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Predicting the Long-Term Performance of a Structural Best Management Practice with the BMP ToolBox Model

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Abstract

It is costly to constantly sample to monitor the performance of a structural best management practice (BMP). Alternatively, occasional sampling might not be adequate. The BMP ToolBox model, developed by Tetra Tech and Prince George's County in Maryland, USA, assesses the performance of a structural BMP treatment site. The study applied the BMP ToolBox model to a BMP site in Taiwan to test its validity. The case study site was designed to remove pollution from nonpoint sources (tea gardens) in order to maintain water quality in the Feitsui Reservoir. The BMP ToolBox model was calibrated and verified using two years of sample data. Results were satisfactory with the coefficient of determination (R^2) for calibration and verification being 0.87 and 0.8, respectively. Furthermore, the one-factor-at-a-time method (OFAT) was applied in a sensitivity analysis to identify sensitive model parameters. Several hydrographs were created to predict BMP performance. The positive relationship between the total phosphorus (TP) removal rate and the recurrence interval was observed: rainfall with longer durations showed increased removal rates compared to shorter periods of rainfall. The BMP Toolbox model was successfully applied, and a process for evaluating the long-term operation of structural BMP sites was established.

Key words: structural BMP; pollution removal evaluation; BMP ToolBox

Introduction

Structural best management practices (BMPs) are designed with eco-friendly technology to remove pollution from structural wetlands, retention ponds, filters, grass beds, etc. Some structural BMP measures are also regarded as natural treatment systems (NTSs). An NTS uses natural physical, chemical, and biological processes to reduce water pollution. NTSs share similar advantages with structural BMPs, such as high treatment efficiency, low cost requirement, and easy operation and maintenance; however, both methods require more land than conventional treatment plants. BMPs generally differ from NTSs because BMPs are developed for nonpoint source pollution, whereas NTSs are used for water treatment and waste treatment (Reed *et al.*, 1998; Thomeby *et al.*, 2006). In Taiwan, ecological engineering has been promoted since 2001. Many BMPs and NTSs have been applied to treat different types of pollution, including nonpoint source pollution (Kao *et al.*, 2001; Lin and Hsieh, 2003; Chen *et al.*, 2009), industrial wastewater (Chen *et al.*, 2006; Chang *et al.*, 2008), swine wastewater (Lee *et al.*, 2004; Chen *et al.*, 2008), aquaculture wastewater (Lin *et al.*, 2002, 2003), and others (Jing and Lin, 2004; Fan *et al.*, 2009).

Evaluating the performance of such treatment systems can be a challenge because of the large requirement of sufficient field samples and the necessity of constant monitoring. Field samples provide data on current performance levels, and subsequent monitoring ensures the quality of pollution treatment. Unfortunately, limited resources can prevent adequate levels of sampling and monitoring. It is costly to have qualified personnel collect field samples and analyze water quality. In addition, BMP sites are frequently located in remote districts (especially in the case of protection areas for rivers and reservoirs), which increases the labor intensity of fieldwork. Thus, it is desirable to have a model capable of assessing the performance of BMP sites. The BMP ToolBox model, developed by Tetra Tech and Prince George's County in Maryland, USA, was designed to evaluate the reduction of storm pollution and peak storm volume from structural BMP sites (Tetra Tech, 2003).

Although conventional nonpoint source pollution models simulate pollution loads in storm events, the BMP ToolBox model evaluates the amount of pollution removed by a single structural BMP unit or treatment train. This function makes the model appropriate for BMP site sampling and monitoring.

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Once the model is validated, it can be used to predict the performance of BMPs, and assist in the design of new BMP sites or in the modification of existing sites. In addition, reliable prediction enables field sampling and monitoring to be more efficient. The purpose of the current study was to test the usefulness of the BMP ToolBox model with real structural BMPs in Taiwan. A structural BMP treatment train was implemented and samples were collected over a period of 2 years. In addition, a process was developed to evaluate the performance of structural BMPs using the BMP ToolBox model, field observations, and scenario analysis of design storm. The resulting process will benefit a range of engineering applications.

Methods and Materials

Process for evaluating performance of structural BMPs

This study presents the use of a BMP model. A complete modeling process is necessary to ensure the validation of the model; the process can be a general flowchart for evaluating the performance of structural BMPs (Fig. 1). The process links field observations to simulations, giving consideration to weather conditions and uncertainty effects. It is important to use field sample data to separately calibrate and verify a model or to validate the model's goodness of fit. Model calibration usually requires massive calculations to obtain the proper parameters from a broad range of values if there are no realistic parameters for a case study. To shorten the search time, a sensitivity analysis is useful to facilitate the efficiency of calibration. If the parameters are not deterministic values but are with distributed property, uncertainty analysis is needed to illuminate the uncertainty effects of the model outcomes.

