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Sustainable management strategies for an urban-type and low dissolved oxygen stream using measured biochemical coefficients

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ABSTRACT

A water quality model, QUAL2K, with the measured biological coefficients was employed to develop sustainable management strategies for an urban-type stream. To master the data of hydrological and receiving water quality, three surveys were conducted at 20 sampling stations along the Wan-Nian stream in the Pingtung city of southern Taiwan. Then the biochemical coefficients including deoxygenation, nitrification, and reaeration rate coefficients, and sediment oxygen demand were measured and incorporated with influent pollutant loadings and boundary conditions to calibrate and verify the developed model. Simulation evaluated with the mean absolute percentage error method fits reasonably well except for a suspended solid sampled on 16 January 2011. The improvement goal for attaining the water quality of the Wan-Nian stream was set at Class C regulated by the Taiwan EPA. The assimilative capacity of the stream studied to Carbonaceous Biochemical Oxygen Demand (CBOD) and NH_3–N was estimated to be around 1,399 and 79 $kg\,day^{-1}$, but the collected sewage was about 5,831 and 189 $kg\,day^{-1}$, respectively, far exceeded its self-purification capacity. After reducing the pollutant loadings, the model results revealed that the water quality could reach the minimum Class C criteria. Water quality management strategies such as wastewater interception and diversion to the treatment plant as well as installation of contact aeration treatment units were drafted according to the model results after pollutant reduction. The present study demonstrates that the simulation analysis using QUAL2K is promising to frame the water quality management strategies of an urban-type river.

Keywords: Sediment oxygen demand; Kinetic coefficient; Water quality management; Assimilative capacity

1. Introduction

The Wan-Nian stream, an urban-type river located in southern Taiwan, has a length of 5.14 km along the main stream and a catchment area of 13.35 km^2 (Fig. 1). In the study area, most of the industrial and municipal sewage was not handled properly and was directly discharged into the Wan-Nian stream, resulting in the deterioration of its

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water quality, especially triggering low dissolved oxygen (DO) and high ammonia (NH_3–N) problems [1]. The low DO is mainly caused by significant oxygen consumption owing to a high carbonaceous and nitrogenous biological oxygen demand (BOD) in the receiving water.

According to the monthly surveyed data released by the Pingtung County Environmental Protection Bureau from April 2009 to June 2011, the overall water quality of the Wan-Nian stream stood in the range between moderately and seriously polluted based on the river pollution index (RPI) evaluated by DO, BOD, NH_3–N, and suspended solid (SS) [2]. The average concentrations of DO, BOD, NH_3–N, and SS were 2.82 ± 1.74, 11.2 ± 8.63, 3.13 ± 1.20, and $18.9 \pm 14.3\,\mathrm{mg\,L^{-1}}$ in the upstream reaches and 3.25 ± 1.47, 10.3 ± 5.43, 2.88 ± 1.18, and $14.6 \pm 7.79\,\mathrm{mg\,L^{-1}}$ in the downstream reaches, respectively [2]. The water quality had drastically improved by diverting the lightly polluted water from the upstream sources of agricultural tail water and subterranean drainage since January 2010 [3]. Therefore, the DO raised from 1.6 to $3.8\,\mathrm{mg\,L^{-1}}$ and the BOD decreased from 13.2 to $9.4\,\mathrm{mg\,L^{-1}}$ monitored in the years 2010 and 2011 [2]. But the NH_3–N concentrations were still high (around $3.1\,\mathrm{mg\,L^{-1}}$), which may be due to an intense application of fertilizers in the farmlands.

The simulation of flow rate (Q), DO, BOD, NH_3–N, and SS variations under various management scenarios in rivers receiving pollutants has been an integral component of water pollution control and management over the past 30 years. Recently, several methods have been developed for modeling the stream water quality [4–12]. However, many studies adopted numerous runs to manipulate the fitness between the model results and surveyed data via rigorous calibration and verification processes to obtain the key biochemical coefficients such as deoxygenation (k_1), nitrification (k_n), and reaeration (k_2) rate coefficients, and sediment oxygen demand (SOD) [4–8]. Moreover, the coefficients obtained might be extremely high or low and might be not applicable for further modeling processes. Therefore, the present study adopted measured biochemical coefficients incorporated with influent pollutant loading and boundary conditions to calibrate and verify the developed model.

