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Applying environmental models to determine total maximum daily loads for reservoir watershed management

C.-L. Chang[1] · T.-Y. Hong[1]

Abstract

To protect the reservoir water quality, it is required to control and reduce the pollution sources in its upstream watershed area. This study applies the EPA's Storm Water Management Model and the Vollenweider model to assess the relationship between the pollution sources in the Luliao Reservoir Watershed and the water quality of the Luliao Reservoir. The purpose of this study is to determine the total maximum daily loads in the watershed on the basis of a target water quality concentration of the receiving waterbody. The results show that the allowable total phosphorous (TP) load is about 855 kg/yr when considering a target TP concentration of 24 µg/L. To reach this target, the TP load needs to have about 1222 kg/yr reduction. Moreover, this study analyzes the spatial variation of TP load and the pollution hotspots in the Luliao Reservoir Watershed. The pollution control and reduction strategies are recommended to preferentially implement in the pollution hotspots.

Keywords Environmental model · Reservoir watershed management · Total maximum daily loads (TMDLs) · Reservoir water quality

Introduction

Compared to a river system, the self-purification capacity of a reservoir system is relatively low. When pollutants flow into a reservoir system, it may result in eutrophication problems, damage the water quality, and influence the normal functions of the system (Beeton and Edmondson 1972; Rast and Thornton 1996; Schindler 2006; Smith and Schindler 2009). As a result of the increased world population and water demand, it is important to maintain and improve the water supply function of a reservoir system. However, urbanization changes the environmental systems and brings many challenges for sustainable reservoir watershed management (Said et al. 2006; Kojiri 2008; Cooke et al. 2016).

Pollution control is important for successful reservoir watershed management. Point source pollution and nonpoint source pollution can both deteriorate the water quality of a reservoir system, but their control and management strategies are different. Proper effluent standards are required for point source pollution control. Nonpoint source pollution is more difficult to control and reduce than point source pollution (Wu and Chen 2013). Best management practices, which include structural and non-structural practices, are widely used for nonpoint source pollution control (Mostaghimi et al. 2000; D'Arcy and Frost 2001; Damodaram et al. 2010; Liu et al. 2013).

The concept of total maximum daily loads (TMDLs) was originally developed for the Clean Water Act in the USA. To protect the water quality of a receiving waterbody, the TMDLs consider effluent-based control and ambient-based control. The TMDLs, which are the maximum allowable pollution loads, need to be determined by the assimilative capacity of a receiving waterbody and calculated from a target water quality concentration and a flow state (Boyacioglu and Alpaslan 2008; Jha et al. 2010; Steinman and Ogdahl 2015; Chen et al. 2016). Total phosphorous (TP) is the main pollutant causing eutrophication (Conley et al. 2009; Chang and Liu 2015). Thus, a target TP concentration in a reservoir is the critical consideration to determine the maximum allowable TP load in a watershed.

This study combines a watershed model and a reservoir model. The EPA's Storm Water Management Model

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✉ C.-L. Chang
  f89541201@ntu.edu.tw

[1] Department of Water Resources Engineering and Conservation, Feng Chia University, No. 100 Wenhwa Rd., Seatwen, Taichung 40724, Taiwan

(SWMM) is applied to calculate the total pollution load and to analyze the pollution hotspots in the study watershed. The Vollenweider model (VM) is used to evaluate the water quality of the receiving waterbody, i.e., the water quality of the study reservoir, under the scenarios with different pollution loads in the study watershed. The TMDLs are calculated from a target water quality concentration of the reservoir system. The analyses in this study are significant for developing proper pollution control and reduction strategies for reservoir watershed management so that it contributes to reservoir water quality protection.

