

# Discussion on Reservoir dispatch during a sudden accident of water pollution in a long distance river

FANG Shen-guang, CUI Li-qin, He Yong

(Pearl River Hydraulic Research Institute, Research Center of Engineering Technology of the Pearl River Coast and Estuary of the Ministry of Water Resources, Guangzhou 510611, China)

**Abstract:** A mathematical model of river hydrodynamics with cascade reservoirs and pollutant has been established and verified by using analytic solutions of partial differential equation for transportation and diffusion. Ten dispatch schedules of single or multi-reservoirs have been set up and executed according to that a pollution accident occurred upstream or downstream to a reservoir. It shows that which dispatch schedule should be selected was decided by sensitive factors of a target river segment downstream. A dispatch model of large flux with short time duration by utilizing a reservoir nearest to the segment was more appropriate for which was more sensitive to concentration than other factors, while a model of appropriate flux discharge with long time duration was more suitable for those being more sensitive to extra concentration retention of pollutants. Compared with a single reservoir dispatch, multi-reservoirs have larger effective storage capacity to reduce the loss by a sudden water pollution accident better by supplement water step by step from upstream to downstream.

## 1 Introduction

As the rapid development of economy and society with industrial layout and transfer, the risk of sudden water pollution accident rise quickly year by year, while ecology disaster would be triggered and serious negative effect on water environment occurred under inadequate response for its uncertainty, high harmfulness, hard to deal with, and urgency<sup>[1]</sup>, such as the total leakage of 33.6t crude phenol solution into the Sanhe River in the upper Youjiang river system caused by a traffic accident in Fu Ning County, Wenshan, Yunnan Province on June 7, 2008<sup>[2]</sup>, water pollution<sup>[3]</sup> occurred in Tingjiang river by Zijin Mining in August 2010 and the illegal dumping accident of the chromium slag<sup>[4]</sup> in Qujing, Yunnan in August 2011 and so on. Some efforts have been made to control the loss of sudden water pollution accidents by joint operation of cascade reservoirs<sup>[5]</sup>. For example, during the Beijiang River tin pollution accident in Guangdong in 2005, some measures have been taken to increase upstream reservoir discharge to dilute pollutants and use artificial small flood peaks to accelerate the transfer of contaminants to downstream treatment areas to control the deterioration of pollution accidents. Reservoirs of Dapu and Mashi in the upper reaches of the Liujiang river have been dispatched to dilute contaminants during a tin water pollution accident in Longjiang river, Guangxi in 2012 to ensure drinking water safety for the Liuzhou city downstream. In 1980s, that clear water have been piloted to the Xuanwu Lake in Nanjing city to obviously

improve the water quality<sup>[6]</sup> was the first example of using the reservoir operation to deal with the sudden water pollution in China. Effects of three kinds of emergency measures of water diversion to deal with the fuel leakage accident at the Wujing wharf in the lower Yangzi river have been evaluated through the establishment of a two-dimensional model by Kuang, et al<sup>[7]</sup>. Su<sup>[8]</sup> drew up different emergency water diversion schemes for the possible locations of sudden water pollution accidents along the coast based on rivers and water conservancy projects in Chongzuo city. The effects of pollution diffusion in Thai Lake by discharging nine different fluxes from Taipu sluices of water conservancy project hub in Wangyu river have been analyzed by Kuang, et al<sup>[9]</sup>. The two stages of shear diffusion and attenuation by dilution for contaminants water mass movement in a sudden water pollution accident in the middle reaches of Xijiang River have been proposed by Fang S. G., et al<sup>[10]</sup>. A mathematical model of hydrodynamic and pollutant transport and diffusion in a long-distance river with cascade reservoirs has been established for simulating single or cascade reservoir joint dispatching schemes to explore a rational dispatch pattern under a sudden water pollution accident.

