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# Variations of model performance between QUAL2K and WASP on a river with high ammonia and organic matters

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**ABSTRACT**

Two water quality models, Water Quality Analysis Simulation Program (WASP) and QUAL2K, were selected and applied to evaluate the performance variations of a river with high ammonia and organic matters in southern Taiwan. Through the appraisal of fit levels with the mean absolute percentage error method, the overall model results of WASP were better than those of QUAL2K. Assimilative capacity of the concerned Tonggang River simulated by WASP is 16.5% more than that by QUAL2K to achieve the Class B water quality standards regulated by Taiwan EPA. The total invested capital for clean pig farming and sewage interception estimated by WASP was $65,402 and $12,381,600 less by QUAL2K, respectively. Levels of water quality improvement and respective costs of several proposed pollutant reduction strategies including sewage interception and clean pig farming practice were also evaluated. This study demonstrates that variations of the model results occurs as using WASP and QUAL2K to estimate the improvement effects of water quality under various reduction strategies. Therefore, more efforts are required to verify the robustness and suitability of the proposed models.

*Keywords:* Water quality management; Pollutant reduction; Assimilative capacity; Clean pig farming practice

## 1. Introduction

The Tonggang River located in southern Taiwan maintains abundant flow all year round (Fig. 1). The length and watershed area of the Tonggang River are 44.1 km and 472.2 $km^2$, respectively. Annual average water supplies for agricultural and industrial uses are around 18.64 and 8.17 million $m^3$, respectively [1]. Due to the shortage of potable water supply during the dry season in southern Taiwan, the abundant flow of the Tonggang River is planned to be a prior candidate for drinking water source by the authority. However, most of the livestock and municipal sewage were not properly handled and were directly discharged into the Tonggang River, resulting in the deterioration of its water quality, especially triggering the problems of high ammonia ($NH_3$-N) and organic matters. Therefore,

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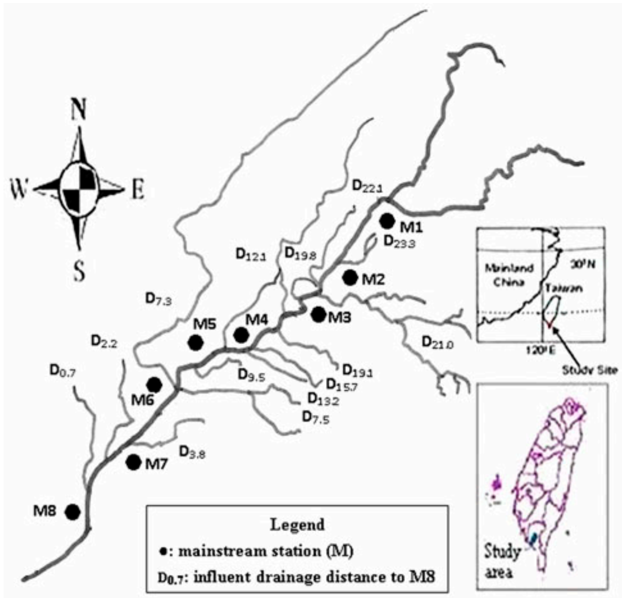


Fig. 1. Sampling stations and influent drainages along the Tonggang River.

improving the water quality of the Tonggang River to comply with the standards of drinking water source is an urgent work to meet the demands of water supply.

According to the monthly monitoring data released by the Environmental Protection Administration (EPA) of Taiwan from 2008 to 2011, the overall water quality of the Tonggang River stood in the range between lightly and moderately polluted in the upstream reaches and slightly moved to moderately and seriously polluted in the downstream reaches based on the river pollution index evaluated by dissolved oxygen (DO), biochemical oxygen demand (BOD), $NH_3$-N, and suspended solids (SS) [2]. Improperly handled wastewaters discharged from the animal husbandry especially the pig farms are the main pollution sources [3]. Table 1 displays that the respective pollution contribution ratios of BOD and $NH_3$-N from the pig farms were 66.7–70.5% and 72.8–74.8% [3]. The concentrations of $BOD_5$, $NH_3$-N, and DO stood in the range of 0.5–18.2 (3.9 ± 2.81, $n$ = 48), 0.08–10.3 (1.97 ± 2.21, $n$ = 48), and 1.2–8.4 (5.5 ± 1.53, $n$ = 48) $mg\,L^{-1}$, respectively [4]. Water quality evaluated by $BOD_5$, $NH_3$-N, and DO still did not conform to the Class B standards, that is, BOD and $NH_3$-N less than respective 2.0 and 0.3 $mg\,L^{-1}$, and DO greater than 5.5 $mg\,L^{-1}$, regulated by Taiwan EPA [3,4]. The existing states of water quality prohibit its effective utilization for drinking water source.

