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Model-based carrying capacity investigation and its application to total maximum daily load (TMDL) establishment for river water quality management: A case study in Taiwan

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ABSTRACT

The carrying capacity of a river was explored through combining use of HEC-RAS and Qual2K and the obtained results were applied to establishing the total maximum daily load (TMDL) system for water quality management, considering three water quality protection (i.e., long-, mid- and short-term) targets and two wastewater reduction strategies (i.e., individual- and group-reductions). Group-reduction control strategy was regarded as a better pollution control measure, in which more pollution reduction in high volume wastewater discharges resulted in a better improvement of river water quality. While many studies statistically investigated the conceptual framework of carrying capacity under the premises of mass balance between pollution sources and sinks, this study quantified the carrying capacity and established a TMDL system based on the respective water quality criteria using water quality modelling.

1. Introduction

Water is indispensable to all forms of life. To ensure the long-lasting of human civilization, the United Nations has proposed the sustainable development goals (SDGs) of 2030, in which water resource conservation, utilization, consumption and reclamation are among the major tasks that should be enforced (Mugagga and Nabaasa, 2016). Along with these concepts, sustainable water resource management has been regarded as an inevitable responsibility of the government and water quality protection becomes an important work to assure human sustainability.

Over the years, water quality modelling has been considered as a useful tool for water quality optimization, which was applied to exploring the suitability of proposed pollution control policies (Bui et al., 2019; Elshorbagy and Ormsbee, 2006; Taherisoudejani et al., 2018). For example, Nadiri et al. (2018) used the supervised committee fuzzy logic model to predict the effluent water quality of a wastewater treatment plant. Wang et al. (2019b) conducted a river basin water resource optimization study combining the calculation modules of allocation, optimization and simulation for water quantity and quality prediction. Ishikawa et al. (2019) analysed a water quality risk using the Advanced Industrial Science and Technology-Standardized Hydrology-based AssessmeNt tool for chemical Exposure Load (AIST-SHANEL) model. Abokifa et al. (2016) utilized a modelling technique to calculate the disinfectant residuals in the dead ends of a drinking water distribution system and an enhanced accuracy was achieved by considering the spatio-temporal variation of flow demands. Crabtree et al. (1999) applied the model simulation to estimating the integrated environmental impact assessment and cost-benefit analysis for strategic management of ambient water bodies.

Kamal et al. (2020) conducted simulations of various pollutant discharge scenarios using QUAL2K software, and mapped with ammonium nitrogen as the core pollutant using an integrated QUAL2K-GIS. The methodology and analysis developed in this study can assist various stakeholders and authorities in identifying problematic areas and determining the required percentage of pollution reduction to improve the Skudai River water quality. In the study by Hoang et al. (2019), the outputs of SWAT model were

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used as inputs to the QUAL2K to simulate the water quality of Cau River in Vietnam. The obtained results could be used to support water quality management and control in the Cau River basin. Gomez et al. (2019) investigated the ability to improve flood inundation forecasts at short-to medium-range (1–7 days) time scales using the Hydrologic Engineering Center's River Analysis System (HEC-RAS) coupled to a regional hydrological ensemble prediction system (RHEPS). The results showed that the integrated models can be used to enhance the skill of flood inundation forecasts and may serve to enhance the spatial representation of flood forecasts several days in advance. Wang et al. (2018) developed the polygon-based riparian vegetation simulation module (RVSM) and integrated such model into HEC-RAS one-dimensional flow model to predict spatially-explicit seed germination, seedling establishment, plant growth and mortality in response to fluvial processes. The results demonstrated that the HEC-RAS-RVSM system reproduced the coverage increase of cottonwood, riparian shrub, invasive species and grass as well as the coverage decrease in mixed forest over the eight-year. The RVSM was able to capture sites for cottonwood establishment observed on certain point bars.

Given the complexity and dynamic features of the natural aquatic environment, many studies have been reported on the applications of modelling technique to a variety of scenarios with different physical and chemical simplifications for water quality management. Among the well-documented water quality models, Qual2K is popular because it is straight-forward and easy to use (Barmaki and Nadoushan, 2018; Chaudhary et al., 2019; Yang and Yu, 2018). It calculates water quality using the concept of mass conservation. Its inability to evaluate hydraulic characteristics accurately is an often-observed disadvantage. In order to correct such a weakness, Fan et al. (2009) used the HEC-RAS to calculate the hydraulic parameters, which were subsequently substituted into the mass transport equation for water quality simulation. The combining use of HEC-RAS and Qual2K was shown to be able to calculate the water quality of a river accurately.

To manage the aquatic environment, the surface water body classification and criteria were proposed as the ultimate goal of water quality standards oftentimes. Meanwhile, the discharge permit system and compliance of effluent water quality standards were also enforced as a parallel measure for water pollution control. Unfortunately, water pollution incidents and deterioration of ambient water quality have been observed from time to time. Given the possible occurrence of water pollution incidents, the TMDL control system becomes an attractive alternative for improving water quality since the enforcement of effluent discharge standards may not be as effective as expected, especially for the areas where industrial factories are densely established (Lai et al., 2013; Leveque and Burns, 2017). A TMDL is the estimated maximum amount of a pollutant allowed to be released into a water body to meet a designated water quality standard for that particular pollutant. A TMDL system should include the determination of a pollutant reduction target and the allocation of waste load reduction to the pollution sources.

