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Phosphorus Load Reduction Goals for Feitsui Reservoir Watershed, Taiwan

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Abstract The present paper describes an effort for developing the total maximum daily load (TMDL) for phosphorus and a load reduction strategy for the Feitsui Reservoir in Northern Taiwan. BASINS model was employed to estimate watershed pollutant loads from nonpoint sources (NPS) in the Feitsui Reservoir watershed. The BASINS model was calibrated using field data collected during a 2-year sampling period and then used to compute watershed pollutant loadings into the Feitsui Reservoir. The simulated results indicate that the average annual total phosphorus (TP) loading into the reservoir is 18,910 kg/year, which consists of non-point source loading of 16,003 kg/year, and point source loading of 2,907 kg/year. The Vollenweider mass balance model was used next to determine the degree of eutrophication under current pollutant loading and the load reduction needed to keep the reservoir from being eutrophic. It was estimated that Feitsui Reservoir can becoming of the oligotrophic state if the average annual TP loading is reduced by 37% or more. The results provide the basis on which an integrated control action plan for both point and nonpoint sources of pollution in the watershed can be developed.

Keywords TMDL · HSPF/BASINS model · Total phosphorus (TP) · BMPs · Settling velocity · Hydraulic residence time

1 Introduction

The traditional watershed pollutant control strategy in Taiwan is to control point source first and then nonpoint source pollutants. However, the major sources of pollution of many watersheds in Taiwan, especially for many drinking water reservoirs located in rural or forested areas, NPS pollution is usually the dominating source and therefore a well-established water pollution control strategy should be put into place to achieve an integrated point and NPS management (Lin, Yu, & Lee, 2000).

There are many activities that take place in watersheds, such as growing mountain vegetables, tea, betel nuts and fruit tree plantations, tourism, development of hillsides and construction of roads, which have led to untreated nutrients caused by silt, pesticides and fertilizers entering into reservoirs with runoffs due to lack of water and soil conservation efforts. The result is eutrophication and siltation of reservoirs, adversely impacting the use of water resources and therefore increasing costs for facilities associated with water purification.

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The objective of nonpoint pollution surveys is to understand the varieties of pollutants and to estimate the pollution amount in order to evaluate the impact on the receiving water bodies. According to research on NPS pollution, NPS pollution has direct relations with land use types (Atsushi & Kiyoshi, 1999; Johnes & Heathwaite, 1997; Worral & Burt, 1999). Thus, its quantity is frequently expressed by the unit time of land use type and amount of pollution per unit area. Lo and Yu (1994) use export coefficient as factors to quantify NPS pollution. Export coefficient of pollution is an important parameter in quantifying NPS pollution, whereby comparisons can be made on pollutant loads of different types of land use in watersheds. Expressed as the multiplication of area size of land and unit load plus pollutant load of different types of land (Corbitt, 1999), it is also the easiest and most frequently adopted parameter to estimate the total amount of pollution in watersheds. In addition, Universal Soil Loss Equation, loading functions, computer model simulation, NPS control branch are also adopted for the purpose of making estimates, though they demand more data (Jennifer & Hamish, 2000). The use of export coefficient of pollution to estimate the NPS pollution load in watersheds is widely adopted in Taiwan (Wen, 2000), particularly in the assessment of long-term pollution. Since uncertainties exist as to time and space of NPS pollution, data concerning unit load of pollution are not easily accessible, which vary with types of land use and are affected by factors like hydrology and climate.

This research has compiled data from previous studies on NPS pollution in Taiwan as listed in Table I. These studies are categorized into stormwater monitoring, NPS modeling and load estimate from field data. Although a number of NPS studies have been completed, relatively data on NPS pollution are still rather limited.

1.1 Major issue analysis

Feitsui Reservoir is the most important water resource in Taiwan, providing high-quality water supply for millions of people in the Greater Taipei area. However, due to watershed pollution resulting from excessive development of land and inadequate treatment of wastewater and polluted runoff generated by the construction of Taipei-Ilan Freeway, a major road-building project, the eutrophication problem of the reservoir has become more severe in recent years. According to the water quality monitoring annual report published by TFRA (2003), the Carlson Trophic Status Index (CTSI) was greater than 40 in every single month in 2002, among which two of them were higher than 50, signifying that water quality had reached the near-eutrophic state. The eutrophication of the reservoir's water quality is directly correlated to both excessive amounts of nutrient input and heavy rainfalls in the upstream watersheds (Pai, 2000).

Kuo (1998) indicated that phosphorus is the limited factor causing eutrophication problems for

Table I TP export coefficient values as reported in literature in Taiwan

Land use	TP (kg/ha/year)	Investigation location	Reference
Forest land	0.95	Feitsui Reservoir Watershed	Lin et al., 2003
	0.20	Feitsui Reservoir Watershed	Kuo, 1998
	0.60	Feitsui Reservoir Watershed	Sadao, 1984
	0.35	Meinung Reservoir Watershed	Wen, 2000
Barren land	3.00	Feitsui Reservoir Watershed	Kuo, 1998
	0.42	Hsin Tien Creek Watershed	Lo & Yu, 1994
Tea garden	1.43	Feitsui Reservoir Watershed	Lin et al., 2003
	1.71	Feitsui Reservoir Watershed	Lo & Yu, 1994
	0.03	Tsengwen Reservoir Watershed	Wen, 2000
Betel nut farm	0.32	Tsengwen Reservoir Watershed	Wen, 2000
Fruit farm	0.40	Hsin Tien Creek Watershed	Lo & Yu, 1994
Rice farm	0.24	Hsin Tien Creek Watershed	Lo & Yu, 1994
Agricultural land	0.36	Feitsui Reservoir Watershed	Sadao, 1984
	0.40	Meinung Reservoir Watershed	Wen, 2000

Feitsui Reservoir, based on the ratio of nitrogen (N) to phosphorus (P), which reached 10 or more during the past 7 years. Moreover, through analyzing the long-term observed data from 1987 to 2003, the monthly moving average CTSI values, published by TFRA (2003), which produced the long-term trend demonstrated in Figure 1. Figure 1 shows that the minimum value of the CTSI moving average since 1996 has been greater than 40, whereas the minimum of 2002 is higher than 45, clearly demonstrating the trend of eutrophication. Hence, both of the trends from the N/P ratio and CTSI demonstrate that reducing phosphorus yield from watershed is a significant task to prevent the water quality of Feitsui Reservoir from deteriorating.

