Effect of sampling duration on the performance evaluation of a stormwater wetland

Siping Niu, Kisoo Park and Youngchul Kim

ABSTRACT

In this study, the effect of sampling duration on the performance estimate for a stormwater wetland over both rainy and dry days was evaluated for the appropriate design of sampling duration. As the cumulative percentage volume (V_p), the ratio of cumulative stormwater volume concerning time to the total stormwater volume, varied between 60 and 100%, generally, the inflow total suspended solids, turbidity and total chemical oxygen demand (TCOD) event mean concentrations (EMCs) did not vary significantly, whereas the total nitrogen (TN) and total phosphorus (TP) EMCs were relatively stable. Compared to the inflow, the corresponding outflow EMCs changed much less as V_p changed. And these variations both from inflow and outflow EMCs did not result in significant changes in the removal efficiencies. The investigation during the dry days between two consecutive storm events showed that outflow pollutants did not change to a considerable extent after 1 day of the previous rainfall event. This study identifies the possibility of shortening the rainy sampling duration, because the performance of stormwater wetlands is usually estimated based on removal efficiencies rather than pollutant concentrations. Also, the sampling during dry days should be performed at least 1 day after a rainfall event.

Key words | base flow, constructed wetland, consecutive rainfall events, stormwater, sampling duration

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INTRODUCTION

Non-point source (NPS) pollution such as stormwater runoff is now the leading contributor to the pollution of receiving waters (Lee *et al*. 2007; Yu *et al*. 2012). In response to this, numerous best management practices (BMPs) have been proposed and implemented to decrease the spread of the NPS pollution worldwide (Otto *et al*. 2008; Yu *et al*. 2013). As one of the important BMPs, stormwater wetlands have been widely constructed to control NPS pollution both in impervious and pervious areas (Smith *et al*. 2000; Li *et al*. 2009).

Usually, the BMPs are required to provide specific pollutant removal efficiency (e.g. 80% total suspended solids (TSS) reduction) (Balascio & Lucas 2009; Yi *et al*. 2010), and a comparison between BMPs is also made by removal efficiency. Therefore, researchers often want to determine the efficiency of the BMPs (USEPA & ASCE, 2002). The removal efficiency of a wetland treating wastewater can be easily obtained using grab sampling, because the flow rate and pollutant concentration of waste water are relatively constant. However, for a wetland receiving stormwater, it has to be obtained based on event mean concentrations (EMCs) which are equal to the flow-proportional average concentration, and on composite sampling, because of the significant variation in the flow rate and concentration with respect to time during the rainfall events (Griffin 1995; Heaney & Lee 2006). Unfortunately, there is no specific guideline for the duration of composite sampling. It is usually performed based on a hydrograph together with a minimum sampling number (Leecaster *et al*. 2002), and monitoring is suggested to be terminated when flow reaches the base flow value (Kadlec & Wallace 2008), i.e., the flow rate prior to the rainfall event. In this regard, collecting sufficient flow number samples is labour intensive, expensive and time-consuming (USEPA & ASCE, 2002; Park *et al*. 2009). Several studies have been performed to improve the sampling design for stormwater monitoring. Leecaster *et al*. (2002) identified that the amount of detectable trend in the mass emissions and concentration was

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determined for sample sizes of 3 and 7, and single storms were most efficiently characterized (small bias and standard error) by taking 12 samples following a flow-interval schedule and using a volume-weighted estimator of mass emissions. Lee *et al*. (2007) tried to use grab samples in lieu of flow-weight composite samples. According to their study, averaging 12 grab samples is a much better estimate of the EMC, but can still result in error. They also provided an alternative strategy, which may result in lower overall cost with improved accuracy and variability in the mass emissions by selecting a subset of sites from each monitored category using a flow-weighted composite sampler. However, these efforts were mainly focused on decreasing the sample number rather than sampling time and few studies were performed toward sampling for BMP evaluation.

Moreover, stormwater runoff can be stored temporarily in the wetland and then may subsequently be released. Therefore, even though the hydrology in the dry days reaches the condition prior to the rainfall, the pollutant behaviour with respect to time over dry days is also a determining factor for the performance evaluation (USEPA & ASCE, 2002).

