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Using a systematic approach to develop water quality management strategies in the Nankan River, Taiwan

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ABSTRACT

The Nankan River, located in northern Taiwan, is one of the most contaminated rivers in Taiwan. The pollution of this river causes odor problems and affects use of the water resources. In this study, a systematic river basin water quality management strategy was developed to simulate water quality, evaluate wastewater management alternatives, and cost-effectiveness strategy plans for the Nankan River restoration and its water quality improvement. The main tasks consist of river water sampling and analysis, water quality modeling, total maximum daily load (TMDL) calculation, river pollution index (RPI) evaluation, and cost-effectiveness analysis (CEA). The QUAL2K model, developed by US Environmental Protection Agency, was adopted as the river water quality modeling framework in this study. The modeling effort was supported including four water quality data-sets of the river. Results of the water quality modeling show that the calculated TMDL for biochemical oxygen demand (BOD) and ammonia loading were 1,334 and 889 kg/day, respectively. Approximately, 1,334 kg/day of BOD and 889 kg/day of ammonia needed to be reduced to improve the RPI from "serious pollution" level to "moderate pollution" level. Results also reveal that the odor problem caused by dimethyl sulfide and dimethyl trisulfide could be removed after the water quality improvement. Results from the CEA show that an annual cost of US$ 8 million is required to reach the acceptable RPI level (moderate pollution). The developed strategies can be used as decision-making tools for water pollution control and river basin water quality management for the Nankan River and other similar rivers.

Keywords: Cost-effectiveness analysis; Key performance indicators; Point sources pollution; QUAL2K; River basin management; Total maximum daily load

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1. Introduction

Human activities and natural disasters have brought enormous stress to the water environment worldwide. Nutrient loading into rivers and streams is one of the major concerns in water quality management. Overloading of nutrients (such as nitrogen and phosphorus) causes eutrophication problems. Eutrophication affects water quality and aquatic life in rivers, and increases the costs of water treatment. Rivers and streams pollutions are serious due to large establishment of high-tech industries, rapid of economic growth, floods, and earthquakes in Taiwan. The main water pollution sources are livestock wastewater from hog farms, municipal wastewater, industrial wastewater, and non-point source (NPS) pollutants from agricultural areas. The pollution of these rivers causes odor problems and affects use of the water resources [1–7]. In recent years, ecological and natural treatment systems have been applied by Taiwan Environmental Protection Administration (EPA) for river water quality and ecological environment improvement. The techniques promoted by Taiwan EPA included on site river water purification systems, cobble contact beds, constructed wetland, and pig toilets. This was to meet the treatment goals of (1) dissolved oxygen (DO) $> 2\,mg/L$, (2) no odor, and (3) vitalization of the water front and river bank. The primary water quality problem in the region is point source biochemical oxygen demand (BOD) and ammonia (NH_3-N)-related DO depression in the water column of rivers and streams. DO levels below $5\,mg/L$ represent poor water quality, violating the surface water quality standards promulgated by Taiwan EPA. To maintain DO above a given threshold, the assimilative capacity of the river must be maintained to cope with the pollutant loading along the river. This goal can be achieved by controlling the river flow rate and wastewater pollutant loading [8–11].

Since 2009 the Taiwan EPA has been actively promoting integrated watershed management program (IWMP) and progressively revising the key performance indicators (KPI) [12]. The IWMP across political and administrative boundaries by bringing together all interests upstream and downstream according national soil conservation plan of national sustainable development guideline in Taiwan. The IWMP considers not only technical, but also socioeconomic and ecological aspects. The KPI have five categories including “water quality and esthetics,” “conservation approaches and tools,” “public participation,” “administration efficiency and effectiveness,” and “water front.” This KPI has been applied in all performance evaluation programs. In 2010, the Taiwan EPA completed the national-wide evaluation of 25 administrative divisions including river and reservoir watersheds. Specialists from environmental engineering, water analysis, ecosystem and water–soil conservation, water supply, and water resource areas were participated. As far as the implementation of total maximum daily load (TMDL) program is concerned, the Taiwan EPA also has carried out simulation studies of major heavily polluted rivers and proposed implementation strategies dealing with point source and NPS pollutants. Through water quality modeling results, the regulatory agencies can have comprehensive water quality information and the fate of relevant pollutants as to design and implement pollution control programs, and develop management strategies to meet the water quality in short-, medium-, and long-range goals.

A TMDL is an estimate of the maximum pollutant loading from point and nonpoint sources that receiving water can accept for another expression without violating water quality standard. Determining a TMDL is difficult for a combination of point and non-point pollutant sources because of fundamentally different nature of the two sources. Basically, most implementation has focused on point source requirements rather than on nonpoint loading. TMDL is established to achieve and maintain water quality standards when excessive BOD, low DO, and excessive nutrients and eutrophication impair the water quality of natural water. A water quality standard is the combination of a designated use for a particular body of water and the water quality criteria designed to protect that use. One of the key elements in a nutrient TMDL is specific application of nutrient enrichment endpoints, which are influenced by a broad array of factors and process, including physical factors, biological factors, and human impacts. In practice, DO concentration is the most commonly applied as assessment endpoint in TMDL for the river basin management [13–17].

The purpose of this study was to develop a systematic approach of river basin management by using a TMDL. The TMDL consists of point source pollution, nonpoint source pollution, river pollution index (RPI), odor, contaminants of emerging (CEC), and cost-effectiveness analysis (CEA). The odor is considered of indole, skatole, dimethyl sulfide (DMS), and dimethyl trisulfide (DMTS) in the study. The QUAL2K model was used to simulate the fate and transport of water quality pollutants, and develop water quality management strategies. A field-monitoring program including four water quality data-sets was conducted to support the modeling analysis for the Nankan River in Taiwan. The model simulates the fate and transport of constituents that include conductivity, suspended solids (SS), BOD, ammonia, and DO concentrations. Further, calibrated and verified with the field data, the model was used a TMDL to evaluate a number of wastewater management alternatives designed to reduce loading of BOD and ammonia, and to improve the RPI and odor (no DMS, DMTS, skatole, and indole) in this river. In addition, the cost-effectiveness (CE) ratio shows the relationships wastewater treatment effective with annual cost is acceptable for BOD improvement. The developed water quality model can be utilized a decision-making tool of an urban-type river for the management authority.