1.2 Objectives

The main objectives of the present paper is to provide a comprehensive summary of the NPS pollution data collected so far in Taiwan, and to propose a water quality management strategy for Feitsui Reservoir watershed based on a TMDL analysis.

In order to perform an effective TMDL analysis, it is necessary to (1) estimate the TP loads of point and NPS pollution in watersheds, under the critical condition of the receiving water body's maximum pollution loads; (2) the BASINS model and the Vollenweider mass balance model are used to analyze the assimilative capacity of the water body's pollutants, and (3) develop strategies for pollution load allocation and control technologies.

2 Methods

2.1 Study area

The Feitsui Reservoir watershed, shown in Figure 2, is located in Taipei County and is known for its abundant natural tourism resources and the high economic valued crop (e.g., Wenshan green tea). Tourism and tea farming, lead to more agricultural activities and land development that contribute to the problem of NPS pollution.

Feitsui, with a watershed area of 303 km^2 and a total storage volume of 406 million m^3 at its normal maximum water level, supplies drinking water to more than four million people in the Greater Taipei area. A survey shows that the major types of land use in the Feitsui watershed are forestland (about 88% of the total area of watersheds) and tea garden (about 4% of the total area of watersheds), both of which contribute to NPS pollution (Lin & Hsieh, 2003). This study uses

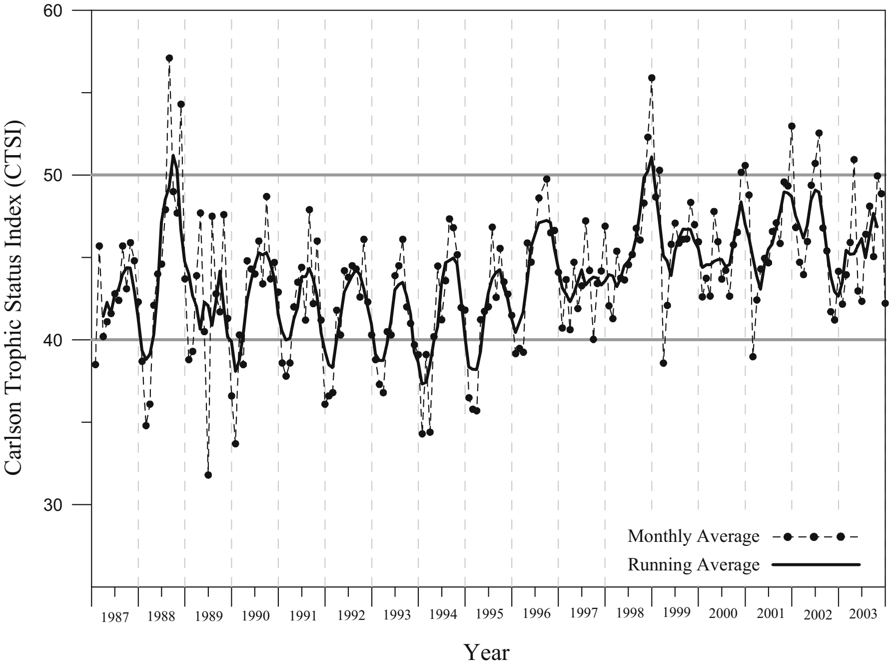
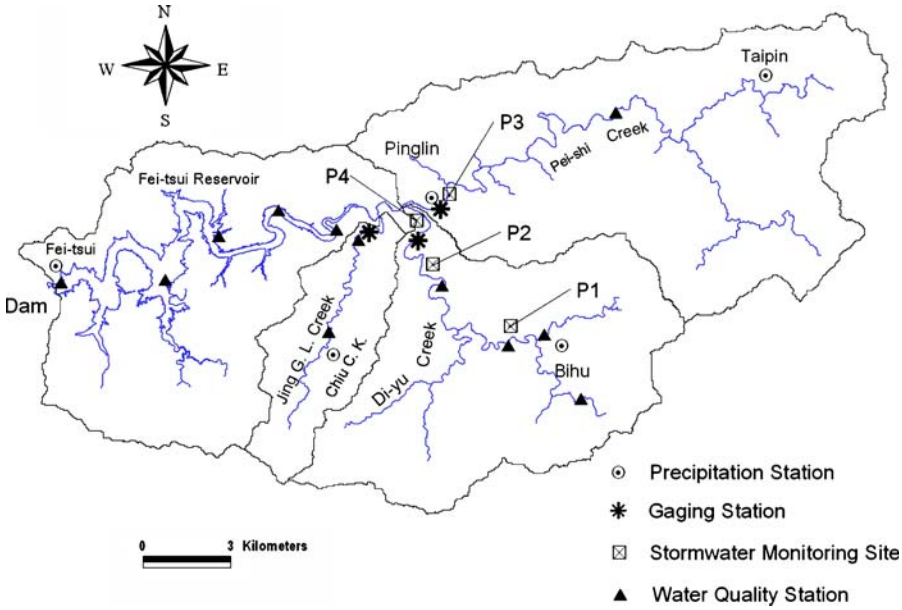


Figure 1 The long-term trend of CTSI variations in the Feitsui Reservoir.

Figure 2 Study area and monitoring station.



the NPS pollution concentration produced from the runoff of monitored stormwater and the estimated pollution load generated from hydrology modeling as the sources for the TMDL analysis.