In this study, based on the assumption that the monitoring was completed when inflow reached the base flow value, the performance of a stormwater wetland with respect to percentage volume (V_p) varying with the sampling duration time was investigated; and the variation of pollutant concentration during the dry days between two consecutive rainfall events was detected.

MATERIALS AND METHODS

Site description

The studied wetland, covering 3,500 m^2, was built in Jeongeup City, the Republic of Korea. It was one of the national BMP sites installed as a demonstration facility, reducing NPS pollution from a watershed area of ~ 64 ha in Keum River Basin. The wetland components include a settling pond, intermittent mechanical aeration pond, deep and shallow marshes, and a polishing pond (Figure 1). The size and macrophyte information of the components is listed in Table 1. Aeration was controlled by the operation of circuits, with 3 h on followed by 3 h off.

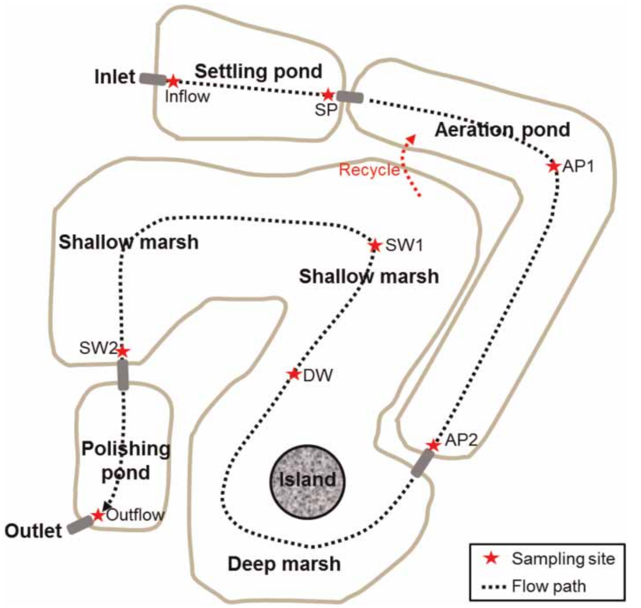

Figure 1 | Investigated stormwater wetland.

Sampling and sample analysis

During rainy days, inflow and outflow samples were collected beginning at the initiation of the rainfall event and ending when the flow receded to the dry weather level, even though there is a delay between the initiation of the rainfall and the

Table 1 | Characteristics of the stormwater wetland system

Item	Settling pond	Aeration pond	Marsh wetland	Polishing pond	Total
Surface area (m^2)	288	600	1,892	243	3,023
Surface area percentage (%)	9.53	19.85	62.59	8.04	100
Mean water depth (m)	1.2	1.2	1.4	1.53	1.31
Volume (m^3)	351	708	2,592	373	4,024
Volume percentage (%)	8.72	17.59	64.41	9.27	100
Macrophytes	*Petroselinum crispum* var. *neapolitanum*	*Phragmites australis*	*Phragmites australis, Typha latifolia*	*Nelumbo nucifera*	

initiation of the inflow. The grab sampling method and flow composite strategy were used. The number of samples and sampling frequency was set by the rainfall depth, intensity and duration. The flow depth and velocity were measured to determine the flow rates. The flow velocity was measured using a flow meter (Global Water FP101). Moreover, continuous sampling between the consecutive rainfall events was performed to investigate what possibly occurred during the dry days. The sampling interval was 10 h.

The TSS, total chemical oxygen demand (TCOD), total nitrogen (TN), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), and total phosphorus (TP) of the water samples were analyzed following *Standard Methods for the Examination of Water and Wastewater* (APHA *et al.* 1995).

Data analysis

Based on the assumption that monitoring was completed when base flow was reached, the performance of stormwater wetland with respect to V_p was investigated. And the inflow and outflow EMCs and removal efficiencies corresponding to V_p of 60, 70, 80, 90 and 100% were pursued. The flow volumes, EMCs and removal efficiencies were calculated using the following equations:

$$V_t = \int Q_t \mathrm{d}t \quad (1)$$

$$\mathrm{EMC} = \frac{\int Q_t C_t \mathrm{d}t}{\int Q_t \mathrm{d}t} \quad (2)$$

$$\text{Removal efficiency } (\%) = \frac{\mathrm{EMC_{in}} - \mathrm{EMC_{out}}}{\mathrm{EMC_{in}}} \quad (3)$$

where C_t is the concentration of the pollutant (mg/L) corresponding to time t, and $\mathrm{EMC_{in}}$ and $\mathrm{EMC_{out}}$ are the inflow and outflow EMCs, respectively.

