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Performance evaluation of a full-scale natural treatment system for nonpoint source and point source pollution removal

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Abstract This study presents a full-scale performance of a natural treatment system (NTS) facility in Taiwan with nearly 2 years of observations. The study site, composed of several treatment ponds in series, was designed primarily to reduce polluted stormwater runoff from tea gardens and partially to untreated domestic wastewater from nearby villages. Thus, both nonpoint source and point source pollution are treated in this system. From 28 field samplings in 2006–2007, the NTS site shows satisfactory treatment performance and the effluent water quality is significantly improved. Seven of the 28 sampling events are storm events (nonpoint source pollution) and the remainder are from regular monitoring (point source pollution). The average volume of influent and effluent is 533 CMD and 196 CMD, respectively. In order to determine the removal efficiency, several assessment measures are employed in an attempt to obtain unbiased conclusions. They are removal rate (RR), efficiency rate (ER), summation of loads (SOL), flux rate (FR), and effluent probability method (EPM). The average percent removal efficiency of NH_3-N is 53.5–75.2% and of TP is 59.0–84.7%, in which the highest result is calculated by SOL method and the lowest rate is obtained from RR. In FR evaluation, larger treatment capacity for NH_3-N than for TP is provided in the site and the average FR is respectively 0.230 g/m^2 day and 0.017 g/m^2 day. Of the methods examined, EPM is the only method capable of illustrating data distribution. Finally, recommendations on the usefulness of these measures are summarized to facilitate the understandings of NTS performance evaluations.

Keywords Natural treatment systems (NTS) · Performance assessment · Stormwater runoff · Removal efficiency

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Introduction

Natural Treatment System (NTS) is an alternative onsite treatment using natural attenuation ability to purifying polluted flow. Natural treatment system, with advantages of cost effectivity and minimum operation requirement, is widely applied in wastewater treatment and is considered as the main technology in best management practices (BMP) for nonpoint source pollution-control (USEPA 2004). The NTS is not limited to-specific types; instead, many environment-friendly treatment systems utilizing natural energy and-biodegradation as domain mechanisms can be-classified as a NTS facility. Leverenz et al. (2002) summarized several types of natural onsite treatment system including surface flow constructed wetlands, subsurface flow constructed wetlands, ecological systems, evapotranspiration systems, and lagoons. Among these NTS types, constructed wetlands (CW) have been widely applied as an efficient treatment system for wastewater, especially in developing countries (Kivaisi 2001). The flexibility of NTS application permits the treatment of various types of wastewater (Rousseau et al. 2004), such as sewage treatment plant effluent (Toet et al. 2005), industrial wastewater (Chen et al. 2006), stormwater runoff (Carleton et al. 2000), and domestic wastewater (Belmont et al. 2004). Recently, a vertical flow CW was proved to remove pharmaceuticals and personal care products (Matamoros et al. 2007).

Feitsui Reservoir supplies drinking water for almost five millions people in Taipei City (the capital city) and Taipei County and is the most important water source in Taiwan. According to the water quality monitoring annual report of Taipei Feitsui Reservoir Administration, the Carlson Trophic Status Index (CTSI) indicated that the water quality in Feitsui Reservoir is reaching near-eutrophic state. Several impact factors contribute to the eutrophication, including excessive amounts of nutrient input and heavy rainfalls in upstream watersheds. Non-point sources (NPS) are concluded as the dominant pollution source and require appropriate BMPs (Lin and Hsieh 2003). Responding to this requirement, several pollutions control strategies have been implemented, including the establishment of NTSs to reduce polluted runoff and to control alga propagation (Chou et al. 2007). The NTS facility constructed in DuNan site is an exceptions it treats both nonpoint source and point source pollution. Not only the storm runoff from tea gardens is treated in DuNan NTS system but also the domestic wastewater from nearby villages is directed into the system. The system was composed of four treatment units, including free water surface wetlands and subsurface flow wetlands. After nearly 2 years of monitoring, the DuNan site shows satisfactory performance on pollution removal and the water quality in Feitsui Reservoir is improved.

The improved water quality in effluent is easily observed by sampling analysis; however, it is difficult to conclude a deterministic evaluation for the system performance. Many assessment measures are suggested to evaluate constructed BMPs and NTS. For example, USEPA (1999) reported Event Mean Concentration (EMC) or Summation of Loading (SOL) is proper to assess removal rate of suspended solid, total phosphorous, and ammonia nitrogen. USEPA (2002) recommended that Effluent Probability Method (EPM) and Box Plot to analyze sampling data since they are capable of showing extreme events and distribution types. Chen (2006) compared the methods of Removal Rate (RR) and Efficiency Ratio (ER) and concluded that the variability of stormwater runoff might affect the assessment results. In order to evaluate the performance of the DuNan site, the measures, ER, RR, SOL, and EPM are employed to give a whole view of the pollution removal efficiency. Besides, a new assessment measure with flux idea is proposed, named Flux Rate (FR). The FR method considers exposure pathway that treats pollutants not considered in other assessment methods. The general calculation and comparison of the measures are demonstrated in this study to facilitate the efficiency assessment.

In "Material and methodology", the dimension of the case study structure is demonstrated and the approaches of efficiency assessment are presented. The sampling observations of the site and the evaluation of pollution removal rate are discussed in "Results and discussions". Finally, a brief summary of this study is concluded in "Conclusions".

Material and methodology

Site conditions and features

The study site is located in Feitsui Reservoir watershed to investigate the control of the reservoir eutrophication. The two major land use in Feitsui Reservoir watershed are forest (85.9%) and agricultural (6.6%) use by the tea industry (EPA of ROC 2005). Thus, the main nonpoint source is from tea gardens surrounding the watershed. This study site, nestled near DuNan Bridge, was constructed to purify water quality of Pashin Creek that flows into the Feitsui Reservoir (Fig. 1). The study site is therefore called DuNan site in this study. The DuNan site was designed to treat storm runoff from tea gardens. In addition, small quantity of domestic wastewater from neighboring villages is also collected into this NTS facility. Because both nonpoint source and point source pollution are treated in the same site, the sampling scheme was scheduled separately for storm events and regular monitorings. Although two influents flowed in, only one effluent is sampled for the overall evaluations. Figure 2 depicts the layout of the NTS facility and a photo of the site.

