

## Modelling the effect of water diversion projects on renewal capacity in an urban artificial lake in China

Xueping Gao, Liping Xu and Chen Zhang

### ABSTRACT

To improve the water environment, manual water diversion projects were scheduled to bring freshwater to an urban artificial lake to dilute and divert pollutants out of the lake. A three-dimensional numerical model was used to study the effect of diversion schemes on the transport of dissolved substances by using concepts of water renewal time and water age. The model results showed that the impact of diversion schemes on transport processes was strongly influenced by hydrodynamic conditions induced by inflow/outflow discharges. Shorter water timescales occupied the west and east lake, implying a faster water renewal occurrence therein. Water ages were highly variable, both spatially and temporally. Longer water age was exhibited in the inner lake and bays. An exchange rate of 89.3% was obtained at the 5 m<sup>3</sup>/s discharge condition under 60 days' duration, with integral renewal time of approximately 50 days. The distribution of water age showed that it only took less than 10 days for the substance discharged at the inlets to be transported to the outlets. The results offer useful information for understanding the efficiency of water exchange by diversion projects and can be used to estimate the water renewal capacity for environmental assessment purposes.

**Key words** | artificial lake, diversion project, exchange rate, water age, water renewal time

Xueping Gao  
Liping Xu  
Chen Zhang (corresponding author)  
State Key Laboratory of Hydraulic Engineering  
Simulation and Safety,  
Tianjin University,  
Tianjin 300072,  
China  
E-mail: [emil@tju.edu.cn](mailto:emil@tju.edu.cn)

### INTRODUCTION

Urban artificial lakes are constructed for water supply, flood control, recreation or some other direct human use. Urban lakes can be important habitats for varieties of aquatic life, as well as an aesthetic resource to human communities. With growing urban population and levels of industrialization, a pleasant urban water environment is inevitably needed in development. However, urban lakes are vulnerable to the accumulation of toxic and/or potentially toxic contaminants from urban stormwater runoff, atmospheric deposition, as well as untreated discharge of industrial wastewater and municipal sewage (Zeng *et al.* 2009). Water functioning and landscape usage will be deeply affected due to worsening water quality once the pollution load is beyond the self-purification capacity of urban lakes.

A water diversion project is a physical way for water body restoration that can transfer freshwater into a polluted lake for environment protection. This kind of engineering

measure has been applied in many cases, such as Moses Lake (Welch *et al.* 1992) by adding low-nutrient dilution water, Lake Pontchartrain (McCallum 1995) by the release of freshwater from the Mississippi river in the USA, and an artificial lake (Gao *et al.* 2015) by transferring water from the Yellow River.

As is well known, processes controlling contaminant distributions in semi-enclosed water bodies are linked to the renewing timescales. Because a certain time has elapsed since the substance is transported to a location of concern within a water body, it is vital to select a suitable timescale parameter for representing mass exchange and transport process (Shen & Haas 2004). Various timescales are useful tools to estimate the water renewal and transport capacity, such as renewal time (Koutitonsky *et al.* 2004; Ribbe *et al.* 2008), age (Li *et al.* 2011; Shen *et al.* 2011), residence time (Arega *et al.* 2008) and exposure time (de Brauwere *et al.*

2011; Delhez & Deleersnijder 2012). Many applications of water renewal timescales have focussed on rivers, estuaries and oceans with intense water exchange induced by tide and wind. Some cases of water renewal timescales are found on large lakes, such as Lake Tanganyika (Gourgue et al. 2007) and Lake Taihu (Li et al. 2011).

The water renewal capacity was studied by using residence time, exposure time and connectivity as timescales in an ecological reconstructed lagoon, which was mainly influenced by wind and the depth of the tidal inlet in our previous study (Gao et al. 2013). In the tidal system, the exposure time may be a more informative measure of the time spent in a domain, because it allows water parcels (or tracer) to leave and return to the domain of interest (de Brauwere et al. 2011). Hence, it is challenging and important to select the appropriate timescales in water renewal research of different types of water bodies. This paper aims in a similar manner to do some research work on the water renewal capacity in an urban artificial lake, without water returning to the domain of interest. In consideration of this, alternative timescales, such as water renewal time and water age, should preferably be calculated under manual scheduled water diversion projects.

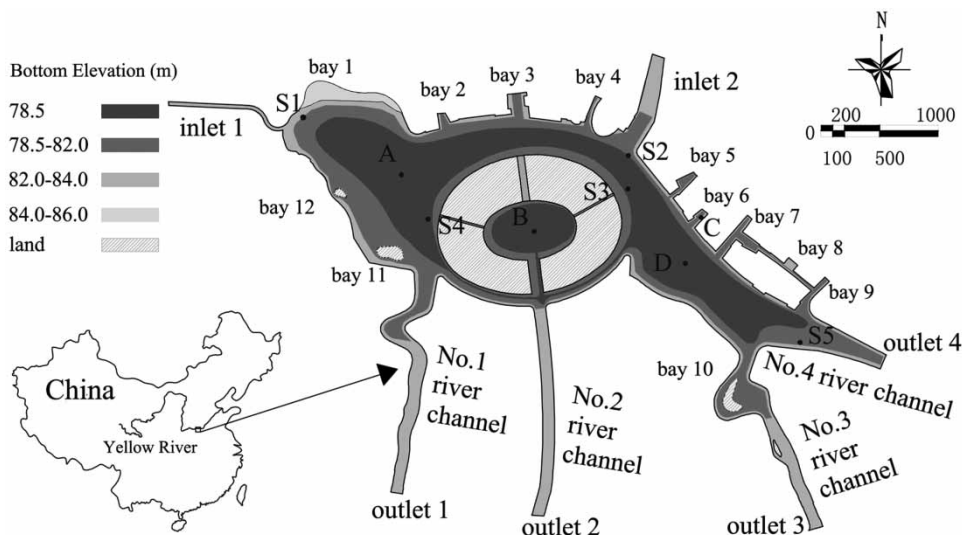
The aim of this paper is to study water renewal capacity using concepts of water renewal time and water age under two groups of scheduled discharge scenarios to Dragon Lake. A three-dimensional Environmental Fluid Dynamics

Code (EFDC) was used to investigate renewal timescales of dissolved tracers in Dragon Lake. Detailed tasks of this study are as follows. (1) To obtain the water renewal capacity by calculating water renewal times under original and upgraded water diversion projects. The simulations reported in this paper provide insight into the spatial distribution of basin to regional water renewal times. (2) To investigate the impacts of original and upgraded water diversion projects on the spatial and temporal variability of water age. These estimates that provide better information for understanding the exchange and transport process should be of interest for the overall management and future developments of the urban artificial lake, which can be used as urban landscape for city development.

## MATERIALS AND METHODS

### Study area

Dragon Lake is an artificial lake located in Zhengdong New District, Zhengzhou, China ( $34^{\circ}49'41.50''\text{N}$ ,  $113^{\circ}43'9.49''\text{E}$ ). The lake occupies an area of  $5.6\text{ km}^2$ , with a volume of roughly  $26.8\text{ million m}^3$ . Judging from the location and map of Dragon Lake (Figure 1), it is 6.3 km from north to south and 6 km from west to east with mean and maximum water depth of 4.5 m and 7.0 m, respectively. Central



**Figure 1** | Location and map of Dragon Lake: the inner lake (representative Station B), No. 1 and No. 2 inlets, Nos 1–4 river channels and the other 12 bays.

