Linking watershed and eutrophication modelling for the Shihmen Reservoir, Taiwan

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Abstract The Shihmen Reservoir, located in northern Taiwan, features the second storage volume of impoundments on the island. The watershed of the Shihmen Reservoir has been subjected to serious pollutants due to anthropogenic interference. This study applies a watershed model, BASINS, to simulate the flow and nutrients loads from the watershed. BASINS then drives the CE-QUAL-W2 model for water quality predictions in the reservoir. The watershed modelling results are compared with field data. They reveal that significant nutrient loads were generated from the watershed during storms. The model calibration and verification were achieved with water surface elevation, temperature, and water quality constituents including nutrients, dissolved oxygen, and chlorophyll *a* in the reservoir using the eutrophication model.

Keywords CE-QUAL-W2; eutrophication modelling; Shihmen Reservoir; Taiwan; watershed model

Introduction

Eutrophication has been one of the major water quality problems in lakes and reservoirs in many parts of the world. High phytoplankton biomass levels in a reservoir primarily results from point and nonpoint nutrient loads into the reservoirs. An overabundance of algae biomass may cause water quality problems, such as diurnal dissolved oxygen fluctuation, oxygen depletion in the bottom waters, taste and odour in the water supply, filter clogging at water treatment plants, and affecting water-contact sports and recreation (Kuo *et al.*, 2006). A quantitative study of lake and reservoir eutrophication, and its potential mitigating actions, is quite complex as many physical, chemical, and biological processes must be incorporated into the modelling framework.

In watershed modelling, several researchers (e.g. Fontaine and Jacomino, 1997; Claudia *et al.*, 2002; Wang and Linker, 2006) used the HSPF model to simulate discharge, nutrient, and sediment concentration in the different watersheds. The HSPF model has been demonstrated as a powerful tool.

Eutrophication modelling of lakes and reservoirs started over 30 years ago (Chen, 1970; Thomann *et al.*, 1975; Lung *et al.*, 1976). Because water movement and mixing processes are key to biochemical kinetics in the water column, the ability to couple multidimensional hydrodynamic ad mass transport simulations with kinetics is crucial to many water quality-modelling studies. With an improved understanding of the eutrophication processes and hydrodynamics, as well as more advanced computing capabilities, multidimensional lake and reservoir hydrodynamic and water quality models have been developed and applied to study water quality issues (Lung, 2001; Leon *et al.*, 2003).

The Shihmen Reservoir (Figure 1) is a multipurpose hydraulic engineering project that provides irrigation, power generation, public water supply, and flood control. Likewise, it

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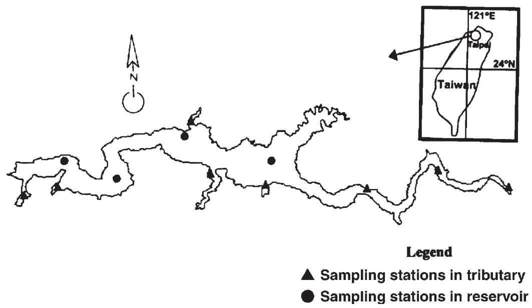

Figure 1 Location map for the Shihmen Reservoir

is a scenic attraction. Since its commissioning in 1964, the reservoir has contributed much to agricultural and industrial development in northern Taiwan, the betterment of standards of living, the increase of employment opportunities, and the prevention of calamities such as floods and droughts. The reservoir is 16.5 km long, and has a 763 km^2 catchment area, covering the Taoyuan, Hsinchu, and Ilan counties. The water level is at 245 m, while the dead water level is at 195 m. Its effective storage capacity at present is $2.33 \times 10^8\ m^3$. The Water Resources Bureau of Taiwan takes water samples from the reservoir to test water quality every month. Efforts are made to monitor and control water quality in the reservoir and safeguard the quality of drinking water for the public. Figure 2 shows the configuration of sub-watershed above the Shihmen Reservoir.