2. Previous research on river water quality modeling for TMDL

Environmental fate and transport models, including watershed, hydrodynamic, and receiving water models been used in many TMDL studies for water quality management of rivers and streams. Santhi et al. [18] used a watershed simulation model, Soil and Water Assessment Tool, to quantify the effects of phosphorus control measures on stream water quality. A TMDL program has been initiated for the North Bosque River Watershed in Texas, USA, where point and nonpoint sources of pollution are of a concern. Impairment was determined under narrative water quality criteria related to excessive aquatic plant growth. This paper describes the impact of these practices on phosphorus. The benefits of phosphorus control measures for wastewater treatment plants (WWTP) resulted in greater improvement in stream concentrations, while control measures on dairies made greater difference on phosphorus loadings. Results were used to inform the TMDL stakeholder group of possible controls that could reduce phosphorus loadings and concentrations in the Bosque River Watershed. Stow et al. [19] developed a TMDL to reduce nitrogen inputs into the Neuse River Estuary to address the problem of repeated violations of the ambient chlorophyll a criterion. Three distinct water quality models were applied to support the TMDL: a two-dimensional laterally averaged model (CE-QUAL-W2 model), a three-dimensional model (WASP model), and a probability network model (Neu-BERN model). This successful application of mechanistic models to the Neuse River Estuary has provided insight into the response of the waterbody to external loadings and environmental conditions. Turner et al. [20] utilized QUAL2Kw model to quantifiably link nutrient and periphyton to impairments and determine the TMDL that will achieve water quality objectives for DO and pH in nutrient enrichment of the South Umpqua River. The model was used to quantify nonpoint source loading, determine the pollutant of concern, estimate natural conditions, and calculate a phosphorus TMDL during summer, low-flow conditions. Control of both nonpoint and point sources is required to achieve the low instream phosphorus concentrations necessary to meet water quality criteria. Lai et al. [21] developed an integrated two-model system composed of a multimedia watershed model (IWMM) and a river water quality model (WASP/EUTRO) to effectively simulate the impacts of NPS on Kaoping River Basin water quality. Results demonstrate that the integral approach could develop a direct linkage between upstream land use changes and downstream water quality. Using water quality modeling alone would underestimate the impact of NPS pollution on river water quality. The introduction of the integrated two-model system shows a significant advance in estimating the water quality, and as river basin management TMDL of the basis. Chen et al. [22] as WASP/EUTRO model to address technical challenges associated with modeling for water quality management in Taiwan's rivers (the Dansui River and the Chungkang River). In the study, the modeling results of two rivers were presented to demonstrate the associated technical issues and difficulties, as well as recommend further effort to meet these challenges.

As reviewed from previous research, there are few river water quality modeling using TMDL approach. For that reason, a more comprehensive water quality model incorporating TMDL, KPI, and CE strategy

Fig. 1. Implementation of the concept of river basin management.

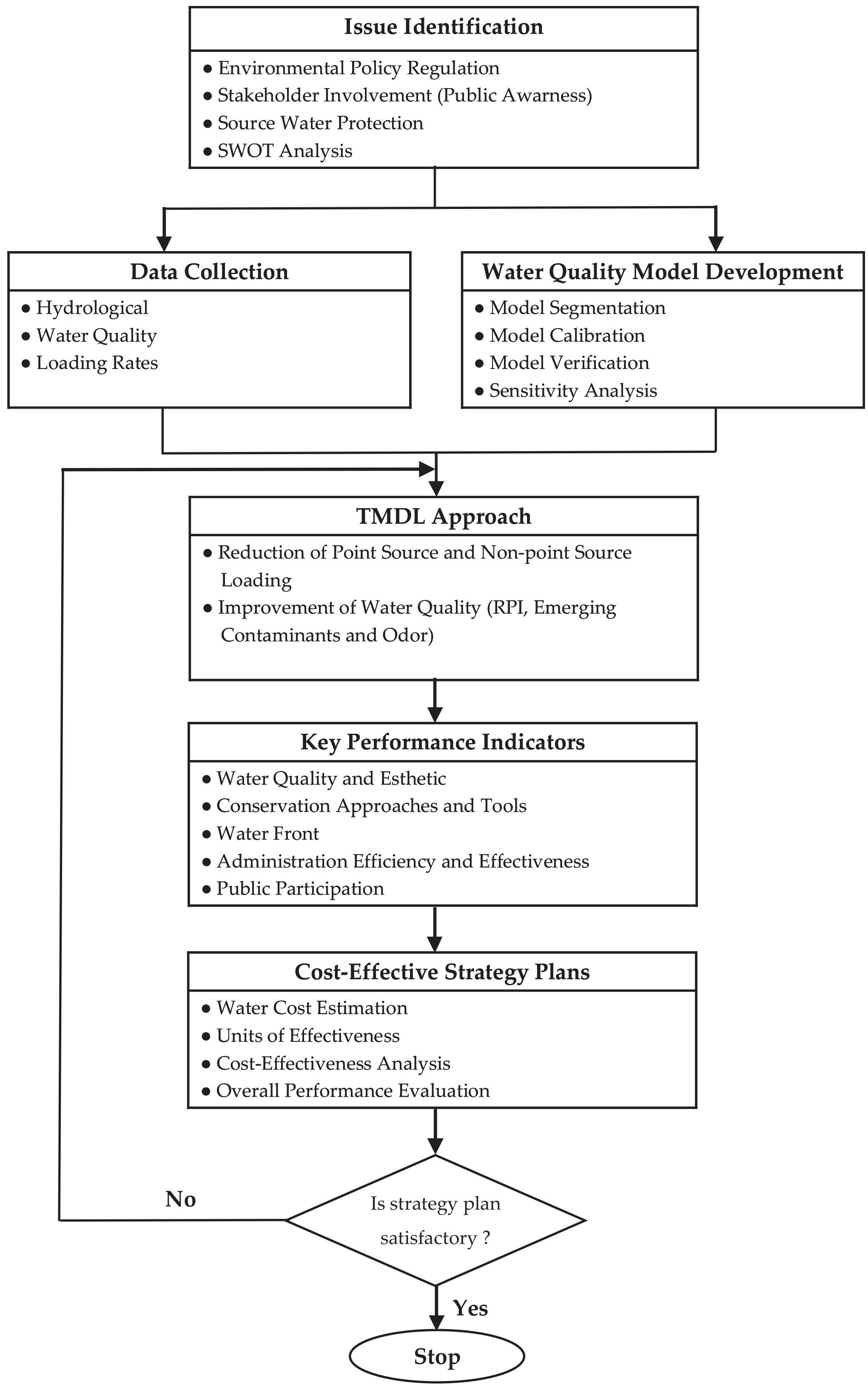

Fig. 2. Systematic approach to development of a river basin management using TMDL.