Kang et al. (2006) employed the soil and water assessment tool (SWAT) to establish the TMDL program for a small watershed including rice paddy fields in Korea. Zhang et al. (2015) developed an environmental decision support system which was applied to constructing the TMDL framework for Beiyun River pollution control. In the study by Liang et al. (2016), a Bayesian approach was employed for model parameter uncertainty analysis of a TMDL system, and wide ranges of allowable loads were obtained through uncertainty propagation. Wu et al. (2018) employed an integrated modelling framework to evaluate the water balance and carrying capacity in a continental river basin of northwest China by coupling the SWAT, water resources supply and consumption model, principal component analysis (PCA) and fuzzy comprehensive evaluation (FCE). Kr Gurjar and Tare (2019) employed the water quality modelling technique to estimate the organic loading capacity and the result was applied to river water quality management. Wang et al. (2019a) investigated the comprehensive carrying capacity of selected water bodies from the perspectives of (1) the water resource balance capacity, (2) water resource pressure and driving force and (3) water resource development and utilization capacity. Ahmadisharaf and Benham (2020) applied the Generalized Likelihood Uncertainty Estimation (GLUE) to Hydrological Simulation Program-FORTRAN (HSPF) to evaluating two bacteria reduction scenarios from a developed TMDL that dealt with the bacterial impairment in the US. The results showed that achieving water quality goals with very high reliability was not possible, even with extreme levels of pollutant reduction. The risk-based management framework can be used to propagate watershed model uncertainty and assess performance of alternative pollutant reduction scenarios, enabling decision makers to understand the reliability of a given scenario in achieving water quality goals. Obviously, many TMDL studies emphasized the waste allocating strategy considering the removal of all the aqueous contamination once produced to maintain the environmental quality in the investigated area. Meanwhile, some of these studies investigated the TMDL compliance using statistical approaches while the other might establish the modelling framework considering physical transport and chemical reactions in the aquatic environment.

Generally, the TMDL system has been recognized as an effective strategy for pollution mitigation in addition to the concentration-based control measures. In the literature, many studies conducted the carrying capacity and TMDL investigations using statistical approaches considering the balance between pollution sources and sinks, hoping to maintain the environmental quality under the stress of industrialization and urbanization. Nevertheless, the quality improvement of the aquatic environment remains questionable because (1) the pollution discharges in the area of interest may not all be observed and eliminated and (2) pollution mitigation by natural attenuation may not be as effective as expected.

In the present study, a different approach was employed in the present study, in which the carrying capacity of a river was determined based on a prescribed protection criterion and the corresponding remediation strategies were proposed to calculate the amount of contamination allowed to be discharged into the investigated water body. This study aimed to establish a TMDL system using the carrying capacity with respect to the designated water quality criteria and to evaluate the effects of wastewater reduction strategies through water quality modelling. To the best of our knowledge, little-to-no research has been reported on evaluating the carrying capacity of a waterbody and planning the TMDL control measures based on the prescribed criteria in combination with a modelling framework. The combination of HEC-RAS and Qual2K was applied to simulating the water quality of Jing-Mei Creek. The verified water quality model was further used to estimate the carrying capacity and establish an exemplary TMDL system. Different pollution reduction strategies were proposed, and the improvement in water quality was compared.

2. Materials and methods

2.1. Study background

In the present study, the Jing-Mei Creek in northern Taiwan was selected as the investigated watershed because it is an important urban water resource of high degree of biodiversity. The hydraulic and water quality data were adopted from the database maintained by Water Resources Agency and Taiwan Environmental Protection Administration (TEPA). In the investigated watershed, two water quality monitoring stations were installed (i.e., Bao-Chiau and

Wan-Sho) and 20 municipal wastewater discharges were identified as the major sources of water pollution. The contamination loadings were analysed (TEPA, 2005), and their flowrates were measured and are reported in Table 1.

In the investigated area, domestic sewage and surface runoff were the major pollution sources. The biochemical oxygen demand (BOD), suspended solid (SS), ammonium nitrogen (NH_3—N) as well as dissolved oxygen (DO) were the four water quality indices investigated. BOD and NH_3—N are the main aqueous contaminants in domestic sewage, and SS is the major pollutant in surface runoff. DO is an often-used water quality index that reflects the vitality of an aquatic environment in an integrated assessment. The monitoring data collected by the TEPA were employed in this study for model calibration and verification.

2.2. Model establishment

For the water quality simulation of Jing-Mei Creek by Qual2K, the river was divided into 46 segments according to its hydraulic and topographical characteristics (as shown in Fig. 1). Also shown in Fig. 1 is the geographic map of Jing-Mei Creek. A geographical location with an apparent change in river width, water depth or riverbed slope was delineated as the end of one segment and the beginning of the next one. Each segment was assumed to be a completely-stirred tank reactor (CSTR). In the present study, Q_{75}, the flowrate at which the chance of the actual flowrate equalling or exceeding the designated flowrate is 75%, was used as the simulated flowrate.

