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Development of integrated catchment and water quality model for urban rivers*

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Abstract: This paper presents the development of an urban river water quality model which considers the physical-biochemical processes within rivers and the incorporated urban catchment rainfall-runoff process developed with the time–area method. Unlike other models that simulate the hydrological and receiving water quality processes in the rural areas of the watershed scale, the model developed here is typically efficient for simulating the water quality response to nonpoint loadings from urban drainage systems, where the hydrological process is disturbed by artificially pumped discharge in wet-weather periods. This model is employed to assess the river water quality restoration in Nanfei River in Hefei City, China, where the model is calibrated against the measured data (i.e., the COD, the BOD_5, the NH_3-N, and the DO) in 2010, and the model parameters are suggested. It is shown that the nonpoint pollutants from the urban catchments contribute 34%-47% of the total pollutant inputs (i.e., the COD, the BOD_5, and the NH_3-N), despite their low flow component of 13.4%. Apart from the improvement of the wastewater treatment plant effluent (i.e., Grade IV of the Surface Water Quality Standard), a nonpoint loading reduction of 27.2%, 25.1%, and 35.3% of the COD, the BOD_5, and the NH_3-N are anticipated to meet the designated surface water quality standards of Grade V.

Key words: river water quality, integrated model, catchment modeling, urban river, Caohu Lake watershed, nonpoint load

Introduction

The urban expansion across China has significantly affected all types of ecosystems, leading to an increased pollution and other adverse effects on natural resources. The urbanization turns the natural or agricultural land into residential and commercial areas, as a result, the increased imperviousness of the area and its urban activities lead to an increased runoff and the water quality deterioration. Although combined or separate sewer systems are used in urban areas to treat polluted water, the wet-weather sewer overflows may occur during rainfall periods. The drainage overflow may discharge directly into streams and rivers, resulting in severe water pollution problems[1,2].

The water quality modeling is considered as a required element in supporting the water quality management decisions, not only in determining the requirements for meeting the water quality standards, but also in calculating the effectiveness of actions in limiting the pollutant sources for a designated use. The use of deterministic models is thus essential to fully capture the changing dynamics that describes the complex interactions between the catchment and the urban rivers. These changing dynamics, driven mainly by land-use activities, urban drainage systems, and hydrologic behavior, can severely impact the receiving water quality. To account for the strong complex interactions between the catchment and the urban rivers, an integrated catchment approach is required for the numerical modeling of such environments, in which the parameters that drive the water and pollutant fluxes out of a catchment into an urban river are to be determined. However, the numerical modeling of such catchment-river systems as a single entity is often ineffective, as the physical processes in the components of these systems often differ. Therefore, numerical models of such

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systems are developed by coupling the catchment and urban river models.

Many models, typically, the waterbody or watershed models, were developed. The hydrological models, the hydrologic simulation FORTRAN (HSPF) and SWAT, are comprehensive river basin models that provide an integrated framework for modeling various hydrological and quality processes[3-8]. They are used worldwide and their applications were reported in literature. For example, Lian et al.[4] developed a one-dimensional unsteady state flow model (UNET) for the main branch of the Illinois River, which was coupled with the HSPF model to calculate the flow routing. In a study of the impact of *Escherichia coli* (*E.coli*) loadings from the Mignonne River catchment in France, Bougeard et al.[6] integrated a SWAT catchment model with the MARS 2-D hydrodynamic model. Xie and Lian[7] reported results calibrating and evaluating SWAT and HSPF models with hydrologic data in the Illinois River Basin, in terms of the relative performance of the two models in hydrologic simulations and the model behaviors. Using the HSPF, Fonseca et al.[8] developed an integrated hydrological and water quality model to assess the impact of point and nonpoint pollution sources on the water quality of a Lis River tributary (Lena River), a 176 km^2 watershed in the Leiria region of Portugal. There were also studies concerning the integration of a catchment scale runoff model with a receiving water model[9-15]. For example, Bedri et al.[10] presented a marine water quality forecasting system for real-time and short-term predictions based on the MIKE modeling suite, including an integrated catchment-coastal model and a database management system. The integrated model is validated in an Irish catchment-coastal system using hydrodynamic and water quality data. Using the environmental fluid dynamic code (EFDC), Chan et al.[11] developed a three-dimensional deterministic model to interpret the complex variations of the Hong Kong beach water quality, which depends on the tidal level, the solar radiation, and the watershed-scale hydrometeorological factors.

However, such considerations are not completely adequate for rivers in an inland city's urban area. The above-mentioned modeling approaches in particular account for various sources of the pollution discharge into receiving water bodies for a large-scale catchment or watershed scale, where the agricultural runoff and swine and livestock wastewaters constitute one of the principal sources of the diffused pollution. By contrast, the wet-weather discharges from urban drainage systems constitute the principal sources of diffused sources in the rivers that flow through densely populated areas. To prevent accumulated runoff and flooding events in a city's urban area, a storm pump station is usually set up at the catchment outlet, as a result, the artificial storm pump operations alter the hydrologic processes on the pervious and impervious land surfaces described by these developed models. Therefore, it is necessary to have an urban runoff model that is adaptable to catchments characterized by the storm pipe gravity discharge or the pumping discharge. Additionally, the inland rivers running through cities usually have less upstream inflow in the dry season and augment an intense flow for short periods following the precipitation. The calibration of an integrated catchment-water quality model is needed to support the water pollutant abatement schemes in this area.

