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Water pollution risk simulation and prediction in the main canal of the South-to-North Water Transfer Project

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SUMMARY

The middle route of the South-to-North Water Transfer Project (MRP) will divert water to Beijing Tuancheng Lake from Taocha in the Danjiangkou reservoir located in the Hubei province of China. The MRP is composed of a long canal and complex hydraulic structures and will transfer water in open channel areas to provide drinking water for Beijing, Shijiazhuang and other cities under extremely strict water quality requirements. A large number of vehicular accidents, occurred on the many highway bridges across the main canal would cause significant water pollution in the main canal. To ensure that water quality is maintained during the diversion process, the effects of pollutants on water quality due to sudden pollution accidents were simulated and analyzed in this paper. The MIKE11 HD module was used to calculate the hydraulic characteristics of the 42-km Xishi-to-Beijuma River channel of the MRP. Six types of hydraulic structures, including inverted siphons, gates, highway bridges, culverts and tunnels, were included in this model. Based on the hydrodynamic model, the MIKE11 AD module, which is one-dimensional advection dispersion model, was built for TP, NH_3-N, COD_{Mn} and F. The validated results showed that the computed values agreed well with the measured values. In accordance with transportation data across the Dianbei Highway Bridge, the effects of traffic accidents on the bridge on water quality were analyzed. Based on simulated scenarios with three discharge rates (ranged from 12 m^3/s to 17 m^3/s, 40 m^3/s, and 60 m^3/s) and three pollution loading concentration levels (5 t, 10 t and 20 t) when trucks spill their contents (i.e., phosphate fertilizer, cyanide, oil and chromium solution) into the channel, emergency measures were proposed. Reasonable solutions to ensure the water quality with regard to the various types of pollutants were proposed, including treating polluted water, maintaining materials, and personnel reserves.

1. Introduction

Earth's water resources are unevenly distributed with respect to both time and space. With the development of social economy, traditional inner-basin water transfer could not meet the increasing water demand of industrial production and living. This serious situation has made constructing large water diversion projects urgent. Compared to world-famous water transfer projects, such as the California State Water Transfer Project, the Central Valley Project, and the Snowy Mountains Scheme in Australia, the single Chinese MRP (the middle route of the South-to-North Water Transfer Project) had a longer main canal (i.e., 1277 km long) and many complex hydraulic structures (Null et al., 2014; VanRheenen et al., 2004; Erskine et al., 1999). The wide water supply areas, complex channel characteristics and joint regulating rules for the types of hydraulic structures made the MRP more difficult to analyze with regard to water flow. Additionally, channel construction cut through original roads and hindered people from travelling freely. Thus multiple bridges were constructed to make up for the inconveniences, which increased the likelihood of water pollution accidents above and then into the main canal. For instance, when traffic accidents occur with wagons or vehicles filled with toxic and harmful substances, there is the risk of their cargo being spilled into the channel, seriously polluting the water. Chemical and petrochemical products were the most dangerous pollutants for various sudden water-pollution accidents (He et al., 2011). The benzene and nitrobenzene events that occurred in Songhua River in 2005 and the leakage of industrial wastewater containing arsenic in Yangzonghai Lake in the Yunnan Province in

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2008 had seriously affects on the local social and economic development as well as the way of life in China (Peng et al., 2013). Accordingly, to ensure the water quality in the canal, it was essential to analyze the concentration changes of different pollutants with respect to sudden pollution accidents.

A one-dimensional (1D) river hydrodynamic model was used as the numerical model of long, narrow natural rivers and artificial canals. It used the average of the sectional water level and discharge to simulate the longitudinal water flow distribution and variation; it was widely applied in long-distance water diversion projects and simple 1D rivers (Zhang and Shen, 2007). For large diversion projects, scholars utilized numerical discretization using the Saint-Venant equations (Arico and Tucciarelli, 2007). Based on above method of numerical discretization, water levels at the upstream gates assumed to be constant as the upstream boundary, the continuity equation and discharge equation of water levels at the upstream and downstream of control structures were replaced by the scattered Saint-Venant equations to be used as the methods of structures and to be applied to irrigation scenarios (Lozano et al., 2010; Yan et al., 2011). Diversion and check gate were regarded as inner boundaries; gate flow formulas using Taylor expansions were scattered jointly with Saint-Venant equations (Fang et al., 2009; Zhang et al., 2007). Scholars usually met single hydraulic structures and proposed specific methods; conversely, this paper addressed six types of structures. Thus, the relationships between structures had to be considered. The MIKE11 HD module was applied widely to hydraulic structures and could represent multiple types of hydraulic structures, such as weirs, gates, bridges and culverts. MIKE11 was adopted to analyze the inundation with weirs of Elmley Marshes in southeast England and establish control strategies considering sluice gates, spillways and turbines of the Hoa-Binh reservoir in Vietnam (Ngo et al., 2007; Thompson et al., 2004). River water quality models provided simulations and predictions of water quality indexes in time and space using mathematical methods to solve water quality equations and by computer technology to simulate the physical, chemical and biological transformation process of pollutants (Boxall et al., 2002; Whitehead et al., 1997). The common 1D river water quality model included Streeter–Phelps model and WASP (Water Quality Analysis Simulation Program). Streeter–Phelps model reflected the relationships between BOD and DO; WASP was excellent at simulating phosphorus balance and analyzing the relationships between phosphorus and algae in reservoirs (Ernst and Owens, 2009).

