Risk Assessment of Pollution Emergencies in Water Source Areas of the Hanjiang-to-Weihe River Diversion Project

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Abstract. [Objective] This study quantitatively evaluated risk probabilities of sudden water pollution accidents under the influence of risk sources, thus providing an important guarantee for risk source identification during water diversion from the Hanjiang River to the Weihe River. [Methods] The research used Bayesian networks to represent the correlation between accidental risk sources. It also adopted the sequential Monte Carlo algorithm to combine water quality simulation with state simulation of risk sources, thereby determining standard-exceeding probabilities of sudden water pollution accidents. [Results] When the upstream inflow was 138.15 m³/s and the average accident duration was 48 h, the probabilities were 0.0416 and 0.0056 separately. When the upstream inflow was 55.29 m³/s and the average accident duration was 48 h, the probabilities were 0.0225 and 0.0028 separately. [Conclusions] The research conducted a risk assessment on sudden water pollution accidents, thereby providing an important guarantee for the smooth implementation, operation, and water quality of the Hanjiang-to-Weihe River Diversion Project.

1. Introduction
In recent years, water pollution accidents have occurred frequently in China. Because sudden water pollution accidents are characterized by substantial unpredictability, risk assessment of river water quality after accidental pollution is of great significance to the water quality management of water diversion projects. Xu Xinyi et al.[¹] analyzed water quality risks of the first stage of the South-to-North Water Transfer East Line Project according to the project’s water quality requirements, pollution control objectives, and pollution remediation programs. Basing their work on the collection and analysis of water quality information, Lu Hongwei et al.[²] found that water pollution, especially in Junshan, China, had potential ecological risks. Wen Jun et al.[³] employed Spearman’s rank correlation test, correlation analysis, and variance analysis to analyze water quality risks in the Fuchun River and Xinan River watersheds. The waters in the two watersheds met the water quality requirements, with low risks of deterioration. Basing their work on the definition of risk, Li Jingbo et al.[⁴] specified the definitions, connotations, and function expressions of urban water supply risks, and predicted the prospect of water supply insurance. Chang Fuxuan et al.[⁵] took the middle line of the South-to-North...
Water Transfer Project as their research object. They combined risk identification with random simulation, long sequence reservoir calculation, orthogonal experiments, and range analysis to explore water supply risks in the middle and lower reaches of the Hanjiang River and sensitivity to the various influencing factors. The results showed that the water shortage risk index was most sensitive to water demand and least sensitive to water transfer. Using a groundwater monitoring system, Zhang Nan et al.\cite{6} simulated a and chloride shift in underground water in Jilin City and carried out a risk assessment on pollution accidents caused by chloride ions. Ma Li et al.\cite{7} discretized the models and simulated velocity fields in Huainan’s Huai River based on a surface water modeling system (SMS), a Navier–Stokes equation, and a finite element method. They simulated water quality in that area by RMA4 modules of SMS and proposed to limit coastal pollutant emissions, thereby providing bases and references for water conservation in the Huai River. Basing their work on existing research in China, Chai Zengkai et al.\cite{8} introduced the use of Bayesian networks in the identification of water quality risks and employed hydrodynamic models for water quality risk assessment and prevention research. When constructing forewarning index systems for transboundary water pollution accidents, Li Erping et al.\cite{9} modified the model of health risk assessment proposed by the US EPA and considered it an important forewarning index.

Our research considered water conveyance lines of a water diversion project as an organic whole and on this basis studied water quality, which indicates whether residence in the water receiving areas have safe drinking water. Using a sequential Monte Carlo algorithm, we combined water quality simulation and state simulation of risk sources with Bayesian networks, thus quantitatively assessing standard-exceeding risks of sudden water pollution accidents under the influence of multiple risk sources.

2 Basic Theories and Methods

2.1 Sequential Monte Carlo Algorithm\cite{10}

In this study, we used the time series Monte Carlo\cite{11-12} model of power system reliability assessment to determine the risk of sudden water pollution accidents in rivers.