The objective of the present study was to employ the enhanced stream water quality (QUAL2K) model with measured biochemical coefficients to simulate and forecast the water quality after the implementation of various pollution control measures and then to develop management strategies to meet the restoration goals of Class C water quality standards, i.e. DO greater than $4.5\,\mathrm{mg\,L^{-1}}$, BOD, NH_3–N, and SS less than the respective 4, 0.3, and $40\,\mathrm{mg\,L^{-1}}$, regulated for the Wan-Nian stream. The ultimate goal of the present study was to apply the developed model to evaluate the improvement alternatives to the effects of water quality as well as to provide the authority to frame the water pollution control and management strategies.

2. Materials and methods

2.1. Modeling approach

QUAL2K, one of the most popular and convenient water quality models, is mainly employed to handle the major one-dimension (1D) mass transport mechanisms such as advection and dispersion that are significant only along the main flow direction [13,14]. For this model, a river is simulated as a string of computational units with the same hydro-geometric characteristics, hydraulic properties, as well as biochemical rate constants. Thus, the above-mentioned data are required to forecast the water quality and further to develop the concerned river model. Detailed illustrations and manipulations of this model can be found in the literature [11,15,16].

2.2. River segmentation

The QUAL2K modeling framework requires a water system segmented into a number of completely mixed water cells. Taking the various hydro-geometric, hydraulic, and water quality properties of the reaches into account, a total length of 5.14 km from the upstream boundary (30 m upper Yingchun bridge, M1) to downstream boundary (Niuchouhis bridge, M5) was divided into 17 segments along the mainstream of the Wan-Nian stream, each of which was 300 m long, except segment 17 which was 340 m (Fig. 1).

2.3. Sampling programs

The hydrological and water quality data on the major pollutant sources along the Wan-Nien stream were surveyed at 20 sampling locations on 28 November 2010, 16 January and 27 March 2011 to support the model calibration and verification (Fig. 1). The first set of surveyed data was utilized for model calibration, and the second and third sets of data were employed for model verification. The hydraulic parameters such as cross-section area,

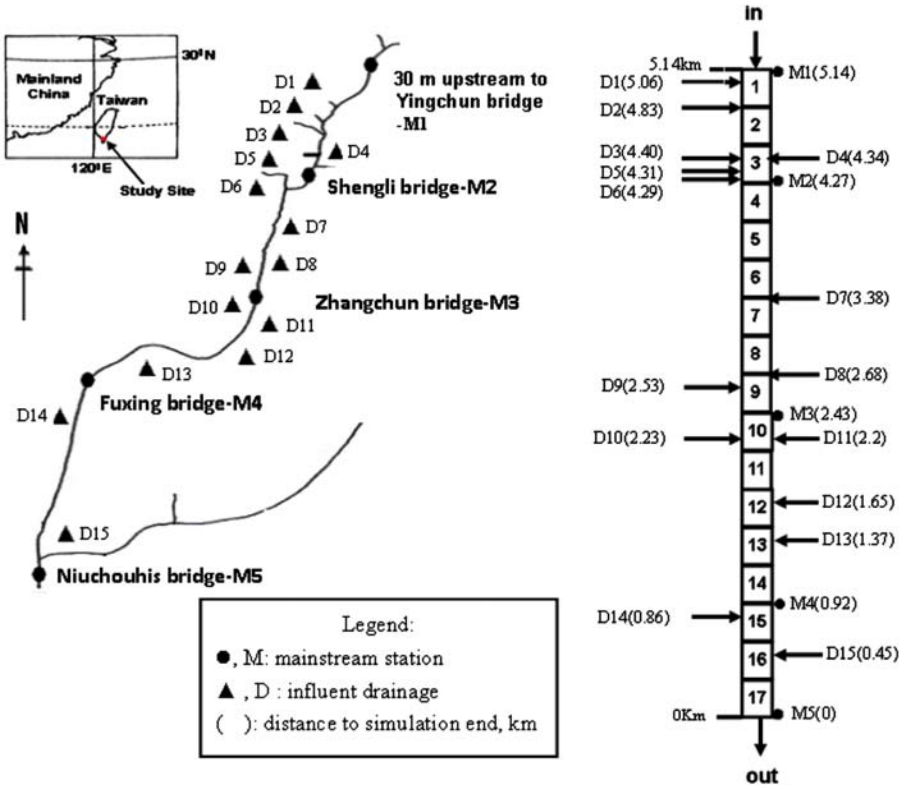

Fig. 1. Sampling stations and 1D water quality modeling grids for the Wan-Nian Stream.

