Check for updates

Fast and optimal decision for emergency control of sudden water pollution accidents in long distance water diversion projects

Yu Qiao, Xiaohui Lei, Yan Long, Jiahong Li, Yilin Yang, Yu Tian,
Youming Li, Ye Yao and Wenjuan Chang

ABSTRACT

Long distance water diversion projects transfer clean water to cities for industrial, agricultural and domestic use; there is a great risk of sudden water pollution accidents. Without a fast and optimal decision for emergency control in response to sudden water pollution accidents, dispatchers or decision-makers will not be prepared to respond to the accidents during the process of an emergency spill. To address this gap, a framework for fast and optimal decision support in emergency control is reported in this paper. The proposed fast and optimal decision system covers four stages. In this study, the analytical hierarchy process integrated with grey fixed weight clustering was used to determine the gate closing mode. The emergency control strategy in ice cover formation period is presented. A case study was examined in the demonstrative project conducted in the Middle Route of the South-to-North Water Diversion Project in China. The relative errors of the arrival time of the peak concentration and the peak concentration in monitoring points between the actual monitoring values and the formula calculation values are less than 18%.

Key words | analytical hierarchy process, emergency control, fast and optimal decision, grey fixed weight clustering, long distance water diversion projects

Yu Qiao
Xiaohui Lei
Jiahong Li
Yu Tian
State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin,
China Institute of Water Resources and Hydropower Research,
Beijing, 100038, China

Yu Qiao
Construction and Administration Bureau of South-to-North Water Division Middle Route Project,
Beijing 100038, China

Yan Long (corresponding author)
School of Water Conservancy and Hydroelectric Power,
Hebei University of Engineering,
Handan, Hebei Province 056002, China
E-mail: *450138331@qq.com*

Jiahong Li
Yilin Yang
Ye Yao
State Key Laboratory of Hydraulic Engineering Simulation and Safety,
Tianjin University,
Tianjin 300072, China

Youming Li
Bgi Engineering Consultants Ltd,
Beijing, 100038, China

Wenjuan Chang
China Three Gorges University,
Yichang, Hubei, 443002, China

ABBREVIATIONS AND SYMBOLS

WDPs	Water diversion projects	x_{ij}	Observation value
SNWDP	South-to-North Water Diversion Project	$X = (x_{ij})_{3\times 6}$	The observation value matrix of each cluster object
MR-SNWDP	Middle Route of South-to-North Water Transfer Project	A	The gate closing mode evaluation judgment matrix
LDWDP	Long distance water diversion projects		
AHP	Analytical hierarchy process	E	The evaluation matrix

doi: 10.2166/ws.2020.053

Downloaded from http://iwaponline.com/ws/article-pdf/20/4/1356/704884/ws020041356.pdf
by guest

W	The weight of each index
σ_i^k	The comprehensive clustering coefficient
AT	Arrival time of the peak concentration
CP	The peak concentration in monitoring points
MV	Monitored value
CV	Calculated value
RE	Relative error

INTRODUCTION

In recent years, with rapid economic development and increasing anthropogenic activities, sudden water pollution accidents have become the focus of environmental problems (Rui *et al.* 2015). Unlike other pollution accidents, sudden water pollution accidents have characteristics of varied and complex pollution sources (Zhang *et al.* 2010; Moss *et al.* 2015), the pollution pathway and degree are unpredictable (Morscheidt *et al.* 2013). To address the problem of uneven distribution of water resources on economic development, an increasing number of water diversion projects (WDPs) have recently been implemented, such as the California State Water Project and the Central Arizona Project in the United States and the South-to-North Water Diversion Project (SNWDP) in China (Huang & Niu 2015). Open-channels, complex operation conditions, higher water quality requirements, diverse types and the increasing number of water pollution risk sources are the characteristics of long distance water diversion projects (LDWDP). Once a sudden water pollution accident occurs, if the treatment is unreasonable and not timely, it will not only cause harm to the water channel but also bring great economic and environmental disasters to humans and society (Zhang *et al.* 2012; Shi *et al.* 2014; Fan *et al.* 2015). In addition to property damage and loss of lives, water pollution caused by sudden accidents in WDPs is a significant issue in China (Posthuma *et al.* 2014; Mi *et al.* 2015). Emergency control plays a key role in disaster mitigation, it is important to develop a fast and optimal decision to ensure that the emergency control of sudden water pollution accidents is reasonable. Therefore, a fast and optimal decision can help dispatchers to make correct and timely optimal decisions, which is an important scientific and technological support for the safety of a project.

At present, many scholars have done a lot of studies on the early warning systems, emergency control systems, and environmental risk analysis and response systems. These studies have played an important role in accident treatment and evaluation (Tang *et al.* 2015), water quality and risk assessments (Grifoll *et al.* 2011; Shi *et al.* 2017), risk prediction and analysis (Tang *et al.* 2016) and reducing the hazards of sudden water pollution accidents in recent years. For example, a real-time rapid emergency control model was proposed to cope with sudden water pollution accidents (Xu *et al.* 2017). An emergency response system was established to properly and proactively deal with safety incidents (Duan & He 2015). A simple conceptual model was developed to support local authorities making rapid technical decisions. (Rebelo *et al.* 2014). These systems have provided beneficial support for early warning and regulation of pollution accidents. But, further analysis of these systems showed that many of these systems still have several limitations. Specifically, in the study of emergency control, the systems rarely focused on fast optimization; and mainly concentrated on qualitative research, rather than quantitative studies. For example, in 2011, an oil event spill occurred in the Qiantang River, which is the source of drinking water for several cities in Zhejiang Province. The emergency team just determined the pollution scope through sampling analysis and then took measures to deal with it (Hou *et al.* 2013).