Materials and methods

Study area

The Luliao Reservoir Watershed provides the setting for this case study. Figure 1 shows the location of the Luliao Reservoir Watershed in southern Taiwan. The total area of the watershed is about 7.75 km². The average elevation is about 114 m. Table 1 shows the land uses in the study area. The most land use in the watershed, about 54%, is forest. The land use for agricultural activities is about 38%, and the area for centralized human activities is only 3%. The Luliao Reservoir has severe siltation problems. These problems influence the normal functions of the reservoir. Thus,

**Table 1** Land uses in the Luliao Reservoir Watershed

Land use	Area (km²)	Area percentage (%)
Agriculture	2.96	38.19
Forest	4.17	53.82
Building	0.23	3.03
Water	0.38	4.97
Sum	7.75	100.00

it is required to improve the watershed system for solving the problems in the reservoir system.

Environmental models

As mentioned earlier, it is critical to determine the TMDLs and to implement pollution control and reduction strategies based on a target pollution concentration of the receiving waterbody. Mathematical methods and models play an important role for these analyses and applications (DePinto et al. 2004; Borah et al. 2006; Wang et al. 2015). Watershed models are required for the calculation of the pollution loads and the analysis of the pollution hotspots in a watershed system. Reservoir models are required for simulating the water quality of a reservoir system. Moreover, it is important to combine the simulation processes and results of watershed models and reservoir models for analyzing the relationship

Fig. 1 Study area: the Luliao Reservoir Watershed: **a** model calibration, **b** model validation
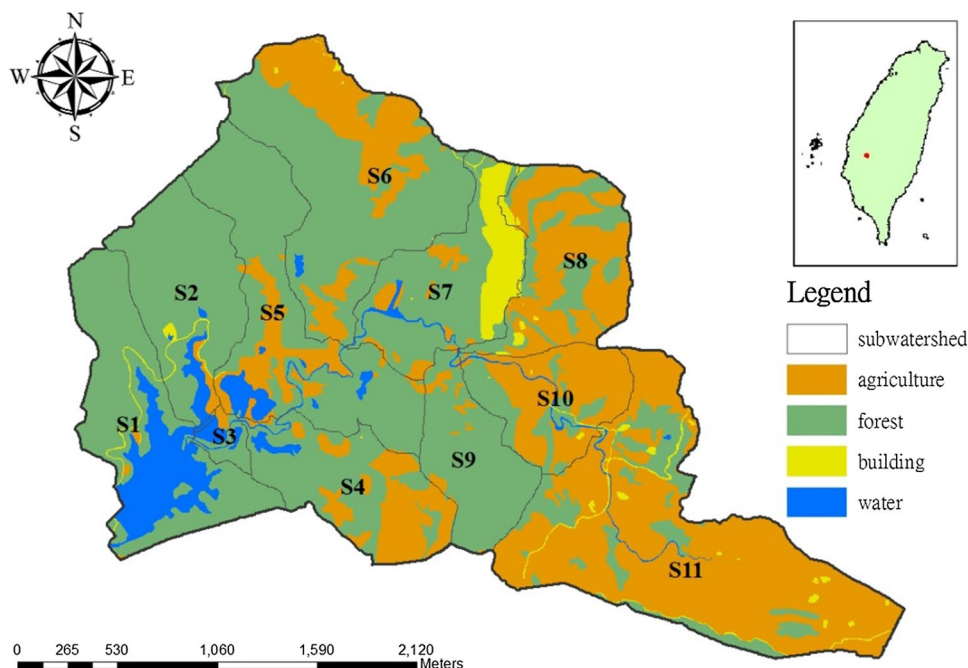
between the pollution loads in the watershed and the reservoir water quality (Chen et al. 2016).

The SWMM is a dynamic hydrology–hydraulic water quality simulation model for urban areas and non-urban areas. The model is widely used to simulate the quantity and quality of runoff in a watershed system. The calculation of runoff considers rainfall and rainfall abstraction. The SWMM uses initial pollution concentration, buildup function, and washoff function to calculate pollution loads and to simulate pollution concentrations. In addition, the SWMM is used to predict the performance of specific types of low impact development (LID) facilities (Gironás et al. 2010; Rosa et al. 2015; Tsai et al. 2017). This study applies the SWMM to calculate the pollution loads and to analyze the spatial variation of environmental pollution in the study watershed.