After calibrated parameter values have been identified, the models are tested with another set of field data to verify their applicability. If the results of this test are satisfactory, the model is considered to be valid. If not, more field data may be needed to improve the calibration of the model. Failure to verify a model may also mean that alternative models are considered. Once the model is validated, the treatment performance of structural BMPs can be predicted under particular weather conditions. In the present study, weather conditions associated with storms were needed, including rainfall intensity and duration.

The prediction of BMP performance can contribute to the practice of engineering design. Modeled simulations also allow for the planning of more efficient monitoring. The process does not stop with prediction and application; the results of subsequent monitoring can serve as feedback for further improving a model or may supplement engineering design. Continuous monitoring provides data for the treatment performance of the BMP sites, which can further validate a model.

BMP ToolBox model

It is useful to have a model capable of evaluating the pollution removal efficiency of structural BMPs. The BMP ToolBox model was originally developed by Tetra Tech and Prince

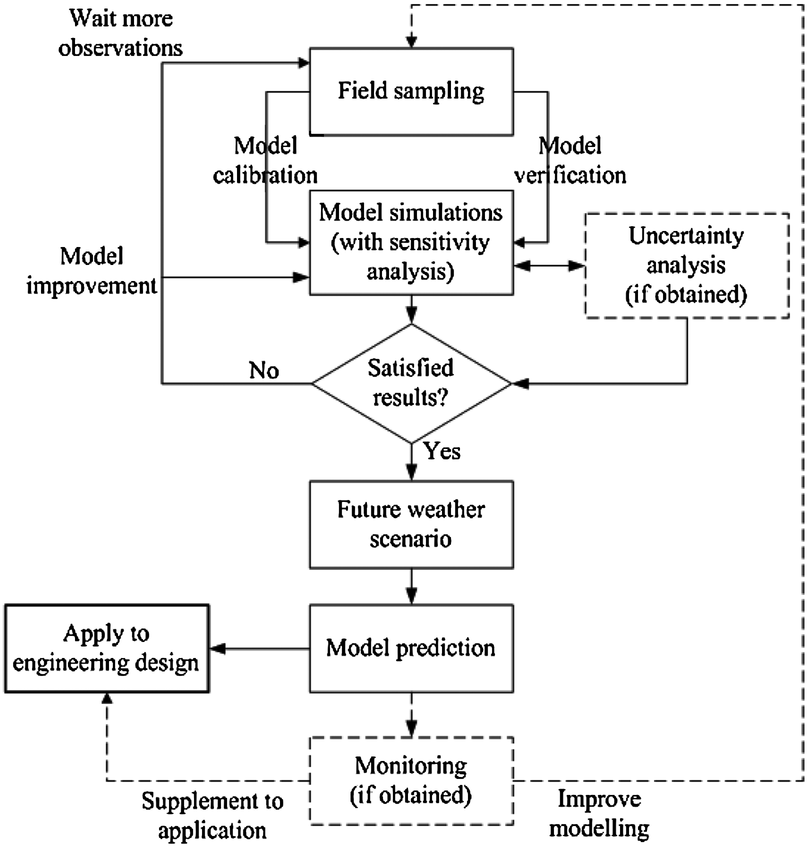
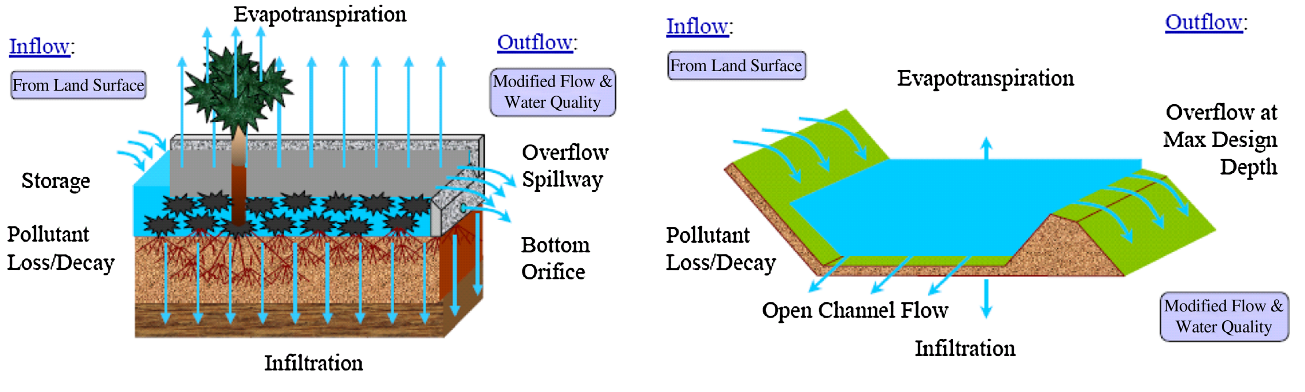


FIG. 1. Conceptual process for evaluating the long-term performance of structural best management practice (BMP).



