# Characteristics of pollutant transport influenced by emergent transfer of downstream polluted water: A case study of Xiaolangdi Reservoir, China

**Z Z Yu[1], L Zhang[2,4], J J Zhang[1], R L Xia[2] and H Zhu[3]**

[1]Water Resources Protection and Research Institute, Yellow River Basin Water Resources Protection Bureau, Zhengzhou 450004, P.R. China
[2]Yellow River Institute of Hydraulic Research, YRCC, Zhengzhou 450003, P.R. China
[3]College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, P.R. China

E-mail: hkyzhanglei@163.com

**Abstract.** Sudden water pollution in the Yellow River have brought serious economic and social losses to the basin. To better study the characteristics of pollutant transport due to aforementioned water pollution downstream of Xiaolangdi Reservoir, a mathematical model coupling of rainfall-runoff, hydrodynamic and advection-diffusion simulation was established. The emergency response to pollutant transport was analyzed by adjusting discharge of the Xiaolangdi Reservoir. The results show that the discharge is non-linearly related to the arrival time of pollutant at some important sections such as the downstream water intakes, duration and peak concentration. Moreover, compared with the previous data, the discharge from Xiaolangdi Reservoir reduced, while pollutant's arrival time was relatively longer, which means emergency response should take more time. However, the dilution for pollutant concentration decrease relatively as discharge increases. The results can be used for reference considering scientific emergency operation in Xiaolangdi Reservior to deal with sudden water pollution downstream.

## 1. Introduction

The Yellow River, with an estimated length of 5464 km, is the second-longest river in China and the fifth-longest in the world. Its midstream is filled with a large amount of mud and sand when passing through the Loess Plateau, resulting in the most sediment-laden river worldwide [1]. At present, the Yellow River provides 2% national water resources, 10% for Chinese and 15% of cultivated land in the basin. However, in recent years, the Yellow River Basin has witnessed frequent sudden water pollution, leading to not only huge economic losses, but also social instability. It has been a new threat to water supply security and normal function of water body in river basin. Statistic data suggest that, among about 76 water pollution incidents in the Yellow River Basin from 1993 to 2009, 60% occurred in the mainstream, especially in the sections of Lanzhou, Longmen-Sanmen Gorge's reach and the lower reaches of Xiaolangdi Reservoir. What's more, 65% incidents released COD, ammonia and other conventional organic pollutants, oil pollution accidents accounted for 25% in particular. In addition, leakage of chemicals, such as heavy metals, cyanide, benzene and acid also matters.

Reservoirs play a vital role of contributing significant social benefits, for instance, flood control, irrigation, hydroelectricity and water supply. On the other hand, water releases of reservoirs can alleviate negative impacts of sudden water pollution downstream. So the emergency operation in reservoirs is designed accordingly. Shi et al [1] investigated the necessity and feasibility of adjusting water allocation for pollution dilution in the lower reaches of Yellow River. Cheng and Qian [2] evaluated three emergency plans for water pollution incidents through a fuzzy comprehensive evaluation model by adopting inadequate data. However, occurrence time and location decides the uncertainties of water pollution, thus making timely and accurate responses is difficult [3]. Water quality models are flexible, fast and cost-effective tools to simulate and forecast pollutant concentration in time and space [4-7]. Zhang et al [8] set up a 1-D water quality model to simulate the case of Songhua River pollution incident, which indicates that the model can be used forforecast or reservoir regulation under varied hydrological conditions concerning water pollution incidents. Moreover, Grifoll et al [9] presented a similar management system based on water quality model that was adopted by the Spanish harbours.

The processes of pollutants' transport are affected by factors such as hydrodynamic conditions, channel morphology, velocity and wind direction, reservoir operations and so on [10,11]. Though discharged water from reservoirs is crucial to alleviate negative impacts of sudden water pollution lack of scientific corresponding emergency plans is common at present in China [12]. To be precise, current emergency plans are usually combinations of experiences or copies of solutions to low feasibility and ineffective implementation. As a result, comprehensive researches on the effect of reservoir emergency operations on the pollutants transport are necessary.