The pollution load entering the reservoir includes point source pollution and nonpoint source pollution. Most point source pollution in the study area comes from domestic sewage. This study estimates the pollution load from point sources by the population and the unit TP load per person per day. The pollution load from nonpoint sources is related to the land-use conditions. This study analyzes the spatial variation of land use by Geographic Information System (GIS). The parameters of the buildup function and washoff function are varied under different land-use conditions.

The VM is usually used in the simulation of TP concentration in reservoirs or lakes. This model is a one-dimensional mass balance model. It assumes that the amount of TP in reservoirs is lost resulting from sediment settlement (Vollenweider 1971; Dillon and Rigler 1974; Kirchner and Dillon 1975). This study uses the VM to assess the water quality of the study reservoir. The TP concentration of the reservoir is calculated by Eqs. (1–3). In Eq. (1), the TP concentration of the reservoir (P) is calculated by the input TP load from upstream watershed area (M), the lost proportion (R_p), and the outflow discharge (Q_{out}). In Eq. (2), R_p is calculated by the settling velocity (v) and the hydraulic load (q_s). In Eq. (3), q_s is obtained by considering the inflow discharge (Q_{in}) and the reservoir surface area (A).

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

$$R_p = \frac{v}{v + q_s} \tag{2}$$

$$q_s = \frac{Q_{in}}{A} \tag{3}$$

The VM is a steady-state model. This study estimates the average TP load per year from the upstream watershed area by the SWMM. Moreover, this study considers the effect of

pollution delivery and assumes that only parts of pollution load from upstream watershed area enter the reservoir. Most of the pollution load entering the reservoir comes from the subwatersheds surrounding the reservoir.

Results and discussion

Calibration and validation results of environmental simulation

To improve the reliability of simulation results, it is required to find the regional parameters through the process of model calibration and validation. The Luliao Reservoir Watershed is divided into 11 subwatersheds for the watershed simulation in this study. The location of the measurements and predictions is at the outlet of Subwatershed 11 (S11). This study follows the official standard environmental measurement method for analyzing observed flow and water quality. The observed data in 2016 are used for the model calibration and validation. This study collects twelve observed data including low-flow and high-flow situations. The six data from January to June are used for model calibration, and the other six data from July to December are used for model validation.

Table 2 summarizes the basic input data of these subwatersheds for the SWMM. These environmental data are analyzed by GIS. Table 3 summarizes the basic parameters for the SWMM which are determined by the model calibration and validation. This study uses the power function to estimate the pollutant buildup and the event mean concentration to estimate the pollutant washoff. The power function and the event mean concentration are defined as Eqs. (4) and (5).

$$B = \min\left(C_1, C_2 t^{C_3}\right) \tag{4}$$

$$W = C_1' Q^{C_2'} \tag{5}$$

In Eq. (4), pollutant buildup (B) accumulates proportionally to time (t) raised to some power, until a maximum limit is achieved, where $C_1 =$ maximum buildup possible (mass per unit of area), $C_2 =$ buildup rate constant, and $C_3 =$ time exponent. In Eq. (5), the rate of washoff (W) in mass per second is proportional to the runoff rate raised to some power, where $C_1' =$ washoff coefficient, $C_2' =$ washoff exponent, and $Q =$ runoff rate. The event mean concentration is a special case of the rating curve washoff where the exponent (C_2') is 1.0 and the coefficient (C_1') represents the washoff pollutant concentration in mass per liter.