Business District islands are situated in the centre, surrounded by water of the inner lake and the outer lake. Freshwater can be diverted from the Yellow River into the lake via two inlets at the end of the two river channels, which are located, respectively, at the mouth and the back of the dragon. Four outlets are placed at the end of the four river channels.

To maintain a good ecological environment when environment problems occur, freshwater from the mighty Yellow River is transferred into the lake via two inlets to form specific water diversion projects, under which water exchange takes place so as to dilute the polluted water and flush pollutants out of the lake. Furthermore, due to the high concentration of sediment in the Yellow River, water from the Yellow River will be purified to an available standard, such that water transferred into the lake is fresh. The design inflow rate at each inlet is scheduled as  $5 \text{ m}^3/\text{s}$  by the administrative centre. Therefore, the maximum inflow rate adds up to  $10 \text{ m}^3/\text{s}$  in the research.

### Model description

The EFDC model incorporates hydrodynamics, salinity, temperature, dye, multi-size cohesive and non-cohesive sediments, toxicants and water quality state variable transport into a comprehensive model. The model has been extensively tested and applied to more than 100 modelling studies worldwide for modelling circulation, thermal stratification, sediment transport, water quality and eutrophication in reservoirs (Sebnem 2008; Zhang et al. 2013, 2015), lakes (Jin & Ji 2004; Li et al. 2011, 2013), rivers (Shen & Haas 2004) and estuaries (Arega et al. 2008).

The model uses boundary-fitted curvilinear-orthogonal coordinates in the horizontal plane and a sigma (or stretched) transformation in the vertical direction. It uses a combination of finite-volume and finite-difference techniques to ensure conservation of mass, which may pose a problem in finite-element methods. Furthermore, a curvilinear-orthogonal mesh can accurately represent the complex lake boundaries and has the advantage of computational efficiency over unstructured grid models. More details of the governing equations for the EFDC model, the governing mass-balance equation and the numerical schemes can be found in Hamrick (1992) and Tetra Tech (2007).

## Water renewal timescales

### Water renewal time

Water renewal time, sometimes also referred to as the flushing or ventilation timescale, is an important quantity in aiding the classification of the environmental state (Ribbe et al. 2008). Three approaches can be used: the Lagrangian particle tracking approach, the dissolved tracer method or a combination of both. The dissolved tracer method is through extensive field measurements, time series analysis, and coupled hydrodynamic and advection-dispersion numerical modelling (Koutitonsky et al. 2004). To briefly describe the hydrodynamic functioning of the system and to estimate the spatial distribution of the local renewal time (LRT) and its corresponding integral renewal time (IRT) in Dragon Lake, the dissolved tracer method is used in this study. For better understanding of the water exchange induced by water diversion projects, the initial concentration of tracers within the whole lake is prescribed to be 1 (arbitrary units), representing the original water. Freshwater without tracers will be diverted into the lake.

The decrease of the passive tracer is calculated after water diversion projects to form the basin to regional renewal timescales (IRT and LRT) of the lake. The renewal timescale  $T_{\text{renewal}}$  is defined as the LRT when the initial tracer concentration at a certain point within the lake is reduced to a certain threshold value. As well, IRT can be obtained as the time when 80% of the original waters in the lake have been replaced by freshwater (Ribbe et al. 2008).

$$T_{\text{renewal}} = T(C_i(t) < C_{\text{threshold}}) \quad (1)$$

where  $C_{\text{threshold}}$  represents the tracer concentration that decreased to 20% of the initial concentration, i.e., 0.2 in this study;  $T_{\text{renewal}}$  is the water renewal time to be estimated;  $C_i(t)$  is the calculated tracer concentration at cell  $i$  and time  $t$ .

Water exchange rate is also an effective indicator to represent how fast the water inside the lake is replaced by freshwater. Exchange rate is obtained by examining the spatially averaged dissolved tracer concentrations in all layers as a function of time. Specifically, the exchange rate is the percentage of new water transferred into the lake that replaces the water remaining in the lake. The larger

exchange rate, the better water exchange the lake achieves. The equation is shown as:

$$\beta_t = \frac{1 \times V - \sum_{i=1}^n V_i(t) \times C_i(t)}{1 \times V}, t = [0, T] \quad (2)$$

where  $\beta_t$  is the exchange rate, %;  $V$  is the total volume of the lake,  $m^3$ ;  $V_i(t)$  is the individual volume at cell  $i$  and time  $t$  in the numerical model of the lake;  $T$  is the total simulation time.

### Water age

In this paper, water age is defined as ‘the time that has elapsed since the particle under consideration left the region in which its age is prescribed as being zero’. The concept of age of a water parcel has been usually used as a timescale to quantify pollutant transport in lagoons, estuaries and oceans (Deleersnijder et al. 2001; Shen & Haas 2004). The age concept was applied to study the impacts of water transfer on the transport of dissolved substances in Lake Taihu (Li et al. 2011, 2013). More specifically, the age is zero at the inlets of the lake and the age at any given location is representative of the time elapsed for a dissolved substance to be transported from its source to that location (Shen & Wang 2007). In this study, water age is applied as an indicator to assess the water renewal capacity in the lake induced by water renewal projects.

In renewal water studies, the total water is divided into two contributions: the original water that is initially in the domain of interest and the renewal water that progressively replaces the original water. Clearly, the original water concentration  $C_0$  and that of the renewing water  $C_i$  must satisfy the relation  $C_0 + C_i = 1$  at any location and time (Delhez et al. 1999; Deleersnijder et al. 2001). Assuming that there is only one tracer discharged into the lake and no other sources and sinks of the tracer within the lake, the transport equations for calculating the tracer and the age concentrations can be written as follows (Shen & Wang 2007):

$$\frac{\partial c(t, \bar{x})}{\partial t} + \nabla(uc(t, \bar{x}) - K\nabla c(t, \bar{x})) = 0 \quad (3)$$

$$\frac{\partial \alpha(t, \bar{x})}{\partial t} + \nabla(u\alpha(t, \bar{x}) - K\nabla \alpha(t, \bar{x})) = c(t, \bar{x}) \quad (4)$$

where  $c$  is the tracer concentration;  $\alpha$  is the age concentration;  $u$  is the velocity field;  $K$  is the diffusivity tensor;  $t$  is time;  $\bar{x}$  is coordinate. The mean water age ‘ $a$ ’ can be calculated as follows:

$$a(t, \bar{x}) = \frac{\alpha(t, \bar{x})}{c(t, \bar{x})} \quad (5)$$

Equations (3)–(5) were used to compute the water age using the EFDC model with specified initial and boundary conditions.

### Model application

#### Model setup

Dragon Lake is a typical shallow urban lake with gentle slope. Variation of the flow in the vertical direction is much smaller than that of the other two directions. The computational grid (Figure 2) was developed for the urban lake, containing 2,808 active cells in the horizontal plane with a length of 29–97 m in the  $x$ -axis and 15–52 m in the  $y$ -axis oriented towards the north. Three evenly distributed layers were employed in the vertical direction to better simulate the bottom topography.