At the beginning, the site was particularly designed for the storm water from nonpoint source. However, the storm water is the only influent and a satisfied water level in treatment ponds cannot be maintained when no rain falls. Moreover, the infiltration in the site is very strong. Without other inflow the site consequently dried up in the most time. Therefore, new water source was needed. The untreated domestic wastewater from neighbor village or Pashin Creek water was considered to supplement the water quantity. But the quantity of wastewater is too small to increase water level in either retention ponds or eco-pond. Thus, sufficient water quantity of upstream Pashin Creek was pumped into the treatment system. The water quality in upstream Pashin Creek does not be contaminated by nonpoint sources and could also serve as clean water to dilute polluted storm runoff.

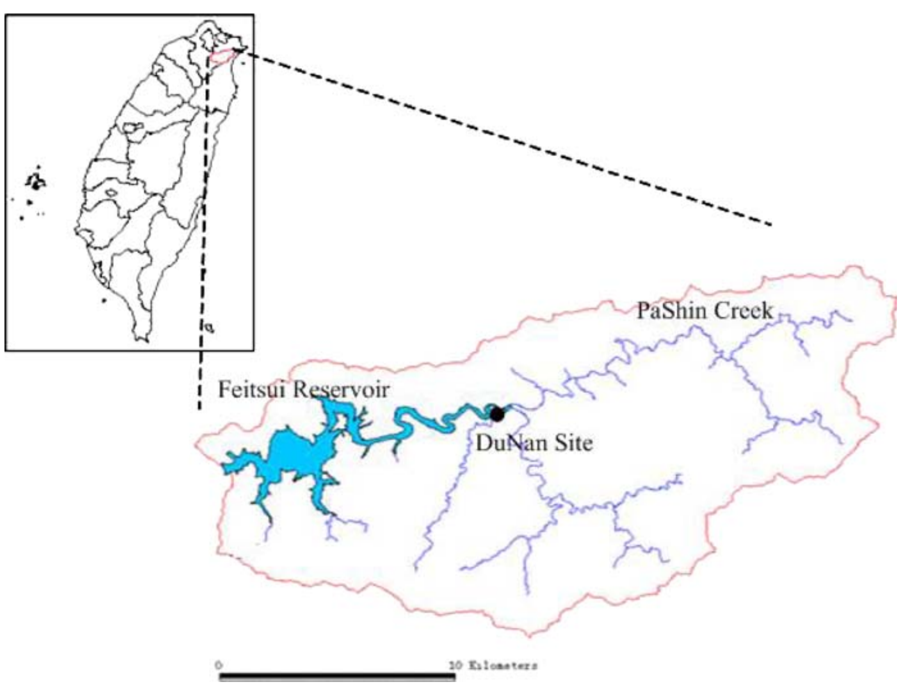

Fig. 1 The location of DuNan site and Feitsui Reservoir

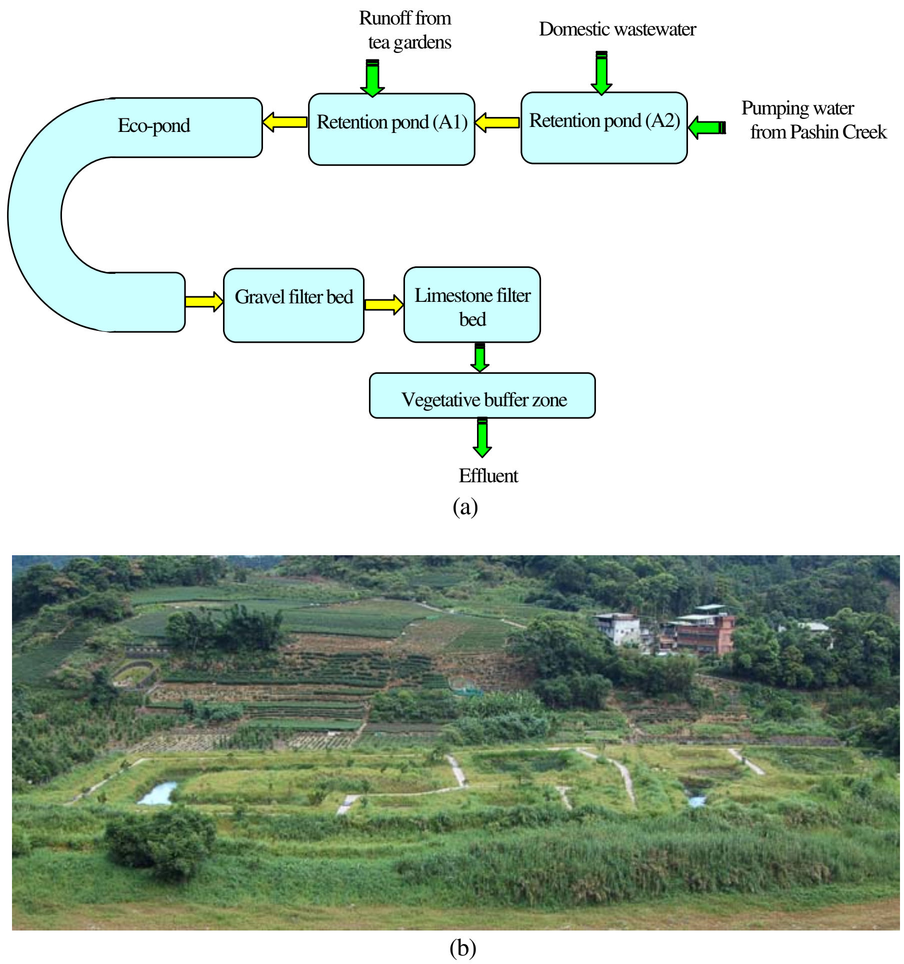

Fig. 2 (**a**) Layout of the DuNan NTS site and (**b**) the field photo

Pumping Pashin Creek water as an additional water source was disagreed by some experts. They suggested that no new water flow was needed. The water level in ponds could be controlled by proper device, such as a control valve. Even no water in the most time, the storm water from tea gardens in rainy day is still able to be retained and reduced. The water pumping from Pashin Creek is not automatically and continually and the additional maintenance and operation of the pump and pipe are required. After the arguments, the administration agency finally decided to pump water and to rebuild a new ecological system.

