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Development and application of a water pollution emergency response system for the Three Gorges Reservoir in the Yangtze River, China

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Abstract

There are many watercraft and production accidents in the Three Gorges Reservoir Area (TGRA) of the Yangtze River in China every year. Accidents threaten the water quality of the 1085 km^2 surface area of the TGRA and millions of local people if oil and chemical leakage were to occur. A water pollution management system for emergency response (WPMS_ER) was therefore designed for the management of pollution in this area. An integrated geographic information system (GIS)-based water pollution management information system for the TGRA, called WPMS_ER_TGRA, was developed in this study. ArcGIS engine was used as the system development platform, and Visual Basic as the programming language. The models for hydraulic and water quality simulation and the generation of body-fitted coordinates were developed and programmed as a dynamically linked library file using Visual Basic, and they can be launched by other computer programs. Subsequently, the GIS-based information system was applied to the emergency water pollution management of a shipwreck releasing 10 tons of phenol into the Yangtze River during two hours. The results showed that WPMS_ER_TGRA can assist with emergency water pollution management and simulate the transfer and diffusion of accidental pollutants in the river. Furthermore, it can quickly identify the affected area and how it will change over time within a few minutes of an accident occurring.

Key words: water pollution emergency; emergency response management information system; the Three Gorges Reservoir

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Introduction

The world-famous Three Gorges are situated on the middle reaches of the Yangtze River and have a total length of 193 km. The newly constructed Three Gorges Dam has created an immense reservoir, which has a length of 663 km, a water surface area of 1085 km^2, and a total reservoir capacity of 39.3 billion m^3. The Three Gorges Reservoir Area (TGRA) is by far the biggest of hydropower plants newly constructed in China, and its installed capacity roughly equals that of 15 nuclear power stations. There are more than 8500 commercial ships operating in the reservoir, and 17 cities and more than 1700 industrial enterprises located by the reservoir. Industrial, municipal and ship effluent has become the main pollution source for the Yangtze River and resulted in averagely 12 water pollution accidents in the TGRA every year. Water pollution accidents are a crucial problem for the TGRA and directly endanger the drinking water supply for more than 30 million people and the aquatic ecosystem. On the basis of international experiences, the World Bank provided the Chinese government with policy recommendations aimed at water pollution prevention and response (World Bank, 2007). To reduce the damage caused by pollution accidents, emergency management systems for water pollution are necessary to help water stakeholders quickly make decisions and respond.

Samuels and Bahadur (2006) developed a geographic information system (GIS)-based integrated emergency system that can simulate the movement and transformation of radioactive substances in drinking-water pipes. Current advanced air-quality monitoring and emergency response techniques have been carefully analyzed by Dabberdt et al. (2004). They evaluated laser radar, global positioning system (GPS), microwave radiation, and vehicular and traditional near-Earth remote sensing (RS) technologies, and also discussed the transport model of atmospheric pollutants. Warda and Johnson (2007) used geospatial technology (mainly GISs, GPSs and RS) for urban forest protection and emergency management. Wang et al. (2008) used the one-dimensional (1D) MIKE-11 model to simulate the pollutant arrival time and concentration at various locations after water pollution accidents. The

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present article explains how to design and apply a new water pollution management system for emergency response (WPMS_ER) in the TGRA. This information system has functions that include dynamic management of pollution sources, water quality inquiry and assessment, numerical simulation of velocity and concentration fields, and strengthens emergency management functions in emergency pollution incidents. On receiving basic pollution accident information, the system can quickly simulate the pollution migration and transformation processes, automatically generate statistics regarding the affected area and the extent of the polluted area in various places after an accident occurs, and provide contingency measures for decision support.

1 Structure of the management information system

The WPMS_ER_TGRA system is a newly developed river pollution management information system (MIS). ArcGIS Engine, a collection of GIS software components, was used as the software development tool. A professional model was programmed to provide special calculation and analysis functions to help decision making in river water pollution management, and was integrated with WPMS_ER_TGRA. The overall structure of the system is shown in Fig. 1, the system includes four levels: a database, a model-based system, a GIS, and a user-friendly interface.