A Class A BMP **B** Class B BMP

FIG. 2. BMP types of the BMP ToolBox model (reproduced from Tetra Tech, 2003). (**A**) Class A BMP, and (**B**) Classs B BMP.

George's County in Maryland, USA (Tetra Tech, 2003). The model applies to structural BMPs located in developing areas, which are designed to reduce peak runoff and avoid potential nonpoint pollution. The BMP ToolBox model is used to compare the pollution of a site before and after the development, and to evaluate the benefit of settling structural BMPs. The function of evaluating treatment removal in a structural BMP unit makes the BMP ToolBox different from conventional nonpoint source pollution models. Conventional models focus on the generation of nonpoint source pollution and its effect on water quality in receiving water bodies.

Because of the success of the BMP ToolBox model, the Tetra Tech and Untied States Environmental Protection Agency (U.S. EPA) cooperated to develop a decision tool for stormwater management called SUSTAIN (System for Urban Stormwater Treatment and Analysis). The SUSTAIN model is operated under an ArcGIS platform and has several components, including the BMP ToolBox and optimization module. A full description of SUSTAIN can be read in Lai *et al.* (2007). To date, the model has not been released publicly, but its application can be found in U.S. EPA projects (U.S. EPA, 2009).

The level of pollution flowing into BMPs units is obtained by a pollution generation model, such as the Hydrological Simulation Program—FORTRAN (HSPF), or by on-site observations. With the known quality and quantity of nonpoint source pollution in influents, the BMP ToolBox model assesses the pollution removal efficiency in effluents. BMP type and dimensions influence the treatment performance. The model classifies structural BMPs in terms of the treatment mechanisms they provide. The treatment functions of Class A BMPs include retention, interception, and vegetation; typical examples are wet retention ponds and eco-ponds. Class B BMPs are open channel units, designed mainly for directing runoff and collecting the flow; infiltration and filtration are the major treatment mechanisms. Grass swales and grass belts are Class B BMPs. Schematic illustrations of the two types of BMP are shown in Fig. 2.

In the calculation of pollution removal mechanism, the assumption of one-dimension batch reactor is used [Eq. (1)], where a situation in which the pollution concentration in the reactor is uniform, there is zero dispersion interaction ($u = 0$) and first-order kinetic degradation is applied. Equation (1) can be transformed into Equation (2), and used as the formula for simulating water quality. Further details about the model are addressed elsewhere (Tetra Tech, 2003; Zhen *et al.*, 2006).

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - u\frac{\partial C}{\partial x} - r \qquad (1)$$

$$C = C_0 \times e^{(-K_T t)} \qquad (2)$$

where C is the concentration of pollution in the effluent (mg/L), D and u are the diffusion and dispersion coefficients, respectively, r is the reaction rate, C_0 is the initial pollution concentration (mg/L); K_T is the first-order kinetic reaction coefficient (1/day); and t is the reaction time (day).

Case study

The study site was located in the Feitsui Reservoir watershed, which has become mesotrophic due to nonpoint source pollution (Lin and Hsieh, 2003). The BMP at this site treats storm runoff from tea gardens and small quantities of domestic wastewater from neighboring villages. Figure 3 depicts the layout of the BMP facility, which is composed of five treatment units: two retention ponds, one eco-pond, and two filter beds. The total treatment area is 2,953 m^2, and the total hydraulic retention time is 5.24 days. The two retention ponds retain storm water and treat polluted water with natural treatment mechanisms such as oxidization, settling, and filtration. The retention ponds provide the physical treatment mechanism, whereas the eco-pond is used for chemical treatment. Chemical treatment in the eco-pond is accomplished by the cultivation of many local plants that absorb pollutants. The filter beds enable the infiltration mechanism that reduces the quantity of surface runoff and sediment into a receiving water body. More details about the case study and the Feitsui Reservoir watershed, including the unit dimensions, can be found in Chen *et al.* (2008).

The sampling scheme was scheduled for both storm events and regular monitoring. The monitoring plan began in February 2006 and ended in December 2007. During the observation period, 31 sampling events were collected, including 7 storm events. The storm water was sampled when

