A real-time, rapid emergency control model for sudden water pollution accidents in long-distance water transfer projects

Guobin Xu, Yan Long and Chao Ma

ABSTRACT

A real-time, rapid emergency control (EC) model is proposed to cope with sudden water pollution accidents in long-distance water transfer projects. The EC model outputs the method of EC based on pollutant properties. A generalized form of EC model is proposed and tested with a demonstrative project. The rapid prediction formulas of emergency control parameters (ECPs) are proposed under different states of water diversion. The closing times of check gates and the pollution range are calculated by the rapid prediction formulas of ECPs. A case study is examined under the scenario of a sucrose spill in a demonstrative project conducted in the Fangshui to Puyang channel of the Beijing–Shijiazhuang Emergency Water Supply Project in the middle route of the South-to-North Water Transfer Project. The relative errors of peak concentration and arrival time of peak concentration are less than 20%. However, we could not use an actual toxic soluble pollutant to validate the EC model, so we performed the experiment with sucrose to test the EC model based on its concentration variation. The final result shows that the model is able to play a fundamental role in the decisions involved in the Emergency Environmental Decision Support System.

Key words | emergency control, emergency control parameters, rapid prediction formula, water pollution

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ABBREVIATIONS AND SYMBOLS

Symbol	Description (Unit)
B	Bottom width (m)
BSP	Beijing–Shijiazhuang Emergency Water Supply Project
C	Concentration of the pollutant (mg/L)
C_0	Concentration of the pollutant on the plane (mg.s/L)
C_m	Peak concentration (mg/L)
D	Peak transport distance (m)
D^0	Peak transport distance in response time (m)
D^R	Peak transport distance during emergency control (m)
EC	Emergency control
ECP	Emergency control parameters
E_x	Dispersion coefficient (m^2/s)
h	Water depth (m)
H	Gate opening (m)
i	Bottom slope
K	First order decay constant (d^{-1})
L	Length (m)
L^D	Distance between pollution source and downstream check gate (m)
M	Pollutant loadings (mg)
m	Slope factor
MR-SNWTP	Middle route of South-to-North Water Transfer Project
n	Manning roughness coefficient
Q	Discharge (m^3/s)

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T	Arrival time (s)
T^0	Response time (s)
T^b	Travel times of water wave (s)
T^{close}	Closing time of check gate (s)
T^s	Stability time (s)
v	Velocity (m/s)
W	Pollutant longitudinal length (m)
W^0	Pollutant longitudinal length in response time (m)
ΔW	Pollutant longitudinal length during emergency control (m)
x	Distance from source (m)

INTRODUCTION

With the rapid economic development and the enhancement of human activities, sudden water pollution accidents occur frequently in China (Zhang *et al.* 2011). Sudden water pollution accidents have characteristics of varied and complex pollution sources (Ding *et al.* 2003; Zhang *et al.* 2010; Tang *et al.* 2016). The pollution pathway and pollution degree are changeable and unpredictable (Tang *et al.* 2015). Sudden pollution accidents frequently happening in rivers, lakes, and groundwater have significantly polluted local water resources and the ecological environment. Consequently, these polluted water events damage ecosystems (Posthuma *et al.* 2014; Mi *et al.* 2015) and are harmful to local politics, economy and safety of life (Duan *et al.* 2011; Zhang *et al.* 2012; Shi *et al.* 2014).

To address the serious restriction of water resources for economic development, the Middle Route of the South-to-North Water Transfer Project (MR-SNWTP) was constructed. It provides drinking water to northern China (e.g. Beijing, Tianjin). The MR-SNWTP significantly relies on gravity to transfer water in an open canal. Extra auxiliary power is provided in areas that contain hydraulic structures. The open canal decreases the construction costs, but the transferred water is exposed to the air, which adversely increases the risk of water pollution (Tang *et al.* 2015). Once this happens, there will be serious local loss and the influence will expand to the downstream water supply. A prompt and feasible emergency solution is urged to be proposed according to pollutant information, such as pollutant belt length and concentration distribution.

When a severe sudden water pollution accident occurs in the upstream reaches of a river that threatens downstream areas, there is a strong need to control the pollutant (Hou *et al.* 2014). There are three key questions of interest about river pollution as follows: (1) How large is the peak concentration of the pollutant now and how large will it be after control? (2) When will the pollutant arrive downstream? (3) How long will it take for check-gate closing?