Most of sudden water pollution occurred in the lower reaches of Xiaolangdi Reservoir. Therefore, this paper established a mathematical water quality model for the downstream of Xiaolangdi Reservior to simulate the processes of pollutants transport of accidental water pollution. Numerical calculation can rapidly track the concentration transport and diffusion in real-time for a long-distance river, in addition, a series of simulations were conducted to study the effect of emergency operation on the pollutant transport. Conclusions drawn from this paper can be used as a scientific basis for the emergent operation in Xiaolangdi Reservoir, thereby improving the index system of emergent water dispatch for the water conservancy projects, and optimizing reservoir operation modes.

## 2. Materials and methods

### *2.1. Study area*

Xiaolangdi Reservoir, the largest one in the Yellow River Basin and one of the most challenging projects in the world, has a total design storage capacity of $1.265\times10^{10}$ m$^3$ and a controlled drainage area of $6.94\times10^5$ km$^2$. Its vital role is to control flood and sediments of the Yellow River, 128 km upstream of Huayuankou Hydrological Station [13,14]. The reach downstream of Xiaolangdi Reservoir is one of most economically and socially developed areas in China, which is also the water resource for downstream regions such as Zhengzhou City, Kaifeng City, Puyang City, Jinan City, Binzhou City and Dongying City. This area also transfers water to Hebei Province, Tianjin City, Qingdao City, Zibo City and other regions outside the basin. However, unbalanced supply and demand in terms of quantity and quality is seen in this region as water resource is highly developed and utilized.

Due to the long-term deposition of excessive silts, the lower reaches of the Yellow River is recognized as "River on the Ground" globally. The silts from the middle reaches form sediments here, elevating the river bed 4 m to 6 m above the surrounding ground beside the dikes. In the lower reaches of the Huayuankou station, the riverbed has even been several meters above the plains on the both sides, leading to high risk in this area. There are few tributaries in the area downstream of Xiaolangdi Reservoir. Therefore, in order to control river flow, levees with a total length of more than 1400 km are built along the banks except the segment between Dongping Lake on the southern bank and Jinan City.

This study covers the region flown through by the mainstream of 895.7 km from Xiaolangdi Dam to the estuary of Yellow River, across Henan Province and Shandong Province (see figure 1). The study area includes Yiluo River and Qin River, two bigger tributaries, as well as other ones such as Xinmang River, natural Wenyan Drainageand Jindi River. Due to small flow, other rivers were not taken into consideration in this paper (especially in the non-flood period, the discharge is basically less than 1 $m^3/s$).

