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Study on Practice of Improving Water Quality in Urban Rivers by Diverting Clean Water

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***Abstract*—**With rapid development of industrialization and urbanization, water environmental deterioration is widespread in majority of urban rivers, which seriously affects city image and life satisfaction of residents. As an emergency measure to improve water quality, clean water diversion is introduced for water environmental management. Lubao River and Southwest River, two urban rivers in typical plain tidal river network, are identified as technically and economically feasible for the application of clean water diversion. One-dimensional hydrodynamic-water quality model is developed to simulate temporal and spatial variations of water level and water quality, with satisfactory accuracy. The mathematical model after calibration is applied to investigate hydrodynamic and water quality variations in rivers as well as determine the optimum operation scheme of water diversion. Assessment system is developed for evaluation of positive and negative effects of water diversion, demonstrating the effectiveness of clean water diversion and the necessity of pollution reduction.

***Keywords*—**Assessment system, clean water diversion, hydrodynamic-water quality model, tidal river network, urban rivers, water environment improvement.

I. Introduction

URBAN rivers are of great significance to the construction of an ecological environment in a city. However, with rapid development of industrialization and urbanization, most of urban rivers have been contaminated by domestic and industrial sewage, gradually deteriorating water environment. Improving the landscape and water quality in rivers thus becomes a critical challenge for urban development.

Different from natural river and artificial channel, urban river is characterized by shallow water depth, low flow rate, and few aquatic organisms. Resulting from these particular hydraulic characteristics and discharge of urban wastewater, there is a small environmental capacity and a fragile ecological system in urban rivers [1].

Diverting clean water through the operation of water conservancy facilities, such as sluices and pumping stations, has been proved to be useful for water environmental management, which can not only dilute the contaminated water, but also decrease water age, benefit the oxygenation of water body and degradation of oxygen-consumption pollutants, enhance the self-purification ability in rivers [2]-[6]. Application of clean water diversion requests hydrodynamic condition, abundant water resources and favorable water quality, which can be appropriately met in plain tidal river networks [5], [7]-[10]. Since clean water diversion requires a low investment but responds instantly [4], [11], it becomes an economical supplementary method for pollution treatment and control in river systems.

Clean water diversion has been successfully applied to restoration of eutrophic lakes in many countries, such as the Veluwe Lake in Netherlands [12], the Moses Lake [13]-[15] and the Pontchartrain Lake [9] in the USA, as well as the Taihu Lake [2], [3], [11], [16]-[18] in China. However, clean water diversion has been studied mostly experimentally but seldom theoretically. When practicing this method, the primary problems are how to regulate the discharge schedule of sluices or pumping stations and how to track the effect of improving water quality in real-time. Assessment system for the implementation effects of water diversion has been developed and applied in shallow lakes [2], [3], [13], [17], [19] but still missing in urban rivers.

In this study, taking Southwest River and Lubao River in Foshan City, Guangdong Province, China as examples, a mathematical model is introduced to analyze the responses of hydrodynamic and water quality to several diversion schedules. Different schemes are compared to evaluate their impacts on the surrounding environment, so as to demonstrate the feasibility and effectiveness of clean water diversion and the necessity of pollution abatement. The optimal operation scheme is selected to provide a theoretical basis for the two rivers to maintain a preferable water environment in Foshan City.

II. Study Area

Foshan, a national historical and cultural city in China, plays an important role in the Pearl River Delta Economic Zone. However, Lubao River and Southwest River, two main urban rivers flowing through Foshan, bring negative effects to the urban landscape and comprehensive development, since they were severely contaminated within the past several decades.

The locations of Southwest River and Lubao River are shown in Fig. 1. Lubao River, whose length is about 34 km, originates in Lubao Sluice, flows through Sanshui District and Huadu District, and finally enters into Southwest River in Nanhai District. Southwest River, with a length of 38 km, is the second biggest tributary of the North River. It originates in Southwest Sluice, flows through Foshan and Guangzhou City,

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and finally enters into the Pearl River in Baiyun District, Guangzhou City.

