for the simulation of the pollutant discharge accidents in various small rivers. The analytical solution of one-dimensional water-quality model can be obtained by using Fourier transform, and the concentration field of the pollutants can be calculated by equation (6).

\[
C(x,t) = \frac{M}{\hat{h}^{(0)}(k) \sqrt{4\pi D_t}} \exp \left[ -\left( \frac{x-u'_t t}{4D_t} \right)^2 \right] \cdot \exp(-k_x t) \tag{6}
\]

where \( \hat{h}^{(0)}(k) \) is the water level of the stream segment \( x \) from the accident point at the time of \( t \) hour. At present, there are many calculation methods on the longitudinal dispersion coefficient of pollutants. In this study, Fisher formula was used to estimate the value of \( D_x \), that is,

\[
D_x = 0.01u'^2 \cdot hu, \text{ where } u = \sqrt{ghJ}.
\]

The pollutant degradation coefficient \( k_x \) can reflect the variation of pollutants along the length of river, which is an important parameter to calculate the pollutant load. Moreover, it is related to river hydraulics, pollutant species, river bedroughness, aquatic organisms and other factors. It is generally believed that the degradation coefficient of pollutants \( k_x \) is linear with the flow velocity of river sections, which can be calculated as follows:

\[
k_x = \alpha u + \lambda \tag{7}
\]

where, the value of coefficient \( \alpha \) and \( \lambda \) can be obtained according to the experimental model test. It is generally considered that the values of \( \alpha \) and \( \lambda \) range from 0.4 to 0.8, and 0.04 to 0.08, respectively. In the present study, \( \lambda = 0.5 \) and \( \alpha = 0.06 \).

(3) Estimation on the allowable maximum value of pollutant concentration

When the sudden pollution accident occurs, the threshold of the risk level concentration may be \( C^*_0 \) at the downstream reach of the occurrence site \( x_n \). The allowable maximum value of pollutant concentration at the water quality sensitive area or the monitoring control section is \( C_{\text{max}} \), which is shown as follows:

\[
C_{\text{max}} = (C^*_0 - C_0)A \sqrt{4\pi D_t} \cdot \exp(k_x t) \tag{8}
\]

\( C_0 \) represents the background concentration of the pollutants in the upstream of the river.
When \( C_{\text{max}} \geq C_0^* \), a pollution risk distance may be caused, and vice versa when \( C_{\text{max}} \leq C_0^* \). According to the value of \( C_{\text{max}} \), decisionmakers can quickly evaluate the scale affected by the accident to predict the key areas that need to be prevented, and to establish the corresponding plan and measures. The maximum time of the accident, \( T_m \), is defined as the total time when the concentration value of the center of the pollution zone is higher than a certain level of hazard threshold, which was shown as follows:

\[
T_m = \frac{1}{K} \ln \frac{m}{4\sqrt{\pi D_x} (C_0^* - C)}
\]  

The total length of the polluted river section caused by sudden water pollution accident is defined as the longest distance of accident hazard \( X_m \), which can be expressed as follows:

\[
X_m = \frac{um^2}{4\pi D_x A^2 (C_0^* - C_0)^2}
\]

On the polluted area which is formed by the instantaneous point source discharge of pollutants in sudden water pollution accident, the concentration range of the polluted area is defined as the damage radius of accident. After the pollutants are instantaneously discharged into the river, the pollution mass with higher concentration is just beginning to form. Then, the pollutants migrate downstream along with the movement of the river water and the concentration value of the pollutants in river water exceeds the pollution threshold to a certain extent through the effects of degradation and dispersion, resulting in the gradual expansion of the polluted area and scope. When the range is expanded to the maximum radius \( R_m \), it shrinks. At this time, \( \tau \) is the time to reach maximum radius, and the formula used to calculate it was shown as follows:

\[
\tau = \frac{1}{2K} \left[ \ln \frac{m}{A \sqrt{4\pi D_x} (C_0^* - C_0)} - 0.5 \right]
\]

\[
R_m = 2\sqrt{\pi D_x} \times \sqrt{\ln \frac{m}{\sqrt{\pi D_x} A (C_0^* - C_0)} - K \tau}
\]

2.2. Verification of Model Parameters
The middle reaches of the Weihe River with a length of 180km located from Baoji city to Xianyang city were taken as the research area for the verification of model parameters. Three contaminants, including COD, BOD, NH3—N, and water level and flow were measured during June 20 to July 5, 2016. These data were collected twice a day from the monitoring sites including Fengling (S1), Linjiaucun (S2), Yimenzheng (S3), Weijiabu (S4) and Jiangzhang (S5) in the Weihe River (figure 1).