The TP load from upstream watershed area simulated by the SWMM is the important input for the VM. Table 4 summarizes the important input data and parameters for the VM used in this study. The settling velocity (v) is

Table 2 Basic input data for the SWMM

Subwatershed	Area percentage of impervious surface (%)	Area (m^2)	Width (m)	Slope (%)	Length (m)
S1	4.82	759419	1155	25.66	1121.90
S2	6.85	565353	775	34.62	791.84
S3	6.02	61969	320	19.94	330.56
S4	14.65	532231	1170	43.16	1018.61
S5	9.27	863291	1290	33.05	1160.75
S6	13.46	1102112	1380	39.35	1606.60
S7	28.00	566066	965	38.41	883.05
S8	24.08	573775	925	45.06	1075.48
S9	6.61	387178	650	48.53	808.55
S10	22.68	417400	935	47.32	1035.33
S11	40.00	1483659	2190	38.55	1728.38

Table 3 Basic parameters for the SWMM

Object	Parameter	Validated value	Range
(a) Parameters for flow simulation			
Surface runoff	Manning's n for pervious areas	0.1	0.1–0.8
	Manning's n for impervious areas	0.01	0.01–0.05
Infiltration (Horton infiltration)	Maximum Infiltration rate (mm/hr)	3	0.25–25
	Minimum Infiltration rate (mm/hr)	0.5	0.25–25
	Decay constant (1/hr)	4	>0

Object	Parameter	Validated value			Range
		Agriculture	Forest	Building	
(b) Parameters for TP simulation					
Buildup (power function)	Maximum buildup possible (kg/m^2)	1	0.5	2	>0
	Buildup rate constant (1/day)	0.8	0.3	1.5	>0
	Time exponent	1	1	1	>0
Washoff (event mean concentration)	Washoff coefficient (mg/L)	0.8	0.3	1.5	>0
	Washoff exponent	1	1	1	>0

Table 4 Basic input data and parameters for the VM

Parameter	Value	Data source
Total TP load (M)(g/yr)	2077410	Calculated by the SWMM
Settling velocity of TP (v)(m/yr)	12	Determined by the model calibration and validation
Inflow discharge (Q_{in})(m^3)	27631093	The average of monitoring data
Outflow discharge (Q_{out})(m^3)	23661349	The average of monitoring data
Reservoir surface area (A)(m^2)	1158800	Design report

determined as 12 m/yr by comparing the observed and simulated water quality of the Luliao Reservoir.

This study uses R-square (R^2) and mean absolute percentage error (MAPE) to evaluate the calibration and validation results. Figure 2 and Fig. 3, respectively, show the calibration and validation results of the flow simulation and the TP simulation. Table 5 shows the values of R^2 and MAPE in model calibration and model validation by the SWMM. The results indicate that the R^2 are larger than 0.5 and the MAPE are less than 50% for all of the calibration and validation results of the watershed simulation. Thus, the reliability of the flow simulation and the TP simulation
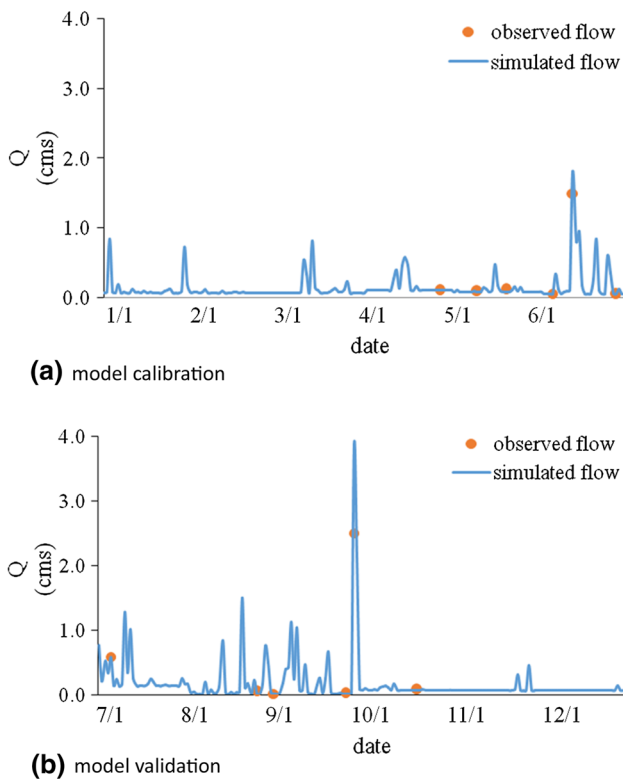
(a) model calibration

