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Water Quality Evaluation in Tidal River Reaches of Liaohe River Estuary, China Using a Revised QUAL2K Model

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Abstract: Rivers in the Liaohe River Estuary area have been seriously polluted by discharges of wastewater containing petroleum pollutants and nutrients. In this paper, The Enhanced Stream Water Quality Model (QUAL2K) and its revised model as well as One-dimensional Tide Mean Model (1D model) were applied to predict and assess the water quality of the tidal river reach of the Liaohe River Estuary. Dissolved oxygen (DO), biochemical oxygen demand (BOD_5), ammonia nitrogen (NH_3-N) and total phosphorus (TP) were chosen as water quality indices in the two model simulations. The modelled results show that the major reasons for degraded rivers remain petroleum and non-point source pollution. Tidal water also has a critical effect on the variation of water quality. The sensitivity analysis identifies that flow rate, point load and diffuse load are the most sensitive parameters for the four water quality indices in the revised QUAL2K simulation. Uncertainty analysis based on a Monte Carlo simulation gives the probability distribution of the four water quality indices at two locations (6.50 km and 44.84 km from the river mouth). The statistical outcomes indicate that the observed data fall within the 90% confidence intervals at all sites measured, and show that the revised QUAL2K gives better results in simulating the water quality of a tidal river.

Keywords: tidal river reach; water quality evaluation; revised QUAL2K model; uncertainty analysis; Liaohe River Estuary

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1 Introduction

River water-related environmental problems have caused widespread concern, and the evaluation of water quality has thus become a primary objective in river basin management. In this context, river water quality modelling has become increasingly recognised as an important tool owing to its valuable information for effective water management. Various types of water quality models have been developed during the last few decades. Some of them can be applied to simulate river water quality. The widely used framework for shallow stream systems is the steady-state models, such as Streeter-Phelps model (S-P model), the Enhanced Stream Water Quality Model (QUAL) series. The S-P model (Streeter and Phelps, 1925) is a classical water quality model that was derived to study the oxygen levels in surface waters. QUAL assumes that the major transport mechanisms, advection and dispersion, are significant only along the main direction of flow (Park and Lee, 2002). Dynamic models include Water Quality Analysis Simulation Program (WASP), Hydrodynamic and Water Quality Model (CE-QUAL-W2), Water Quality for River-Reservoir Systems (WQRRS), *etc*. For example, CE-QUAL-W2 is

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a two-dimensional (2D), longitudinal/vertical, hydrodynamic water quality model for surface water systems (Ostfeld and Salomons, 2005). Some of the models are complicated, whereas others are rather simple (Cox, 2003; Lindenschmidt, 2006). The complex 2D or 3D models are not easy to perform and involve a number of specific parameters that are difficult to measure. Parsimonious models can not describe the processes of intricate hydrodynamics, so their simulated results might not be reliable. Given these circumstances, the one-dimensional (1D) water quality models have been widely accepted where simulated data are limited (Mahamah, 1998). As a 1D model, QUAL2K is one of the best tools for water quality simulations due to its flexibility, ease of use and free availability.

QUAL2K is a United States Environmental Protection Agency (USEPA)-sponsored river and stream water quality model that can simulate various water quality parameters in dendritic streams that are well mixed laterally and vertically (Chapra and Pelletier, 2003). It is an updated version of QUAL2E (Brown and Barnwell, 1987) with several modifications to solve previous problems (Park and Uchrin, 1997; Pelletier *et al*., 2006). QUAL2K allows for multiple waste discharges, withdrawals, tributary flows and incremental inflow and outflow. It can simulate up to 15 water quality constituents in any combination. Numerous typical applications of the model have been developed and utilized to various river systems in many countries (Carroll *et al*., 2006; Kannel *et al*., 2007a). Fan *et al*. (2009) acquired excellent simulation results by using QUAL2K and Hydrologic Engineering Center's River Analysis System (HEC-RAS) integration to assess the impact of tidal effect. In the present study, the study reach simulated is a dendritic tidal river that has a steady current and the transport is dominated by longitudinal changes. Thus, the assumptions of 1D process are reasonable. In addition, the available data for model simulation are very scarce. For these reasons, QUAL2K is chosen as an appropriate model of water quality simulation.

Models are always simplifications of the real systems. Modelling is subject to uncertainties from model structure, hydrological inputs and a host of other input and neglected parameters (Tao, 2008). Even if input data reflect, or are at least representative of, conditions believed to be true, the simulated results may be inaccurate. Furthermore, modellers rarely know input parameters with exact certainty (Brown and Barnwell, 1987). Therefore, uncertainty analysis helps to elucidate the linkages between input and output values and demonstrates the reliability of predicted results (Paliwal *et al*., 2007).

In this study, we aim to simulate and evaluate water quality in the tidal river reach of the Liaohe River Estuary area employing QUAL2K model (USEPA, 2009), its revised model as well as One-dimensional Tide Mean Model (Xie, 1996), and to realise the performance of the revised QUAL2K. We tend to acquire critical factors affecting water quality using sensitivity analysis, and examine the accuracy of simulated data using uncertainty analysis. This study will provide an important foundation for exploring the relationship between water quality and pollution control strategies in future work.