Due to the lack of an effective emergency control system for sudden water pollution accidents, the main purpose of this study is to establish a fast and optimal decision for emergency control of sudden water pollution accidents in LDWDP. This fast and optimal decision applies to sudden soluble water pollution accidents and sudden floating oil pollution accidents. Furthermore, the optimal decision is examined with a sudden water pollution accident that occurred in the Middle Route of the South-to-North Water Diversion Project(MR-SNWDP), China.

FRAMEWORK FOR FAST AND OPTIMAL DECISION

In this study, the proposed fast and optimal decision covers four stages, namely qualitative analysis, quantitative calculation, qualitative decision-making, and quantitative

Downloaded from http://iwaponline.com/ws/article-pdf/20/4/1356/704884/ws020041356.pdf
by guest

decision-making. The frame diagram of the fast and optimal decision is given in Figure 1.

Stage 1: qualitative analysis

Once a sudden water pollution accident happens, the pollutants are detected by monitoring systems; the number and position of monitoring points influence the detection time, and timely detection of accidents is crucial for optimal control. Dispatchers or decision-makers will alert about the accident and analyze the characteristics of the accident channel and the nature of pollutants according to the engineering parameters and the results from water quality monitoring points. The accident channel geometry and its hydraulic characteristics, degree of gate opening and pollutant types can then be determined. According to the accident information, the dispatchers or decision-makers can determine whether the gate should be closed or not. If the accident does not affect the water diversion project and water quality, the normal water transfer mode will be maintained. Otherwise, the degree of gate opening should be adjusted. A hydraulic sketch of the channels and the check gates is given in Figure 2.

Stage 2: quantitative calculation

Once a sudden water pollution accident happens, if the dispatchers or decision-makers cannot quickly and effectively determine the gate closing mode, which expresses the order of gate closing, the gate closing mode is divided into synchronous gate closing, 'upstream first closing' of asynchronous gate closing and 'downstream first closing' of asynchronous gate closing (Yang & Zhou 2010), this will lead to errors for the control scheme and delay the rescue time. If the gate is closed too fast, water in the channel may continually oscillate and cause the canal system to be out of control (Cui *et al.* 2014). Besides, unreasonable selection of the gate closing mode will lead to a sharp decrease in the flow, while plants or algae in channels will be affected if they are in this state for a long time (Mallika & Richardson 2009). Therefore, it is important to study the gate closing mode. Based on this, stage 2 is divided into two steps: determining the gate closing mode and putting forward the formula and condition of the decision parameters.

Step 1: determination of gate closing mode

The selection of the gate closing mode mainly depends on the gate control effect and operation technology. The grey fixed weight clustering can objectively and quantitatively evaluate the advantages and disadvantages of different gate closing modes. The analytic hierarchy process (AHP) (Al-Harbi 2001) will change the multi-state variables that affect the control effect of the gate closing into a single-state variable so that the gate control effect can be easily realized, and the results of the state evaluation can be given quantitatively. Therefore, in this paper, the AHP and grey fixed weight clustering are combined to determine the gate closing mode.

First, the evaluation system of the gate closing mode is determined. The gate closing mode is divided into synchronous gate closing, 'upstream first closing' of asynchronous gate closing and 'downstream first closing' of asynchronous gate closing (Yang & Zhou 2010), which are cluster objects. The observation value matrix of each cluster object is $X = (x_{ij})_{3\times 6}$. Emergency decision-makers need to evaluate and judge the corresponding gate closing modes according to the observation value x_{ij}, and determine the grey class; thereby the gate closing mode is determined. The selection principle of the index is to directly reflect the gate closing effect. To meet the needs of the evaluation of the gate closing mode, the evaluation system established in this paper is shown in Figure 3.

Then, taking the expert investigation on each index with the AHP method, the gate closing mode evaluation judgment matrix A is obtained. The weight of each index is W, and W is obtained by solving matrix A. The scoring criteria of the evaluation indexes described in Table 1 are then developed for evaluation systems. Experts can assign a score in combination with a real accident. The gate closing mode is divided into three categories: best, better and poor. The gradation criterion of each index is shown in Table 2. According to Table 2, the central values of the three grey classes are $a_1 = 55$, $a_2 = 65$, $a_3 = 75$, $a_4 = 85$, respectively. Considering the actual situation, the extension value of the index field is $a_0 = 40$, $a_5 = 100$. The triangle whiten function

Downloaded from http://iwaponline.com/ws/article-pdf/20/4/1356/704884/ws020041356.pdf
by guest