Table 1
Water quality and pollutant contribution of the Tonggang River

| | BOD | $NH_3$-N | DO |
|---|---|---|---|
| Concentration range ($mg\,L^{-1}$) (average ± standard deviation, samples) | 0.5–18.2 (3.9 ± 2.81, $n$ = 48) | 0.08–10.3 (1.97 ± 2.21, $n$ = 48) | 1.2–8.4 (5.5 ± 1.53, $n$ = 48) |
| Respective pollution contribution ratio from pig farms[a] (%) | 66.7–70.5 | 72.8–74.8 | – |
| Class B standard[b] ($mg\,L^{-1}$) | <2.0 | <0.3 | >5.5 |

[a]Respective pollution contribution ratio from pig farms = pollutant loadings from pig farms/total pollutant loadings.
[b]Class B standard regulated by Taiwan EPA.

Recently, several methods such as the Enhanced Stream Water Quality (QUAL2E/K) model, Water Quality Analysis Simulation Program/Eutrophication (WASP/EUTRO), and Watershed Hydrologic and Water Quality Modeling (HSPF) have been developed for modeling the water quality of rivers and basins receiving pollutants, but they are frequently employed individually [5–14]. In 2005, Pingtung County Government of Taiwan stated that the allowable influent BOD and $NH_3$-N loadings into the mainstream (24.2 km) of the Tonggang River were 2,365 and 314 $kg\,d^{-1}$ using QUAL2K model [18]. While during the dry season of 2008, Taiwan EPA (2008) reported that the allowable influent BOD and $NH_3$-N loadings into the mainstream (44 km) of the Tonggang River were 36,218.1 (57.4% of total discharge amounts) and 1,395.8 $kg\,d^{-1}$ (8.8% of total discharge amounts) using WASP model [19]. As indicated in the literature, model selection, reach segmentation, and model length of the target river resulted in the variations of assimilative capacity and improvement effectiveness of water quality. Therefore, the present study selected QUAL2K and WASP/EUTRO models to understand their performances on simulation of the river water quality.

The objective of this study is to evaluate the variations of model performance between QUAL2K and WASP on simulation and prediction of the water quality after implementation of various pollution control measures to achieve the restoration goals of Class B water quality standards regulated for the Tonggang River. Levels of water quality improvement and respective costs of the proposed pollutant reduction strategies are also investigated.

## 2. Materials and methods

### 2.1. Modeling tools

QUAL2K, one of the most frequently employed water quality models, is applicable to a well-mixed river and handles the major one-dimension (1-D) mass transport mechanisms such as advection and dispersion that are significant only along the main flow direction [11–14]. For this model, a river is simulated as a string of computational units with 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 model of the river in concern. Detailed illustrations and manipulations of this model can be found in the literature [11–14]. QUAL2K is capable to simulate the transport of pollutants and to assess the impacts of pollutant loadings including quantity, quality, and location on the receiving water body. Owing to the great flexibility for multiple applications, user can have a combination of up to 16 water quality variables. A 1-D configuration of QUAL2K is employed to simulate the spatial distribution of water quality variables including SS, BOD, DO, $NH_3$-N, and TP. The corresponding mass balance equation for a constituent concentration ($C_i$) in a reach ($i$) can be written as

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

where $C_i$, $V_i$, $Q_i$, $E_i$, $W_i$ represent the concentration [$\mathrm{M\,L^{-3}}$], volume [$\mathrm{L^3}$], effluent [$\mathrm{L^3\,T^{-1}}$], dispersion coefficient [$\mathrm{L\,T^{-1}}$], and external constituent loadings of reach $i$ [$\mathrm{M\,T^{-1}}$], respectively; $S_i$ represents the sources and sinks of the constituent due to reactions and mass transfer mechanisms in reach $i$ [$\mathrm{M\,L^{-1}\,T^{-1}}$]; and $Q_{ab,i}$ represents the flow abstraction from element $i$ [$\mathrm{L^3\,T^{-1}}$].