2.2 Water quality and flow observation

The Taipei Feitsui Reservoir Administration (TFRA) is in charge of hydrology, precipitation and water quality monitoring system, and its major facilities include precipitation station, gauging station, water quality station, etc. (Figure 2). TFRA has collected data over 10 years, among which rainfall and stream records have been compiled by automatic monitoring equipment. However, water quality stations of the reservoir and watershed collect water quality samples only once a month, which cannot truly reflect the NPS pollution during stormwater. Therefore, this study conducted two sampling surveys in 2001 and 2002 by establishing stormwater monitoring sites and used all weather samplers to collect runoffs in the stormwater period to estimate the amount of NPS pollution. There were four stormwater monitoring sites: two located at the forestland watershed outlet (P1) and the tea garden outlet (P2), and the other two located at the upstream of Pei-shi Creek (P3) and Di-yu Creek (P4) in the watershed (Figure 2). According to the research reports over the years analyzing stormwater sampling conditions (Wen, 2000), the representative stormwater samples have to be subject to the critical conditions which identify the storm event monitored as (1) without rainfall event before 72 h of this storm event, (2) the rainfall intensity and duration of storm event should be within ±50% hourly average of historical record. However, there are only five or six events a year meeting such conditions in the Feitsui Reservoir. Therefore, every candidate rainfall events become very precious.

Samples were taken from four events of effective stormwater in 2001 under the two stormwater monitoring sites in Pei-shi Creek (P3) and Di-yu Creek (P4) and only two samples were collected in 2002. The total of six stormwater events distributed from March to November. With the information from watershed hydrology, hydraulics and water quality monitoring stations set up by the TFRA, this study is able to use detailed hydrology, precipitation and water quality monitoring data together with our own stormwater sample data to perform calibration and verification using the BASINS model.

2.3 Model description and implementation

The model used in the present study is BASINS, or “Better Assessment Science Integrating point and nonpoint Sources”. The BASINS model is an integrated GIS, data analysis and modeling system designed to support watershed based analysis and TMDL development. In the Feitsui Reservoir Watershed, TMDL analysis, the nonpoint source model (HSPF) within BASINS was used for watershed nonpoint phosphorus loading computations. HSPF estimates nonpoint sources loads at the watershed scale based on various land uses. Continuous simulations were used to create a time series of water quality variations.

In order to obtain accurate and precise simulation results, a model must undergo the calibration and verification procedures. Trial and error method is utilized for model calibration to regulate the input parameters. When simulated values are closed to the observed values, a set of usable calibration input parameters is obtained. However, the trial and error method process is a time-consuming task, therefore we used an efficient calibration operation procedure: (1) first, collecting related calibration reference data, which indicated by Bergman, Green, and Donnangelo (2002), as the principal calibration factors, (2) and then following this, with previously simulated data on study area as done by Lin and Hsieh (2003), the range of the calibration values are confined. Through these two procedures, it is possible to rapidly obtain the calibration parameters. This research applies the HSPF/BASINS model, which consists of three main modules, including PERLND, IMPLND and RCHRES. Among which, PERLND and IMPLND modules simulate surface nonpoint sources pollutant, and RCHRES module simulates the transmission of surface runoff pollutant in a river channel.

Through the above-described procedures, the calibration parameters for this research in PWATER submodel include the following relationship UZSN (Upper zone nominal soil moisture storage), INFILT (Index to the infiltration capacity of the soil), KVARY (Groundwater recession flow parameter used to describe non-linear groundwater recession rate), DEEPFR (The fraction of groundwater inflow), INTFW (Interflow inflow parameter) and IRC (Interflow recession parameter). Additionally, associated with water quality simulation related PQUAL submodel, the WSQOP (Wash off by overland flow) expresses the rate at which 90% of pollutant can be scoured at a time when the unit of surface runoff is small. A larger WSQOP value indicates greater difficulty in scouring pollutant, and that pollutant density is likely to drop.

The estimation of NPS pollutant loads in watersheds generally relies on modeling and stormwater sampling. The calibration and verification of this research's model parameter include both water quantity and quality, based on the monitoring data produced by the TFRA. In terms of water quality, the stormwater samples collected under this research and the monthly watershed water quality data monitored by the TFRA are the data sources for calibration and verification by the BASINS model.

2.4 Sensitivity analysis of parameters

After verifying this model, the model can be approved for the task of simulation in specific watershed. Then, the model verified immediately performs the sensitivity analysis of the model parameters to determine the level of influence of each parameter on flow and quality. With sensitivity analysis focusing on the variation of a single model parameter and other parameters remaining fixed, we can determine the level of influence of the parameter on the simulation block. The objective of sensitivity analysis on the model parameters is to understand the level of influence of the parameters on water quality block; in other words, to probe which parameters have greater influence on water quality block. At the time of applying the model, more care must be taken when selecting the parameters' values that exhibit a higher level of sensitivity. The parameters indicating less sensitivity can be estimated.

HSPF/BASINS is a complex model containing the magnitude of the inputs parameters. Some of them are required, but not all. It, hence, is inevitable that how to screen the key input parameter based on the model response to specific inputs. In this study, the method of Nominal Range Sensitivity (NRS) is applied to identify the most important inputs and prioritize data collection needed.

The NRS is utilized to evaluate the effect on model outputs performed by individually varying only one of the model inputs across its entire range of plausible values, while holding all other inputs at their nominal or base-case values (Fontaine & Jacomino, 1997). This sensitivity analysis of HSPF/BASINS employs a single observed storm event came up on Sep. 2 to 3, 2001 for the analysis task. Based on the storm event selected, we alter the value within entire range of the particular input variable and fix other parameters to find out level of influence of the parameter on the

Table II Event mean concentrations (EMCs) and export coefficients of TP

Sampling	P1		P2	
	Land use: Forest		Land use: Tea garden	
	Precipitation station: Bihu		Precipitation station: Pinglin	
	Annual average rainfall: 3,837 mm		Annual average rainfall: 3,495 mm	
Date	EMCs (μg/l)	Export coefficient (kg/ha/year)	EMCs (μg/l)	Export coefficient (kg/ha/year)
2001/05/27	221	1.28	279	1.46
2001/10/15	157	0.90	232	1.22
2001/04/17	131	0.75	251	1.32
2002/05/17	134	0.77	257	1.35
2002/07/31	170	0.98	378	1.98
2003/05/27	219	1.26	284	1.49
2003/08/03	382[a]	2.19[a]	310	1.62
2003/10/15	145	0.85	243	1.27
2003/05/17	146	0.84	214	1.12
2003/07/03	156	0.90	286	1.50
Average	164	0.95	273	1.43

[a] Singular value

simulation block. The sensitivity can be represented as a positive or negative percentage change compared to the nominal solution. The sensitivity analysis can be repeated for any number of individual model inputs.