This paper presents a water quality modeling for Nanfei River in Hefei City, in central China. As the largest tributary of China's Caohu Lake, this river has been a hot research topic in China's ongoing major science and technology programs aiming at assessing its water quality restoration scheme and abating the water pollutant discharging into Caohu Lake. For this reason, the main goal of this work is to develop and calibrate a water quality model for the prediction of the water quality under different scenarios (i.e., the impact of point and nonpoint sources), and for obtaining the necessary information to promote a proper water pollution control scheme in this area.

Fig.1 Depiction of Nanfei River's urban catchments

1. Materials and methods

1.1 *Description of study area*

The Nanfei River is located in the western part of the Caohu Lake Basin, with a total length of approximately 70 km. The study area is the river's urban section passing through Hefei City, with a length of 16.9 km (Fig.1, Table 1). The river's upstream is Dongpu Reservoir, which is the drinking water source of Heifei City. Therefore, in dry-weather periods, there is almost no upstream water inflow. The river's dry-weather discharge is mainly from the treated wastewater from the city's two wastewater treatment plants (WWTPs), i.e., the Wangtang WWTP and the Wangxiaoying WWTP.

Table 1 Catchments related to Nanfei River's urban reach

No.	Catchments	Area/ km^2	System mode	Discharge mode
1	Sili River	3.7	Separate storm and sewers	Gravity discharge
2	Banqiao River	5.6	Separate storm and sewers	Gravity discharge
3	Changfeng Rd.	1.0	Separate storm and sewers	Pumping discharge
4	Hupuoshan-zhuang	0.98	Separate storm and sewers	Pumping discharge
5	Xinghua	2.9	Combined sewers	Pumping discharge
6	Xiaoyaojin	0.95	Combined sewers	Pumping discharge
7	Dongdajie	2.1	Combined sewers	Gravity discharge
8	Shuanghe	0.9	Separate storm and sewers	Pumping discharge
9	Fenghuang-qiao	0.32	Separate storm and sewers	Pumping discharge
10	Shijia River	8.13	Separate storm and sewers	Gravity discharge
11	Chiying	0.96	Separate storm and sewers	Pumping discharge
12	Tangqiao	5.1	Separate storm and sewers	Pumping discharge
13	Xiliying	3.1	Separate storm and sewers	Pumping discharge
14	Erli River	11.3	Separate storm and sewers	Gravity discharge

1.2 *Modeling approach*

1.2.1 Receiving water quality model

The river's longitudinal scale is much larger than its lateral and vertical ones, therefore, a one-dimensional, cross-sectional averaged, time-dependent model is sufficient. The water flow equation is based on the Saint-Venant equation:

$$B_t \frac{\partial \zeta}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\alpha \frac{Q^2}{A}\right) + gA\frac{\partial \zeta}{\partial x} + g\frac{n^2 Q^2}{Ah^{4/3}} = 0 \tag{2}$$

where x and t are the longitudinal distance and time, respectively, A is the cross-sectional area of the river, Q is the river discharge, ζ is the river water level, h is the river water depth, q is the lateral inflow, g is the acceleration due to gravity, and n is the bottom roughness coefficient.

Specifically, the lateral inflow into the model includes the point sources and the tributary discharges in the dry-weather season, and the urban runoff discharges in the wet-weather season. The dry-weather discharge of each source is measured directly, and the urban runoff discharge is determined by using the urban runoff model described below.

In the case of one-dimensional flow, the advection-dispersion equation for the transport of pollutants in the rivers can be formulated as

$$\frac{\partial (AC)}{\partial t} + \frac{\partial (QC)}{\partial x} = \frac{\partial}{\partial x}\left(AE_x \frac{\partial C}{\partial x}\right) - f_R(C) + W_p \tag{3}$$

where C is the pollutant constituent concentration, E_x is the longitudinal dispersion coefficient, $f_R(C)$ is a generic term for reactions involving the pollutant C, W_p includes the external point source load and the nonpoint source load, that is, $W_p = W_{\text{point}} + W_{\text{runoff}}$, where W_{point} is the point source load and W_{runoff} is the nonpoint source load.

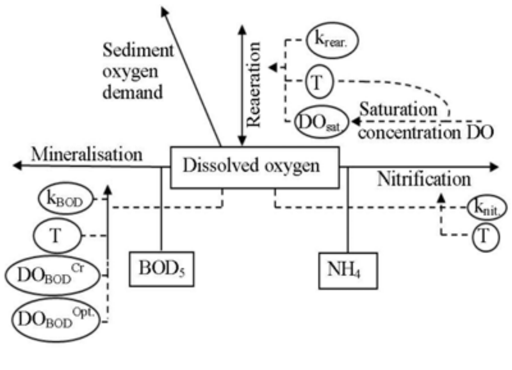


Fig.2 Modeled transformation process

The following types of reactions were considered: (1) the degradation of the dissolved carbonaceous substances and nitrogen species, (2) the dissolved oxygen balance, including the depletion by the degradation processes, and the sediment oxygen demand and supply by the physical re-aeration. In Fig.2, the interactions between the model processes are shown along with the model variables considered.