WASP handles the mass transport (advection and dispersion) and kinetics in separate modules, thereby providing greater flexibility for applying the modeling framework to systems with multiple segments [5,8]. EUTRO is a component of WASP that is capable to model the transport kinetics between water column and sediment bed of eight water quality variables. The linear DO balance with nitrification module is the complexity level of EUTRO model implemented for this study, incorporating five water quality variables: $NH_3$-N, nitrite/nitrate ($NO_2$-N/$NO_3$-N), carbonaceous BOD (CBOD), DO, and organic nitrogen (org-N). A 1-D configuration of WASP is employed to simulate the spatial distribution of water quality variables including electrical conductivity (EC), BOD, DO, and $NH_3$-N. Detailed illustrations and manipulations of this model can also be found in the literatures [5,10,11]. The corresponding mass balance equation can be written as follows:

$$\frac{\partial C}{\partial t} = -\frac{\partial}{\partial x}(U_x C) + \frac{\partial}{\partial x}\left(E_x \frac{\partial C}{\partial x}\right) + S_L + S_B + S_K \quad (2)$$

where $C$ = concentration of constituent [$\mathrm{M\,L^{-3}}$], $U_x$ = longitudinal advective velocity [$\mathrm{M\,L^{-1}}$], $E_x$ = longitudinal dispersion coefficient [$\mathrm{L^2\,T^{-1}}$], $t$ = time [T], $S_L$ = direct and diffuse loading rate [$\mathrm{M\,L^{-3}\,T^{-1}}$], $S_B$ = boundary loading rate [$\mathrm{M\ L^{-3}\ T^{-1}}$], $S_K$ = total kinetic transformation rate, positive is source, negative is sink [$\mathrm{M\,L^{-3}\,T^{-1}}$].

### 2.2. Sampling program and model segmentation

The hydrological and water quality data on the major pollutant sources along the Tonggang River were surveyed at 23 sampling stations including 8 mainstream stations ($M_1$–$M_8$ from upstream to downstream) and 15 drainage stations ($T_{23.3}$, $T_{22.1}$, $T_{21.0}$, $T_{19.8}$, $T_{19.1}$, $T_{15.7}$, $T_{13.2}$, $T_{12.1}$, $T_{10.1}$, $T_{9.5}$, $T_{7.5}$, $T_{7.3}$, $T_{3.8}$, $T_{2.2}$, $T_{0.7}$ from upstream to downstream) on 13 April 2008 and 9 October 2010 to support the model calibration and verification (Fig. 1). Receiving water quality parameters such as temperature, pH, DO, EC, CBOD, $NH_3$-N, $NO_2$-N/$NO_3$-N, and org-N were analyzed with the standard methods and their values were used for comparison with the model results. The results showed that the water quality of influent drainages was worse than that of mainstream, because they collected almost all the livestock and municipal wastewater of the catchment of Tonggang River [15–17]. The major influent pollutant loadings affecting the receiving water quality came from tributary $M_1$, $T_{21.1}$, $T_{12.1}$, $T_{7.5}$, $T_{7.3}$, $T_{0.7}$ for CBOD and $M_1$, $T_{12.1}$, $T_{7.5}$, $T_{7.3}$, $T_{3.8}$, $T_{0.7}$ for $NH_3$-N. QUAL2K and WASP modeling framework require a water body segmented into a number of completely mixed cells. Based on the river characteristics and model structure of WASP, a total length of 25 km from the upstream boundary M1 to the downstream boundary M8 was divided into 25 segments along the mainstream, each of which was around 1.0 km. For QUAL2K, a total length of 25 km from $M_1$ to $M_8$ was segmented into 7 reaches and 50 computational units along the mainstream, each of which was 0.5 km. Because the vital kinetic coefficients adopted in WASP and QUAL2K model might vary with river characteristics and locations, pollutant sources, seasons, and management policies of local authority, this study performed several field tests to obtain the biochemical coefficients including deoxygenation ($k_1$), reaeration ($k_2$), and nitrification ($k_n$) rate coefficients as well as sediment oxygen demand (SOD). Therefore, this study adopted measured biochemical coefficients incorporated with influent pollutant loadings and boundary conditions to calibrate and verify the developed model.

