Dynamic simulation of water resources in an urban wetland based on coupled water quantity and water quality models

Weibo Zeng, Youpeng Xu, Xiaojun Deng, Longfei Han and Qianyu Zhang

ABSTRACT

Water quality in wetlands plays a huge role in maintaining the health of the wetland ecosystem. Water quality should be controlled by an appropriate water allocation policy for the protection of the wetlands. In this paper, models of rainfall/runoff, non-point source pollution load, water quantity/quality, and dynamic pollutant-carrying capacity were established to simulate the water quantity/quality of Xixi-wetland river network (in the Taihu basin, China). The simulation results showed a satisfactory agreement with field observations. Furthermore, a 'node-river-node' algorithm that adjusts to the 'Three Steps Method' was adopted to improve the dynamic pollutant-carrying capacity model and simulate the pollutant-carrying capacity in benchmark years. The simulation result shows that the water quality of the river network could reach class III stably all year round if the anthropogenic pollution is reduced to one-third of the current annual amount. Further investigation estimated the minimum amount of water diversion in benchmark years under the reasonable water quantity-regulating rule to keep water quality as class III. With comparison of the designed scale, the water diversion can be reduced by 184 million m^3 for a dry year, 191 million m^3 for a normal year, and 198 million m^3 for a wet year.

Key words | coupling model of water quantity/quality, dynamic pollutant-carrying capacity, minimum amount of water diversion, urban wetland

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INTRODUCTION

The wetland ecosystem is a natural complex area which plays an important role in regulating climate, degrading pollutants, purifying water, and protecting biodiversity. Water quality and quantity is the key factor of wetland formation, development, succession and demise (Zhou *et al.* 2008), and has become the hot topic of wetland research (Marion & Brient 1998; Cui & Liu 2001; Trepel and Palmeri 2002; Jiang *et al.* 2005; Zhang *et al.* 2005; Yang *et al.* 2007). However, growing water pollution has led directly to the destruction of ecosystem structure and degradation of wetland functions. Therefore, there is an urgent need to improve wetland water quality and protect the wetland ecological environment.

The purpose of model simulation and water quality assessment is to evaluate the water quality of the environment scientifically and accurately, and to provide the basis for water environment management (Freni *et al.* 2011; Hijosa *et al.* 2011; Carey *et al.* 2011; Zhang *et al.* 2012). There are several research papers on water allocation and coupling of water quality and water quantity.

Lind (2002) found that water quality in Chapala Lake, Mexico, was dependent on water quantity, indicating that both water quality and water quantity should be considered in research on water resources. Vink & Moran (2009) showed that disjointed problems exist in water quality and quantity management in the Bowen basin in Queensland and suggested that water quality–quantity issues should be managed as an integrated system. In order to achieve a water quality goal of the reservoir downstream, Hayes *et al.* (1998) developed an optimal regulating model for water quantity, water quality and power generation, and investigated general daily flow-regulating rules for reservoirs in the Cumberland basin. Pingry *et al.* (1990) studied upstream main tributaries of the Colorado River watershed through the establishment of a joint water quantity and water quality regulating decision support system. The study

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addressed how to balance planning for water resource allocation and water pollution treatment when both water resource allocation and contamination treatment level are variables. Loftis et al. (1985) combined water simulation models and model optimization methods to study joint regulating methods for lakes based on the comprehensive consideration of water quantity and water quality objectives. Genius (2006) applied a harmonized method of water quantity and water quality to establish a system evaluation model to solve water quality problems related to a dam in Rethymno, on the island of Crete in Greece. Lall et al. (1987) constructed a multi-objective surface water and ground water management model, considering the treatment cost of surface and ground water. Afzal et al. (1992) established a linear programming model for water quality optimization based on an area of Pakistan's irrigation system. Optimal crop acreage and groundwater exploitation in a special period could be obtained through the calculation results of the models. This study reflects the approach of joint water quality and water quantity regulation.

In summary, the idea of jointly regulating water quality and quantity has become the trend of water resource allocation research. However, corresponding studies for wetlands is relatively rare. Therefore, coupling water quantity and quality models in support of the management of an urban wetland is quite new. In this paper, Xixi wetland was selected as the study area, and models of rainfall/runoff, non-point source pollution load, water quantity/quality, and dynamic pollutant-carrying capacity were established to simulate the water quantity and water quality process, The objective of this paper is to: (1) evaluate the pollutant-carrying capacity; (2) predict the total sewage amount; and (3) estimate the minimum amount of water diversion to meet the target water quality. The results are of significance to the allocation of water resources, improvement of the urban wetland water environment, and implementation of dynamic water allocation management.

STUDY AREA

Xixi wetland is located in the west of Hangzhou, Zhejiang Province, 30°15′–30°17′ north and 120°02′–120°16′ east (Figure 1), with total area of about 10.08 km^2 and a