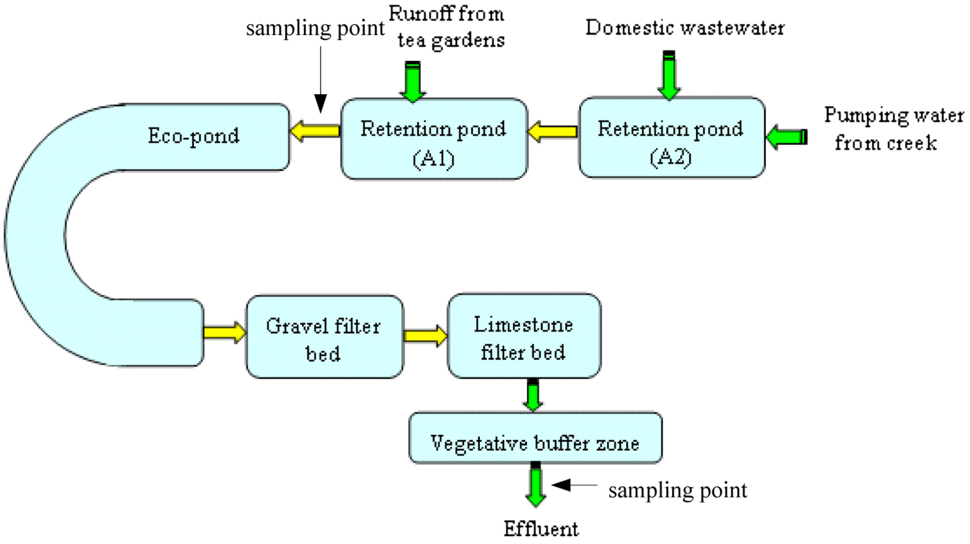


FIG. 3. Layout of the study BMP site in Feitsui Reservoir, Taipei, Taiwan.

cumulative rainfall was over 30 mm within a 24-h period. The rainfall data was based on the official records, which were announced immediately by the administration agency on the internet. In addition to storm events, regular sampling was scheduled once per month in dry weather, and the results were used to compare with water quality in storm events.

In storm event samplings, 24 bottles of water were sampled in one storm event and the associated flow rates were measured. These samples were arranged according to the flow rate and the water quality of the composite sample that was identified as the event mean concentration. In comparison to storm events, the flow in dry weather did not fluctuate significantly, so only one sample was obtained to represent the mean water quality. The arithmetic average concentrations of nitrogen-ammonia (NH_3-N), total phosphorus (TP), chemical oxygen demand (COD), and suspended solid (SS) in the influent during storm events were 2.30, 0.14, 20.91, and 25.89 mg/L, respectively. The average water quality of the influent during dry weather events was slightly higher than this, with the average concentrations of NH_3-N, TP, COD, and SS being 0.25, 0.06, 20.52, and 7.59 mg/L, respectively. According to the differences between the sampling concentration in the influent and the effluent, the pollution removal rate of NH_3-N, TP, COD, and SS, was 48.6, 74.4, 69.3, and 59.7% during storm events, respectively. The rates during dry weather events were less than those during storm events: 58.3, 43.6, 45.6, and 36.5%, respectively.

Results and Discussion

Results of the model simulation

We used the data from 2006 to calibrate the model, and the data from 2007 to verify the model. The extent to which the model simulations and field observations were correlated was assessed with the following statistics: coefficient of correlation (R), coefficient of determination (R^2), root-mean-square error (RMSE), N-S coefficient of efficiency (EF), and coefficient of determination (CD).

Due to a lack of local experiences using the model in Taiwan, the model parameters were calibrated from a very wide range. The default ranges of parameters were used, and the calibrated parameters were derived from a trial-and-error method. The results of the calibration are shown in Fig. 4A. Both hydrology and water quality were simulated; however, this model only simulates flows in hourly periods, and the time does not always match the sampling time, especially during dry weather. The results of the flow simulation were not adopted in this study. The simulation of TP is presented because it is the most limiting nutrient in terms of eutrophication status for the Feitsui Reservoir (Chou *et al.*, 2007). The model calibration is targeted at phosphorus simulation, but the calibrated parameters result in satisfactory levels for nitrogen simulation.

Of the 10 samples from 2006, 5 were affected by site-specific operations, including pipe and aquatic maintenance. These events resulted in the water quality of the effluent being worse than that of the influent, and thus gave a negative value for the removal rate. The ecosystem of the BMP site needed time to recover from these disruptions, and samples obtained during the recovery period might not truly reflect the effect of pollution treatment. Therefore, the data for these samples was excluded from the model simulation. For similar reasons, the data for 7 of 21 samples obtained in 2007 were also not included. Figure 4B shows the results of the model simulation using the calibrated model parameters and field data from 2007. The correlation test results are summarized in Table 1. The coefficient of determination (R^2) was 0.87 and 0.8 for calibration and verification, respectively.

Table 2 summarizes the verified model parameters used with the BMP ToolBox in the case study. All parameters were obtained through a trial-and-error process, except the dimensions of BMP constructions, which are the dimensions of the study site. The model inputs are classified into four categories: BMP construction, soil, vegetation, and treatment rate. Surface soil parameters are used to simulating the mechanism of infiltration. Due to waterproof nature of the bottoms of the retention ponds and eco-pond, parameters for surface soil are only assigned to the two filter beds. Vegetation parameters are for the retention ponds and eco-pond, where plants contribute to pollution removal; there is no vegetation on the filter beds. Therefore, zero growth coefficients were assigned for the two filter beds. Higher growth coefficients imply vegeta-