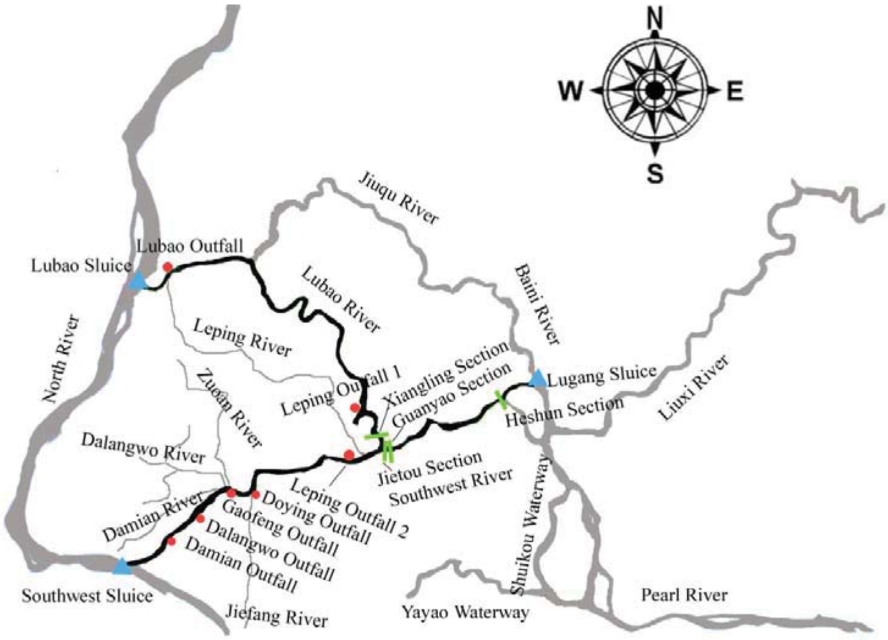

Fig. 1 Locations of Lubao River and Southwest River. The lines shown in dark black are our study area, Lubao River and Southwest River, while the ones shown in gray are the key river network around. The triangular symbols represent the sluices. The circular symbols represent the outfalls along Lubao River and Southwest River. The short line segments represent the sections used for data measurement and validation

Flood discharge used to be the main function of these two rivers, with satisfactory water quality. However, owing to the development of economy, a large amount of domestic, agricultural, and industrial sewage from Sanshui District and Nanhai District is discharged into the rivers, resulting in the excess of phosphorus, ammonia nitrogen (NH_3-N), and chemical oxygen demand (COD). Current social economic condition and urgency of water environmental improvement lead to the necessity of clean water diversion.

According to *The function division of surface water environment in Guangdong Province* [20], the water environmental objective of Southwest River is that the water qualities in the upper reach before Guanyao Section and the lower reach after Guanyao Section should be better than class IV and class III, respectively. (According to *China National Environmental Quality Standards for Surface Water* [21], water quality classification of NH_3-N and COD is shown in Table I.)

Pearl River system is one of the typical plain tidal river networks. The abundant water runoff and comparatively good water quality in the North River, as well as the tidal hydrodynamics in the Pearl River bring feasibility to the practice of clean water diversion. Water is diverted from the North River, through the operation of Lubao Sluice and Southwest Sluice, to dilute the contaminated water and activate water flow. Meanwhile, water could be diverted from downstream reach by tidal energy. However, present operation schedules of these sluices are irregular, simply relying on hydrological condition and personal experience. The imperative task is to develop a preferable diversion scheme for water environment management. The existing sluices offer economic efficiency, since no additional facility or equipment is required.

TABLE I
WATER QUALITY CLASSIFICATION OF NH_3-N AND COD (MG/L).

Water quality classification	I	II	III	IV	V	Worse than V
NH3-N	≤0.015	≤0.5	≤1.0	≤1.5	≤2.0	>2.0
COD	≤15	≤15	≤20	≤30	≤40	>40

III. METHODS

A. Mathematical Model

In order to evaluate the implementation effect of clean water diversion and develop the scheme scientifically, hydrodynamic model and water quality model are introduced to describe the changes of water flow and contaminant concentrations, respectively.

