



Application of water quality model to analyze pollution hotspots and the impact on reservoir eutrophication

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Abstract Sustainable reservoir watershed management is crucial to maintain a water supply system. The purpose of this study is to assess the pollution sources of the Bao-Shan Reservoir, which is an off-stream reservoir and is the study reservoir herein. Most water source of the Bao-Shan Reservoir is from the Shang-Ping Watershed. This study applies the EPA's Storm Water Management Model (SWMM) and the Vollenweider model (VM) to analyze the pollution hotspots in the reservoir watershed and the impact of the pollutions on the reservoir water quality. The results indicate that non-point source pollution is the main pollution in the Shang-Ping Watershed. The pollution hotspots are located in the sub-watersheds S1, S3, S4, and S5. These sub-watersheds have higher total phosphorus (TP) loads per unit area. In order to protect the water quality of the Bao-Shan Reservoir, this study suggests that the TP load entering the reservoir needs to be reduced by about 16% to 24%. The control of non-point source pollution needs to be preferentially implemented in the Shang-Ping Watershed. The analysis and discussion in this study are a useful reference for reservoir watershed management.

Keywords Eutrophication · Pollution hotspot · Reservoir management · Water quality model

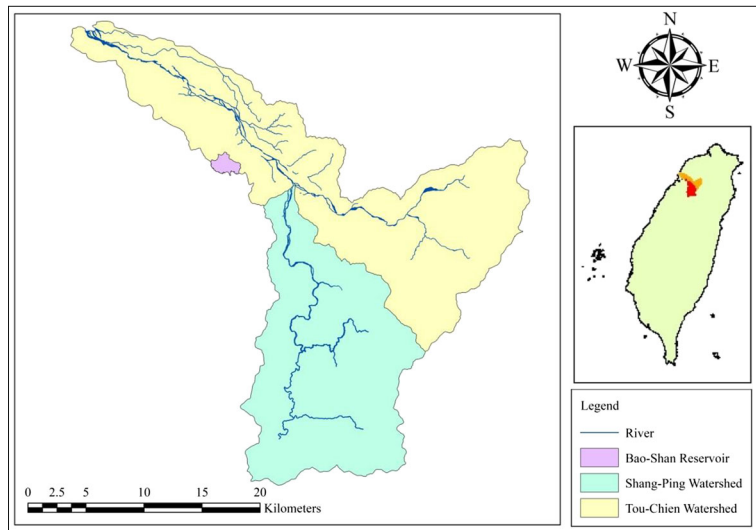
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Introduction

Although Taiwan has abundant rainfall, its steep terrain, fast-flowing streams, and uneven rainfall result in limited water resources and high environmental vulnerability. In addition, global climate change has even increased the difficulty of water resource management and environmental protection (Stakhiv 2011; Chartzoulakis and Bertaki 2015; Cosgrove and Loucks 2015; Arnell and Gosling 2016; Chiang et al. 2017). In order to maintain a stable water supply system, people build reservoirs to store water to meet the continuous water demand from the non-continuous natural water supply. More than 50% of the world's reservoirs have the main purpose of storing water (Votruba and Broža 1989; Chaves et al. 2003). In Taiwan, reservoirs also play an important role in the use and distribution of water resources (Wang et al. 2018).

Since the reservoirs provide raw water to the water treatment plants, the water quality of the reservoir will affect the operation and efficiency of the water treatment plants (Yeh 1985; O'Melia 1998; Chang and Liao 2012; Coelho and Andrade-Campos 2014). Due to urbanization, increased land use and environmental development have increased pollution load entering the reservoir, which can affect the water quality of the reservoir and even lead to reservoir eutrophication. Since a reservoir is a static system, its self-purification capacity is lower than that of a dynamic system. Eutrophication can damage the environment and the normal function of the reservoir (Rast and Thornton 1996; Balcerzak 2006; Schindler