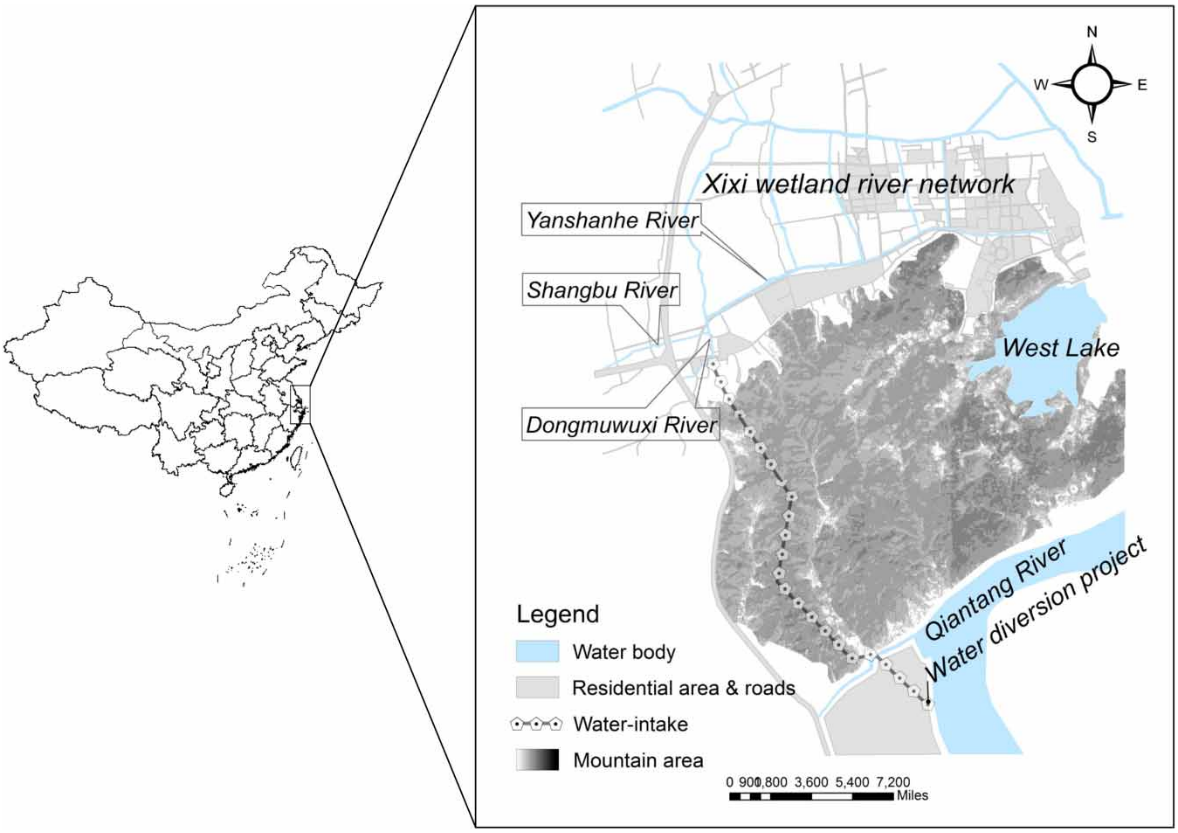

Figure 1 | Vicinity map of the Xixi wetland.

population of about 300,000. Terrain in the region slopes from southwest to northeast with ground elevation ranging from 2.0 to 5.6 m. The annual average evaporation and rainfall of this area are 758 mm and 1406 mm respectively, and the annual precipitation days are about 150. Water surface ratio of the region reaches to 70%, and the density of the water channel network is as high as 25 km/km^2. Rate of water flow in this area is about 0.03–0.07 m/s, with the average annual level being about 1.5 m. The main tributary rivers include Shangbu River and Dongmuwu River. Because the watershed and terrain limit the availability of water, water in the river network basically tends to remain stagnant with little outflow. According to the investigation and analysis of the census of pollution sources of Hangzhou City and pollution sources of Beijing-Hangzhou Grand Canal, there is no industrial wastewater, so the sources of pollution mainly originate from sewage, agricultural production and rural life at present. The Qiantang River water diversion project was built in 2009 and its design discharge (25.0 m^3/s), water level (4.0 m) and average annual diversion scale (390 million m^3) have effectively accelerated the water flow, thereby greatly improving the water quality. However, the project is unable to solve the existing environmental quality issues in the region completely. In 2009, only the water quality in Yanshan River, Jiangcun section, complied to class V (Table 1) and the others were slightly better, complying to class III or IV, whereas, in 2010–2011, all sections complied to class V. Water quality of the river network can hardly reach class III, which was planned for water functional areas.

Table 1 | Standard limit values of monitoring items of surface water environmental quality standard (GB3838-2002) issued by State Environment Protection Administration of PR China (mg/L)

	I	II	III	IV	V
COD	15	15	20	30	40
NH_3-N	0.15	0.5	1.0	1.5	2.0
TP	0.02	0.1	0.2	0.3	0.4

MATERIALS AND METHODS

Generalization of river network

Figure 2 shows the generalized river network based on the natural river network and its main tributaries. The principle of this approach is the equivalence of hydraulic characteristics of the generalized – and actual – river networks. We can get the same water conveyance and storage for the generalized and actual networks by appropriately increasing the channel density near the water intakes (Wu *et al.* 2006). Based on this principle, we merged streams, which basically does not affect the overall discharge capacity. River networks of the generalized study area contains 39 river segments and 26 nodes in total (Figure 2). The 177 main cross-sections are modelled as trapezoidal cross-sections by merging the minor tributaries, so as to minimize the total error of the flow cross-section.