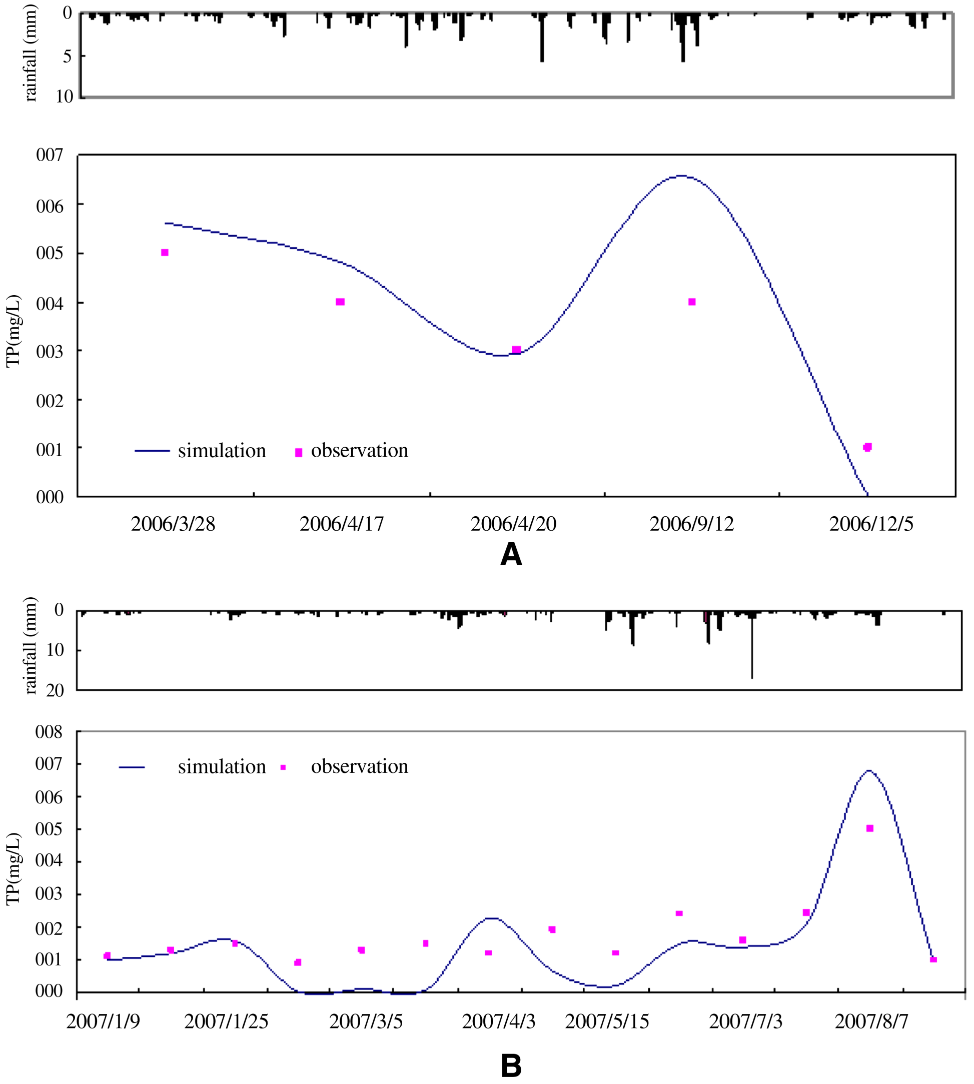


FIG. 4. (**A**) Results of model calibration using the 2006 data set, and (**B**) results of model verification using the 2007 data set.

tion that is more active. The first-order decay reaction was designed for pollution removal in this model. The decay coefficients are assigned for different pollutants. The first-order reaction dynamic coefficients shown in Table 2 are the decay coefficients of TP, obtained using a trial-and-error method.

The use of the validated model to simulate the continuous performance of the study site across 2006–2007 resulted in a satisfactory match between simulated results and field observations. Higher pollution removal rates were observed during storm events than during dry weather events, which might be associated with high pollution concentration from storm runoff and an increased treatment ability of the BMP under these conditions. The model simulation produced results that matched these observations.

Table 1. Summary of Correlation Test Results

Method	R	R^2	*RMSE*	*N-S*	*CD*
Calibration	0.93	0.87	0.01	0.59	0.4
Verification	0.89	0.8	0.01	0.16	0.36

RMSE, root-mean-square error; N-S, Nash-Sutcliffe coefficient of efficiency; CD, coefficient of determination.

Results of sensitivity analysis

The model was used in Taiwan for the first time, and knowing the sensitivity of model parameters is helpful for further applications. The one-factor-at-a-time method (OFAT) (Daniel, 1973; Frey *et al.*, 2003) was applied in conducting the sensitivity analysis. Twenty-two parameters were examined in five types of BMP constructions. Testing all 22 parameters for each BMP unit required 110 calculations.