1) Hydrodynamic Model

One-dimensional open channel unsteady flow equations, namely Saint-Venant equations, as shown in (1), describe the movement of water flow [7], [22], [23].

$$\begin{cases} \dfrac{\partial A}{\partial t}+\dfrac{\partial Q}{\partial x}=q \\ \dfrac{\partial Q}{\partial t}+\dfrac{\partial}{\partial x}\left(\dfrac{\alpha Q^2}{A}\right)+gA\dfrac{\partial h}{\partial x}+g\dfrac{Q|Q|}{C^2AR}=0 \end{cases} \quad (1)$$

where Q is the rate of flow, m^3/s; x is the distance in the flow direction, m; t is the elapsed time, s; h is the water stage above datum, m; q is the lateral inflow, m^2/s; A is the cross-section area, m^2; α is the cross-sectional velocity distribution coefficient; C is Chezy resistance coefficient, $m^{1/2}/s$; R is the hydraulic radius, m; g is the acceleration due to gravity, m/s^2.

2) Water Quality Model

One-dimensional convection-diffusion equation shown as (2) reflects two transportation mechanisms: a) convection transport under average flow rate and b) diffusion transport due to concentration gradient [24]-[26]. Since NH_3-N and COD are the dominant contaminants in Lubao River and Southwest River and urgent to be reduced [20], this convection-dispersion equation is adopted as water quality model to study the improvement efficiency in water quality.

$$\frac{\partial AC_1}{\partial t}+\frac{\partial QC_1}{\partial x}-\frac{\partial}{\partial x}(AD_L\frac{\partial C_1}{\partial x})=-AKC_1+C_2q \qquad (2)$$

where C_1 is the concentration, mg/L; D_L is the dispersion coefficient, m^2/s; K is the linear attenuation coefficient; C_2 is the concentration of lateral inflow, mg/L; q is the lateral inflow, m^2/s.

B. Numerical Methods

MIKE 11, a one-dimensional unsteady hydraulic modeling package developed at the Danish Hydraulic Institute [24], is introduced to solve the aforementioned mathematical model.

The solutions of (1) are based on a 6-point implicit finite difference Abbott-scheme developed by Abbott and Ionescu [27]. Equation (2) is solved using a fully temporal and spatial central implicit finite difference scheme which is unconditionally numerically stable. The matrixes of the linear difference equations are solved with a double sweep algorithm [7], [24].

C. Modelling

1) Simulation Domain

Based on the geographical map of Guangdong Province, river network is generalized and simulation domain can be found in Fig. 1 (the black lines). The terrain data of riverbed and river bank provided by Foshan Hydrological Bureau are collected to depict the river cross-sections.

2) Boundary Conditions of Hydrodynamics

The flow rate time series of Southwest Sluice and Lubao Sluice are set as upstream boundary condition, while water level measured at Lugang Sluice is used as downstream boundary condition. In addition, the tributaries of Southwest River, namely Damian River, Dalangwo River, Zuoan River, Jiefang River, and Leping River are considered as point sources in the simulation domain. The locations of these sluices and tributaries are shown in Fig. 1 and the monthly average flow rates in each tributary can be found in Table II.

3) Boundary Conditions of Water Quality

NH_3-N and COD are regarded as two typical indicators of water quality in this study. The upstream and downstream boundary conditions of water quality, as well as the water quality in tributaries are based on the data measured in-situ.

Generalization of river pollution sources is conducted in accordance with the flow and water quality observed. The pollution sources can be classified into four items: a) domestic sewage, b) pesticide and fertilizer remains, c) livestock breeding contaminants, and d) industrial wastewater. The layout of the key sewage outfalls along Southwest River and Lubao River is shown in Fig. 1. Supposing the pollutant contents are almost constant throughout the year, the concentrations of NH_3-N and COD at each outfall are calculated and given in Table III.

D. Scenario Prediction

Based on the water environmental objective mentioned in Section II, several hypothetic scenario cases are designed in Table IV, such as regulating the discharge schedule of the upstream sluices and reducing the pollutant discharged quantity. The calibrated model is applied to simulating the water level and water quality responses to these designed scenario cases, so as to study the improvement efficiency of clean water diversion on water environment in Lubao River and Southwest River.

1) The First Group of Scenario Cases

On condition that the pollution discharged maintains the present status shown in Table III, it is of great concern that how the operation schemes of Lubao Sluice and Southwest Sluice influence the water quality in the two rivers.