2.5 Evaluation of reservoir assimilative capacity

Studies have shown that total phosphorus (TP) is the major cause of entrophication in Feitsui Reservoir (Lin & Hsieh, 2003). The assumptions of zero-dimension TP mass balance model of the Vollenweider Model (1968) are: (1) reservoirs are a completely mixed water body; (2) steady state condition, representing annual/seasonal average condition; (3) the limiting factor of reservoir eutrophication is phosphorus; (4) TP is used as a measure of trophic status. According to the theorem of mass balance, the mass balance model of TP is as follows:

$$V\frac{dp}{dt} = W_t - v_sA_sp - Qp \tag{1}$$

Where V is the water volume of the reservoir; p is TP concentration in the reservoir surface water; Q is the outflow rate; t is time; W_t is the phosphorus loading from external sources; v_s is the net settling velocity; A_s is the reservoir surface area, $A_s = V/H$; and H is the water depth of the reservoir.

Under steady state conditions, Equation (1) can be expressed as:

$$p = \frac{W_t}{Q + v_sA_s} = \frac{W'}{v_s + {}^{H}/_{T_d}} \tag{2}$$

In the above equation, W' is the aerial loading ($= W_t/A_s$, g/m^2/year); q is hydraulic overflow rate ($= H/T_d$, m/year); T_d is the hydraulic residence or detention time; v_s is settling velocity obtained from the result by integration of empirical and theoretical approach. Base on budget calculation approach, Vollenweider (1968) estimate theoretically that the value is equal to 10 m/year. On the other hand, a number of researches indicate that settling velocity most commonly adopt the value within the range from 5 to 20 m/year. Moreover, Kirchner and Dillon (1975) describes that the v_s is the apparent settling velocity of TP, which is equal to $\alpha v'$; v' is sinking velocity of settleable particulate phosphorus. α is the fraction of TP which represented by settleable particulate phosphorus. In this paper, we use Howang et al.'s (2000) investigative result that they indicated that v' is about 0.0023 m/h for 1 μm particulate (at 20 °C), and we suppose α equal to 0.5, thus, v_s is equal to 10 m/year approximately. Thus, Equation (2) can be written as:

$$p = \frac{W'}{10 + q} \tag{3}$$

With respect to the use of a single nutrient concentration standard for determination of the eutrophic state of a reservoir, the US Environmental Protection Agency (USEPA, 1974), suggested that, if the TP concentration is below 0.01 g/m^3, the reservoir is regarded as oligotrophic, whereas a reservoir is regarded as eutrophic if its TP concentration is greater than 0.02 g/m^3. Therefore, the following two equations can be obtained:

$$W'_{10} = 0.01(10 + q) \tag{4}$$

$$W'_{20} = 0.02(10 + q) \tag{5}$$

3 Results and Discussions

3.1 Field investigation: TP export coefficient

Forestland and tea gardens together account for 92% of the total area of the Feitsui watershed. Unit load of pollution obtained from sampling was used to estimate the amount of NPS pollution. The analyses of the 10 events are listed below in Table II.

Comparisons of the research's estimated results and the estimates of domestic reservoirs watersheds indicate that uncertainty of pollution loads leads to the export coefficient values status for the range intervals. The estimated TP of forestland is with an average of 0.95 kg/ha/year while the estimated TP of tea gardens is with an average of 1.43 kg/ha/year. The past surveys conducted on Feitsui, Techi, Tsengwen and Meinung reservoirs showed the forestland TP to be 0.20 to 1.80 kg/ha/year, and the tea gardens TP to be 0.03 to 1.71 kg/ha/year (Hwang, Wen & Yu, 1999).

3.2 Model calibration and verification

According to this, BASINS parameter values, produced by the calibration and verification of observed data, are used to simulate the entire Feitsui Reservoir watershed, which is divided into four sub-watersheds, namely Pei-shi Creek sub-watershed, Di-yu Creek sub-watershed, Jing-Gua-Liao Creek sub-watershed and Near Reservoir sub-watershed for the purpose of simulation along with the locations of hydrology monitoring stations and geographical features.

The results of calibration and verification of water quantity and quality by the BASINS model are shown in Figure 3.

The use of Pearson Product-moment Correlation Coefficient to compute the correlation coefficient (r) is to obtain the degree of linear relationship between the observed values and simulated values. The 2001 data are used for model calibration while the 2002 data are used for model verification. The coefficient of water quantity simulated and observed values are between 0.87 and 0.93 whereas the coefficient of water quality is between 0.82 and 0.86.

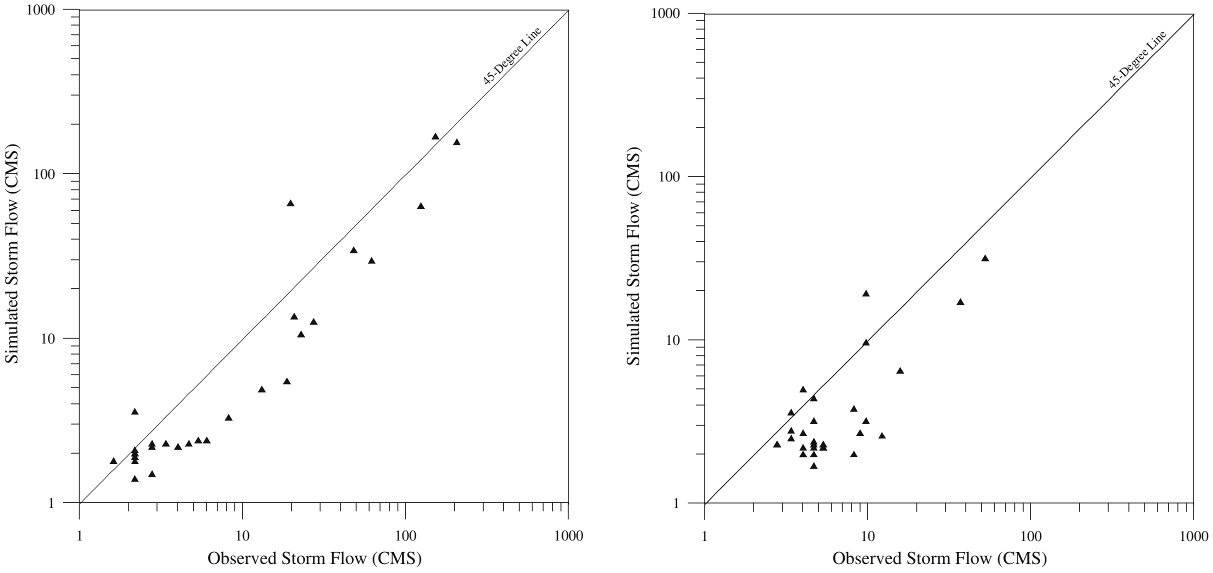
When the HSPF model is adopted for hydrology, flow and water quality simulations, the soundness of the simulated results is judged by whether they and the observed values fall within a specific error boundary (Donigian, Imhoff, Bicknell & Kittle, 1984; Bergman et al., 2002). When the percentage of error in simulating hydrology and hydraulics is above 25%, simulating sediment above 35%, then it is not applicable. In the event of simulating water quality, the percentage of error should not be greater than 40%. When both calibration and verification are within the boundary, the established parameter group and data simulation is acceptable.