2 Materials and Methods

2.1 Study area

The Liaohe River Estuary area is located at the north part of Liaodong Bay, Bohai Sea, and in the southeastern part of the Liaohe River Basin that has a watershed of 2.19×10^5 km^2 and is 1430 km in length (Liu *et al*., 2008). This area is not only an important base for petroleum exploitation and chemical industry, but also a major base for paddy planting and aquaculture. Point- and non-point pollution sources have resulted in serious deterioration of river water quality due to discharging from petroleum enterprises, residents, and farming activities (Zhang, 2006; Wang *et al*., 2009). The water quality of the estuary area has been markedly degraded, which exerts tremendous adverse effects on ecological development and severely threatens the environment of vicinal sea area of Liaodong Bay.

The study area is a typical dendritic river system (Fig. 1). There are six major tributaries that join the main stem of the Liaohe River. The river sluice at Hezha, which is 44.84 km from the river mouth, was built in 1968 to meet the demand for irrigation and fresh water for industry and agriculture. In general, the river sluice is closed during the non-flood season (Liu *et al*., 2003). The estuary area has a normal mixed semi-diurnal tide. The sea tide is arrested by the river sluice. When the sluice is closed, the multi-year average tidal range is 0.74 m at Panshan Hydrology Station (2.52 km below Hezha). The tidal water in the river mouth is an intensified tide with a maximum tidal range of over 4 m (Pan,

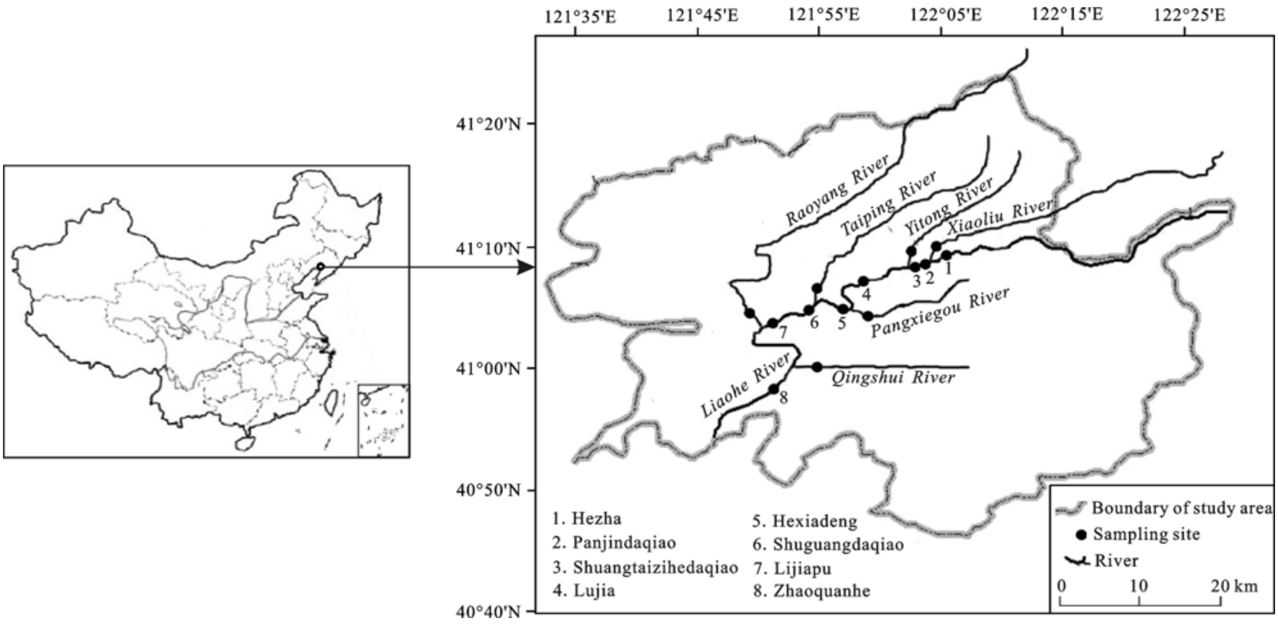


Fig. 1 Study area and sampling sites in Liaohe River Basin, Northeast China

2005; Wu *et al*., 2010). Given this context, the study area covers a tidal river reach of about 45 km in the mainstream from Hezha to the river mouth.

2.2 Methods

2.2.1 Data collection

Some hydraulic parameters required in models, such as river geometries (reach depth and bottom width) and flow rate, were measured in the sites; others, such as pH, electric conduction and water quality indices were analyzed in the laboratory. The meteorological data were obtained from the Meteorology Department of Panjin City, Liaoning Province. DO, BOD_5, NH_3-N and TP were chosen as water quality indices. The water quality data for 2006–2009 were acquired from the Environmental Monitoring Station of Panjin City. To gain more accurate water quality information, sampling campaign (MEP, 2009a; 2009b) was carried out during April and November 2010. The 14 locations (Fig. 1) were chosen as the sampling sites. The sampling events were scheduled to monitor critical low flows.