## 2 Mathematical Model

### 2.1 Equations of Hydrodynamic and Transport and Diffusion for pollutants in a River

Continuous equation:

$$B \frac{\partial Z}{\partial t} + \frac{\partial Q}{\partial s} = 0 \quad (1)$$

Movement equation:

$$\frac{\partial Q}{\partial t} + 2 \frac{Q}{A} \frac{\partial Q}{\partial s} + (gA - B) \frac{Q^2}{A^2} \frac{\partial Z}{\partial s} - \left( \frac{Q}{A} \right)^2 \frac{\partial A}{\partial s} + g \frac{|Q|Q}{AC^2 R} = 0 \quad (2)$$

Transport and diffusion equation:

$$\frac{\partial (AC)}{\partial t} + \frac{\partial (QC)}{\partial x} = \frac{\partial}{\partial x} \left( DA \frac{\partial C}{\partial t} \right) + c_i q \quad (3)$$

Where  $s$  is distance, m;  $Q$  is flux,  $\text{m}^3/\text{s}$ ;  $Z$  is water level, m;  $g$  is gravitational acceleration,  $\text{m}/\text{s}^2$ ;  $t$  is time, s;  $A$  is cross-section area,  $\text{m}^2$ ;  $R$  is hydraulic radius, m;  $n$  is the roughness coefficient of the river channel;  $D$  is the diffusion coefficient ( $\text{m}^2/\text{s}$ );  $C$  is the concentration of the pollutant ( $\text{mg}/\text{m}^3$ );  $q$  is the source or sink per unit length of the grid ( $\text{m}^3/\text{s}/\text{m}$ );  $c_i$  is the concentration of pollutants in the source or sink. In order to ensure the upwind characteristics of the pollutant transport and diffusion model, in the process of discreteness and calculation of the convection items in equation (3), it is necessary to determine the flow direction of each grid node, and at the same time, the pollutant transport and diffusion in the river system is mainly Convective shearing dominates, turbulence diffusion effects are relatively small, and therefore neglected during calculation. The one-dimensional hydrodynamic mathematical model uses the Preissmann four-point implicit difference scheme to discretize, and the chasing method is used to solve the large-scale diagonal sparse equations obtained by discrete method.

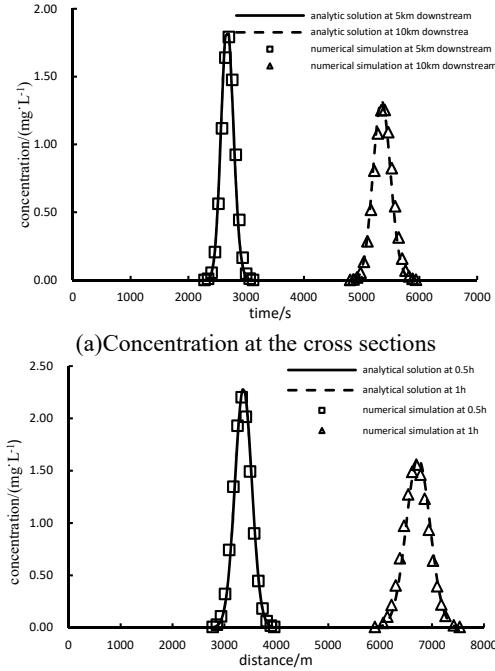
## 2.2 model verification

To verify the accuracy and reliability of the mathematical model, a prismatic trapezoidal channel have been set up with a length of 10km, a bottom width of 67.5m, a slope of 1:2.5 and a bottom slope of 0.15% with 0.027 given for the channel roughness coefficient. The upper boundary condition is maintained at a constant flow rate of 2000 $\text{m}^3/\text{s}$  and the water level for the downstream boundary is determined by the uniform flow formula for an open channel and kept constant. It is assumed that 1 tons of soluble refractory pollutants are suddenly leaked at a section of the upper reaches of the river, the process of pollutant concentration at the downstream sections of 5km and 10km from the upper boundary and the distribution of pollutant concentration in the river channel at the time of 0.5h and 1h were estimated. The analytical solutions of the transport-diffusion equation (3) are given as follows:

$$C = \frac{M_0}{\sqrt{4\pi Dt}} \exp \left( -\frac{(x-ut)^2}{4Dt} - kt \right) \quad (4)$$