The drainage area of the DuNan site is 3 ha covered mostly by tea gardens. The design flow rate in this CW system is 600 CMD, collecting occasional stormwater, domestic wastewater, and Pashin Creek pumping water. The site is composed of five treatment units, including two retention ponds, one eco-pond, and two filter beds (Fig. 2). Two retention ponds are settled to retain storm water and to treat polluted water with natural treatment mechanism, such as oxidization, settling, and filtration. Two serial retention ponds are expected to offer sufficient time for treatment process. The retention ponds provide mostly physical treatment mechanism; meanwhile, the eco-pond is placed to strengthen chemical treatment, where many local plants are cultivated for pollution absorption. Due to the plants hinder water flow in the eco-pond, the small flow rate might cause insect growing. The full discussions on removal mechanism can be found in literatures, such as Urbonas (1994) and USEPA (1999).The detail unit dimensions are listed in Table 1. The total treatment area is 2,953 m^2 and the total hydraulic

Table 1 The design dimensions of the DuNan site

Treatment units	Length (m)	Width (m)	Surface area (m^2)	Water depth (m)	Storage volume (m^3)	Hydraulic retention time (day)	Hydraulic loadings (m^3/m^2day)
Retention pond (A2)	32	20	640	1.2	659.59	1.10	0.94
Retention pond (A1)	25	24	600	1.2	621.30	1.04	1.00
Eco-pond	95	15	1,425	1.4	1,812.95	3.02	0.42
Limestone filter bed	12	12	144	0.4	23.04	0.04	4.17
Gravel filter bed	12	12	144	0.4	23.04	0.04	4.17
Total	–	–	2,953		3,140	5.24	

retention time is 5.24 days. Local vegetations are cultivated, including over 30 aquatic species and ten terrestrial species and the total amount is over 5,000.

The monitoring plan began at February, 2006. Two influents and one effluent are sampled. The influent from domestic wastewater and pumping water from Pashin Creek are monitored monthly as dry weather flow. The storm water is sampled when cumulative rainfall is over 30 mm within a 24 h interval. The rainfall data was used based on the official records, which was announced immediately by administration agency on internet. Once the rainfall reached the sampling standard, we sampled the two influents and one effluence in site and analyzed them in laboratory. The samplings were not made by automatic machine. We went to the field to sample water and measure the flow. In addition to the storm events, we measured the water quality monthly in regular time.

The water flow rate was measured in different ways. The pumping water flow from Pashin Creek was measured by the pump rate and the volume of domestic wastewater and tea gardens runoff was measured by weirs. The flow rate was calculated from the dimension of weir and the water level of overflow. In monthly regular monitoring, the water sample and water flow measure was made once each time because the flow is stable. However, more than one sample was measured in storm events and the sample interval is about 10 to 20 min. Water quality of pH, temperature, dissolved oxygen (DO), chemical oxygen demand (COD), suspended solid (SS), ammonia nitrogen (NH_3-N), and total phosphorous (TP) are analyzed. The flow rate is calculated by container estimation according to administration method (NIEA W020.51C).

Assessment methods of NTS performances

To give an unbiased assessment, five evaluation approaches are employed to evaluate the pollution removal performance. They are removal rate (RR), efficient ratio (ER), summation of loads (SOL), flux rate (FR), and effluent probability method (EPM). The brief descriptions of these measures are summarized as follows.

Removal rate

Pollution concentration removal rate is the most commonly-used measure. Removal Rate (RR) compares directly water concentration in inlet and outlet samplings. The expression of RR is as Eq. 1, where C_{in} and C_{out} is the concentration of influent and effluent, respectively.

$$\text{RR}\,(\%) = \left(\frac{C_{in} - C_{out}}{C_{in}}\right) \times 100\% \tag{1}$$

Efficiency ratio

Efficiency Ratio (ER) is similar to RR, but the concentration is replaced by the Event Mean Concentration (EMC; Eq. 2). EMC is the ratio of the total pollution mass to total runoff volume. In a single stormwater event, the average pollution concentration is used in the computation. Distribution of pollution concentration is depended on storm intensity and duration time; thus, the EMC is usually used to describe the average pollution concentration for stormwater events.

$$\mathrm{ER}\,(\%) = \left(\frac{\text{average EMC}_{in} - \text{average EMC}_{out}}{\text{average EMC}_{in}}\right) \times 100\% \quad (2)$$

where EMC_{in} is EMC of influent and EMC_{out} is of effluent.

$$\mathrm{EMC} = \frac{\sum_{i=1}^{n} C_i V_i}{\sum_{i=1}^{n} V_i} \quad (3)$$

where, C_i is the average pollution concentration in a sampling period, V_i refers to the runoff volume in duration time i, and n is the sampling numbers.

Summation of loads (SOL)

SOL is also a percent measure, but unlike RR and ER, SOL uses pollution mass change instead of concentration. The expression of SOL is as Eq. 4. The detailed assumptions and comments about SOL method was given in the technical memorandum of ASCE and USEPA (1999).

$$\mathrm{SOL}\,(\%) = \left(\frac{L_{in} - L_{out}}{L_{in}}\right) \times 100\% \quad (4)$$

where

$$\mathrm{L} = \sum_{i=1}^{n} C_i V_i$$

Flux rate

The notion of pool(s) is a simplified assumption to describe transition of a substance in organism or nonorganism compartments. For example, in aquatic system, phosphorous is distributed in either waterbody or plankton. The waterbody and plankton can be regarded as pools of phosphorous and the transition of phosphorous can be calculated between pools. The transition quantity is denoted as flux rate, the number of substance transisting from one pool to others by unit area or volume in particular time period. The flux rate is also used for the mass balance between systems. Unlike RR and ER, the traditional methods for evaluating efficiency of pollution removal always focus on the change of pollution concentration (or mass) but ignore the life time inside the treatment system. The total treatment area and retention time are impact factors of pollution removal but are not considered in conventional approaches. It is inappropriate to compare the performance of a small treatment system to a large one. Flux rate considering exposure path of pollutants provides a new measure to evaluate efficiency assessment for BMPs.

$$\text{flux rate} = \frac{C_{in} Q_{in} - C_{out} Q_{out}}{A} \quad (5)$$

where A is the lateral area of the treatment system

Effluent probability method

Effluent Probability Method (EPM) incorporating probability distribution is recommended to assess BMP performances (ASCE and USEPA 1999; USEPA 2004). The use of the EPM is preferred over other methods as it measures BMP efficiency with various pollutant concentrations and rainfall intensities (Strecker et al. 2000). All influent and effluent samplings are ranked according to pollution concentration and depicted in a cumulative probability graph. Thus, two parallel curves of cumulative probability and the treatment efficiency of CWs are revealed. A log transformation of both influent and effluent EMCs are needed to elicit the probability graph since log normal distribution is generally better for water quality samples. The distance between the two parallel curves indicates the level of removal rate and different removal efficiency are found for different influent concentrations. The distributions of water quality of samplings have to be verified by statistical test to ensure the rationality of distribution assumption. Chi-Square statistic and Kolmogorov–Smirnov test was suggested by Burton and Pitt (2001) for EPM methods.