3.3 Sensitivity analysis

Based on NRS, an observed storm event is utilized on this analysis. Consequently, on the stronger rainfall calibration results obtained from sensitivity analysis, we carry out BASINS simulation model water volume and water quality parameter TP pollutant sensitivity analysis of ±50% and ±75%. The results are outlined in Table III. From the sensitivity analysis outlined in Table III, the associated with LZSN (lower zone nominal storage), INFILT (index to the infiltration capacity of the soil), INTFW (interflow inflow parameter) and LZETP (lower zone E-T parameter) parameters appear higher sensitivity.

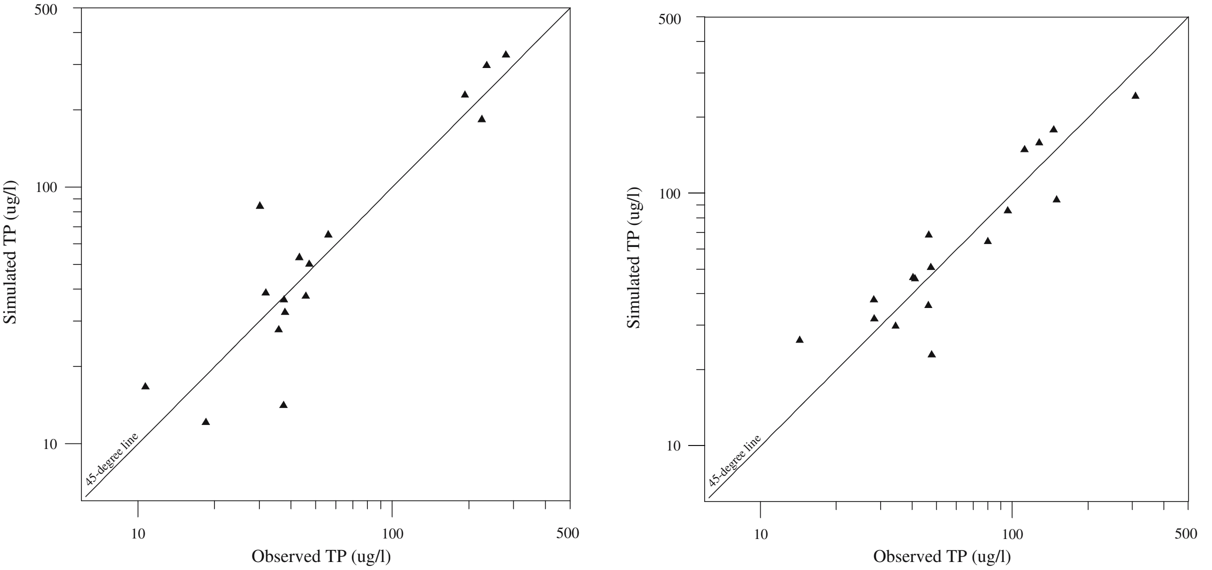
3.4 Estimated result of TP export amount in watersheds

From above analysis, it indicated that HSPF was adopted to simulate TP export loads, and with the simulation period of 6 years between 1998 and 2003, it generated average annual TP loads of NPS in the Feitsui Reservoir watershed to be 16,003 kg/year, including 3,631 kg/year in Di-yu Creek, 5,824 kg/year in Pei-shi Creek, 1,626 kg/year in Jing-Gua-Liao Creek and 4,922 kg/year in the Near Reservoir watershed. The distribution of the mass-flow time series of NPS (TP) pollution export from 1998 to 2003 is shown in Figure 4. Each of 6 years has individual mass-flow time of NPS (TP) distribution. The daily TP load was generated from HSPF/BASIN and the



(a) Calibration of Flow(r=0.93)

(b) Verification of Flow (r=0.87)



(a) Calibration of TP(r=0.82)

(b) Verification of TP(r=0.86)

Figure 3 The results of calibration and verification of BASINS/HSPF model.

Table III Sensitivity analysis of key input parameters

Key input parameters	Specific input values	Sensitivity			
		+ 50	+ 75	− 50	− 75
LZSN	5.5 (cm)	−14∼+9	−14∼+13	−18∼+22	−33∼+56
INFILT	2.0×10^{-2} (cm/h)	−26∼+12	−38∼+17	−13∼+28	−33∼+65
INTFW	3.5	−29∼+7	−41∼+8	−12∼+28	−27∼+47
LZETP	0.1	−6∼+3	−6∼+5	0∼−2	+1∼−3

accumulation of 1 year formed the annual TP load for certain year. When calculating the reservoir assimilative capacity of TP, considerations should be given not only to the TP export loads of NPS pollution, but the point source pollution of the water body. Thus, the amount of pollution is estimated based on the sources of point source pollution in each simulated subwatersheds. Refer to “A report of implementation efficiency on protecting water quality/quantity for Taipei Water Source Domain”, published by Taipei Water Management Committee (TWMC, 2003), the sources of point source pollution include domestic wastewater (lack of sewers area) and wastewater produced by leisure activities. The loading of TP is estimated on the basis of population and its equivalent. The population is surveyed which include 8,576 residents and 392,400 visitors per year. And 8 mg-TP/l of the equivalent concentration of wastewater is employed. The discharge of each resident is 220 l/person/day and 20 l/person for visitor. Thus, the TP loading of entire watershed is 5,572 kg/year which consists of 5509 kg/year from domestic wastewater and 63 kg/year from leisure activities. And according to the percentage of population served by wastewater treatment plant (1998: 0%; 1999: 43%, and 2000~2003: 61%), we could calculate the TP loading of point source.