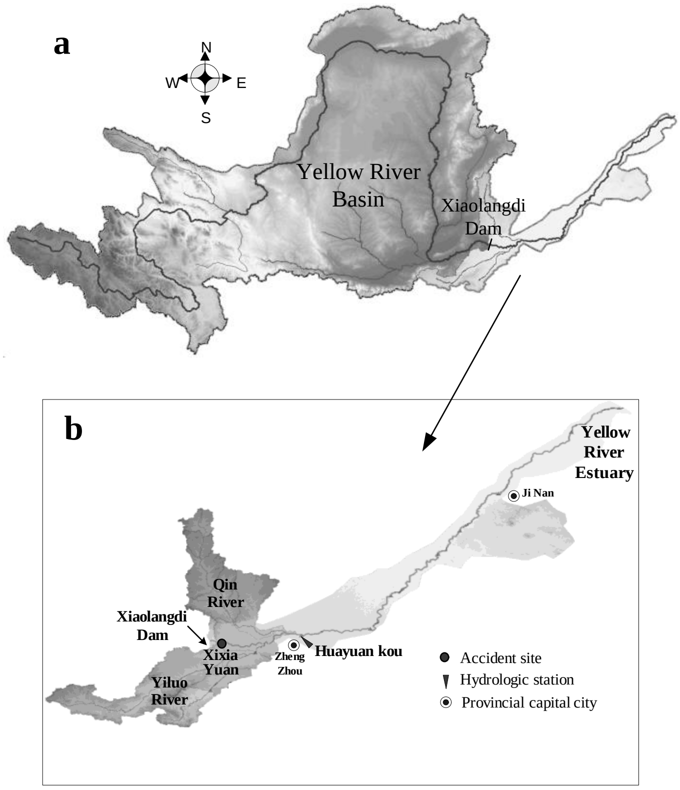



**Figure 1.** Yellow River Basin (a), computational domain (b).

*2.2. Model description*

*2.2.1. Scenario setup.* In dry season from January to February, water pollution frequency is relatively high in the Yellow River Basin [15]. Assuming that the sudden water pollution occurred at 11:00:00 in the Xixiayuan section (16 km away from the downstream of Xiaolangdi Dam) on January 10, 2008. At the same time, a water-dissolvable and non-degradable liquid substance (non-heavy-metal substance) was discharged into the Yellow River with the concentration of 1000 mg/L and discharge speed of 20 $m^3/s$. Moreover, immediately after the pollution, Xiaolangdi Reservoir changed operating mode and launched emergent water transfer.

To be noted, the real releasing discharge from Xiaolangdi Reservoir is 711 $m^3/s$ (see figure 2). Based on numerical experiments, 10 kinds of reservoir operation schemes were designed, namely constant discharged flows of 150 $m^3/s$, 200 $m^3/s$, 300 $m^3/s$, 400 $m^3/s$, 500 $m^3/s$, 600 $m^3/s$, 700 $m^3/s$, 800 $m^3/s$, 1000 $m^3/s$, and 1500 $m^3/s$ were adopted simultaneously. As the hydrodynamic conditions changed, the time of pollutants' arrival time at some important sections such as the downstream water intakes, duration along with the peak concentration were analyzed.

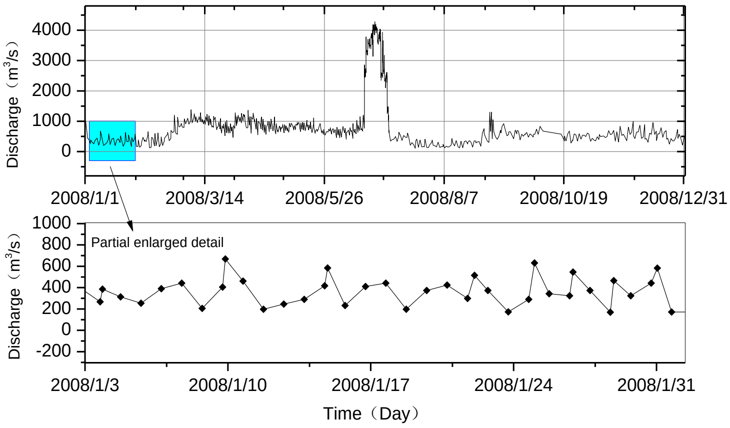



**Figure 2.** Releasing discharge with measured time from Xiaolangdi Reservoir in January, 2008.

*2.2.2. MIKE 11 model and parameters determination.* MIKE 11 is based on the Saint-Venant equations and can represent a wide range of hydraulic structures including weirs, gates, bridges and culverts commonly within rivers. Furthermore, an extensive description of the model has been given by Post et al [16], Monninkhoff and Li [17], as well as Thompson et al [18]. Although the multidimensional mathematical models have been used to simulate and forecast the hydrodynamics and water quality in water bodies over years [19-23], the one-dimensional models remain appropriate and convincing for accidental water pollution in a long river. In this paper, the proposed MIKE 11 model was applied to simulate the temporal-spatial changes of water quality based on hydrodynamic, rainfall-runoff and convection-diffusion. By changing the releasing discharge, the effects of emergency operation on the pollutant transport were investigated.