The model is mainly driven by atmospheric forcing, inflow/outflow and neglects the effect of surface wind stress and others. Inflow/outflows include six river

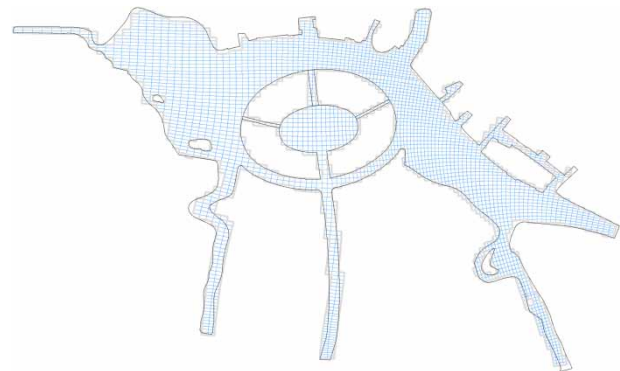


Figure 2 | Computational domain and structured grids used for model simulation.

channels. Initial conditions were set for surface elevation and flow velocity. Taking the normal water level 85.5 m as the initial surface elevation and the initial water velocity is 0. The two inlets and four discharge outlets are controlled by inflow/outflow. Water temperature is treated as a constant during model simulation. The effect of the initial conditions will disappear gradually as the computation reaches a steady state after several hours of numerical simulation. The model was numerically integrated with a time step of 100 s during the whole simulation period.

### Model calibration and validation

The Dragon Lake model was calibrated with the water level, using the dataset measured at Stations S3 from 9 September 2013 to 11 January 2014. It is verified with the water level using the dataset measured at Stations S4 from 28 March to 6 June 2014. Statistical methods such as root-mean-squared error (RMSE), common statistical measures coefficient of correlation (CC), average error (AE) and average absolute deviation  $\delta$  were used for calibration and validation (Chau *et al.* 2005; Lin *et al.* 2006; Azamathulla *et al.* 2009).

In the EFDC model, the Mellor–Yamada turbulence closure scheme (Mellor & Yamada 1982) is used to calculate the vertical turbulent viscosity  $A_v$  and the vertical turbulent diffusivity  $A_b$ . The horizontal diffusion coefficient  $A_H$  is determined by Smagorinsky (1963), and the non-dimensional viscosity parameter in the Smagorinsky formula is set to a constant value of 0.2 (Berntsen 2002). Bottom roughness ( $n$  in the Manning equation) was changed from 0.025 to 0.032 until a reasonable agreement was reached between the model and the observations. The sensitivity analysis results indicate that significant changes in roughness

height resulted in only small changes in the model results such as water level and velocity.

Figure 3 shows comparisons of model-simulated water levels against the observed data at each station. Table 1 summarizes the results of the statistical error quantification methods for calibration and validation of water level at Stations S3 and S4. The values of RMSE for the two datasets are both 0.17 m. The values of CC vary from 0.94 to 0.98, indicating an excellent agreement between model results and observations. Overall, the model reproduces the main features of the hydrodynamic conditions in the lake reasonably well.

### Model simulation scenarios

In this study, three main factors were used to define the scenarios: the diverted inflow water volume, the project duration and engineering measurements in bays and the inner lake (Zou *et al.* 2014). Since transport processes highly depended on freshwater discharges from the two inlets, wind and precipitation were not taken into account when setting up the various scenarios. For all scenarios, the model configurations and other parameter settings mentioned before except the driving factors (Figure 4), were kept the same as Scenario A1.

In practical lake management, the diverted water volume from the Yellow River was scheduled as 25.92 km<sup>3</sup> during the project time. Hence, the model experiments were to be conducted for 30 days under the high flow condition (10 m<sup>3</sup>/s) and for 60 days under the low flow condition (5 m<sup>3</sup>/s), which were illustrative of a typical fully operational monthly and bimonthly diversion schedule. Scenarios A1 and B1 were taken as the original water diversion projects. Taking the

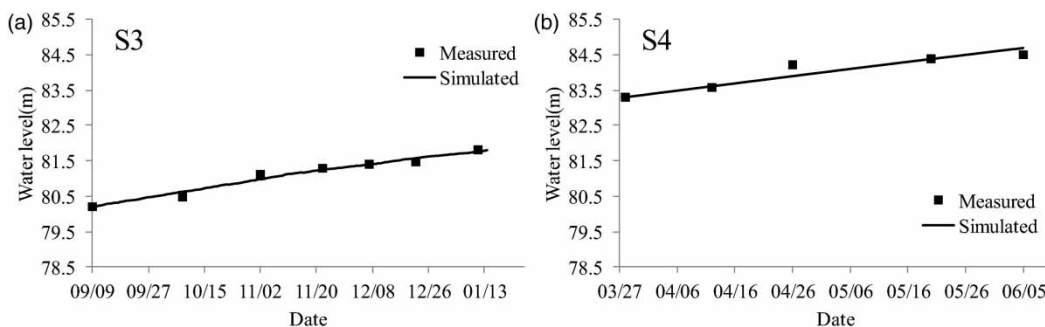
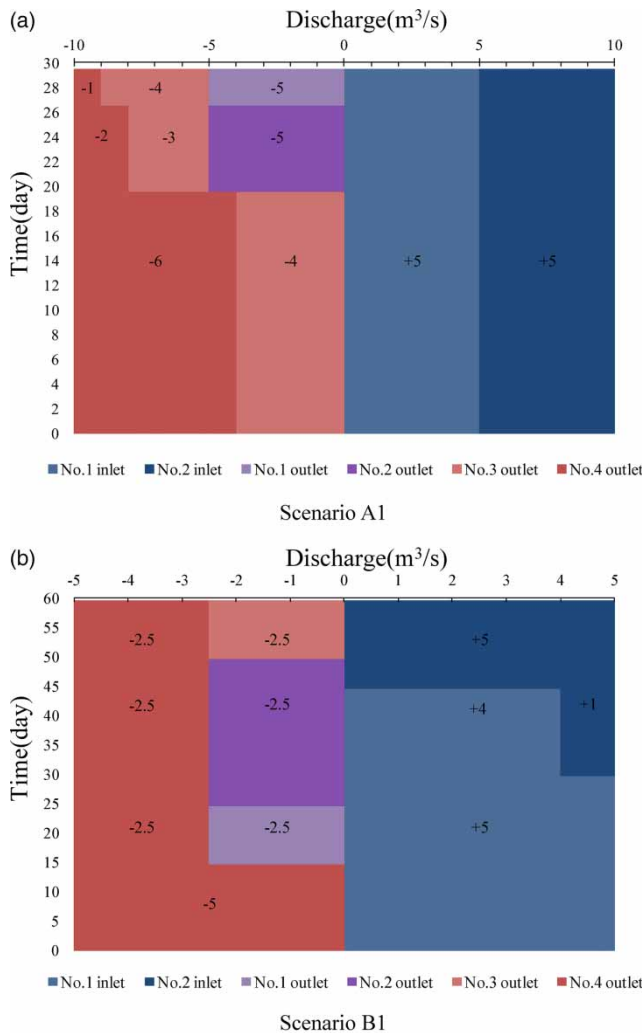


Figure 3 | Time series of simulated water levels (solid lines) and observed data (black squares) at Station S3 (a) and Station S4 (b).