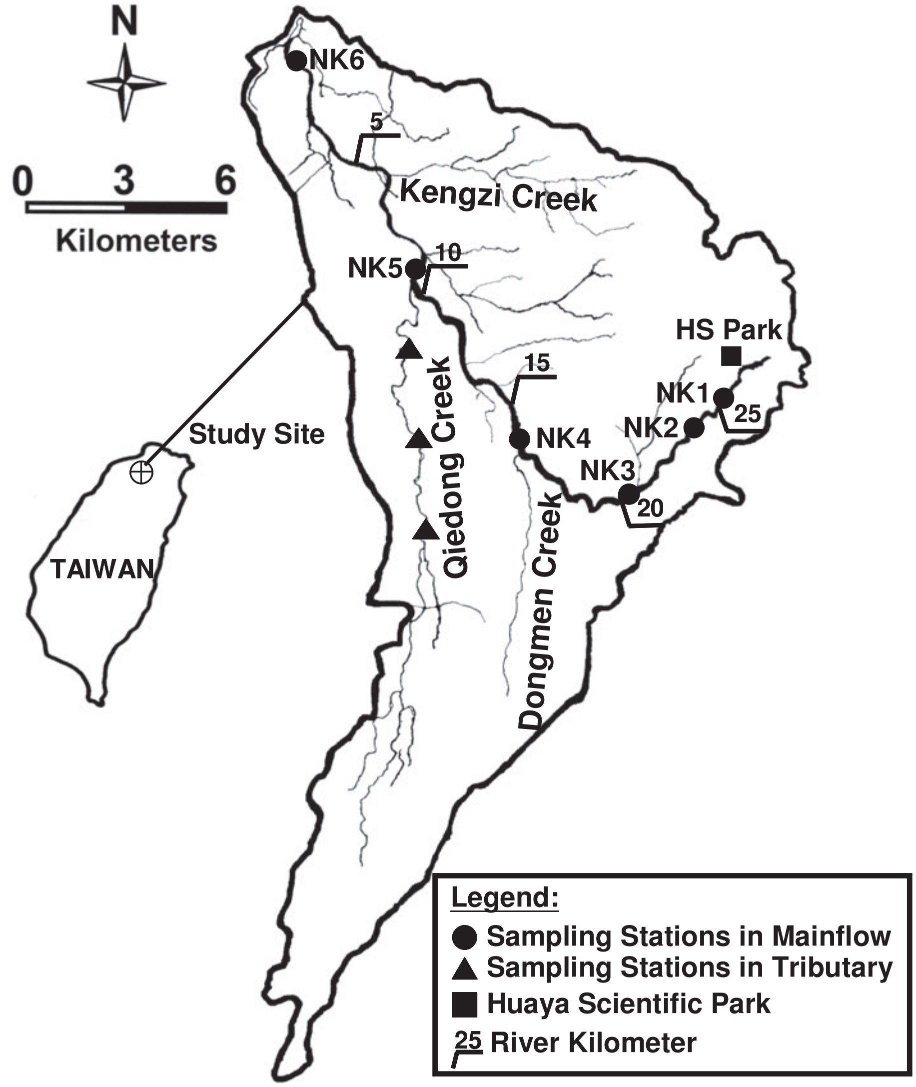

Fig. 3. Location of Nankan River and its sampling points.

plans in water quality management of river basin system is required.

3. Methodology

In this study, the implementation of the concept of river basin management primarily refers to the plan, do, check, and action processes, as shown in Fig. 1. A research framework was proposed that is systematic approach to develop a river basin management process using TMDL including (1) issue identification; (2) data collection and water quality model development; (3) TMDL approach; and (4) cost-effective strategy plans. Fig. 2 shows using systematic approach for the development of river water quality management strategies processes.

3.1. Study area and data collection

The Nankan River is covered by commercial and industrial prosperity of the Taoyuan metropolis in northern Taiwan. The river is approximately 44 km long with a catchment area of $2.14 \times 10^8\,m^2$. Its water quality has been routinely monitored since 2002, at a frequency of once a month by the TEPA. There are nine water quality sampling stations in the mainflow and its tributaries (see Fig. 3). The main water quality problems are that persistent high-level BOD and ammonia have been inspected in the river, resulting from upstream inflows and delivering significant contaminant loads from the industrial and domestic sewage wastewaters. The Nankan River receives high-tech industries wastewater primarily from the Huaya Scientific Park at the upstream boundary. In addition, the domestic sewage wastewater most contribution sources mainly from Dongmen Creek located at mid-stream reach of the River.

The hydrological and receiving water quality data used to support the model calibration and verification. The receiving water quality data on 2009 and 2010 were conducted at six sampling locations along the Nankan River. Hydrological and water quality sampling stations comprises NK1, NK2, NK3, NK4, NK5, and NK6 which located 25.1, 23.9, 20.4, 16.0, 9.5, and 1.7 km from the downstream river mouth, respectively (see Fig. 3).

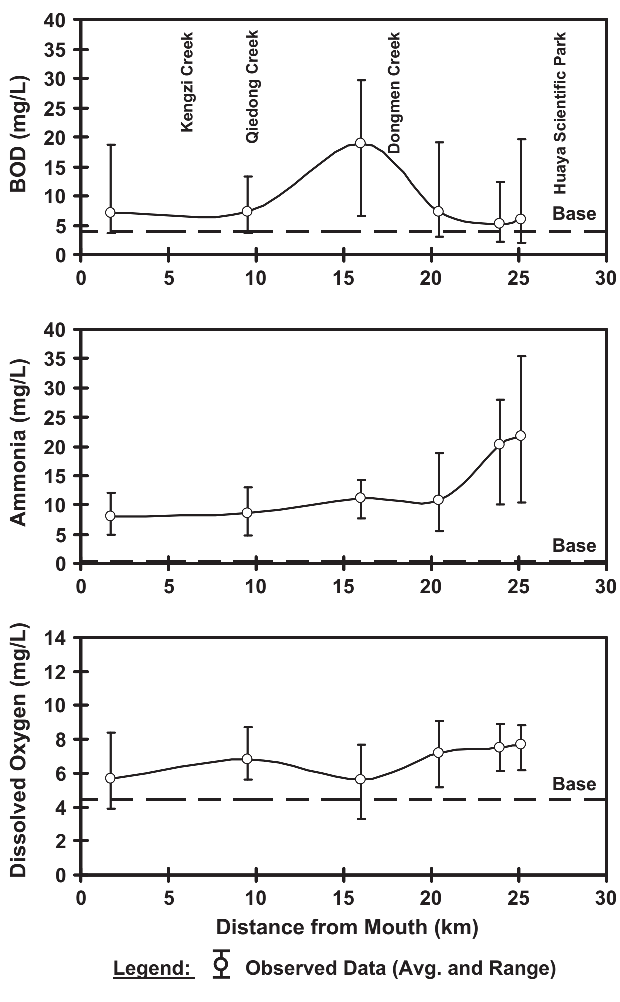

Fig. 4. Measured BOD, ammonia, and DO concentrations at Nankan River during January 2008–December 2010.

Hydraulic geometry parameters such as width, water depth, cross-sectional area, and velocity were measured to provide data for model segmentation. River flows were measured at these six sampling locations along the Nankan River. Receiving water quality including temperature, conductivity, SS, BOD, ammonia, and DO were for analysis and their values were used for comparison with the model results. Fig. 4 show the spatial plots of BOD, ammonia, and DO concentrations measured at Nankan River during January 2009–December 2010, reflecting poor water quality in the River. Particularly, high BOD and ammonia concentrations were observed in the Nankan River. In addition, measured average flow rates and water quality data from WWTP of the Huaya Scientific Park discharge the Nankan River on 2009 and 2010 are presented in Table 1.

The pollutant loading rates calculated by flow rate and respective concentrations from upstream tributaries and drainages are the major inputs to the model. Fig. 5 shows the BOD and ammonia loading rates for these four sets along the Nankan River. Loads from the three major tributaries, including Dongmen Creek, Qiedong Creek, and Kengzi Creek dominate the primary input to the Nankan River. The Dongmen Creek pollution is most serious among the three creeks. The BOD average loading rates were 3,831, 2,074, 2,408, and 2,967 kg/day on March–May 2009, June–September 2009, March–May 2010, and June–September 2010, respectively. The ammonia average rates loading were 1,143, 2,557, 1,111, and 1,253 kg/day between these dates. In addition, there are other point source loads directly into the river.