Fig. 1 Study area: the Bao-Shan Reservoir and the Shang-Ping Watershed



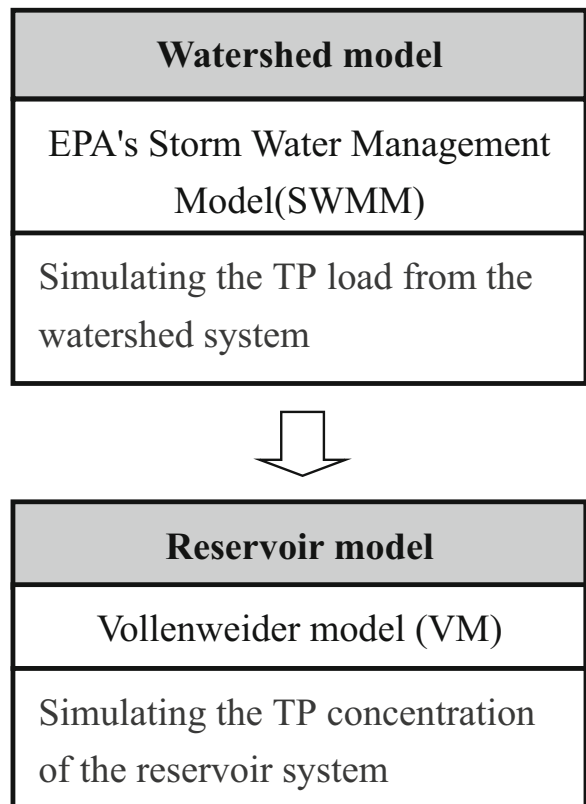
2006; Smith and Schindler 2009). Therefore, it is crucial to reduce the pollution load entering the reservoir and to protect the water quality of the reservoir (Said et al. 2006; McDonald et al. 2011; Cooke et al. 2016; Yazdi and Moridi 2017).

Nutrients, such as phosphorus, nitrogen, and silicon, can impact reservoir water quality and even lead to reservoir eutrophication. Many studies have shown that phosphorus is the main pollutant causing eutrophication (Vollenweider 1971; Dillon and Rigler

Table 1 Land uses in the study area

(a) Land uses in the Bao-Shan Reservoir Watershed and the Shang-Ping Watershed											
Land use	Shang-Ping Watershed				Bao-Shan Reservoir Watershed						
	Area (km ²)		Area percentage(%)		Area(km ²)		Area percentage(%)				
Agriculture	10.81	4.63			0.25	7.76					
Forest	216.48	91.36			2.24	70.2					
Building	4.08	1.75			0.09	2.88					
Water	2.86	1.22			0.59	18.32					
Barren land	2.44	1.04			0.03	0.84					
Sum	236.67	100			3.20	100					
(b) Analysis of land uses of the 9 sub-watersheds in the Shang-Ping Watershed											
Sub.	Agriculture		Forest		Building		Water		Barren land		Sum
	Area (km ²)	%	Area (km ²)	%	Area (km ²)	%	Area (km ²)	%	Area (km ²)	%	Area (km ²)
S1	4.45	14.61	23.3	76.52	1.56	5.12	1.11	3.65	0.03	0.10	30.45
S2	0.81	4.41	17	92.54	0.37	2.01	0.08	0.44	0.11	0.60	18.37
S3	2.29	7.82	25.4	86.69	0.86	2.94	0.53	1.81	0.22	0.75	29.3
S4	1.57	5.68	24	86.89	0.58	2.10	0.59	2.14	0.88	3.19	27.62
S5	0.25	4.56	4.98	90.88	0.15	2.74	0.06	1.09	0.04	0.73	5.48
S6	0.33	1.17	27.6	97.63	0.14	0.50	0.15	0.53	0.05	0.18	28.27
S7	0.05	0.24	20.8	99.09	0.01	0.05	0.05	0.24	0.08	0.38	20.99
S8	0.01	0.05	20.9	97.12	0.14	0.65	0.13	0.60	0.34	1.58	21.52
S9	1.05	1.92	52.5	96.03	0.27	0.49	0.16	0.29	0.69	1.26	54.67
sum	10.81	4.57	216.48	91.47	4.08	1.72	2.86	1.21	2.44	1.03	236.67