**Table 1** | The CC, RMSE, AE and  $\delta$  for water level at S3 and S4

Parameter	Location	CC	RMSE (m)	AE (%)	$\delta$ (%)
Water levels	Station S3	0.98	0.17	-0.16	0.17
	Station S4	0.94	0.17	0.04	0.13

**Figure 4** | Specific model simulation schemes for Scenarios A1 (a) and B1 (b). The total inflow rate equals to the outflow rate. +: inflow rate; -: outflow rate. The corresponding upgraded scenarios contain pumped inflows at the bays and pumped outflow at the inner lake (figures not shown).

pumped inflow at the 12 bays and pumped outflow at the inner lake into consideration, Scenarios A2 and B2 were scheduled as the upgraded scenarios compared to the original ones.

Scenario A1 (Figure 4(a)) involved diverting water from the Yellow River by two channels via the No. 1 and No. 2

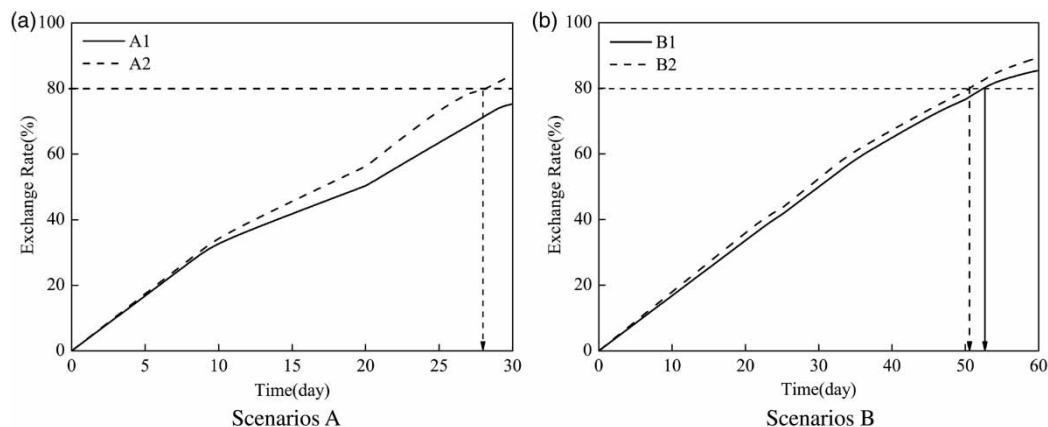
inlets to Dragon Lake. Within 1 month's duration (30 days), the two channels would transfer a total of 25.92 km<sup>3</sup> water into the lake. The outflow rate of the four river channels would vary with time as scheduled in the scenarios. The total diversion flow rate of the two inlets (maximum flow rate: 5 m<sup>3</sup>/s individually) was 10 m<sup>3</sup>/s. The sum of outflow rates of the four outlets always equalled to the total inflow rate so as to keep the water balance consistent. Scenario A2, as an upgraded case of A1, took pumped inflows near the 12 bays into consideration for the purpose of better water exchange in these sub-zones. Water volume pumped out of the inner lake was the same as the volume pumped in at the other 12 bays, with 0.34 m<sup>3</sup>/s flow rate (not shown). This explanation also applies to Scenarios B. However, inflow discharge from the Yellow River halved to 5 m<sup>3</sup>/s compared to that of Scenarios A. Scenario B2 also involved pumped inflow at the 12 bays and outflows in the inner lake (Figure 4(b)).

## RESULTS AND DISCUSSION

### Characteristics of water renewal and pathways

Exchange rate of the four cases topped at 75.3%, 84.0%, 85.4% and 89.3%, respectively, when simulations terminated. It is apparent that the exchange rate of Scenario A1 did not reach the requirement of 80%, indicating insufficient water renewal under 30 days' duration (Figure 5(a)). The best water renewal was in Scenario B2 with the exchange rate of 89.3% (Figure 5(b)). The average velocity in the lake was very small with a unit below the scale of mm/s. Places with water velocity below 0.0005 m/s or 0.001 m/s are defined as backwater areas, where water flows extremely slowly and water exchange hardly occurs. For each of the two types of scenarios, the average velocity of the second was larger than the first, i.e., 0.0026 m/s (Scenario A2) > 0.0024 m/s (Scenario A1). However, less backwater area was exhibited in the scenarios with larger average velocity (Table 2).

The reverse correlation between average velocity and backwater area illustrates that the upgraded scenarios represent better hydrodynamic features with higher exchange rates. Water exchange rate is proved to be a useful indicator



**Figure 5** | Time series of old water exchanged by freshwater within the lake under Scenarios A and B during water diversion scheme time.

**Table 2** | Statistic characters of flow field

Model scenario	Average velocity (m/s)	Velocity $\leq 0.0005$ m/s		Velocity $\leq 0.001$ m/s	
		Backwater area (BA) (km <sup>2</sup> )	% of BA	Backwater area (BA) (km <sup>2</sup> )	% of BA
A1	0.0024	1.84	35.1	2.87	54.6
A2	0.0026	1.06	20.2	2.13	40.5
B1	0.0013	1.67	32.0	3.11	59.2
B2	0.0015	1.10	21.0	2.54	48.3

to assess the integral water renewal performance. The percentage of original waters remaining in an estuary as a function of time was obtained, demonstrating that higher exchange rates were achieved when more discharges were included (Koutitonsky *et al.* 2004). It was argued that renewal was assumed when 90% of water within the domain had been replaced, i.e., the initial concentration was larger than the threshold value of 90 (Ribbe *et al.* 2008). As well, the change rate of water age was used for the effectiveness of the improved Yangtze River Diversions on mitigating eutrophication in Lake Taihu (Li *et al.* 2013).

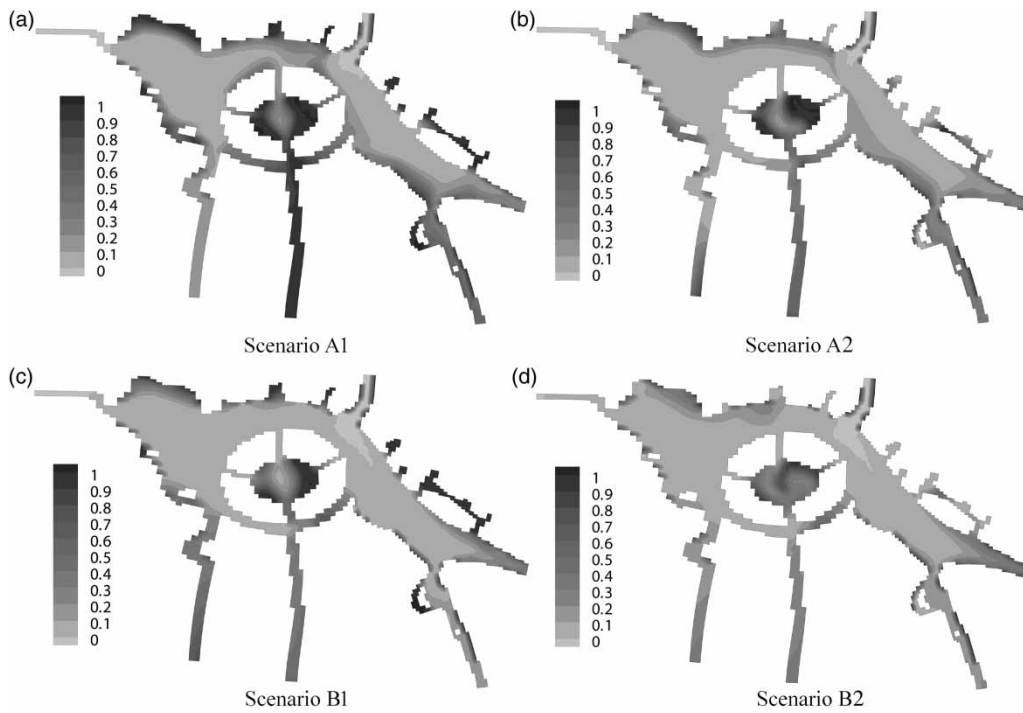
The distribution of the passive tracer was captured for each scenario during the whole simulation time. The renewal pathway was indicative of the depth integrated flow throughout the lake. Most of the main lake had been renewed by freshwater for the original scenarios (A1 and B1). Better exchange results occurred in the upgraded scenarios (A2 and B2) with freshwater reaching both the main lake and other bays (Figure 6). One point we should