In the formula (4),  $u$  is the average velocity of cross section,  $\text{m}/\text{s}$ ;  $x$  is the distance from the pollution source section to a location downstream, m;  $M_0$  is the initial surface source strength of water pollution,  $\text{g}/\text{m}^2$ ;  $K$  is the pollutant attenuation coefficient,  $\text{s}^{-1}$ . Neglecting the vertical and lateral diffusion of pollutants, the frictional velocity 0.11 $\text{m}/\text{s}$  of the section, the initial surface strength 934.929 $\text{g}/\text{m}$  and the longitudinal diffusion

coefficient  $D = 6.01hu^* = 7.4\text{m}^2/\text{s}$  were calculated. Fig.1 shows the variation of the concentration of pollutants at the sections with time and the comparisons of numerical simulation and analytical solutions of pollutant concentration distributions, which verifies the accuracy and reliability of the established mathematical model for the transportation and diffusion of pollutants.



**Fig. 1** Comparisons for numerical simulation and analytical solutions

## 3 Sudden water pollution accidents and reservoir dispatch schemes

### 3.1 Simulated conditions

A virtual river of 1000km length with rectangular cross section was designed here with three cascade reservoirs arranged in Fig.2, while the bottom width of the river was set as 100m and the roughness coefficient as 0.056. Due to dam construction, the continuity of water flow was lost, which lead to the unavailability of the Saint-Venant equations. In order to achieve the purpose of simultaneous calculations and incorporate the reservoir scheduling plans, the concept of sub-networks divided by dams is introduced here and special nodes set for water control projects to connect the various river reaches into a computational whole, details preferred to related literature [11]. According to the river and cascade reservoir layout topology, 4 river sections, 4 sub river networks and 8 nodes can be distinguished here. The external boundary conditions and the reservoirs' scheduling schemes can be implemented by controlling the nodes set up for them and the reservoirs.

### 3.2 Sudden accident formulation

Two sudden water pollution accidents are set up as

following according to the relative positions of cascade reservoirs and pollution sources as shown in Fig.2.

(1) Pollution Accident 1: Proposed pollutants enter the river from a cross section 10km downstream away from No. 2 Reservoir.

(2) Pollution Accident 2: Proposed pollutants enter the river from a cross section with the same distance of 50km downstream away from No. 1 Reservoir and upstream from No. 2 Reservoir.

It's assumed that pollution water entered the river initially at the time 0 and reached a maximum flux of  $50\text{m}^3/\text{s}$  at 2 o'clock, while the flux maintained to the time of 10 o'clock and dropped gradually to  $0\text{ m}^3/\text{s}$  at 12 o'clock. The concentration of the pollutants contained in the sewage is set to 1.0, and the background in the river channel is set to 0 initially, regarded as unacceptable if exceeding the critical value of 0.0001 in numerical simulations. The No. 1 node represented as the upper boundary of the river is set to a constant inflow of

$1000\text{m}^3/\text{s}$  and the water level at the node 8 as the downstream boundary was kept constant as 7.8m. In addition to the reservoirs involved in dispatch, the water level of other reservoirs is always maintained at a normal operating level and 4 concentration monitoring sections were set up along the river.

### 3.3 Reservoir regulation scheme formulation

Ten reservoir regulation schemes formulated to deal with the 2 pollution accidents in Table 1, while scheme 1 to 9 were for accident 1 with scheme 10 and 11 for accident 2, detailed as following:

(1) For pollution accident 1, about 6 regulations (from scheme no.1 to no.6 as shown in Table 1) were formulated of using only reservoir no.1 to explore the effect of different discharge flux and scheduling duration on pollutant transportation and