Several available water quality models and early-warning models could be applied to answer these three questions for eliminating or decreasing the impacts of water pollution accidents (Mannina & Viviani 2010; Zorica & Breton 2014; Fan *et al.* 2015). Many studies have been conducted to establish mathematical models by employing a one-dimensional (1D) advection–dispersion equation, along with sufficient knowledge of the physical–chemical properties of chemicals and hydrology (Lee & Seo 2007; Fan *et al.* 2012). In recent years, various systems have been researched and developed to produce early warnings and trigger emergency responses to sudden water pollution accidents. For example, a real-time, dynamic early-warning model was proposed to cope with sudden water quality pollution accidents affecting downstream areas with raw-water intakes (Hou *et al.* 2014). A sudden water pollution acute events index system was established to reduce water environment degradation in Tongzhou District (Zhang *et al.* 2015). A geographic information system (GIS)-based generic real-time risk assessment framework was presented to calculate the time of travel and concentration of contaminants and that possessed an improved capability to predict spills and chemical transport (Samuels *et al.* 2006; Camp *et al.* 2010; Jiang *et al.* 2012). These systems offer valuable tools for warning, and for response to decrease pollution. They can also manage and display data with GIS. However, most of the existing studies about sudden water pollution models or early warning systems possess the following limitations: (1) they need a large amount of data and numerical simulation time; (2) they mainly focus on water pollution simulation and emergency measures under normal water transfer, and rarely on emergency control (EC); (3) they mainly do not involve real-time, rapid EC.

Because of the current lack of an efficient EC model (hereinafter called EC model) for sudden soluble water pollution accidents, the primary objective of the present study is to develop a real-time, rapid EC model for sudden soluble water pollution accidents in long-distance water transfer projects. The model is applicable to sudden soluble water pollution accidents that occur in water transfer projects that have many check gates. The model produces a method to calculate the closing time of check gates, and rapid prediction formulas of pollutant under different states of water diversion. Moreover, a pilot test performed by simulating a sudden water pollution accident in the South-to-North Water Transfer Project of China is used to evaluate the performance of this model.

METHODOLOGY

Definition of EC

EC

In practice, the EC of MR-SNWTP for sudden soluble water pollution refers to hydraulic safety and pollutant control both being realized by implementing control by check gates. After a water pollution accident has occurred in a water transfer project, if the peak concentration of pollutant satisfies the water quality requirement, normal water diversion is supported. If the peak concentrations of pollutant exceed the water quality requirement, control by check gate is needed. Hence, the methods of EC include normal water diversion and control by check gates.

Emergency control parameters

When soluble water pollution accidents occur, the check gates upstream and downstream are closed immediately. In the process of the check gates closing, the pollutant moves downstream with the flow, and the pollution range grows at the same time. After the check gates are fully closed, the pollutant fluctuates with the water, and there will be stabilization after a certain period of time. Hence, three emergency control parameters (hereinafter called ECPs), which reflect the process of pollutant advection and diffusion, are put forward. They are peak transport distance (D), pollutant longitudinal length (W) and peak concentration (C_m), respectively. The distance between pollution source and downstream check gate is denoted as L^D. Before the EC, there is a response time (T^0). In the response time, the pollutant peak transport distance is denoted as D^0, and the pollutant longitudinal length is denoted as W^0. In the process of EC, the pollutant peak transport distance is denoted as D^R and the pollutant longitudinal length is denoted as ΔW. The schematic representation of pollutant advection and diffusion under EC is presented in Figure 1.

Framework for the EC model

EC is one of the most important components in the Emergency Environmental Decision Support System for response to a water pollution accident in a water transfer project. When a sudden water pollution accident occurs, confirming the method of EC involves the pollution range at the end of EC. Therefore, the EC model is developed for a sudden water pollution accident in a water transfer project (Figure 2).

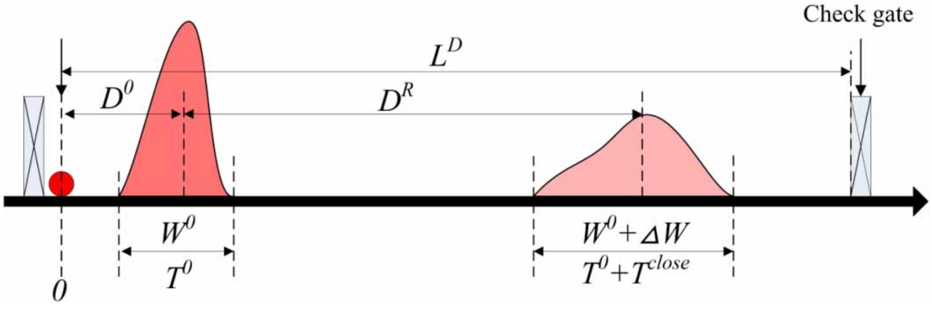

Figure 1 | A schematic representation of pollutant advection and diffusion under EC.