The analysis of the odors in the Nankan River provided the rationale for pollution and strategies control. Research has showed that primary odor consists of indole, skatole, DMS, and DMTS [12]. Besides, to understand the characteristics of CEC concern, Taiwan EPA and Taiwan Water Resource Agency have established the pollutant database for the Candidate Contaminant List of emerging in public water supply systems since

Table 1
Measured average flow rates and water quality from WWTP of the Huaya Scientific Park on 2009 and 2010

Item	2009	2010
Flow rate (CMD)	54,021	53,756
Temperature (℃)	26.2	25.9
pH	7.5	7.4
COD (mg/L)	48.7	44.5
BOD (mg/L)	14.3	11.2
SS (mg/L)	9.5	11.3

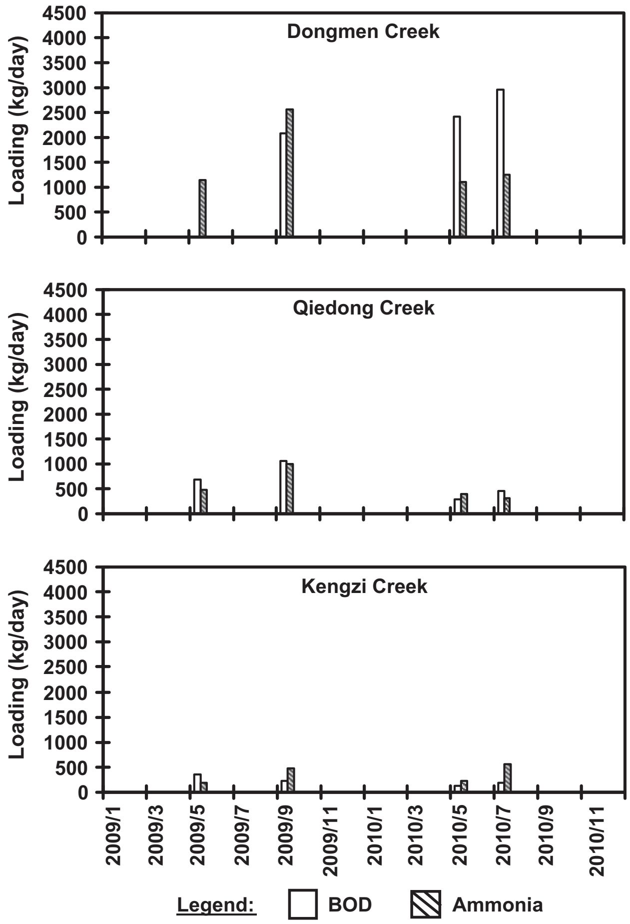

Fig. 5. Measured BOD and NH_3-N loading rates at Dongmen Creek, Qiedong Creek, and Kengzi Creek at quarter average on March–May 2009, June–September 2009, March–May 2010, and June–September 2010.

the beginning of the 2000 [23]. Therefore, the CEC also consider in river basin management in Taiwan.

3.2. SWOT analysis of Nankan River

The SWOT analysis was built in order to identify strengths, weaknesses, opportunities, and threats in the Nankan River Basin. The SWOT analysis for water quality management of Nankan River is shown in Table 2. The SWOT analysis is going to develop water quality strategies for river basin management.

3.3. Stakeholder involvement

Public participation is an important factor in successful TMDL. Public participation includes the stakeholder involvement, river patrol and audit, public education, and outreach. The involvement of the stakeholders was to be adopted in development of the water quality management strategies in the river basin. Stakeholders participation in the whole process including dischargers, citizen groups, and legal agency [24,25].

3.4. River pollution index

The RPI has been widely used to classify the degree of pollution the following water quality constituents includes the BOD, SS, ammonia, and DO by Taiwan EPA. The RPI integral into river water quality were: uncontaminated of <2.0, light pollution of 2.0–3.0, moderate pollution of 3.1–6.0, and serious pollution of >6.0 (see Table 3). The RPI levels at stations NK1 to NK6 of the Nankan River from 2006 to 2010 by TEPA water quality data are presented in Table 1. Result shows the water quality is between moderate and serious polluted of the Nankan River. The station NK4 is the most contaminated, resulting from upstream inflows (Dongment Creek) and delivering a significant amount of domestic sewage wastewater.

3.5. Modeling approach

The QUAL2K model was selected for the Nankan River basin TMDL development. QUAL2K is a river and stream water quality model that is intended to represent a modernized version of the QUAL2E model [26]. QUAL2K is supported by USEPA and has been used extensively for TMDL development and point source permitting issues across the country, especially for issues related to DO concentrations. It is a one-dimensional model with the assumption of a completely mixed system for each computational cell. QUAL2K assumes that the major pollutant transport mechanisms, advection and dispersion, are significant only along the longitudinal direction of flow. The model allows for multiple waste discharges, water withdrawals, tributary flows, and incremental inflows and outflows. The processes employed in QUAL2K address nutrient cycles, algal growth, and DO dynamics. A comprehensive description of QUAL2K model can be found in Chapra et al. [27].

In this QUAL2K model, the mass balance equation for a constituent in an element is written as

$$\frac{dc_i}{dt} = \frac{Q_{i-1}}{V_i} c_{i-1} - \frac{Q_i}{V_i} c_i - \frac{Q_{\text{out},i}}{V_i} c_i + \frac{E_{i-1}}{V_i}(c_{i-1} - c_i) + \frac{E_i}{V_i}(c_{i+1} - c_i) + \frac{W_i}{V_i} + S_i \quad (1)$$

where c_i, V_i, Q_i, E_i, W_i represent the concentration, volume, effluent, dispersion coefficient, and external

Table 2
SWOT analysis for water quality management of the Nankan River

Strengths	Opportunities
• The river pollution remediation and marine pollution prevention is environmental policy objectives of government magistrate. • Taiwan EPA is support promote the river remediation. The factors includes industrial city, population concentrated, transportation network and convenient, and located the international airport. • River basin located in Taoyuan County. Therefore, water quality management by the Taoyuan County EPA responsible. There is no problem across other cities and the counties. • The public authority is fully authorized and assert. Such as source control (industrial area) and ground investigation heavy penalties.	• Tertiary institutions, NGO, and companies support on environmental protection. They can combine with external resources to help promote the river patrol and remediation. • Integration of the county of tertiary Department of Environmental Engineering and the establishment of the industrial services group. To assist vendors pollution abatement consulting services. • Higher environmental awareness of civil society. They are willing to assist the pollution source tracking and reporting for government. • Major rivers have completed the investigation and planning. The remediation objectives and implementation strategies of rivers are more explicit.
Weaknesses	**Threats**
• Numerous industrial zone and sources of pollution-intensive in Taiwan. Enforcement serious lack of human. • Population continues to increase and slow construction of sewage. Impact the water environmental health. • Inadequate funding for river pollution remediation.	• Sustained increase in population and industrial zone, resulting in serious environmental load. • Increasing of High-tech industries. The unidentified environmental pollution increased water health risk. • The river base flow shortage and results decline of the assimilative capacity of pollutants. Water quality shows that serious pollution of rivers.

Table 3
The RPI of the Nankan River from 2006 to 2010

Station	RPI				
	2006	2007	2008	2009	2010
NK1	4.67	4.58	4.19	4.10	4.43
NK2	4.79	4.92	4.27	4.06	4.28
NK3	4.98	4.83	4.48	4.54	4.83
NK4	6.73	6.13	6.06	6.33	6.18
NK5	5.46	4.96	4.96	4.92	4.70
NK6	6.10	5.54	5.52	5.83	5.48

Note: Uncontaminated of PRI < 2.0, light pollution of RPI is 2.0–3.0, moderate pollution of RPI is 3.1–6.0, and serious pollution of RPI > 6.0.

loadings of the constituent to element i, respectively; S_i represents the sources and sinks of the constituent due to reactions and mass transfer mechanisms in element i; and $Q_{\mathrm{out},i}$ represents flow abstraction from element i.