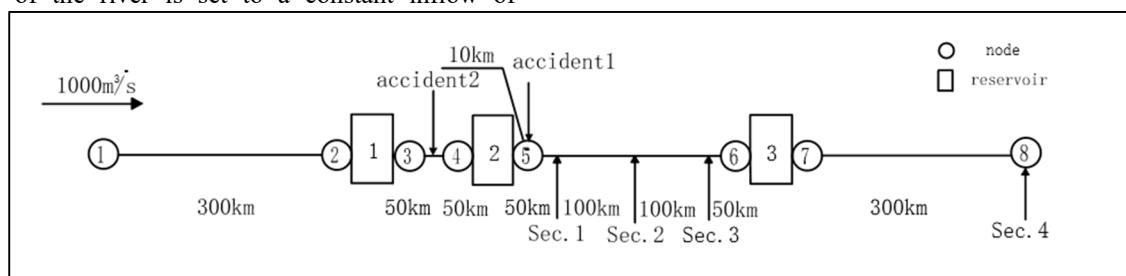


Fig.2 Diagram of river network and node layout

Table 1 Emergency Response Plan for sudden pollution accidents

pollution accidents	Scheduling scheme	Scheduling reservoir	discharging flux /( $\text{m}^3 \cdot \text{s}^{-1}$ )	Start time	End time	Duration /h
accident1	scheme 1	Reservoir 1	2000	0	24	24
	scheme 2	Reservoir 1	2000	0	48	48
	scheme 3	Reservoir 1	2000	0	72	72
	scheme 4	Reservoir 1	3000	0	12	12
	scheme 5	Reservoir 1	3000	0	24	24
	scheme 6	Reservoir 1	4000	0	12	12
	scheme 7	Reservoir 1	2000	0	24	24
		Reservoir 2	2900	20	28	8
	scheme 8	Reservoir 1	2000	0	24	24
		Reservoir 2	2000	63	71	8
	scheme 9	Reservoir 1	2000	0	12	12
		Reservoir 2	2000	0	40	40
accident2	scheme 10	Reservoir 1	2000	0	32	32
		Reservoir 2	3000	18	30	12

diffusion in the river. Schemes 7 to 9 were formulated to explore the efficiency of joint scheduling of reservoir 1 and 2.

(2) For pollution accident 2, the efficiency of joint scheduling has been explored when sudden pollution accident occurred between the two reservoirs.

## 4 Scheduling Analysis

### 4.1 Dispatch Under Accident 1

(1)The curve type of concentration with time from the Sec.1 to Sec.4 which the distances away to the pollution source increased in sequence changed from the apex to the stout one, which showed that the peak concentration

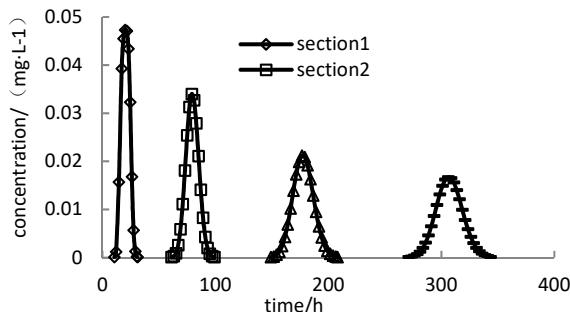
of pollutants decreases gradually, and the concentration duration of exceeding the critical value increases in turn.

(2)Compared the results under dispatch scheme 1, 2 and 3 simulated, dispatch duration of the reservoir 1 under the condition of a same discharge has little effect on the peak of pollutant concentration at the monitoring cross sections downstream, such as the peak value at the section 1, 2 and 3 remained unchanged at 0.0371 and at the section 4 reduced slightly to 0.034. However, it had affected obviously the concentration duration of exceeding the critical value at the cross sections, while the farther the distance, the longer time it affects. For example, the extra concentration duration at Sec.1 remains unchanged at 16.5h under different dispatch schemes and extends at Sec.4 from 71.5h under the condition of no dispatch scheme to 62h under the scheme