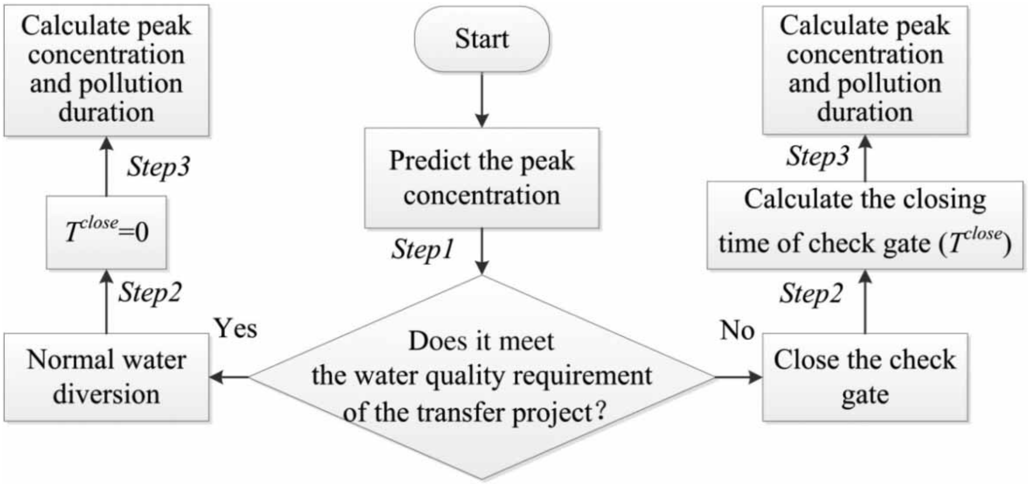

Figure 2 | Schematic of the EC model.

Step 1 is to predict the peak concentration. In this step, the time of arrival at the downstream gate is calculated based on the rapid prediction formulas of ECPs under normal water diversion. Then, the arrival time is incorporated into the peak concentration prediction formula to obtain the peak concentration. The method of EC (step 2) is determined based on the calculation results of step 1. If the peak concentration satisfies the water quality requirement of the transfer project before the pollutant arrives downstream of the check gate, normal water diversion is supported. Conversely, control by check gate is supported. Step 3 is used to provide the data of pollution range based on the rapid prediction formulas of the ECPs after EC. In practice, steps 1 to 3 can be executed continually and their execution is triggered by new input data. Therefore, the EC model can be used as a dynamic approach to control pollutants. Based on the EC model depicted in Figure 2, a generalized framework of an EC model for a pollution accident in a water transfer project is proposed based on the rapid prediction formulas of the ECPs (see Figure 3).

In this study, the rapid prediction formulas of the ECPs under different states of water diversion can be obtained by a set of simulations based on a 1D water quality model. The closing time of the check gate (hereinafter called T^{close}) is calculated based on the rapid prediction formulas of the ECPs. The concrete steps of the methodology graphed in Figure 3 will be described in the following sections.

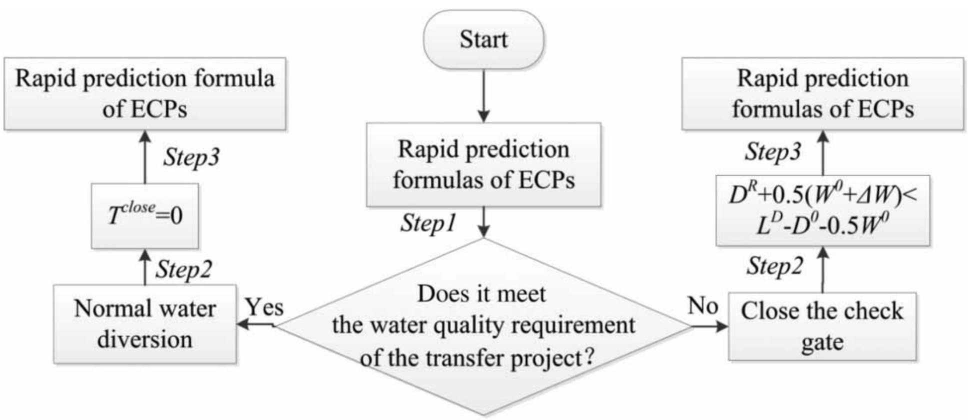

Figure 3 | A generalized form of the EC model for a pollution accident in a water transfer project.