The water quality data were collected from the Northern Region Water Resources Bureau and analysed to understand the characteristics of the water quality in the Shihmen Reservoir. The monthly average trophic state index (TSI) of the Shihmen Reservoir from 1994 to 2003 is presented in Figure 3. It shows that the water quality is in the

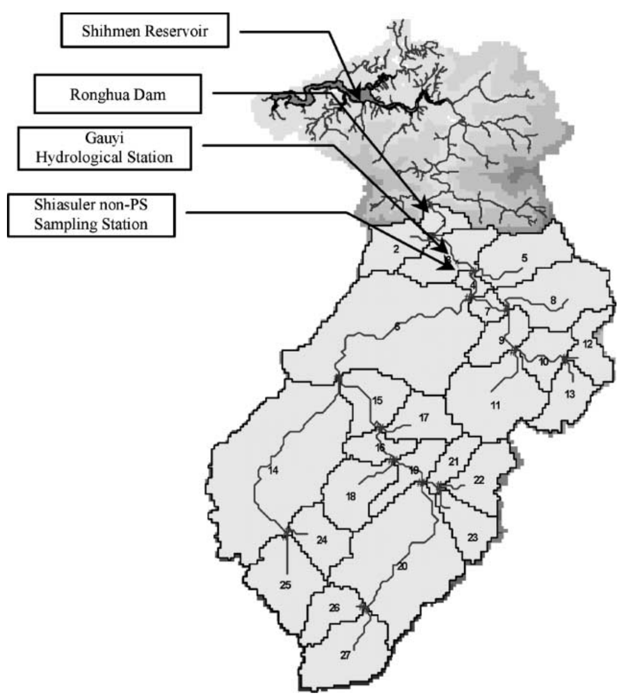

Figure 2 Shihmen Reservoir watershed

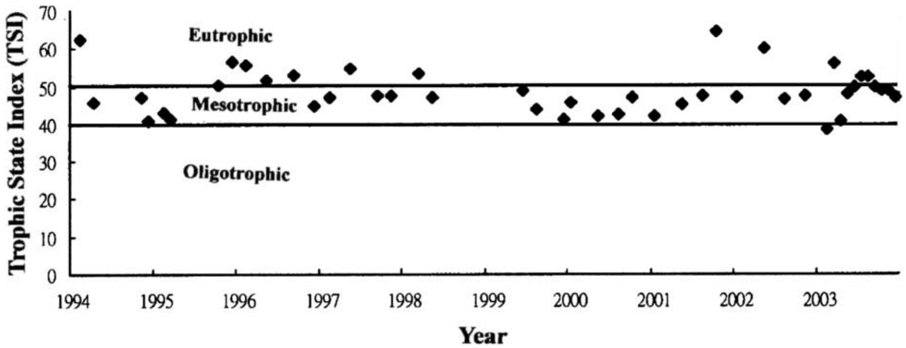

Figure 3 The trend of eutrophication assessed by the Carson index for the Shihmen Reservoir

mesotrophic to eutrophic state. The reservoir has suffered serious pollutants from the watershed.

In the present study, watershed and eutrophication models were linked to simulate the water quality in the Shihmen Reservoir, a eutrophic water system. Both models were verified with available field data. Model results of key water quality constituents, such as nutrients and algal biomass, closely match the field data.

Methods

Watershed model

The Better Assessment Science Integrating Point and Non-point Sources (BASINS) model was used in the study for watershed simulations. The modelling framework, supported by the US EPA, has been used widely by regulatory agencies in performing watershed and water quality-based studies (Lahlou *et al.*, 1998). It is a surface water quality assessment tool, supported by geographical information system (GIS) data. Through the use of GIS, BASINS has the flexibility to display and integrate a wide range of information (e.g. land use, point source discharges, and water supply withdrawals) at a scale chosen by the user.

BASINS consists of a number of sub-models, such as HSPF, QUAL2E, and SWAT. The HSPF module simulates the nonpoint flows and nutrients in the watershed. Its code contains three components: PERLND (for pervious land), IMPLND (for impervious land), and RCHRES (for stream channels and mixed reservoirs).