The generalized river network for the lower reaches of Xiaolangdi Reservoir is shown in figure 3. In addition, 390 measured cross-sections and some meteorological input data (radiation and rainfall) were obtained from a hydrology almanac in 2008. Moreover, water intake in the study area was taken into account.

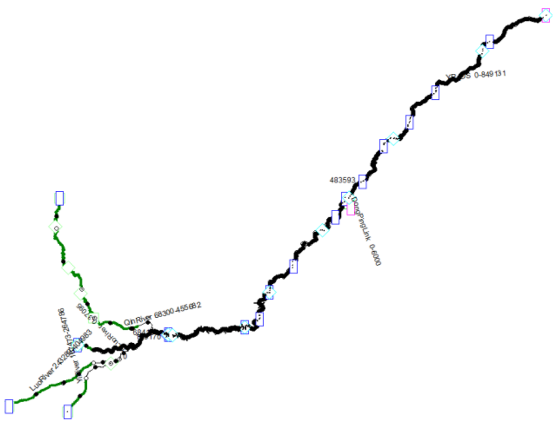


**Figure 3.** The river network in the study area.

The value of pollutant concentration was set at 0mg/L in the entire river network except for the accidental pollution source in order to calculate the incremental concentration of pollutant to rivers. The inflow boundary conditions were consisted with measured discharges from four hydrological stations at Xiaolangdi dam, Luhun, Changshui and Kongjiapo as well as measured water levels of estuary for the outflow boundary conditions. In view of the discharge exchange between Dongping

Lake and the mainstream of Yellow River, the Dongping gate has been considered in the model. But during simulation, the gate was kept closed. The simulation time was from 9:30:00, January 3 to 0:00:00 February 1 in 2008 and the time step $\Delta t = 3$ minutes, to ensure computational stability.

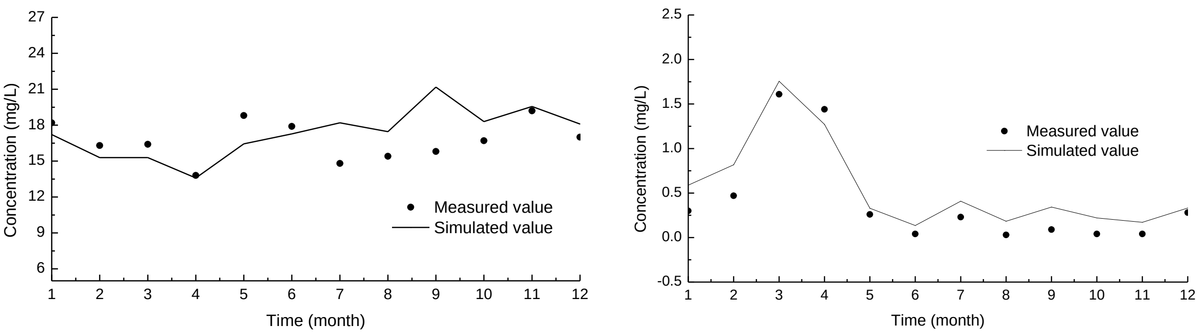
As for long-distance pollutant transport, water qualityhas little direct relation to the diffusion coefficient. In this study, the value was set as a constant of 10 $m^2/s$, and the one MIKE 11 parameter used for calibration was the roughness coefficient within the river network. According to complex and varied terrains of simulated regions in the downstream of Yellow River, the roughness coefficients varied greatly. For example, the value was set from 0.011 $s/m^{1/3}$ to 0.017 $s/m^{1/3}$ from Xiaolangdi to Gaocun, while at 0.014 $s/m^{1/3}$ for lower reaches of Gaocun, vertical roughness coefficients were from 0.8 $s/m^{1/3}$ to 1.8 $s/m^{1/3}$ in the entire simulated reaches.