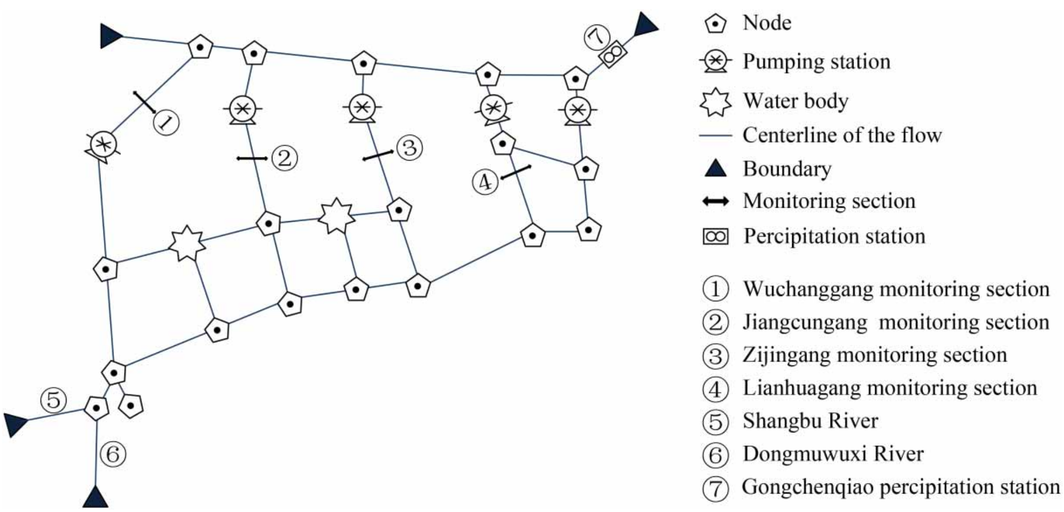

Figure 2 | Generalized diagram of the Xixi wetland river network.

Hydrology model

Water quantity model

The Saint-Venant equations are the control differential equations for water quantity of a one-dimensional river based on mass and momentum conservation. The variables for the study are water level and flow, and the expressions are as follows:

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=q$$

$$\frac{\partial Q}{\partial t}+2\mu\frac{\partial Q}{\partial x}+\left(gA-B\mu^2\right)\frac{\partial h}{\partial x}-\mu^2\frac{\partial A}{\partial x}+gA\frac{\mu|\mu|}{C^2R}=0$$

where Q is flow (m^3/s); A is the sectional area (m^2); x is the position variable; t is the time variable; q is lateral inflow (m^3/s); B is the width of the stream (m); μ is the section's flow average velocity (m/s); g is the acceleration of gravity; h is the water level (m); C is Chezy's coefficient ($m^{1/2}/s$); and R is the hydraulic radius (m).

Water quality model

The control differential equation for water quality of a one-dimensional river is a convection–diffusion equation based on mass conservation. The concentration was taken as the study variable, and its expression is:

$$\frac{\partial(Ac)}{\partial t}+\frac{\partial(Qc)}{\partial x}=\frac{\partial}{\partial x}\left(AE\frac{\partial c}{\partial x}\right)-Akc+L$$

where A is the sectional area (m^2); c is the pollutant concentration (mg/L); t is the time variable; x is the position variable; Q is the sectional flow (m^3/s); E is the longitudinal dispersion coefficient (m^2/s); k is the integrated degradation coefficient (s^{-1}); and L is the pollution source term (mg/(m·s)).

Runoff model and confluence model

Based on the topographical and geomorphological features of this study area, runoff calculations mainly considered runoff from paddy fields and the southern hills of this area. H_1–H_2 is the range of water depth suitable for growing rice, H_3 is the water depth of submergence rice can tolerate, H is the water storage depth of paddy fields, and H_e is the maximum drainage capacity of paddy field; then the amount of surface water diversion and drainage can be represented as follows:

$$\begin{aligned}
&R_2=H_2-H \quad H<H_1\\
&R_2=0 \quad H_1\le H<H_3\\
&R_2=H-H_3 \quad 0<H-H_3<H_e\\
&R_2=H_e \quad H-H_3\ge H_e
\end{aligned}$$

When the computed result $R_2>0$, paddy fields drain water out, and when $R_2<0$, paddy fields accept water. Using the water balance equation and recursive daily. We can get a paddy field's initial water depth of $t+1$ day:

$$H_{t+1}=H_t+P_t-E_t-I_t-R_{st}$$

where H_t is paddy field initial water depth of day t; P_t is the precipitation; E_t is the evaporation; I_t is the infiltration; R_{st} is the discharge of surface water. Considering that this study area covers a small number of hectares, rainfall/runoff is calculated using the Soil Conservation Service model. The basic relationship is:

$$\frac{N}{F}=\frac{Q}{P-I_a}$$

where P is the precipitation (mm); Q is the runoff quantity (mm); I_a is the initial losses (mm); F is the later losses (mm) and N is the maximum possible retention volume after runoff begins (mm), which also can be called the retention index and is the upper limit of later losses.

Dynamic pollutant-carrying capacity model

The 'Three Steps Method' (Zhang et al. 1982) of a river network's water quantity and quality mathematical models forms an efficient algorithm of a river network that follows the 'channel-node-channel' solving order. However, the pollutant discharge information related to each channel section is no longer contained in the node equations, which are solved at first. This leads to the water quality model using the 'Three Steps Method' being unable to calculate the water pollutant-carrying capacity. This paper uses a 'node-channel-node' algorithm to calculate the river network's dynamic pollutant-carrying capacity, and the algorithm fits the 'Three Steps Method' algorithm of the water quality model. Finally, the node equation (solved first) of water quality models of a river network can be expressed as:

$$A_TC_T=\vec{B}_T'$$

where A_T is the coefficient matrix; vector C_T is the node's concentration and vector B_T is the right-hand member. If we distinguish the pollutant emissions of nodes from the right-hand group, and then set $\vec{B}_T = \vec{B}'_T + \vec{W}'_T$, and multiply the equation on both sides with the inverse matrix of the coefficient matrix, the resulting equation would be:

$$C_T = A_T^{-1}\vec{B}_T + A_T^{-1}\vec{W}'_T$$

where $\vec{W}'_T$ is allowable input mass of pollutant for each node. The linear programming model as follows was used to solve allowable entry amounts:

$$maxZ' = \sum_{i=1}^{M} W'_{T_i}$$

$$A_T^{-1}\vec{W}'_T = \vec{S}_T - A_T^{-1}\vec{B}_T$$

$$\vec{W}'_T \geq \vec{O}$$

where $maxZ'$ is the maximum allowable entry amount, and $\vec{O}$ is the zero vector. The following linear programming model was adopted to solve the allowable discharge amounts of each channel associated with the study nodes:

$$\begin{aligned}
&maxZ = \sum_{i=1}^{m_1} Z_i \\
&A_{c_1}^{-1}\vec{W}_{c_1} \leq \vec{S}_{c_1} - A_{c_1}^{-1}\vec{B}_{c_1} \\
&A_{c_2}^{-1}\vec{W}_{c_2} \leq \vec{S}_{c_2} - A_{c_2}^{-1}\vec{B}_{c_2} \\
&\qquad\qquad \cdots\cdots \\
&A_{c_{m_1}}^{-1}\vec{W}_{c_{m_1}} \leq \vec{S}_{c_{m_1}} - A_{c_{m_1}}^{-1}\vec{B}_{c_{m_1}} \\
&\sum_{i=1}^{m_1} Q_{\mathrm{i,n}_i+1} \\
&\vec{D}_{c_i}^T\vec{W}_{c_i}^T \leq Q_T C_T - \sum_{i=1}^{m_1} Q_{\mathrm{i,n}_i+1}P_{c_i} \\
&\vec{W}_{c_i} \geq \vec{O} \quad i = 1, 2, \ \ldots\ldots, m_1
\end{aligned}$$

where m_1 is the number of upstream channels that are related with this node; Z_i is the allowable discharge amount of each associated upstream channel of the study node; A and B are the coefficient matrix of each channel equation and right-hand column vector, respectively; S is the relevant water quality standard of each channel; Q and C are flow and concentration of relevant channel sections, respectively; $\vec{D}_{ci}^T$ is the water quality degradation coefficient of relevant channels, Q_T is the total flow entering this node; C_T is pollutant concentration of this node; the column vector $\vec{W}_c$ shows the allowable discharge amounts of relevant channels, and $\vec{O}$ is the null vector. Finally, the allowable discharge amount of each node can be calculated as:

$$W_T = Q_T C_T - \sum_{i=1}^{m_1} Q_{\mathrm{i},n_i+1} C_{i,n_i+1}$$

where Q_{i,n_i+1} and C_{i,n_i+1} are the end sectional flows and concentrations of pollutants in nodes related to the upstream channels, respectively.

RESULTS AND DISCUSSION

Validation of models

In this paper, the export coefficient for non-point source pollution of different soil types in the study area was from related research in the Taihu basin, and the domestic pollution export coefficient was calculated in accordance with the urban life source of pollution discharge coefficient manual issued by the leading group office of the State Council for the first national pollution sources census: chemical oxygen demand (COD) 75 g/(d·person), NH_3-N 7.5 g/(d·person), total phosphorus (TP) 0.86 g/(d·person); the roughness coefficient values range from 0.018 to 0.040; pollutant degradation coefficient: COD 0.1/d; NH_3-N 0.1/d; TP 0.05/d.

Rainfall runoff

Shangbu River and Dongmuwu River are located in the upstream of the study area. In this paper, the simulation of rainfall and runoff in 2010 was based on the runoff model and confluence model (Figures 3 and 4). Due to the absence of monitoring data, validation of the rainfall runoff model was omitted. However, it is necessary to point out that hourly rainfall data were used to simulate runoff in the current year. The runoff parameters and convergence model are highly reliable and precise and were validated by sufficient data and tested through years of practical use in Zhejiang Province.

Water level and flow

Figures 5 and 6 show the comparison of simulated and measured flow value of Wuchanggang and Jiangcungang

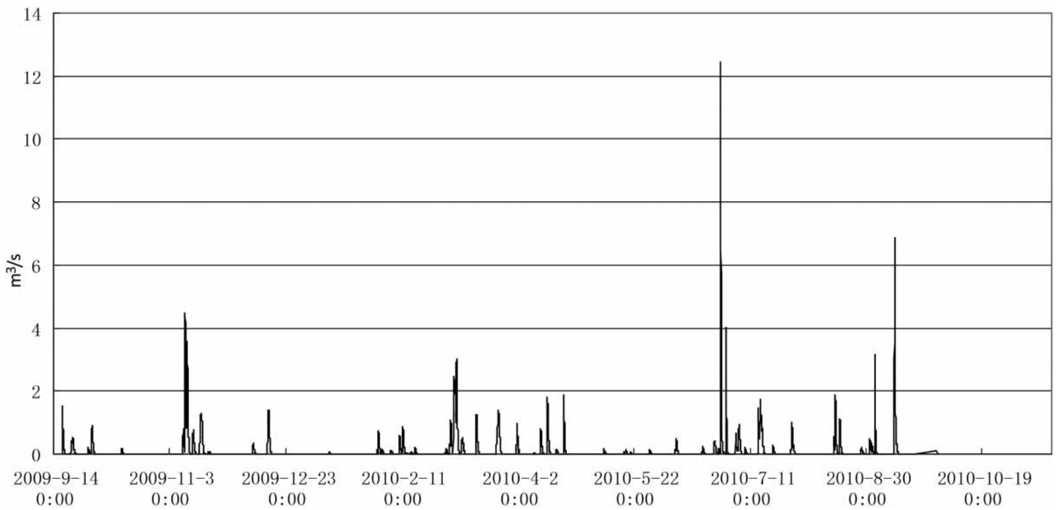

Figure 3 | Inflow of Shangbu River (m^3/s).