2.1.1 State Simulation of Risk Sources

During the state simulation, operating states of risk sources were simplified into two kinds; namely, the normal operating state and the accidental state. The risk sources were deemed to operate in accordance with the process of “normal–accidental–normal–accidental.”\cite{13}

In the accidental state, pollutant leakage strength is a random variable, where T is the duration of the various states of risk sources. According to the model hypotheses of Sun Pengcheng for the sequential Monte Carlo algorithm, the average duration of the normal operating state and the average duration of leakage in the accidental state are T1 and T2 respectively. The transfer rate of risk sources from the normal operating state to the accidental state or from the accidental state to the normal operating state is

\[ \lambda = \frac{1}{T_1} \quad \mu = \frac{1}{T_2} \]  

The probabilities in the normal operating state and the accidental state are described as

\[ P_1 = \frac{\lambda}{\lambda + \mu} \quad P_2 = \frac{\mu}{\lambda + \mu} \]  

2.1.2 State Duration Models

The duration of an accident varies depending on the risk sources. When a leakage accident lasts for a short time, it is deemed a transient event. Generally, the leakage duration of definite leakage accidents follows an exponential distribution. The calculation formula of accident duration T3 is
\[ T_3 = -T_{MTTR}\ln r \]  

where \( T_{MTTR} \) is the average accident duration, and \( r \) is the uniform random number of \( U(0,1) \).

### 2.2 Risk Assessment Models for Water Quality

#### 2.2.1 Bayesian Theory

Assume that \( H \) and \( E \) are two random variables, \( H = h \) is a hypothesis, and \( E = e \) is valid. When \( E = e \) and a probability estimation is done on \( H = h \), \( P(H = h \mid E = e) \) is called a posterior probability. In this case, the Bayesian theorem can be expressed with prior probability and posterior probability as

\[
P(H = h \mid E = e) = \frac{P(H = h)P(E = e \mid H = h)}{P(E = e)}
\]

#### 2.2.2 Water Quality Models

Water quality models are established based on hydrodynamic models. Pollutant transport, transformation, and accumulation in waters have a great effect on water quality. Pollutant transport in water mainly consists of transport with water flow, dilution, and mixing:

\[
\frac{\partial}{\partial t}(hc) + \frac{\partial}{\partial x}(uhc) + \frac{\partial}{\partial y}(vhc) = \frac{\partial}{\partial x} \left( hD_x \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left( hD_y \frac{\partial c}{\partial y} \right) - Fhc + s
\]

where \( D_x \) and \( D_y \) are diffusion coefficients on the \( x \)- and \( y \)-axes separately, \( H \) is the average depth of the water, \( c \) is the mass concentration of pollutants, \( F \) is the attenuation coefficient, \( s \) is a water quality parameter, and the meanings of the other letters are defined in the motion equation.

### 3 Survey Content

The Hanjiang-to-Weihe River Diversion Project is a key project for interbasin water transfer in Shaanxi Province. It consists of six parts: the Huangjinxia Hydro Project, the Huangjinxia Pump Station, the Huangshan Tunnel, the Sanhekou Hydro Project, the Qinling Tunnel, and the Heihe Reservoir Construction. According to the preliminary analysis, the Hanjiang-to-Weihe River Diversion Project transfers water by tunnels, with low risks of water pollution accidents. Therefore, this research studied sudden water pollution accidents at the upper stream of the Huangjinxia in Yang County, as shown in Fig. 1.

**Figure 1** Survey Region

#### 3.1 Determination of the Bayesian Network Structure

Sudden water pollution accidents are characterized by diverse accident forms, suddenness, serious consequences, and great handling difficulties. They are categorized by the location of risk sources
(stationary sources, mobile sources, and watershed sources). On this basis, the research systematically analyzed and identified risks of sudden water pollution accidents on the project. It fully considered major risk sources, temporospatial features of pollution accidents, and the measured water quality of the survey region. Because there were no large-scale industrial enterprises near Huangjinxia, the research classified stationary sources and mobile sources into the same category, employed scenario analysis, and considered only the leakage of toxic pollutants caused by traffic accidents on the Hanjiang Bridge. Based on the above analysis, Bayesian network based risk assessment models for water quality were constructed, as shown in Fig. 2.

![Figure 2: Bayesian Network of the Survey Region](image)

### 3.2 Risk Assessment Standards for Water Quality
According to the water quality assessment in Section Mengjiadu and Section Huangjinxia, chemical oxygen demand (COD) severely exceeded the standards. The water transfer lines of the Hanjiang-to-Weihe River Diversion Project met the requirements of Environmental Quality Standard for Surface Water (GB3838-2002) for domestic water, indicating that water in this region met Type III water quality.