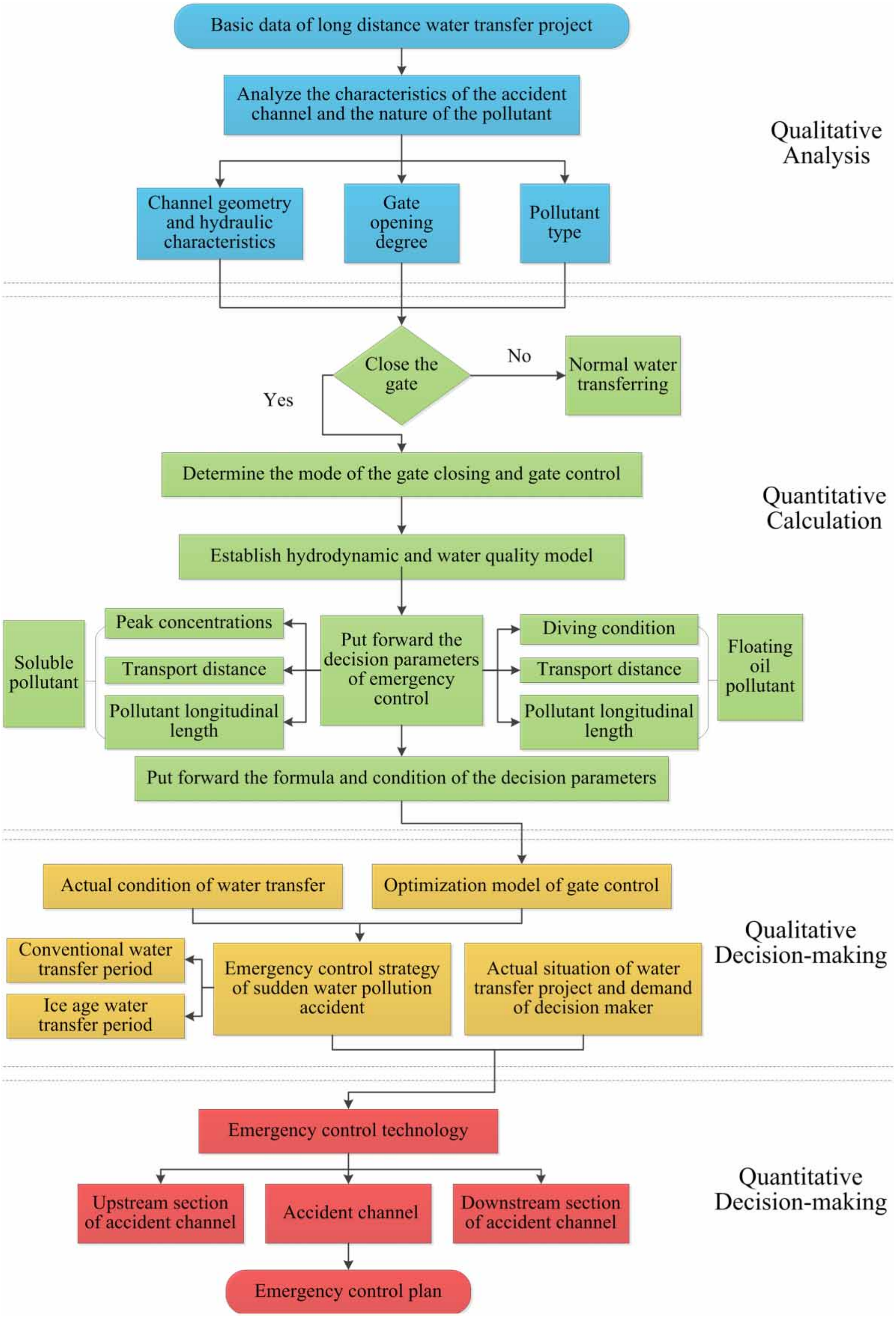

Figure 1 | Frame diagram of fast and optimal decision.

Downloaded from http://iwaponline.com/ws/article-pdf/20/4/1356/704884/ws020041356.pdf
by guest

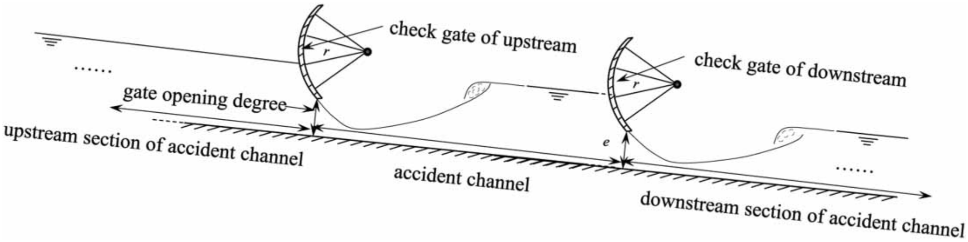

Figure 2 | Hydraulic sketch of the channels and the check gates.

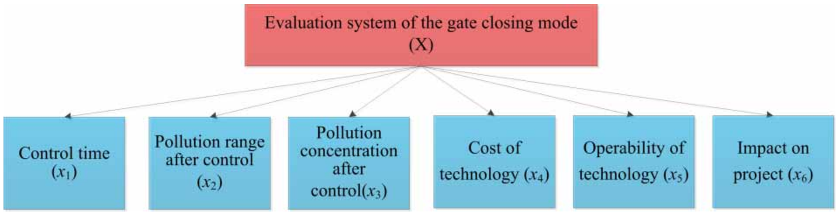

Figure 3 | Evaluation system of the gate closing mode.

is expressed as Equations (1)–(3).

$$f_j^1(x) = \begin{cases} 0, & x \notin [40, 75] \\ (x-40)/(60-40), & x \in [40, 60] \\ (75-x)/(75-60), & x \in [60, 75] \end{cases} \tag{1}$$

$$f_j^2(x) = \begin{cases} 0, & x \notin [55, 85] \\ (x-55)/(70-55), & x \in [55, 70] \\ (85-x)/(85-70), & x \in [70, 85] \end{cases} \tag{2}$$

$$f_j^3(x) = \begin{cases} 0, & x \notin [65, 100] \\ (x-65)/(80-65), & x \in [65, 80] \\ (100-x)/(100-80), & x \in [80, 100] \end{cases} \tag{3}$$

Finally, the comprehensive clustering coefficient σ_i^k of each index is calculated according to Equation (4). The clustering results of the gate closing mode are shown in Table 3. As can be seen from Table 3, the check gates of upstream and downstream need to be closed simultaneously in the emergency control of the LDWDP. This conclusion is consistent with the results proposed by Lian *et al.* (2013).

$$\sigma_i^k = \sum_{j=1}^{m} f_j^k(x_{ij}) \cdot \eta_j \tag{4}$$

Step 2: putting forward the formula and condition of the decision parameters

Once a water pollution accident happens, the check gates of upstream and downstream will be closed immediately. In the process of check gates closing, the pollutants will move to the downstream with flow, and the pollution range will grow at the same time. After the check gate is fully closed, pollutants will fluctuate with water, and end in being stable after a certain time. Hence, decision parameters of emergency control (hereinafter called ECPs), which reflect the process of pollutants advection and diffusion, are put forward. They are transport distance, pollutants' longitudinal length, peak concentration, and diving condition, respectively. Through statistical analysis of the numerical simulation results, the formula and condition of the decision parameters are put forward, as shown in Table 4.