Actually, the following equations are used to simulate the model variables of interest:

$$f_R(\mathrm{COD}) = -k_{\mathrm{COD}}(\mathrm{COD})\theta_{\mathrm{COD}}^{T-20} \tag{4}$$

$$f_R(\mathrm{BOD}_5) = -k_{\mathrm{BOD}}(\mathrm{BOD}_5)\theta_{\mathrm{BOD}}^{T-20}\frac{(\mathrm{O}_2 - \mathrm{DO}_{\mathrm{BOD}}^{\mathrm{Cr}})}{\mathrm{DO}_{\mathrm{BOD}}^{\mathrm{Opt}} - \mathrm{DO}_{\mathrm{BOD}}^{\mathrm{Cr}}} \tag{5}$$

$$f_R(\mathrm{NH}_4) = -k_{\mathrm{nit}}(\mathrm{NH}_4)\theta_{\mathrm{nit}}^{T-20}\frac{(\mathrm{O}_2 - \mathrm{DO}_{\mathrm{nit}}^{\mathrm{Cr}})}{\mathrm{DO}_{\mathrm{nit}}^{\mathrm{Opt}} - \mathrm{DO}_{\mathrm{nit}}^{\mathrm{Cr}}} \tag{6}$$

$$f_R(\mathrm{DO}) = k_{\mathrm{rear}}[\mathrm{DO}_{\mathrm{sat}} - (\mathrm{O}_2)]\theta_{\mathrm{rear}}^{T-20} - f_R(\mathrm{BOD}_5) - f_R(\mathrm{NH}_4) - \mathrm{SOD} \tag{7}$$

where k_{COD} is the first-order decaying coefficient of the COD at 20°C, θ_{COD} is the temperature coefficient of the COD, k_{BOD} is the first-order decaying coefficient of the BOD$_5$ at 20°C, θ_{BOD} is the temperature coefficient of the BOD$_5$, $\mathrm{DO}_{\mathrm{BOD}}^{\mathrm{Cr}}$ is the critical dissolved oxygen concentration for the BOD$_5$ degradation, $\mathrm{DO}_{\mathrm{BOD}}^{\mathrm{opt}}$ is the optimum dissolved oxygen concentration for the BOD$_5$ degradation, k_{nit} is the ammonia nitrification coefficient at 20°C, θ_{nit} is the temperature coefficient of the ammonia, $\mathrm{DO}_{\mathrm{nit}}^{\mathrm{Cr}}$ is the critical dissolved oxygen concentration for the ammonia nitrification, $\mathrm{DO}_{\mathrm{nit}}^{\mathrm{opt}}$ is the optimum dissolved oxygen concentration for ammonia nitrification, k_{rear} is the atmospheric re-aeration coefficient, $\mathrm{DO}_{\mathrm{sat}}$ is the saturation oxygen concentration, θ_{rear} is the temperature coefficient of the dissolved oxygen, and SOD is the sediment oxygen demand.

1.2.2 Urban catchment runoff model

In this study, the urban runoff computation concept is based on the time–area method. Specifically, the runoff amount is controlled by the size of the contributing area and a continuous hydrological loss, i.e.:

$$q_{\mathrm{runoff}} = \sum_{i=1}^{t}(1-a)(1-\beta)RF \tag{8}$$

$$W_{\mathrm{runoff}} = \sum_{i=1}^{t}(1-a)(1-\beta)RFC \tag{9}$$

where q_{runoff} is the simulated urban catchment runoff input into the watercourse, W_{runoff} is the simulated urban catchment pollutant input into the watercourse, t is the time of concentration, which is the time from the most distant part of the catchment to the point of outflow, i is the computational time step, a is the hydrological reduction factor, accounting for the water losses caused by, e.g., the evapotranspiration and the imperfect imperviousness, etc. on the contributing area, β is the portion of the catchment runoff intercepted by the WWTP due to the installed end-of-pipe interception sewers for the combined sewer system, R is the rainfall intensity for each precipitation event, F is the time-related surface area, and C is the time-related runoff concentration.

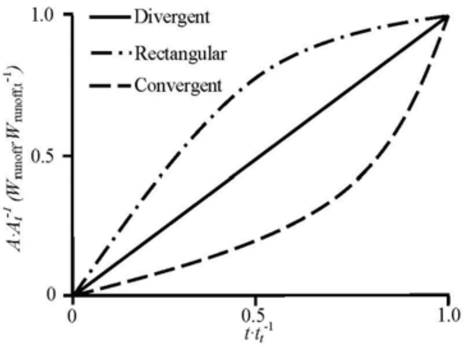


Fig.3 Pre-defined time–area curves for runoff pollutant computation

Generally speaking, to estimate the time-related runoff pollutant input into the river, three types of time-area curves are available: the rectangular catchment, the divergent catchment, and the convergent catchment (Fig.3). Specifically, in Fig.3, the time-area curve characterizes the shape of the catchment, relating the flow time, i.e., the concentric distance from the outflow point, to the corresponding catchment sub-area, A_t represents the catchment surface area, t_t represents the time from the most distant part of the catchment to the point of outflow, $W_{\mathrm{runoff},t}$ represents the total runoff pollutant input into the river for each rainfall event, which can be estimated by

$$W_{\mathrm{runoff},t} = q_{\mathrm{runoff},t} \times \mathrm{EMC} \tag{10}$$

where $q_{\mathrm{runoff},t}$ is the total runoff input into the river for each rainfall event, EMC is the event mean concentration at the catchment outfall, representing a comprehensive flow-weighted runoff concentration of various land-use types in the urban catchment area.