(b) model validation

Fig. 2 Calibration and validation results of the flow simulation: **a** model calibration, **b** model validation

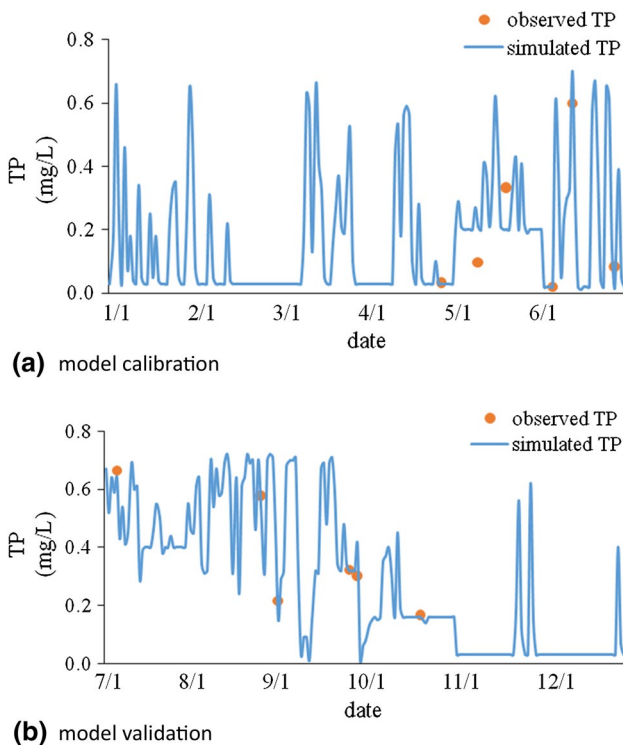**(a)** model calibration

(b) model validation

Fig. 3 Calibration and validation results of the TP simulation: **a** TP loads, **b** TP loads per unit area

Table 5 Evaluation of the calibration and validation results

Simulation	R^2	MAPE	(%)
Flow simulation	Calibration	0.99	10.2
	Validation	0.99	25.5
TP simulation	Calibration	0.88	41.6
	Validation	0.91	13.5

is both satisfactory. Moreover, the average observed and simulated TP concentrations of the Luliao Reservoir are about 0.054 mg/L and 0.058 mg/L, respectively. The MAPE in the prediction of reservoir water quality is about 7%. The results indicate that the simulation of reservoir water quality is also satisfactory.

## Hotspots analysis of spatial environmental pollutions

Table 6 shows the TP loads from the 11 subwatersheds in the Luliao Reservoir Watershed. The TP load is contributed from 78% of nonpoint source pollution and 22% of point source pollution. The results indicate that nonpoint source pollution problems are more severe than point source pollution problems so that nonpoint source pollution control strategies are relatively important in this watershed. Nonstructural best management practices, such as land-use management, and structural best management practices, such as grassy swale or bio-retention, can be implemented for reservoir watershed management.

Pollution hotspots analysis is helpful for selecting the locations for implementing pollution control and reduction strategies in priority. Figure 4 shows the spatial variation of TP loads in the Luliao Reservoir Watershed. The results show that the Subwatershed 11 (S11) has the highest TP load due to its largest area. When considering the TP loads per unit area, the spatial variation of TP loads has a little change. The Subwatershed (S7), Subwatershed (S8), and Subwatershed (S10) have relatively high TP loads per unit area. They can be regarded as pollution hotspots in the Luliao Reservoir Watershed. The TP loads from nonpoint source pollution are even more than 80% in the S8 and S10; thus, compared to point source pollution problems, these subwatersheds need to face more challenges for solving nonpoint source pollution problems.