Water samples were collected (MEP, 2009b), transported and analysed by standard methods (SEPA, 2002). DO was measured *in situ* by using a portable probe and by iodimetry in the laboratory. BOD_5, NH_3-N and TP were tested in the laboratory. BOD_5 concentration was determined by measuring the decreases in oxygen concentration during a 5-day incubation at 20℃. NH_3-N concentration was determined by Nessler′s reagent colourimetric method. TP concentration was determined after converting total phosphorus compound into phosphates by oxidising and decomposing organic matter and was quantified colourimetrically by the ascorbic acid reduction method using a calibration curve (Ghosh and Mcbean, 1998; Kannel *et al*., 2007b).

2.2.2 QUAL2K model and predicted method

QUAL2K has a general mass balance for a constituent concentration (C) in river as (Chapra and Pelletier, 2003):

$$\frac{\partial C}{\partial t}=\frac{\partial(AD\frac{\partial C}{\partial x})}{A\partial x}-\frac{\partial(AUC)}{A\partial x}+\frac{\mathrm{d}C}{\mathrm{d}t}+\frac{S_{\mathrm{C}}}{V} \tag{1}$$

where C is the concentration of a constituent; V is the volume of river water; U is the average velocity of river water; D is the dispersion coefficient; A is the estuary cross-sectional area; S_C is the external sources or sinks of the constituent; t is the time in days; x is the distance of a river reach (in the direction of flow).

The basic equation solved by QUAL2K is a 1D advection-dispersion mass transport equation, which is numerically integrated over space and time for each water quality constituent. This equation includes the effects of advection, dispersion, dilution, constituent reactions and interactions, and sources or sinks.

For the prototype representation of river reaches, the river was discretised according to its hydraulic properties. The total study length of the Liaohe River, 45 km, was divided into eight reaches and further subdivided into 45 computational elements with length of 1 km each. Tributaries were not modelled explicitly, but can be identified as point sources. The measured river geometry was used to determine the hydraulic characteristics in each reach using the trapezoidal method. The velocity, cross-sectional area and depth were computed by using the Manning equation. Detailed descriptions of the above methods are provided in full in the QUAL2K user's manual (Chapra *et al.*, 2007).

The above-mentioned four indices were simulated with QUAL2K based on the pollution characteristics and valuation requirements. QUAL2K was calibrated and verified by using average spring and fall conditions during 2006–2009. Monitoring data in 2010 and average data during 2006–2010 were compared with simulation results in this study. In addition, river water quality was simulated by using QUAL2K without considering the tidal effect in order to investigate the influence extent of the tide. Model parameters were obtained from various published studies and some parameters were set as defaults in QUAL2K (Chapra *et al.*, 2007; Cho and Ha, 2010). The model was run when the input conditions met the demands of the simulation. The model was continually calibrated by adjusting the system parameters appropriately until the reasonable agreement between model-predicted results and field measurements was obtained.

2.2.3 Revised QUAL2K model

To simulate water quality, the flow velocity and water depth are required. They can be calculated by using Manning equation in QUAL2K model. It is hypothesized that each reach in the river is idealized as a trapezoidal channel. Under conditions of steady flow, the Manning equation can be used to express the relationship between flow and depth as (Chapra *et al.*, 2007):

$$Q = \frac{S_0 A}{nP} \tag{2}$$

where Q is the flow of river water; S_0 is the bottom slope of a trapezoidal channel; n is the Manning roughness coefficient; P is the wetted perimeter.

The cross-sectional area of a trapezoidal channel is computed as (Chapra *et al.*, 2007):

$$A = [B + 0.5(S_1 + S_2)H]H \tag{3}$$

where B is the bottom width of a trapezoidal channel; S_1 and S_2 are the two side slopes of a trapezoidal channel; H is the depth of river water.

The wetted perimeter is computed as (Chapra *et al.*, 2007):

$$P = B + H\sqrt{S_1^2 + 1} + H\sqrt{S_2^2 + 1} \tag{4}$$

The flow velocity can then be determined from the equation (Chapra *et al.*, 2007):

$$U = \frac{Q}{A} \tag{5}$$

The calculated results of some hydraulic parameters may be inaccurate in the tidal river, because QUAL2K does not consider tidal effect in its calculations (Fan *et al.*, 2009). Therefore, the tidal level was chosen to evaluate the influence of tidal effect in this study. Given the assumption that river and tidal water were totally mixed, the average tidal level (1.55 m above mean sea level) in the river was selected because the water quality monitoring data were obtained under average tidal conditions. Due to the revised water depth when the tidal level was included, other relative hydraulic parameters, such as Q, A, P, U, within the tidal section were re-calculated by applying the Manning equation.

2.2.4 One-dimensional Tide Mean Model (1-D Model)

When the change of one tidal cycle ($Q = A \cdot U$) is considered, the 1-D model is described by (Xie, 1996):

$$\frac{\partial(AC)}{\partial t} = \frac{\partial(AD\frac{\partial C}{\partial x})}{\partial x} - Q\frac{\partial C}{\partial x} - KC + S_C \tag{6}$$

where K is the mass decay rate.