Fig. 2 Combination of the watershed model and the reservoir model



1974; Sigua et al. 2006; Steinman and Ogdahl 2015). Thus, the total maximum daily load (TMDL) of total phosphorus (TP) entering the reservoir must be determined. The TMDL represents the maximum allowable load and needs to be determined by the assimilative capacity and a target TP concentration of the reservoir (Boyacioglu and Alpaslan 2008; Conley et al. 2009; Chang and Liu 2015a; Steinman and Ogdahl 2015; Chen et al. 2016; Chang and Hong 2019). This study uses a major reservoir watershed system in Taiwan as the study area. The objective of this study is to analyze the sources of pollution entering the reservoir, including point source pollution and non-point source pollution. This study applies the EPA’s Storm Water Management Model (SWMM) to analyze the pollution sources and the spatial variation of pollution hotspots in the reservoir watershed and uses the Vollenweider model (VM) to assess the impact of the pollutions on the reservoir water quality. These analyses and discussions are important for proposing appropriate pollution control strategies and can provide useful references for other reservoirs around the world.

Methods

Description of study area

The Bao-Shan Reservoir, which is an off-stream reservoir, provides the setting for this case study. The area of the Bao-Shan Reservoir Watershed is only about 3.2 km². The total storage capacity is 5,470,000 m³. The normal water level is 141.6 m. It supplies water to the Hsinchu area for domestic use and to the Hsinchu Science-Based Industrial Park for industrial use. About 90% of the water in the Bao-Shan Reservoir comes from the Shang-Ping River, which is a tributary of the Tou-Chien River in central Taiwan. The environmental conditions in the Shang-Ping Watershed are related to the water quantity and water quality responses near the Shang-Ping Weir and the total amount of pollutants entering the Bao-Shan Reservoir. Figure 1 shows the location of the Bao-Shan Reservoir and the Shang-Ping Watershed in Taiwan. The Shang-Ping Watershed covers an area of about 236.7 km². This study divides the Shang-Ping Watershed into 9 sub-watersheds. Table 1 shows the land uses in the Shang-Ping Watershed

Table 2 Input data and parameters for the SWMM

(a) Geographical data				
Sub-watershed	Area (km ²)	Slope (%)	Length (m)	Area percentage of impervious surface (%)
S1	30.45	46.22	12,081.2	5.21
S2	18.37	55.44	1466.1	5.71
S3	29.3	61.54	10,369.0	5.87
S4	27.62	72.28	9829.0	8.33
S5	5.48	70.67	4436.5	5.81
S6	28.27	72.28	6704.4	5.30
S7	20.99	70.82	1573.7	5.49
S8	21.52	70.71	4228.6	6.39
S9	54.67	69.94	7676.8	6.70
(b) Basic parameters				
Object	Parameter	Validated value	Range	
Surface runoff	Manning's <i>n</i> for pervious areas	0.4	0.1–0.8	
	Manning's <i>n</i> for impervious areas	0.06	0.01–0.06	
Infiltration (Horton infiltration)	maximum Infiltration rate (mm/h)	4.5	0.25–25	
	minimum Infiltration rate (mm/h)	0.5	0.25–25	
	decay constant (1/h)	4	> 0	
Buildup (power function)	maximum buildup(kg)	0.025 (agriculture)	> 0	
		0.015 (forest)		
		0.030 (building)		
		0.031 (barren land)		
	Rate constant (1/day)	1	> 0	
	Power constant	0.5	> 0	
	Wash-off (event mean concentration)	Wash-off pollution concentration (mg/L)	0.030 (agriculture)	> 0
0.020 (forest)				
0.035 (building)				
0.036 (barren land)				
	Wash-off exponent	1	> 0	

and the Bao-Shan Reservoir Watershed. In the Shang-Ping Watershed, most areas are forests. The proportion of agricultural area and building area in the downstream areas is higher than that in upstream areas.