Step 1: Prediction of the peak concentration

1D water quality model

For a long-distance water transfer project, the depth and width are very small compared with the length, so the pollutants discharged into the river will be mixed in the cross-section after they flow at a certain distance away from the leak point. Therefore, the problem of calculating water quality can be simplified as a 1D transport problem, which assumes that the pollution concentration in the cross-section is homogeneous and changes only with the flow direction.

The 1D advection–dispersion equation is the basic equation of a water quality model, which only considers the longitudinal distribution of pollutants along the river. This equation assumes that pollutants are equally distributed instantaneously in uniform transverse as follows (Knopman & Voss 1987):

$$\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial x} = \frac{\partial}{\partial x}\left(E_x\frac{\partial C}{\partial x}\right) - KC \tag{1}$$

where E_x is the dispersion coefficient, which is calculated according to an experience formula (US Army Corps of Engineers 2002); and K is the first-order decay constant. In this paper, compared with pollutant advection and diffusion, the influence of biochemical reactions is very weak; so the biochemical reactions can be ignored. Hence, the first-order decay constant is equal to zero in the water quality model.

Rapid prediction formulas of ECPs under normal water diversion

1. Peak transport distance and peak concentration

For inert pollutants, assume that the moment of the sudden soluble water pollution accident is obtained immediately; 1D river pollutant transport can be expressed as follows (Fischer *et al.* 1979):

$$C(x, t) = C_0\frac{v}{\sqrt{4\pi E_x t}}\exp\left[-\frac{(x - vt)^2}{4E_x t}\right] \tag{2}$$

Based on Equation (2), when $x = vt$, the value of C is the greatest, namely the peak concentration (C_m). Therefore, the peak transport distance (D) and peak concentration (C_m) can be expressed as follows:

$$C_m = \frac{Mv}{Q\sqrt{4\pi E_x}}T^{-0.5} \tag{3}$$

$$D = vT \tag{4}$$

2. Pollutant longitudinal length

In the process of 1D river pollutant transport, pollutant concentration with time is a Gaussian distribution. According to the area ratio of a Gaussian distribution, the ratio of the total pollutant within the scope of 6σ is 99.74% (Fu 1987). Therefore, the width of diffusion is defined as 6σ. And another form of the dispersion coefficient which can be measured by pollutant concentration change rate is as follows:

$$E_x = \frac{1}{2}\frac{\partial\sigma^2}{\partial t} \tag{5}$$

The longitudinal tensile speed of pollutants can be represented as:

$$v = \frac{6\sigma}{t} = \frac{6\sqrt{\int 2E_x dt}}{t} = 6\sqrt{2}E_x^{0.5}t^{-0.5} \tag{6}$$

Therefore, the pollutant longitudinal length (W) calculation formula is as follows:

$$W = \int_0^T 6\sqrt{2}E_x^{0.5}t^{-0.5}dt = 12\sqrt{2}E_x^{0.5}T^{0.5} \tag{7}$$

Predicting the peak concentration

Based on Equations (4) and (7), the time of arrival at the downstream check gate is calculated, which can be incorporated into the peak concentration prediction formula (Equation (3)) to obtain the peak concentration. The arrival time can be calculated as follows:

$$T = \left(36E_x + vL^D - 6\sqrt{36E_x^2 + 2E_x vL^D}\right)/v^2 \tag{8}$$

Step 2: Calculation of T^{close}

Rapid prediction formulas of ECPs under EC

In accordance with the characteristics of water transfer in the MR-SNWTP, the geometric size and hydraulic condition of the channel are shown in Table 1. In this study, 47 simulation scenarios (Table S1, Supplementary material, available with the online version of this paper) are proposed and each simulation scenario consists of eight parameters, including length, bottom width, water depth, slope factor, bottom slope, Manning roughness coefficient ($n = 0.015$, FSRSNP 2005), flow discharge and pollutant loadings.

In the process of numerical simulation, check gates are closed synchronously. The closing time of a check gate is from 15 min to 180 min with 15 min as an interval. In this paper, after the upstream check gate, different pollutant loadings are spilled into the channels instantaneously; and the moment of the sudden soluble water pollution accident is obtained immediately.