Dispersion can not be neglected because it is an important companion factor during the migration process of pollutants in estuary areas with tidal effects. The dispersion coefficient D is determined by a trace method where salinity is identified as a trace agent and its values are based on actual measurements. Accordingly, the equation can be rewritten as (Xie, 1996):

$$\frac{\partial S}{\partial t} + U\frac{\partial S}{\partial x} = D\frac{\partial^2 S}{\partial x^2} - KS \tag{7}$$

where S is the salinity.

Using this model, simulated results were compared with monitoring data and the results of the revised QUAL2K. The source of data and predicted methods of

1-D model referred to the above correlative content of QUAL2K.

2.2.5 Similar coefficient method

The similar coefficient method (angular cosine method) was used to compare the approach degree between the observed values and the predicted values.

The angular cosine method is described by (Mei and Zhou, 2002):

$$\cos\alpha = \frac{\sum_{k=1}^{n} X_k Y_k}{\sqrt{(\sum_{k=1}^{n} X_k^2)(\sum_{k=1}^{n} Y_k^2)}} \tag{8}$$

where α is the angular; X_k is the observed data; Y_k is the predicted data; k is the quantity of data.

When two experimental results are identical, $\cos\alpha = 1$; or else $\cos\alpha = 0$.

2.2.6 Sensitivity analysis method

The sensitivity coefficient of any water quality parameter can be calculated by using the following formula (Parvathinathan, 2002; Palmieri and de Carvalho, 2006):

$$S_{ij} = (\frac{\Delta Y_j / Y_j}{\Delta X_i / X_i}) \tag{9}$$

where S_{ij} is the sensitivity coefficient for output Y_j to input X_i; X_i is the base value of input variable i; ΔX_i is the magnitude of input perturbation i; Y_j is the base value of output variable j; ΔY_j is the sensitivity of output variable j.

2.2.7 Uncertainty analysis method

Uncertainty analysis in this study was performed by applying a Monte Carlo simulation that is used for numerically examining a complex system. The technique was used to simulate water quality parameters from the given set of input parameters. Input variables were sampled randomly from predetermined probability distribution and the model was simulated to give different outputs for each sample selected (Caviness *et al.*, 2006; Kim and Je, 2006). The different outputs were statistically analysed to evaluate the uncertainty of model predictions.

Here we used a Monte Carlo simulation to determine the probability distribution and confidence intervals of the predicted values (Shen *et al.*, 2008) and evaluate the feasibility of the revised QUAL2K. The Monte Carlo simulation included 500 runs of the revised QUAL2K model which generated 500 output values for the four indices.

3 Results and Discussion

3.1 Observed profiles

The observed profiles of water quality at monitoring locations including the mainstream and tributaries in 2010 are shown in Table 1. The average concentration of DO in the mainstream ranges from 0.95 mg/L to 6.80 mg/L, BOD_5 from 3.41 mg/L to 16.60 mg/L, NH_3-N from 4.02 mg/L to 7.49 mg/L and TP from 0.11 mg/L to 0.47 mg/L. As shown in Table 1, water quality is generally good in the upstream area, except for the area around Hezha, but deteriorates seriously below midstream, especially after the confluence with the Pangxiegou River and the Yitong River.

3.2 Simulation results

3.2.1 Predicted profiles

The predicted profiles of the revised QUAL2K and 1-D Model at monitoring locations were calculated and the results are shown in Table 2.

3.2.2 Angular cosine

In Table 3, the angular cosine value of QUAL2K shows its limitation for tidal river although the hydraulic characteristics of the river meet the requirements for QUAL2K simulation. Consequently, it is necessary to improve the properties of QUAL2K by revising some input parameters. Although both the revised QUAL2K and 1-D Model can be applied to simulate water quality well, the modelled results of the former are more accurate than the results of the latter by comparing the cosine values. Therefore, the revised QUAL2K is probably more suitable to simulate the tidal river.

3.2.3 Water quality simulation

The downstream riverbed in the Liaohe River slopes at 1/12000 (Pan, 2005), and the water quality within this section is affected significantly by tide. Tidal water plays an important role in alterations of the concentrations of river pollutants. Figure 2 depicts the variation in water quality using the three models.