The paired-sample test and Pearson correlation analysis were employed to detect the difference and relationship between water parameters, respectively. All statistical analyses were performed using SPSS software (Version 11.5 for Windows).

RESULTS AND DISCUSSION

Hydrology of the investigated stormwater events

The variations in the inflow and outflow rates from the studied wetland connected to time are shown in Figure 2. For the investigated events, the duration between the flow rates starting to ascend and completely returning to the base flow varied from <10 to 31 h for both the inflow and outflow. Moreover, the appearance of peak rate of inflow was prior to that of outflow. In accordance with previous studies (Kadlec & Wallace 2008), both influent and effluent rates following each peak value exponentially decreased with respect to time ($p < 0.05$). Furthermore, the outflow took more time to reach its base flow compared to the inflow. Therefore, monitoring is usually carried out based on inflow hydrology.

EMC values and removal efficiency with respect to V_p

Mainly because of the first flush on the influent side, the inflow EMC and removal efficiency varied significantly depending on the pollutants as V_p was <60% (not shown here). The changes in the inflow and outflow EMCs as well as the removal efficiency concerning the V_p, which is ≥60%, are shown in Figures 3 and 4.

Compared to the true values, as V_p was in the range of 60–90% the inflow TSS EMC was similar or higher (Figure 3 (a)), whereas the outflow TSS EMC (Figure 3(b)) was similar or slightly lower. For event 1, the obvious variation in the

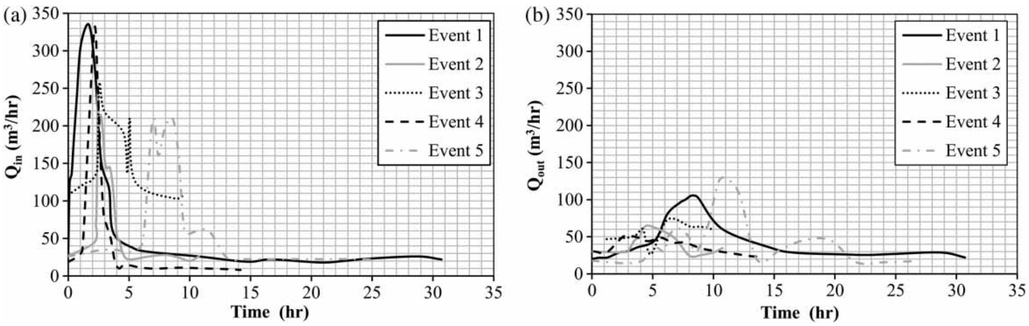

Figure 2 | Inflow and outflow rates with respect to time (Q_{in} and Q_{out} are the inflow and outflow rates, respectively).