Stage 3: qualitative decision-making

The temperature can be greatly variable along with the areas and the time. Therefore, it is necessary to formulate corresponding emergency control strategies for sudden water pollution accidents in different water diversion periods. The

Downloaded from http://iwaponline.com/ws/article-pdf/20/4/1356/704884/ws020041356.pdf
by guest

Table 1 | Scoring criteria of the evaluation indexes

	Scores		
Index	**100**	**70**	**40**
Control time (x_1)	Emergency control needs a short time	Emergency control needs a time	Emergency control needs a long time
Pollution range after control (x_2)	$W \leq 5$ km	5 km $\leq W \leq$ 10 km	$W \geq 10$ km
Pollution concentration after control (x_3)	$C \leq 10\%$ of initial concentration	10% of initial concentration $\leq C \leq$ 30% of initial concentration	$C \geq 30\%$ of initial concentration
Cost of technology (x_4)	Low investment cost	Medium investment cost	High investment cost
Operability of technology (x_5)	Little difficulty	Some difficulty	Considerable difficulty
Impact on a project (x_6)	No impact on project	Slight impact on project	Serious impact on project

Note: The scoring criteria of the evaluation indexes were adapted from the earlier paper by Long *et al.* (2016).

Table 2 | Gradation criterion of each index

Grade	**Poor**	**Better**	**Best**
Scores	$65 \geq X^1 \geq 55$	$75 \geq X^2 \geq 65$	$85 \geq X^3 \geq 75$

Table 3 | Clustering results of gate closing mode

Closing mode	**Poor**	**Better**	**Best**	σ_i^k	**Result**
Synchronous gate closing	0	0.3426	0.7936	0.7936	Best
'Upstream first closing' of asynchronous gate closing	0.2569	0.5026	0.4913	0.5026	Better
'Downstream first closing' of asynchronous gate closing	0.4721	0.4036	0.4546	0.4721	Poor

emergency control strategy of sudden water pollution accidents in the conventional water transfer period has been proposed by Long *et al.* (2016). And the emergency control strategy in an icing period is presented**.** This strategy is divided into two parts: normal channel emergency control and frozen channel emergency control. Soluble pollutants and floating oil pollutants are considered in each part respectively. In China, there are four seasons: spring, summer, autumn and winter, and the temperature changes greatly along with the time. Generally, spring, summer, and autumn are normal water transfer periods, and winter is the icing period. Surface water may be frozen, it is necessary to formulate corresponding emergency control strategies for sudden water pollution accidents, some channels may form stable ice cover in the icing period, ice cover may be damaged if the emergency control is improper, and then secondary disasters such as ice dams or ice plugs will happen, water conveyance flow may reduce or even be interrupted, the consequences are more severe than in a normal water transfer period. So it is necessary to formulate emergency control strategies in an icing period according to factors such as the location of the sudden water pollution accident, the pollutant types, and decision-makers' need. When a sudden water pollution accident occurs in unfrozen channels, emergency control strategies should be selected based on pollutant types and ensures pollutants do not spread into the ice channels. When a sudden water pollution accident occurs in a frozen channel and the pollutants are only on the ice cover, the ice cover is equivalent to a protective layer, pollutants should be quickly coped with using activated carbon, activated carbon fiber felt, jute, straw, and cotton yarn. Once pollutants enter the water body through the ice cover, the emergency control strategies should ensure the ice cover is not damaged. The detailed emergency control strategy in an icing period is shown in Figure 4.

Stage 4: quantitative decision-making

According to the location of the accident, the channels are divided into three parts: upstream sections of the accident

Downloaded from http://iwaponline.com/ws/article-pdf/20/4/1356/704884/ws020041356.pdf
by guest

Table 4 | The formula and condition of the decision parameters

Type of pollutant		**Decision parameters**	**Formula or condition**	**Formula number**
Soluble pollutant	Before control	Transport distance (D)	$D = vT$	(5)
		Pollutant longitudinal length (W)	$W = \int_0^T 6\sqrt{2}E_x^{0.5}t^{-0.5}dt = 12\sqrt{2}E_x^{0.5}T^{0.5}$	(6)
		Peak concentration (C_m)	$C_m = \frac{Mv}{Q\sqrt{4\pi E_x}}T^{-0.5}$	(7)
	Emergency control	Transport distance (D)	$D = \begin{cases} vT^{close} & (T^{close} < T^b) \\ \frac{1}{2}vT^{close} + 9.8\left[\left(T^b\right)^{4/3}\ln T^{close} - \left(T^b\right)^{1.6}\right] & (T^{close} > T^b) \end{cases}$	(8)
		Pollutant longitudinal length (W)	$W = \begin{cases} \frac{n \times SPW \times T}{T^g} & T \leq T^g \\ \frac{SPW \times [(1-n)T + nT^s - T^g]}{T^s - T^g} & T^g < T \leq T^s \\ SPW = p^{0.04}\left[\frac{LhE_xT^{close}}{25QT^b} + 15T^bv(\frac{E_x}{hv})^{-0.6}\right] & T \geq T^s \end{cases}$ in which, $p = M/10\text{t}, n = 0.9\left(\frac{T^{close}}{T^b}\right)^{0.1} T^s = T^{close} + 2T^b$	(9)
		Peak concentration (C_m)	$C_m = \begin{cases} C_0 - \frac{C_0 - k \times SPC}{T^g} \times T & T \leq T^g \\ \frac{SPC \times (k \times T^s - T^g) - (k-1) \times SPC \times T}{T^s - T^g} & T^g < T \leq T^s \\ SPC = 0.3\left(\frac{vT^b}{L}\right)^{0.3}\frac{Mv}{Q\sqrt{E_x(T^{close} + T^b)}} & T \geq T^s \end{cases}$ in which, $k = 1.1\left(\frac{T^b}{T^{close}}\right)^{0.1}$	(10)
Floating oil pollutant		Transport distance (D)	$D = (v + 0.02v_w)T$	(11)
		Pollutant longitudinal length (W)	$\frac{dW}{dt} = 0.5v$	(12)
		Diving condition	$\begin{cases} e = 0.55 & if\ 0.7 < v < 0.8 \\ 0.4 \leq e < 0.55 & if\ 0.5 < v \leq 0.7 \\ 0.35 \leq e < 0.4 & if\ v \leq 0.5 \end{cases}$	(13)

Note: E_x-Dispersion coefficient, m^2/s; *e*-Gate opening, m; *h*-Water depth, m; *L*-Length of channel, m; *M*-Pollutants loadings, mg; Q-Discharge, m^3/s; *SPW*- Steady longitudinal length, m; *SPC*-Steady peak concentration, mg/L; *T*-Travel time, s; T^b-Travel times of water wave, s; T^{close}-Closing time of check gate, s; T^g-the time of turning point, s; T^s-Stability time, s; v-Velocity, m/s; v_w-Wind speed, m/s.