### 2.3. Mean absolute percentage error

A dimensionless index called the mean absolute percentage error (MAPE) was used to assess the variations between the surveyed and modeled values. The less the MAPE values are, the closeness the measured and modeled values. DeLurgio (1998) 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%) [18].

## 3. Results and discussion

### 3.1. Mass transport modeling

Steady-state mass transport modeling is designed to track the attenuation of a conservative tracer along the Tonggang River prior to the BOD/DO modeling [19,20]. The dispersion coefficients were obtained using the conservative EC data collected on 13 April 2008 as inputs to the QUAL2K and WASP/EUTRO model. The calibration results showed that the dispersion coefficients ranged between 1 and 55 $m^2 s^{-1}$ along the mainstream. Fig. 2(a) and 2(b) reveals the EC variations along the mainstream of model results and surveyed data on 9 October 2010. 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 models were then used to track the concentrations of water quality parameters concerned in the receiving water. As shown in Table 2, the modeling results evaluated by the MAPE method showed that the fit levels of QUAL2K (2.1–15.0%) were close to those of WASP (4.1–14.9%).

### 3.2. Model calibration and validation

The water quality models of QUAL2K and WASP/EUTRO were first calibrated with the data obtained from eight sampling stations ($M_1$–$M_8$) along the mainstream on 13 April 2008 (Table 3) using the same measured biochemical coefficients, that is, 0.2–0.4 $d^{-1}$ for $k_1$, 0.78–6 $d^{-1}$ for $k_2$, 0.05–0.1 $d^{-1}$ for $k_n$, and 0.37–3.2 g $O_2$ $m^{-2}$ $d^{-1}$ for SOD. Then, the data collected from 9 October 2010 (Table 3) were employed to verify the models also using the measured biochemical and other calibrated model coefficients. The boundary conditions of the model include the loadings of $CBOD_5$, DO, $NH_3$-N, $NO_3$-N, $NO_2$-N, org-N, and TP derived from the data of each survey at the upstream and downstream reaches and drainages.

As shown in Fig. 3, the model results of spatial DO, $CBOD_5$, and $NH_3$-N matched the field data reasonably well and both had the similar trend of variations. In terms of MAPE analysis, the values lay between 12.0–46.8% (good–reasonable) and 7.1–45.6% (excellent–reasonable) simulated by QUAL2K and WASP model, respectively (Table 2). Overall, the fit levels of the concerned parameters using WASP were better than those using QUAL2K.

### 3.3. Assimilative capacity and pollutant reduction amounts

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 this study, the minimal improvement goal is Class B (DO >5.5 mg $L^{-1}$, BOD <2.0 mg $L^{-1}$, $NH_3$-N <0.3 mg $L^{-1}$) according to the standards of surface water quality regulated by the Taiwan EPA. After the developed model was calibrated and verified, adjusting the influent pollutant loads discharged into the mainstream

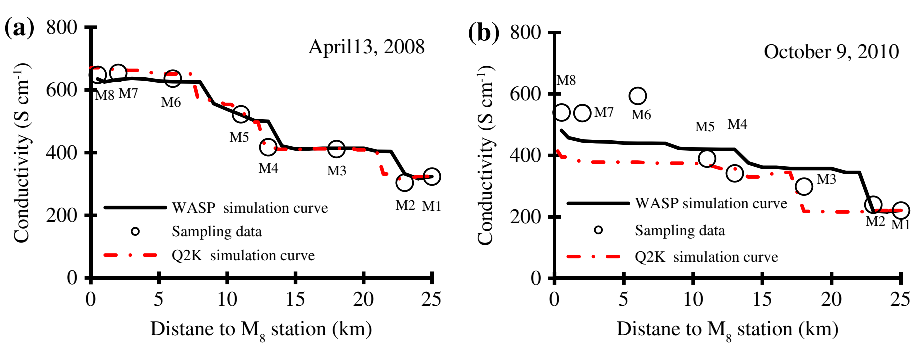


Fig. 2. Model results and surveyed data of EC sampled on (a) 13 April 2008 and (b) 9 October 2010.