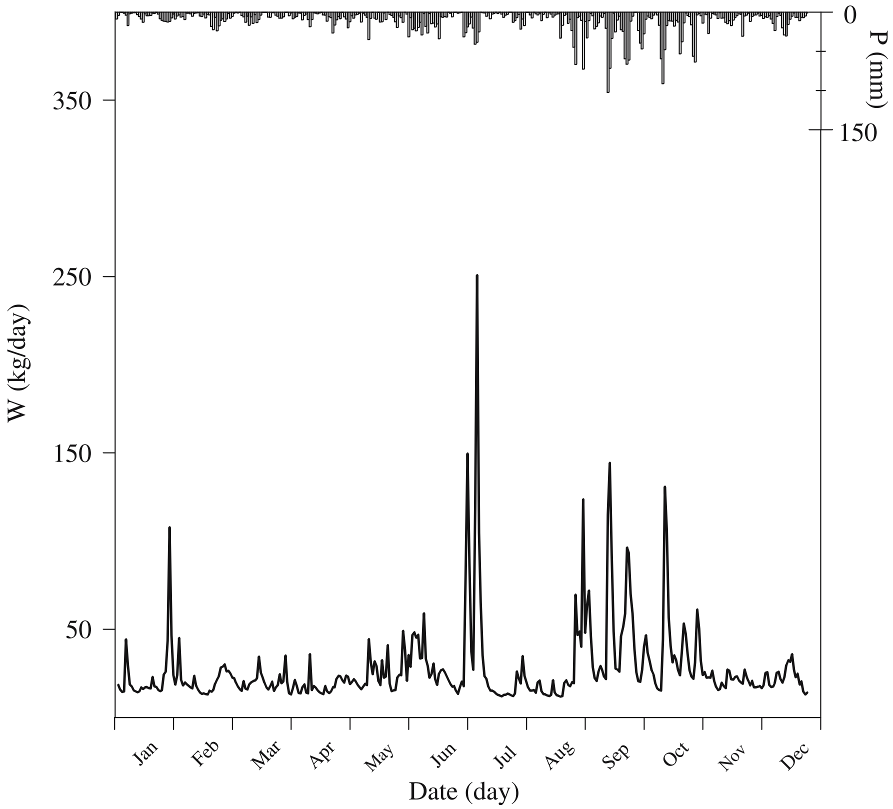


Figure 4 The 6-year average of the temporal variation of TP mass (wt) transport into Feitsui Reservoir during 1998–2003.

The above-simulated results were used to estimate the annual TP export loads in the Feitsui Reservoir watershed between 1998 and 2003, which are compared with historic studies shown in Table IV.

3.5 Evaluation of reservoir assimilative capacity

Vollenweider proposed the TP predictor model in 1968, which has been widely applied in the evaluation of reservoir assimilative capacity (Lee, Huang, Tung, & Yeh, 2001; Moustafa, 1998) and employed in this study to analyze the assimilative capacity of Feitsui Reservoir. The categorization standard of the degree of reservoir eutrophication of this research is based on Carlson Trophic Status Index (CTSI) and the categorization of reservoir eutrophication formulated by the USEPA (1974). TP is used to classify the degree of Feitsui Reservoir eutrophication and the Vollenweider model is adopted to evaluate reservoir assimilative capacity so the TP reduction in the watershed to maintain oligotrophic water quality can be estimated.

Equations (4) and (5) are depicted in Figure 5, in which the eutrophic level can be anticipated by the TP aerial loading W' and reservoir operator $q = H/T_d$. If, for a certain waterbody, the reference point with coordinates of W' and $q = H/T_d$ falls on or above the 20 μg/l TP-curve, the water body is in the state of eutrophication. If the reference point is on or below the 10 μg/l TP-curve, then the water body is in the oligotrophic state and if the point falls in between the curves, the water body is in the state of mesotrophication. In accordance with the BASINS model, the estimated TP pollutant loads in the Feitsui Reservoir watershed between 1998 and 2003 are listed in Table IV. The characteristic values of annual reservoir operation detailed in Feitsui Reservoir Annual Operation Reports are: the average water height of the reservoir (H); the average reservoir detention time (T_d); reservoir's surface area (A_s) and TP loading (W_t) in Table V. After computation, the yearly aerial TP loading (W') and the hydraulic overflow rate (q) are obtained as demonstrated in Table V. The results in Table V are evaluated using the Vollenweider model, and Figure 5 illustrates the relationship between TP loadings and reservoir operation characteristics between 1998 and 2003.

Specifically, Figure 5 shows that among the 6 simulated years, 1998, 2002 and 2003 fall into Eutrophic Zone while 1999, 2000 and 2001 are within Mesotrophic Zone. As a result, eutrophication of the reservoir is not only directly correlated to the total amount of pollutants but also to the characteristics of reservoir operations. Consequently, it could be postulated that the impact of a specific phosphorus loading might be lessened by changing the reservoir operating scheme in such way that the hydraulic overflow rate, q, is increased, which would lead to a reduction of the phosphorus concentration in the reservoir. The BASINS model estimates that the average TP pollutant load in the Feitsui Reservoir watershed is 18,910 kg/year, so the reservoir's TP concentration needs to be maintained below 10 ppb to ensure the reservoir's water quality index remains at oligotrophic state. Therefore, according to the relationship between TP loading and reservoir operation characteristics between 1998 and 2003 under the analysis of the Vollenweider model (Figure 5), it is established from the regression equation that the TP loading in the Feitsui Reservoir watershed needs to be

Table IV Simulated annual loads of TP in the Feitsui Reservoir Watershed (kg/year)