water depth as well as flow velocity of the drainages and reaches were measured to provide the input data for each segment. The receiving water quality parameters such as temperature, pH, chlorophyll-a, DO, electric conductivity (EC), SS, carbonaceous biochemical oxygen demand ($CBOD_5$), NH_3–N, total Kjeldahl nitrogen (TKN), total phosphorus (TP), PO_4^{3-}, NO_2–N, and nitrate nitrogen (NO_3–N) were analyzed with the standard methods and their values were used for a comparison with the model results. The RPI, a popular water quality evaluation index used in Taiwan, only comprises parameters of SS, BOD, NH_3–N, and DO. Therefore, only EC was used for mass transport modeling, and four parameters in the RPI were utilized for model calibration and verification in the present study. The pollutant loading rates calculated by the flow rates multiplying the respective concentrations discharged from the upstream drainages were the major inputs, which were then incorporated into the QUAL2K model with the boundary conditions.

2.4. Mean absolute percentage error

A dimensionless index called the mean absolute percentage error (MAPE) was used to evaluate the variations between the surveyed and modeled values. The less the MAPE values are, the closeness between the measured and modeled values. DeLurgio proposed four levels of goodness of fit according to the values of MAPE such as excellent (MAPE < 10%), good (10–20%), reasonable (20–50%), and poor (> 50%) [17].

2.5. Biochemical coefficients

The vital kinetic coefficients in the QUAL2K model vary with the river characteristics and locations, pollutant sources, seasons, and management policies of local authority, etc. To better master the variations in water quality of the Wan-Nian stream, the present study conducted several tests to obtain the biochemical coefficients.

2.5.1. Deoxygenation, nitrification, and reaeration rate coefficients

The test method of k_1 is similar to that of BOD by measuring the DO in water for 30 d or longer. The DO data of the first 10 d and the following 20 d collected were then employed to obtain the biochemical coefficients k_1 and k_n. Details of the processing data can be found in the literature [15,16]. While the in-stream k_2 values were obtained using the Tsivoglou equation based on the measured flow speed, cross section area of watercourse, and the slope of river bed in the receiving water [17].

2.5.2. Sediment oxygen demand

Not enough sediments were observed between the stations M2, M3, and M4 due to concrete pavement of the river bed; therefore, the SOD tests were only conducted *in situ* at the stations M1 and M5. The schematic flow diagram of the SOD apparatus used is shown in Fig. 2. At the location selected, a stainless container of the SOD system was slowly and stably placed at the bottom of the river and then the gas exhausted through the mouth. An on-site DO probe was employed to monitor the attenuation of the background DO and then used to compensate the system DO for any further SOD calculation. Each SOD test was carried out for at least 4 h. The collected DO data were processed to obtain the respective SOD values via the Thomann and Mueller equation [19].

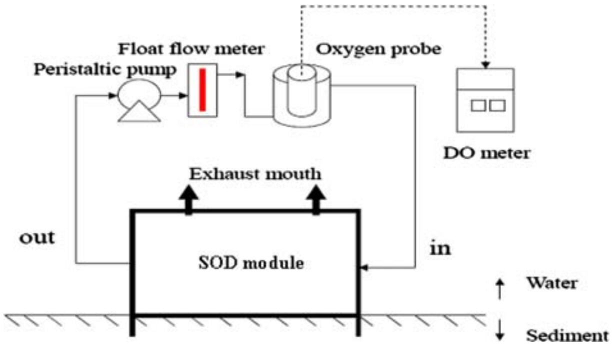

Fig. 2. Schematic flow diagram of SOD system.