Table 2
Fit levels evaluation of the model results with MAPE method

| Model | 13 April 2008 | | | | 9 October 2010 | | | |
|---|---|---|---|---|---|---|---|---|
| | EC | CBOD | $NH_3$-N | DO | EC | CBOD | $NH_3$-N | DO |
| QUAL2K | Excellent (2.1%)[a] | Reasonable (23.1%) | Reasonable (26.5%) | Reasonable (22.0%) | Good (15.0%) | Good (18.1%) | Reasonable (46.8%) | Good (12.1%) |
| WASP/EUTRO | Excellent (4.1%) | Reasonable (22.8%) | Reasonable (39.9%) | Good (13.2%) | Good (14.9%) | Good (18.3%) | Reasonable (45.6%) | Excellent (7.1%) |
| Overall performance | WASP ≒ QUAL2K | | | | WASP > QUAL2K | | | |

[a]Excellent: MAPE value <10%; Good: 10% <MAPE value <20%; Reasonable: 20% <MAPE value <50%; Poor: MAPE value <50%.

Table 3
Water quality data sampled on 13 April 2008 and 9 October 2012

| Mainstream station | 13 April 2008 | | | 9 October 2010 | | |
|---|---|---|---|---|---|---|
| | DO ($mg\,L^{-1}$) | CBOD ($mg\,L^{-1}$) | $NH_3$-N ($\mu g\,L^{-1}$) | DO ($mg\,L^{-1}$) | CBOD ($mg\,L^{-1}$) | $NH_3$-N ($\mu g\,L^{-1}$) |
| $M_1$ | 6.2 | 1.2 | 892.0 | 6.8 | 2.8 | 330.0 |
| $M_2$ | 6.7 | 1.1 | 970.0 | 7.2 | 2.0 | 110.0 |
| $M_3$ | 6.5 | 3.2 | 610.0 | 6.5 | 2.0 | 60.0 |
| $M_4$ | 6.0 | 1.5 | 902.0 | 6.5 | 2.2 | 320.0 |
| $M_5$ | 5.5 | 4.9 | 1,250.0 | 6.6 | 3.9 | 370.0 |
| $M_6$ | 3.2 | 4.9 | 5,480.0 | 4.8 | 3.5 | 2,180.0 |
| $M_7$ | 4.5 | 8.1 | 1,360.0 | 6.1 | 3.6 | 1,810.0 |
| $M_8$ | 3.8 | 5.3 | 6,022.0 | 5.8 | 4.8 | 1,390.0 |