1. Peak transport distance

As shown in Figure 4(a), when T^{close} is less than the travel times of water waves (T^b), D will keep nearly constant from the time that the check gate has finished closing. In this situation, D is proportional to velocity and T^{close}. As shown in Figure 4(b), when T^{close} is greater than T^b, D will keep nearly constant after a time of twice T^b plus T^{close}. In this situation, D is divided into two parts. The first part is the transport distance under the action of the water conveyance velocity during T^{close}, which is related to travel time and velocity. The second part is the transport distance under the reciprocating motion. The reciprocating motion directly affects v and E_x. Meanwhile, the speed of gate closing, which has an impact on reciprocating motion, is directly associated with the gate opening (H) and T^{close}. Finally, the relationships between D, v, H, E_x, T^b and T^{close} are established with the dimensional analysis method, and its mathematical expression can be written as follows:

$$D = \begin{cases} vT^{close} & T^{close} < T^b \\ \frac{1}{2}vT^{close} + \frac{0.02vT^{close}\sqrt{E_xT^b}}{H} & T^{close} > T^b \end{cases} \quad (9)$$

2. Pollutant longitudinal length

In this study, the stability time (T^s) of W is defined as the time when W nearly keeps constant. The stability times of

Table 1 | The geometric size and hydraulic condition of the channel

L (km)	*B* (m)	*h* (m)	*m*	*i*	*n*	*Q* (m^3/s)	*M* (t)
15–30	15–30	4.5–8.0	1.5–3.0	1/15,000–1/30,000	0.015	60–300	0.01–2,500

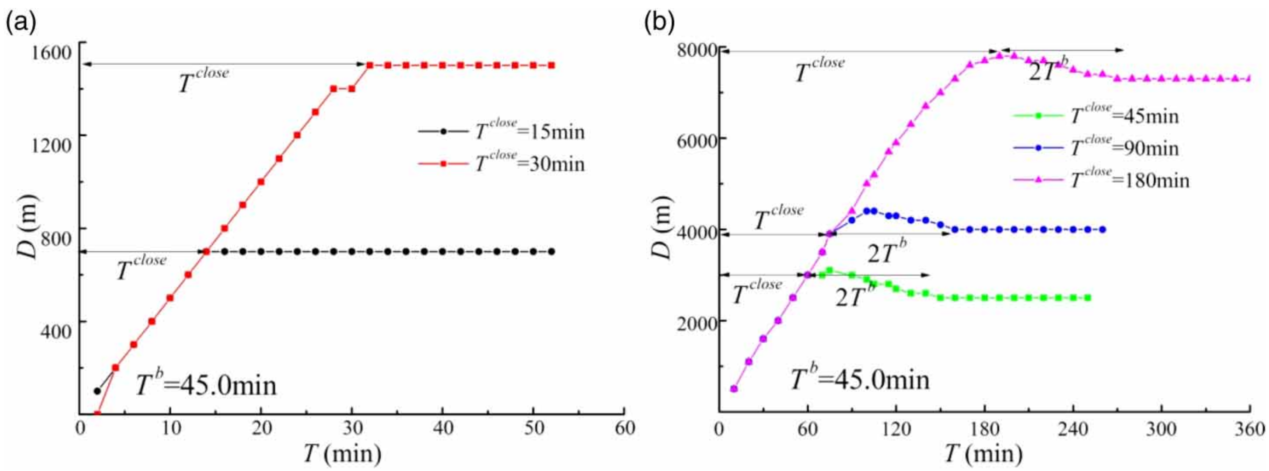

Figure 4 | Temporal variations of D under different T^{close}; $L = 20$ km, $B = 20$ m, $m = 2.0$, $h = 4.5$ m, $I = 1/20{,}000$, $Q = 100$ m^3/s and $M = 10$ t.

W are almost parallel in different scenarios; and T^s is nearly equal to twice T^b plus T^{close} (Figure 5(a)), which can be represented as:

$$T^s = 2T^b + T^{close} \tag{10}$$

Equation (10) is incorporated into Equation (7) to yield

$$W = 12\sqrt{2}E_x^{0.5}\left(2T^b + T^{close}\right)^{0.5} \tag{11}$$

To ensure the rationality of Equation (11), the comparison between the calculated values and simulated values under different T^{close} is presented in Figure 5(b). The W by the HEC-RAS model is the simulated value. The W by the rapid prediction formula (Equation (11)) is the calculated value. It shows that the relative error ranges from 2.2% to 18.3% in all scenarios, and all meet the precision requirement for the prediction of pollutant longitudinal length.

3. Peak concentration

According to the law of conservation of mass, the stability time (T^s) of W and C_m is the same. Hence, Equation (10) is incorporated into Equation (3) to yield

$$C_m = \frac{Mv}{Q\sqrt{4\pi E_x}}\left(2T^b + T^{close}\right)^{-0.5} \tag{12}$$

To ensure the rationality of Equation (12), the comparison between the calculated values and simulated values under different T^b is presented in Figure 6. The C_m by the HEC-RAS model is the simulated value. The C_m by the rapid prediction formula (Equation (12)) is the calculated value. It shows that the relative error ranges from 1% to 16% in all scenarios, and all meet the precision requirement for the prediction of peak concentration.