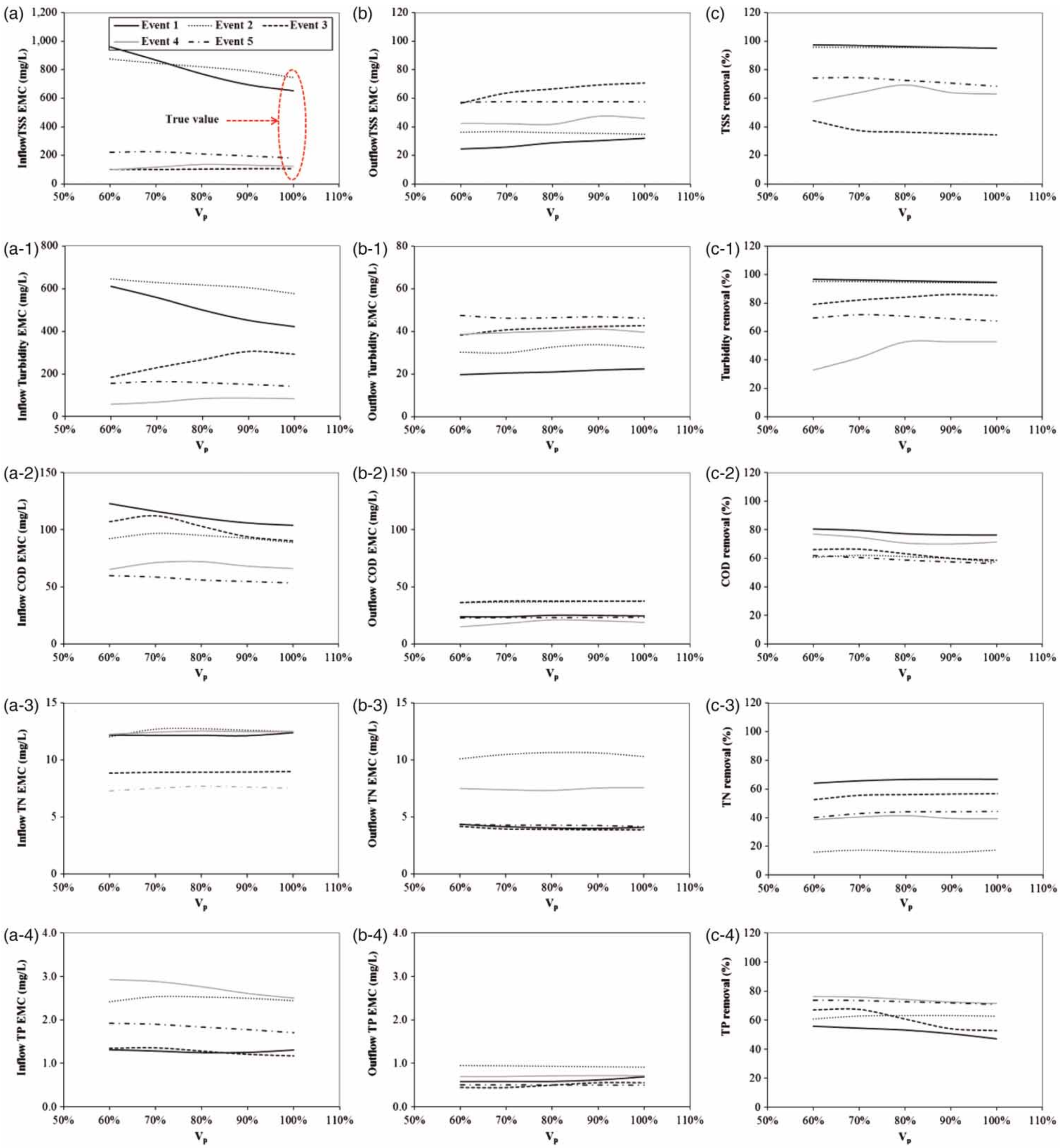

Figure 3 | Change in EMCs and removal efficiency with respect to V_p (the return of base flow of the influent was implemented as the sampling end indicator; the data corresponding to 100% are true values).

EMC with V_p occurred because the very high rainfall intensity contributed a large amount of sediment to the runoff during a short time. However, the removal efficiencies did not show any statistical difference ($p < 0.05$) even though the EMC fluctuated to some extent (Figure 3(c) and Figure 4(a)). This low vitiation of the removal efficiencies was closely related to the relatively higher inflow EMC in comparison to the outflow EMC. For example, in the case