The interaction between different functional parts of WPMS_ER_TGRA can be described as follows. Firstly, the GIS components read digital maps from the spatial database and the user can set the boundary/initial conditions for model-based calculation, including editing the pollution-source information and entrance-cross-section parameters, such as the flow rate and water quality. The boundary and initial information is entered into a spatial-object-based database. The mathematical models

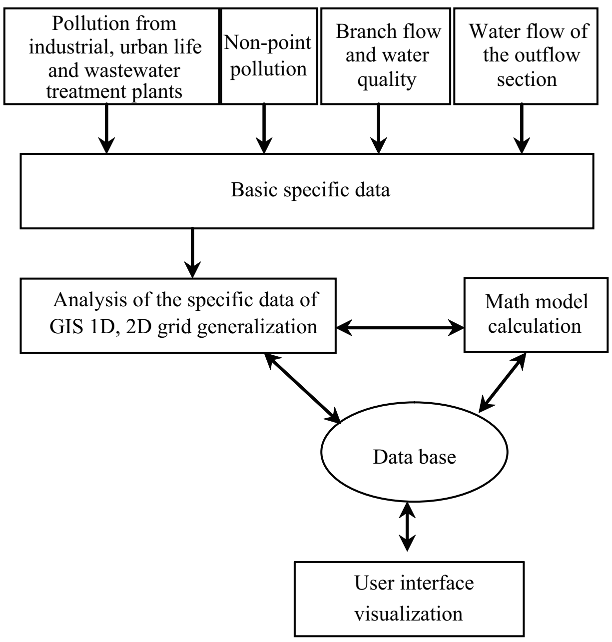

Fig. 1 Overall structure of WPMS_ER_TGRA.

subsequently read these basic data from the database, and conduct calculating tasks based upon preset programs. The outputs, such as velocity vectors and concentrations of target pollutant parameters at different positions, are also stored in the spatial-object-based database. Finally, the results are visually displayed on the user interface as thematic digital maps, which provide the decision maker with quantitative spatial-temporal modeling data.

2 Database

WPMS_ER_TGRA uses Geodatabase to store the initial basic data and the data generated through the models, which include basic spatial data, information on pollution sources, water quality and hydrological monitoring data, velocity vector field data, pollutant concentration field data, water quality assessment data, parameters for model set, and water quality standards and regulations. The spatial database not only includes the basic spatial information shown on the digital map, but also the geographical data of the computational grids, which can represent the physical domain of the Yangtze River in mathematical models with a vast array of grid nodes. In Geodatabase, nearly all data have geographical properties and are stored as attribute data of spatial objects. Hence, the spatial data and non-geographical data can be stored in a one-to-one style based on the same identification number in the database. Information on pollution accidents such as industrial enterprise accidents and ship capsizing is stored in an array of special data, which can be added to and edited by the user after the accident.

3 Model-based system

A model-based system is a collection of programming modules that normally have special functions that execute calculation and analysis tasks and help the user make reasonable decisions with useful computing output. WPMS_ER_TGRA includes a one-dimensional (1D) dynamic water-quality model, a two-dimensional (2D) hydraulic model of steady flow, a 2D dynamic water-quality model, a 2D body-fitted coordinate (BFC) model for generating the complex boundary conditions of rivers, and a model of fuzzy comprehensive water-quality assessment (Zhai et al., 2006, 2007; He et al., 2006).

3.1 Grid generalization model

Grid generalization is a key step in realizing the information attributes of all elements (such as the Yangtze River, branches, point source pollution, and nonpoint source pollution) in the watershed to be illustrated by the mathematical model. The WPMS_ER_TGRA grid generalization model employs simple 1D and 2D models for the large-scale complex-boundary conditions of rivers.

For 1D grid generalization, the system uses the spatial topology analysis function in ArcGIS to draw the Philip line of the Yangtze River, and automatically establishes 35,500 computational grids along the Philip-line in 20 m increments. This divides the river's topology into a great number of points. The spatial topology modules of ArcGIS can automatically match the pollution sources and the Yangtze River branches to the generated grids, which greatly enhance data acquisition efficiency.

Natural rivers have irregular three-dimensional shapes, which make the geometric and boundary conditions difficult to characterize. In WPMS_ER_TGRA, the Body-Fitted Coordinate (BFC) system, which can transform irregular geometries of a physical domain into simple and regular geometries of a computational domain, is automatically generated with the help of ArcGIS spatial analysis modules and a newly developed BFC generating model based on boundary fitting differential equations (Mao et al., 2008).

3.2 Hydraulic/water-quality model

3.2.1 Selection of the model equation

The general 1D and 2D governing equations for natural river-flow field simulation and water-quality field simulation in a Cartesian coordinate system can be expressed as follows.