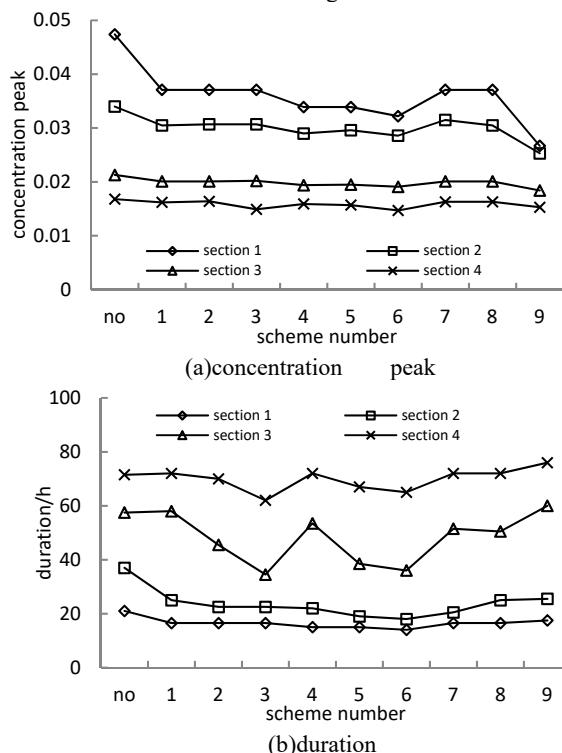
### 3.

(3)Compared the results under dispatch scheme1 and 5 with scheme 4 and 6, the more the flux discharged by the dispatch reservoir, the more the peak concentration dropped under the same schedule time, and the drop range decreased to the downstream direction along the river. The extra concentration duration at a section would decrease with increasing of flux discharged and appear different variation tend with distance downstream away to the source. For example, the extra concentration duration at Sec.1 to Sec.3 extended from 1.5h to 19.5h, while reduced to 5.0h at Sec.4 when flux discharged from Reservoir 1 increased from 2000m<sup>3</sup>/s to 3000m<sup>3</sup>/s. It shows that there is best effect on reducing extra duration at the distance downstream away to the pollution source under the condition of increasing flux discharged.

(4) Scheme 3 represents a dispatch model with smaller flux and relatively longer time durations and scheme 6 represents another model of larger flux and relatively short time durations to deal with



**Fig.3** Pollutant concentration at cross sections without scheduling



**Fig.4** Pollutant characteristics at cross sections in accident 1 sudden water pollution accidents. The peak concentrations and extra durations at Sec.1 and Sec.2

which are closer to the pollutant source than others decreased more under scheme 6 than under scheme 3. However, the two dispatch schemes have little effect on peak concentration at Sec.3 and Sec.4 and there was more reducing of extra concentration delay under dispatch scheme 3 than scheme 6.

(5)In scheme 7 of joint dispatch, Reservoir 1 has been put in use initially and then flood peak produced would be increased from 1900 m<sup>3</sup>/s to 2900m<sup>3</sup>/s by dispatching Reservoir 2 when it reached at the dam location. The dispatch duration of Reservoir 1 is 24 hours and 8 hours for Reservoir 2, while the total dispatch stopped at 28 o'clock. Compared results from scheme 1 and 7, there is little difference of the peak concentrations at all sections downstream and extra durations at Sec.1 and Sec.4. However, durations at Sec.2 and Sec.3 under scheme 7 reduced more about 4.5h and 6.5h respectively than under scheme 1. It shows that dispatch targets under clear effect factors confirmed for designated reaches downstream can be achieved only by selecting dispatch reservoirs appropriate distance from the pollution source.