The Qual2K model, developed by US Environmental Protection Agency, was employed for water quality simulations. In the Qual2K model, the mass balance for a constituent (C) in an element (i) is expressed as,

$$\frac{dC_i}{dt} = \frac{Q_{i-1}}{V_i}C_{i-1} - \frac{Q_i}{V_i}C_i - \frac{Q_{out,i}}{V_i}C_i + \frac{E_{i-1}}{V_i}(C_{i-1} - C_i) + \frac{E_i}{V_i}(C_{i+1} - C_i) + \frac{W_i}{V_i} + S_i \tag{1}$$

in which C_i, V_i, Q_i, E_i, W_i represent the concentration, volume, effluent, dispersion coefficient, and external constituent loading of element i, respectively; S_i represents the sources and sinks of the constituent due to reactions and mass transfer mechanisms in element i; $Q_{out,i}$ represents flow abstraction from element i. To simulate the water quality, the degradation constant of each contaminant and hydraulic characteristics of flow velocity and water depth are required. All the parameters were obtained from previous studies or calibration. The re-oxygenation constant, k_2, may be calculated using equations (2)–(4):

$$\text{O'Connor} - \text{Dobbins: } k_2 = 3.93\frac{U^{0.5}}{H^{1.5}} \quad \left(H > 0.61\text{m and } H > 3.45U^{2.5}\right), \tag{2}$$

$$\text{Owens} - \text{Gibbs: } k_2 = 5.32\frac{U^{0.67}}{H^{1.85}} \quad (H < 0.61), \tag{3}$$

$$\text{Churchill: } k_2 = 5.026\frac{U}{H^{1.67}} \quad (\text{situation other than the above}), \tag{4}$$

where U represents the flow velocity (m/s), and H represents the water depth (m). The required flow velocity and water depth were obtained with equations (5) and (6), as proposed by Leopold and Maddock (1953):

$$U = aQ^b, \tag{5}$$

Table 1
The calculated carrying capacities and reduction percentages of BOD, SS and NH_3—N for the investigated wastewater discharges.

Drainage channel	Monthly flowrate (CMS)	SS, kg/day						BOD, kg/day						NH_3—N, kg/day					
		Carrying Capacity			Reduction Ratio, %			Carrying Capacity			Reduction Ratio, %			Carrying Capacity			Reduction Ratio, %		
		short	Mid	long[a]	short	mid	long[a]	short	mid	long[a]	short	mid	long[a]	short	mid	long	short	mid	long
The drainage next to Mu-Zha MRT Workshop	0.075	1373	498	–	0	0	–	460	233	–	0	80	–	149	90	15	0	0	70
Wan-Fang Pumping Station	0.319	2201	1375	–	0	0	–	495	302	–	10	90	–	220	137	56	30	60	90
Mu-Xin 2nd Sluice Gate	0.020	521	293	–	0	0	–	138	100	–	0	97	–	43	25	13	0	0	0
Dao-Nan Pumping Station	0.102	512	353	–	0	0	–	132	66	–	70	95	–	49	26	14	30	60	80
Zhi Nan Xi	0.218	696	414	–	0	0	–	282	188	–	0	0	–	57	33	18	30	60	80
Wu Ming Xi Pumping Station	0.007	544	362	–	0	0	–	241	157	–	0	0	–	3	1	10	50	70	0
Mu-Xin Pumping Station	0.037	223	117	–	0	0	–	94	47	–	40	60	–	45	25	13	0	10	60
Lao Quan Xi Pumping Station	0.059	749	489	–	0	0	–	402	288	–	0	0	–	66	38	19	0	0	30
Bao-Kao Pumping Station	0.107	832	508	–	80	90	–	258	166	–	70	80	–	92	55	27	0	0	40
Bao-Chiau Pumping Station	0.186	724	402	–	30	60	–	160	104	–	91	93	–	48	28	17	70	90	90
Tie-Gong 3rd Water Gate	0.129	245	156	–	0	40	–	111	72	–	90	90	–	19	11	7	90	94	96
Bao- Yi Pumping Station	0.191	197	131	–	60	80	–	98	49	–	92	95	–	5	2	1	98	99	99
Shi-Jian Pumping Station	0.099	68	42	–	60	70	–	72	34	–	80	90	–	3	1	1	97	98	99
Zhong-Gang Pumping Station	0.295	242	178	–	30	50	–	216	102	–	80	80	–	11	17	3	94	91	99
Bao-Yuan Pumping Station	0.218	319	206	–	30	60	–	93	75	–	90	90	–	7	7	2	97	97	99
Pi-Fu Pumping Station	0.090	121	74	–	10	40	–	58	23	–	90	90	–	8	7	1	90	99	99
Shih-Sin 3rd Water Gate	1.662	1723	1005	–	60	80	–	689	574	–	90	91	–	158	107	45	90	92	97
Wu-Ji Section Water Gate	3.344	3322	2166	–	70	80	–	1271	953	–	92	95	–	289	187	103	91	94	97
Jing Mei Xi 1st Sluice Gate	0.311	349	188	–	80	90	–	201	107	–	90	92	–	27	17	8	91	94	98
Xin Dian Xi 2nd Sluice Gate	0.131	135	78	–	0	0	–	105	47	–	80	90	–	11	7	4	80	90	94

[a] The ultimate goal of ambient water quality is less stringent than the mid-term target, therefore long-term target criteria were adopted from the mid-term target criteria.