In general, the key kinetic coefficient of the river water quality model includes the BOD_5 deoxygenation rate, nitrification rate, reaeration coefficients, and sediment oxygen demand (SOD). However, uncertainty of the model results lies in the main constraints and limitations of deriving the in-stream key kinetic coefficient. Therefore, continuing monitoring the receiving water with a robust post-audit modeling would be useful in tracking the success of the water quality management strategies in the future [10].

3.6. Statistical analysis of model results

A qualitative evaluation of the success of the model calibration in this study can be made by inspection of the agreement between the calculated temporal distributions and the data. A variety of statistical comparisons may be appropriate to quantify model comparison with field data. The comparison of mean absolute and the root-mean-square errors were evaluated as follows [28]:

Means absolute error:

$$\overline{x} = \frac{\sum |x_i - C_i|}{N} \tag{2}$$

where $\overline{x}$ = mean absolute error, x_i = model results, C_i = field data, and N = number of data points.

Root-mean-square error:

$$r = \left[\frac{\sum (x_i - C_i)^2}{N}\right]^{0.5} \tag{3}$$

where r is the root-mean-square error.

3.7. Cost-effectiveness analysis

CEA is useful tool for program evaluation and is most practical when comparing projects of similar sizes [29,30]. Therefore, the CEA approach was used to implement river water quality management strategy plans in the study. CEA seeks to identify and place dollars on the costs of a program. It then relates these costs to specific measures of program effectiveness. Analysts can obtain a program's CE ratio by dividing costs by what we term units of effectiveness:

$$\text{Cost} - \text{Effectiveness ratio} = \frac{\text{Total cost}}{\text{Units of effectiveness}} \tag{4}$$

Units of effectiveness are simply a measure of any quantifiable outcome central to the program's objectives.

Summaring the present value of the costs (PVC) in each year, the PVC for the whole project is

$$\begin{aligned} \text{PVC} &= C_1 + \frac{C_2}{(1+r)^1} + \frac{C_3}{(1+r)^2} + \cdots + \frac{C_r}{(1+r)^{r-1}} \\ &= \sum_{t=1}^{T} \frac{C_t}{(1+r)^{t-1}} \end{aligned} \tag{5}$$

where r = a social discount rate, C_t = each year's costs, and t indicates the year from 1 to T.

The PVC is then to calculate the CE ratio. Substituting Eq. (5) into Eq. (4), the CE ratio can be expressed as:

$$\text{Cost} - \text{Effectiveness ratio} = \frac{\text{PVC}}{\text{Units of effectiveness}} \tag{6}$$

In this study, the annual cost taken into consideration includes the (1) planning design with engineering facilities and sustainable management fees of site river water purification system and (2) pollution inspector fee of river. The work operating considerations were investment of 20 years and 3% discount rate for site river water purification system. The unit of effectiveness is based on the annual investment in BOD water quality improvement benefits. The results obtained from the product of BOD reduction pollution loads of year and wastewater treatment cost of WWTP.

4. Results and analyses

4.1. Model development

The QUAL2K mode was developed based on the data provided in problem settling and river characterization. The QUAL2K model is configured as 26 segments and each of which was 1,000 m along the longitudinal cross-section watercourse for the 25.1 km reach from the upstream to downstream boundary (river mouth) of the Nankan River. In addition, water quality data required by the QUAL2K model include upstream and downstream boundary conditions, and geometric data for each segment. Depth and width for each segment are derived as a function of flow and hydraulic coefficients.

In this study, numerous model runs were conducted to calibrate the water quality model parameters (i.e. kinetic coefficients and constants). In general, the parameters for the water quality model are consistent with literature values [31–33]. For this study, a BOD deoxygenation rate and a nitrification rate of 0.15 and 0.12 day^{-1} was used in the model calibration and verification analysis, respectively. The Tsivoglou equation [34] was adopted in this study for calculating in-river reaeration coefficients due to the small flow rates in the receiving stream. The reaeration coefficients were between 0.13 and 17.07 day^{-1}. There was no available data on SOD in the Nankan River. Literature values ranging from 1 to 2 $\text{gm}\,O_2/\text{m}^2/\text{day}$ for aged sludge downstream of the outfall were reported by Thomann and Mueller [32]. An SOD of 0.48 $\text{gm}\,O_2/\text{m}^2/\text{day}$ was adopted in this study.

4.2. Model calibration and verification

Mass transport modeling is designed to track the attenuation of a conservative tracer along the Nankan River prior to the BOD/DO modeling. The QUAL2K model was configured to model specific conductivity. Boundary conditions from tributaries and point sources are incorporated into the model. Fig. 6(a)–(d) shows the model calculated conductivity levels and measured values in the Nankan River (at six locations) from the steady-state mass transport analysis for quarter average on March–May 2009, June–September 2009, March–May 2010, and June–September 2010. Model results match the spatial trend of conductivity very well. Since receiving high-tech