Model application

Combination of water quality models

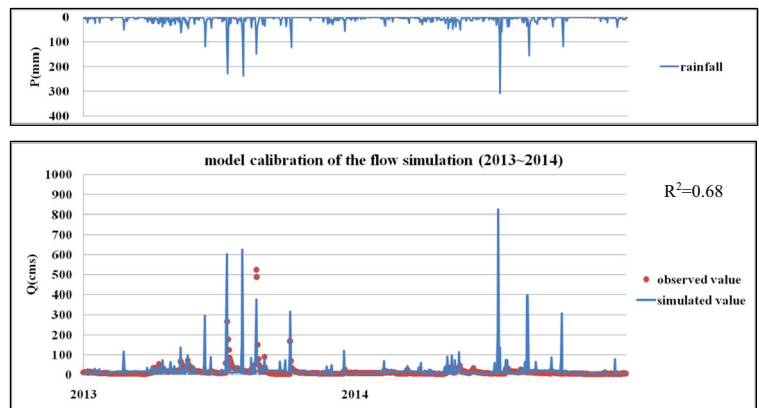
Water environmental systems are complex. Environmental modeling is important before implementing appropriate and effective environmental strategies (Lung 2001). Many environmental models such as watershed models and reservoir models have been developed and applied to the prediction of environmental responses and changes. Since most water in the Bao-Shan Reservoir comes from the Shang-Ping Weir, the pollution in

the Shang-Ping Watershed is the main source of pollution affecting the water quality of the Bao-Shan Reservoir. Therefore, this study combines a watershed model and a reservoir model to analyze the pollutions in the watershed system (the Shang-Ping Watershed) and the impact of the pollutions on the reservoir system (the Bao-Shan Reservoir). Figure 2 shows the way to combine the water quality models in this study. Combining watershed models with reservoir models is of great significance for the analysis of reservoir watershed problems.

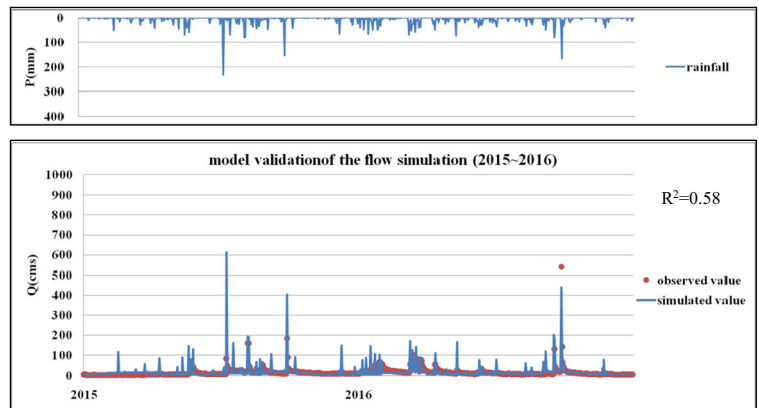
Watershed model—SWMM

The SWMM developed by the US Environmental Protection Agency is a dynamic water quality model. The model has been widely used to simulate water quantity

Fig. 3 Calibration and validation results of the flow simulations in the Shang-Ping Watershed

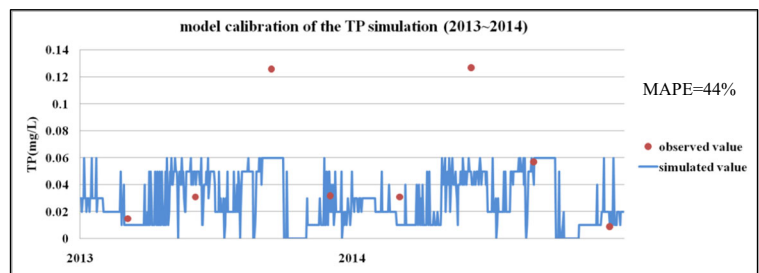


(a) model calibration

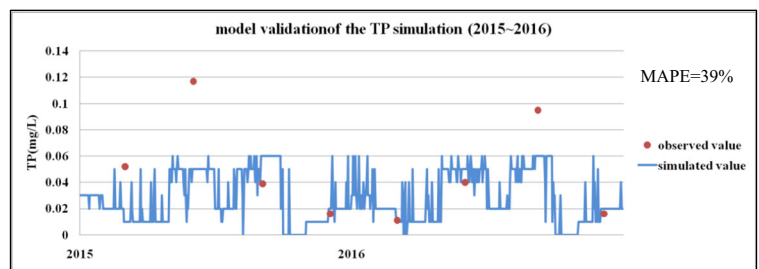


(b) model validation

Fig. 4 Calibration and validation results of the TP simulations in the Shang-Ping Watershed