Calculation of T^{close}

In this study, T^{close} is calculated based on the rapid prediction formulas of the ECPs, as follows:

$$D^R + 0.5(W^0 + \Delta W) < L^D - D^0 - 0.5W^0 \tag{13}$$

Equations (4), (7), (9) and (11) are incorporated into Equation (13) to yield

$$\begin{aligned} &\frac{1}{2}vT^{close} + \frac{0.02vT^{close}\sqrt{E_xT^b}}{H} \\ &\quad + 0.5\left[12\sqrt{2}E_x^{0.5}\left(2T^b + T^{close}\right)^{0.5}\right] < L^D - vT^0 \\ &\quad - 0.5\left[12\sqrt{2}E_x^{0.5}\left(T^0\right)^{0.5}\right] \end{aligned} \tag{14}$$

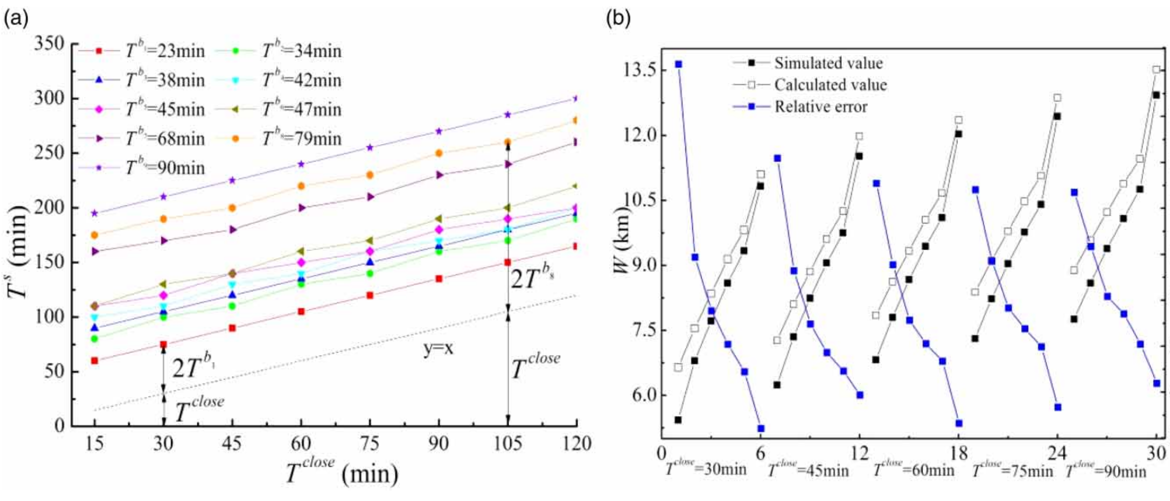

Figure 5 | (a) T^s under different scenarios; (b) the comparison between the calculated values and simulated values under different T^{close}.

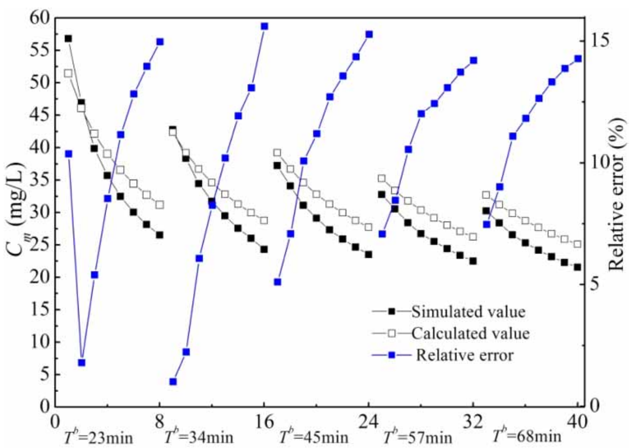

Figure 6 | The comparison between the calculated values and simulated values under different T^b.