Downloaded from http://iwaponline.com/ws/article-pdf/20/4/1356/704884/ws020041356.pdf
by guest

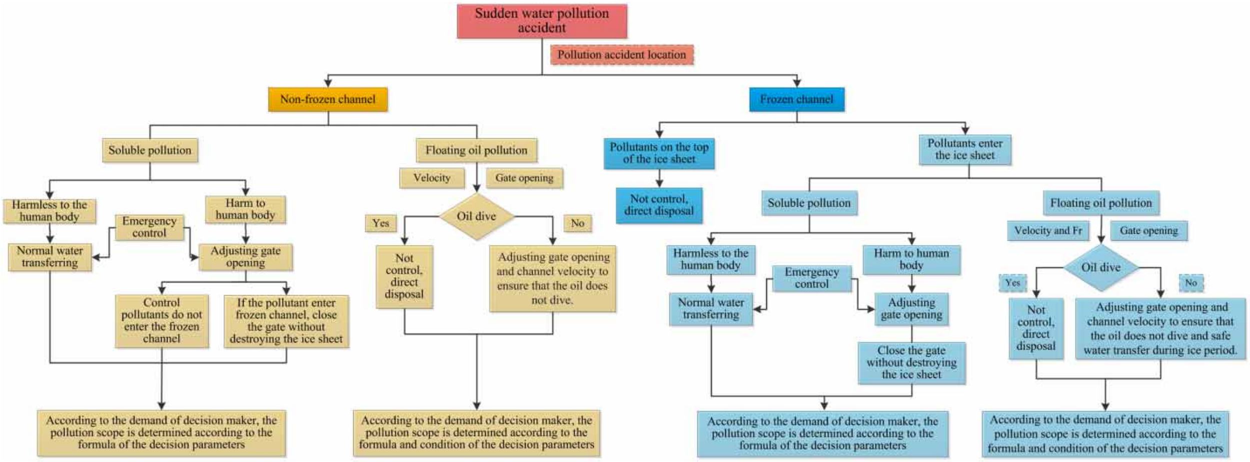

Figure 4 | The emergency control technology strategy in an icing period.

channel, accident channel, and downstream sections of the accident channel. For upstream sections of the accident channel, water supply for upstream branches should stay normal by adjusting the inflow. For upstream sections of the accident channel, water supply for upstream branches should stay normal by adjusting the inflow. For the accident channel, water supply should be interrupted if water does not meet quality requirements; pollutants should be coped with as soon as possible. For downstream sections of the accident channel, water supply for downstream branches should be satisfied as far as possible by the operation of the check gates. The hydraulic sketch of the channels and the check gates is given in Figure 2.

According to the emergency control strategy, the emergency control plan should be determined considering the actual situation of the water diversion project and the demand for decision-makers.

CASE STUDY

General background

The Middle Route of the South-to-North Water Diversion Project transfers clean water from the Taocha Dam of the Danjiangkou Reservoir in Hubei Province, as shown in Figure 5. The Middle Route crosses the Huaihe River, Haihe River, and Yellow River basins and finally arrives at Beijing's Tuancheng Lake. With a length of 1,277 km, MR-SNWDP transfers clean water to nearly 150 cities, 58 million inhabitants and 151 thousand hectares of land via open-channels, culverts, and pipes under extremely strict water quality requirements.

To improve the actual emergency treatment capacity of the emergency water pollution accident, the demonstrative project was conducted in Fangshui to Puyang channel of MR-SNWDP, which is 12.5 km in length, and the flow of water transfer during the demonstrative project was 5 m^3/s (Long *et al.* 2016). Since MR-SNWDP was supplying water to Beijing and Tianjin at that time, consider the safety of water transfer, sucrose was selected as the pollutant material in the demonstrative project. At 9:00–9:05 on March 22, 2014, 1,000 kg sucrose was released into the channel at the Baiyunzhuangbei Bridge, which is 2.148 km from the upstream of Puyang check gate. Three monitoring points were exclusively established in the upstream of the Puyang check gate and the basic information is shown in Table 5.

Fast and optimal decision

In this study, we use sucrose to simulate soluble pollutants to validate our fast and optimal decision. The concrete method steps and results are explained as follows.

Stage 1: qualitative analysis

In this study, we assume that sucrose is a toxic soluble pollutant, the accident channel is the channel for Fangshui

Downloaded from http://iwaponline.com/ws/article-pdf/20/4/1356/704884/ws020041356.pdf
by guest