Results and discussions

Water quality in DuNan site

The water quality monitoring plan started at February 2006 and is still ongoing. A total of 28 events were sampled, including seven stormwater events and 21 regular events (dry weather). The average inflow rate is 533 CMD and the outflow rate is 196 CMD. The loss of influent volume might be infiltrated into soil or be retained in treatment ponds. Infiltration is one of the major removal mechanisms in natural treatment system. Infiltration can affect both particle transport and dissolved runoff; especially for high removal efficiency of particle pollutants. The performance of infiltration is significantly relied on texture of soil. A finer soil can even result in a better removal efficiency of dissolved pollutants. In addition, hydraulic diffusion and chemical diffusion might control the dissolved pollutants in infiltration (Wiertz and Marinkovic 2005). In DuNan site, the nutrient pollutions are concerned. Due to the dissolved forms of nutrient pollutants are less than particle ones, the dissolved pollutants did not analyzed. However, infiltration can help to remove not only particle but also dissolved pollutants. For example, in Krutz et al. (2003) study, more infiltration volume turned out more trapping efficiency of dissolved pollutant (atrazine). Therefore, infiltration function was taken place in the DuNan site and was likely benefit to its performance. The flow rate of influent and effluent at the study site is shown in Fig. 3. The variability in the influent flow rate occurs because (1) part of the influent was from the pumping of water from Pashin Creek and the pumping time varies from day to day, and (2) the occurrence of the occasional storm. At the initial period, the difference of inflow and outflow rate is not significant. After September 2006, due to evaporation and high infiltration, the effluent water quantity is significantly less than the influent. In addition, the pipe block and hydraulic retention might also affect the variability.

The water quality is summarized in Table 2. The average concentrations of NH_3-N, TP, COD, and SS of storm water are 2.30, 0.14, 20.91, and 25.89 mg/L, respectively. The average water quality of the influent in dry weather (0.25, 0.06, 20.52, and 7.59 mg/L), is much better than that of stormwater flow, especially in terms of nutrient pollutant and SS. The concentration of NH_3-N and TP in stormwater (as nonpoint source) is almost ten times and two times higher than in dry weather (as point source). This finding suggests that the runoff through tea gardens carried more nutrients and might cause eutrophication in receiving waterbody if not treated. The concentration of SS is higher in storm runoff because of soil erosion. The COD concentrations are similar in stormwater and dry weather flow.

Box-and-Whisker Plot (Box Plot) displaying data distribution and extreme value in the same graph is commonly used for data analysis (Tukey 1977). The Box Plot of DuNan site is shown in Fig. 4. The NH_3-N and TP concentration in effluent are lower than in influent, implying that the removal of nutrient is efficient in DuNan site. The

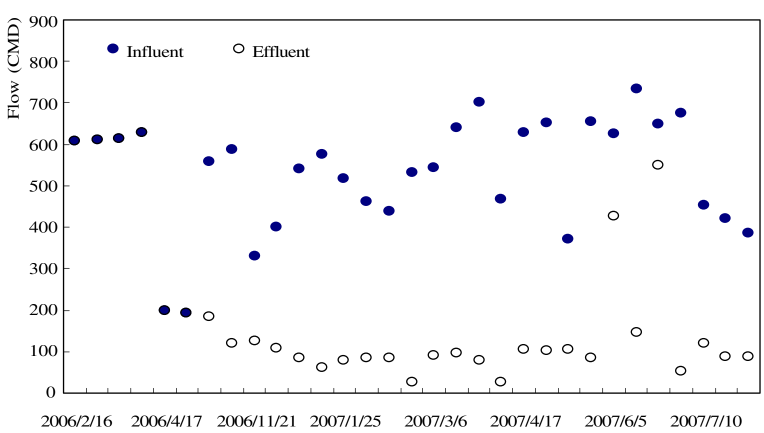

Fig. 3 The flow rate of influent and effluent in DuNan site

Table 2 Results of water quality sampling and RR

Events	Sampling date (mm/dd/yy)	NH_3-N (mg/L)			TP (mg/L)			COD (mg/L)			SS (mg/L)		
		Influent	Effluent	RR (%)	Influent	Effluent	RR (%)	Influent	Effluent	RR (%)	Influent	Effluent	RR (%)
Stormwater	04/06/2006	1.18	0.44	62.7	0.16	0.03	82.0	4.0	8.7	/	13.80	3.50	74.6
(nonpoint source)	04/10/2006	13.90	5.08	63.5	0.47	0.03	93.0	11.7	2.8	76.1	3.00	3.00	0.0
	03/05/2007	0.31	0.24	22.6	0.01	0.01	0.0	26.8	10.0	62.7	48.65	6.00	87.7
	03/06/2007	0.34	0.20	41.2	0.02	0.15	/	15.0	5.0	66.7	45.36	23.00	49.3
	04/10/2007	0.14	0.09	35.7	0.01	0.01	0.0	33.2	10.0	69.9	< 1.0	0.00	/
	06/05/2007	0.11	0.06	46.5	0.03	0.02	40.90	–	–	–	2.51	0.80	68.2
	08/07/2007	0.09	0.03	68.1	0.25	0.05	81.8	34.78	10.00	71.2	42.02	9.00	78.6
Average[a]		2.30	0.88	48.61	0.14	0.04	74.43	20.91	7.75	69.33	25.89	6.47	59.73
Dry weather	02/16/2006	0.26	0.17	34.6	0.10	0.06	37.5	9.8	3.3	66.3	6.80	4.50	33.8
(point source)	03/28/2006	0.20	0.07	65.0	0.11	0.05	54.3	2.8	7.2	/	10.80	25.50	/
	04/14/2006	0.40	0.16	60.0	0.06	0.04	35.5	4.2	11.2	/	2.00	3.00	/
	04/20/2006	0.74	0.08	89.2	0.08	0.03	58.7	2.8	6.4	/	4.00	2.00	50.0
	09/12/2006	0.11	0.09	18.2	0.05	0.04	20.0	50.7	20.0	60.6	3.39	2.00	41.0
	10/03/2006	0.23	0.08	65.2	0.03	0.02	33.3	10.0	3.0	70.0	0.00	0.00	0.0
	11/07/2006	0.27	0.60	/	0.03	0.01	66.7	60.7	50.0	17.6	< 1.0	< 1.0	/
	12/05/2006	0.10	0.05	50.0	0.01	0.01	0.0	3.1	20.0	/	< 1.0	< 1.0	/
	01/09/2007	0.17	0.22	/	0.02	0.01	50.0	73.8	50.0	32.2	< 1.0	< 1.0	/
	01/11/2007	0.28	0.01	96.4	0.23	0.01	94.3	12.1	4.8	60.3	< 1.0	< 1.0	/
	01/25/2007	0.18	0.01	94.4	0.05	0.02	71.2	2.8	2.8	0.0	< 1.0	< 1.0	/
	02/06/2007	0.11	0.06	45.5	0.01	0.01	0.0	17.4	10.0	42.5	< 1.0	< 1.0	/
	02/26/2007	0.42	0.04	90.5	0.07	0.01	87.3	8.8	8.4	4.5	1.5	< 1.0	/
	05/02/2007	0.26	0.05	80.8	0.18	0.10	43.7	7.9	16.2	/	< 1.0	< 1.0	/
	05/09/2007	0.23	0.08	65.2	0.04	0.02	50.0	14.4	20.0	/	0.00	3.33	/
	05/15/2007	0.11	0.04	62.9	0.03	0.01	60.9	–	–	–	–	< 1.0	/
	06/12/2007	0.18	0.05	72.6	0.03	0.02	44.1	23.12	20.00	13.5	2.51	2.50	0.5
	06/20/2007	0.17	0.08	52.1	0.03	0.02	14.9	–	–	–	–	–	–
	07/03/2007	0.11	0.04	62.9	0.03	0.02	54.2	–	–	–	< 1.0	–	/
	07/10/2007	–	–	–	0.03	0.02	26.2	–	–	–	31.20	2.00	93.6
	09/04/2007	–	–	–	0.03	0.01	60.5	–	–	–	–	–	–
Average[a]		0.25	0.13	58.27	0.06	0.03	43.60	20.52	15.14	45.60	7.59	5.19	36.48