3. Results and discussion

3.1. Surveyed data

Overall, the water quality of the influent drainages was worse than that of mainstream as the influent drainages had collected almost the entire municipal wastewater of the Pingtung City, Taiwan. As shown in Table 1, the major influent pollutant loadings affecting the receiving water quality were discharged from the drainages D3–D6 and D15.

Table 2 shows that the measured biochemical coefficients including k_1, k_n, k_2, and SOD used in the present study lay within the range of literature values [18–

Table 1
Surveyed hydrological and water quality data of the Wan-Nian stream

Mainstream station (distance to simulation end, km)	Flow (m^3 h^{-1})	BOD_5 (mg L^{-1})	NH_3–N (mg L^{-1})	SS (mg L^{-1})	DO (mg L^{-1})
M1(5.14)	6,949 ± 3,017	10.2 ± 11.2	1.9 ± 2.5	8.7 ± 3.1	3.2 ± 0.1
M2(4.27)	6,960 ± 810	17.2 ± 7.7	1.0 ± 0.4	14.1 ± 6.5	3.0 ± 0.8
M3(2.43)	7,692 ± 946	15.7 ± 10.7	2.3 ± 2.8	14.9 ± 11.6	3.2 ± 0.5
M4(0.92)	6,865 ± 334	6.5 ± 2.7	1.3 ± 1.2	11.7 ± 4.7	5.4 ± 0.2
M5(0.00)	10,734 ± 2,393	7.6 ± 1.4	3.1 ± 2.2	7.7 ± 2.0	6.5 ± 1.4
D1(5.06)	43.2 ± 0.0	49.1 ± 9.9	5.1 ± 3.3	27.8 ± 10.5	1.0 ± 0.0
D2(4.83)	4.1 ± 0.1	62.1 ± 2.8	4.6 ± 2.5	22.6 ± 9.9	1.0 ± 0.0
D3(4.40)	4,135 ± 3,023	19.1 ± 13.8	1.3 ± 1.3	12.9 ± 9.3	3.7 ± 0.5
D4(4.34)	4,308 ± 3,393	22.0 ± 13.0	1.9 ± 1.7	8.9 ± 6.5	3.1 ± 1.3
D5(4.31)	3,101 ± 2,149	29.0 ± 9.7	1.9 ± 1.8	8.0 ± 3.6	1.7 ± 0.6
D6(4.29)	4,704 ± 3,659	20.5 ± 4.3	1.0 ± 0.4	10.0 ± 6.9	2.7 ± 0.6
D7(3.38)	27.6 ± 37.4	22.0 ± 22.5	0.3 ± 1.7	10.4 ± 14.2	4.4 ± 4.0
D8(2.68)	26.5 ± 18.0	33.4 ± 21.6	4.5 ± 5.2	12.7 ± 1.0	1.9 ± 1.5
D9(2.53)	440 ± 692	3.4 ± 0.8	0.6 ± 0.7	4.0 ± 1.4	6.4 ± 1.7
D10(2.23)	8.0 ± 7.8	87.1 ± 15.0	2.1 ± 1.4	76.7 ± 49.0	0.9 ± 0.6
D11(2.20)	2.7 ± 3.9	59.8 ± 35.9	4.3 ± 3.6	18.7 ± 6.5	0.7 ± 0.3
D12(1.65)	26.6 ± 26.9	27.4 ± 20.6	0.8 ± 0.5	8.9 ± 5.2	4.1 ± 1.3
D13(1.37)	195 ± 336	51.7 ± 13.1	4.7 ± 4.4	36.0 ± 23.6	3.5 ± 1.8
D14(0.86)	61.4 ± 87.2	34.0 ± 19.1	3.4 ± 3.5	22.9 ± 8.0	3.1 ± 0.2
D15(0.45)	5,421 ± 4,911	8.1 ± 3.4	0.8 ± 0.8	10.7 ± 4.1	7.0 ± 2.1

Table 2
Summary of biochemical coefficients of the present study and literature values

Coefficients	This study	Literature values	References
k_1 (d^{-1})	0.35–0.51	0.1–3.0	[19,20]
k_n (d^{-1})	0.12–0.24	0.1–1.5	[20,21]
k_2 (d^{-1})	0.18–2.56	2.2–36.4	[18,21]
SOD ($g\,O_2\,m^{-2}\,d^{-1}$)	0.10–4.96	1.0–10	[19,20]
θ^a	1.065	1.04–1.13	[19,20]

^{a}Correction coefficient of temperature.