(a) model calibration



(b) model validation

Table 3 Input data and parameters for the VM

Parameter	Value	Data source
Total TP load (M)(g/year)	1,038,223	Calculated by the SWMM (the average value from 2013 to 2016)
Setting velocity of TP (v)(m/year)	16	Determined by the model calibration and validation
Inflow discharge (Q_{in})(m ³ /year)	35,280,000	The average of monitoring data (the average value from 2013 to 2016)
Outflow discharge (Q_{out})(m ³ /year)	34,381,925	The average of monitoring data (the average value from 2013 to 2016)
Reservoir surface area (A)(m ²)	601,500	Design report

and water quality responses for a single event or a long-term simulation in watershed systems. The SWMM provides an integrated interface for preparing input data, running hydrologic, hydraulic and water quality simulations, and viewing the simulation results in a variety of formats. The model simulates various hydrologic processes considering rainfall and rainfall abstraction and estimates the pollution loads and water quality responses using initial pollution concentrations, buildup functions, and wash-off functions. In addition, the SWMM can evaluate the performance of green infrastructure practices, such as low impact development (LID) facilities and best management practices (BMPs), in runoff management and pollution control (Gironás et al. 2010; Rosa et al. 2015; Tsai et al. 2017). Since the functions and features of the SWMM are sufficient for the simulations and analyses of this study, the SWMM is chosen as the primary tool for watershed simulation and applied to estimate the pollutions in the Shang-Ping Watershed.

Reservoir model—VM

This study simulates the pollutions in the Shang-Ping Watershed by the SWMM and combines the SWMM with the VM. The purpose is to understand the impact of

the pollution load on the water quality of the Bao-Shan Reservoir. The VM is a one-dimensional mass balance model and usually used in the simulation of TP concentration in reservoir systems (Vollenweider 1971; Dillon and Rigler 1974; Kirchner and Dillon 1975). The TP concentration of the reservoir (P) is estimated by Eqs. (1), (2), and (3). The model assumes that the TP load in a reservoir is lost resulting from sediment settlement. M is the input TP load, i.e., the total pollutants entering the reservoir. Q_{in} and Q_{out} are the inflow discharge and the outflow discharge. R_p is the lost proportion determined by the settling velocity (v) and the hydraulic load (q_s). q_s is calculated by the inflow discharge (Q_{in}) and the reservoir surface area (A).

$$P = \frac{M * (1 - R_p)}{Q_{out}} \quad (1)$$

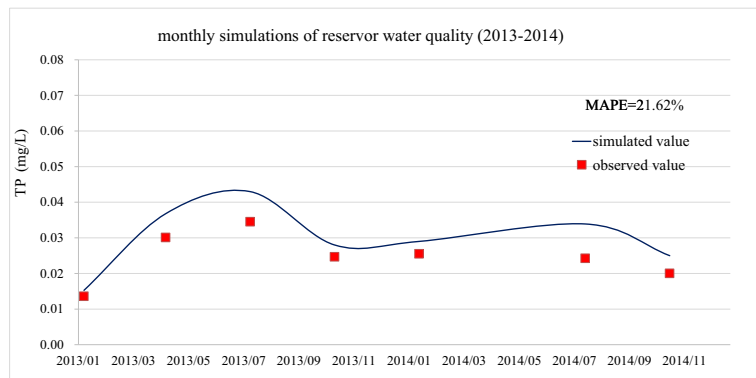
$$R_p = \frac{v}{v + q_s} \quad (2)$$

$$q_s = \frac{Q_{in}}{A} \quad (3)$$

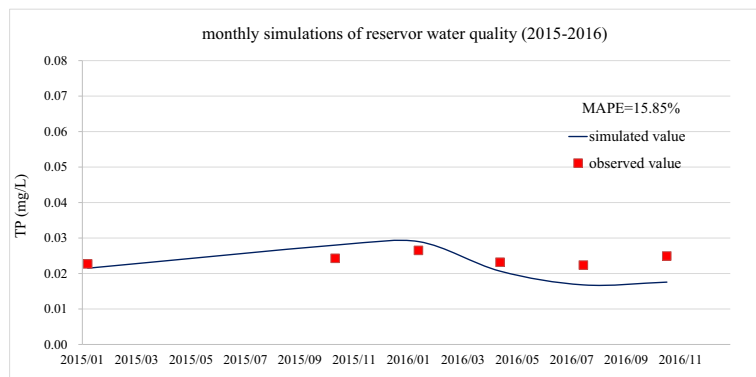
Table 4 Calibration and validation results of the TP concentration of the Bao-Shan Reservoir