/ negative value is generated, – no sample data
[a]The negative value(s) is excluded in RR calculation

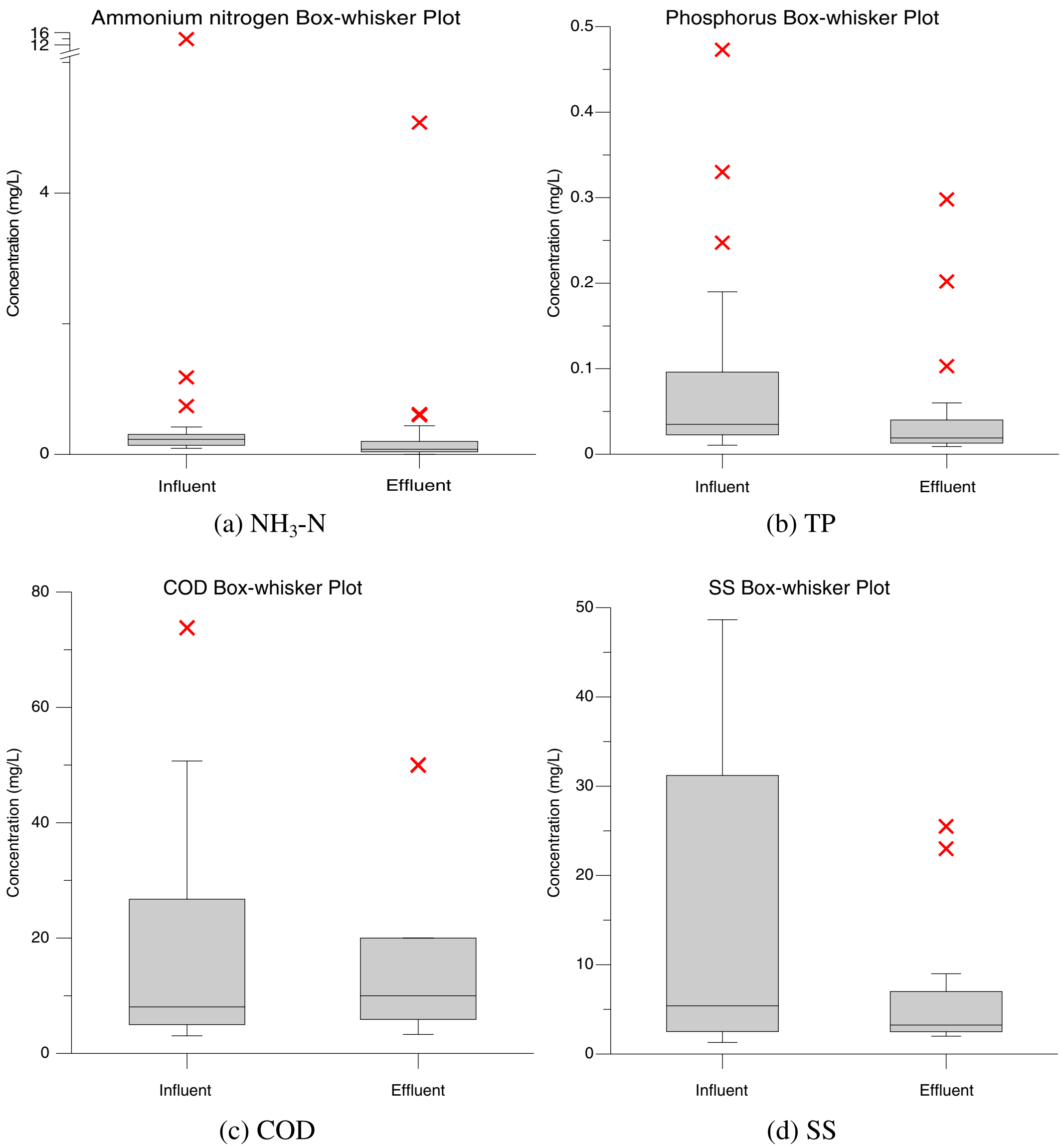

Fig. 4 **a–d** The Box Plot of sampling water quality in DuNan site

data in influent has a wider range than effluent, especially for COD and SS. Positive skewness is observed in influent of TP, COD and SS. Several outliers are appeared in raw data, especially in the nutrient matters. In these calculations, a negative value is regarded as an outlier and should be excluded. Negative values indicate the pollutants concentration in effluent is higher than that in influent. It might be caused by several rational reasons, such as the effects from lateral flows, the disturbance of fishes, or errors in experimental analysis. However, these values would significantly influence the average value in calculation. To the reason, negative values are treated as statistic outlier and are not considered in the evaluation methods.

Assessment results of pollution removal efficiency

The performance efficiency of DuNan site is evaluated with five measures. Three measures, RR, ER, and SOL present percent removal assessment. Flux rate (FR) assesses site treatment capacity and EPM helps to explain data distribution.