During the runoff computation, the continuous runoff process is discretized by the computational time step *dt*. At every time step after the start of the runoff, the accumulated volume from a certain cell is moved in the downstream direction. Therefore, the actual volume from the upstream cell is calculated as a continuity balance among the inflow from the upstream cell, the current rainfall, and the outflow to the downstream cell.

2. Rsults and discussion

2.1 *Model calibration*

2.1.1 Input data

The dry-weather inputs into the model are estimated by using the measured dry-weather flow and the concentration of each point source. Nanfei River is deficient in upstream inflows, because the upstream Dongpu Reservoir serves as the drinking water source for Hefei City. Based on an on-site investigation of Nanfei River, at present, almost all point sources previously discharging into the river are intercepted into the developed sewer pipes, and therefore, the dry-weather flow inputs into the model are mainly from the effluents of two WWTPs (the Wangtang WWTP and the Wangxiaoying WWTP). The recorded WWTP discharge is approximately 2.08 m^3/s and 3.47 m^3/s for the Wangtang WWTP and the Wangxiaoying WWTP, respectively, producing a total pollutant input of 4 944 t/a, 1 497 t/a, and 508 t/a for the COD, the BOD_5, and the NH_3-N, respectively.

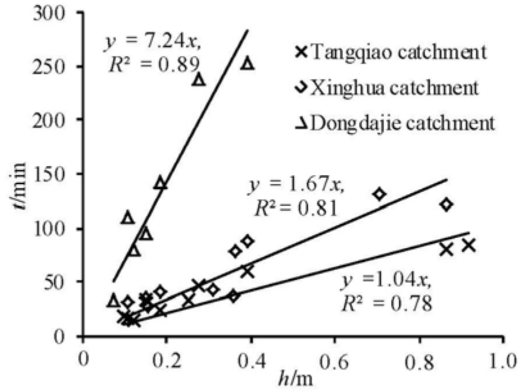


Fig.4 Time of concentration versus rainfall for the urban drainage systems with pumping/gravity discharge in this study area

The wet-weather inputs into the model are based on the product of the runoff volumes and the event mean concentration (EMC) values. As discussed above, the time-related runoff volume discharging into the river is related to the hydrological reduction factor (i.e., the impervious area), the runoff interception ratio, the time of concentration, and the time–area curve. Especially in view of the fact that the artificial operation of the urban drainage system (e.g., the discharge pumping system) may alter the natural hydrologic processes from the most distant part to the point of outflow, the time of concentration needs to be determined based on the measured data in the drainage systems. The time of concentration of the pumping discharge system (i.e., the Xinghua and Tangqiao catchment) and the gravity discharge system (i.e., the Dongdajie catchment) in the study area is measured and compared in Fig.4, where h represents rainfall of each event. For a better comparison, the concentration time of each drainage system is expressed in minutes per square kilometer. Figure 4 shows that the concentration time of the drainage system with the pumping discharge is less than that with the gravity discharge. Specifically, the concentration time under the pumping discharge is approximately 0.1-0.2 times that of the data for the gravity discharge. For example, for a rainfall event of 0.025 m, the concentration time under the pumping discharge is approximately 26 min/km^2-42 min/km^2, whereas the concentration time under the gravity discharge is up to 181 min/km^2. Therefore, a significant difference in the concentration time occurs between the catchments under the pumping discharge and under the gravity discharge, where the pumping facility operations obviously shorten the hydrologic process for urban catchments.

The EMC values of the urban catchments are determined based on the monitoring activities conducted by the authors, consisting of the samples collected at the outlets of several typical combined sewer systems and separate storm sewer systems in the study area. Specifically, the monitoring activities lasted one year, aiming to cover a set of rainfall scenarios, namely, the light rain $(< 0.010\ m)$, the moderate rain (0.010 m-0.025 m), the heavy rain (0.025 m-0.050 m), and the storm events $(> 0.050\ m)$. The monitored values for the catchments are summarized in Table 2.

For the two combined sewer systems monitored, the EMC value of the Xinghua system is larger than that of the Dongdajie system. This is related to the in-pipe sediment erosion due to the wet-weather storm pump operations in the Xinghua system. Usually, the combined sewer pipes should be larger to accommodate the storm flow, which means that they are often oversized for the entered sewage flow, with low velocities that allow the sediments to accumulate. When the storm pump starts on wet-weather days, the sediments retained in the sewer pipes are flushed out, leading to increased COD and BOD_5 associated with the sediments. The separate storm sewer systems with the pumping discharge or the gravity discharge see a similar situation. Table 2 also shows that for the two separate storm sewer systems with the pumping discharge, the EMC value of the Xiliying system is significantly larger than the data of the Tangqiao system. This can be explained by the dry-weather pollutant entries into the storm drains of the two systems. Specifically, the dry-weather pollutant entries into the storm drains of the Xiliying system are larger than the entries into the storm drains of the Tangqiao system, resulting in a relatively larger EMC concentration in the former system. Based on the above discussions, the EMC values