21]. Therefore, their values seemed to be reasonable and were then employed to incorporate with other parameters as the inputs for model calibration and verification.

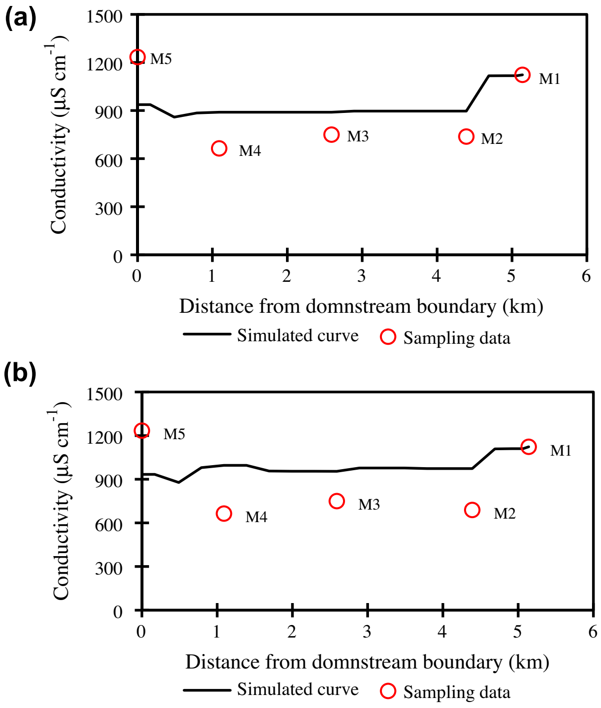

Fig. 3. EC model results vs. surveyed data for the Wan-Nian stream sampled on (a) 16 January 2011 and (b) 27 March 2011.

3.2. Mass transport modeling

The steady-state mass transport modeling was first conducted to obtain the dispersion coefficients using the conservative EC data collected on 28 November 2010 as inputs to the model. The calibration results showed that the dispersion coefficients ranged between 12 and 320 $m^2\ s^{-1}$ along the mainstream. Fig. 3(a) and (b) reveals the EC variations along the mainstream of model results and surveyed data on 16 January and 27 March 2011. The model results mainly fit the measured spatial distribution of EC, certifying the validity of mass transport under steady-state conditions. The calibrated mass transport model was then used to track the concentrations of the water quality parameters concerned in the receiving water.

3.3. Water quality modeling

Five sampling stations along the mainstream including Yingchun bridge (M1), Shengli bridge (M2), Zhangchun bridge (M3), Fuxing bridge (M4), and Niuchouhis bridge (M5) were selected for model calibration and validation. The water quality model was first calibrated with the data collected on 28 November 2010 using the measured biochemical coefficients. While the data obtained from 16 January and 27 March 2011 were then employed to verify the model also using the measured biochemical and other calibrated model coefficients. The boundary conditions of the model include the loadings of $CBOD_5$, DO, SS, NH_3–N, NO_3–N, NO_2–N, organic nitrogen, chlorophyll-a, organic phosphorus, and PO_4^{3-} derived from the data of each survey at the upstream and downstream reaches and drainages.

The model results of spatial DO, $CBOD_5$, and NH_3–N concentrations compared with the data sets of three surveys are shown in Fig. 4. Generally speaking, the model results match the field data reasonably well and both have a similar trend of variations. Fig. 5 shows that the fit levels of the concerned parameters were good or reasonable, except for the case of SS sampled on 16 January 2011. The discrepancy of SS between the model results and field data may be due to the depth of the Wan-Nian stream being very shallow (~0.3–0.7 m). Therefore, the sediments underneath are much easier to be disturbed and resuspended by the river flow speed and sampling process.