This paper identified potential pollution sources under sudden pollution accidents. Based on the MIKE11 HD and AD modules, a one-dimensional hydrodynamic-and-water-quality coupling model was established. By employing a calibrated model to simulate the change processes of four pollutants under nine scenarios, the migration and diffusion regularities of the pollutants were assessed within the channel. Combined with the construction design of diversions, exit gates and check gates of the main canal, reasonable strategies to achieve reasonable polluted water solutions and material reserves were advanced herein. Simultaneously, these measures provided advice and support for normal water transfer when pollution accidents did occur.

2. Study area

The MRP would transfer water from Taocha, which was located in the Danjiangkou reservoir in the Hubei province as Fig. 1. It crossed the Yangtze River, Huaihe River, Haihe River, Yellow River basins and finally arrived at Beijing Tuancheng Lake. With a length of 1277 km, the MRP transferred water to nearly 150 cities and 151 thousand hectares of land via open-channels, culverts and pipes. Thus, the quality of the water had a decisive effect on the entire MRP.

In all, 1750 complicated hydraulic structures were constructed in the MRP. The Beijing–Shijiazhuang Emergency Water Supply Project (BSP) (Fig. 1) began at the Shijiazhuang and ended in Beijing over a distance of 227 km. The BSP regulated and controlled the transfer of water from four reservoirs in the Hebei province. Open channels, culverts, aqueducts, inverted siphons, diversions and highway bridges were all parts of the MRP. The designed discharges of the BSP ranged from 220 m^3/s to 50 m^3/s from south to north. The types and numbers of crossing hydraulic structures in the MRP and BSP were listed in Table 1, while the control structures of the BSP presented in Table 2 were according to the FSRBSP (2003).

All channels were newly excavated, and sections were concrete lining for the MRP. The channel had no direct hydraulic connections between internal and external structures. Furthermore, width isolations of 15 m at both sides of the channels were established to help prevent pollutants from entering the canal. As evidenced in Table 1, a large number of highway bridges that standing across the canal were the primary regions potential contaminated.

The canal from Xishi to Beijuma River in the BSP, which was 42 km in length, was the focus of this research (Fig. 1). The canal consisted of 40 hydraulic structures, including six inverted siphons, two culverts, one aqueduct, two tunnels, two check gates, two diversions and 27 highway bridges, all of which affected flow patterns and states. Which critical, the influences of these structures were difficult to establish using a one-dimensional hydrodynamic model. The Dianbei Highway Bridge was considered as the main potential pollution source location.

3. Methodology

3.1. Data collection

Canal cross-sectional geometries, structure sizes, design discharges and design water levels were obtained from the FSRSNP (2005). Traffic data with respect to the Dianbei Highway Bridge were supplied by the Baoding Municipal Transport Department in Hebei Province.

3.2. One-dimensional hydrodynamic model

3.2.1. Governing equations

Long distance, regular riverbed sections, and uniform riverbed slopes were the obvious characteristics of the MRP. Changes in water level greatly affected the safe and stable operation and control of the MRP. As a consequence, a 1D mathematical model was used to simulate the water quantity and quality. The researched canal consisted of artificial lining channels and was divided into 34 sections. The unified Manning roughness coefficient was $n = 0.015$, according to FSRSNP (2005). The Saint-Venant equations, which consisted of continuity and kinematic equations, were used in this model as follows (DHI, 2007):

$$\text{continuity equation}: \quad B\frac{\partial z}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{1}$$

$$\text{kinematic equation}: \quad \frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{\partial Q^2}{A}\right) + gA\frac{\partial z}{\partial x} + \frac{gQ|Q|}{C^2AR} = 0 \tag{2}$$

where x and t denote spatial and temporal coordinates, respectively; Q and z denote the cross-section discharge and water level, respectively; A and R denote the cross-section area and hydraulic radius, respectively; B denotes the width of the river; q denotes the lateral inflow; C denotes the *Chezy coefficient*; and g denotes the gravitational acceleration. The Saint-Venant equations are scattered using the Abbott–Ionescu 6 implicit difference method,