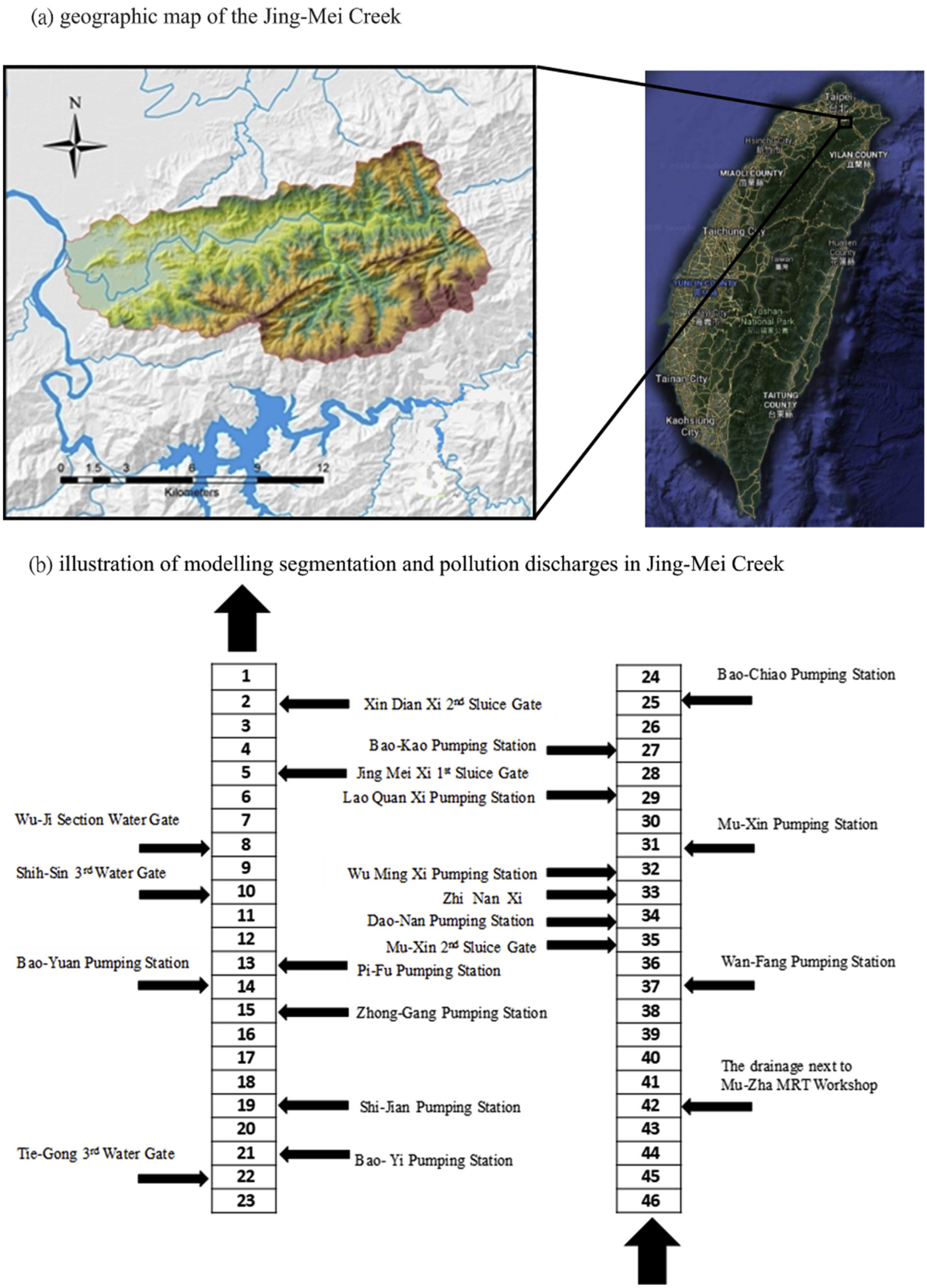

Fig. 1. Schematics of the (a) geographic map of Jing-Mei Creek and (2) illustration of modelling segmentation and pollution discharges in Jing-Mei Creek.

$$H = cQ^d, \tag{6}$$

where Q is the flowrate (m^3/s), and a, b, c, d are the empirical hydraulic characteristic constants. The required re-aeration constants were obtained through equation (2) and (3), or (4) depending on the flow velocity and water depth for each calculation unit. Meanwhile, Fan et al. (2009) indicated that adopting the values of a, b, c and d constant from the literature to obtain the flow velocity and water depth may result in an inaccurate calculation because these literature constants might not properly reflect the hydraulic and topographic characteristics of the investigated watershed. To improve the calculations, these constants (i.e., a, b, c, d) were estimated using HEC-RAS, a hydraulic model developed by the US Army Corps of Engineers (US Army Corps of Engineers, 2019).

HEC-RAS is a one-dimensional steady flow hydraulic model designed for channel flow analysis and floodplain determination. It calculates water surface profiles with the direct step method by assuming a steady and gradually varied flow condition. The basic computational procedure is based on an iterative solution of the energy conservation equation.

Following the methodology in the studies by Fan et al. (2009, 2012), the flowrates were analysed statistically, and the Q_{75} flowrate was used in the water quality simulation. The empirical constants (i.e., a, b, c, and d) in Eqs. (5) and (6) were obtained through HEC-RAS calculation. For a given cross-section, several selected flowrates were calculated using HEC-RAS to obtain flow velocities and water depths, and these water depths and flow velocities were regressed with flowrates to obtain the empirical constants for the specific cross-section. Similar calculations were performed for all cross-sections of the investigated river. These water depth and flow velocity calculation results were utilized to assess the re-aeration constants for river re-oxygenation. The details of Qual2K and HEC-RAS combination use can also be found in the study by Fan et al. (2009).