The identification of sensitive parameters is beneficial for model calibration and subsequent predictions. The sensitivity index (SI) was used to define the sensitivity of model parameters. SI is calculated as the change in output over the change in input: $SI = \frac{(\Delta C/C)}{(\Delta X/X)}$, where C is the model output and x is the input parameter. ΔC represents the difference in output from the original output, and ΔX represents the difference in input from the original input. An SI equal to zero implies

Table 2. Verified Parameters of the Best Management Practice ToolBox Model Used in the Case Study

			Verified parameters for each BMP unit				
Model items		*Model parameters*	*A2 retention pond*	*A1 retention pond*	*Eco-pond*	*Limestone filter bed*	*Gravel filter bed*
BMP construction	Dimension	Length (ft)	65.62	78.74	49.21	39.37	39.37
		Width (ft)	104.99	82.02	311.69	39.37	39.37
	Orifice flow	Orifice height (ft)	1.15	1.8	3.94	2.21	0.9
		Orifice diameter (in)	11.81	5.91	6	6	6
	Weir flow	Type		Triangular			Rectangular
		Height of the weir mouth (ft)	—	0.98	—	—	0.4
		Angle of the weir mouth (^{o})	0	90	0	0	0
		Width of the weir mouth (ft)	3.94	0	4.59	2.62	2.62
Surface soil	Soil structure	Depth (ft)	0	0	0	0.33	0.33
		Orifice rate	0	0	0	1	1
		Flux rate of vegetation layer (in/hr^{-1}/in)	0	0	0	0.8	0.5
	Underdrain structure	Depth of storage layer (ft)	0	0	0	0.98	0.98
		Orifice rate of filter layer	0	0	0	0.4	0.4
Vegetation	Growth coefficient	January to February	0.55	0.55	0.55	0	0
		March	0.4	0.4	0.4	0	0
		April	0.45	0.45	0.45	0	0
		May	0.55	0.55	0.55	0	0
		June	0.75	0.75	0.75	0	0
		July	0.9	0.9	0.9	0	0
		August to September	1	1	1	0	0
		October	0.9	0.9	0.9	0	0
		November	0.7	0.7	0.7	0	0
		December	0.5	0.5	0.5	0	0
Treatment rate	Pollution removal	First-order reaction dynamic coefficient, K_T(1/day)	0.15	0.15	0.15	0.15	0.15
		Removal percentage by underdrain (%)	0	0	0	5	5