Assessment of total maximum daily load management strategies

TP is the main pollutant impacting reservoir water quality and causing eutrophication problems so that it is usually used to evaluate the reservoir water quality. This study uses the TP eutrophication index for evaluating the degree

Fig. 4 Pollution hotspots in the Luliao Reservoir Watershed
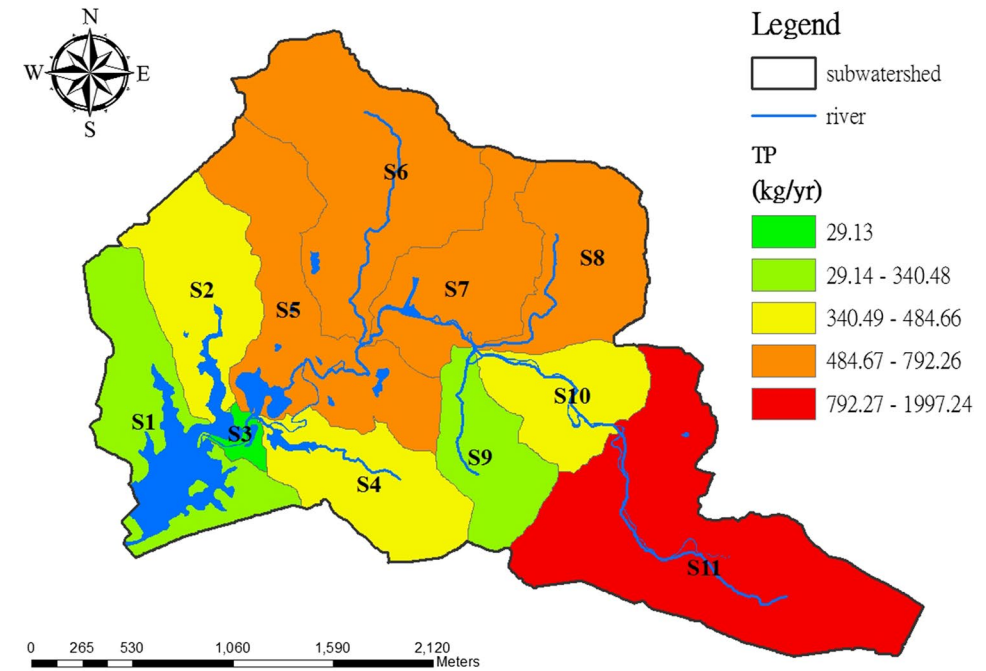
(a) TP loads
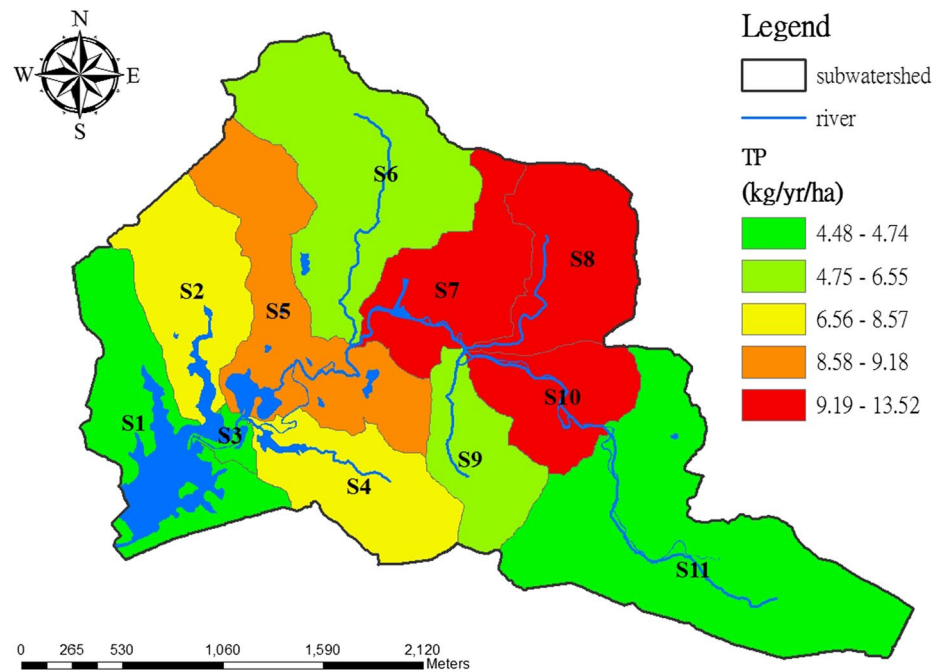
(b) TP loads per unit area