Period	Observed TP concentration (mg/L)	Simulated TP concentration (mg/L)	MAPE
Calibration(2013–2014)	0.0234	0.0223	4.59%
Validation(2015–2016)	0.0243	0.0252	3.93%
2013–2016	0.0238	0.0237	0.48%

Fig. 5 Monthly simulations of reservoir water quality



(a) monthly simulations of reservoir water quality from 2013 to 2014



(b) monthly simulations of reservoir water quality from 2015 to 2016

Table 5 TP loads entering the Bao-Shan Reservoir

Pollutions		Bao-Shan Reservoir Watershed	Shang-Ping Watershed	TP load entering the Bao-Shan Reservoir from the Shang-Ping Watershed
Point source pollution	Load (kg/year)	61	739	103
	%	56%	11%	11%
Non-point source pollution	Load (kg/year)	48	5885	827
	%	44%	89%	89%
Sum	Load (kg/year)	108 (A)	6624	930 (B)

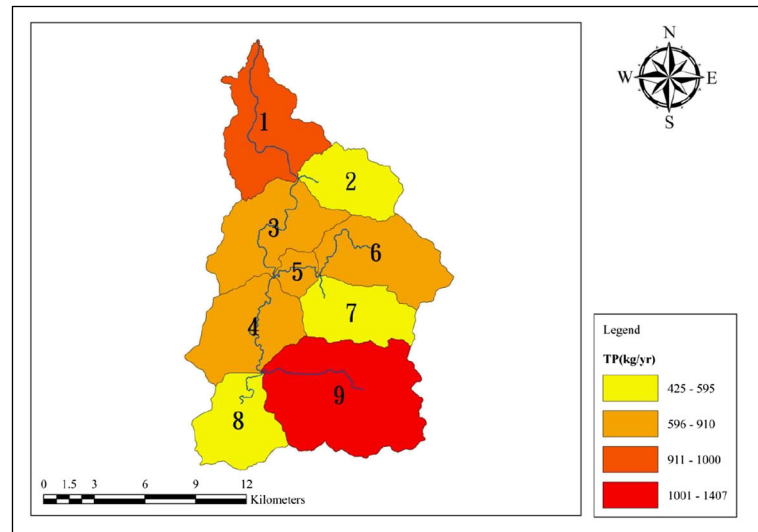
The total TP load entering the Bao-Shan Reservoir is 1038 kg/year, i.e., (A) + (B). The TP loads have already considered “delivery ratio”