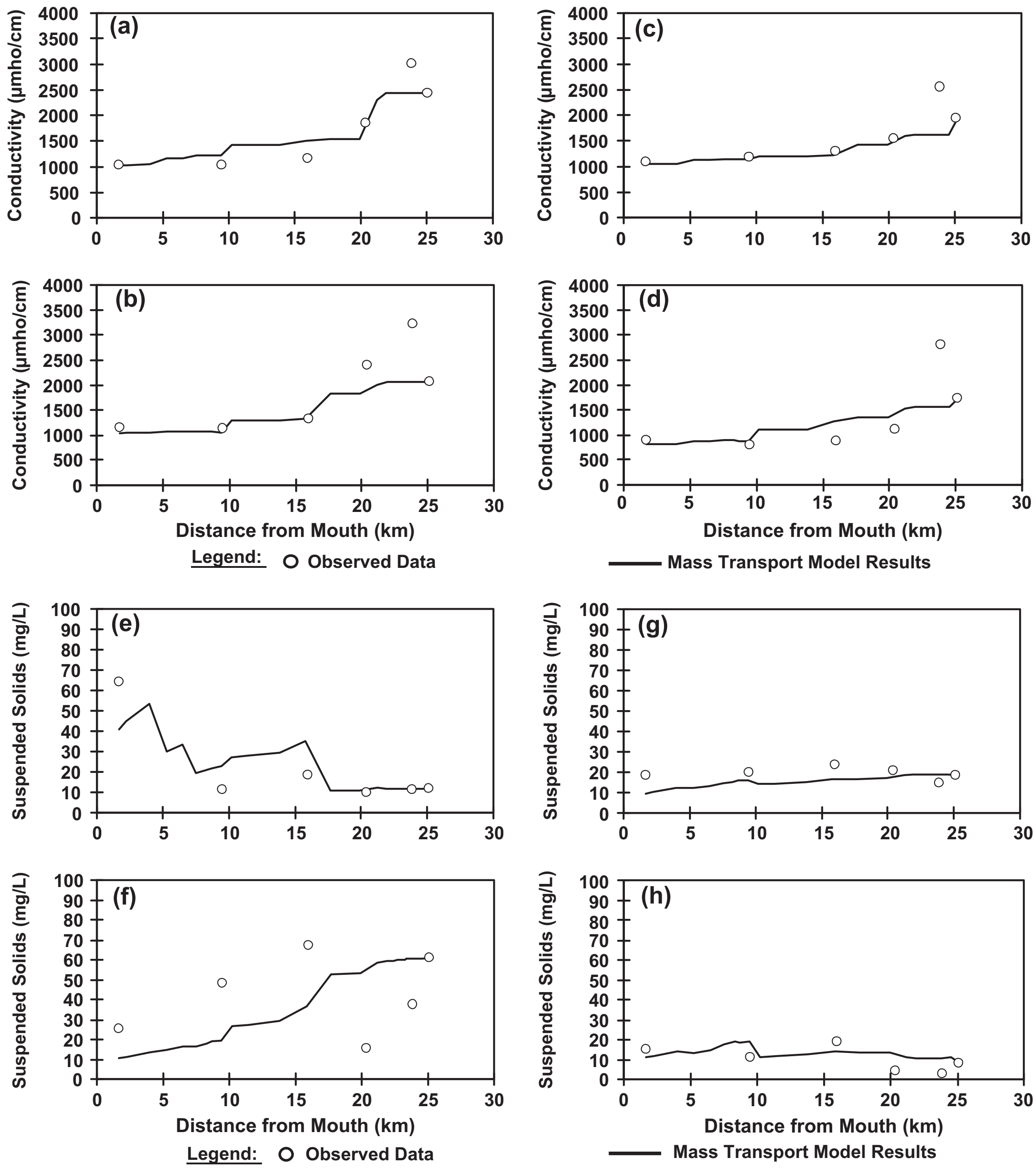

Fig. 6. Steady-state mass transport model results vs. data for the Nankan River at quarter average on March–May 2009, June–September 2009, March–May 2010, and June–September 2010. (a)–(d) specific conductivity, (e)–(h) SS.

industrial wastewater discharge from the Huaya Scientific Park of the Nankan River upstream. In particular, high-level conductivity concentrations in the water column of the river were measured.

The calibrated mass transport model was then used to calculate the concentrations of SS in the receiving water. Because SS ultimately settles into the sediment, the key parameter in modeling SS is the assignment of the settling velocity. For this calculation, a settling velocity of 0.05 m/day was selected. Model results for the SS for quarter average on March–May 2009, June–September 2009, March–May 2010, and June–September 2010 also are presented in Fig. 6(e)–(h). The model results match the spatial trend of SS quite well. The mass transport coefficients developed from this analysis were used in the subsequent water quality simulations.

The water quality model was first calibrated with the quarter average on March–May 2009 and June–September 2009 data-sets. The quarter average on March–May 2010 and June–September 2010 datasets were then used to verify the model using the calibrated model coefficients. The boundary conditions for the water quality model include the ammonia, nitrite/nitrate, BOD, DO, and organic nitrogen at the upstream and downstream of river. BOD, ammonia, and DO loads from point sources are derived from the data for each survey.

The water quality model were with field data for BOD, ammonia, and DO concentrations in the Nankan River for quarter average on March–May 2009 and June–September 2009 are presented in Fig. 7. The BOD levels gradually rose and reached a peak 16 km from river mouth. Water quality surveys revealed that the majority of the Nankan River by the Dongmen Creek of 16.3 km from river mouth. The high-level ammonia was decrease from mainflow upstream to

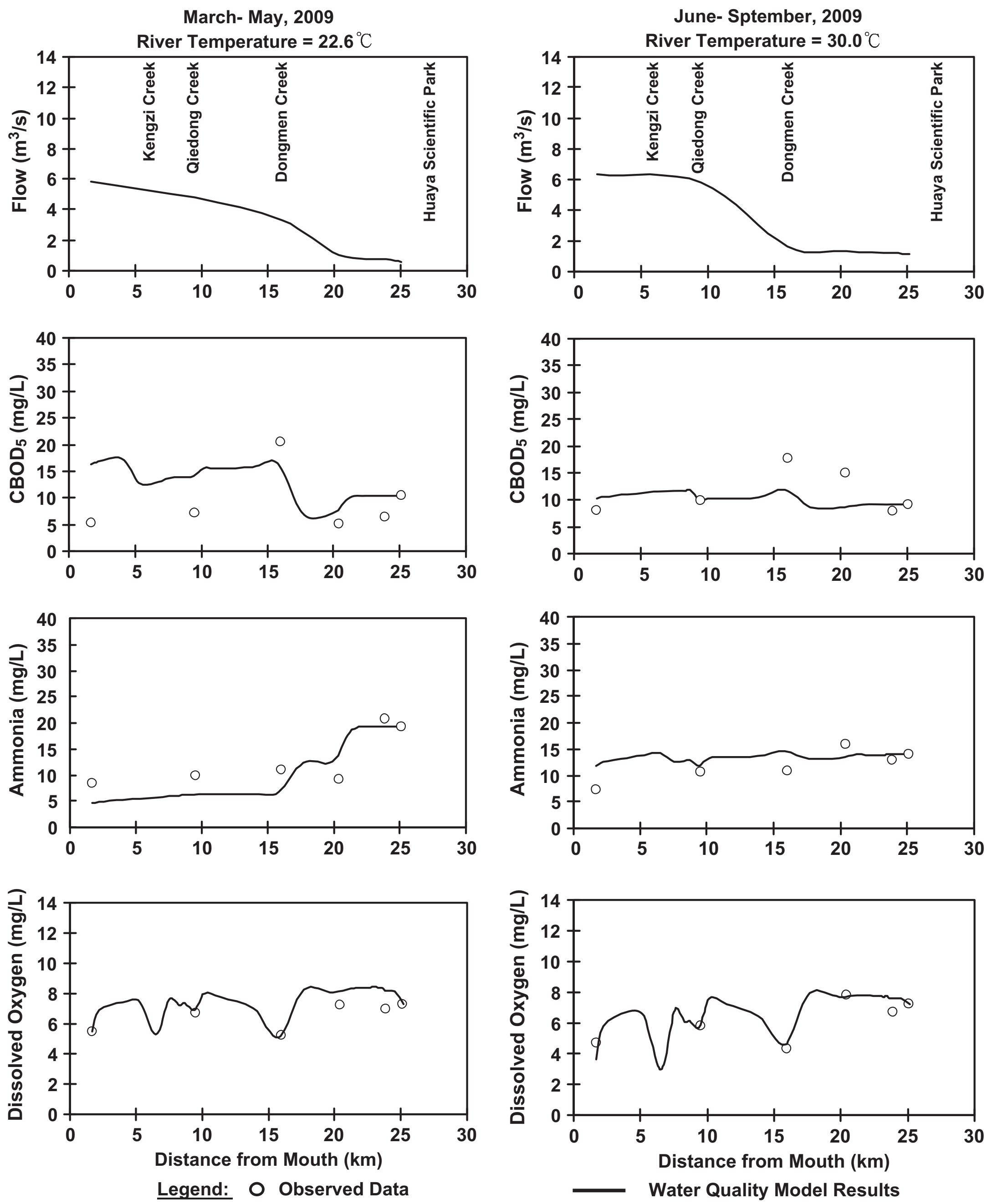

Fig. 7. Steady-state model results vs. data for BOD, ammonia, and DO of average on March–May 2009 and June–September 2009 in the Nankan River.

river mouth in the Nankan River. Due to receiving high-tech industrial wastewater discharge from the Huaya Scientific Park, resulting water quality is rather worse in the upstream of Nankan River for study periods. DO levels almost are above 5 mg/L between these dates although BOD and ammonia concentrations are high. Also shown are the river flows along Nankan River for these two surveys. In general, the model results match the field data reasonably well. Validation of a calibrated model with an independent data-set is meant to under environmental conditions similar to those under which the model was calibrated. With this goal, the calibrated model was applied to average on March–May 2010 and June–September 2010 conditions. The water quality model results of the Nankan River are displayed between these dates and they match the measured data well in study period (see Fig. 8).