of eutrophication. In accordance with the value of the TP eutrophication index, the degree of eutrophication of a reservoir system can be classified into three grades: high degree of eutrophication (demonstrated by a TP concentration that is higher than 24 µg/L), medium degree of eutrophication (demonstrated by a TP concentration that is between 12 and 24 µg/L), and low degree of eutrophication (demonstrated

by a TP concentration that is lower than 12 µg/L) (Carlson 1977; Kratzer and Brezonik 1981; Jarosiewicz et al. 2011).

The average TP load from the Luliao Reservoir Watershed is about 2077 kg/yr. The present water quality of the Luliao Reservoir is about 58 µg/L (high degree of eutrophication). The results indicate that the eutrophication problem of the Luliao Reservoir is severe. The pollution loads

Table 6 TP loads in the Luliao Reservoir Watershed

Subwatershed	Point source pollution		Nonpoint source pollution		Total TP load (kg/yr)
	TP load (kg/yr)	Percentage (%)	TP load (kg/yr)	Percentage (%)	
S1	97.00	28.49	243.48	71.51	340.48
S2	229.56	47.36	255.10	52.64	484.66
S3	7.92	27.18	21.21	72.82	29.13
S4	67.98	15.78	362.90	84.22	430.88
S5	350.54	44.25	441.72	55.75	792.26
S6	1.94	0.27	720.09	99.73	722.03
S7	229.85	30.02	535.69	69.98	765.54
S8	113.51	16.98	555.07	83.02	668.58
S9	49.45	21.93	176.06	78.07	225.51
S10	82.58	17.53	388.39	82.47	470.96
S11	293.52	14.70	1703.72	85.30	1997.24
sum	1523.85	22.00	5403.42	78.00	6927.27

Table 7 TMDL strategies and their performance for improving reservoir water quality

Scenario	TP concentration (µg/L)	TP load (kg/yr)	Pollution reduction (kg/yr)	Reduction rate (%)
Present condition	58	2077.41	–	–
10% of reduction	52.2	1860.00	217.41	10.47
20% of reduction	46.4	1650.50	426.91	20.55
Target TP concentration: 24 µg/L	24	855.00	1222.41	58.84
Target TP concentration: 12 µg/L	12	427.00	1650.41	79.45

from upstream watershed area negatively impact the reservoir water quality. Thus, it is critical to implement TMDL strategies for pollution control and reduction in the Luliao Reservoir Watershed. Table 7 shows the TMDL strategies and their performance for improving reservoir water quality. When the target TP concentration is 24 µg/L, the reservoir water quality can be improved to the medium degree of eutrophication. To reach this target TP concentration of the reservoir water quality, the total maximum TP load from the upstream watershed area is only allowed to be about 855 kg/yr. The TP load needs to have 1222 kg/yr, i.e., 59%, reduction. When the target TP concentration is 12 µg/L, the reservoir water quality can be improved to the low degree of eutrophication. It is difficult to reach this target, because the TP load needs to have 1650 kg/yr, i.e., 79%, reduction.

SWMM and the VM for analyzing the relationship between the pollution sources in the study watershed and the water quality of the study reservoir. Based on a target TP concentration of 24 µg/L of the Luliao Reservoir, the TMDL of TP is about 855 kg/yr. The present TP load is about 2077 kg/yr. The TP load needs to have about 1222 kg/yr reduction. This study analyzes the pollution hotspots in the Luliao Watershed. The pollution reduction strategies are recommended to implement in these areas. The nonpoint source pollution problems are more severe than point source pollution problems in the Luliao Watershed. Thus, best management practices are important for pollution control and reduction.

Conclusion

Environmental models play an important role in environmental management. This study uses the watershed model (SWMM) and the reservoir model (VM) to simulate the TP loads from the upstream watershed area and the response of reservoir water quality. It is significant to combine the

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