Table 2 EMC values for the studied catchments

System mode	System name	Discharge mode	EMC/mg·L^{-1}			Other catchments corresponding to the monitored data
			COD	BOD$_5$	NH$_3$-N	
Combined sewers	Xinghua	Pumping discharge	145-402	46.3-128	10.1-19.0	Xioyaojin
	Dongdajie	Gravity discharge	93-376	30.4-123	7.9-19.3	
Separate sewers	Xiliying	Pumping discharge	148-363	48.6-119	9.2-19.3	Hupuoshanzhuang
	Tangqiao	Pumping discharge	49-267	22.6-101	6.9-20.0	Changfeng Rd., Shanghe, Fenghuangqiao, Chiying, Shijia River
	Sili River	Gravity discharge	56-218	20.6-81	4.2-13.0	Sili River, Banqiao River, Erli River

of other catchments could be determined by comparing these catchments with the monitored catchments from the perspective of the system mode, the discharge mode, and the extent of the non-storm water entries with inappropriate entries into the storm drains in the separate storm sewer systems, as shown in Table 2.

2.1.2 Model calibration results

The water quality model calibration is performed in the following steps: (1) input the upstream/downstream hydrological conditions, and the point/nonpoint source lateral inflow, to simulate the hydrodynamic patterns within the river with the Saint-Venant equation, (2) input the point and nonpoint source pollutant load and the water quality parameters to simulate the temporal and spatial water quality variations over the river, (3) compare the observed and the simulated river water quality concentrations and adjust the model parameters when necessary.

The calibration approach is based on the monthly average values derived from the real-time simulation against the observed values. Statistical criteria commonly used for the model evaluation are the percent bias (PBIAS) and the coefficient of determination (R^2). The percent bias and the coefficient of determination can be calculated as follows:

$$\text{PBIAS} = \frac{\sum_i^n (O_i - P_i)}{\sum_i^n O_i} \times 100 \tag{11}$$

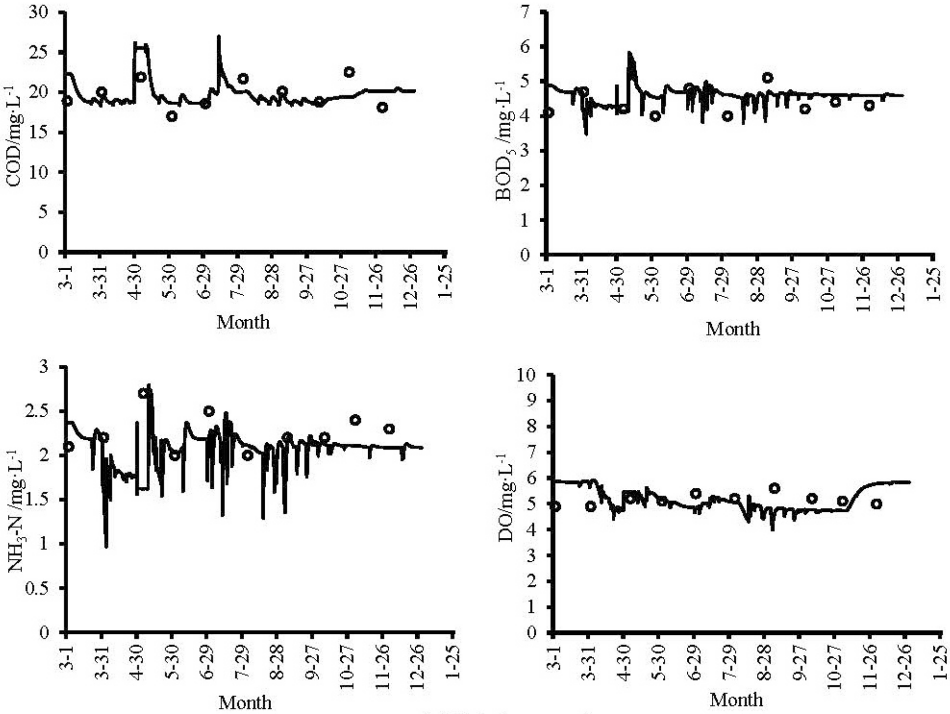
$$R^2 = \left\{ \frac{\sum_{i=1}^n (O_i - \overline{O})(P_i - \overline{P})}{[\sum_{i=1}^n (O_i - \overline{O})^2]^{1/2} [\sum_{i=1}^n (P_i - \overline{P})^2]^{1/2}} \right\}^2 \tag{12}$$

where Q_i is the observed monthly values for the i-th month, P_i is the simulated monthly values for the i-th month, $\overline{O}$ is the mean of the observed monthly values, $\overline{P}$ is the mean of the simulated monthly values, and N is the total number of months.