3.4. Assimilative capacity and pollutant reduction strategies

The calibrated and verified model was used to forecast the water quality associated with its improvement schemes and to estimate the reduction amounts of pollution sources from drainage discharges. In the present study, the minimal improvement goal is Class C according to the standards of surface water quality regulated by the Taiwan EPA.

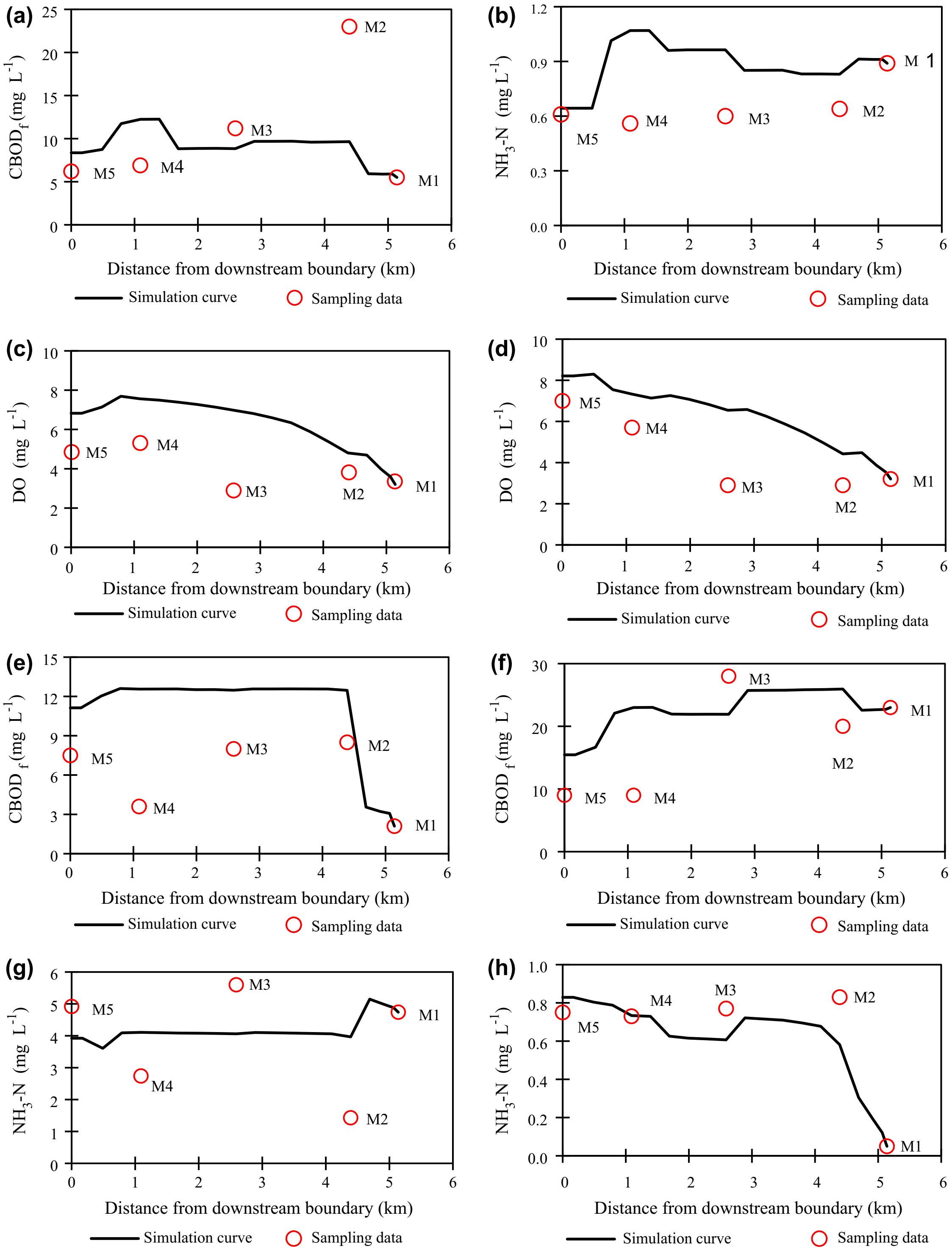

Fig. 4. Water quality model results of (a) CBOD and (b) NH_3–N sampled on 28 November 2010, DO on (c) 16 January 2011 and (d) 27 March 2011, CBOD on (e) 16 January 2011 and (f) 27 March 2011, NH_3–N on (g) 16 January 2011 and (h) 27 March 2011 for the Wan-Nian stream.