*2.2.3. Model calibration and validation*. Water Resources Protection Bureau of Yellow River Basin is responsible for water quality monitoring in study area. Monthly measured water quality data from the bureau at Huayuankou Hydrological Station in 2008 were used to verify the model results. Simulation was carried out in 2008, typical water quality factors of CODcr and NH3-N were shown in table 1.

**Table 1.** The decay coefficients determination (the unit: 1/h).

| Time / Factors | July - October | November-December, January-February | March-June |
|---|---|---|---|
| CODcr | 0.012 | 0.0054 | 0.0083 |
| $NH_3$-N | 0.01 | 0.005 | 0.0075 |

It is demonstrated that the simulated and measured water quality concentration in figure 4. The simulated values of CODcr's and NH3-N's concentrations are basically in agreement with the measured ones with mean relative errors of 9.36% and 15.6% respectively. In particular, variation trends are consistent. So that conclusion can be drawn that the simulated concentration, or furthermore, the model can serve as reasonable approximation of actual water quality changes.




(a) CODcr (b) $NH_3$-N

**Figure 4.** Measured and simulated CODcr, $NH_3$-N concentration at Huayuankou Hydrological Station in 2008.

## 3. Results

### *3.1. Modeling result of pollutant transport*

Magnitude changes of releasing discharge from Xiaolangdi Reservoir range from 150 $m^3/s$ to 1500 $m^3/s$. According to simulation, the outflow from reservoir is the main factor of pollutant transport. As the discharge increases, the flow is capable of diluting the pollutant to a certain degree. Considering Huayuankou section, the peak concentrations of pollutant decrease as discharge increases. However, the earlier pollutant reaches Huayuankou section, the shorter transport lasts (see figure 5). Similar characteristics are seen in other sections.

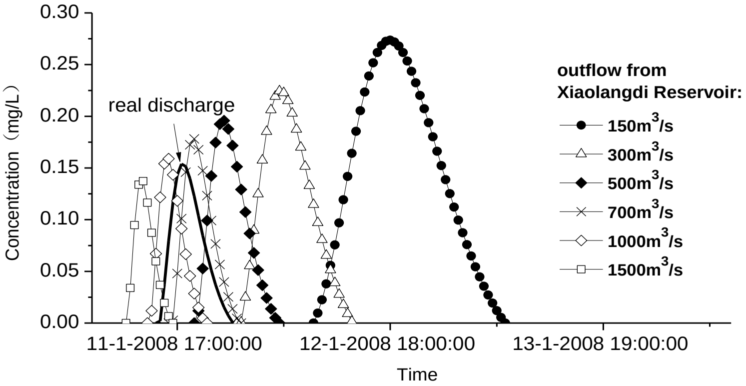



**Figure 5.** Simulated concentration by measured time at Huayuankou Hydrological Station.

When the releasing discharge is under same grade, for example, the Xiaolangdi Reservoir takes emergent water transfer at 200 $m^3/s$, with gradual transport and diffusion of pollutant to the downstream hydrologic sections, such as Huayuankou section, Jiahetan section, Gaochun section, Sunkou section, Aisan section, Luokou section, and Lijin section (the distances from Xiaolangdi Reservoir are increased successively), the peak concentrations are lower, and such duration at seven sections will gradually increase (see figure 6).