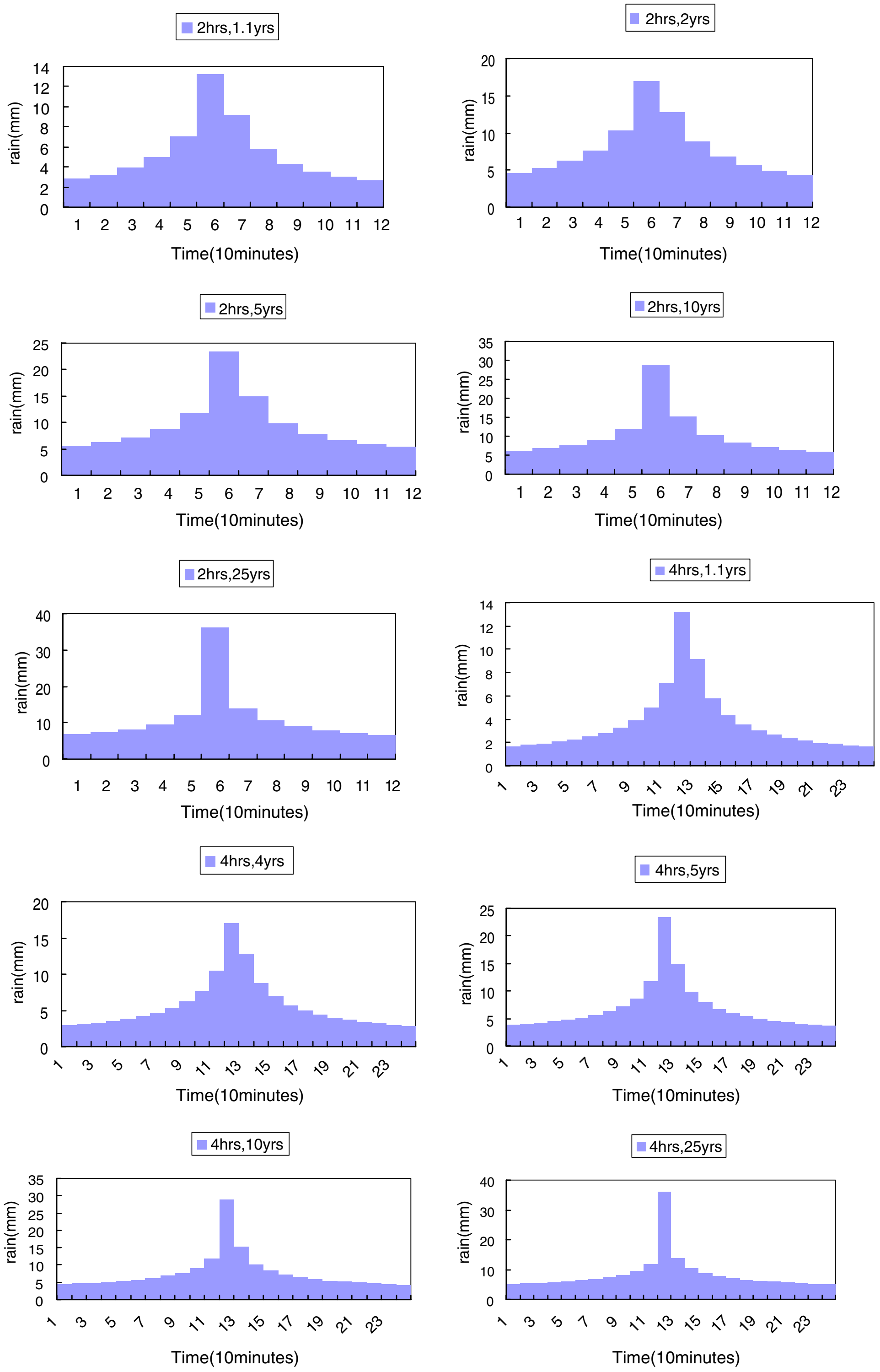


FIG. 5. The results of the designed storm for different rainfall durations and reoccurrence intervals in the case study.

that changes in the input value have no effect on the output. A negative or positive SI suggests that there might be a negative or positive relationship between input and output.

The results of the sensitivity analysis (Table 3) showed that the dimensions of BMP constructions, the design of orifice flow and weir flow, and the value of the first-order reaction dynamic coefficient are sensitive to TP pollution removal. Moreover, the sensitivity of dimension of BMPs is higher than that of decay coefficient, which means the physical mechanisms provided by BMP treatment units are important in removing pollution. The pollution removal is not only dependant on the first-order decay reaction. In contrast, the parameters related to surface soil, vegetation, and underdrain structure are less sensitive to the modeled output. The

Table 3. Sensitivity Analysis of Best Management Practice ToolBox Parameters for Total Phosphorus Simulation (for Sensitivity Index > 0 and Sensitivity Index < 0)

Model parameters	*Length*		*Width*		*Orifice height*		*Orifice diameter*		*Weir height*		*Weir angle*		*Weir width*		*Kt*	
	SI		*SI*		*SI*		*SI*		*SI*		*SI*		*SI*		*SI*	
BMP types	*+50%*	*−50%*	*+50%*	*−50%*	*+50%*	*−50%*	*+50%*	*−50%*	*+50%*	*−50%*	*+50%*	*−50%*	*+50%*	*−50%*	*+50%*	*−50%*
A1 retention pond	0.05	0.07	0.05	0.06	0	0.05	0	0	0.04	0.05	−0.01	−0.01	—	—	0.04	0.06
A2 retention pond	0.04	0.07	0.05	0.06	0.05	0.06	0	−0.01	—	—	—	—	0	0	0.05	0.07
Eco-pond	0.21	0.36	0.21	0.34	0.07	0.32	−0.01	−0.01	—	—	—	—	0.01	0.24	0.16	0.28
Gravel filter bed	0.02	0.04	0.03	0.03	0.01	0.03	0	0	—	—	—	—	0	0.02	0.02	0.02
Limestone filter bed	−0.01	0.01	0.01	0.01	0.01	0.01	0	0	0	0	—	—	0	0	0.01	0.01

SI, sensitivity index.

sensitivity of a model parameter can be different for different types of BMP. For BMP dimensions, the order by rank of sensitivity level is eco-pond, retention pond, limestone filter bed, and gravel filter bed.

Results of future performance prediction

Predicting the future performance of the study site is helpful for field maintenance and monitoring. Storms are the weather conditions typically used for models of rainfall-runoff, which evaluate runoff volume. The average rainfall intensity, rainfall duration, reoccurrence interval, and the intensity-duration distribution are included in the storm design. In the study area, the Horner equation suitably captures the relationship between rainfall intensity and duration, and the Alternating Block Method is commonly used for designing the type of storm (WRO, 1998). The Horner equation is shown in Equation (3).

$$I_t = \frac{a}{(t+b)^c} \qquad (3)$$

where I_t is the average rainfall intensity (mm/h), t is the duration (min), and a, b, and c are the equation coefficients.

The designed storm is illustrated in Fig. 5. Five reoccurrence intervals (1.1, 2, 5, 10, and 25 years) were used in combination with two rainfall durations (2 and 4 h). Because the scenarios are intended to demonstrate normal conditions, the chosen hyetographs frequently occur in the study area. Regarding water quality protection, smaller to medium-sized storms are more important than large storms (Nehrke and Roesner, 2004). The recurrence period of extreme events, such as a 50-year storm or a 100-year storm, can be generated with the same method. The scenario analysis of hyetographs is capable of providing information for prediction and comparison of the long-term performance of the BMP site.