TABLE II
MONTHLY AVERAGE FLOW RATES IN THE TRIBUTARIES OF SOUTHWEST RIVER (M^3/S)

River name	Average flow rate											
	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Damian River	3	5	6	6	7	13	14	18	10	8	7	8
Jiefang River	10	22	20	28	30	50	56	67	50	22	29	31
Leping River	9	9	9	18	31	29	42	50	34	24	24	2
Zuoan River	4	9	10	12	11	17	19	21	14	15	12	9
DalangwoRiver	6	11	11	12	13	14	18	23	13	14	13	10

TABLE III
GENERALIZED WATER QUALITY OF SEWAGE DISCHARGED INTO THE TWO RIVERS

	Site	Sewage discharged [a] (104·t/y)	COD [b] (t/y)	NH3-N [c] (t/y)	COD [d] (mg/L)	NH3-N [e] (mg/L)
Lubao River	Lubao Outfall	595.83	563.42	64.94	94.56	10.90
	Leping Outfall 1	3575.59	1620.99	207.33	45.33	5.80
Southwest River	Damian Outfall	3741.28	2025.77	319.01	54.15	8.53
	Dalangwo Outfall	187.04	417.38	15.31	223.15	8.19
	Leping Outfall 2	1742	3612.99	164.26	207.40	9.43
	Gaofeng Outfall	21.53	65.80	1.83	305.62	8.50
	Dongying Outfall	34.22	90.71	1.79	265.08	5.23

Note: The unit symbol t/y means ton per year. a, b, and c are the annual discharge quantities of sewage, COD, and NH_3-N respectively. d is the average concentration of COD, which is derived from 100·b/a. Similarly, e is the average concentration of NH_3-N, which is derived from 100·c/a.

TABLE IV
HYPOTHETIC SCENARIO CASES

Scenario cases		Clean water diversion				Pollution reduction
		Lubao Sluice		Southwest Sluice		
		Flow rate (m^3/s)	Daily discharge duration (h)	Flow rate (m^3/s)	Daily discharge duration (h)	
Group 1	Case 1	35	8	35	8	No
	Case 2	50		50		
Group 2	Case 3	35		35		Yes
	Case 4	50		50		

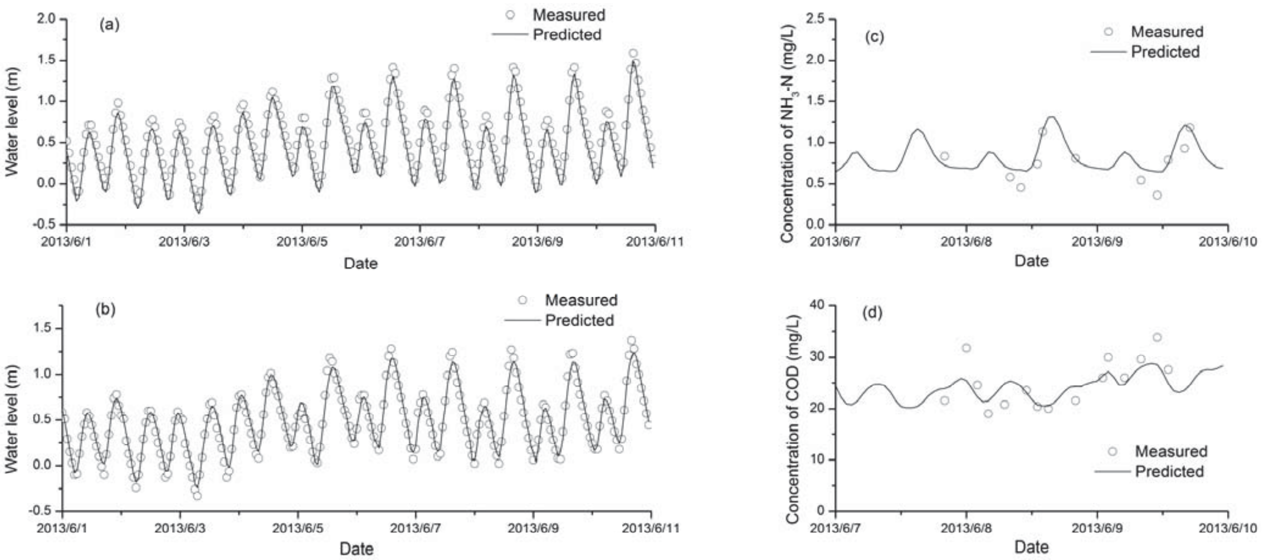

Fig. 2 Comparison between measured and simulated values: (a) water level in Heshun Site; (b) water level in Jietou Site; (c) NH_3-N concentration in Xiangling Site; (d) COD concentration in Jietou Site

As shown in Table IV, two cases are designed, namely the flow rates of water diversion are $35m^3/s$ and $50m^3/s$, respectively, with the daily discharge duration of 8 hours. January, the typical dry season, is selected for calculation and analysis.