2.3. Scenario simulation

To explore the carrying capacity, three different water quality protection levels were simulated, each reflecting the acceptable amount of SS, BOD and NH_3—N in the aqueous phase to different future timelines. The first and second ones were the short- and mid-term targets which were the 80% and 50% of the average concentrations during past five years (2013—2017), respectively. The long-term target was the ultimate water quality goal adopted from the surface water quality criteria proposed by TEPA. Meanwhile, the surface water quality criteria of SS and BOD are less than those of the mid-term targets. Therefore, the long-term targets for SS and BOD were maintained the same as those in the mid-term ones. The target of 80% or 50% of the average concentrations during past five years was determined through consultation with environmental officials and professionals, who suggested an achievable goal should be considered at the beginning stage of TMDL implementation. The water quality indices of SS, BOD and NH_3—N were simulated because they have been employed by TEPA as the classification references for river pollution. The short-, mid- and long-terms water quality targets are shown in Table 2. Generally, the DO concentration is considered as an overall quality of the aquatic environment, and the increase in aqueous DO concentration usually results from the decrease of oxygen-consuming contaminants in the aqueous phase. In this study, the DO concentrations at different scenarios were calculated and compared to the Classes A and C DO surface water quality criteria proposed by TEPA. For water quality assurance, TEPA announced the "Surface Water Bodies Classification and Water Quality Criteria" as a guidance for the planning of water pollution control strategy. For inland surface water bodies, Class A water body can be the source water for 1st public water supply and swimming, and Class C water body can be the source water 3rd public water supply, 2nd aquaculture water supply, and 1st industrial water supply. The detail description of "Surface Water Bodies Classification and Water Quality Criteria" can be found in the supplementary material.

3. Results and discussion

3.1. Model calibration, verification and simulation

For model calibration, the monthly water quality monitoring data collected from January 2013 to December 2015 were used, and those from January 2016 to December 2017 were employed for verification. The root-mean-square-error (RMSE) was calculated as the justification for degradation constants for BOD and NH_3—N, and the settling velocities of SS in the calibration. The carbonaceous and nitrogenous degradation constants and settling velocity of suspended solids were determined to be 0.15, 0.10 1/day and 0.10 m/day through calibration. The river cross section profiles were obtained from the database maintained by the Water Resources Agency. The hydraulic calculated empirical constants were adopted from the study by Fan et al. (2012) and are shown in the supplementary material. The simulation was conducted based on the Q_{75} flowrate considering all the existing pollution discharges. The graphical comparisons of calculated results (i.e., line plots) and monitored data (i.e., box plots) in the model calibration and verification are shown in Fig. 2. For verification, the R square values of the four investigated water quality indices were in the range between 0.71 and 0.83 (i.e., 0.71, 0.79, 0.83 and 0.72 for SS, BOD, NH_3—N and DO, respectively). These results were considered acceptable when field data were used in the model calculation considering the inevitable influence of the environmental dynamics. Overall, the water quality of Jing-Mei Creek calculated by HEC-RAS and Qual2K combination agreed with the monitoring data, and the established model was applied to the carrying capacity and remediation strategy exploration.

The water quality indices of SS, BOD, NH_3—N and DO were simulated and the results are presented in Fig. 3. The short-, mid- and long-term targets for water quality management as well as the results after implementing the investigated remediation strategies are also shown in this figure. The upstream concentrations of SS, BOD and NH_3—N were comparatively low because of little pollution discharge, resulting in a relatively high DO concentration. As the river travelled downstream, more contaminants were generated and the SS, BOD and NH_3—N concentrations were increased above the three designated water quality criteria of this study. Obviously, additional control measures are required if the water quality of Jing-Mei Creek is expected to meet these criteria under current land use and water pollution control practices.

3.2. Carrying capacity determination

Generally, the carrying capacity refers to the amount of contamination allowed without impairing the quality of a water body and it is often estimated on the "mass" basis although the "concentration" remains to be the prevailing concept in describing the water quality. A water quality criterion implies the maximum tolerable concentration of a given contaminant in the aqueous phase and the respective carrying capacity could be determined by not allowing the concentration at the mixing point to exceed the designated target criterion for a given water body that received a wastewater discharge. Once a water quality target is determined, the acceptable mass loading (i.e., carrying capacity) can be

Table 2
Calculated carrying capacities and reduction ratios for BOD, SS and NH_3−N to meet the flowrate-based group reduction remediation strategies for short-term, mid-term and long-term remediation criteria

WQ Index	Water Quality Standard, mg/L			Carrying Capacity, Kg/day			Wastewater Reduction Ratio, %								
							Low (L)			Medium (M)			High (H)		
	short	mid	long	short	mid	long	short	mid	long	short	mid	long	short	mid	long
SS	11.70	7.40	7.40*	15096	9035	-	20	50	-	20	50	-	50	70	-
BOD	2.90	1.80	1.80*	5576	3687	-	60	90	-	80	90	-	90	92	-
NH_3-N	1.04	0.65	0.30	1310	833	377	50	70	92	70	90	93	90	92	95
DO	6.50	6.50	6.50	-	-	-	-	-	-	-	-	-	-	-	-

* The ultimate goal of ambient water quality is less stringent than the mid-term target, therefore long-term target criteria were adopted from the mid-term target criteria.

calculated through the trial and error calculation by increasing the mass loading gradually in the wastewater discharge.