The results of the TP simulation using the validated BMP ToolBox model and the 10 designed storm events are shown in Fig. 6. The range of TP pollution concentration was 0.25–0.4 mg/L for the influent and 0.06–0.19 mg/L for the effluent. The highest level of TP pollution occurred during the 4-h duration and 2-year reoccurrence interval. The TP concentration changed with differently designed storms, but the relationship was not clearly manifested (Fig. 6). For the reoccurrence intervals of 1.1, 5, and 25 years, the TP concentration in the influent after duration of 2 h is higher than the concentration after duration of 4 h. The contrary occurs during the reoccurrence interval of 2 and 10 years, in which the TP

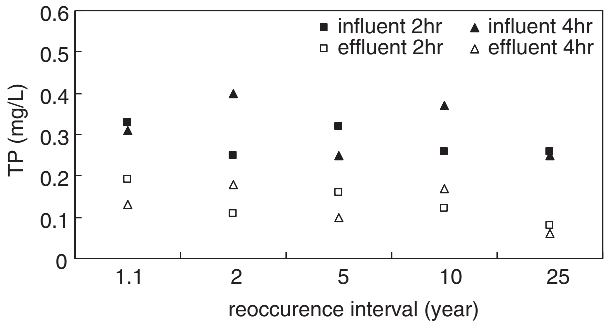


FIG. 6. Total phosphorus (TP) concentration simulations for influent and effluent in designed storms. The solid lines represent the influent TP concentration for two rainfall durations (2 and 4 h); the dotted lines represent effluent results.

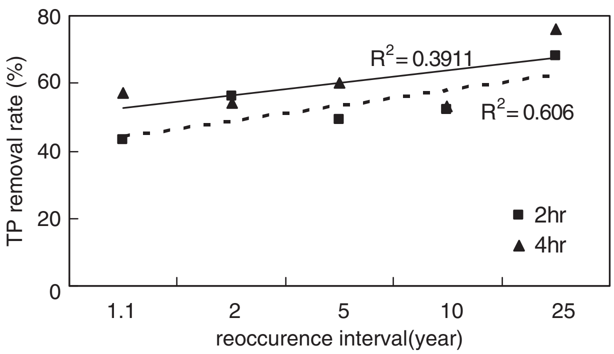


FIG. 7. Predicted TP removal rate for the study site. The lines represent linear trends for two rainfall durations: 4 h (solid line) and 2 h (dotted line).

concentration in the influent after duration of 4 h is much higher than after 2 h. Further analysis of the TP removal rate revealed relatively obvious relationships. The findings were based on the linear regression of the model outputs (Fig. 7). The removal rate of TP changed in relation to storm volume and rainfall intensity. A positive relationship between the TP removal rate and reoccurrence intervals was observed. The coefficient of determination (R^2) is 0.39 and 0.61 for durations of 4 h and 2 h, respectively. In addition, greater removal rates were seen during longer rainfall durations (4 h) than with shorter durations (2 h). The observed trend implied that a higher level of treatment was achieved when the volume of pollution entering the BMP site was high. The general relationships and hyetographs provided in this study can be applied to predict the performance of the BMP site, as well as assist in the engineering design of future BMP construction.

The highest TP removal rate of 76% for storm events corresponded with the 4-h duration and 25-year reoccurrence interval. These results indicate that treatment efficiency is determined mainly by the total quantity of pollutant inputs and the available treatment time; however, the scenario analysis cannot measure the absolute maximum loading capacity of the BMP facility. The loading capacity is determined by the design and maintenance of the BMPs.

Conclusion

The BMP ToolBox model assesses the performance of a structural BMP, and it might be a useful model for BMP researchers, engineers, and managers. This study applied the model to a realistic BMP treatment train in the Feitsui Reservoir watershed in Taiwan to test its applicability. The results of the study showed that the BMP ToolBox model was validated; however, the assumption of first-order dynamic decay in this model might limit its application. The model outputs for long-term performance of BMPs indicate that the TP removal rate is related to reoccurrence intervals of storm and better removal rate was seen during periods of longer rainfall duration (4 h) than with periods of shorter duration (2 h). The general trend implies that there is a higher level of treatment achieved when more pollution enters the BMP site.

A process for evaluating structural BMPs was also developed: one in which weather scenarios are considered to forecast the long-term performance of BMPs. The process is not limited to specific sites, and used for general applications. This process clarifies the functions of field observations, model simulations, and monitoring. The results of monitoring should be reintroduced to the process to verify the validity of the model and to expand the model's application to engineering.

Due to the fact that the BMP ToolBox model is not being developed by the authors, anyone who is interested in this model or wants to access the model can contact Dr. Cheng at mscheng@co.pg.md.us for further information.

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Author Disclosure Statement

No competing financial interests exist.

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