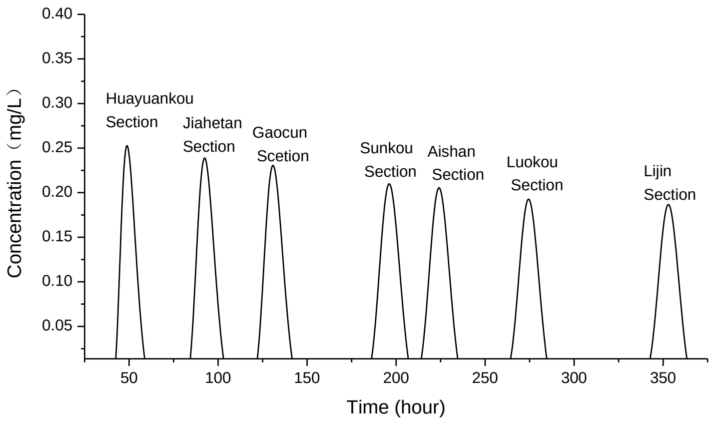



**Figure 6.** Pollutant concentration at downstream sections with discharge of 200 $m^3/s$ from Xiaolangdi Reservoir.

### *3.2. Analysis of pollutant transport characteristics*

As shown in figures 7-9 releasing discharge of Xiaolangdi Reservoir is correlated to arrival of pollutant at eight water intakes, that are HGK, QC, DMX, PL, LXZ, DWM, BZ, DYZ (the distances from Xiaolangdi Reservoir are increased successively) in the form of power function attenuation.

In order to study impact of emergent water dispatches by Xiaolangdi Reservoir and actual discharged flow during the same simulated period on the pollutant transport, a statistical analysis has been conducted as shown in figure 10. Compared with the actual releasing discharge - i.e., not to take any emergent water transfer scheme, discharged flow from Xiaolangdi Reservoir is 150 $m^3/s$, the time of pollutant to be transported to HGK Water Intake (190 km away from the reservoir) increase (delay) by 66.07%, and the peak concentration increase 77.78%; when discharged flow from Xiaolangdi Reservoir is 1500 $m^3/s$, the time length to the same water intake is only decrease(ahead of time) by

12.5%, and the peak concentration is down by 10.79%. In addition, the same rules are applied to pollutant transport to other water intakes.

Therefore, reduction in discharge has a significant impact on the time of pollutant arriving at downstream sections and the peak concentration.