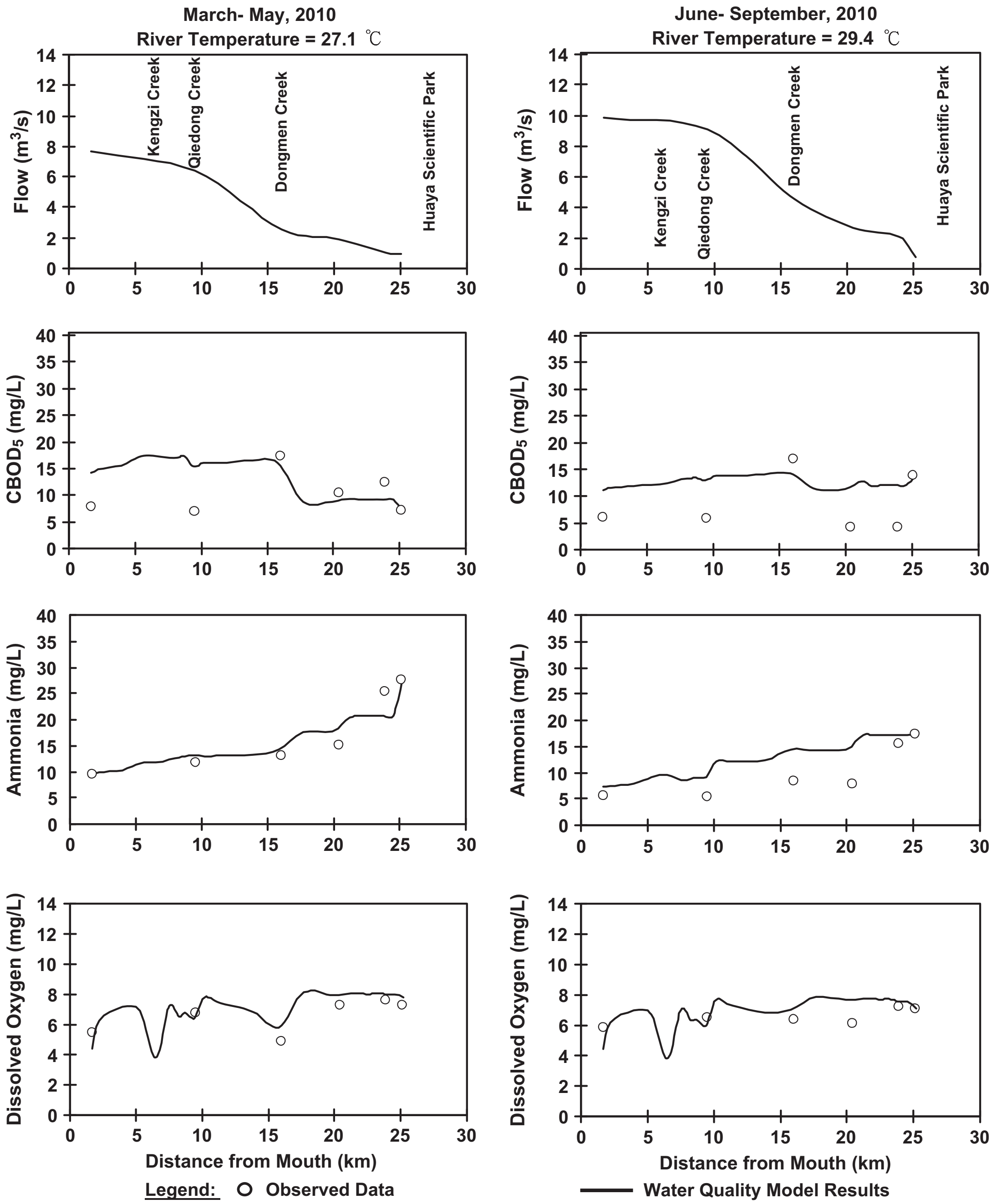

Fig. 8. Steady-state model results vs. data for BOD, ammonia, and DO of average on March–May 2010 and June–September 2010 in the Nankan River.

In addition, a qualitative evaluation of the model calibration can be made by the statistical results. The mean absolute errors of the differences between model results and field data for are 4.01, 2.51, and 0.54 mg/L for BOD, ammonia, and DO, respectively. The corresponding root-mean-squares errors are 5.11, 3.17, and 0.7 mg/L for BOD, ammonia, and DO, respectively. The accuracy of the model appears to be satisfactory for the model prediction and for the evaluation of future TMDL management strategies.

4.3. Application of TMDL development

Once calibrated and verified, the BOD/DO model was used to quantify the point source pollution assessment and determine the TMDL. The first step in determining a TMDL is to identify the appropriate endpoint that is needed for the waterbody to attain its designated use. The Nankan River water quality criterion for BOD and concentration of ammonia the surface water quality standards promulgated by the Taiwan EPA. According to this target, the TMDL was established for the Dongmen Creek, Qiedong Creek, and Kengzi Creek and specifying the allowable BOD and ammonia loading that could enter the Nankan River.

Table 4 shows the two sets evaluation of wastewater alternatives critical conditions for the Nankan River. The BOD loading rates were reduced to 707 and 1,334 kg/day for scenario I and scenario II, respectively. The ammonia loading rates were reduced

Table 4
Two sets evaluation of wastewater alternatives critical conditions for the Nankan River

Water quality parameter	Dongmen Creek	Qiedong Creek	Kengzi Creek
Reduction loading rates of Alternative 1			
BOD (kg/day)	707	0	0
Ammonia (kg/day)	256	0	0
Reduction loading rates of Alternative 2			
BOD (kg/day)	707	406	221
Ammonia (kg/day)	256	464	169