Eutrophication model

This study includes the linking of the CE-QUAL-W2 (called W2) model to simulate the water quality patterns of the reservoir. W2 is a coupled model of hydrodynamics and water quality that has been applied widely to rivers, lakes, reservoirs, and estuaries (Martin, 1988; Gunduz *et al.*, 1998; Kurup *et al.*, 2000; Kuo *et al.*, 2003). It is developed primarily for relatively long and narrow water bodies exhibiting quality gradients in longitudinal and vertical axes. It has the capability to simulate 21 selected biological and chemical constituents, in addition to horizontal and vertical velocities, as well as temperature. The model is based upon the finite difference solution of laterally averaged equations of fluid motion including: (1) horizontal momentum equation; (2) constituent transport equation; (3) free water surface elevation equation; (4) hydrostatic pressure equation; (5) continuity equation; and (6) equation of state relating density as a function of temperature and solids concentration. The unknowns in these equations are the free water surface elevation, pressure, horizontal velocity, vertical velocity, constituent concentrations, and density. The solution of six equations for six unknowns forms the basic structure of the model. The model has the capability to include branches, lateral inflows (i.e. tributaries, point discharges), withdrawals (i.e. water intake structures), head or flow boundary conditions, and several other features that broaden its application to a variety of simulations.

W2 updates hydrodynamics, loading, and outflows at each computational time step. However, water quality terms can be updated less frequently since most biochemical processes require longer time steps compared to hydrodynamic processes. This allows the user to save a considerable amount of computational time.

Results and discussion

Watershed simulation results

BASINS requires hourly meteorological data of precipitation, potential surface evaporation, air temperature, wind speed, solar radiation, dewpoint temperature, cloud cover, and potential evapotranspiration. These field data are obtained from the Northern Region Water Resources Bureau. The monitoring data at the gauge station include flow rates and nutrients. Field data collected over one and a half years (2003 and half of 2004) were used in this study. The calculated flow rates match the data quite well on a real time basis (not shown). The mean absolute difference between model results and field data is quantified and presented in Table 1. Over this one and a half year period, the mean absolute difference is about 6% per year, suggesting that the flow model works well and is capable of producing accurate flow rates for the reservoir model.

Nutrient sampling was conducted at the Shiah-Su-Leh station during the wet seasons of 2003–2004 and the data were used for model validation. The simulated results are shown in Figure 4. It reveals that the model prediction is in reasonable agreement with the measured data. The nonpoint source of total nitrogen and total phosphorus loads predicted using the model indicate that nonpoint loads from the watershed are most significant during storms.

Water quality simulation results

Watershed discharges and nutrient loadings from the BASINS model were incorporated into the W2 model for simulation of the water quality in the Shihmen Reservoir. Field data in 2003 were used to support model calibration and the 2004 data were used

Table 1 Mean absolute difference between model results and field data for runoff volume

Year	Runoff volume ($10^6 m^3$)		Absolute mean difference (%)
	Field	Model	
2003	386.70	352.58	8.8
2004	263.34	255.73	2.9

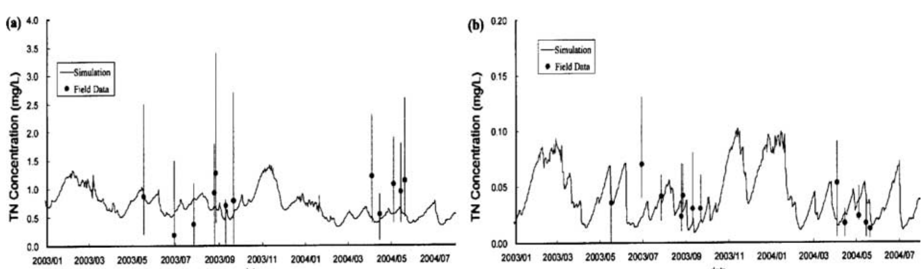

Figure 4 The comparisons of model results and field data from 2003 to 2004 (a) total nitrogen and (b) total phosphorus concentrations

for model verification. The fundamental input data for W2 included reservoir topography (bathymetry), stream temperature, flow, and water quality records, as well as meteorological logs. Reservoir topography was used to define the finite difference representation of the water body. According to this representation, the Shihmen Reservoir was described as a single branch water body with 15 longitudinal segments and 36 vertical layers (Figure 5). The segment length and layer thickness were selected to be 1 000 m and 2 m, respectively. The entire water column was therefore configured with a total of 326 cells. The main inflow data were supplied from one gauge station. Stream flows from small, ungauged tributaries were apportioned according to their watershed areas. The meteorological data were obtained from the Northern Region Water Resources Bureau. Daily average meteorological data were used to calculate solar radiation, equilibrium temperature, and the surface heat exchange coefficient. Monthly water quality data of dissolved oxygen, chlorophyll *a*, total phosphorus, ammonia-nitrogen, nitrate-nitrogen, and nitrite-nitrogen in the reservoir were used for comparisons with model results.