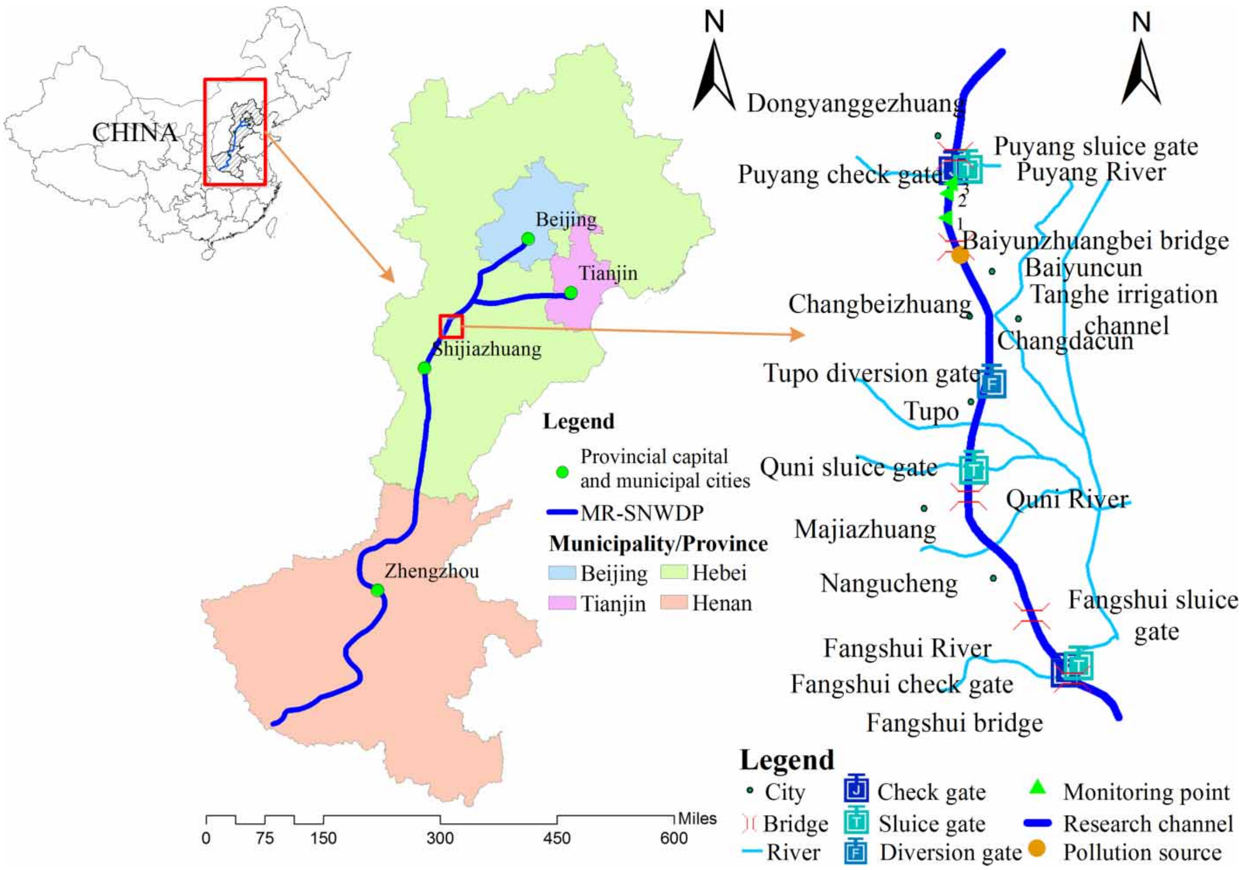

Figure 5 | Schematic of the demonstrative project.

Table 5 | The information of research monitoring points

No.	Distance to Baiyunzhuangbei Bridge (m)	Flow velocity (m/s)	AT (h)	PC (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

Note: AT- Arrival time of the peak concentration; PC-Peak concentration in monitoring points.

to Puyang, the check gate opening degree is 1 m, and there are three water quality monitoring points. The demonstrative channel is divided into three parts: the upstream sections of the accident channel are the upstream sections of the Fangshui check gate; the downstream sections of the accident channel are the downstream sections of the Puyang check gate.

Stage 2: quantitative calculation

Step 1: Determination of gate closing mode.

(1) Establish evaluation judgment matrix A

Through the AHP method to carry on the expert investigation to each index (Figure 3), the gate closing mode evaluation judgment matrix A is obtained.

$$A = \begin{bmatrix} 1 & 4 & 2 & 3 & 3 & 3 \\ 1/4 & 1 & 1/3 & 1/3 & 1/2 & 1/2 \\ 1/2 & 3 & 1 & 1 & 2 & 2 \\ 1/3 & 3 & 1 & 1 & 1 & 2 \\ 1/3 & 2 & 1/2 & 1 & 1 & 1 \\ 1/3 & 2 & 1/2 & 1/2 & 1 & 1 \end{bmatrix}$$

The weight W of the 6 indicators is $W = (\eta_1 = 0.3536,\ \eta_2 = 0.0636,\ \eta_3 = 0.1944,\ \eta_4 = 0.1645,\ \eta_5 = 0.1201,\ \eta_6 = 0.1038)$.

(2) Determination of evaluation index value

Downloaded from http://iwaponline.com/ws/article-pdf/20/4/1356/704884/ws020041356.pdf
by guest

The scoring criteria of the evaluation indexes described in Table 1 are then developed for evaluation systems. The scoring criteria of the evaluation indexes in Table 1 are determined based on expert consultation and literature research.

Each expert determines the actual values of each evaluation index according to the actual situation of the water diversion project. The specific results are shown in Table 6. The evaluation matrix E can be established based on Table 6.

$$E = \begin{bmatrix} 80 & 88 & 75 & 82 & 92 & 76 \\ 68 & 70 & 88 & 75 & 85 & 84 \\ 60 & 75 & 82 & 70 & 80 & 88 \end{bmatrix}$$

(3) Determination of triangle whiten function

Experts can assign a score in combination with a real accident. The gate closing mode is divided into three categories: best, better and poor. According to evaluation matrix E, the central values of the three grey classes are $a_1 = 55$, $a_2 = 65$, $a_3 = 75$, $a_4 = 85$. Then, considering the actual situation, the extension value of the index field is $a_0 = 40$, $a_5 = 100$. The gradation criterion of each index is shown in Table 2. Based on Table 2, the middle value of triangle whitening weight λ_k is determined; $\lambda_1 = 60$, $\lambda_2 = 70$, $\lambda_3 = 80$. Then, the values of a_{i} ($i = 0,1,2,3,4,5$) and λ_k ($k = 1,2,3$) are put into Equation (S1) to get the triangle whiten function, which is expressed as Equations (1)–(3).