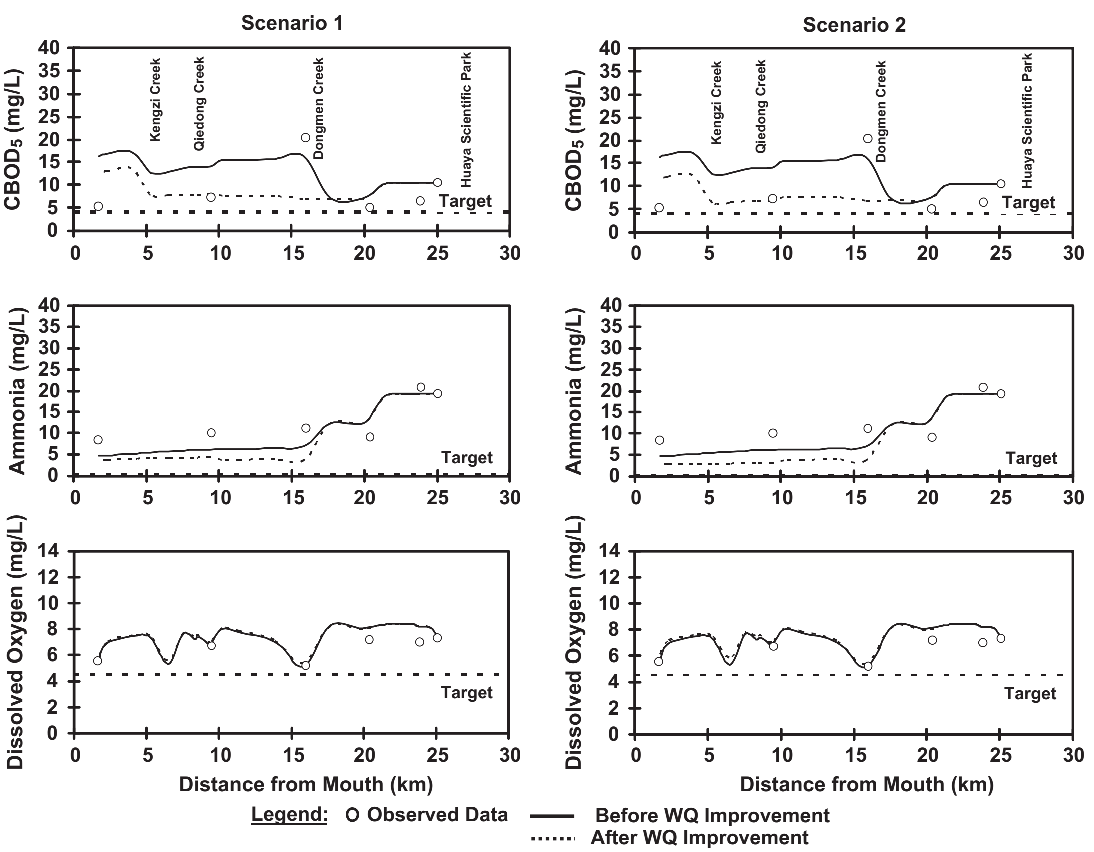

Fig. 9. Two scenarios for the improve meet of assimilative capacity of BOD, ammonia, and DO concentration in the Nankan River.

to 256 and 889 kg/day for scenario I and scenario II, respectively. The results of the model projections are summarized in Fig. 9, showing predicted BOD, ammonia, and DO levels under scenarios I and II. BOD and ammonia level decrease at a location about 16.0 km from the downstream end. In addition, the DO increased in same reach. The water quality improvement evaluation results were supported to improve the RPI and odor as well as CE strategy plans of TMDL in the Rankan River.

Three sets evaluation scenarios and CEA of TMDL for the Nankan River is summaried in Table 5, includes of point source loading reduction, water quality improvement (RPI, odor, and CEC), and CEA. The IWMP and KPI were used to develop those scenarios. The CEA was used to assessment the BOD water quality improvement for water environmental health benefits. In this study, according to planning design with engineering facilities and sustainable management fees of site river water purification system as well as pollution inspector fee of river, the total annual costs of US$ 3,666,666. The costs obtained from follows: (1) US$ 3,333,333 and US$ 233,333 of planning design with engineering facilities and sustainable management fees in site river water purification system, respectively and (2) US$100,000 pollution inspector of river. The net present value of costs (PVC) is US$ 8,292,107 under the discount rate of 3% for investment of 20 years conditions using Eq. (5) calculation. The unit of effectiveness that obtained from the product of BOD reduction pollution loads of year and wastewater treatment cost of WWTP. The CEA results also show that an annual cost of US$ 8,292,107 is required to reach the acceptable RPI level (moderate pollution).

By implementing the TMDL with QUAL2K model to the study river, the effects and performance for the elimination of the point and nonpoint source pollutants were critically assessed. The results showed that pollution inspection, domestic sewage, and industrial wastes reduction were beneficial to the water environment. The TMDL restoration plan suggested that concurrent effort on the receiving waterbody must be carried out to maximize the water quality improvement and integrate watershed management programs into the daily life of the publics in the Nankan River.

Table 5
Three sets evaluation and CEA of TMDL scenarios for the Nankan River

Items	High Scenario I	Medium Scenario II	Low Scenario III
Loading reduction (kg/day)			
Point source (BOD)	1,334	934	667
Point source (ammonia)	889	622	445
Non-point source	–	–	–
Water quality improvement			
RPI	3.1–4.0	4.1–5.0	5.1–6.0
Odor	no DMS and DMTS	no skatole	no indole
CEC	–	–	–
Total cost (US$)	3,666,666	3,666,666	3,666,666
Planning design with engineering facilities cost	3,333,333	3,333,333	3,333,333
Sustainable management cost	233,333	233,333	233,333
Pollution inspector cost of river	100,000	100,000	100,000
PVC (US$, at $r = 3\%$ and $t = 20$ years)	8,292,107	8,292,107	8,292,107
Unit of effectiveness	1,030,626	721,592	515,313
CE ratio	8.05	11.49	16.09

5. Conclusions

A system approach was developed of a river basin water quality management using the QUAL2K model incorporating TMDL approach, KPI, and CE strategy plans in this study. It is recommended to link the KPI with TMDL program as to establish implementation strategy. TMDL is an important tool for water pollution control including point or nonpoint sources. The key factors for success include: (1) government lead and support in term of funding, regulatory framework, and technical guidance; (2) coordination among agencies such as Taiwan EPA and agricultural agency; and (3) stakeholders participation in the whole process including dischargers, citizen groups, and legal agency. In addition, SWOT analysis also serves as a first response to the problems and improvement opportunities observed in the river.

To accomplish the goals of the Taiwan EPA Integrated Watershed Management Plan (IWMP), three major tasks are proposed to the local government to enhance the ecological efficiency, restoration, and conservation. The tasks include: (1) habitat and biodiversity conservation; (2) river corridor protection; and (3) land protection programs and local use ordinances. The local government is also recommended to: (1) promote ecological engineering; (2) routinely maintain major habitats; (3) conduct ecosurvey; (4)

construct or create wetlands; and (5) establish local long-term ecological database including biological indices database to accomplish the above goals. In addition, the other recommended of this study include the following:

(1) The implementation of pollution reduction programs within watershed still need to be strengthened. Construction of sewage lines and control of NPS pollutants should be considered a national priority as to achieve the newly planned national environmental protection plans. Furthermore, it is recommended to simulate water quality using relevant modeling tools as a means to justify the implementation of water pollution control programs.
(2) It is recommended to budget issue, outcome assessment tools, and evaluation of ecological and environmental benefits are considered major steps during the design of and implementation of national water protection policy. Specifically, it is recommended that a national sewage fee, a long over due policy, be implemented as soon as possible to generate revenue necessary for the implementation of TMDL system and the construction of public sewage treatment and storm sewage collection facilities.
(3) Clearly establish roadmaps for various national water protection initiatives to include water quality objective and other quantifiable objectives such as ecological benefits, administrative effectiveness, water front accessibility, and participation by public and stockholders.
(4) Increase the involvement by institutes, commercial entities, individual citizens, and "not-for-profits" organizations (NGO) that have common interest in the specific watershed and adjacent area during the participation stage and later the implementation and the management of the watershed protection programs.
(5) Foster ecological benefits in all watershed management programs. Encourage the participation of local organizations that have deep interest and involvement with and have invested their resources in the ecosystem of the stated watershed.
(6) All action plans of national water pollution prevention and watershed protection must consider how to strengthen the accessibility to water front and integrate watershed management programs into the daily life of the publics.

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