The total pollutant loadings estimated were 5,830.7 kg d^{-1} for CBOD and 188.9 kg d^{-1} for NH_3–N based on the surveyed data of 27 March 2011. As the Class C water quality criteria were adopted as the improvement goal, the assimilative capacity obtained from the developed model of receiving water to

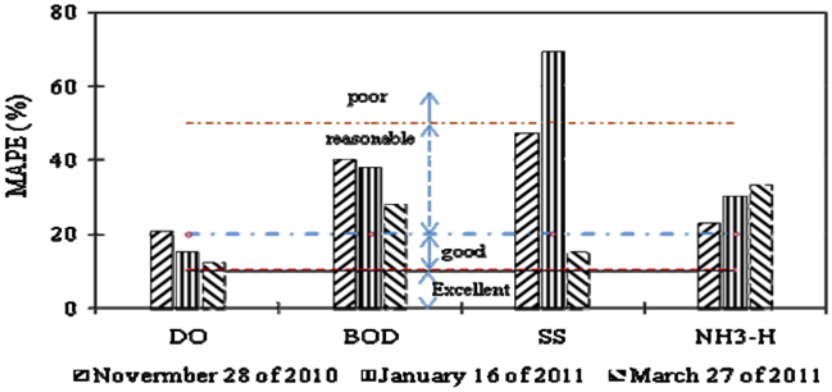

Fig. 5. Fit levels between the model and surveyed results evaluated with MAPE method.

CBOD and NH_3–N was around 1,399.0 and 79.0 kg d^{-1}; therefore, the total quantities of pollutant reduction must be greater than 4,431.6 and 109.9 kg d^{-1}, respectively. After reducing the pollutant loadings, the forecast levels of $CBOD_5$, NH_3–N, and DO via the developed model with measured biochemical coefficients showed that the water quality of the Wan-Nian stream could reach the Class C requirements (Fig. 6). After the developed model was calibrated and verified, adjusting the influent pollutant loads which were discharged into the mainstream from upstream to downstream reaches in sequence to let the model results meet the regulated water standard was carried out. Then, the modified influent pollutant loads were accumulated to obtain the assimilative capacity of the stream concerned.

To achieve the target amounts of pollutant reduction in the sanitary sewer not quite reachable by all