	Non-point source				Point source[a]	
Year	Di-yu Creek watershed	Pei-shi Creek watershed	Jing Gua-Liao Creek watershed	Near reservoir watershed	Entire watershed	Total loads
1998	3,883	8,221	2,358	7,310	5,572	27,344
1999	1,882	4,330	860	4,120	3,176	14,368
2000	3,575	6,958	1,750	6,325	2,173	20,781
2001	3,920	5,080	1,450	5,291	2,173	17,914
2002	4,563	5,126	1,894	4,122	2,173	17,878
2003	3,963	5,226	1,445	2,364	2,173	15,171
Average	3,631	5,824	1,626	4,922	2,907	18,910

[a] Percentage of population served by Wastewater Treatment Plant (1998: 0%; 1999: 43%, and 2000~2003: 61%) (TWMC, 2003)

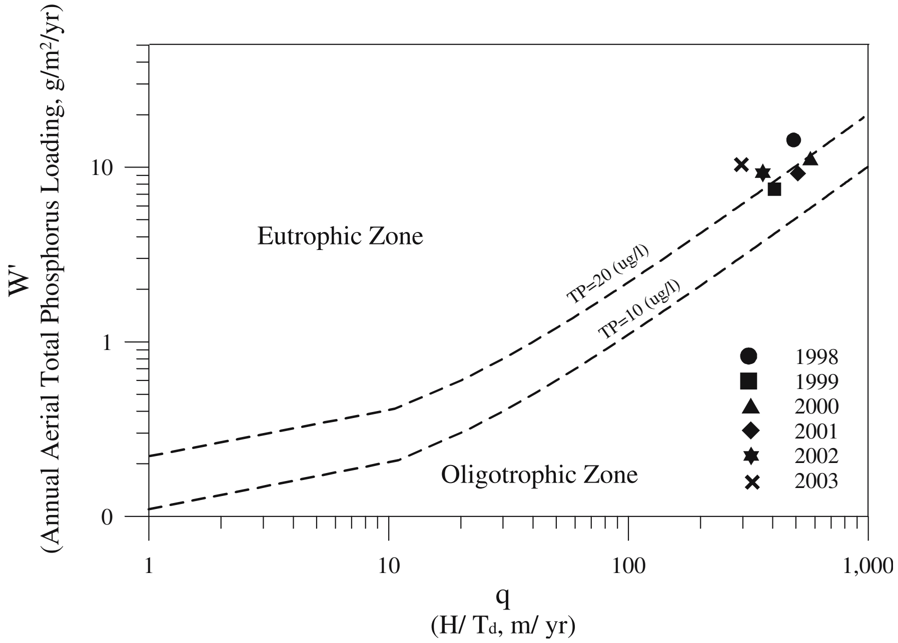


Figure 5 The plot of 6-year evaluation of trophic condition using Vollenweider model.

reduced by 37% (based on 1999) to 60% (based on 1998) (Figure 6) with the reservoir TP concentration remaining at 10 ppb to avoid the state of eutrophication. Recently, a literature (Kuo et al., 2003) also shows similar result. Kuo et al. (2003) employed CE-QUAL-W2, 2-D model, to simulate the Feitsui Reservoir. The results show a 50% reduction of the TP loads will upgrade the mesotrophic condition to oligotrophic condition.

4 NPS Control Strategy

4.1 Control by watershed pollutant load reduction

NPS is the most important factor affecting a reservoir's sustainable management. The establishment of watershed-scale based facilities aimed at the reduction of NPS pollutants is an effective management strategy. In line with the spatial arrangement of facilities in watersheds, BMPs can be categorized into three groups: (1) On-site treatment BMPs, (2) Regional treatment BMPs and (3) Sub-watershed treatment BMPs (Yu & Zhen, 2001). When considering the design of single BMPs, objective conditions, such as geography, hydrology, are major factors. However, if the objective is to eliminate certain amount of NPS pollution in the entire watershed, the issue involves whether the establishment of BMPs in the entire watershed is economically efficient. This study has developed the eutrophication analytical model where BMPs are based on unit watershed. This eutrophication model sets the amount of TP reduction in watersheds within the loading water body assimilative capacity and upon the maintenance of a reservoir's oligotrophic water quality according to the estimates of the BASINS and Vollenweider models in order to plan the establishment of BMPs in watersheds.

In the future, it may employ the BMP module of BASINS with the HSPF model to simulate pollution reduction. The BMP module is based on the concept of the Best Management Practices, directing at pollution reduction of different types of land use. It

Table V The relationship between aerial loading and hydraulic overflow rate

Year	$W' = W_t/A_s$ (g/m^2/year)	$q = H/T_d$(m/year)^a
1998	14.1	460
1999	7.6	403
2000	10.9	577
2001	9.4	507
2002	9.4	365
2003	10.4	294
Average	10.1	434

[a] Date source: Annual report of the TFRA (2003)

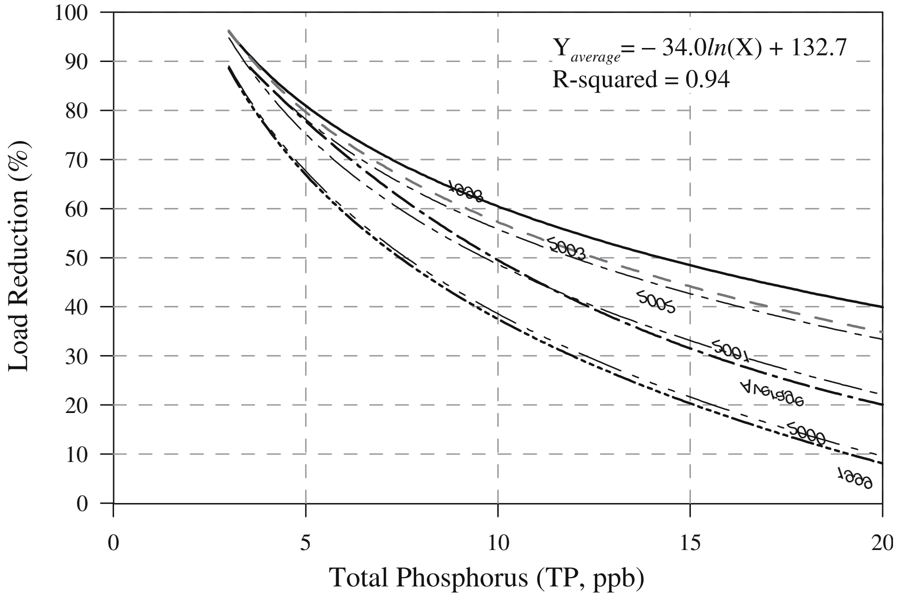


Figure 6 Relationships between tributary load reduction and Feitsui Reservoir TP level.