A water balance of the Shihmen Reservoir was first confirmed with the W2 model using the flow results from BASINS. Figure 6 shows a close match between the simulated and measured water surface elevation for model calibration and verification in the Shihmen Reservoir. The time series data of one and a half years indicate that the surface elevation decreased and reached the lowest in the spring and early summer months of 2003, and raised and reached a peak in the late summer and autumn periods of typhoon and thunderstorms.

Water temperature data were used to evaluate the hydrodynamic results from one-year model runs. Figure 7 shows the vertical profiles of simulated and measured temperature levels in the water column for model calibration results in 2003. Note the model simulation results closely mimic the measured vertical temperature profiles and the seasonal variation of temperature in the water column. The reservoir exhibits a pronounced vertical thermal gradient in the summer and undergoes significant overturning by the end of the autumn. The stratified condition minimizes vertical exchange in the water column.

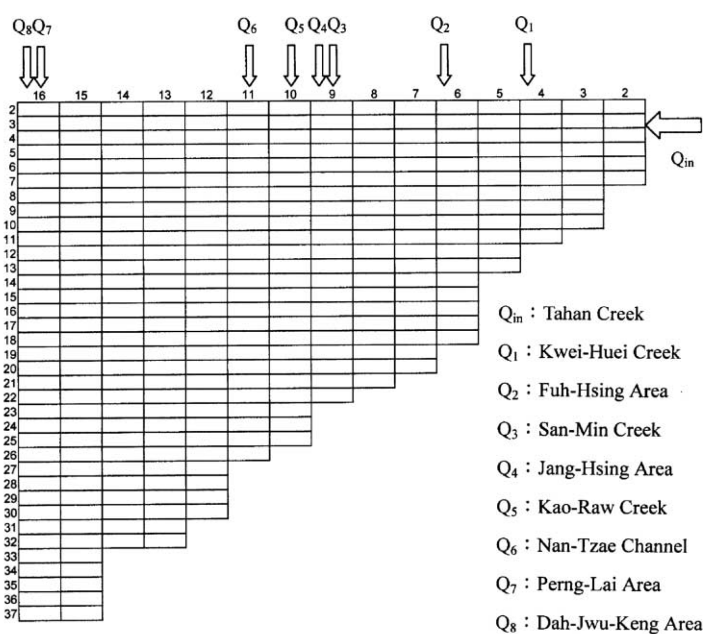

Figure 5 Finite different grid representation for the model of the Shihmen Reservoir

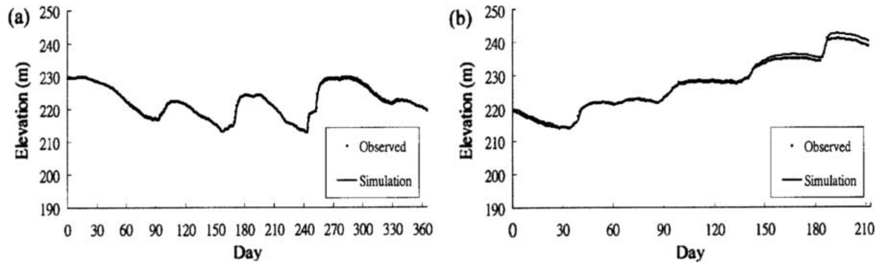

Figure 6 Water surface elevation of model simulation vs. field data (a) 2003 and (b) 2004

Numerical model runs were conducted to calibrate the water quality model parameters. The parameters for the water quality model are the kinetic coefficients in the water column. Figures 8 and 9 show some calibrated results of chlorophyll *a* and total phosphorus, respectively, at the dam site in 2003 at the top, middle, and bottom layers. Note that water depth in the reservoir varies from season to season. The distribution of chlorophyll *a* is influenced by complex factors such as temperature, availability of light, nutrients, and the hydrodynamic mixing processes. Nutrient dynamics are of crucial importance to the water quality components of the model. The calibration and verification