Step 3: Calculation of the peak concentration and pollution range

In this study, the methods of EC include normal water diversion and control by check gates. Hence, the rapid prediction formulas of the ECPs under EC are as follows:

$$D = \begin{cases} vT & T^{close} = 0 \\ vT^{close} & T^{close} < T^b \\ 0.5vT^{close} + 0.02vT^{close}\sqrt{E_x T^b}/H & T^{close} > T^b \end{cases} \quad (15)$$

$$W = \begin{cases} 12\sqrt{2}E_x^{0.5}T^{0.5} & T^{close} = 0 \\ 12\sqrt{2}E_x^{0.5}\left(2T^b + T^{close}\right)^{0.5} & T^{close} > 0 \end{cases} \quad (16)$$

$$C_m = \begin{cases} \dfrac{Mv}{Q\sqrt{4\pi E_x}}T^{-0.5} & T^{close} = 0 \\ \dfrac{Mv}{Q\sqrt{4\pi E_x}}\left(2T^b + T^{close}\right)^{-0.5} & T^{close} > 0 \end{cases} \quad (17)$$

The pollution range mainly reflects on D and W. The peak concentration and pollution range are calculated based on these rapid prediction formulas. First, the method of EC is determined based on the peak concentration. If the method is normal water diversion, T^{close} is equal to zero. If the method is control by check gates, T^{close} is calculated based on Equation (14). And then, T^{close} is incorporated into Equations (15)–(17) to calculate D, W and C_m, respectively.

CASE STUDY

General background

The MR-SNWTP transfers water from Taocha, which is located in the Danjiangkou reservoir in Hubei province, as shown in Figure 7 (Tang *et al.* 2014). According to the requirements of water pollution emergency disposal for the MR-SNWTP, the demonstrative project was conducted in the Fangshui to Puyang channel of the Beijing–Shijiazhuang Emergency Water Supply Project (BSP), which is part of the MR-SNWTP, with a length of 227 km (Figure 7). The Fangshui to Puyang open channel is 12.5 km in length, and the water transfer during the demonstrative project was 5 m^3/s (Long *et al.* 2016).

Sucrose was used in the demonstrative project as the pollutant material. At 9:00–9:05 on March 22, 2014, 1,000 kg of sucrose was released into the channel at the Baiyunzhuangbei Bridge, which is 2.148 km upstream of the Puyang check gate. Three monitoring points were set upstream of the Puyang check gate and the basic information for each monitoring point is shown in Table 2.

EC

In this study, we could not use a real, toxic soluble pollutant to validate the real-time and rapid EC model; thus, we used sucrose to demonstrate the behavior of a soluble pollutant. Because sucrose is harmless to the human body, which satisfies the water quality requirement, normal water diversion is supported after the sudden pollution accident happens. The value of the dispersion coefficient is 3.43 m^2/s in the demonstrative project. The contrast of the calculated values and monitored values of peak concentration and arrival time of peak concentration at each monitoring point is shown in Table 3. The result shows that the calculated values and monitored values corresponded well. The relative errors of peak concentration and arrival time of peak concentration are less than 20%. The model can calculate the concentration change under normal water diversion with a relatively high degree of accuracy, especially the calculation of peak concentration and the arrival time of peak concentration.

If sucrose were considered to be a toxic soluble pollutant, the real-time and rapid EC model is obtained based