2) The Second Group of Scenario Cases

According to *The unified layout plans on water resources in Foshan City* [28], the pollution sources will be regulated and the amounts of NH_3-N and COD of the sewage discharged into Southwest River are about to be reduced by 54% and 16% respectively in 2020. Thus, compared to the first group of scenario cases, keeping the operation schemes of Lubao Sluice and Southwest Sluice unchanged, the pollutant contents are cut down and the second group of scenario cases is shown in Table IV.

IV. RESULTS AND DISCUSSION

A. Model Validation

Figs. 2 (a) and (b) give comparison between measured and simulated water level in Heshun Site and Jietou Site (see Fig. 1). Meanwhile, their correlation can be drawn from Figs. 3 (a) and (b). Obviously, the predicted and observed values of water level are in excellent agreement, whether from the perspectives of phase or tidal range. The correlation coefficients are both in close proximity to 1.0, especially for Heshun Site which is 0.999, indicating that the hydrodynamic mathematical model developed can scientifically describe the movement of water flow in the simulation domain.

Taking Xiangling Site and Jietou Site for validation of water quality simulation, the comparisons between measured and predicted concentrations of NH_3-N and COD are shown in Figs. 2 (c) and (d), respectively. Owing to the mean annual runoff and generalized pollution sources used for calculation, there is a slight deviation between the simulated values and observed ones. However, in general, their variation trends are consistent, with the correlation coefficient is about 0.84 [as shown in Figs. 3 (c) and (d)]. That is to say, the simulated results can acceptably reflect the water quality in the two rivers.

In a word, the mathematical model and the numerical method can be used to simulate the hydrodynamics and water quality changes in Lubao River and Southwest River with sufficient accuracy.