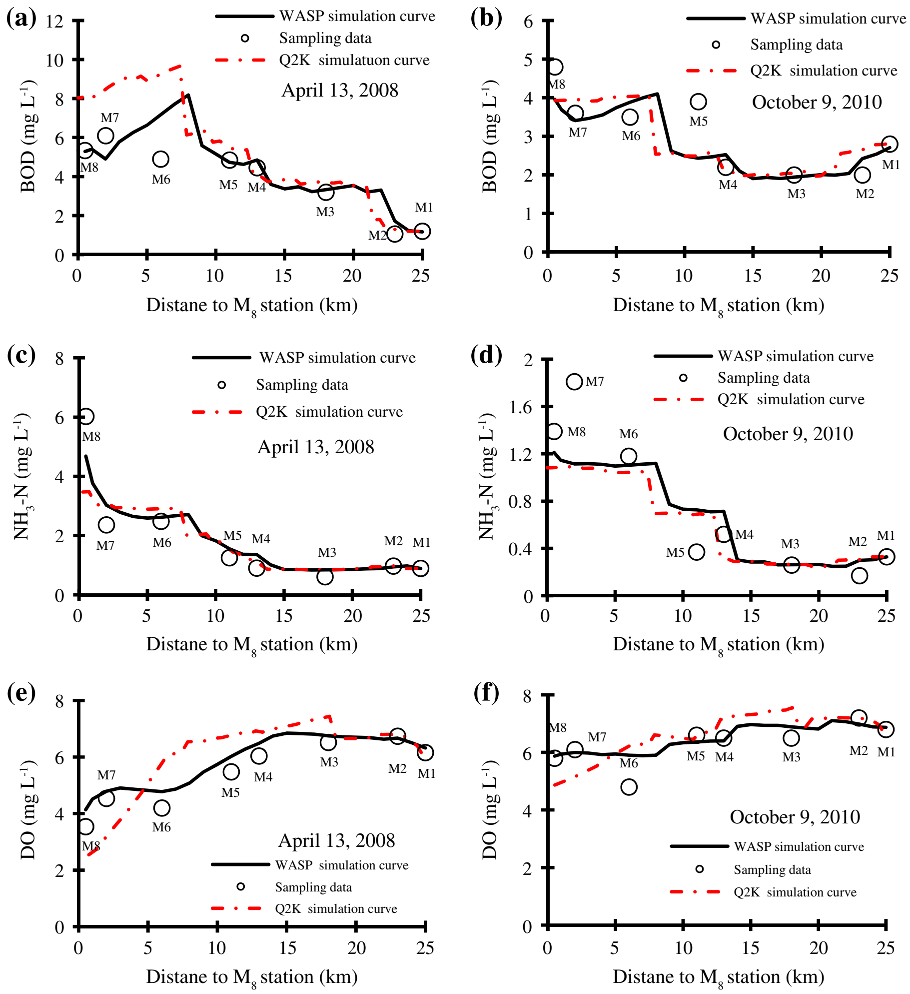


Fig. 3. Water quality model results of CBOD sampled on (a) 13 April 2008 (b) 9 October 2010, $NH_3$-N on (c) 13 April 2008 (d) 9 October 2010, and DO on (e) 13 April 2008 (f) 9 October 2010.

from upstream to downstream reaches in sequence to let the model results meet the regulated water standards. Then, the modified influent pollutant loads were accumulated to obtain the assimilative capacity of the concerned river.

Based on the surveyed data of 9 October 2010, the total pollutant loadings estimated were 15,349.5 and 4,018.7 kg $d^{-1}$ for $CBOD_5$ and $NH_3$-N, respectively. When the Class B water quality criteria was adopted as the improvement goal, the assimilative capacity obtained from the developed QUAL2K model of receiving water to $CBOD_5$ and $NH_3$-N was 7,472.3 and 1,071.2 kg $d^{-1}$; therefore, the total quantities of pollutant reduction must be greater than 7,877.2 kg $d^{-1}$ for CBOD (51.3% reduction of total pollutant discharge) and 2,947.5 kg $d^{-1}$ for $NH_3$-N (73.3% reduction). For the case of WASP/EUTRO, the assimilative capacity of $CBOD_5$ and $NH_3$-N was 9,139.7 and 1,103.2 kg $d^{-1}$. Therefore, influent pollutant loadings must be reduced at least 6,209.8 kg $d^{-1}$ (40.5% reduction) and 2,915.5 kg $d^{-1}$ (72.5% reduction) for $CBOD_5$ and $NH_3$-N, respectively. After reducing the pollutant loadings, the forecast levels of $CBOD_5$, $NH_3$-N, and DO via the developed QUAL2K and WASP/EUTRO model showed that the water quality of the Tonggang River above $M_8$ station could reach the Class B requirements (Fig. 4(a) and 4(b)).

The model results showed that the assimilative capacity to $CBOD_5$ and $NH_3$-N simulated by WASP/EUTRO was 13.2 and 3.3% more than that simulated by QUAL2K to reach the Class B water quality standards of the Tonggang River.