In Table 1, the carrying capacities at the merging points of all investigated wastewater discharges with respect to short-, mid- and long-term targets along Jing-Mei Creek are presented. The short-term target has a higher value as the control criterion, indicating that more contamination is allowed. The sum of all the allowed pollution loadings was regarded as the carrying capacity of the entire investigated water body at the given water quality criterion. The calculated carry capacities for the simulated scenarios are shown in Table 2. For example, the carrying capacities of SS, BOD and NH_3−N with respect to mid-term target were calculated to be 9035, 3687 and 833 kg/day, respectively. However, the water quality of a river varies significantly, depending on the amount of existing contaminants and its spatial location entering into a water body. Therefore, the calculated carrying capacity in the present study reflected the quantity how much contamination was allowed in the investigated watershed and the overall capacity of the water body may need further modification if the location of pollution discharge changes.

The carrying capacity shall vary as the volume of a water body changes since more water should be able to accommodate more contamination. Along with this concept, the upstream carrying capacity of a river is usually lower because of less water volume and it becomes higher as the flow travels downstream due to the increase in flowrate. However, less contamination was produced upstream and the contamination discharge accumulated downstream, resulting in a lower capacity to accommodate additional pollutants. As shown in Table 1, the downstream carrying capacities were smaller than those upstream if the drainage discharges did not exhibit a significant difference in flowrate.

3.3. Single discharge and group reduction remediation strategies

To improve the water quality of Jing-Mei Creek, the required contamination reduction in wastewater discharge with respect to a given remediation target was evaluated, and the results are presented in Table 1. The upstream SS concentration was low, and no additional contamination reduction was required to meet the designated SS water quality target. For BOD and NH_3−N, substantial reductions were required to maintain the water quality not exceeding the designated water quality criteria. As mentioned earlier, the long-term target has a more stringent pollution control standard, allowing less contaminants to be present in the aquatic environment. Therefore, the reduction percentage was expected to increase as the remediation target changes from the short-term target to the long-term one.

The TMDL control strategy could be implemented by calculating the required pollution reduction for each individual wastewater discharge. However, such reduction strategy does not seem practically feasible for a large river that receives many pollution discharges. Usually, a wastewater with a higher volume contains more contamination and its discharge into the environment may pose a significant threat to the public health. To practice the TMDL remediation strategy in a different way, the wastewater discharges were classified into three categories and different reduction strategies were suggested for each category.

Based on the flowrate differences among the investigated pollution discharges, the wastewater discharges were classified into three groups, H group (i.e., the ones with flowrate higher than 1 cms), M group (the one with medium flowrate between 1 and 0.2 cms) and L group (the one with flowrates less than 0.2 cms). Table 2 shows the required group pollution reduction ratios for the short-, mid- and long-term targets. In order to meet the short-term water quality target, 50%, 20% and 20% of SS discharge should be reduced for H, M and L groups of wastewater discharges, respectively. For BOD, 90%, 80% and 60% reductions should be made for H, M and L groups of wastewater discharges, respectively. For NH_3−N, 90%, 70% and 50% reductions should be made for H, M and L groups of wastewater discharges, respectively. The water quality simulations based on the implementation of the group reduction strategies are presented in Fig. 3. In summary, both proposed control measures in the present might reduce the water pollution to meet the designated water criteria. For the real practice of TMDL, to classify the wastewater discharges into groups according to their flowrates is considered applicable and the group-reduction strategy may be enforced to meet the corresponding criteria.

As indicated previously, TMDL has been regarded as a supporting strategy which can be enforced in parallel to the conventional control measure that regulates the concentrations of wastewater effluents. Although the concept of TMDL has been proposed many decades ago, its practical implementation has been reported more often within the past decade. The carrying capacity is a critical parameter that maintains the water quality by determining the allowed amount of pollutant discharge. Due to the heterogeneity and dynamics of the aquatic environment, the