pay attention to is the occurrence of poor water transport in the inner lake and this could mainly be attributed to the influence of the complex configuration of topography. Similarly, it held that the spatial distribution of renewal pathways was attributed to the bowl-shaped bathymetry of the Hervey Bay and its orientation with its main opening facing northwards (Ribbe *et al.* 2008).

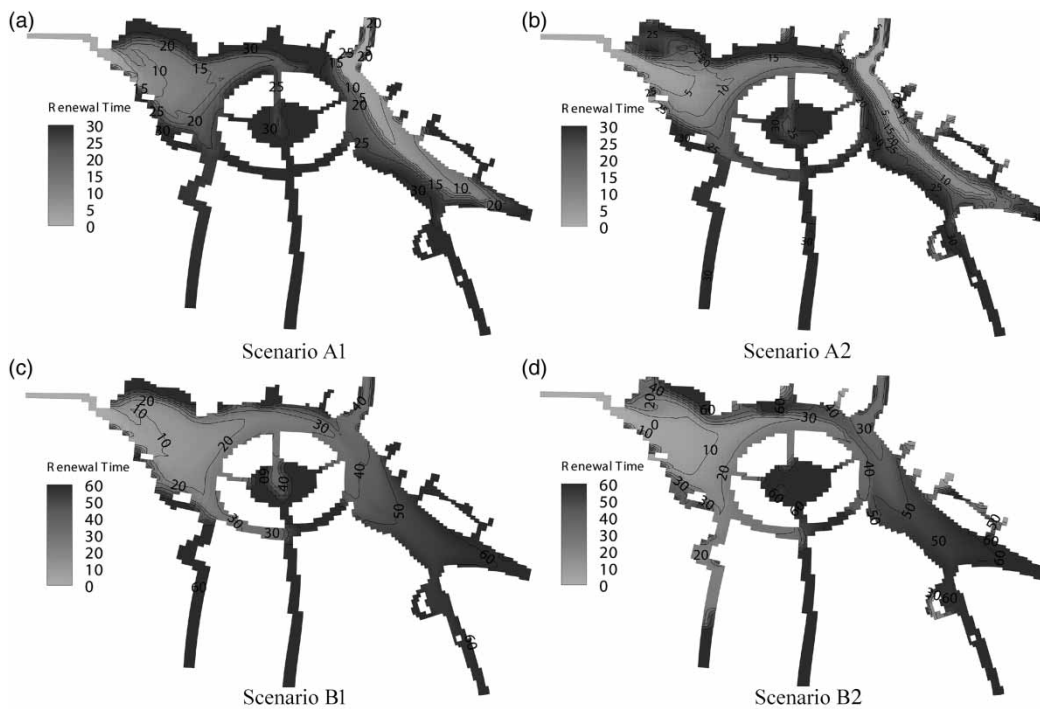
### Influence of water diversion projects on water renewal time

The initial concentration of tracers was prescribed to be 1 (arbitrary units) within the whole lake, standing for the original water. Freshwater without tracers would be diverted into the lake. Once the simulation terminates, the concentration evolution was examined in each grid cell to find the last time step at which it had dropped to or below 20% of its initial concentration. This time was recorded at each grid cell yielding a two-dimensional spatial distribution of the vertical mean LRT. The distribution of LRT within the lake after simulations terminate is interesting. The vertical mean LRT is shown as contour plots in Figure 7. The numbers shown on the contour lines are the mean LRT at that location.

It is apparent that the LRT changed spatially and increased radially into the lake as freshwater moved towards the outlets. Longer renewal times were observed in the inner lake, the four river channels and other bays. When pumped inflows in the bays and outflows in the inner lake were included in the upgraded scenarios (A2 and B2) (Figure 7(b) and 7(d)), renewal times were considerably reduced, as



**Figure 6** | Renewal pathways (vertically averaged and plotted at the last day) for: (a) A1, 10 m<sup>3</sup>/s, 30 days; (b) A2, 10 m<sup>3</sup>/s, 30 days, plus pumped inflows at the bays and pumped outflow at the inner lake; (c) B1, 5 m<sup>3</sup>/s, 60 days; (d) B2, 5 m<sup>3</sup>/s, 60 days, plus pumped inflows at the bays and pumped outflow at the inner lake. Light colour represents 'freshwater' with a value of '0' indicating complete renewal.



**Figure 7** | Spatial distribution of the LRT within the lake for: (a) A1, 10 m<sup>3</sup>/s, 30 days; (b) A2, 10 m<sup>3</sup>/s, 30 days, plus pumped inflows at the bays and pumped outflow at the inner lake; (c) B1, 5 m<sup>3</sup>/s, 60 days; (d) B2, 5 m<sup>3</sup>/s, 60 days, plus pumped inflows at the bays and pumped outflow at the inner lake.



expected. The renewal time near the inlets was about 5 days under Scenarios A (30 days) (Figure 7(a) and 7(b)) to 20 days under Scenarios B (60 days) (Figure 7(c) and 7(d)). Shorter renewal times were found nearby the mouth where freshwater was discharged and this result highlighted the sensitivity of LRT to the outflow discharge and corresponding scheduled time. In Scenario B2, renewal times were in a sequence of 20–50 days (Figure 7(d)), except in the Nos 2–4 river channels and the inner lake. Water is preferably renewed under Scenario B2 with a water exchange of 89.3%, the highest compared to other scenarios (Table 3).

The IRT is presented with renewal assumed to be achieved when 80% of the domain is ventilated (vertical arrows in Figure 5). However, it was argued that renewal timescales were obtained with renewal supposed to be finished when 90% of a bay was renewed in Ribbe *et al.* (2008). Both definitions are optional in practical applications. In this study, once 80% of the original water in the lake is renewed, the renewal situation would be regarded as a reasonably good state from a perspective of management requirements. This adjustable standard would be more feasible and worth recommending to practical lake management. IRT ranged from 28 days (Scenario A2) to over 30 days, implying an insufficient renewal in the lake within 30 days' duration under Scenario A1 (Table 3). For Scenarios B, IRT varied from 50 days to 52 days, both fulfilling renewal requirement within 60 days' simulation time.