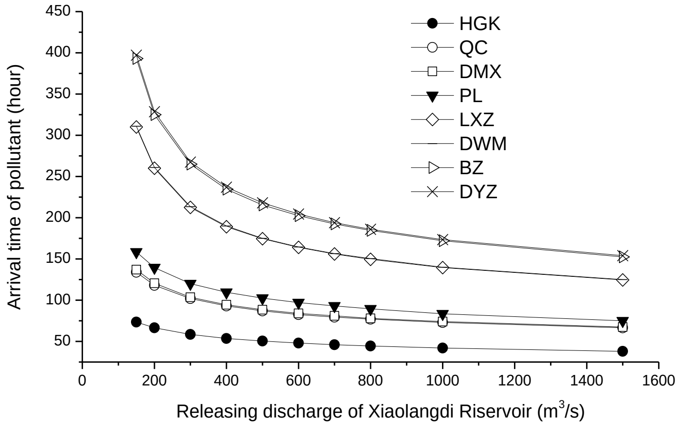



**Figure 7.** Relationship between discharge and arrival time of pollutant at water intakes sections.

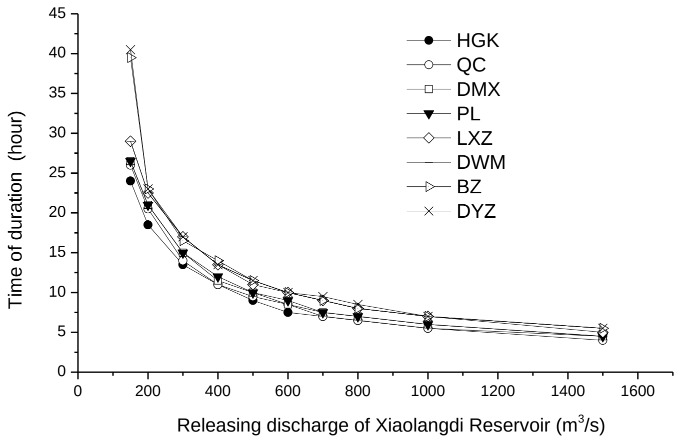



**Figure 8.** Relationship between discharge and duration at water intakes sections.

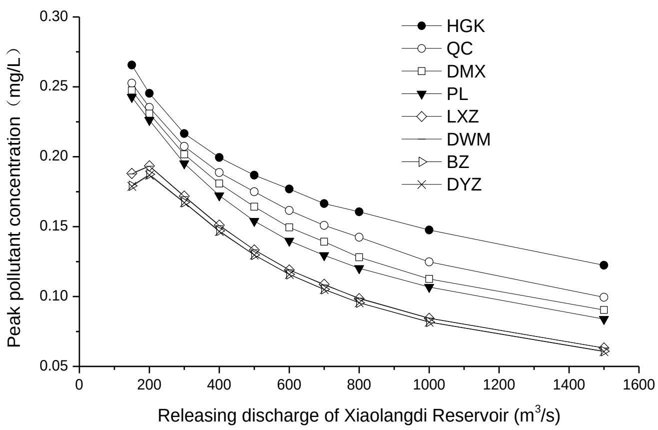



**Figure 9.** Relationship between discharge and peak concentration at water intakes sections.

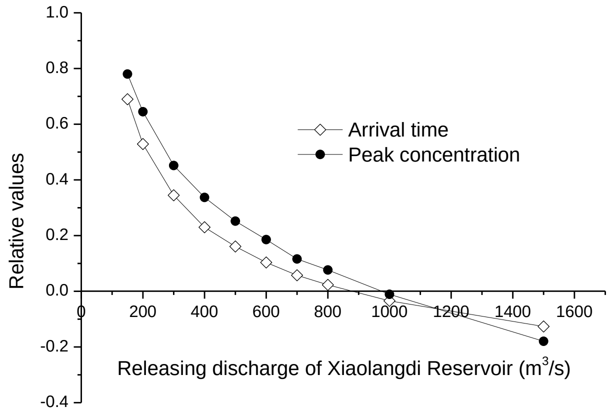



**Figure 10.** Relative values of arrival time and peak concentration in HGK Water Intake.

## 4. Conclusions

A one-dimensional water quality model for the lower reaches of the Xiaolangdi Reservoir has been developed by coupling of the rainfall-runoff, hydrodynamic and advection-diffusion simulation. After appropriate calibration, the model was then applied to Xixiayuan water pollution incidents. The effects of emergency operation on the pollutant transport were investigated by changing discharged flow of the Xiaolangdi Reservoir.

The study is demonstrated in the Xiaolangdi Reservoir, the releasing discharge and the arrival time of pollutant at some important sections such as the downstream water intakes are not in linear relations with duration along with peak concentration. Increased discharge by the Xiaolangdi Reservoir can dilute the pollutant to a certain range. Comparing with the actual discharged flow, the concentration due to dilution effect decreases by a small ratio. However, when the discharged flow reduces, the arrival time is substantially more than that of conventional discharge, which provides more time for further emergency measures. The conclusion can not only enhance our understanding of the characteristic of the pollutants transport under the condition of reservoir emergency operation, but also provide a scientific basis for future emergent water transfer.

## Acknowledgment

This work was supported by the National Natural Science Foundation of China (Grant No. 51709126, 51779101, 51609068); and the fundamental research funds for the central nonprofit research institutions (HKY-JBYW-2018-01).

## References

[1] Shi R L, Sun Z D, Zeng Y, *et al* 2011 Discussions on issues of water allocation for pollution dilution of the lower Yellow River *Yellow River* **33** 58-9(62) (in Chinese)
[2] Cheng C Y and Qian X 2010 Evaluation of emergency planning for water pollution incidents in reservoir based on fuzzy comprehensive assessment *Procedia Environ. Sci.* **2** 566-70
[3] Cui W and Liu C 2006 Considerations on severe sudden accidents of water contamination in Songhuajiang River and Tuojiang River *Water Resour. Prot.* **22** 1-4 (in Chinese)
[4] French J R and Clifford N J 2000 Hydrodynamic modelling as a basis for explaining estuarine environmental dynamics: some computational and methodological issues *Hydrol. Process.* **14** 2089-108
[5] Zheng L, Chen C and Zhang F Y 2004 Development of water quality model in the Satilla River Estuary, Georgia *Ecol. Modell.* **178** 457-82
[6] Bell V A, George D G, Moore R J, *et al* 2006 Using a 1-D mixing model to simulate the vertical flux of heat and oxygen in a lake subject to episodic mixing *Ecol. Modell.* **190** 41-54
[7] Antonopoulos V Z and Gianniou S K 2003 Simulation of water temperature and dissolved