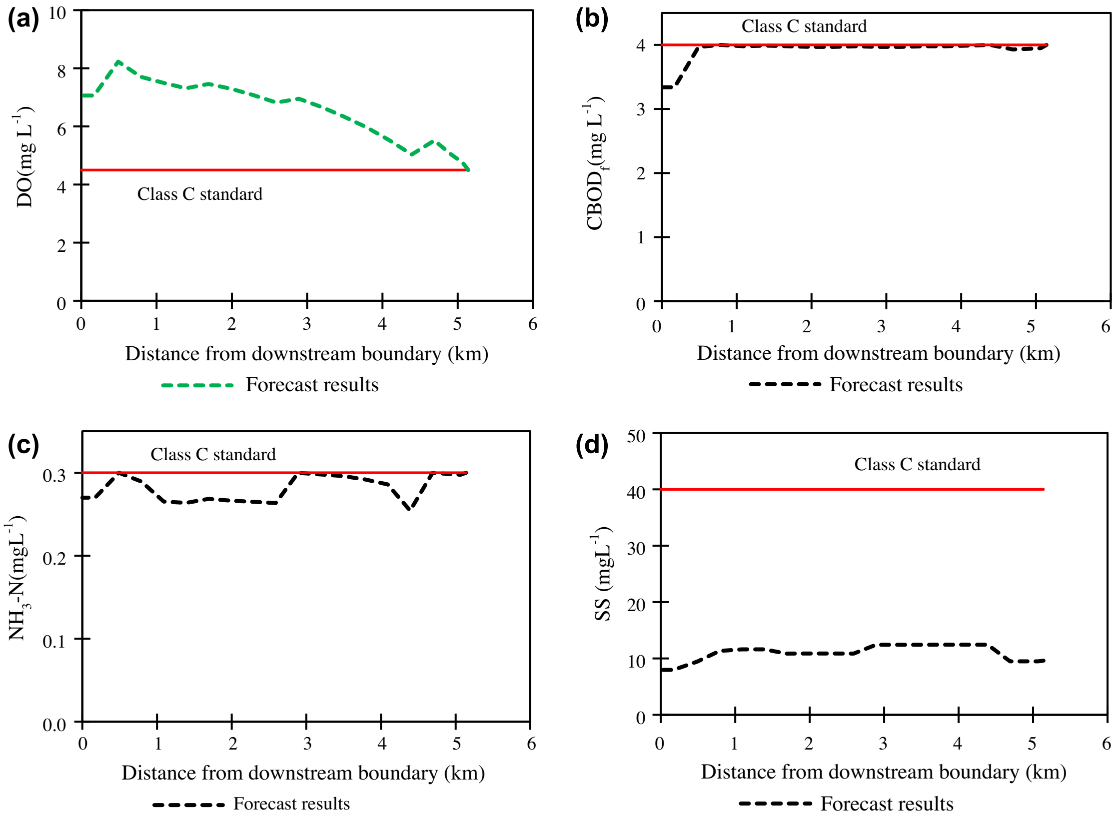

Fig. 6. Simulation results of (a) DO, (b) CBOD, (c) NH_3–N, and (d) SS after reducing the pollutant loadings.

residents in this area, several preventive measures were undertaken such as enhancement to clamp down illegal discharge of untreated wastewater, severe punishment to unlawful proprietors, and encouragement of residents to organize patrol teams to protect the river water quality. Interception of the pollutants discharged from drainages such as D2 and D7–D14 and diversion to the neighboring treatment plant may be one of the effective measures to improve the water quality of the Wan-Nian stream. The total flow rates of those drainages intercepted are around 47,924 $m^3 d^{-1}$, thus the reduction amounts computed are 723.8 and 31.9 $kg d^{-1}$ for CBOD and NH_3–N, around 16.3 and 23.9% of the respective total reduction amounts required. Provided that three gravel contact aeration units are set up near M1, D4, and D15 to treat 33, 50, and 30% of respective influent flow rates of upstream M1, drainages D3–D5, and D15, i.e. 30,000, 20,000, and 45,000 $m^3 d^{-1}$ and designs to cut down 90 and 50% of the respective influent CBOD and NH_3–N. The total reduction amounts of those units will be about 1,613.6 $kg d^{-1}$ for CBOD and 25.1 $kg d^{-1}$ for NH_3–N. Therefore, the combined reduction quantity of both interception and treatment measures will be 2,337.4 $kg d^{-1}$ for CBOD and 57.0 $kg d^{-1}$ for NH_3–N. Around 2,094.2 and 52.9 $kg d^{-1}$ of CBOD and NH_3–N are needed to be tackled. The constructed wetland or in-stream enhanced aeration process may be another alternative to be considered for further purification of the water quality. Actually, the most effective way to restore the water quality of the Wan-Nian stream is to construct the sanitary sewer as early as possible.

4. Conclusions

The study demonstrates that the simulation analysis using QUAL2K with measured biochemical coefficients is promising to frame the water quality management strategies of an urban-type river with low DO and high NH_3–N problems. The model results evaluated by the MAPE method fit reasonably well with the surveyed water quality data. The average reduction ratios of BOD and NH_3–N should be at least 76 and 58% to achieve the improvement goal of Class C. After reducing the pollutant loadings, the forecast levels of $CBOD_5$, NH_3–N, and DO via the developed model with measured biochemical coefficients could reach the regulated water quality. The improvement measures such as wastewater interception and diversion to the neighboring treatment plant as well as the installation of the three gravel contact aeration units are proposed to restore the water quality of the Wan-Nian stream. The constructed wetland or in-stream enhanced aeration process may be another alternative to further improve the water quality of the Wan-Nian stream.

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