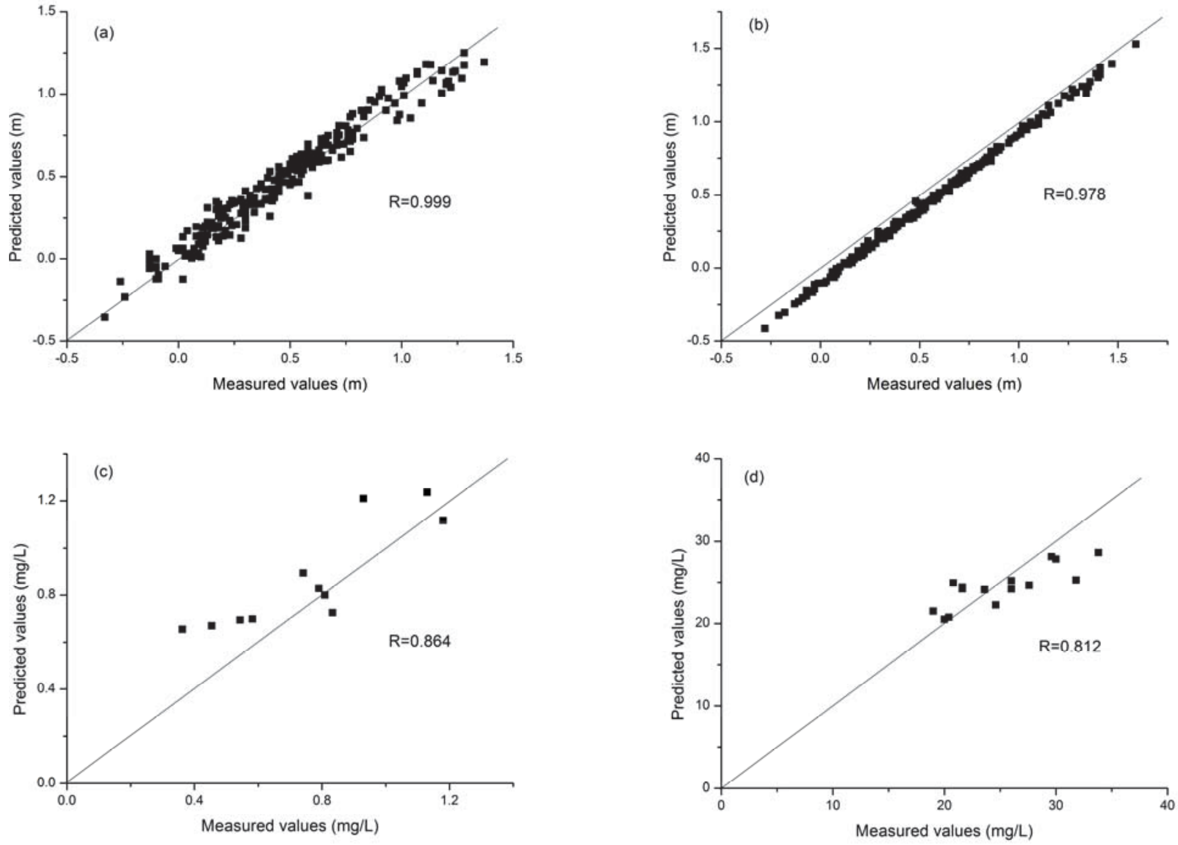

Fig. 3 Correlation between measured and simulated values: (a) water level in Heshun Site; (b) water level in Jietou Site; (c) NH_3-N concentration in Xiangling Site; (d) COD concentration in Jietou Site

B. Effects of Water Diversion

Fig. 4 shows the changes of average NH_3-N and COD concentrations in Southwest River with the distance away from Southwest Sluice under different cases. It can be found that clean water diversion significantly improves water quality within the initial 5km from Southwest Sluice. Due to the sewage discharged from several outfalls, contaminant concentrations increase rapidly form 5km to 8km and water quality keeps in terrible condition from 8km to 23km, the location of Guanyao Section. The relatively clean water from Lubao River flows into Southwest River at Guanyao Section. It is coupled with the effects of tidal fluctuation in the Pearl River, resulting in comparatively satisfactory water quality in the lower reach of Southwest River.

Fig. 5 shows the changes of average NH_3-N and COD concentrations in Lubao River with the distance away from Lubao Sluice. Similarly, water diverted through Lubao Sluice apparently improves water quality in the front end of Lubao River. However, water quality doesn’t change as acutely as in Southwest River, since there are only two main outfalls.

Judging from Fig. 4 and Fig. 5, peak value of contaminant contents could be markedly reduced when increasing water diverting rate. However, in terms of NH_3-N, due to the strong impact brought by the severely contaminated water, even though the water diverting rate reaches to $50m^3/s$ in Case 2, NH_3-N concentration along Southwest River keeps in class V or worse. Water quality in the lower half reach of Southwest River cannot meet the water environmental requirement in these two cases.

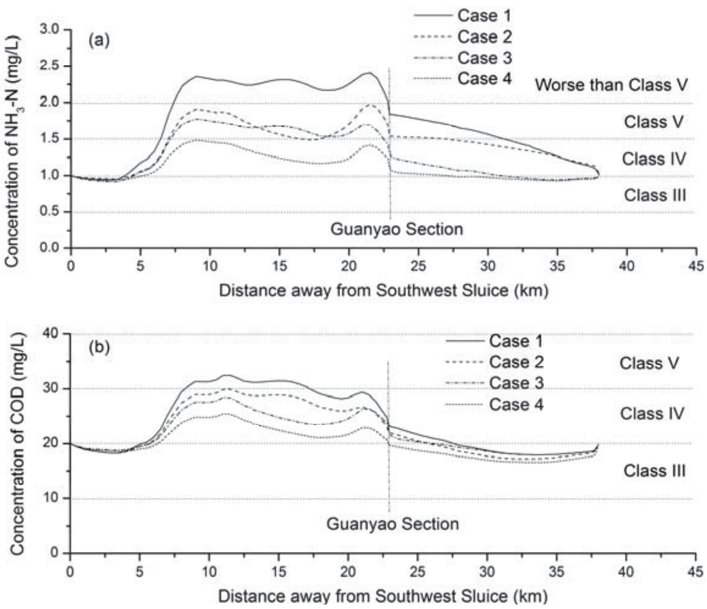

Fig. 4 Variations of contaminants with distance in Southwest River under different scenario cases: (a) NH_3-N; (b) COD