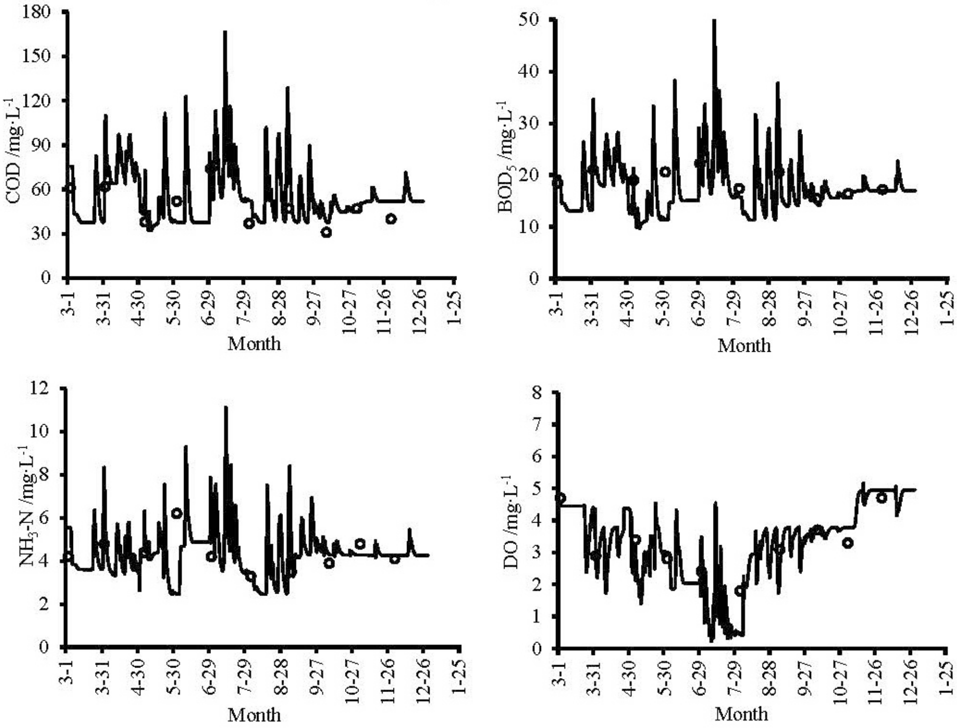
Typically, a satisfactory model performance is achieved when the coefficient of determination is above 0.6 for the monthly simulated constituents, however, a value of 0.5 is still acceptable[16-18]. With regard to the PBIAS, the performance is considered very good for values less than 15%, good for values between 15% and 25%, and satisfactory for values between 25% and 35%.

As mentioned above, the model is calibrated for the following water quality parameters: the dissolved oxygen (O_2), the biochemical oxygen demand (BOD$_5$), the chemical oxygen demand (COD), and the ammonia nitrogen (NH$_3$-N). For the 2010 water quality sampling campaign, a comparison between the modeled and the observed data at two typical stations (i.e., the Xixinzhuang and Dangtu Road stations) is shown in Fig.5. Of the two stations, the Xixinzhuang station represents the background water quality of the river; the Dangtu Road station is the downstream boundary of the modeled river reach, which represents the water quality response to the total point source and nonpoint source pollutant inputs into the river.

Using the model performance criteria, it is found that: (1) at the Xixinzhuang station, PBIAS is 8.1%, 9.0%, 10.5%, and 9.1% for the COD, the BOD$_5$, the NH$_3$-N, and the DO, respectively, and R^2 is 0.65, 0.50, 0.59, and 0.52, respectively, (2) at the Dangtu Road station, PBIAS is 19.8%, 26.3%, 17.6%, and 21.1% for the COD, the BOD$_5$, the NH$_3$-N, and the DO, respectively, and R^2 is 0.74, 0.54, 0.55, and 0.52, respectively. Every coefficient falls within a satisfactory range of the model performance. This shows that the developed modeling approach is well suited for the urban rivers with point source pollutants as well as nonpoint source pollutants from the urban catchments, where the urban drainage system alters the natural hydrologic process of the surface runoff (e.g., through shortened runoff concentration time due to pumping



(a) Xixinzhuang station



(b) Dangtu road bridge station

Fig.5 Model calibration results in terms of COD, BOD_5, NH_3-N, and DO for the 2010 campaign

discharge in wet-weather days, and increased wet-weather discharge concentration due to dry-weather in-pipe sediment deposition and wet-weather sediments being flushed away by storm pump operations).

Based on the modeling calibration, the modeling parameters are suggested as shown in Table 3.

2.2 *Assessment of river restoration measures*

2.2.1 Estimation of water pollutant discharge into the river

Once calibrated, the model can be used to evaluate the impact of the point and nonpoint sources on the

Table 3 Suggested values of the modeling parameters

Parameters	Value
First-order decaying coefficient of COD (k_{COD} /d)	0.05
First-order decaying coefficient of BOD$_5$ (k_{BOD} /d)	0.07
First-order decaying coefficient of ammonia (k_{nit} /d)	0.05
Temperature coefficient of COD (θ_{COD})	1.04
Temperature coefficient of BOD$_5$ (θ_{BOD})	1.04
Temperature coefficient of ammonia (θ_{nit})	1.04
Critical dissolved oxygen concentration for BOD$_5$ degradation ($\mathrm{DO}_{\mathrm{BOD}}^{\mathrm{Cr}}$ /mg·L^{-1})	0.5
Optimum dissolved oxygen concentration for BOD$_5$ degradation ($\mathrm{DO}_{\mathrm{BOD}}^{\mathrm{opt}}$ /mg·L^{-1})	6
Critical dissolved oxygen concentration for ammonia nitrification ($\mathrm{DO}_{\mathrm{nit}}^{\mathrm{Cr}}$ /mg·L^{-1})	0.5
Optimum dissolved oxygen concentration for BOD$_5$ degradation ($\mathrm{DO}_{\mathrm{nit}}^{\mathrm{opt}}$ /mg·L^{-1})	6
Atmospheric re-aeration coefficient (k_{rear} /d)	0.2
Saturation oxygen concentration ($\mathrm{DO}_{\mathrm{sat}}$)	$O_s = 14.55 - 0.3822T + 0.005426T^2$
Temperature coefficient of dissolved oxygen (θ_{rear})	1.02
Sediment oxygen demand (SOD/g·(m^2·d)$^{-1}$)	1.0-2.0
Hydrological reduction factor (a)	0.3-0.4
Portion of urban runoff intercepted into WWTP for the combined sewers (β)	0.15
Pre-defined time–area curve under pumping discharge	Divergent
Pre-defined time–area curve under gravity discharge	Rectangular

Note: T is temperature.