### Effect of water diversion projects on water age distribution

Averaged water ages in Dragon Lake were calculated in every lake region. Four experiments with the same model configuration were conducted to simulate high ( $10 \text{ m}^3/\text{s}$ ) and medium discharge ( $5 \text{ m}^3/\text{s}$ ) conditions within 30 days' and 60 days' duration, respectively. Tracers were continuously released with a constant concentration of 1 unit (arbitrary units) at the two inlets to the lake. The time

series of the vertically averaged water age indicated that water age varied with time and space (Figure 8). Water age at Stations A (representative of the west of the lake) and C (representative of the bays) would decrease drastically under the upgraded scenarios (A2 and B2) compared to the data under the original scenarios (Table 4). However, the water age maximum at Station B (representative of the inner lake) was approximately equal to the simulation duration with no significant difference, demonstrating a longer time needed for freshwater to be renewed. The changes at Station C were larger than other stations, demonstrating a good water renewal effect occurred in the bays when taking pumped inflows into consideration. Nevertheless, a long time was needed for freshwater to be renewed in the inner lake due to its complicated configuration of shape.

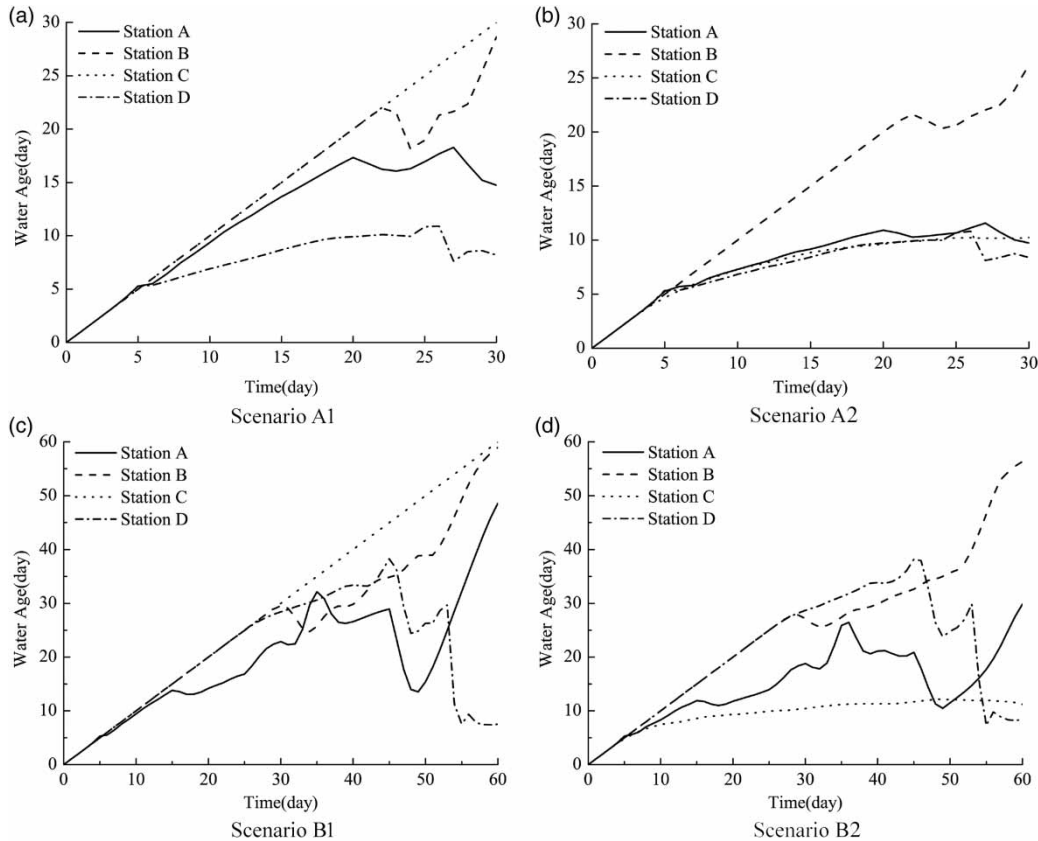
The water age at Stations A and D (representative of the east lake) increased over time up to approximately 30 days and 38 days, respectively, suggesting that water brought in by the inflow tributaries did not reach either of the stations until then. After that, water age varied within a range at Stations A and D, respectively. For Scenarios B, relatively large fluctuations in water age occurred between days 35 and 50 (the time when water was transferred out at the No. 3 outlet) at Station A, and days 30 (the time when water transfer occurred at the No. 2 inlet) and 55 at Station B (Figure 8(c) and 8(d)). This justifies the high temporal heterogeneity and spatial variability of water age depending on hydrodynamic conditions induced by inflow/outflow tributaries (Figure 4).

As shown in Figure 9, water age increased radially towards the open area of the lake, illustrating a strong impact on the water age distribution by the inflow discharged at the two inlets, especially in neighbouring areas of the inlets. The lowest water ages were found at the entrances of the two inlets. Spatially, water ages ranged from 1.0 to 30.4 days, with averages of 18.2 and 17.5 days under Scenarios A1 and A2, respectively. The range was from 1.0 to 60 days, with averages of 32.9 and 30.0 days for Scenarios B1 and B2, correspondingly.

As Delhez & Carabin (2001) pointed out, the age should be interpreted as the time needed for a marked change in the characteristics of the source to affect significantly the conditions at this point. Water age at any location can be

**Table 3** | Summary of basin-averaged exchange rate and IRT

Scenario	A1	A2	B1	B2
Exchange rate	75.3%	84.0%	85.4%	89.3%
Renewal time (d)	>30	28	52	50



**Figure 8** | Time series of water age (days) at Stations A, B, C and D for Scenarios A and B.

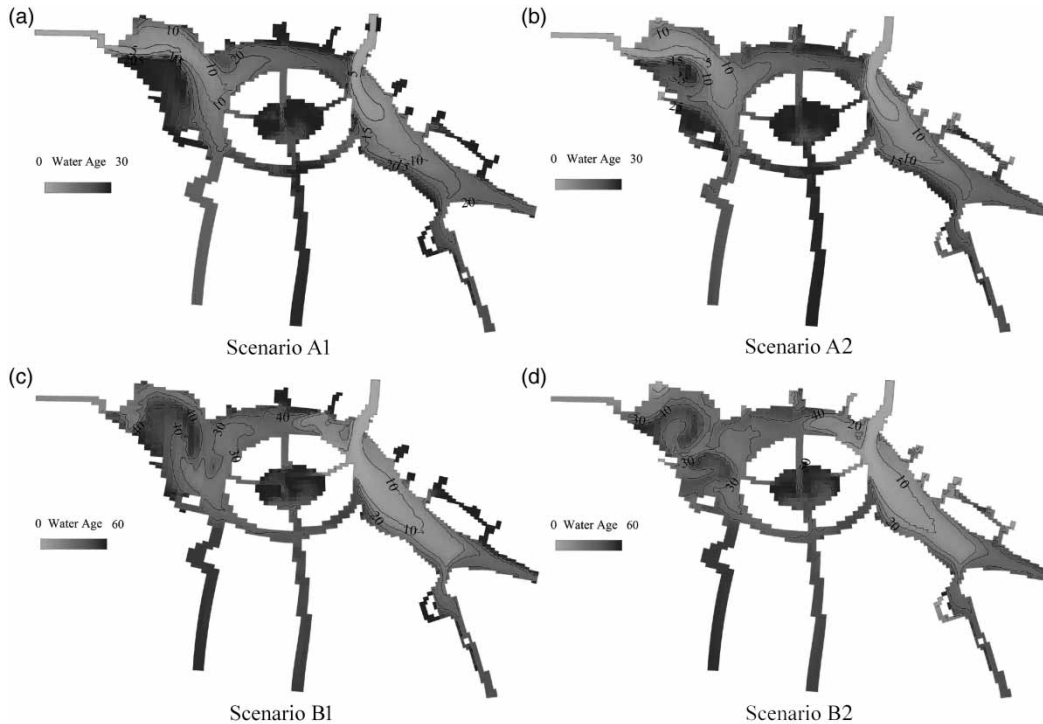
**Table 4** | The average and maximum water age (days) of Stations A, B, C and D under Scenarios A and B