1D hydraulic equations:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$
$$\frac{1}{g}\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x}\right) + \frac{\partial h}{\partial x} = i - J_f \tag{1}$$

1D water quality equations:

$$\frac{\partial (AC)}{\partial t} = \frac{\partial (AE_x \frac{\partial C}{\partial x})}{\partial x} - u\frac{(AC)}{\partial x} - AK_f C + S$$

2D hydraulic equations:

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0$$
$$\frac{\partial h}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} = v_t\left(\frac{\partial u^2}{\partial x^2} + \frac{\partial u^2}{\partial y^2}\right) - g\frac{\partial (Z_0 + h)}{\partial x} - g\frac{n^2 uv}{h^{\frac{4}{3}}}$$
$$\frac{\partial h}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = v_t\left(\frac{\partial v^2}{\partial x^2} + \frac{\partial v^2}{\partial y^2}\right) - g\frac{\partial (Z_0 + h)}{\partial y} - g\frac{n^2 uv}{h^{\frac{4}{3}}}$$

2D water quality equations:

$$\frac{\partial C}{\partial t} + \frac{\partial (uC)}{\partial x} + \frac{\partial (vC)}{\partial y} = \frac{\partial (E_x \frac{\partial C}{\partial x})}{\partial x} + \frac{\partial (E_y \frac{\partial C}{\partial y})}{\partial x} + K_f C + S \tag{2}$$

where, Q (m^3/sec) is the cross-section flow, A (m^2) is the cross-section flow area, q (m^2/sec) is the unit flow along the river bank (inflow is positive and outflow is negative), t (sec) is time, h (m) is the mean water depth, i is the riverbed slope, C (mg/L) is the concentration of simulated pollutant, J_f is the head loss per unit length, u (m/sec) and v (m/sec) are velocities in the x and y directions, respectively, Z_0 (m) is the elevation of the riverbed, n is the roughness of the riverbed, g is gravity, v_t is the turbulent viscosity, E_x and E_y are the mass diffusivity in the x and y directions, respectively, S is the source, and K_f is the reaction rate.

The governing equations are dynamic equations, which can be used for modeling unsteady flow and concentration feeds. However, if we set the boundary conditions to remain unchanged in a designed hydraulic condition and set the computing time long enough, the dynamics of unsteady flow and the concentration field will tend toward a steady state.

3.2.2 Designed hydrological situations for modeling

The TGRA is operated in contra-nature mode (Fig. 2). Until the start of the rainy period, which is at the end of May or in early June, the water level is reduced to 145 m so that there is sufficient equalizing volume available for the heavy precipitation in the following months. After the maximum natural water volume has passed, the water level is raised in October to a maximum of 175 m and peak energy production then begins. From January to April in the following year, the water level decreases because the effluent amount exceeds the inflow amount for the reservoir in that season. However, the water level does not drop below 155 m until May so as to combat sediment accumulation in the reservoir from June to September, the months having the highest precipitation, and wash away some of the existing deposits.

The hydrological conditions obviously vary with seasons, with water levels fluctuating by up to 30 m.

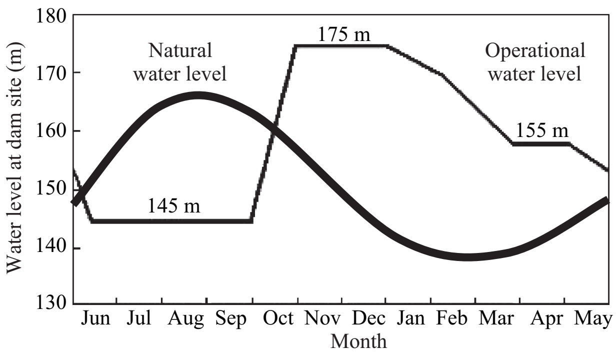

Fig. 2 Annual operational water level for the Three Gorges Reservoir.

Table 1 Designed hydraulic conditions of water-quality modeling

No.	Water period		Immigration flow (m^3/sec)			Level	Remark
			Yangtze River Zhutuo	Jialingjiang Beibei	Wujiang (m) Wulong		
1	Before dam construction	Dry period	2640	388	373	65.8	7Q10 flow*
2		Level period	8536	2120	1627	68.5	Years average flow
3		Rainy period	17,500	5312	3688	70.4	Average flood
4	After dam construction	Dry period	2640	388	373	175	7Q10 flow
5		Dry period	2640	388	373	155	7Q10 flow
6		Rainy period	17,500	5312	3688	145	Average flood

* The 7Q10 flow rate is the average flow rate for 7 continuous days in the dry season with 90% certainty, and it is considered the design value corresponding to the lowest flow.

However, the hydrological conditions remain relatively stable over one season. Therefore, six typical hydrological conditions were selected as the boundary conditions for hydraulic/water-quality simulation, as shown in Table 1.