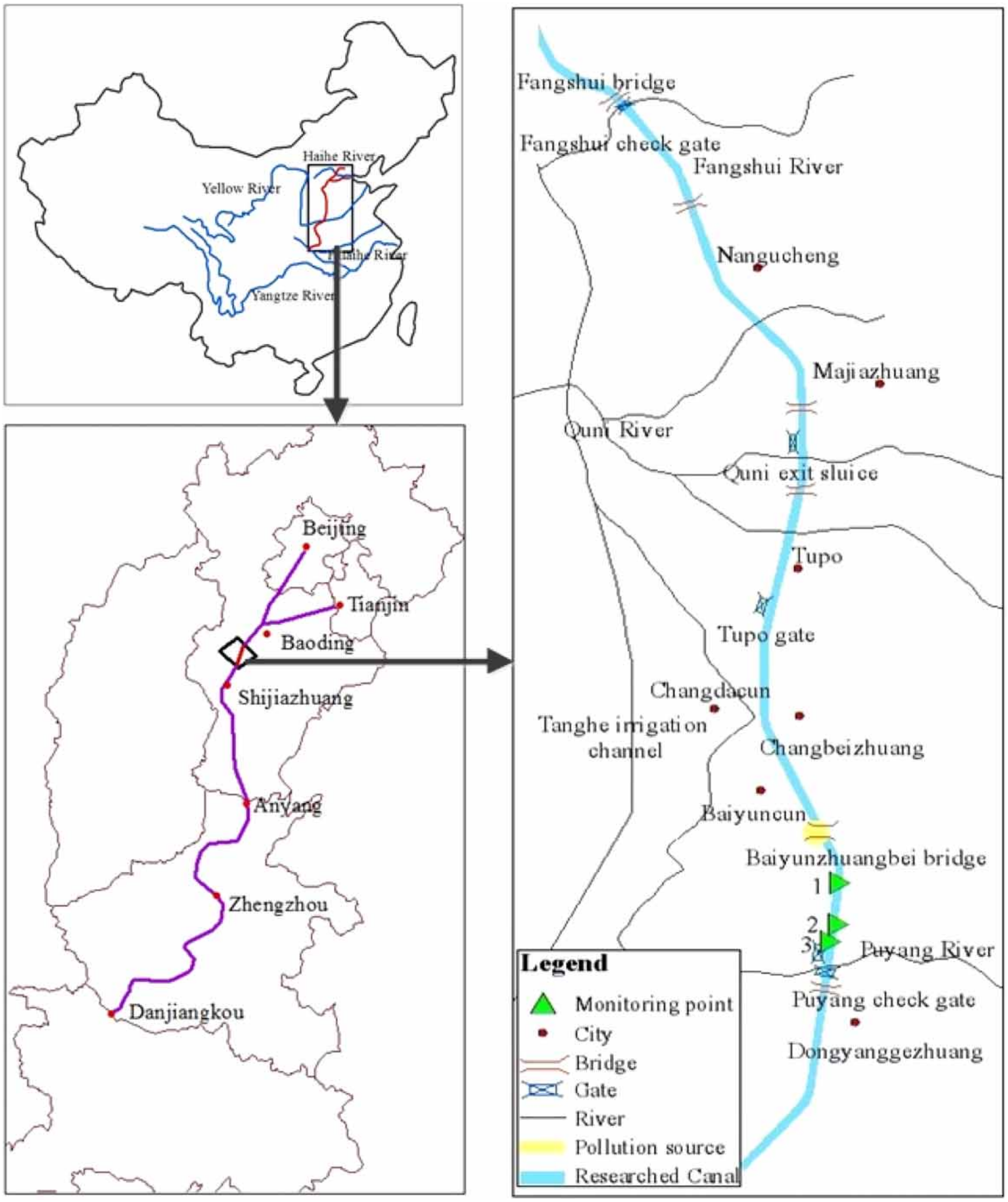

Figure 7 | Schematic of the MR-SNWTP, the BSP and the Fangshui to Puyang open channel.

Table 2 | Information on the research monitoring points

No.	Distance to Baiyunzhuangbei Bridge (m)	Flow velocity (m/s)	Arrival time of the peak concentration (h)	The peak concentration at monitoring points (mg/L)
1	429	0.08	1.33	20.17
2	1,508	0.07	6.08	13.89
3	1,698	0.06	9.08	12.31

on the rapid prediction formulas of the ECPs. In this case, L^D is equal to 2.148 km, T^0 is equal to zero and v is equal to 0.07 m/s. T^b is obtained by Equation (18), and its value is 33 min.

$$T^b = \frac{L}{(\sqrt{gh} + v)} \quad (18)$$

Table 3 | The contrast of the calculated values and monitored values of peak concentration and arrival time of peak concentration at each monitoring point

	Arrival time of the peak concentration (h)			The peak concentration at monitoring points (mg/L)		
No.	Monitored value	Calculated value	Relative error	Monitored value	Calculated value	Relative error
1	1.33	1.49	12.03%	20.17	23.62	17.11%
2	6.08	5.98	1.64%	13.89	13.28	4.39%
3	9.08	7.86	13.44%	12.31	12.56	2.03%

First of all, L^D, v and E_x are incorporated into Equation (8). And the value of the arrival time is equal to 153 min. According to Equation (3), the peak concentration is equal to 22.26 mg/L before the pollutant arrives at the Puyang check gate. According to the calculated result, the concentration of the pollutant does not meet the water quality requirement of the transfer project. Hence, control by check gate is supported after the sudden pollution accident happens. According to Equation (14), the Fangshui check gate and Puyang check gate should be totally closed simultaneously within 25 min of the accident occurring. And then, T^{close} is incorporated into Equations (15)–(17) to calculate D, W and C_m. The values of D, W and C_m are 94 m, 2,326 m and 29.86 mg/L, respectively.

CONCLUSION

This paper has described a real-time and rapid EC model for coping with sudden water pollution accidents. The EC model outputs the method of EC based on pollutant properties. A generalized form of EC model was proposed and tested with a demonstrative project. The proposed method has the following capabilities: (1) it calculates the peak transport distance, pollutant longitudinal length and peak concentration under normal water diversion and control by check gates for further decision-making; (2) it calculates the closing time of check gates when a sudden water accident occurs; (3) a case study was examined under the scenario of a sucrose spill in a demonstrative project conducted in the MR-SNWTP in China. The model is able to play a fundamental role in the decisions involved in the Emergency Environmental Decision Support System.

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