Station	A		B		C		D	
	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
A1	11.9	18.3	14.4	28.7	15.5	30	7.6	10.9
A2	8.2	11.6	14.4	26.2	7.8	10.2	7.5	10.8
B1	19.9	48.6	26.6	59.0	30.5	60.0	20.5	38.3
B2	14.9	29.8	25.7	56.3	9.7	12.2	20.8	38.2

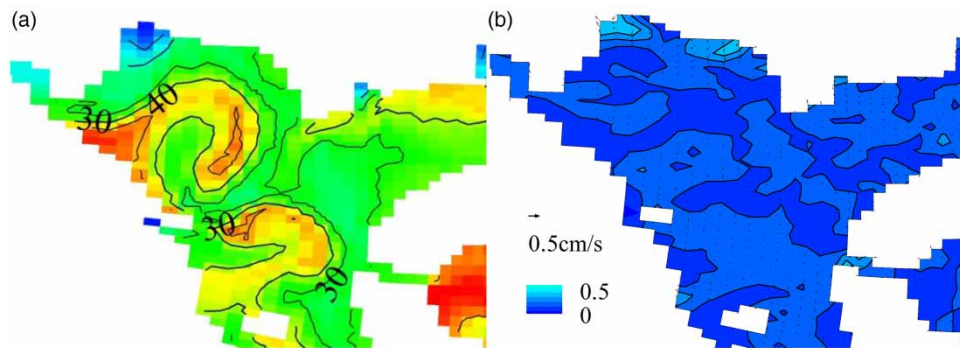
representative of the average time elapsed for water parcels to be transported to that location from the inlets. Compared to this, the concept of water renewal time previously used is somewhat artificial since it is designated manually as the time that 80% of the original water is exchanged in the lake.

It is apparent that the water age distribution showed a clockwise-shaped pattern in Scenarios A2, B1 and B2. As well, an anti-clockwise-shaped pattern also appeared in Scenario B2. Taking Scenario B2 as an example for analysis,

the clockwise-shaped pattern is evident over the northwest part of the lake by the 30-day and 40-day contours (Figure 10(a), dark-coloured part). Relatively low water age (Figure 10(a), light-coloured part) was exhibited in the centre of the clockwise pattern. This suggested that materials were transported more rapidly inside the central area of this pattern and relatively slowly in the mainstem of the clockwise pattern and at the shallow areas adjacent to the riverside bank. This clockwise pattern resembles the residual current



**Figure 9** | Distributions of average water age at the last day of the simulation time for Scenarios A (30 days) and Scenarios B (60 days).



**Figure 10** | Zoom of the northwest part of Dragon Lake: (a) distributions of average water age for Scenario B2; (b) the surface residual current under Scenario B2. The unit of current scale is cm/s.

distribution with low residual currents outwards (Figure 10(b), dark-coloured part) and large residual currents (Figure 10(b), light-coloured part) inside the clockwise pattern. This pattern of residual current distribution is expected to be more pronounced under the 60 days' flow condition (Scenario B2). Relevant findings suggest that the age distribution shows a tongue-shaped pattern with low age in the middle of the channel and relatively high age in shallow areas adjacent to the shoreline. The result illustrates that

materials are transported out of the estuary more rapidly in the middle of the channel (Shen & Wang 2007; Wang *et al.* 2010).

This interesting pattern of the spatial water age distribution in these areas may be explained by two causative factors. One is the mixing hydrodynamic condition attributed to the interactions of rapid discharge rushing into the northwest Dragon Lake from No. 1 inlet and the tributary inflow subsequently discharged at No. 2 inlet. This suggests that the portion of

tracer transported out of the No. 1 inlet is transported back into this part along with that out of No. 2 inlet. The other factor is the continuous pumped inflow at bays No. 11 and No. 12. The influent water is transported outwards through both bays and encounters the mixed flow of the left inflow branch rushing from No. 2 inlet as well as the residual current from No. 1 inlet.

Furthermore, in practical management of urban artificial lakes, a knowledge management system (KMS) (Chau 2007; Wu *et al.* 2009) can be developed on renewal capacity forced by water diversion projects. This KMS is the integration of knowledge management and artificial intelligence technology with numerical models in order to assist application users in modelling the effect of water diversion projects on renewal capacity. It is addressed to simulate human expertise during problem solving by incorporating artificial intelligence and coupling variously descriptive knowledge, procedural knowledge and reasoning knowledge involved in hydrodynamic and transport processes of the lake.

## CONCLUSIONS

The effects of water diversion projects on renewal capacity in an urban artificial lake were investigated by using concepts of renewal time and water age. The distribution of water renewal pathways was highly relative to hydrodynamic conditions induced by different schemes. Shorter renewal time and water age occupied the west and east lake, implying a faster water renewal occurrence therein. More time was needed for water renewal in the inner lake and other bays.

The best water renewal capacity was obtained with an exchange rate of 89.3% at 5 m<sup>3</sup>/s discharge within 60 days' duration. The lowest water ages, less than 10 days, were found especially in the east lake connecting No. 2 inlet and No. 4 river channel. Higher water ages, approximately the durations of the schemes, were prominently shown in the inner lake and other bays. The clockwise-shaped pattern of water age distribution resembled the general residual current distribution induced by water from different sources within the lake. This study paid more attention to the transport process and mainly concerned the impacts of renewal capability forced by water diversion projects. More consideration is essential for ecological impact in subsequent research.

## ACKNOWLEDGEMENTS

This research was supported by the National Natural Science Foundation of China (No. 51279125), the Science Fund for Creative Research Groups of the National Natural Science Foundation of China (No. 51321065) and the Tianjin Municipal Natural Science Foundation (No. 13JCQNJC09200).