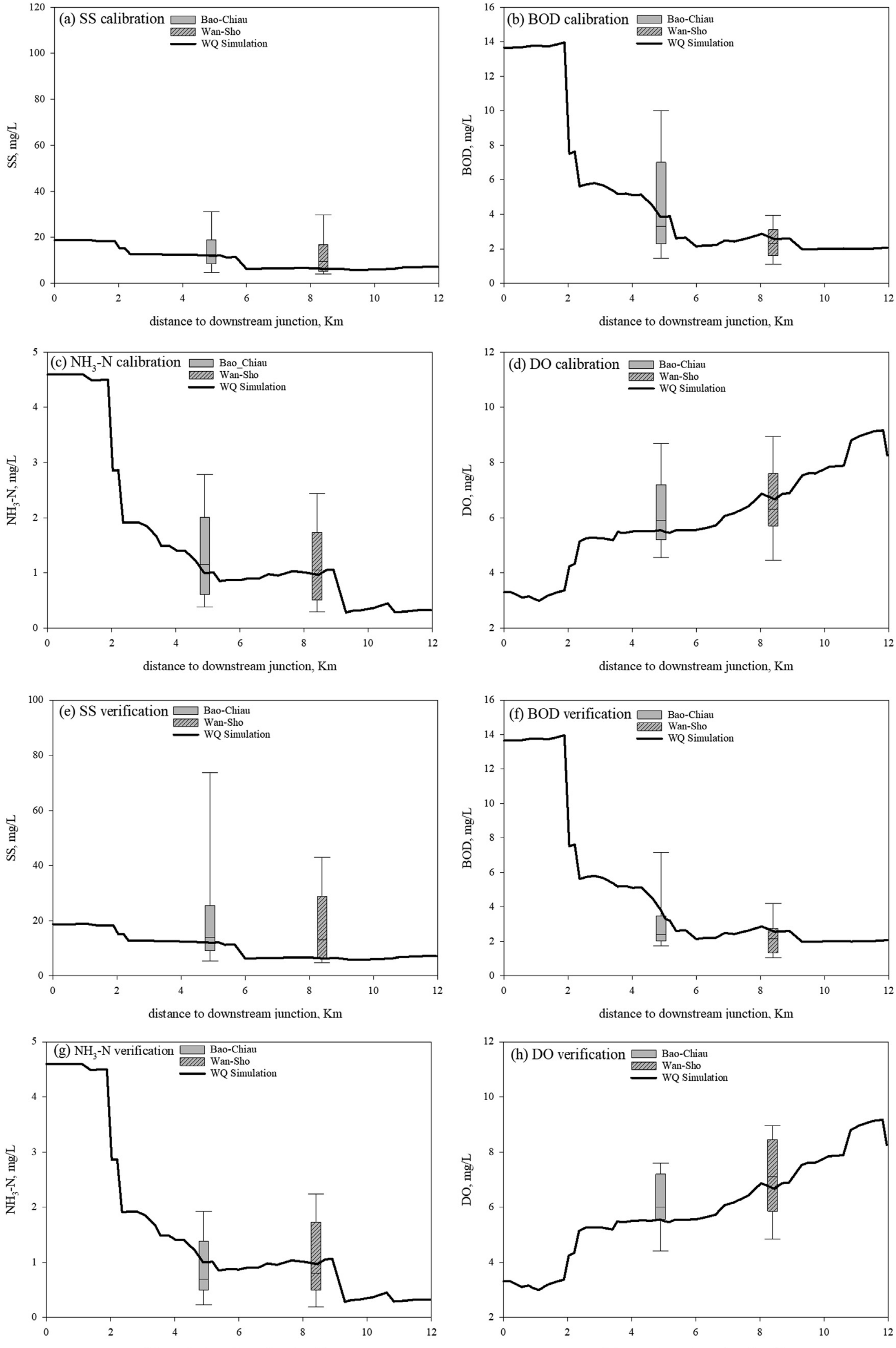

Fig. 2. Model calibration ((a)–(d)) and verification ((e) to (h)) for Jing-Mei Creek simulation.