Table 4 Estimated nonpoint source pollutant inputs into Nanfei River

No.	Nonpoint source	COD/ t·a^{-1}	BOD$_5$/ t·a^{-1}	NH$_3$-N/ t·a^{-1}
1	Sili River	311	94	13.7
2	Banqiao River	467	141	20.5
3	Changfeng Road	98	37	6.7
4	Hupuoshanzhaung	155	51	8.5
5	Xinghua	418	133	22.4
6	Xiaoyaojin	137	44	7.3
7	Dongdajie	234	76	18.2
8	Shuanghe	88	33	6.0
9	Fenghuangqio	31	12	2.1
10	Shijia River	794	301	54.3
11	Chiying	84	32	5.7
12	Tangqiao	498	189	34.1
13	Xiliying	490	161	26.9
14	Erli River	946	285	41.5
	Total	4 751	1 588	268

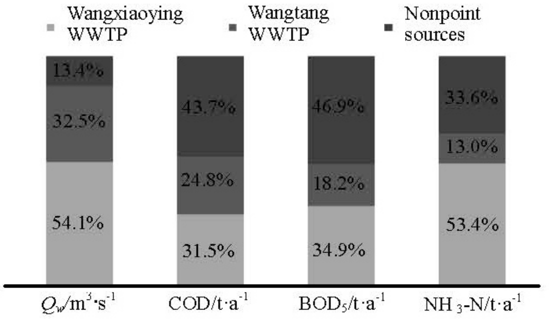
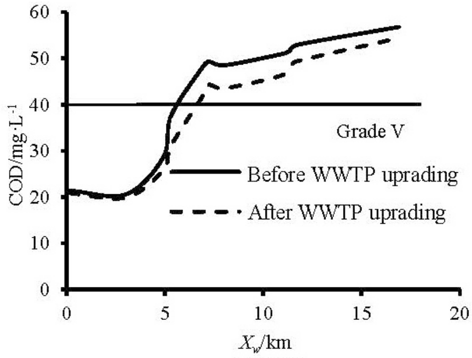
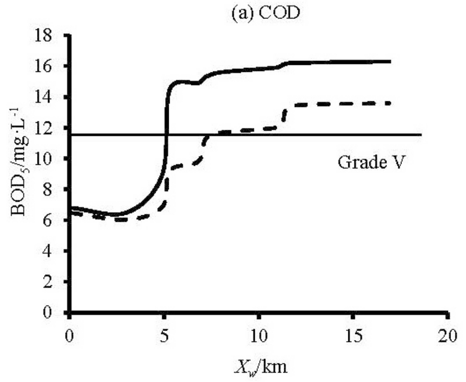


Fig.6 Quantification of point and nonpoint source inputs into Nanfei River

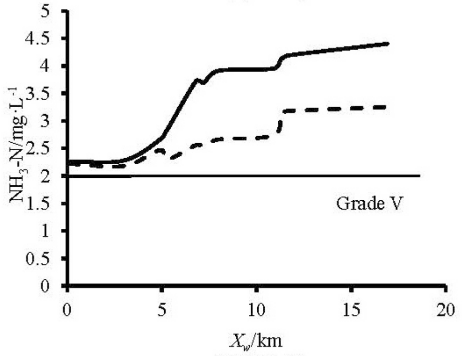
river for the entire simulation period. Estimations of the nonpoint source pollutant inputs into the river are shown in Table 4, and the comparison between the point source and nonpoint source inputs into the river are shown in Fig.6. In this figure, Q_w represents the ratio of two WWTPs and non-point source discharge into Nanfei River. It can be seen that with the flow contributions of 86.6%, the two WWTPs are the dominant sources, however, the nonpoint sources from the catchments contribute 43.7% of the COD, 46.9% of the BOD$_5$, and 33.6% of the NH$_3$-N loads despite their low flow component of 13.4%. Therefore, much attention should be paid to the water pollutant abatement of the point sources as well as the nonpoint sources.



(a) COD



(b) BOD_5



(c) NH_3-N

Fig.7 Predicted water quality over the whole urban reach of Nanfei River

2.2.2 Water quality response to water pollutant abatement schemes

(1) Water quality response to point source pollutant abatement

In view of the fact that the dry-weather inflow is basically from the WWTP in this case, the water quality improvement of the river depends on the upgrading of the two WWTPs. According to the local plan, the wastewater discharge standard of the two WWTPs will be upgraded to Grade IV of China's National Surface Water Quality Standard (GB3838-2002). Specifically, the COD of the WWTP effluent will be lowered from approximately 35 mg/L to 30 mg/L, the BOD_5 of the WWTP effluent will be lowered from approximately 10.3 mg/L to 6 mg/L, and the NH_3-N of the WWTP effluent will be lowered from approximately 3.0 mg/L to 1.5 mg/L.