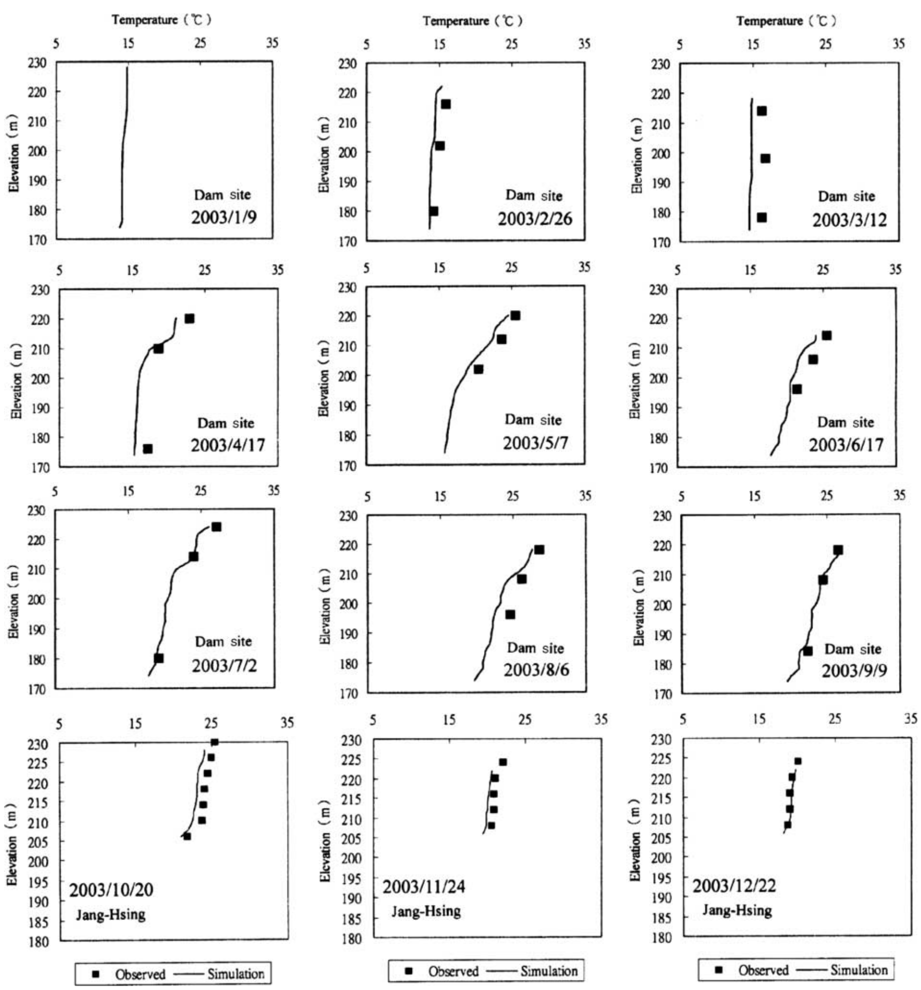

Figure 7 Predicted and observed water temperature for 2003 calibration

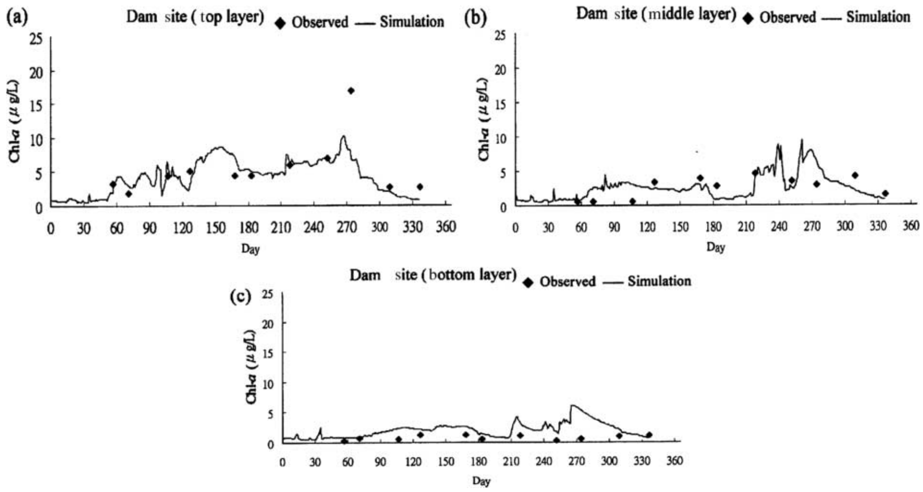

Figure 8 Predicted and observed chlorophyll *a* concentration for 2003 model calibration at dam site (a) surface layer, (b) middle layer, and (c) bottom layer

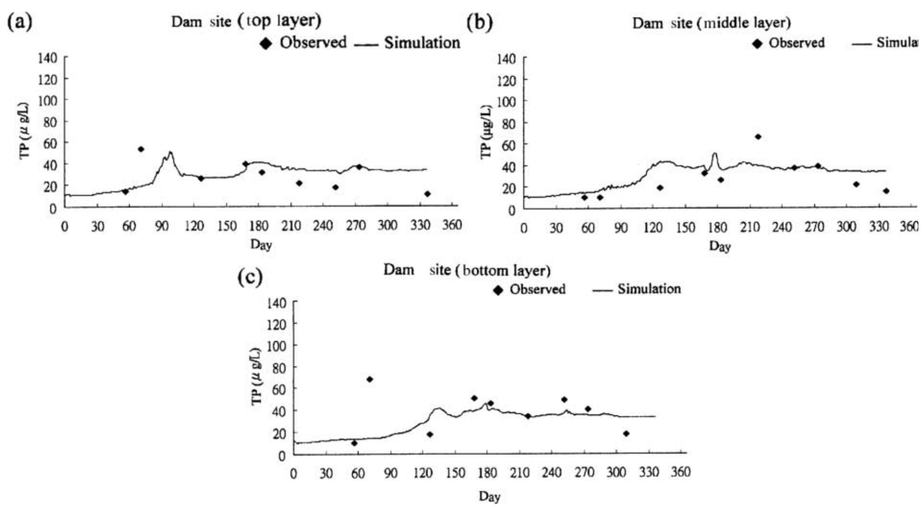

Figure 9 Predicted and observed total phosphorus concentration for 2003 model calibration at dam site (a) surface layer, (b) middle layer, and (c) bottom layer

procedures require consideration of the balance between phytoplankton growth and depletion of available nutrients from the water column. Table 2 presents the verified results of absolute mean and root-mean-square differences. It reveals that simulation and field measurements are in good agreement.

Table 2 Mean absolute and root-mean-square differences between computed and measured concentrations for model verification results

Layer	Chlorophyll *a* (μg/L)		Total phosphorus (μg/L)		Ammonia-nitrogen (mg/L)		Nitrate-nitrogen (mg/L)		Dissolved oxygen (mg/L)	
	AM	RMS	AM	RMS	AM	RMS	AM	RMS	AM	RMS
Top	3.57	6.37	13.35	15.64	0.60	1.17	0.16	0.22	1.50	1.71
Middle	1.46	2.34	14.49	16.29	0.17	0.26	0.17	0.22	1.73	1.86
Bottom	1.76	2.63	11.08	13.84	0.10	0.17	0.16	0.20	2.07	2.24

AM: absolute mean difference; RMS: root-mean-square difference

Conclusion

The study presents the application of watershed and eutrophication models for the Shihmen Reservoir of northern Taiwan. Model results have shown that the majority of nutrient loads from the watershed are generated during storm conditions. The watershed model results are generally in good agreement with the field data at gauge and sampling stations. The nonpoint nutrient loads calculated by the BASINS model were used to drive the eutrophication model. A close match was produced between the simulated and measured water surface elevation for model calibration and verification in the reservoir. The hydrodynamic model reproduced temporal and spatial distributions of temperature in the water column during these simulated periods. Thermal stratification was also reproduced with the correct predictions of the depths of the thermoclinic. Satisfactory model calibration and verification results were yielded in the water quality constituents. The model provides a useful tool to predict the improvement of reservoir water quality for the various management strategies in the watershed.

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