As shown in Fig. 2a, DO concentration tends to decline significantly from the headwater. A possible reason is that salinity increase and stratification lead to a decrease of DO. On the other hand, oxygen in the tidal water is greatly depleted because of the discharged pe-

Table 1 Observed profiles of water quality in Liaohe River

Type	Station	Distance (km)	DO (mg/L)	BOD_5 (mg/L)	NH_3-N (mg/L)	TP (mg/L)
Main river	Hezha	44.84	6.80	16.60	4.02	0.47
	Panjindaqiao	42.54	5.54	6.93	4.52	0.33
	Shuangtaizihedaqiao	41.38	5.28	5.67	5.36	0.28
	Lujia	30.74	3.43	4.84	6.52	0.14
	Hexiadeng	26.86	2.87	4.51	5.84	0.23
	Shuguangdaqiao	24.27	1.28	5.23	7.49	0.17
	Lijiapu	18.44	1.12	4.85	6.01	0.11
	Zhaoquanhe	6.50	0.95	3.41	6.57	0.16
Tributary	Xiaoliu River	44.35	12.45	8.24	1.35	0.18
	Yitong River	37.53	9.73	9.87	4.83	0.47
	Pangxiegou River	27.37	7.64	9.27	3.18	0.34
	Taiping River	25.57	16.41	6.53	1.86	0.38
	Raoyang River	16.63	12.85	7.25	1.73	0.14
	Qingshui River	4.86	7.67	8.87	2.57	0.63

Table 2 Predicted profiles of revised QUAL2K and 1-D Model

Distance (km)	Revised QUAL2K (mg/L)				1-D Model (mg/L)			
	DO	BOD_5	NH_3-N	TP	DO	BOD_5	NH_3-N	TP
44.84	7.20	14.34	3.74	0.42	6.92	12.45	4.13	0.40
42.54	5.45	6.66	4.56	0.27	6.24	6.72	4.45	0.31
41.38	5.62	5.24	4.32	0.29	5.26	6.04	4.73	0.26
30.74	3.96	3.82	5.92	0.19	3.83	5.57	5.63	0.20
26.86	2.17	3.45	5.33	0.25	2.75	5.15	5.16	0.24
24.27	1.77	6.24	6.90	0.18	1.55	5.36	7.28	0.15
18.44	1.35	4.17	6.35	0.14	1.48	4.22	6.34	0.18
6.50	1.44	3.82	6.16	0.13	1.93	2.64	5.58	0.18

Table 3 Angular cosine values between observed and predicted data for four indices

Model	DO	BOD_5	NH_3-N	TP
Revised QUAL2K	0.9951	0.9944	0.9976	0.9905
1-D Model	0.9951	0.9860	0.9969	0.9864
QUAL2K	0.9918	0.9325	0.9952	0.9731

troleum pollutants in the river. The above processes result in the formation of a low DO area in the estuary. Owing to abundant oxygen in tidal water, the DO simulated by QUAL2K is lower at the river mouth without considering tidal effect, whereas DO simulated by 1-D Model is slightly higher at the river mouth because of the overestimation of the tidal effects.

From Fig. 2b, BOD_5 decreases sharply in the vicinity of Hezha and then declines slowly downstream. The main reason for this could be due to dilution of organic pollutants by the tide and intensified degradation of organic pollutants. The high BOD_5 at Hezha could be caused by: 1) impoundment during the dry season; 2) scant fresh water below the sluice; and 3) slow degradation of organic pollutants in the above hydraulic condition. The following two effects cause relatively high BOD_5 from Hezha to the 23 km point: First, seriously contaminated tributaries (such as the Panxiegou River and the Yitong River containing a large number of petroleum pollutants) flow into the mainstream along this river stretch. Second, the water body can not be fully self-purifying because the retention time of pollutants in the river is prolonged and substrates are significantly stirred up by the intensified tide. The simulated BOD_5 with the tidal effect considered is lower in the midstream and downstream because organic pollutants are diluted by increased tidal water and their degradation is also intensified due to higher oxygen levels created by the tide.