## REFERENCES

- Arega, F., Armstrong, S. & Badr, A. W. 2008 Modeling of residence time in the East Scott Creek Estuary, South Carolina, USA. *J. Hydro-environ. Res.* **2**, 99–108.
- Azamathulla, H. M., Ghani, A. A., Zakaria, N. A. & Guven, A. 2009 Genetic programming to predict bridge pier scour. *J. Hydraul. Eng.* **136**, 165–169.
- Berntsen, J. 2002 Internal pressure errors in sigma-coordinate ocean models. *J. Atmos. Ocean. Tech.* **19**, 1403–1414.
- Chau, K. W. 2007 An ontology-based knowledge management system for flow and water quality modeling. *Adv. Eng. Softw.* **38**, 172–181.
- Chau, K. W., Wu, C. L. & Li, Y. S. 2005 Comparison of several flood forecasting models in Yangtze River. *J. Hydrol. Eng.* **10**, 485–491.
- de Brauwere, A., de Brye, B., Blaise, S. & Deleersnijder, E. 2011 Residence time, exposure time and connectivity in the Scheldt Estuary. *J. Marine. Syst.* **84**, 85–95.
- Deleersnijder, E., Campin, J. M. & Delhez, E. J. 2001 The concept of age in marine modelling: I. Theory and preliminary model results. *J. Marine. Syst.* **28**, 229–267.
- Delhez, E. J. M. & Carabin, G. 2001 Integrated modelling of the Belgian coastal zone. *Estuar. Coast. Shelf. S.* **53**, 477–491.
- Delhez, É. J. & Deleersnijder, É. 2012 Residence and exposure times: when diffusion does not matter. *Ocean. Dynam.* **62**, 1399–1407.
- Delhez, E. J., Campin, J. M., Hirst, A. C. & Deleersnijder, E. 1999 Toward a general theory of the age in ocean modelling. *Ocean. Model.* **1**, 17–27.
- Gao, X. P., Chen, Y. Y. & Zhang, C. 2013 Water renewal timescales in an ecological reconstructed lagoon in China. *J. Hydroinform.* **15**, 991–1001.
- Gao, X. P., Li, G. N., Li, G. R. & Zhang, C. 2015 Modeling the effects of point and non-point source pollution on a diversion channel from Yellow River to an artificial lake in China. *Water. Sci. Technol.* **71** (12), 1806–1814.
- Gourgue, O., Deleersnijder, E. & White, L. 2007 Toward a generic method for studying water renewal, with application to the epilimnion of Lake Tanganyika. *Estuar. Coast. Shelf. S.* **74**, 628–640.

- Hamrick, J. M. 1992 *A Three-Dimensional Environmental Fluid Dynamics Computer Code: Theoretical and Computational Aspects*. Special Report No. 317 in Applied Marine Science and Ocean Engineering. College of William and Mary, Virginia Institute of Marine Science, VA, USA.
- Jin, K. R. & Ji, Z. G. 2004 *Case study: modeling of sediment transport and wind-wave impact in Lake Okeechobee*. *J. Hydraul. Eng.* **130**, 1055–1067.
- Koutitonsky, V. G., Guyonnet, T., St-Hilaire, A., Courtenay, S. C. & Bohgen, A. 2004 *Water renewal estimates for aquaculture developments in the Richibucto estuary, Canada*. *Estuaries* **27**, 839–850.
- Li, Y. P., Acharya, K. & Yu, Z. B. 2011 *Modeling impacts of Yangtze River water transfer on water ages in Lake Taihu, China*. *Ecol. Eng.* **37**, 325–334.
- Li, Y. P., Tang, C. Y., Wang, C., Anim, D. O., Yu, Z. B. & Acharya, K. 2013 *Improved Yangtze River Diversions: are they helping to solve algal bloom problems in Lake Taihu, China?* *Ecol. Eng.* **51**, 104–116.
- Lin, J. Y., Cheng, C. T. & Chau, K. W. 2006 *Using support vector machines for long-term discharge prediction*. *Hydrolog. Sci. J.* **51**, 599–612.
- McCallum, B. E. 1995 *Areal extent of freshwater from an experimental release of Mississippi River Water into Lake Pontchartrain, Louisiana, May 1994*. In: *The 9th 1995 Conference on Coastal Zone*, 16–21 July, Tampa, FL, pp. 363–364.
- Mellor, G. L. & Yamada, T. 1982 *Development of a turbulence closure model for geophysical fluid problems*. *Rev. Geophys.* **20**, 851–875.
- Ribbe, J., Wolff, J. O., Staneva, J. & Gräwe, U. 2008 *Assessing water renewal time scales for marine environments from three-dimensional modelling: a case study for Hervey Bay, Australia*. *Environ. Modell. Softw.* **23**, 1217–1228.
- Sebnem, E. 2008 *Effects of thermal stratification and mixing on reservoir water quality*. *Limnology* **9**, 135–142.
- Shen, J. & Haas, L. 2004 *Calculating age and residence time in the tidal York River using three-dimensional model experiments*. *Estuar. Coast. Shelf. S.* **61**, 449–461.
- Shen, J. & Wang, H. V. 2007 *Determining the age of water and long-term transport timescale of the Chesapeake Bay*. *Estuar. Coast. Shelf. S.* **74**, 585–598.
- Shen, Y. M., Wang, J., Zheng, B., Zhen, H., Feng, Y., Wang, Z. & Yang, X. 2011 *Modeling study of residence time and water age in Dahuofang Reservoir in China*. *Sci. China. Phys. Mech.* **54**, 127–142.
- Smagorinsky, J. 1963 *General circulation experiments with the primitive equations: I. The basic experiment*. *Mon. Weather. Rev.* **91**, 99–164.
- Tetra Tech 2007 *The Environmental Fluid Dynamics Code Theory and Computation, Volume 3: Water Quality Module*. Technical Report to USEPA. Tetra Tech, Fairfax, VA.
- Wang, Y., Shen, J. & He, Q. 2010 *A numerical model study of the transport timescale and change of estuarine circulation due to waterway constructions in the Changjiang Estuary, China*. *J. Marine. Syst.* **82**, 154–170.
- Welch, E. B., Barbiero, R. P., Bouchard, D. & Jones, C. A. 1992 *Lake trophic state change and constant algal composition following dilution and diversion*. *Ecol. Eng.* **1**, 173–197.
- Wu, C. L., Chau, K. W. & Li, Y. S. 2009 *Predicting monthly streamflow using data-driven models coupled with data-preprocessing techniques*. *Water. Resour. Res.* **45**, W08432.
- Zeng, F., Wen, J., Cui, K., Wu, L., Liu, M., Li, Y., Li, Y., Zhu, F., Ma, Z. & Zeng, Z. 2009 *Seasonal distribution of phthalate esters in surface water of the urban lakes in the subtropical city, Guangzhou, China*. *J. Hazard. Mater.* **169**, 719–725.
- Zhang, C., Gao, X. P., Wang, L. Y. & Chen, Y. Y. 2013 *Analysis of agricultural pollution by flood flow impact on water quality in a reservoir using a three-dimensional water quality modeling*. *J. Hydroinform.* **15**, 1061–1072.
- Zhang, C., Gao, X. P., Wang, L. Y. & Chen, X. J. 2015 *Modelling the role of epiphyton and water level for submerged macrophyte development with a modified submerged aquatic vegetation model in a shallow reservoir in China*. *Ecol. Eng.* **81**, 123–132.
- Zou, R., Zhang, X., Liu, Y., Chen, X., Zhao, L., Zhu, X., He, B. & Guo, H. 2014 *Uncertainty-based analysis on water quality response to water diversions for Lake Chenghai: a multiple-pattern inverse modeling approach*. *J. Hydrol.* **514**, 1–14.

First received 6 January 2015; accepted in revised form 8 May 2015. Available online 24 June 2015