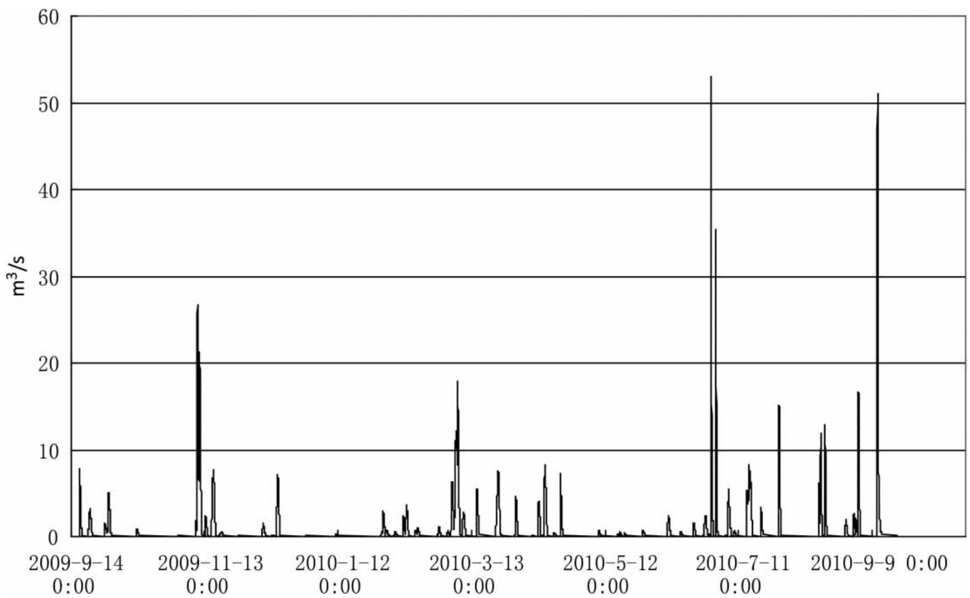

Figure 4 | Inflow of Dongmuwu River (m^3/s).

sections respectively. Figure 7 and Figure 8 show the water level of Zijingang and Lianhuagang sections. The simulated results (Figure 5–8) basically correspond to the peaks and valleys of water level and monitored flow. And the error analysis of the peak value shows that the calibration error of the peak level is within 7% and the calibration error of peak flow is within 10%.

Water quality

Figures 9 and 10 compare the simulated and monitored COD values of Wuchanggang and Jiangcungang sections, respectively. As the comparison shows, the simulated COD value in Wuchanggang section is quite similar to the monitored values. Both data sets correspond to each other well except in December 2009 and in June and August 2010, when the relative error is 6.9% and 10.4% respectively (Figure 9). The relative errors in other periods are within 3.5%. However, the simulated COD value and the measured value in Jiangcungang section diverge widely (Figure 10) and the average relative error for the entire monitoring period is as high as 23.7%. The reason for this is that Jiangcungang is located in densely populated areas that experience large quantities of seemingly random pollutant emissions. As a

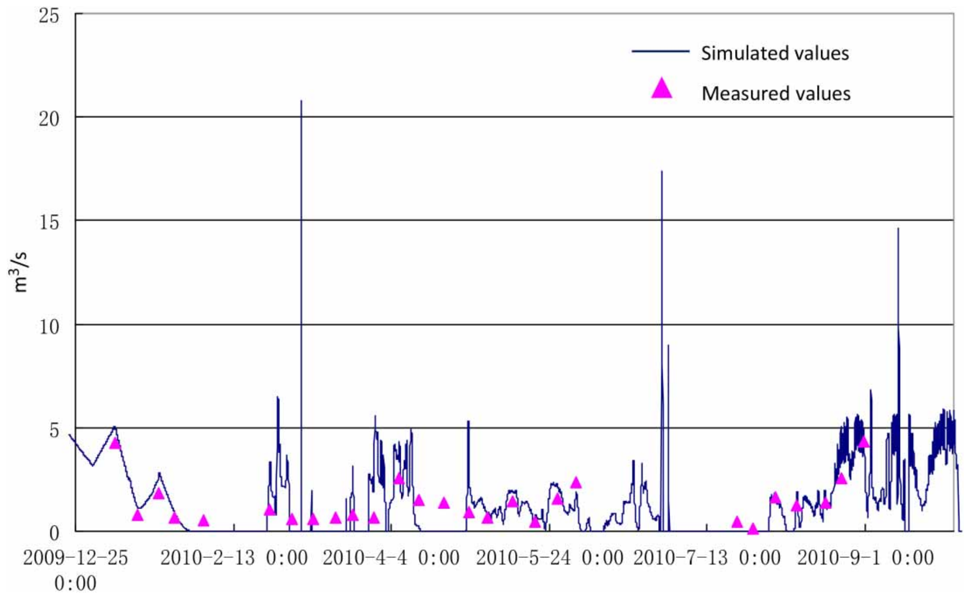

Figure 5 | Simulated and measured flow of Wuchanggang section (m^3/s).