Removal rate

The removal rate (RR) is calculated from the water quality in influent and effluent. The average RR of NH_3-N, TP, COD, and SS are 48.6%, 74.4%, 69.3%, and 59.7% in storm events. But there is high variation of daily RR values caused by system operation and maintenance. For example, RR of NH_3-N increased from 34.6% at February 2006 to 89.2% in April 2006 when regular maintenance occurred. However, as no maintenance occurred during April to September, the RR at September dropped to 18.2%. After continuous and effective maintenance, the rate increased to 96.4% in January 2007. The RR results of the system are drastically influenced by the quality of operation and maintenance. The other example is that many fish are put into ecopool at early March and lead to confounding TP removal, the concentration in effluent is higher than that in influent at 6th, March, 2007. The purpose of putting fishes in to pond is to prevent mosquitoes larvae from thriving. Although the fishes disturb the stable water and brought out some sediment in the initial period, the overall treatment environment became better and the quality of treated water was satisfied when the system was revived. Additionally, the influent concentrations of pollutants may influence the RR results. For example, the RR of COD could be as much as to 70% if the influent concentration is in the range of 10–50 mg/L. Otherwise, negative RR might appeared when the influent concentration is less than 10 mg/L. Higher influent concentration of NH_3-N and TP leads to higher RR values.

The negative RR value implies that treatment facility produces more contamination instead of pollution removal and the irrational data is excluded in performance assessment. The unexpected value might be caused by the time lag in sampling, implying that the batch of effluent being sampled is different from the "same" batch of influent water. The major pitfall of RR method is not considering the hydroretention time. Although RR is the most straightforward way to assess the performance efficiency of any water treatment system, it might produce misleading results such as the negative removal rates.

Efficiency ratio

In the ER method, flow data is required in order to obtain EMC. The EMC is not properly for assessing regular samples since the influent flow rate is represented by only one dry weather flow unlike the distributed flow curve is occurred in stormwater events. Thus, the discussion of ER is confined to the site performance in storm events. The ER of NH_3-N, TP, COD, and SS are 62.4%, 83.4%, 68.0%, and 70.9%, respectively. Comparing with the average RR value (excluding negative ones), the results of ER are higher than the average RR values with the exception of COD pollutant (Table 3). Since the COD concentration is similar in storm and dry weather events, the results of ER and RR are not much variant.

Summation of loads

The SOL is evaluated from the total summation of influent mass and effluent mass. Table 4 displays the example of the calculation process of SOL. The average SOL of NH_3-N, TP, COD, and SS are 75.2%, 84.7%, 81.4%, and 88.8%. The summary of percent removal efficiency of DuNan site is given in Table 5. The removal efficiency of TP is always higher than NH_3-N in storm events; on the contrary, the removal rate of TP is less than of NH_3-N in dry weather events. Regarding to storm events, the removal efficiency of NH_3-N is 48.6%-64.8% and that of TP is 74.4–90.8%. The results of SOL give the highest removal rate and the lowest rate is obtained from RR in both NH_3-N and TP. The different measures lead to about 16% for the efficiency results.

Table 3 ER for storm events and the comparison with RR

Storm events	NH_3-N (%)	TP (%)	COD (%)	SS (%)
ER	62.4	83.4	68.0	70.9
RR	48.6	74.4	69.3	59.7

Table 4 The example of SOL calculation (NH_3-N)

Events	Sampling date	$Q_i(m^3/d)$	$Q_e(m^3/d)$	C_i(mg/L)	C_e(mg/L)	M_i(g)	M_e(g)	SOL (%)
Stormwater (nonpoint source)	2006/4/6	612.36	612.36	1.180	0.440	722.58	269.44	
	2006/4/10	629.58	629.58	13.900	5.080	8,751.16	3,198.27	
	2007/3/5	531.8	27.08	0.310	0.240	164.85	6.50	
	2007/3/6	543.5	91.14	0.340	0.200	184.80	18.23	
	2007/4/10	467.4	26.58	0.140	0.090	65.44	2.39	
	2007/6/5	625.0	426.00	0.112	0.060	70.14	25.56	
	2007/8/7	420.0	86.40	0.094	0.030	39.44	2.59	
Total		–	–	–	–	9,998.41	3,522.98	64.76
Dry weather (point source)	2006/2/16	608.57	608.57	0.260	0.170	158.23	103.46	
	2006/3/28	611.42	611.42	0.200	0.070	122.28	42.80	
	2006/4/17	198.52	198.52	0.400	0.160	79.41	31.76	
	2006/4/20	192.31	192.31	0.740	0.080	142.31	15.38	
	2006/9/12	559.3	183.80	0.110	0.090	61.52	16.54	
	2006/10/3	587.4	118.69	0.230	0.080	135.10	9.50	
	2006/12/5	399.0	107.13	0.100	0.050	39.90	5.36	
	2007/1/11	576.0	60.40	0.280	0.010	161.28	0.60	
	2007/1/25	516.0	78.00	0.180	0.010	92.88	0.78	
	2007/2/6	462.8	86.00	0.110	0.060	50.91	5.16	
	2007/2/26	437.0	86.00	0.420	0.040	183.54	3.44	
	2007/3/20	641.0	95.00	0.211	0.040	135.28	3.80	
	2007/4/17	627.0	104.00	0.237	0.040	148.32	4.16	
	2007/5/2	653.0	102.00	0.260	0.050	169.78	5.10	
	2007/5/9	370.9	105.88	0.230	0.080	85.31	8.47	
	2007/5/15	654.0	85.00	0.108	0.040	70.50	3.40	
	2007/6/12	733.0	147.52	0.183	0.050	133.89	7.38	
	2007/6/20	650.0	548.00	0.167	0.080	108.50	43.84	
	2007/7/3	675.0	53.00	0.108	0.040	72.76	2.12	
Total		–	–	–	–	2,151.71	313.05	85.45

Flux rate

The concept of pool system is applied to the CW site in flux rate calculations. Flux rate has the advantages of revealing the mass balance over time scale. Instead of using surface loading rate, flux rate considers the entire exposure path of pollutants inside the treatment system. Larger FR value means more pollutants are being retained in systems and less likely to flow out. The FR also gives information about the time required for purification. The average FR value of NH_3-N and TP in storm events is 0.433 0.025 g/m^2 day, respectively. The FR value is relatively small in normal day events. The value is 0.026 g/m^2 day for NH_3-N and 0.008 g/m^2 day for TP. The intercomparison of

Table 5 The average removal efficiency of NH_3-N and TP in DuNan site

Event	NH_3-N				TP			
	RR (%)	ER (%)	SOL (%)	EPM[a] (%)	RR (%)	ER (%)	SOL (%)	EPM[a] (%)
Storm	48.6	62.4	64.8	–	74.4	83.4	90.8	–
Dry weather	58.3	–	85.5	–	43.6	–	78.6	–
Average	53.5	–	75.2	65.2	59.0	–	84.7	45.6

[a]The percent rate is calculated by the cumulative probability of 50% in EPM diagram

pollutant types shows that the treatment amount of NH_3-N is much higher than TP as there was more NH_3-N initial concentration. However, the FR values do not provide insights into the treatment efficiency of each pollutant type. The FR only gives the information about the treatment capacity of NTSs and is beneficial for site design but does not provide a relatively comparison between pollutants removal.