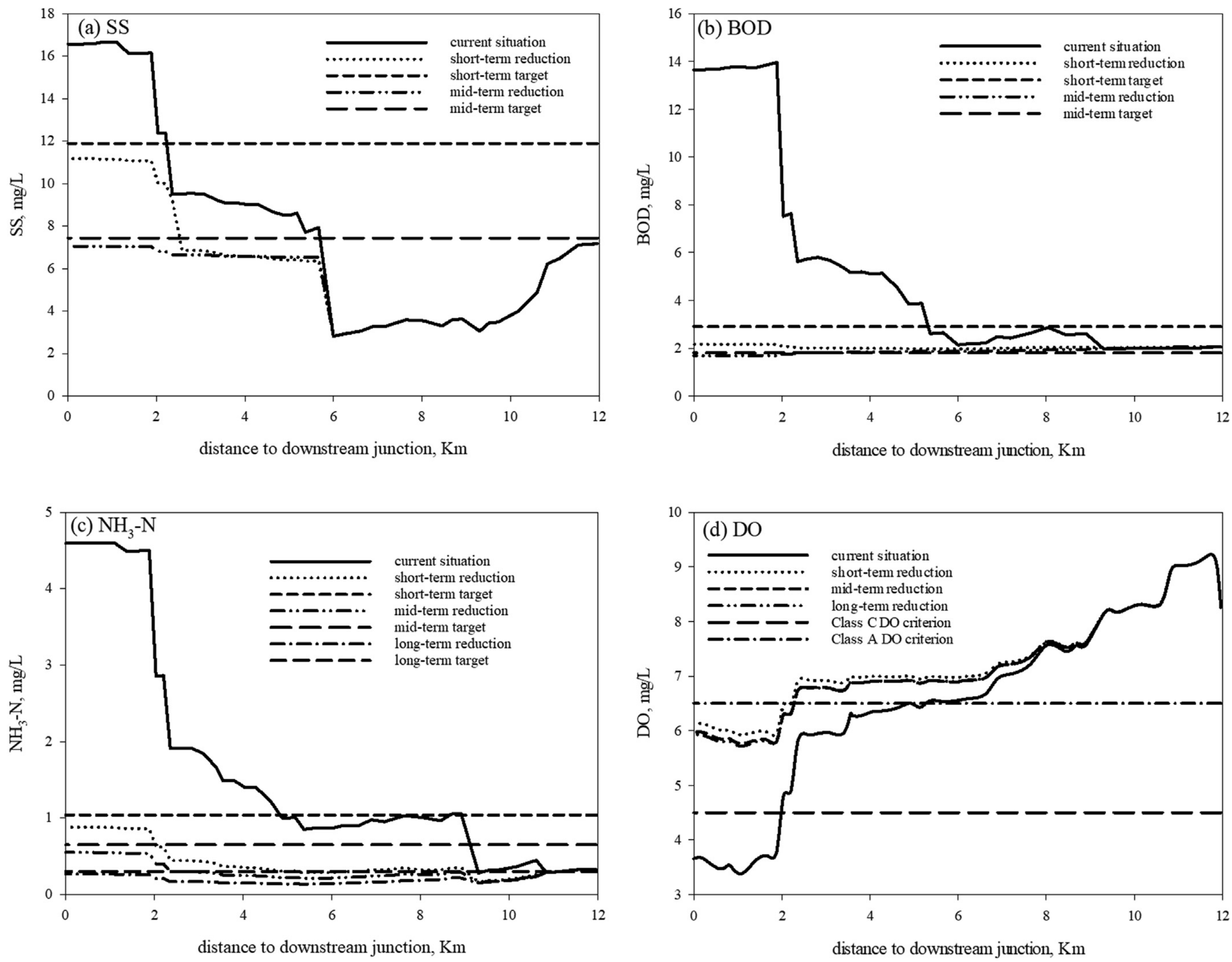

Fig. 3. Simulated SS, BOD, NH_3—N and DO concentrations for current situation and scenarios based on the control strategies of flowrate-based group reduction to meet the short-, mid- and long-term remediation criteria.

assessment of the carrying capacity of a selected water body is complicated, and different considerations may lead to different assessment results. Many studies reported the application of TMDL concept using the idea of mass conservation, considering that all the pollution discharge should be treated or removed completely, thus exhibiting no extra stress to the environment (Kang et al., 2006; Wang et al., 2019a; Wu et al., 2018). In contrast, the present study employed the modelling technique to predict the carrying capacity of a water body, and a TMDL strategy was proposed to meet the water quality criteria by reducing water pollution discharge.

3.4. Implications for water quality management

In Taiwan, the discharge permit system remains to be the major control measure for pollution discharge reduction. For some areas with massive industrial wastewater discharge, the governing agencies started to consider the TMDL system as a supporting tool for pollution reduction. Therefore, this study is a preliminary investigation for establishing the framework of the TMDL system in Taiwan. The Jing-Mei Creek was selected because it is a relatively small watershed with less pollution discharge, which is considered appropriate for such experimental study. Three stepwise water quality protection criteria were considered as the short-, mid-, and long-term targets, i.e., the (1) 80% and (2) 50% of the average concentrations between 2013 and 2017, and (3) surface water quality criteria proposed by TEPA. By using the water quality of Jing-Mei Creek, this study proposed a methodology for establishing the TMDL framework that can be applied to the river water quality protection in the future.

The enforcement of a TMDL control system requires all the contaminant-releasing sectors in the designated area to reduce their pollution discharge in compliance to a prescribed criterion. Although TMDL is regarded an attractive option for water pollution control, a more stringent effluent standard may increase the capital investment and management cost for the wastewater treatment processes to meet such standard. It should be noted that the group reduction strategy requires more pollution reduction since the river carrying capacity may accommodate the pollution discharge (i.e., no reduction required) in the upstream section if single discharge strategy is considered. Another issue deserving further exploration is the monetary investments of these two investigated strategies.

In many countries, comprehensive water quality and hydraulic monitoring systems are not available to capture the dynamic features of water quality and quantity. Instead, the water quality and hydraulic parameters were monitored through manual sampling and analysis periodically. Therefore, many related studies were conducted assuming the low flowrate situation (i.e., Q_{75} in the present study), and the water resource management strategy was planned under this condition. Similar to many other countries in the world, the carrying capacity and TMDL system of this study were established based on the low flowrate assumption. If the condition other than low flowrate is considered, the carrying capacity and TMDL system should be re-evaluated. The results demonstrated the applicability of proposed a modelling framework to assessing the carrying capacity and establishing the TMDL system.

4. Conclusions

The water quality modelling technique combining HEC-RAS and Qual2K was shown capable of assessing the carrying capacity of a river, which could be used to determine the maximum contamination allowed with respect to a designated water quality criterion. Through a proper contamination reduction strategy, the water quality could be expected to meet designated criteria. In the present study, the carrying capacity and a TMDL system for Jing-Mei Creek were investigated considering three different water quality targets and two different wastewater control strategies. The long-term control target had the most stringent water quality criteria, leading to the least carrying capacity among the three investigated situations. By implementing the strategy that considered the reduction in wastewater discharge individually, the water quality can be improved to meet the expected target. For the group-reduction control strategy, more pollution was reduced resulting in better water quality. In the practice of in-situ wastewater control, the group-reduction control strategy was regarded as a more appropriate control measure because of its ease in application and apparent improvement in water quality.

CRediT authorship contribution statement

Chihhao Fan: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Data curation, Resources, Supervision, Project administration, Funding acquisition. **Kai-Hsuan Chen:** Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft. **Ya-Zhen Huang:** Visualization, Investigation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.125251.

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