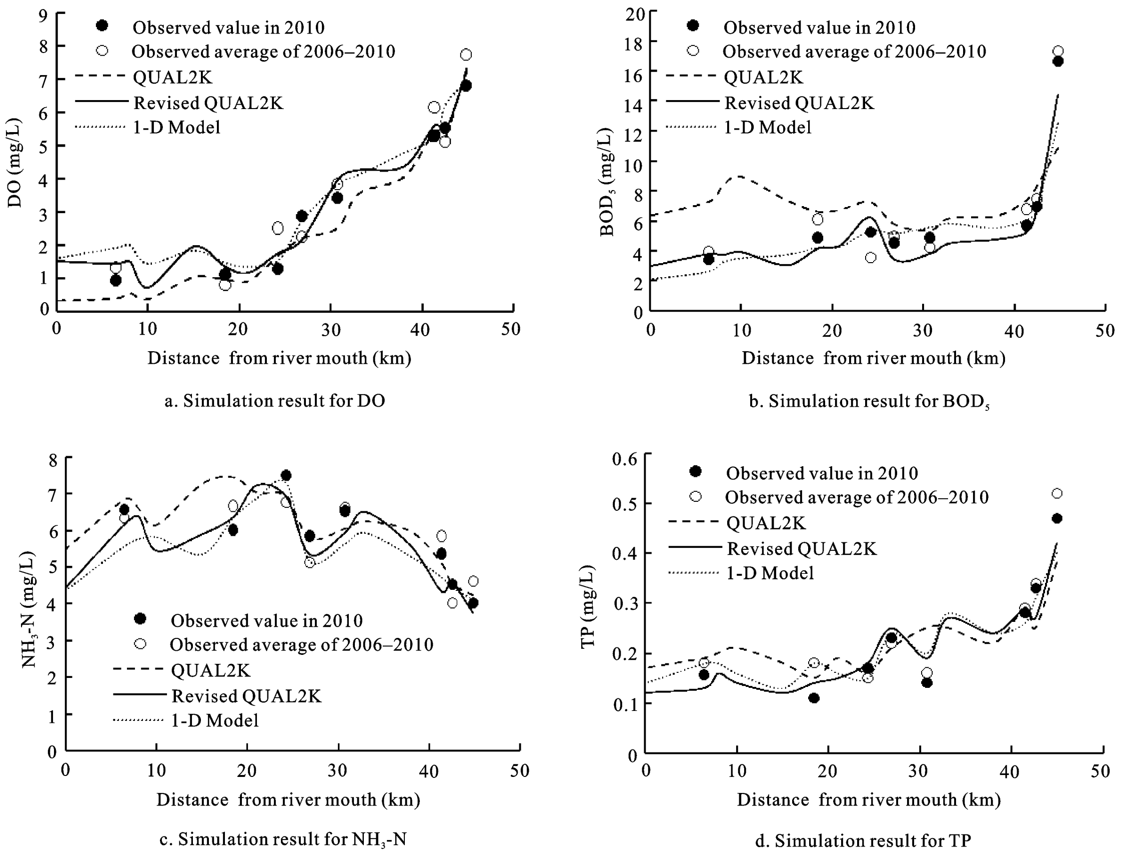


Fig. 2 Simulation results for four indices

Figure 2c shows the variation in NH_3-N concentration. A possible reason for the high NH_3-N in the mid-stretch may be the discharge of agricultural and municipal wastewater. NH_3-N decreases at the river mouth because it is partly oxidised by oxygen in the tidal water.

TP is relatively higher in Hezha because of the non-point source pollution of agricultural and domestic wastewater. TP is usually considered to be the limiting nutrient for aquatic bioactivity, and it is largely removed through biodegradation or sedimentation (Ning *et al.*, 2001; Fan *et al.*, 2009). All of the discharged TP slightly decreases along the river. This explanation is supported by the TP concentration profile shown in Fig. 2d.

Figure 2 illustrates that the simulation results of the revised QUAL2K match the observed data and follow the same trend as 1-D Model and QUAL2K simulations. This tendency proves that the simulation results of QUAL2K and its revised model can reflect the real variation of river water quality though the observed data are limited. The results with tidal effect show better agreement with the observed data, although there is no significant discrepancy between the simulation values with or without tidal effect. Consequently, the simulation results are more accurate when the tidal effect is considered, and the estimation bias with the revised QUAL2K simulation can be reduced. In conclusion, the revised QUAL2K is found to be capable of assessing tidal river water quality of the Liaohe River Estuary.

3.2.4 Sensitivity coefficient

Different sensitivity coefficients for the four water quality indices in the revised QUAL2K simulation were calculated and the results are shown in Fig. 3.

Figure 3a shows that the flow rate, reaeration rate and oxygen consumption rate have marked effects on DO. From Fig. 3b, point load, oxidation rate and settling rate are significant in accurately predicting BOD_5. Diffuse load, nitrification rate and oxidation rate are more sensitive for NH_3-N (Fig. 3c) while diffuse load, settling rate and decay rate are more sensitive for TP (Fig. 3d).

Based on the results of the sensitivity analysis, the most sensitive paremeters for the four indices are the flow rate, the point load and diffuse load. These results also suggest that many of the parameters have little impact on the four water quality indices. The results can provide the basis for water resource agencies to adopt the most appropriate management strategies to reduce the pollution load.

3.3 Monte Carlo simulation

The four indices measured at two locations (6.50 km and 44.84 km from the river mouth) and the output probability distribution were employed to assess the revised QUAL2K performance using 90% confidence intervals (Fig. 4).

Table 4 summarises the statistical results of the predicted ranges of the four indices. There is good agreement between the observed and simulated mean values. The measured data are distributed close to the simulated mean values. Ranges of bias percentage are mostly as low as 1.5% at the two locations. The statistical outcomes suggest that DO, NH_3-N and TP predictions are reliable and BOD_5 results are also acceptable. However, discrepancies between observation and simulation are apparent in certain locations. The Hezha site shows the greatest bias, which may be due to the load fluctuations at that site. The bias for DO and BOD_5 are highest (0.094 and 0.563, respectively) at the 44.84 km location.