Results and discussion

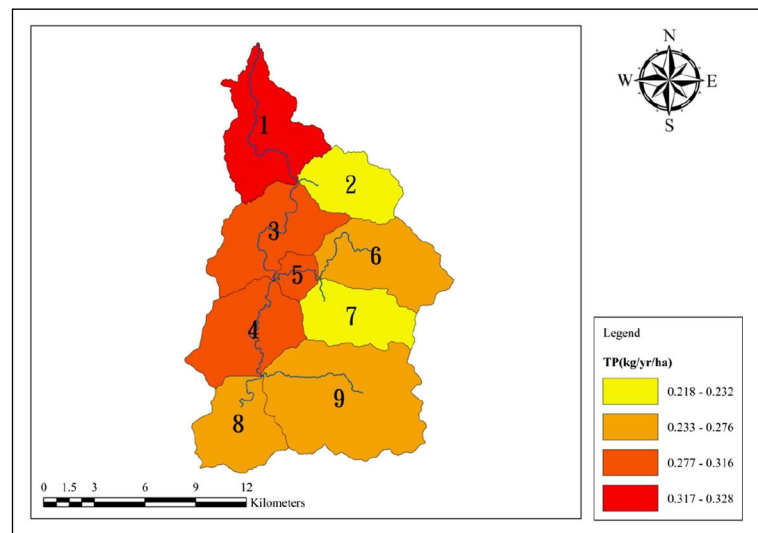
Model calibration and validation

Model calibration and validation are very important processes before applying environmental models to simulate environmental responses. Model users need to adjust the parameters and search for appropriate parameters of the model to improve the reliability of simulation results, i.e., to reduce the differences between the simulated values and the observed values. Model calibration and model validation are processes of comparing the simulation results to the monitoring data. This study uses the monitoring data from 2013 to 2014 for model calibration and the monitoring records from 2015 to 2016 for model validation. Our water quality monitoring data is quarterly, and water quantity monitoring data is daily. The water quality and water quantity simulations are daily in the watershed system. Table 2 shows the basic input data and parameters for the SWMM. Most geographical input data are prepared

Fig. 6 Pollution hotspots in the Shang-Ping Watershed



(a) TP loads



(b) TP loads per unit area

by the geographical information system (GIS), and the parameters are determined by model calibration and validation.

Figure 3 shows the calibration and validation results of the flow simulations in the watershed system. In the calibration and validation of the flow simulations, the values of R square (R (Balcerzak 2006)) between the observed and simulated values are about 0.68 and 0.58, respectively. Since the R^2 values are larger than 0.5, it indicates that the flow simulation results are satisfactory. Figure 4 shows the calibration and validation results of the TP simulations in the watershed system. In the calibration and validation of the TP

simulations, the values of mean absolute percentage error (MAPE) are about 44% and 39%, respectively. Since the values of MAPE are less than 50%, it indicates that the reliability of TP simulation results is acceptable.

This study also completes the calibration and validation of the VM to simulate the water quality of the Bao-Shan Reservoir. Table 3 shows the basic input data and parameters for the VM. Table 4 shows the model calibration and validation results of the TP concentration in the reservoir system. The TP load from the Shang-Ping Watershed is simulated by the SWMM. The total TP load entering the Bao-Shan Reservoir is about 1038 kg/year that

results in an average reservoir TP concentration of 0.024 mg/L in the last 5 years. The settling velocity (v) is determined as 16 m/year by comparing the observed and simulated water quality of the Bao-Shan Reservoir. In the model calibration and validation of reservoir water quality, the values of MAPE are 4.59% and 3.93%, respectively, in the annual simulations. The MAPE of the average TP concentration simulation from 2013 to 2016 is only 0.48%. Figure 5 shows the monthly simulations of reservoir water quality. The values of MAPE are about 21.62% (from 2013 to 2014) and 15.85% (from 2015 to 2016), respectively, in the monthly simulations. Since the values of MAPE are less than 50%, the simulation results of reservoir water quality are satisfactory.

Analysis of pollution hotspots

Table 5 shows the sources of pollution entering the Bao-shan Reservoir, including point source pollution and non-point source pollution. The delivery ratio of the pollution from the Bao-Shan Reservoir Watershed is given by 0.25. The values of the delivery ratio of the pollution from the Shang-Ping Watershed are between 0 and 0.2. They are determined by the SWMM model based on the location of the sub-watersheds. The total TP load from the Shang-Ping Watershed is 6624 kg/year, and only about 14% of these pollutions enter the Bao-Shan Reservoir. The TP loads entering the Bao-Shan Reservoir are about 930 kg/year and 108 kg/year, respectively, from the Shang-Ping Watershed and from the Bao-Shan Reservoir Watershed. The analysis results indicate that about 90% of the pollution in the Bao-Shan Reservoir comes from the Shang-Ping Watershed and only 10% of the pollution comes from the surrounding area of the reservoir. The Bao-Shan Reservoir Watershed has about 56% point source pollution and 44% non-point source pollution. However, non-point source pollution is the main pollution (about 89%) in the Shang-Ping Watershed. Therefore, compared with the control of point source pollution, the control of non-point source pollution needs to be preferentially implemented in the Shang-Ping Watershed.