The WPMS_ER_TGRA system uses the finite difference method (FDM) to solve the 1D or 2D hydraulic/water-quality equations. The FDM has a smaller computer memory requirement and higher calculating speed comparing with other numerical calculation methods such as the finite volume method and finite element method, which are helpful in dynamic modeling (Mao et al., 2008; Costa and Don, 2007).

To reflect the influences of the velocity, water depth, and river morphology on the model parameters, and to ensure the verified mathematical models based on natural hydrological conditions before dam construction are applicable after dam construction, the following empirical formulas were used to transform model parameters into expressions of relevant hydraulic parameters on the basis of previous research outputs (Li et al., 2002; Li and Liao, 2002; Peng et al., 2005; Xie et al., 2008).

$$\begin{aligned} E_x &= K_E\left(\frac{B}{h}\right)^{2.1}\left(\frac{u}{u_*}\right)^{0.7} hu_* \\ E_y &= Ki^{1.07}\frac{u^{0.48}}{u_*^{0.24}}\left(\frac{B}{h}\right)^{0.089} \\ \nu_\tau &= \frac{\pi}{8}C_n u_* h \\ k_{fj} &= A_j + B_j\frac{u}{h} \end{aligned} \tag{3}$$

where, u_* (m/sec) is the friction velocity, B (m) is the water surface width, u (m/sec) is the average sectional velocity, h (m) is the average depth, i is the river slope, and k_{fj} is the reaction coefficient of pollutant j. The other parameters K_E, K, C_n, A_j and B_j need to be set and verified in verifying the model.

We used the hydrology and water quality data of 16 monitoring sites, and the pollution loads for the receiving water body of the TGRA in the dry and level periods of 2003, to set the parameters of a 1D hydraulic/water-quality mathematical model. We used the data from the 2003 rainy period to verify the model. The calculation takes full account of the influences of nonpoint source pollution in different water periods.

To set and verify the parameters of the 2D hydraulic/water-quality mathematical model, the hydrology, water quality data and the pollution loads in the dry and level periods of 2003 from the Wanzhou control section were used. The Wanzhou section water quality and hydrological data from the level period of 2003, the Chongqing section data from the rainy period of 2003, and the Fuling section data from the dry period of 2003 were applied as verification data for the 2D hydraulic/water-quality model.

3.3 Programming of the mathematical model in WPMS_ER_TGRA

To combine the mathematical model and GIS components in WPMS_ER_TGRA, we used the Visual Basic programming language, form a dynamically linked library (DLL) file and convert the mathematical model, which has a special function that can be employed by another program. This development creates conditions for a modular water environment Management Information System (MIS) that can be applied to any river. The functions provided by the DLL include a 2D mesh function, a 1D concentration-field simulation function, a 2D flow-field simulation function, and a 2D concentration-field simulation function.

4 Application of WPMS_ER_TGRA

WPMS_ER_TGRA is used to provide immediate emergency management functions in the case of water pollution accidents. The system is based primarily on the rapid simulation of pollution migration over time. Using the GIS analysis and query functional modules, WPMS_ER_TGRA can identify and show the location and affected area of excessive pollution at various points in time, help relevant regional and sector leaders issue alerts, and provide them with decision support. For example, within 10 min, the system can predict what the pollution dispersion conditions will be in 48 hours. The maximum, minimum and average relative errors of pollutant concentration prediction are: 19.36%, 0.22%, and 9.95% for chemical oxygen demand (COD); 20.76%, 4.85%, and 9.91% for ammonia; 21.41%, 4.16%, and 9.10% for total nitrogen; 21.11%, 8.21%, and 16.56% for total phosphorus based on model calibration.

The simulation analysis of pollution incidents is mainly divided into three steps: adding or editing the accident pollution source, quickly calculating the concentration field and its movement with time, and analyzing and visually displaying simulation results. To show the emergency management function of the system, numerical analysis and visualized simulation based on an assumptive case, a ship capsized in the Dadukou district of Chongqing municipality, releasing 10 tons of phenol into the Yangtze River over the course of 2 hours, is illustrated as follows.

4.1 Addition of the accident pollution source

When the user receives basic information concerning the pollution accident, they immediately add a pollution source at the location where the accident happened, and edit the corresponding attribute data: the incident name (capsized ship pollution), pollutant (phenol), original pollutant concentration (100,000 mg/L), and duration of continual emission (7200 sec). The remaining attribute data, such as the node number of the accident location in the calculation grid and the name of the affected body of water, can be automatically added by the system using the GIS topology analysis module.