### 3.3 Parameter Calibration and Model Validation
Initial conditions of the research are described below: the simulation time step was 500 s, the number of simulation time steps was $6 \times 10^4$, the duration was 165 d, and the water level elevation was 480 m. Water quality models were calibrated based on the water quality of Huangjinxia in 2014 and 2015. After calibration, the attenuation coefficient was 0.2/d and the horizontal diffusion coefficient was 1. The calibration results are shown in Figs. 3 and 4.

![Figure 3: Parameter Calibration of Water Quality Models](image)

![Figure 4: Validation of Water Quality Models](image)

### 3.4 Simulation Results and Discussions
It was assumed that the background concentration of pollutants in the survey region was 0.010 g/L, the upstream inflow was 138.15 m$^3$/s, the leakage flow of pollutants was 1.0 m$^3$/s and there was no precipitation or nonpoint source pollution. According to the rating of accident probabilities, the accident probability $P$ was set at 0.1%. 
Figure 5 post-accident changes in COD concentration in Section O₁ and Section O₂ respectively.

In this case, the spatiotemporal distribution of pollutants 6h, 12h and 24h after the accident is shown below:
The average accident duration was assumed to be 6 h, 12 h, 24 h, and 48 h respectively, and the standard-exceeding probabilities were calculated in accordance with the risk assessment models for pollutant leakage. The results are shown in Table 1.

| TMTTR (h) | Standard-Exceeding Probability | Section O1 | Section O2 |
|-----------|--------------------------------|------------|------------|
| 6         | 0.0126                         | 0.0027     |            |
| 12        | 0.0215                         | 0.0035     |            |
| 24        | 0.0309                         | 0.0048     |            |
| 48        | 0.0416                         | 0.0056     |            |

According to Figs. 5 and 6, the COD concentration in Section O1 reached the maximum (0.14 g/L) when t = 13.0 h, whereas that in Section O2 peaked (0.0291 g/L) when t = 49.0 h. When the upstream inflow remained unchanged, the COD concentration exceeded standards for 6.0 h in Section O1 and 8.0 h in Section O2. According to Table 1, the standard-exceeding probabilities in Section O1 and Section O2 were 0.0126 and 0.0037 separately when the average accident duration was 6 h, 0.0215 and 0.0045 separately when the average accident duration was 12 h, 0.0309 and 0.0038 separately when the average accident duration was 24 h, and 0.0416 and 0.0056 separately when the average accident duration was 48 h.

It was assumed that the background concentration of pollutants in the survey region was 0.010 g/L, the upstream inflow was 55.29 m³/s. The results are shown in Table 2.

| TMTTR (h) | Standard-Exceeding Probability | Section O1 | Section O2 |
|-----------|--------------------------------|------------|------------|
| 6         | 0.0104                         | 0.0007     |            |
| 12        | 0.0135                         | 0.0012     |            |
| 24        | 0.0196                         | 0.0019     |            |
| 48        | 0.0225                         | 0.0028     |            |

According to Table 2, the standard-exceeding probabilities in Section O1 and Section O2 were 0.0104 and 0.0007 separately when the average accident duration was 6 h, 0.0135 and 0.0012 separately when the average accident duration was 12 h, 0.0196 and 0.0019 separately when the
average accident duration was 24 h, and 0.0225 and 0.0028 separately when the average accident duration was 48 h.

4 Conclusions
(1) This research studied sudden water pollution accidents in the Han Jiang River to Yangxian County Golden Gorge water intake and evaluated upstream sources of risk and pollution accidents. The results show that when the upstream inflow was 138.15 m³/s and the average accident duration was 48 h, the probabilities were 0.0416 and 0.0056 separately. When the upstream inflow was 55.29 m³/s and the average accident duration was 48 h, the probabilities were 0.0225 and 0.0028 separately.

(2) The results show that in different waters, the greater the probability of an upstream accident, the greater the rate of exceeding pollution standards after the accident; in the same waters, the longer the average duration of the accident, the greater the probability of exceeding pollution standards. Therefore, exceeding the time of leakage can effectively reduce the probability of exceeding the standard risk.

(3) By studying the assessment of water pollution accident risk and simulating the migration of pollutants in different waters, the accident probability of exceeding the standard in different durations can be obtained, thus helping to determine the safety of water quality for the implementation and operation of the Hanjiang-to-Weihe River project.

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