assumes that NPS pollution elimination facilities are established in a type of land use with the defined pollution reduction rate to simulate the amount of pollution under different elimination facilities and allocation so that pollution reduction strategies can be formulated in a more concrete manner. The types of land use in the Feitsui Reservoir watershed include forestland, agriculture land (tea gardens, fruit farms, etc.), grassland, bare land, construction site, roads and so forth, so this research focuses on model simulation for pollution reduction strategies of point source pollution and NPS arising from land use. Table IV illustrates the distribution of simulated pollutant load of sub-watersheds. As per analysis on site surveys, simulation models and Geographic Information System (GIS), Critical Contributing Area (CCA) can be defined. The BASINS simulation results show that Pei-shi Creek is the area that contributes the most TP (accounting for 36%), followed by the area near the reservoir (33%), Di-yu Creek (21%) and Jing-Gua-Liao Creek (10%). In terms of the spatial allocation of pollution sources, the Pei-shi Creek sub-watershed has the most complicated land use type with highest concentration of tea gardens, human habitation and camping grounds. However, the surveys show that the amount of pollution generated by forestland and grassland in the Feitsui Reservoir watershed is high. In addition to the larger size of such land, the destruction of forestland and illegal occupation and use is also an important factor, leading to huge increase in the amount of pollution in watersheds. Due to the aforementioned reasons, Pei-shi Creek is viewed as the major pollution export area that should be accorded with priority in the establishment of BMPs in order to accelerate the reduction of NPS pollution.

4.2 Control by changing reservoir operating scheme

In addition to watershed pollutant load reduction, it is also possible to control pollutant concentration in the reservoir by adjusting the operating scheme for the reservoir in terms of reservoir release. From Equation (3), it can be seen that the phosphorus concentration in the reservoir is related to both the input loading, W', and the ratio of reservoir depth to the hydraulic residence time, H/T_d. If the loading, W', is kept as constant, then the larger the value of H/T_d, the lower the phosphorus concentration in the reservoir. In general, the reservoir release rate is controlled in accordance with the water demand, power generation, and also the need to lower the reservoir water level in anticipation of a high flow event such as a typhoon or hurricane. However, the possibility of using reservoir release as a means of improving water quality, either in the reservoir or in the river downstream, might be of interest under certain circumstances. The following is an illustration of using reservoir operation for improving water quality in the reservoir.

The Feitsui Reservoir operation records during the years 1987–2003 were reviewed and the following information were obtained:

- Average water pool level (H) – 157 m. Range – 144 m to 162 m.
- Average hydraulic residence time (Td) – 131 days. Range – 92 to 181 days.

From the above reservoir operation data, it was estimated that the ratio of H vs. T_d could vary from a minimum of 294 m/year to a maximum of 623 m/year.

The 6-year average phosphorus loading from the Feitsui Reservoir watershed was estimated as 10.1 g/m^2/year. Using a target reservoir phosphorus concentration of 10 ppb as the goal, three possible reservoir operation scenarios were developed as described below:

1. No watershed phosphorus loading reduction is required, but the ratio of H/T_d needs to be maintained at 900 m/year in order to keep reservoir phosphorus concentration at 10 ppb.
2. With a 37% watershed phosphorus load reduction, the required H/T_d ratio is 530 m/year.
3. With a 60% watershed phosphorus load reduction, the required H/T_d ratio is 360 m/year.

Assuming a full reservoir pool level of 170 m, a hydraulic residence time of 69 days is required under Scenario #1 above. Such an operating scheme might not be practical due to demands of water for water supply and other beneficial uses. It is therefore suggested that Scenario #2 or #3 above could be considered by the authorities for controlling water quality in the reservoir when relevant conditions are met.

On the other hand, we feel that under certain situations, reservoir operation might be a feasible technique for improving water quality. A case in point is the release of water to augment flows in a downstream river to increase the river's assimilative capacity. In the Feitsui Reservoir situation, it might be possible to use the technique during non-typhoon periods, i.e., from November to March. We examined the operating records from 1987 to 2003 and found that an H to T_d ratio of as low as 294 m/year actually existed. Under Scenario #3, an H to T_d ratio of 360 m/year is needed to keep the TP concentration below 10 ppb. This ratio is well within the range of values found in the existing operating records and therefore should be feasible to achieve.

5 Conclusions

During the investigation period, data on pollutant event-mean-concentrations (EMCs) and flows were obtained for the Feitsui Reservoir watershed in Taiwan and used to calibrate and verify the BASINS model. Plots showed that simulated flows and pollutant concentrations agreed reasonably well with the observed data. Storm runoff monitoring results indicate that the value of TP export coefficient for forestland is 0.95 kg/ha/year and for tea gardens, 1.43 kg/ha/year. The calibrated BASINS model was used to conduct a 6-year (1998–2003) reservoir watershed simulation and to provide estimates of the annual average TP loading into the Feitsui Reservoir from its watershed. From the application of the simulated results and the analysis by the Vollenweider model, it is established from the regression equation that TP loading in the Feitsui Reservoir watershed needs to be reduced by at least 37% in order to keep TP concentration at 10 ppb and avoid the state of eutrophication. In terms of spatial allocation, Pei-shi Creek is the major pollution producing area so it should be considered as a priority in the establishment of NPS control facilities (BMPs) when NPS pollution control plans are formulated. The study also examined the possibility of using reservoir operation schemes for controlling pollutant concentration in the reservoir. By adjusting reservoir releases and therefore the hydraulic residence time, the concentration of phosphorus in the reservoir can be reduced according to the surface loading theory. It is recommended that the authorities consider the possibility of incorporating water quality considerations into the design of reservoir operating schemes.

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