The analyzed results demonstrate that the model simulation is robust with very little bias caused by uncertainties of the input variables. The majority of the measured data are consistent with the simulation data, which illustrates that the Monte Carlo simulation method can yield reasonable estimations of the uncertainties. In this regard, Monte Carlo simulation has proved to be a better technique in assisting modellers to ascertain the reliability of data predicted from the re-

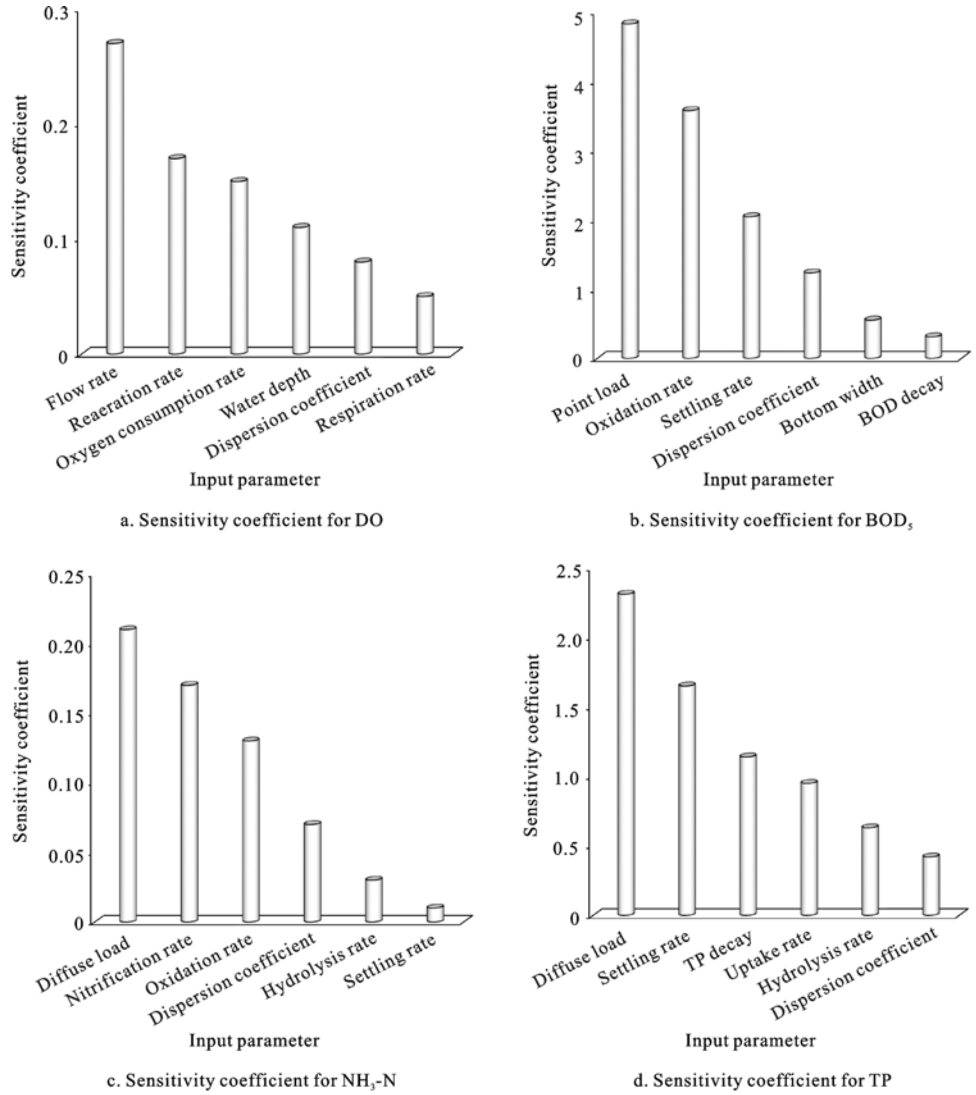
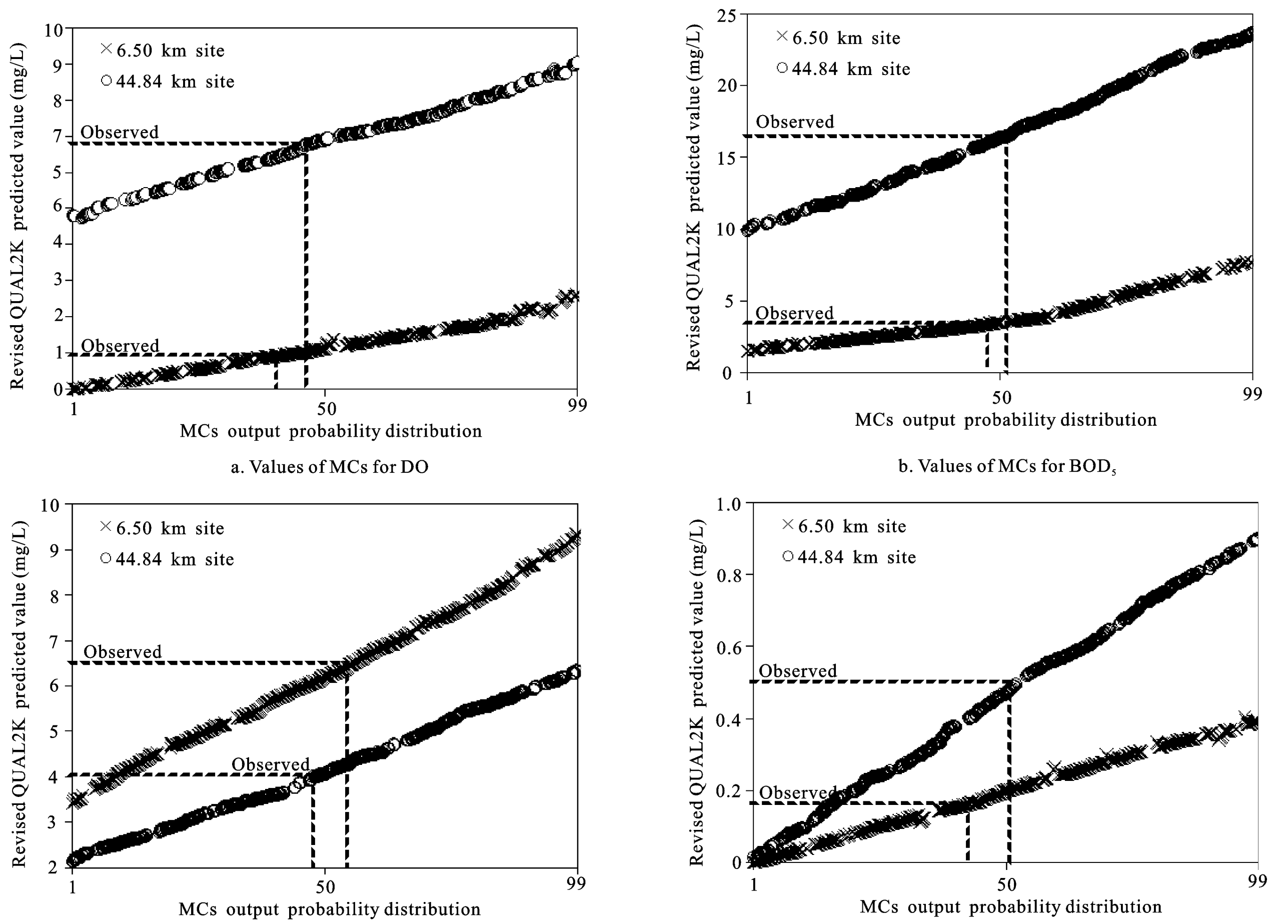