Table 6 | Specific results of the evaluation indexes

Index	Synchronous gate closing	'Upstream first closing' of the asynchronous gate closing	'Downstream first closing' of the asynchronous gate closing
Control time (x_1)	80	68	60
Pollution range after control (x_2)	88	70	75
Pollution concentration after control (x_3)	75	88	82
Cost of technology (x_4)	82	75	70
Operability of technology (x_5)	92	85	80
Impact on a project (x_6)	76	84	88

$$f_j^k(x) = \begin{cases} 0 & x \notin [a_{k-1}, a_{k+2}] \\ (x - a_{k-1})/(\lambda_k - a_{k-1}) & x \notin [a_{k-1}, \lambda_k] \\ (a_{k+2} - x)/(a_{k+2} - x - \lambda_k) & x \notin [\lambda_k, a_{k+2}] \end{cases} \tag{S1}$$

(4) Determination of comprehensive clustering coefficient σ^{ik}

The weight $W = (\eta_1, \eta_2, \ldots, \eta_j)(\mathrm{j} = 6)$ and triangle whiten function $f_j^k(x)$ are incorporated into Equation (4). Finally, the comprehensive clustering coefficient of each index is obtained, as shown in Table 3.

Step 2: Calculate each decision parameter. The value of the dispersion coefficient is 3.43 m^2/s in the demonstrative project. According to the formula (Table 4), the REs between MV and CV in each monitoring point are shown in Table 7. Compared with the practical monitoring, their REs are less than 18%.

Stage 3: qualitative decision-making

The demonstrative project of MR-SNWDP was carried out in April. There was no ice in the channel at that time, which can be considered as a conventional water transfer period.

For the upstream sections of the Fangshui check gate, water supply for upstream branches should remain normal by adjusting the inflow. For the accident channel (Fangshui to Puyang), water supply will be interrupted if water does not meet quality requirements, the pollutants should be coped with as soon as possible. For the downstream sections of the Puyang check gate, the water supply for downstream

Table 7 | Comparison results

	AT (h)			PC (mg/L)		
No.	MV	CV	RE	MV	CV	RE
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%

Note: MV-Monitored value; CV-Calculated value; RE-Relative error.

Downloaded from http://iwaponline.com/ws/article-pdf/20/4/1356/704884/ws020041356.pdf
by guest

branches should be satisfied as far as possible by the operation of running at a normal level.

Stage 4: quantitative decision-making

In this case, v is equal to 0.07 m/s. T^b is 33 min. For the accident channel, according to the formula of the decision parameters (Table 4), the Fangshui check gate and Puyang check gate should be closed simultaneously within 60 min after the accident occurrs. And the values of transport distance, pollutant longitudinal length, and peak concentration are 94 m, 2,326 m and 29.86 mg/L, respectively.

CONCLUSION

This paper has proposed an entire framework of a fast and optimal decision system for emergency control of sudden water pollution accidents in the Long Distance Water Diversion Project. The proposed fast and optimal decision system has been examined in the demonstrative project conducted in the Middle Route of the South-to-North Water Diversion Project in China. Fast and optimal decision plays a fundamental role during the process of an emergency spill. Through the above research, the paper draws the following conclusions:

- The proposed framework for fast and optimal decision is reasonable and logical; it can be used as a reference for managers and other emergency control systems.
- The analytical hierarchy process (AHP) and grey fixed weight clustering can be combined to solve the quantitative calculation problem of optimal decision. The method can objectively and quantitatively evaluate the advantages and disadvantages of different gate closing modes. The combined method is simple and satisfied with fast and optimal decisions.
- The presented emergency control strategy in an icing period is described in detail. The strategy is divided into two parts: normal channel emergency control and frozen channel emergency control. Soluble pollutants and floating oil pollutants are considered in each part respectively. The emergency control strategy can be applied in other emergency controls of sudden water pollution accidents.
- The presented emergency control strategy in different channels is described in detail. For upstream sections of the accident channel, water supply for upstream branches should remain normal by adjusting the inflow. For the accident channel, water supply should be interrupted if water does not meet quality requirements; pollutants should be coped with as soon as possible. For downstream sections of the accident channel, water supply for downstream branches should be satisfied as far as possible by the operation of the check gates.
- The Middle Route of the South-to-North Water Diversion Project is selected as a demonstrative project to examine the proposed framework for fast and optimal decision, the case study was examined under the scenario of a sucrose spill in the demonstrative project in China; the relative errors of the arrival time of the peak concentration and the peak concentration in monitoring points between the actual monitoring values and the formula calculation values are less than 18%.
- Scholars and managers should combine with the actual situation of the water diversion project and the demand of decision-makers, to establish fast and optimal decision for emergency control of sudden water pollution accidents especially, because hydraulic characteristics, engineering parameters, and pollutant types may be different in each project.
- The case study in this paper did not examine the emergency control strategy in an icing period; we expect that scholars can do in-depth research into the emergency control strategy in an icing period, and apply the presented emergency control system to improve the framework and methods.

ACKNOWLEDGEMENTS

This study is supported by the Major National Science and Technology Project (2017ZX07108-001), National Natural Science Foundation of China (51609167) and Open Research Fund of State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin (China Institute of Water Resources and Hydropower Research)

Downloaded from http://iwaponline.com/ws/article-pdf/20/4/1356/704884/ws020041356.pdf
by guest

(IWHR-SKL-201704). The writers also acknowledge the assistance of anonymous reviewers.

REFERENCES

Al-Harbi, A. S. 2001 Application of the AHP in project management. *Int. J. Proj. Manage* **19** (1), 19–27.

Cui, W., Chen, W. X., Mu, X. P. & Bai, Y. B. L. 2014 Canal controller for the largest water transfer project in China. *Irrig. Drain.* **63**, 501–511.