Effluent probability method

As shown in Fig. 5, the EPM graphical figure provides probability information of efficiency in terms of pollution concentration. The method is based on the assumption that the rank of pollution concentration in influent is consistent with that in effluent and a parallel curve is then formed. The EPM results (excluded outlier samples) indicate

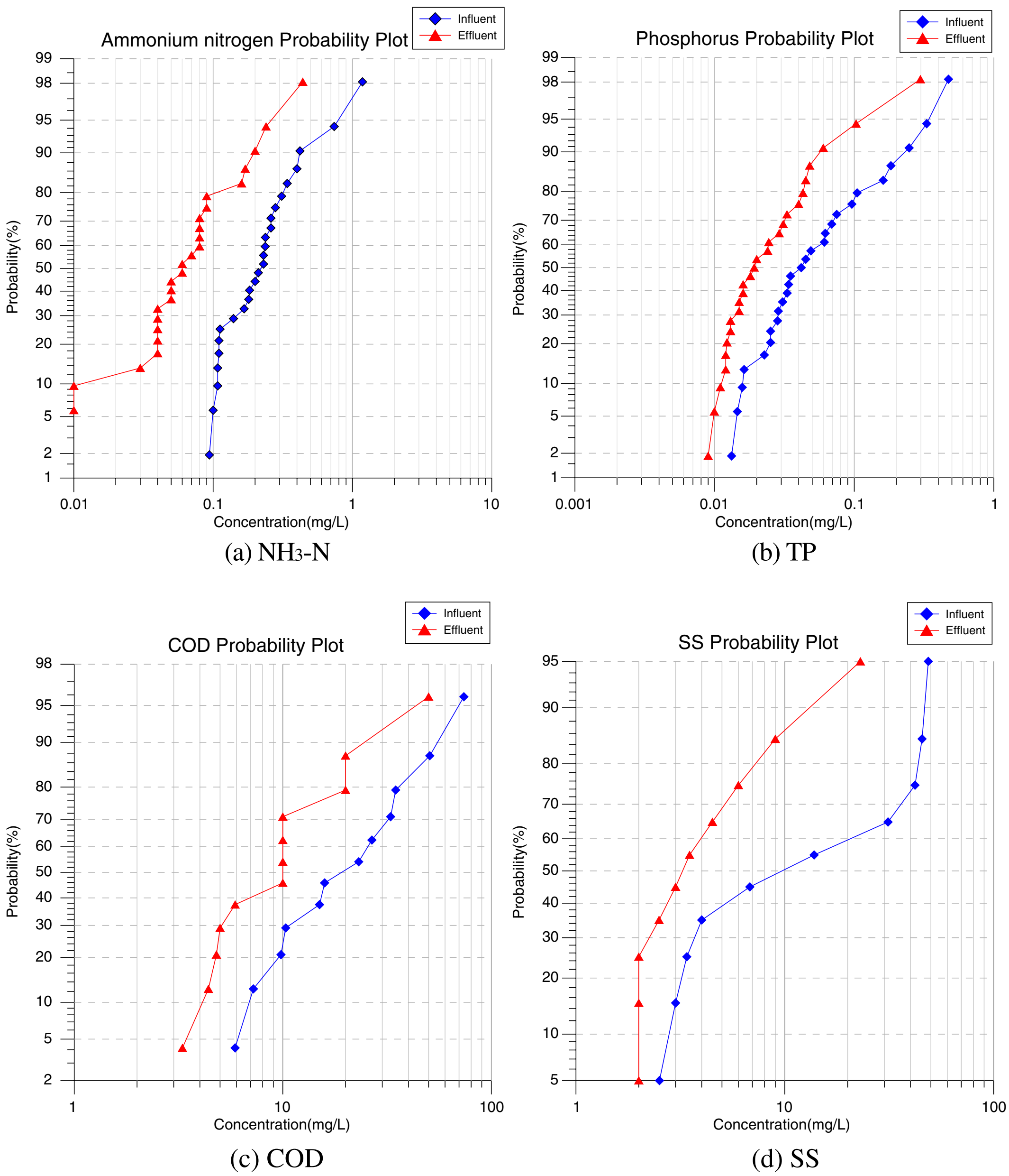

Fig. 5 **a–d** The EPM of water quality observed in DuNan site (excluding outlier value)

Table 6 Comparisons of the efficiency assessment approach

Measures	Flow data needed	PS/NPS application	Infiltration effect	Illustration of data distribution
RR	No	Both	Low	No
ER	Yes	NPS only	Low	No
SOL	Yes	Both	High	No
FR	Yes	Both	High	No
EPM	No	Both	Low	Yes

that the four pollutants were removed efficiently from the study site. The effluent concentrations are all lower than influent concentrations. The NH_3-N plot shows better removal efficiency for influent concentrations ranging from 0.1 to 1 mg/L and decreasing removal efficiency with increasing influent concentration (Fig. 5a). The removal efficiency of TP pollution is relatively consistent. The removal rates of TP in low influent concentrations are less than those in high concentrations. The same phenomenon is observed in SS data as well. In addition, the average percent removal rate can be calculated from the cumulative probability of 50%. For example, the influent and effluent of NH_3-N is respectively 0.23 and 0.08 mg/L at cumulative probability of 50% and the removal rate is 65.2%, which can be used as representative value. Similarly, the removal rate of TP is 45.6% in EPM result. Table 5 gives the summary of the average removal efficiency results.

Summary of the use of the different measures

Many approaches can be used to assess pollution removal efficiency. However, there is no "cookbook" approach to the use of these measures. Selecting methods is often intuitively and arbitrarily, depending on limited available information. To facilitate the understandings of these measures, their properties are summarized in Table 6. The properties are categorized into four terms, i.e., flow data, PS/NPS application, infiltration effect, and illustration of data distribution. Flow data indicates the necessary of flow data in the site. For example, RR is calculated only by the water quality of influent and effluent; therefore, flow data is not needed. PS/NPS application stands for the application for either PS or NPS. All these measures can be used in both PS and NPS removal assessment with the exception of ER, which is only for NPS. Infiltration serves as one of the removal mechanisms in NTS facility. Thus, the performance assessment would be affected significantly by the level of field infiltration, especially for those measures accounting for the infiltration into calculation process, such as SOL and FR. Among the five measures, only EPM with graphical illustration is able to show data distribution instead of an average deterministic rate. With the four indicators, based on available site information, users can easily select the appropriate (or multiple) measure to implement performance assessment.