oxygen distribution in Lake Vegoritis, Greece *Ecol. Modell.* **160** 39-53
[8] Zhang B, Qin Y, Huang M, *et al* 2011 SD–GIS-based temporal–spatial simulation of water quality in sudden water pollution accidents *Comput. Geosci.* **37** 874-82
[9] Grifoll M, Jordà G, Espino M, *et al* 2011 A management system for accidental water pollution risk in a harbour: the Barcelona case study *J. Marine. Syst.* **88** 60-73
[10] Wang Q G, Zhao X H, Wu W J, *et al* 2008 Advection diffusion models establishment of water pollution accident in middle and lower reaches of Hanjiang river *Adv. Water Sci.* **19** 500-4 (in Chinese)
[11] Yu Z Z and Wang L L 2011 Factors influencing thermal structure in a tributary bay of Three Gorges Reservoir *J. Hydrodyn.* **23** 407-15
[12] Zhao S F, Zhang X F and Li H 2009 Analysis of the emergency system for sudden water pollution incident in the Yellow River *Yellow River* **31** 13-4 (in Chinese)
[13] Wang H, Yang Z, Saito Y, *et al* 2006 Interannual and seasonal variation of the Huanghe (Yellow River) water discharge over the past 50 years: connections to impacts from ENSO events and dams *Global. Planet. Change* **50** 212-25.
[14] Chen J, Zhou W and Sun P 2009 Effects of water-sediment regulation by Xiaolangdi Reservoir on channel erosion in the lower Yellow River *Int. J. Sediment. Res.* **3** 1-7
[15] Si Y M and Li Y H 2004 Establish quick reaction mechanism against the key water pollution events in the Yellow River *Yellow River* **26** 28-9 (in Chinese)
[16] Post D A, Kinsey-Henderson A E, Stewart L K, *et al* 2003 Optimising drainage from sugar cane fields using a one-dimensional flow routing model: a case study from Ripple Creek, North Queensland *Environ. Modell. Softw.* **18** 713-20
[17] Monninkhoff B L and Li Z 2009 Coupling FEFLOW and MIKE11 to optimise the flooding system of the Lower Havel polders in Germany *Int. J. Water* **5** 163-80
[18] Thompson J R, Sørenson H R, Gavin H, *et al* 2004 Application of the coupled MIKE SHE/MIKE 11 modelling system to a lowland wet grassland in southeast England *J. Hydrol.* **293** 151-79
[19] Cerco C F and Cole T 1993 Three-dimensional eutrophication model of Chesapeake Bay *J. Environ. Eng.* **119** 1006-25
[20] Heniche M, Secretan Y, Boudreau P, *et al* 2000 A two-dimensional finite element drying-wetting shallow water model for rivers and estuaries Adv. *Water Resour*. **23** 359-72
[21] Koçyigit M B and Falconer R A 2004 Three-dimensional numerical modelling of wind-driven circulation in a homogeneous lake *Adv. Water Resour.* **27** 1167-78
[22] Missaghi S and Hondzo M 2010 Evaluation and application of a three-dimensional water quality model in a shallow lake with complex morphometry *Ecol. Modell* **221** 1512-25
[23] Nesterov O and Chan E S 2010 A two-dimensional high-resolution model for depth-average hydrodynamics simulations in the Singapore Strait *Adv. Geosci.* **18** 135-48