### 3.4. Water quality improvement strategies

Based on the data released by Taiwan EPA in 2007 and 2008, the respective pollution contribution ratios

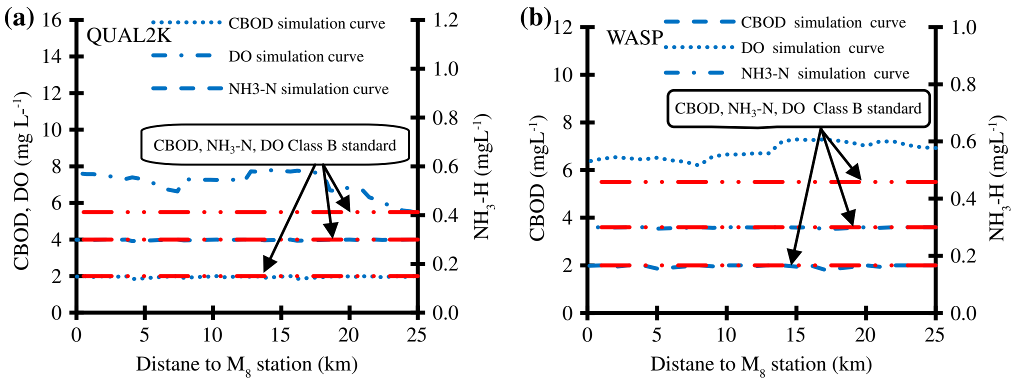


Fig. 4. Simulation results using (a) QUAL2K and (b) WASP model after reducing the pollutant loadings.

of BOD and $NH_3$-N produced by the pig farms along the Tonggang River were 66.7–70.5% and 72.8–74.8%, respectively [1]. Therefore, reduction of the pollutant loadings from the pig farms is a crucial means to improve the water quality. Several feasible preventive measures such as promotion of clean pig farming as well as sewage interception and then diversion to the neighboring treatment plant were proposed to improve the water quality of the Tonggang River. Clean pig farming technology, a practice to train the hogs to defecate and urinate at a designated location called hog toilet, is promoted by Taiwan EPA as an effective and economic measure to improve the water quality of the target stream.

If a pig is assumed to produce 40 g CBOD per day, the number of pigs raised in each tributary can be computed according to the above-mentioned daily pollutant contribution ratios. In addition, 60% of pollutant loadings were expected to be removed by the clean pig farming practice [21]. As shown in Figs. 5 and 6, for the case of the clean pig farming practice, the pollutant loadings must at least reduce 82 and 81% modeled by respective QUAL2K and WASP to reach the class B water quality regulation. If the sewage interceptions at drainages of $T_{0.7}$, $T_{2.2}$, $T_{3.8}$, $T_{7.3}$, $T_{7.5}$, $T_{10.1}$, $T_{12.1}$, and $T_{15.7}$ are adopted to reach the regulated water quality of class B, the pollutant loadings must at least reduce 81 and 77% modeled by QUAL2K and WASP, respectively.

### 3.5. Cost estimation

Two water quality improvement measures were proposed to reduce the influent pollutants from drainages into the mainstream. There were 545,045 pigs raised within the catchment of Tonggang River [21]. For the case of clean pig farming practice, the unit installation cost was estimated to be 12 US\$ $pig^{-1}$ [21]. Therefore, the total construction costs were around \$5,363,242 and \$5,297,840 modeled by QUAL2K and WASP, respectively (Table 4). The construction costs per kg CBOD and per kg $NH_3$-N reduction with QUAL2K were slightly higher than those with WASP. As for the case of sewage interception, the unit installation cost was computed to be 660 US\$ $m^{-3}$ d of interception flow that resulted in the total construction costs around \$250,727,400 and \$238,345,800 simulated by respective QUAL2K and WASP model (Table 4)

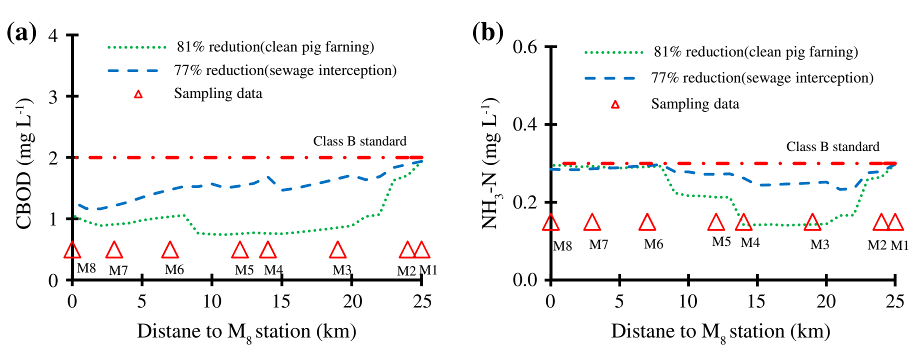


Fig. 5. Variations of (a) CBOD and (b) $NH_3$-N after implementing the water quality improvement strategies simulated by QUAL2K.