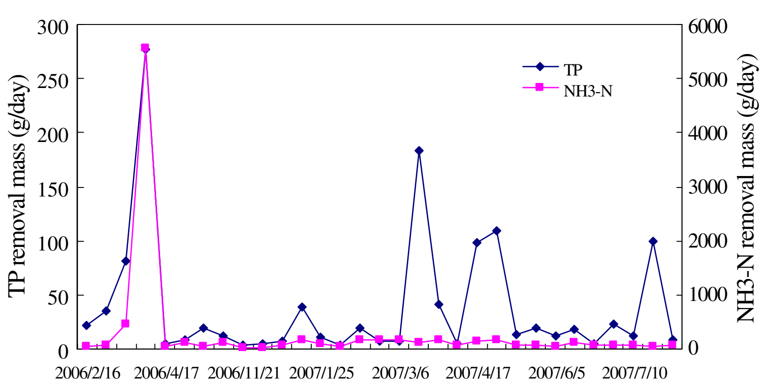

Fig. 6 Removal mass of NH_3-N and TP in monitoring period

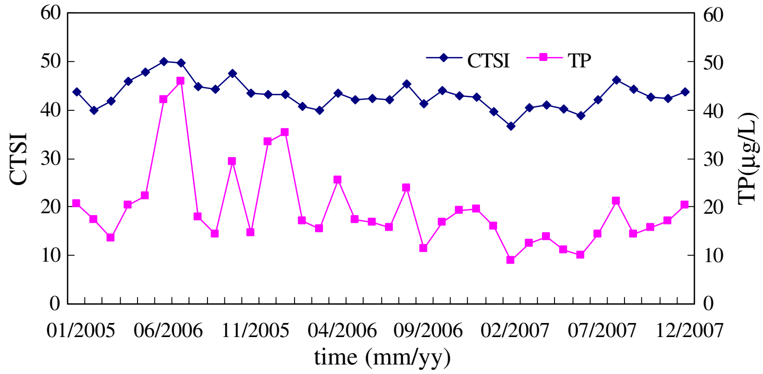

Fig. 7 Water quality in Feitsui Reservoir in recent 3 years

Water quality improvement in Feitsui Reservoir

Based on the actual observations in DuNan site, the removal nutrient mass is shown in Fig. 6. The scale on the left column of Fig. 6 shows the removal mass for TP and the right scale for NH_3-N. The average removal mass of NH_3-N and TP in the monitoring period is 281.0 and 39.1 g/day, respectively. In other words, the average annual removal pollutions are estimated as 103 and 14.3 kg/year for NH_3-N and TP, respectively. In the first month, the RR of TP is 37.5% but increases to 46.5% because of regular maintenance. However, the system performance reduced to 38.2% after 11 months. Due to the lack of good maintenance, the removal efficiency is unstable between the third to the 11th month. Once the DuNan site is reconditioned at the 12th month, the RR of TP recovered to 47.4% and the phosphorous removal quantity increased from 16.57 to 25.21 g/day.

Figure 7 shows the change of TP and Carlson Index (CTSI) of Feitsui Reservoir from the year of 2005 to 2007. The eutrophication level improved gradually throughout the 30 months. The average of CTSI is from 45.18 in 2005 to 41.51 in 2007 and the average of TP is from 24.34 to 14.64 μg/L through the 3 years. According to Chou et al. (2007), the average annual TP loading into the Feitsui Reservoir is 18,910 kg/year. It implies that 0.07% of total TP is removed from the DuNan system.

The improvement of water quality in Feitsui Reservoir is definitely contributed by various efforts, such as expanding the sewage system and best management practice for nonpoint source pollution control. The surface area of DuNan site is about 0.3 ha (2,953 m^2) and is not possible to remove significant pollutants from the whole watershed (the total area is 303 km^2). Based on the sampling data, the treatment efficiency per treatment area is estimated about 343.3 kg/ha per year of NH_3-N and 47.7 kg/ha per year of TP. Therefore, if all TP pollution is desired to be removed from Feitsui Reservoir by NTS systems, the treatment areas need about 400 ha. However, application of NTS is not the only way to control pollutions. Limited by the available site and the cost, structural and non-structural BMP should be considered simultaneously to improve reservoir water quality.

Conclusions

This study demonstrates a full-scale natural treatment system with a 2-years of monitoring. The system was designed primarily to purify polluted stormwater runoff from tea gardens and to ease the increasing eutrophication in the Feitsui Reservoir. In addition to nonpoint source pollution, domestic wastewater is also treated in the site. From field observation, the study site demonstrated nice treatment ability in either nonpoint source or point source pollution. However, due to the different types of treatment ponds (with varying dimensions), types of vegetations, influent sources, storm conditions, etc. incorporated into this particular NTS, it is difficult to evaluate its performance efficiency. Different measures applied to a single site would lead to varying conclusions. In order to obtain an unbiased assessment, five measures are applied in this study. They are removal rate (RR), efficiency ratio (ER), summation of loads (SOL), flux rate (FR), and effluent probability method (EPM). The RR and ER are concentration percent removal approach utilizing direct pollution concentration and event mean concentration (EMC). The SOL is a mass percent removal measure. The FR is a new measure explored in this study to consider exposure path of pollutants throughout the treatment system, and EPM is strongly recommended for BMP evaluation by USEPA (2002). The different measures result in difference by as much as 25% (average TP results).

This study is not aimed to rank the preferability of the measures but to provide insight about the use of these assessments, including the calculation, data input, sampling time, and the final expression. The selection of efficiency measures are basically dependant on the site conditions and project requirements. The percent removal of RR is the simplest measure with minimum data requirement. If a complete set of flow data is available, ER and SOL provide more objectively results. If the mass retaining ability is considered, the FR provides supplement information for site design or retrofit. However, regardless of the measure used, regular maintenance is key factor for a NTS performance. A good operation and maintenance schedule would be very helpful to extend the lifetime and the treatment capacity of a NTS facility. The guidelines of a good maintenance and inspection can be found in USEPA website, e.g. the USEPA Stormwater Control Operation and Maintenance database (USEPA 2006).

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