Using the calibrated model, the prediction of the annually averaged water quality over the whole urban reach shows that the COD, the BOD_5, and the NH_3-N will be improved by 9.4%, 24.6%, and 31.6%, respectively, as shown in Fig.7. In this figure, X_w represents the longitudinal distance down the Dongpu Reservoir. However, the river water quality still does not meet the designated water-use objective (i.e., Grade V of China's National Surface Water Quality Standard, GB3838-2002). Therefore, the abatement of the nonpoint source pollutants from the urban catchments should be further considered.

(2) Water quality response to nonpoint source pollutants abatement

With the designated water-use objective in mind, the overall allowable water pollutants received by the river can be estimated by using the following equation[19]

$$W_L = Q_0(C_S - C_0) + \sum_{i=1}^{m} q_i(C_S - C_0') + \sum_{j=1}^{n} kV_j C_S \qquad (13)$$

where W_L is the allowable water environmental capacity under the designated water-use objective, Q_0 is the upstream inflow, C_s is the critical value of the water quality constituents for the designated water-use objective, C_0 is the background concentration of the water quality constituents in the upstream inflow, C_0' is the background concentration of the water quality constituents in the side discharge, m is the number of side discharges, q_i is the side discharge of the i-th source, V_j is the volume of the river segment j, and n is the number of river segments.

In this equation, the first and second items on the right represents the water environment capacity due to the water discharge dilution, the third item on the right represents the capacity due to the chemical and biological degradation within the river, and the degradation coefficients are determined based on the calibrated model[20,21]. In this case, as there is almost no upstream inflow, Eq.(13) can be simplified as follows

$$W_L = \sum_{i=1}^{m} q_i(C_S - C_0') + \sum_{j=1}^{n} kV_j C_S \qquad (14)$$

After the two WWTPs are upgraded to Grade IV of China's National Surface Water Quality Standard, both the water flow dilution capacity raised by the WWTP effluents and the degradation capacity within the river urban reach are available. Therefore, the abatement of the nonpoint source pollutants to meet the designated water-use can be estimated as follows

$$P=\frac{W_{NP}-W_{NP,A}-W_L}{W_{NP}} \tag{15}$$

where W_{NP} is the actual total nonpoint source pollutant input into Nanfei River's urban reach, $W_{NP,A}$ is the allowable total nonpoint source input corresponding to the specified water-use objective, $W_{NP,A}=q_{\text{runoff},A}C_s$, $q_{\text{runoff},A}$ is the estimated total catchment runoff input into the river, and P is the percentage of the nonpoint source pollutants to be cut off for meeting the specified water-use objective.

Table 5 Abatement of nonpoint source pollutants for the attainment of the water-use objective

	COD/ $\text{t}\cdot\text{a}^{-1}$	BOD_5/ $\text{t}\cdot\text{a}^{-1}$	NH_3-N/ $\text{t}\cdot\text{a}^{-1}$
Dilution capacity	1 750	700	88
Degradation capacity	621	217	31
Total water environment capacity	2 371	917	119
Nonpoint source pollutant input	4 751	1 588	268
Allowable nonpoint source input	1 087	272	54
Percentage of nonpoint pollutants to be reduced	27.2%	25.1%	35.3%

Table 5 shows the estimated allowable maximum pollutant inputs into Nanfei River's urban reach under the designated water-use of Grade V and the planned WWTP effluent of Grade IV. Correspondingly, the nonpoint source pollutants from the urban catchments will be reduced by 27.2%, 25.1%, and 35.3% for the COD, the BOD_5, and the NH_3-N, respectively.

3. Conclusions

An integrated catchment and water quality model for urban rivers is developed and successfully calibrated using the water quality data collected for a period of almost one year, from Nanfei River in Heifei City of China's Caohu Lake watershed. It is shown that the model can be used to predict the water quality under different scenarios (i.e., the impact of the point and nonpoint sources and the maximum load assessments) in the urban catchments. Unlike other models that often simulate the rainfall-runoff and the receiving water quality processes in the rural area of the watershed scale, the developed model here is typically efficient for simulating the water quality response to the nonpoint source pollutants from urban drainage systems, where the natural hydrological process is disturbed due to the artificial discharge pumping operations in wet-weather periods.

The results from the model show that the nonpoint source pollutants play an important role in the pollution in Nanfei River. Specifically, the nonpoint pollutants from the 14 catchments contribute 34%-47% of the total pollutant inputs (i.e., the COD, the BOD_5, and the NH_3-N) throughout one year, despite their low flow component of 13.4%. Even if the WWTP effluent is upgraded to Grade IV of China's National Surface Water Quality Standard, the river water quality indicators for the COD, the BOD_5, and the NH_3-N are found still above the maximum recommended values (i.e., Grade V of Surface Water Quality Standard), due to the excess input of the nonpoint pollutants. An average reductions of 27.2%, 25.1%, and 35.3% of the COD, the BOD_5, and the NH_3-N loads from the urban catchments are necessary to comply with the designated surface water quality standards. Measures to alleviate the nonpoint loads may include the source control actions (e.g., low-impact design), the incipient sewer overflow pollution control using storage facilities, and the clean-up of in-pipe sediments during dry-weather periods. Generally speaking, the results indicate that the integrated catchment and water quality model could provide a basis for decision support actions for the river water quality restoration and protection, particularly in urban areas where the nonpoint loadings from the drainage systems are above the allowable limits.

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