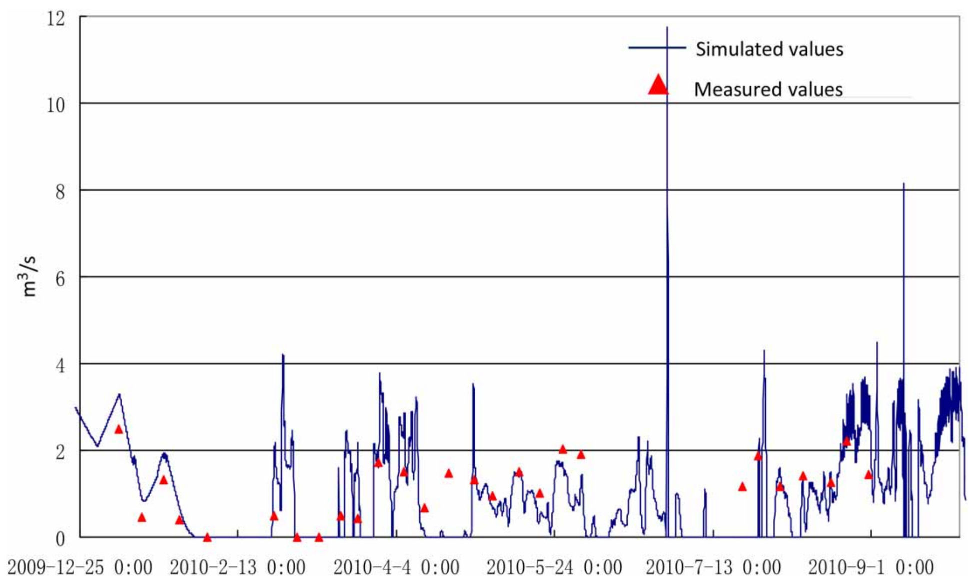

Figure 6 | Simulated and measured flow of Jiangcungang section (m^3/s).

result, the measured value of the section here is rather high and deviates widely when compared with the simulated results. However, Wuchanggang is the suburbs of the study area, where pollution emissions are more stable, so the modeled water quality agrees well with the measured values.

Water flow in benchmark years

The total water volume of a river network mainly depends on the volume of runoff and intake in the local area. Therefore, the selection for benchmark year mainly needs to consider these two features. Pearson type III frequency distribution was applied for the frequency analysis for 55 years of historical rainfall data (1953–2007) from the precipitation stations of the study area. The years 1983, 1991, and 1968 were selected as benchmark wet, normal, and dry years respectively, corresponding to 11.96%, 48.82%, and 89.32% of annual rainfall frequency of this region. Artesian diversion is adopted in the study area, but it is affected by the tide of the Qiantang River. So,

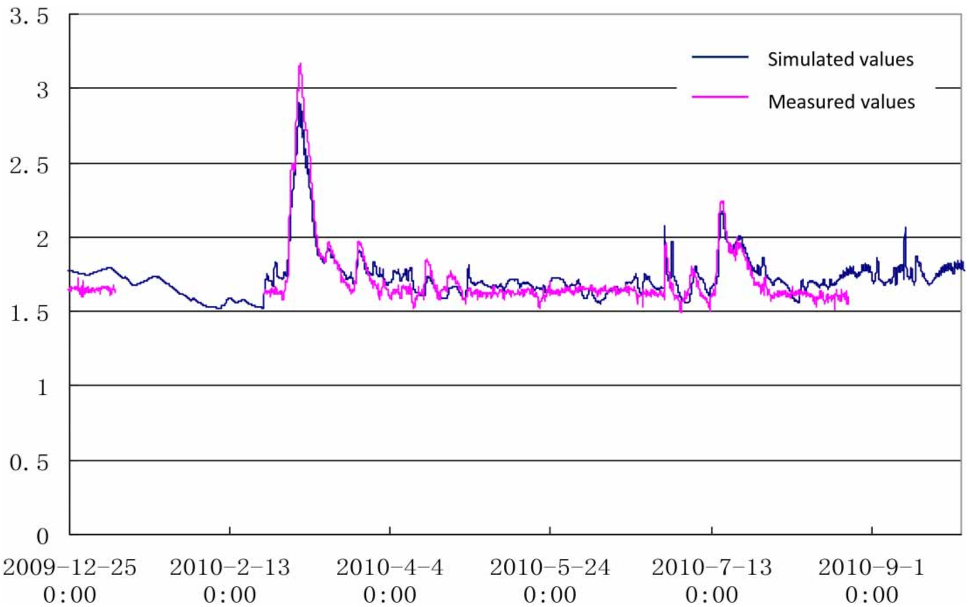

Figure 7 | Simulated and measured water level of Zijingang section (m).

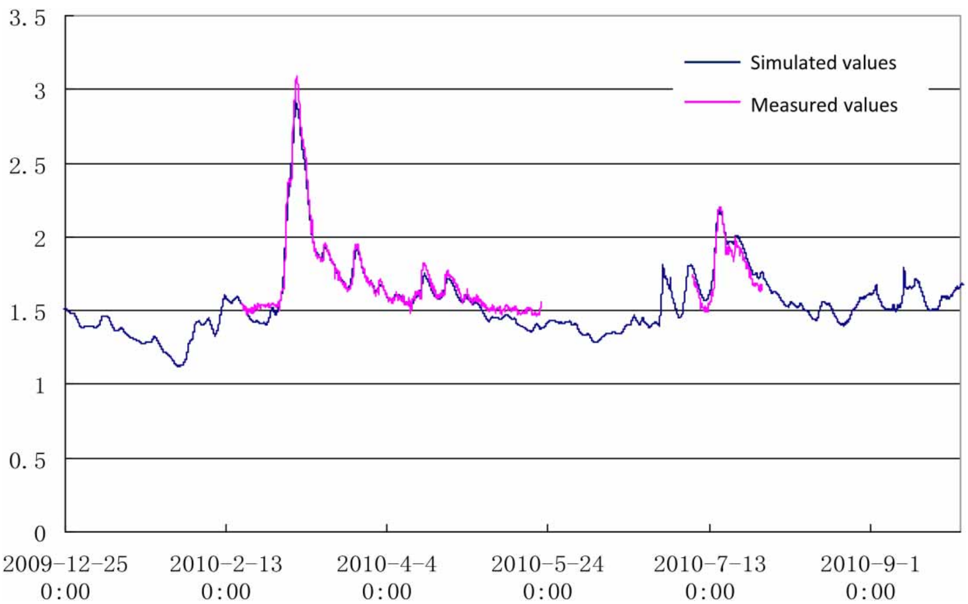

Figure 8 | Simulated and measured water level of Lianhuagang section (m).

we took the lower tide level (2010) as the current diversion condition, and combined the data with precipitation and evaporation data to calculate water volume of each benchmark year (Table 2) based on the runoff and confluence model.