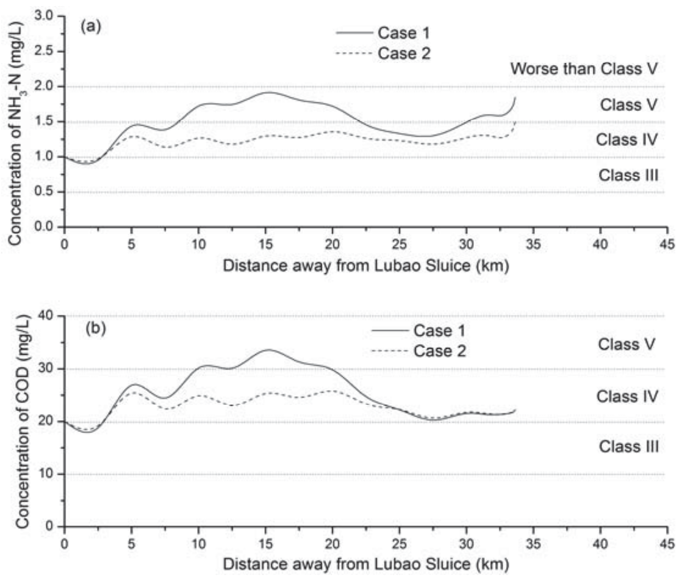

Fig. 5 Variations of contaminants with distance in Lubao River under different scenario cases: (a) NH_3-N; (b) COD

C. Pollution Reduction

The above analysis illustrates the effectiveness of diverting clean water on water environment improvement and meanwhile confirms the necessity of pollution reduction, especially for NH_3-N content. After pollution reduction, under the conditions of Case 4, water quality of Southwest River maintains in class IV on the whole, even attains to class III in the downstream reach after merging with Lubao River.

Consequently, if the pollution is cut down as expected and the diverting flow rates of the two upstream sluices reach $50m^3/s$, water quality in Lubao River and Southwest River can achieve the objective established by the environmental protection bureau.

D. Assessment System

Previous practice and experimental studies of clean water diversion seldom take into consideration its impacts on surrounding environment. Besides the efficiency of water environmental improvement, assessment system for clean water diversion in river system includes the impacts on upstream, downstream rivers and intake area itself.

Based on the pollution control scheme determined, diverting quantity from the North River through Lubao Sluice and Southwest Sluice doesn't amount to 6% of runoff in the North River. However, if relying on water diversion to meet the objective without pollution reduction, diverting quantity accounts for 11% of runoff in the North River, which would bring a huge impact on the ecological environment in dry season. Besides, excessive water diversion would raise the water levels in Lubao River and Southwest River, threatening the security of urban waterlogging prevention and navigation. Furthermore, clean water diversion is only a temporary supplementary method [3], [8], [10], [16], while pollution regulation is the essential measure. Fortunately enough, thanks to the large volume and environmental capacities in the Pearl River, the impact brought to the downstream river is negligible.

V. Conclusions

Practice of improving water environment in urban rivers by diverting clean water is studied and primary conclusions can be drawn as follows.

a) Lubao River and Southwest River, two urban rivers in typical plain tidal river network, are identified as technically and economically feasible for the application of clean water diversion.
b) One-dimensional hydrodynamic-water quality model is developed for computation and simulation. The results of model validation show that the predicted values are in excellent agreement with the measured ones, indicating that the mathematical model can scientifically describe the water environmental condition in the simulation domain.
c) Several scenario cases are simulated and compared utilizing the calibrated model. According to the computed results, diverting clean water by optimizing the operation schemes of Lubao Sluice and Southwest Sluice is effective to improve the water quality of Lubao River and Southwest River. However, since the pollution is severe in Southwest River, it is imperative to cut down the pollution discharge along with clean water diversion to meet the water environmental requirements completely.
d) Based on the water quality objective, the pollution control scheme is determined as Case 4 shown in Table IV. Namely the concentrations of NH3-N and COD discharged into Southwest River are reduced by 54% and 16% respectively, meanwhile the water diversion rate and daily duration of Lubao Sluice and Southwest Sluice reach 50m3/s and 8 hours respectively.
e) Assessment system for clean water diversion is established in river networks. Diversion scheme developed in this study imposes insignificant impacts on the water flow in the North River, the ecological environment in the Pearl River as well as the security in Lubao River and Southwest River.

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