The simulation and verification on the water level and flow of the Weihe River were performed by using the data measured from June 21 to July 5, 2016. The determination of water quality parameters is a process of trial and repeated simulation, which is usually based on the existing information of river water quality and the variation of pollutants in the water flow. First, the initial parameters were selected and the calculated results were compared with the measured values, and then the parameters were adjusted until the simulation accuracy could meet the requirements that square of deviation (\( \delta^2 \)) was in the range of 0.72-0.85. The attenuation coefficient was obtained by comparing the simulated value of COD with the measured value (figure 2), the maximum error of the simulated value was 8%, and the overall effect was better.
Figure 1. Research area and monitoring sites.

Figure 2. Comparison of the measured and simulated values of water level, flow and water quality.

Through the simulation of the water level and flow in Weihe River section, the relevant parameters of the hydrodynamic model including the water level, flow and the water quality were determined. The results showed that the simulation values of the water level and flow in the selected section were close to the measured values of those, and the relative error was less than 5%, which was within the allowable error range, indicating that the model can be applied to hydrodynamic simulation.

3. Risk Estimation of Pollution Accidents

3.1. Concentration Changes of Pollutants

The pollutant emission of the sudden pollution and the values of the pollutant water quality were assumed to put it as pollutant mass of 1000 kg leads to concentration of pollutant of 0.05 mg/L. The pollution distribution over time relied on the purification capacity of the river itself rather than engineering measures. The concentrations of pollutants in different sections changed with time. The data in figure 3 showed that, after 5 hours in entrance the concentration of pollutants began to exceed...
the standard pollution concentration. And 15 hours after the accident, the concentration of pollutant reached the maximum. After 45 hours the contaminant concentration decreases to the water quality standard. The time to exceed the standard contaminant concentration was of 30 hours. Then, it dropped to the standard range of water quality at 60 km, 50 km and 40 km from the accident point, the maximum concentrations of pollutants were decreased significantly by 14%, 18% and 25% respectively. However, the pollution time was prolonged.

Figure 3. Concentration changes of pollutants in different sections under natural condition.

The data shown in figure 4 demonstrated the changes of pollutant distribution at different time. The finding showed that the maximum contaminant distance in natural rivers was 28 km. Meanwhile, it depends on the time in 24 hours. The maximum concentrations of pollutants were decreased by 30 to 40% over time at each time interval of 60 hours and 48 hours. In this case distance reach 60km and 50 km, respectively. The maximum contaminant concentration distance moved forward by 20% and the total length of pollution sections was approximately reduced by 25 to 45%.

Figure 4. Distribution of pollutant concentrations in different sections under natural condition.

3.2. Risk Assessment of Emergent Disposal
The method of water diversion and flushing out pollutants was used for the emergent disposal of sudden water pollution accident. The process was that the flow of the river water was increased to 30 m$^3$·s$^{-1}$ and lasted 24 hours, and then it was increased to 60 m$^3$·s$^{-1}$ for another 24 hours.

As shown in figure 5, the pollutant groups were reduced quickly after increasing the flow of river water. Moreover, the time when the front pollutants reached each section was shorter with the increase of the flow rate. The maximum concentration of contaminants was reduced by 37% to 46%. The time taken for pollutant concentration to exceed the standard was reduced by 25% to 45%, and the time of continued excessive contamination risk was reduced by 30% to 41%. The pollutant concentration with
high risk only occurred at 40 km and 50 km from the accident point, and that at 60 km no longer existed.