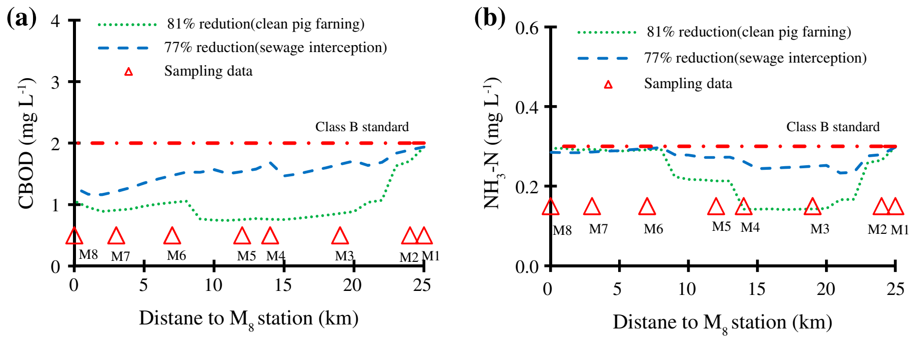


Fig. 6. Variations of (a) CBOD and (b) $NH_3$-N after implementing the water quality improvement strategies simulated by WASP.

Table 4
Cost analysis for proposed water quality improvement strategies

| Model | Improvement measure | Pollutant reduction (%) | Total construction cost (US dollar, $) | Daily reduction amounts | | Unit construction cost | |
|---|---|---|---|---|---|---|---|
| | | | | CBOD ($kg\ d^{-1}$) | $NH_3$-N ($kg\ d^{-1}$) | CBOD ($\$\ d\ kg^{-1}$) | $NH_3$-N ($\$\ d\ kg^{-1}$) |
| QUAL2K | Clean pig farming | 82 | 5,363,242[a] | 12,167 | 3,050 | 441 | 1,758 |
| | Sewage interception | 81 | 250,727,400[b] | 12,223 | 3,466 | 20,513 | 72,340 |
| WASP | Clean pig farming | 81 | 5,297,840 | 12,345 | 3,110 | 429 | 1,703 |
| | Sewage interception | 77 | 238,345,800 | 12,383 | 3,513 | 19,248 | 67,847 |

[a]Total construction cost = 12 $/pig × 545,045 pigs (total number of pigs) × 0.82 (pollutant reduction) = $5,363,242.
[b]Total construction cost = 660 $/CMD × 469,000 CMD (total interception flow) × 0.81 (pollutant reduction) = $250,727,400.

[21]. The construction costs per kg CBOD and per kg $NH_3$-N reduction with QUAL2K were also higher than those with WASP. The total invested capitals for clean pig farming and sewage interception estimated by WASP was $65,402 and $12,381,600 less by QUAL2K, respectively. As shown in Table 4, the investment cost for clean pig farming practice was much lower than that for sewage interception to improve the water quality of Tonggang River to the Class B standards regulated. Therefore, promotion of clean pig farming practice will be a prior alternative and an efficient measure to improve the water quality of river seriously polluted by the wastewater from livestock industry.

## 4. Conclusions

In this study, QUAL2K and WASP are selected to evaluate their model performances including fit levels, assimilative capacity and pollutant reduction amounts, and unit construction cost on a river with high ammonia and organic matters. Through the appraisal of fit levels with MAPE method, the overall model results of WASP worked better than those of QUAL2K. Assimilative capacity of the concerned river simulated by WASP is 16.5% more than that by QUAL2K to achieve Class B water quality regulated by Taiwan EPA. The total invested capitals for clean pig farming and sewage interception computed by WASP was $65,402 and $12,381,600 less by QUAL2K, respectively. Therefore, promotion of clean pig farming practice is an effective and economic measure to improve the water quality of river seriously polluted by the wastewater from livestock industry.

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