The result shows that in a wet year, the volume of local water resources is only around 50 million m^3 (167 m^3 per capita), which is slightly higher than the average water consumption (116.7 m^3 per capita) for daily domestic use of 2010 in the area. This amount definitely cannot meet the water demand and so the water diversion from Qiantang River is much needed.

During a normal flow year, nearly 40 million m^3 of water is available in the study area, or about 133 m^3 per capita; that is, even if this amount were fully used, it only equals the domestic per capita water consumption.

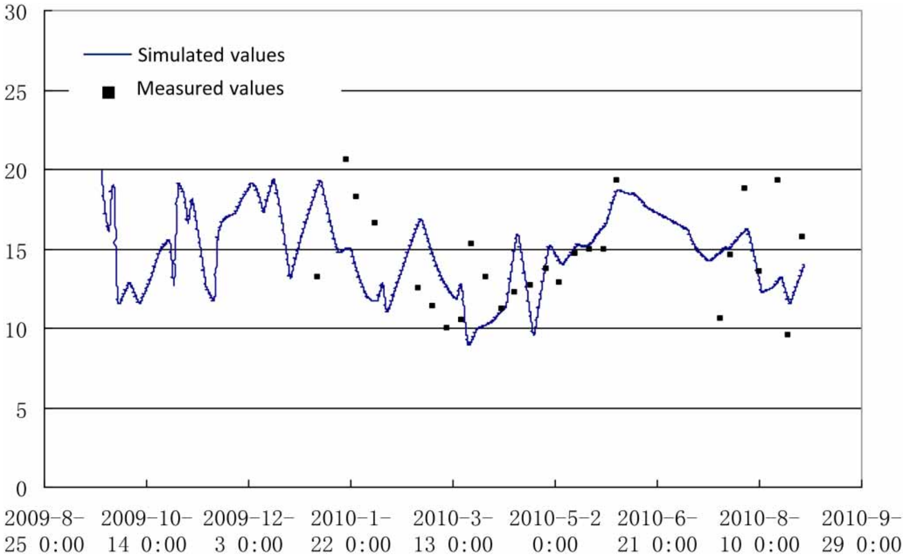

Figure 9 | Simulated and measured COD concentration of Wuchanggang section (mg/L).

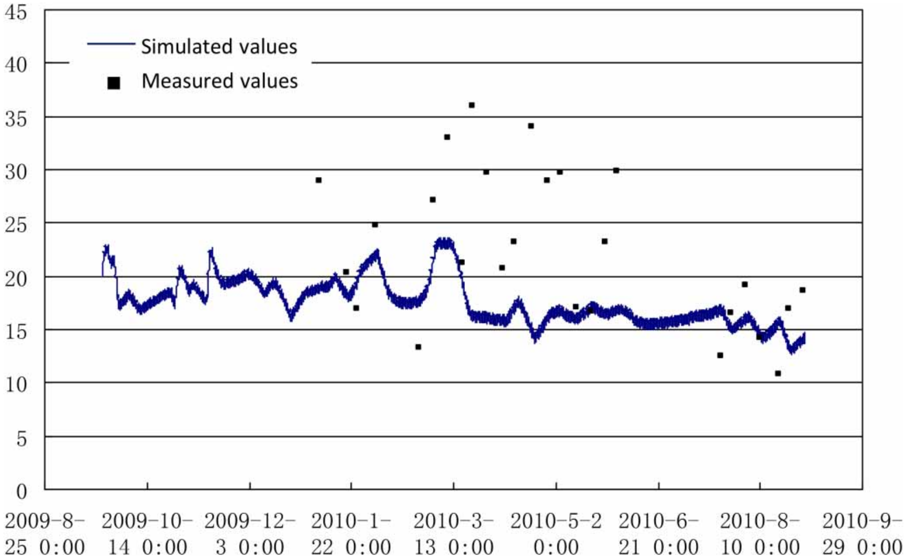

Figure 10 | Simulated and measured COD concentration of Jiangcungang section (mg/L).

Table 2 | Water availability in benchmark years (million m^3)

	Wet year (1983)	Normal year (1991)	Dry year (1968)
Shangbu River	28.2	22.5	17.1
Dongmuwu River	4.3	3.4	2.6
The southern mountain area	6.4	5.1	3.9
Xixi wetland	11.1	8.9	06.7
Total amount	50.0	39.9	30.3

In a dry year, less than 30.3 million m^3 of local water is available or about 101 m^3 per capita, which does not meet the consumptive water demand.