This study also applies the SWMM to analyze the spatial variation of pollution hotspots, as shown in Fig. 6. It is significant to preferentially implement appropriate pollution control and reduction strategies in the areas with high pollution loads. The results show

that the sub-watersheds S1 and S9 contribute higher TP loads than other sub-watersheds resulting from their relatively large areas. When considering the pollution yield per unit area, the sub-watersheds S1, S3, S4, and S5 contribute higher TP loads for the Bao-Shan Reservoir. Table 6 summarizes the TP loads from each sub-watershed in the Shang-Ping Watershed. The sub-watershed S1 close to the Shang-Ping Weir has the highest TP load per unit area. The percentage of forested area is the lowest in the sub-watershed S1; contrarily, the percentages of agricultural area and building area are relatively high. The result indicates that the pollution loads are indeed related to the land use conditions.

Pollution reduction strategies

The degree of eutrophication of a reservoir system can be classified into three grades according to the TP concentration. When the TP concentration of the reservoir is higher than 0.024 mg/L, it has a high degree of eutrophication. When the TP concentration of the reservoir is between 0.012 and 0.024 mg/L, it has a medium degree of eutrophication. When the TP concentration is lower than 0.012 mg/L, it has a low degree of eutrophication (Brezonik 1984; Sigua et al. 2006; Sheela et al. 2011; Chang and Liu 2015b). The average TP concentration of the Bao-Shan Reservoir is about 0.024 mg/L in the recent years, indicating that the eutrophication problem exists in this reservoir. This study recommends

Table 6 TP loads from the sub-watersheds in the Shang-Ping Watershed

Sub-watershed	Area (km ²)	Point source pollution (kg/year)	Non-point source pollution (kg/year)	TP loads (kg/year)	TP loads per unit area (kg/year/ha)
S1	30.45	95.2	904.6	999.8	0.328
S2	18.37	57.2	367.4	424.6	0.231
S3	29.3	91.6	818.6	910.2	0.311
S4	27.62	86.2	784.9	871.1	0.315
S5	5.48	17.1	154	171.1	0.312
S6	28.27	88.3	689.3	777.6	0.275
S7	20.99	65.5	392.2	457.7	0.218
S8	21.52	67.3	519.7	587	0.273
S9	54.67	170.7	1254.3	1425	0.261
sum	236.67	739.1	5885.0	6624.1	0.28

Table 7 Efficiency of the pollution reduction strategies

Scenario	TP concentration ($\mu\text{g/L}$)	TP load (kg/year)	Pollution reduction (kg/year)	Reduction rate (%)
Present condition	23.7	1038	-	-
Target TP concentration: 20 $\mu\text{g/L}$	20.0	875	163	15.7
Target TP concentration: 18 $\mu\text{g/L}$	18.0	788	250	24.1
Target TP concentration: 12 $\mu\text{g/L}$	12.0	525	513	49.4

that the TP concentration can implement staged reduction strategies and applies the VM to predict the efficiency of water quality improvement under different pollution reduction strategies. Table 7 shows the efficiency of several pollution reduction strategies. The first target is 0.020 mg/L, i.e., A-class water quality standard. The second target is 0.018 mg/L, which is a condition for stable reservoir water quality without eutrophication problems. In order to achieve these goals, the TP load entering the Bao-Shan Reservoir needs to have a pollution reduction rate of 16% to 24%.

Conclusions

This study combines water quality models to assess the pollution sources of the Bao-Shan Reservoir. The results show that there are about 56% point source pollution and 44% non-point source pollution in the surrounding area of the reservoir. However, non-point source pollution is the main pollution in the Shang-Ping Watershed. Since most of the water in the Bao-Shan Reservoir comes from the Shang-Ping Watershed, it is necessary to first implement pollution control strategies in the Shang-Ping Watershed. Compared with point source pollution, the control and reduction of diffuse pollution are relatively important. The pollution hotspots in the Shang-Ping Watershed are located in the sub-watersheds S1, S3, S4, and S5, which have relatively high TP loads. The pollution control strategies need to be implemented in these areas in priority. Due to the eutrophication of the water quality of the Bao-shan Reservoir, this study suggests that the TP load entering the reservoir needs to be reduced by about 16% to 24% to maintain good water quality. The findings in this study are significant to relative

reservoir management agencies and can be important references for other reservoirs.

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