Figure 6 indicated that the maximum contaminant distance under the conditions with the flow of 30 m$^3$/s$^{-1}$ and 60 m$^3$/s$^{-1}$ at different time moved forward 34% and 49%, respectively, which were higher than that under normal condition. In the absence of water flush, that is, under the condition of normal flow, the pollutant concentration exceed 1.0 mg/l at 30 km. and the moving distance of the pollutant concentration was only 10 km and 5 km at the flow of 30 m$^3$/s and 60 m$^3$/s, respectively. With the increase of the flow, the vertical lengths of pollutants were increased and the overall concentration of the pollutants was decreased significantly.

![Figure 5](image1.png)

**Figure 5.** Concentration changes of pollutants in different sections under the flow condition of 30 m$^3$/s$^{-1}$ and 60 m$^3$/s$^{-1}$.

![Figure 6](image2.png)

**Figure 6.** Distribution of pollutant concentration under the conditions with the flow of 30 m$^3$/s$^{-1}$ and 60 m$^3$/s$^{-1}$ at different time.

As the flow was increased, the indexes for pollution risk were decreased and the contamination risk occurred much earlier (figure 7). In addition, as the pollution risk section moved forward and the distance from the accident point increased. Within 24 hours, the pollution risk indexes which exceeded 0.5 were relatively large under the natural condition or at the flow of 30 m$^3$/s$^{-1}$. However, there was no section with high-risk index under the flow of 60 m$^3$/s$^{-1}$. At 36 hours, the sections with high risk were significantly decreased as the result of the method of water diversion and flushing out pollutants.
can be reduced by the method of the

Figure 7. Changes of risk indexes for different sections with different flow on 24 hours and 36 hours after the accident.

4. Discussion

In this study, the estimated results on the water quality, water level and the flow of the Weihe River basin, which were obtained from the one-dimensional hydrodynamic model, were compared with the measured values. The estimated results were basically identical to the measured data. The relative error of the estimated values was less than 8.6%, which was within the error range of contaminant coefficient (<9.2%). The result showed that the method used in this study was an ideal tool that can be applied in the risk assessment of sudden water pollution accidents.

The results in the present study are consistent with those in previous studies on simulating the changes of pollutant concentrations in river water using other methods [25, 26]. The peak concentration of pollutants can be reduced to a certain extent by the method of water flushing and dilution. The travelling speed of the pollution cloud became faster. The overall concentration of pollutants and the risk of contamination were reduced with time. Meanwhile, the decline on the overall concentration of pollutants became more obvious with the increase of the flow. Besides, the length of the pollution group was increased. It is considered that the water diversion can reduce the total amount of pollutants in water, while it can accelerate the downstream movement of pollutants and dilute them, thus reducing the risk of the overall concentration of pollutants and increasing and increasing the radial diffusion range of pollutants at the initial moment. So, the emergency time for the sensitive area of the downstream can be reduced by the method of water diversion and flushing out pollutants. However, at the same time, it can also extend the scope of pollution group and may lead some risk on the emergency treatment of sensitive areas at the downstream such as the functional area of water.

Through above the analysis, it can be summarized that there are both advantages and disadvantages to use the emergency measures based on the flow to deal with sudden water pollution accidents. In the actual application process, the flow of water diversion should be calculated according to the actual situation such as the location of accidents, flow and the total amount of pollutants, thereby taking appropriate contingency measures to reduce the pollution risk. The water quality standard for different rivers should be determined, while the dilution degree of the pollutants that influence the amount of flushing wastewater should be also determined for the risk prediction management.

5. Conclusion

According to the variation of the pollution group along the river under different emergency engineering at different times, the moving and diffusion process of pollutants in sudden water pollution accidents and the changes of pollutant concentrations can be simulated by the one-dimensional hydrodynamic model established in this study. Meanwhile, the longest distance of the accident hazard, the length and size of longitudinal dissociation and the risk range of the pollutants can be quantitatively predicted.
In the present study, through the simulation the moving and diffusion process of pollutants in sudden water pollution accidents by one-dimensional hydrodynamic model, it was found that the purpose of improving water quality in a short time and decreasing the risk of water pollution accidents could be achieved by using the emergency measures based on different water flow. At the same time, this method can also guarantee the safety of water supply after the accidents. So, it is considered to be a useful tool for emergency treatment of sudden water pollution accidents. In addition, this study can provide the basis for the optimization of contingency plans for sudden water pollution accidents.

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