Pollution load of benchmark years

From the analysis of ratio of total mass of pollutant discharged in benchmark years (Table 3) to domestic sewage discharged (Table 4) in the current year (2010),

Table 3 | Total mass of pollutant discharged of benchmark years (t)

	COD	NH_3-N	TP
1983	704.4	156.53	10.44
1991	586.95	130.43	8.69
1968	528.3	117.40	7.83

Table 4 | Total mass of pollutant discharged of current year (t) (2010)

	COD	NH_3-N	TP
Non-point pollution	586.95	130.43	8.69
Water diversion	3270	170.04	20.71
Domestic pollution	2380	253	27.2
Total	6237	553	56.6

the domestic sewage is the main source of pollution in benchmark years.

Dynamic pollutant-carrying capacity of benchmark years

The dynamic pollutant-carrying capacity is the maximum load of pollutants that can be accommodated under specified environmental objectives. It is influenced by a dynamic process, which is related to flow characteristics, water quality objectives, and pollutant characteristics (Fu *et al.* 2008). In this study, the improved dynamic pollutant-carrying capacity model was used to simulate the annual average pollutant-carrying capacity (Table 5) of benchmark years with the diversion scale (218 million m^3) of the current year as basis.

With reference to the total amount of pollutant (Table 4) in the current year (2010), the comparison shows that the discharged amount of pollutants, except phosphorus, has exceeded the pollutant-carrying capacity of benchmark years. Obviously, the water volume difference of less than 10 million m^3 (Table 2) has no influence on water quality. This means the most efficient way to improve the water quality is to cut down the pollutant emission in this area.

Table 5 | Pollutant-carrying capacity of benchmark years (t)

	COD	NH_3-N	TP
Dry year	5156	265.2	67.87
Normal year	5348	270.0	69.31
Wet year	5550	275.1	70.83

Reduction of pollution load and prediction of water quality in benchmark years

Through comparison of the total amount of pollutant of current year (2010) and pollutant-carrying capacity of benchmark years, it can be inferred that the target water quality cannot be reached without increasing the flow. Since non-point source pollution is not easily controlled and domestic sewage is the main source of pollutants, sewage should be controlled for pollutant reduction. Based on the dynamic pollutant-carrying model and total mass of pollutant discharged in benchmark years, the required standard water quality could be reached throughout the year if the sewage was reduced to one-third of the total mass of pollutant in current year (COD 759.9 t, NH_3-N 80.72 t, TP 8.55 t). Table 6 shows the distribution of pollutant after domestic sewage reduction.

The minimum amount of water diversion in benchmark years

The designed amount of the annual water diversion of Qiantang River Diversion Project is to improve the water quality of whole Xixi wetland river network, to reduce the water consumption of the regional environment and to alleviate the pressure of water consumption in the downstream area. Through the coordinated scheduling of water diversion and monitoring of water quality, the amount of water diversion can be determined accurately. With the constraint of pollutant concentration of each section, based on tests and calculations, the minimum amount of water diversion can be determined by a regulating scheme. The diversion should be given priority when the contaminant concentration reaches 90 percent of water quality standard limit,

Table 6 | The distribution of pollutant after domestic sewage reduction (t)

	COD	NH_3-N	TP
Dongmuwu River	21.20	2.25	0.24
Liuxia River	21.57	2.29	0.24
Yanshan River	195.2	20.75	2.23
Jiangcungang	97.62	10.55	1.02
Zijingang	132.9	14.11	1.52
Lianhuagang	78.73	8.31	0.89
Yile River	43.46	4.60	0.49
Fengjia River	69.59	7.28	0.77
Yuhangtang River	110.8	11.78	1.27
Total amount	759.9	80.72	8.55

while, normally, the maximum flow will be set to 10 m^3/s. By comparing the minimum diversion scale with the designed scale, the diversion demand can be reduced to 184 million m^3 in a dry year, 191 million m^3 in normal years, and 198 million m^3 in a wet year (Table 7). Compared to the current situation, there is a big decrease in diversion.

CONCLUSIONS

The coupling of water quantity and water quality models in urban wetland management proved to be useful. In this paper, rainfall/runoff, non-point source pollution load, water quantity/quality, and dynamic pollutant-carrying capacity models were established based on long-term records of precipitation, water level, flow rate as well as data of Xixi wetland. The results of a 1-year simulation showed a satisfactory agreement with field observations.

The main contaminant in the study area is ammonia nitrogen followed by total phosphorus. The domestic sewage accounted for a large proportion of total amount of pollutant in benchmark years and it clearly affects the water quality of the river network.

Less than 10 million m^3 separating different benchmark years can hardly influence the water quality of the study area without water diversion. As the non-point source pollution is not easily controlled, the results show that, unless sewage is reduced, the required water quality in the river network cannot be achieved. Nevertheless, with water diversion and a two-thirds reduction in the total mass of current year to 759.9 t/y COD, 80.72 t/y NH_3-N, 8.55 t/y TP, a stable class III water quality can be attained all year round in the river network.

With the constraint of class III water quality and adopting a reasonable water quantity regulating rule, the minimum amount of water diversion in benchmark years can be estimated. The water diversion of a dry year can be reduced by 184 million m^3, a normal year by 191 million m^3, and a wet year by 198 million m^3 of wet year.

In this paper, simulation of Xixi wetland water resources were carried out based on the coupling of water quantity and water quality models. However, a complex engineering system is required to configure and optimize the water regulation scheme with the application of hydraulic engineering. Therefore, to trace and monitor variations of water quality and quantity and patterns of sewage transfer, and to solve the relationships between water diversion and sewage discharge, water diversion and water consumption of surrounding areas requires further research. A more accurate estimation of the amount of water diversion and determination of a reasonable water allocation scheme in both time and space can be expected.

Table 7 | Comparison of water diversion amount (million m^3)

	Wet Year	Normal Year	Dry Year
Total amount	192	199	206
Less than current year	26	19	12
Less than designed scale	198	191	184

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