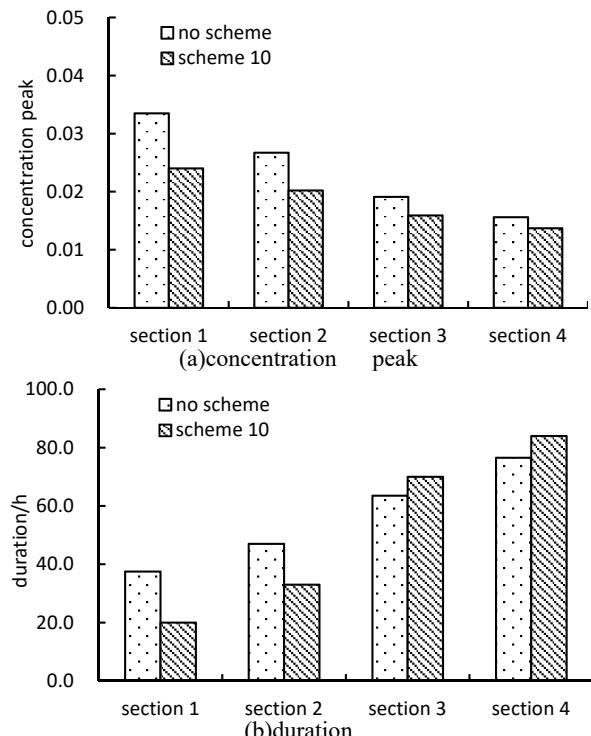
(6)A relay dispatch has been executed in the scheme 8, which Reservoir 1 has firstly worked when pollution accident emerged and discharged a flux of 2000 m<sup>3</sup>/s for 24 hours, and Reservoir 2 downstream would been put in use and also discharged the flux of 2000 m<sup>3</sup>/s for 8 hours after the flood wave formulated by Reservoir 1 completely passed through the dam of Reservoir only in 63 hours. Compared with those in scheme 1, the peak concentration at all cross sections downstream would not be improved, while extra concentration duration at Sec.1, 2 and 4 were the same except at Sec.3 decreasing about 7.5hours. Since it's rather late of dispatching Reservoir 2, it has no effect on water quality improvement at Sec.1 and 2 downstream close to its dam compared with the dispatch of only Reservoir 1 in scheme 1.

(7)In scheme 9, Reservoir 1 and 2 have been put in use simultaneously when an accident occurred, while a flux discharged by Reservoir 1 would be replenished to Reservoir 2 at 2000 m<sup>3</sup>/s for 12 hours and the same flux have been discharged by Reservoir 2 for 40 hours. Compared with those in scheme 1, 7 and 8, concentration peaks at Sec.1 to Sec.4 have been dropped significantly, while the closer to the Reservoir 2, the more the extent. However, extra concentration durations at all sections downstream have been increased and the farther the cross section was, the more obvious the duration. Compared with other schemes, concentration at cross sections downstream have been cut rapidly for the dispatching of Reservoir 2 early, but pollution mass downstream close to the dam of Reservoir 2 in the river have also been expanded more quickly by strongly shearing and dispersion, which leaded to the increasing of durations at cross sections downstream.

## 4.2 Dispatch Under Accident 2

A joint dispatch model has been discussed briefly when a pollution accident occurred between two reservoirs as shown in Fig.2. Under the accident Reservoir 1 would be

scheduled to discharge  $2000 \text{ m}^3/\text{s}$  firstly for 32 hours and push the pollution mass downstream. When the mass (exceeding the critical value defined before) arrived at the dam of Reservoir 2 at 18h, a flux of  $3000 \text{ m}^3/\text{s}$  would be discharged by the reservoir for 12 hours. The results by numerical simulations for scheme 10 have been shown as in Fig.5 and analyzed as following:



**Fig.5** Pollutant characteristics at cross sections in accident 2

(1)Compared with no dispatch, concentration peaks at all cross sections have been cut down obviously and the closer the distance to the pollution source, the more extent it dropped under the scheme 10, for example, the peak at Sec.1 had been reduced by 28.3% and Sec.4 reduced by 12.2%.

(2)The durations at Sec.1 and Sec.2 have been decreased about 17.5 and 14.0 hours under the scheme 10 compared with no any dispatch, however, durations at Sec.3 and Sec.4 have been increased about 6.5 and 7.5 hours. Obviously, it's necessary to clarify the main factors affecting the target river segment and then appropriate scheduling reservoirs have been selected carefully to draw up a joint scheme.

### 4.3 Discussions

In reality the available storage capacity of a reservoir has been limited and a reasonable dispatch scheme was deserved to be studied in detail for controlling the loss by an accident in a river. Some discussions on results of one reservoir or more of dispatching above were done as followings:

(1)When a sudden pollution accident occurred downstream of a reservoirs: 1) If concentration is a more sensitive to a target river segment downstream, the nearest reservoir upstream to the pollution source would be more appropriate for dispatching to formulate a sharp

and thin type of flood process with short-term and large flood peak, which not only can cut down pollutant concentration largely, but also push the pollution mass moving downstream quickly along the river. However, reservoirs upstream too far away from the river segment would not be a well choice for answering for an accident. 2) If extra pollutant concentration durations are more sensitive to a river segment downstream, under a limited available reservoir storage capacity flux discharged from a reservoir of dispatching should be maintained to an appropriate extent for prolonging dispatching time as much as possible to cut down retention time at the target segment downstream. In addition, the distance of a reservoir for dispatching to a pollution source downstream would also have a large impact on extra concentration durations at a river segment from analysis above and the efficiency of a dispatch schedule would be discounted by selecting a reservoir too close or too far to the pollution source. Therefore, a reservoir with a suitable distance from the pollution source downstream would be a good choice for dispatching to cut down more efficiently the durations at a river segment downstream for a river with cascade reservoirs.

(2)When a sudden pollution accident occurred in a reservoir, a scheduling plan should be formulated according to the functional requirement of the reaches upper and downstream of the reservoir. For example, if the reservoir is an important protection source of water supply for nearby towns it's proposed to open the discharge facilities as early as possible to cut down pollutant concentration and duration in the reservoir when an accident occurred. However, the opening time was advised to be delayed as long as possible and flux discharged by a reservoir with a simple function to be reduced to the full to control the impact on a river segment downstream for its important water functions.

(3)When cascade reservoirs more than one in a river would be put in use in a joint schedule: 1) if an accident occurred downstream to all the reservoirs and a target river segment was more sensitive to pollutant concentration, that one closest to the pollution source was advised to be dispatched firstly as soon as possible to reduce concentration rapidly, while others could be used to supplement one by one from upstream to downstream; however, if a river segment downstream was more sensitive to concentration durations, distances from the pollution source to reservoirs should be taken into account to decide which one was more suitable for the schedule. A reservoir closest to the source may not be a good choice at this moment of its more efficient on enlarging pollution mass moving downstream along the river for more strong shearing and discretion. If a reservoir was determined to be suitable for the dispatch of reducing concentration durations at a segment, a replenishment schedule of one by one from upstream to downstream in a river with cascade reservoirs could be taken into account for prolonging dispatch duration to push off pollution mass as soon as possible. 2) when an accident occurred between cascade reservoirs and the functions of the reservoir or a target river segment

downstream was important, a schedule of increasing flux discharged simultaneously by reservoirs close upstream and downstream to the pollution source could be drafted up to reduce pollutant concentrations. However, if a river segment downstream was more sensitive to concentration durations, a reservoir closest to the source was advised to be put in use as soon as possible to push the pollution mass off the target segment if which was very close to the reservoir and the source. If the segment was far away from the reservoir and the source, the range of pollution mass should be decreased to the full by dilution of flux discharged by cascade reservoir available storages before it reached it, or a stable and suitable flux could be maintained by cascade reservoirs as long as possible to control the volume of pollution mass caused by diffusion of shearing and discretion and pushed off the target segment rapidly.

## 5 Conclusions

(1) When only one reservoir was available for a pollution accident, a suitable schedule should be decided based on the distance of a target river segment downstream and its sensitive factors. The reservoir would not be a good choice for dispatching to deal with an accident if a target segment was too far away from it with concentration being a more sensitive factor. When a target river segment was close to the reservoir, a dispatch schedule of a large flux in short time duration discharged was more suitable for reducing pollutant concentration as soon as possible of which was more sensitive to the segment, while of an appropriate flux with a long duration would be a good choice when extra concentration duration was more sensitive.

(2) When a pollution accident occurred in a reservoir, a dispatch plan should be executed based on the function of the reservoir and a river segment downstream. When water quality of the reservoir was important for water supply and ecological safety, it is necessary to open the discharge facilities as soon as possible to reduce pollutant concentration and duration delayed in the reservoir. If a target river segment downstream was defined as an important functional area, it was advised to delay the time of opening gates and cutting down flux discharged to reduce the impact on it.

(3) When a sudden pollution accident occurred in a river with cascade reservoirs, a larger available storage capacity than only one for dispatching would be taken advantage of fully to supplement one by one from upstream to downstream. According to sensitive factors to a target river segment, prolonging dispatching duration or enlarging flux discharged based on a larger available storage capacity than only one can be used to reduce a water pollution loss as much as possible.

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