Duan, W. & He, B. 2015 Emergency response system for pollution accidents in chemical industrial Parks, China. *Int. J. Environ. Res. Public. Health* **12**, 7868–7885.

Fan, F. M., Fleischmann, A. S., Collischonn, W., Ames, D. P. & Rigo, D. 2015 Large-scale analytical water quality model coupled with GIS for simulation of point sourced pollutant discharges. *Environ. Model Softw.* **64**, 58–71.

Grifoll, M., Jordà, G., Espino, M., Romo, J. & Sotillo, M. G. 2011 A management system for accidental water pollution risk in a harbour: the Barcelona case study. *J. Marine Syst.* **88**, 60–73.

Hou, D., Song, X., Zhang, G., Zhang, H. & Loaiciga, H. 2013 An early warning and control system for urban, drinking water quality protection: China's experience. *Environ. Sci. Pollut. Res.* **20**, 4496–4508.

Huang, H. & Niu, J. Y. 2015 Compensative operating feasibility analysis of the west route of South-to-North Water Transfer Project Based on M-Copula function. *Water Resour. Manag.* **29**, 3919–3927.

Lian, J. J., Wang, X., Liu, C. Y. & Ma, C. 2013 Emergency regulation for sudden water pollution accidents of open channel in long distance water transfer project. *J. Tianjin Univ. (Sci. Technol.)* **46** (1), 44–50 (in Chinese).

Long, Y., Xu, G. B., Ma, C. & Chen, L. 2016 Emergency control system based on the analytical hierarchy process and coordinated development degree model for sudden water pollution accidents in the Middle Route of the South-to-North Water Transfer Project in China. *Environ. Sci. Pollut. Res.* **23**, 12332–12342.

Mallika, A. U. & Richardson, J. S. 2009 Riparian vegetation change in upstream and downstream reaches of three temperate rivers dammed for hydroelectric generation in British Columbia, Canada. *Ecol. Eng.* **35**, 810–819.

Mi, Y., He, C., Bian, H., Cai, Y., Sheng, L. & Ma, L. 2015 Ecological engineering restoration of a non-point source polluted river in Northern China. *Ecol. Eng.* **76**, 142–150.

Morscheidt, W., Cavadias, S., Rousseau, F. & Silva, B. D. 2013 Pollution of the Rhine River: an introduction to numerical modelling. *Educ. Chem. Eng.* **8**, 119–123.

Moss, J. A., McCurry, C., Tominack, S., Romero, I. C., Hollander, D., Jeffrey, W. H. & Snyder, R. A. 2015 Ciliated protists from the nepheloid layer and water column of sites affected by the Deepwater Horizon oil spill in the Northeastern Gulf of Mexico. *J. Deep-Sea Res. I* **106**, 85–96.

Posthuma, L., Wahlstrom, E., Nijenhuis, R., Dijkens, C., Zwart, D., van de Meent, D., Hollander, A., Brand, E., den Hollander, H. A., van Middelaar, J., van Dijk, S., Hall, E. F. & Hoffer, S. 2014 The Flash Environmental Assessment Tool: worldwide first aid for chemical accidents response, pro action, prevention and preparedness. *Environ. Int.* **72**, 140–156.

Rebelo, A., Ferra, I., Gonçalves, I. & Marques, A. 2014 A risk assessment model for water resources: releases of dangerous and hazardous substances. *J. Environ. Manage.* **140**, 51–59.

Rui, Y. K., Shen, D. T., Khalid, S., Yang, Z. G. & Wang, J. C. 2015 GIS-based emergency response system for sudden water pollution accidents. *Phys. Chem. Earth* **79–82**, 115–121.

Shi, B., Jiang, J. P., Liu, R. T., Khan, A. U. & Wang, P. 2017 Engineering risk assessment for emergency disposal projects of sudden water pollution incidents. *Environ. Sci. Pollut. Res.* **24**, 14819–14833.

Shi, S. G., Cao, J. C., Feng, L., Liang, W. Y. & Zhang, L. Q. 2014 Construction of a technique plan repository and evaluation system based on AHP group decision-making for emergency treatment and disposal in chemical pollution accidents. *J. Hazard. Mater.* **276**, 200–206.

Tang, C. H., Yi, Y. J., Yang, Z. F. & Sun, J. 2015 Risk forecasting of pollution accidents based on an integrated Bayesian Network and water quality model for the South to North Water Transfer Project. *Ecol. Eng.* **11**, 3824–3831.

Tang, C. H., Yi, Y. J., Yang, Z. F. & Sun, J. 2016 Risk analysis of emergent water pollution accidents based on a Bayesian network. *J. Environ. Manage.* **165**, 199–205.

Xu, G. B., Long, Y. & Ma, C. 2017 A real-time, rapid emergency control model for sudden water pollution accident in long distance water transfer project. *Water Sci. Tech.-Water Sup.* **1**, 73–83.

Yang, M. & Zhou, F. 2010 A study of hydraulic control of the open channel water diversion system under combined control of all check sluices. *J. Xi'an Univ. Technol.* **26**, 202–205 (in Chinese).

Zhang, W. J., Lin, X. Y. & Su, X. S. 2010 Transport and fate modeling of nitrobenzene in groundwater after the Songhua river pollution accident. *J. Environ. Manage.* **91**, 2378–2384.

Zhang, L. F., Dong, L., Ren, L. J., Shi, S. X., Zhou, L., Zhang, T. & Huang, Y. R. 2012 Concentration and source identification of polycyclic aromatic hydrocarbons and phthalic acid esters in the surface water of the Yangtze River Delta. *J. Environ. Sci.* **24** (2), 335–342.

First received 25 October 2019; accepted in revised form 23 March 2020. Available online 7 April 2020

Downloaded from http://iwaponline.com/ws/article-pdf/20/4/1356/704884/ws020041356.pdf
by guest