4.2 Dynamic simulation of the accidental pollution

After the basic data on the pollution accident is stored in Geodatabase, WPMS_ER_TGRA can use 1D or 2D dynamic mathematical models as required and quickly simulate the pollutant distribution in different time courses on the basis of selected hydrological conditions such as

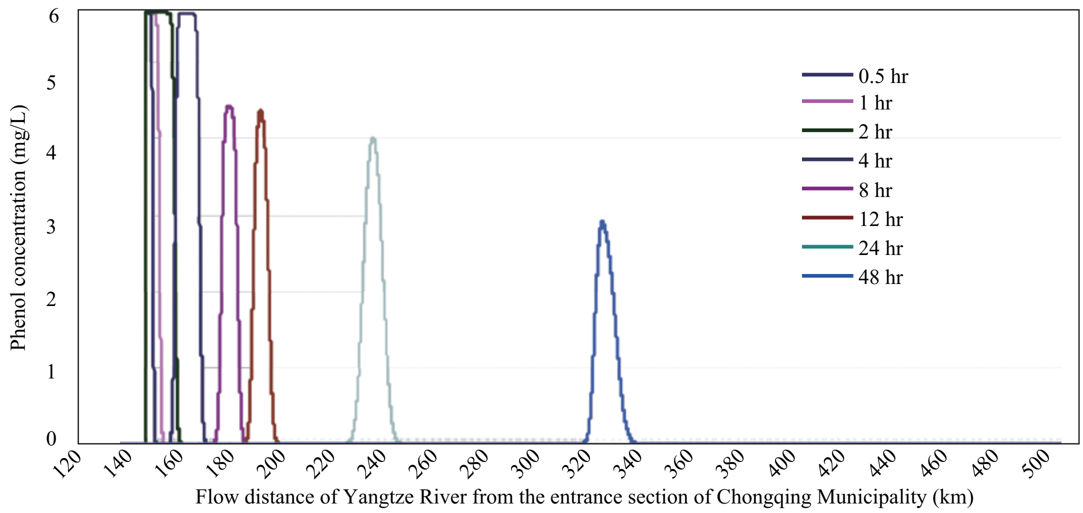

Fig. 3 Changing pollution belt in the Yangtze River at various times after an accident.

Table 2 Variation in the affected distance and concentration of phenol after the pollution accident

Items	Time after the accident							
	0.5 hr	1 hr	2 hr	4 hr	8 hr	12 hr	24 hr	48 hr
Length of the excessively polluted area (km)*	4.12	7.64	13.48	13.6	11.7	13.32	21.18	20.88
Maximum concentration in the polluted area (mg/L)	5.65	5.65	5.65	5.65	4.42	4.37	4.01	2.90
Average concentration in the polluted area (mg/L)	3.61	4.08	4.60	3.61	2.14	1.89	1.5	1.13
Name of affected district	Dadukou	Dadukou, Nan-an	Dadukou, Nan-an	Nan-an, Yuzhong, Jiangbei	Nan-an, Jiangbei	Nan-an, Jiangbei	Yubei, Changshou	Fuling, Fengdu

* The excessively polluted area is the area where the phenol concentration exceeds the water quality standard of class II (phenol $\leqslant$ 0.002 mg/L).

"the 145 m water level after dam construction". The users can set the Duration after the accident happing, for instance 2 hr, 4 hr, 12 hr, then after modeling calculation, the system will predict the location of pollution area and concentration field of the simulated pollutant with colorful highlighted digital map.

4.3 Analysis of the simulation results

WPMS_ER_TGRA can automatically analyze and generate statistics for the city and area affected by the accident with the help of the query and analysis components of the GIS. Table 2 shows the affected areas and the scope of the problem after the system analyzes the excessive pollution. Figure 3 shows the changing pollution belt at 0.5, 1, 2, 4, 8, 24, and 48 hr after the accident.

5 Conclusions

The following conclusions are derived from the results obtained in this study.

(1) A new integrated GIS-based water pollution emergency response management information system for the Three Gorges Reservoir—WPMS_ER_TGRA—was developed.

(2) Through the rapid simulation and analysis of the pollutant diffusion process following a ship capsizing, it was shown that WPMS_ER_TGRA possesses emergency management functions useful for handling a sudden pollution accident. The system can calculate and show the location of excessively polluted areas and the extent of the impact in a short period after an accident, thereby providing decision support and helping the relevant regions and departments to issue alerts.

(3) 1D and 2D dynamic hydraulic/water-quality mathematical models suitable for the GIS-based decision support system were programmed. Special mathematical models that are flexible and can be employed by different programs were programmed and compiled in DLL format.

(4) The model can be utilized to predict the pollutant concentration and has good accuracy, and can provide guidance for water pollution emergencies.

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