Fig. 3 Sensitivity coefficients for four indices



a. Values of MCs for DO

b. Values of MCs for BOD_5

c. Values of MCs for NH_3-N

d. Values of MCs for TP

MCs is Monte Carlo simulation

Fig. 4 Monte Carlo simulation for four indices

Table 4 Monte Carlo simulations of four indices

Statistic value	Location (6.50 km)				Location (44.84 km)			
	DO	BOD_5	NH_3-N	TP	DO	BOD_5	NH_3-N	TP
Observed (mg/L)	0.953	3.414	6.573	0.164	6.806	16.601	4.023	0.475
Revised QUAL2K predicted (mg/L)	0.962	3.410	6.567	0.178	6.712	16.038	4.019	0.465
Bias	0.009	–0.004	–0.006	0.014	–0.094	–0.563	–0.004	–0.010
Predicted minimum (mg/L)	0.006	1.557	3.430	0.002	4.802	9.901	2.161	0.012
Predicted maximum (mg/L)	2.212	5.723	9.321	0.394	8.933	23.680	6.348	0.901
90% confidence level (mg/L)	0.310–1.904	2.077–5.132	4.352–8.237	0.056–0.341	5.363–8.232	11.643–22.023	2.702–65.705	0.140–0.789

vised QUAL2K. The observed values of the four indices fall within the 90% confidence intervals at each location, which fully verifies that the modelled results of the revised QUAL2K are very reliable for simulating the processes although this model tends to slightly over-predict or under-predict at some locations.

Simulation results indicate that the probability of water quality variables deviating from the observed levels is low, making future scenario predictions more realistic when using the same input parameters. The results also provide information to direct the planning of an efficient monitoring programme for parameters affecting discharge indices, which will greatly reduce model prediction uncertainty.

4 Conclusions

This study simulated water quality indices (DO, BOD_5, NH_3-N and TP) of the Liaohe River with tidal effects using QUAL2K, its revised model as well as 1-D Model. Results based on similar coefficient methods indicate that including tidal effects significantly improves the performance of QUAL2K, and the simulated outcomes of the revised QUAL2K are more accurate than 1-D Model, although both can be applied to simulate water quality. When BOD_5 and TP are simulated, the revised QUAL2K showed better accuracy.

The variation in concentration of DO and NH_3-N shows that the water quality in the tidal river reach gradually, but significantly, deteriorates as it flowed from upstream. The discharge of petroleum and non-point source pollution aggravates river pollution. Flow rate, point load and diffuse load have most effect on the four indices while many other parameters have little impact on the indices in the revised QUAL2K simulation. The observed four indices fall within the 90% confidence intervals at all measured river locations and the ranges of bias percentage are mostly as low as 1.5%. The results of uncertainty analysis verify that the revised QUAL2K is a better model giving simulation data that generally matched the observed data well.

The revised QUAL2K has been proved to be a valuable tool for water quality management of tidal river. The present research results will make prediction more realistic when using the same input parameters and provide a foundation for exploring the relationship between water quality and management strategies in future work.

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