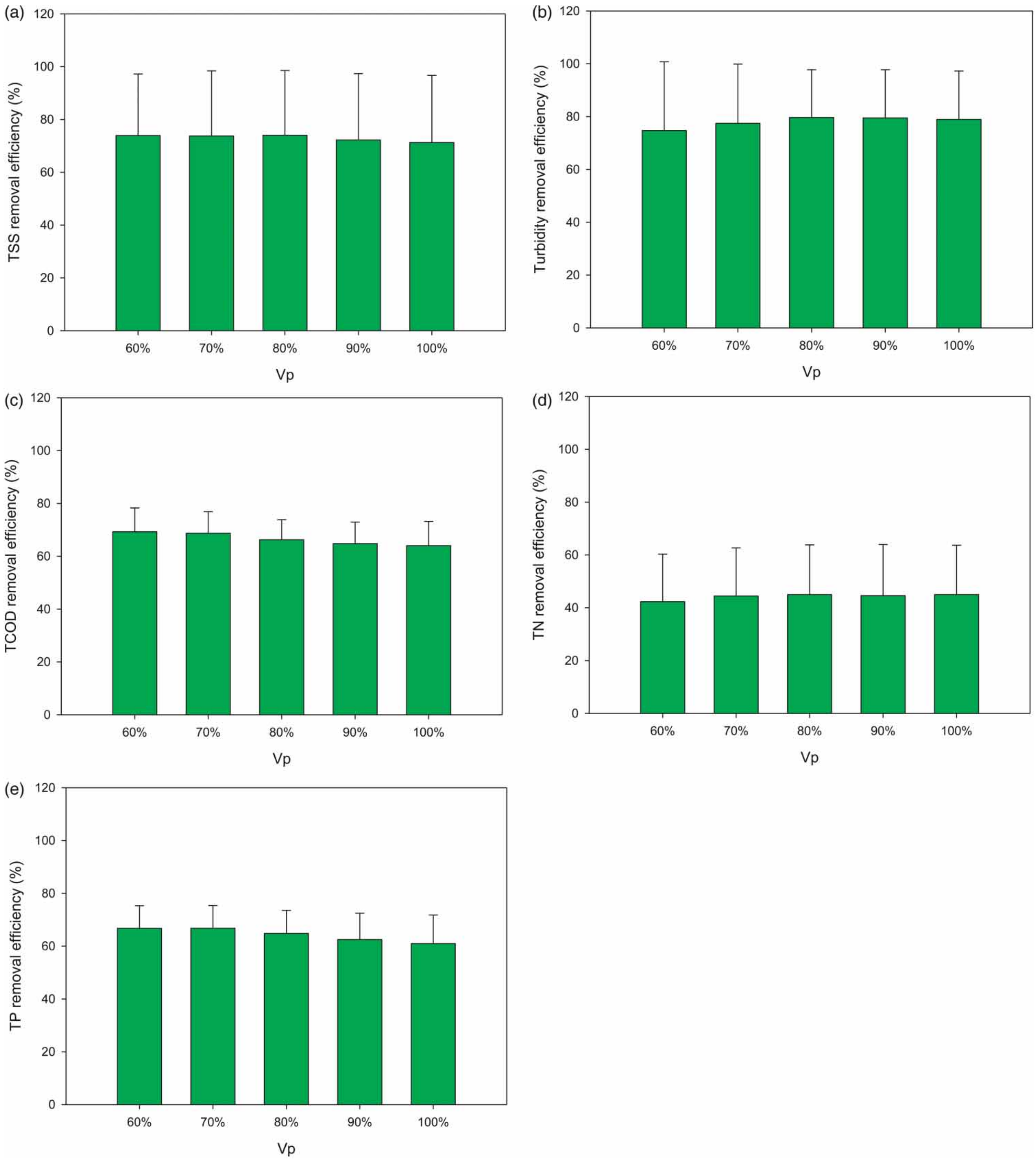

Figure 4 | Statistical analysis of EMC and removal efficiency concerning V_p.

of event 1, the ratios of the inflow to outflow EMCs with V_p of 60% and 100% were 2.6% and 4.9%, respectively, and the corresponding removal efficiencies were 97.4% and 94.1%, respectively.

The inflow turbidity EMC increased (event 3), decreased (events 1 and 2), or was relatively stable (events 4 and 5) with an elevated V_p (Figure 3(a-1)). However, the outflow turbidity did not change obviously with V_p (Figure 3(b-1)).

The removal efficiency had considerable variation as V_p changed on some occasions (Figure 3(c-1)). However, overall the removal efficiencies were stable and equal to the true values regardless of change in V_p ($P < 0.05$), especially as V_p >70%.

For the five investigated events, only the inflow TCOD EMCs of events 1 and 3 varied considerably with increasing V_p (Figure 3(a-2)). Basically, the inflow EMC was more sensitive to the inflow volume. Nonetheless, neither the outflow EMC nor the COD removal efficiencies varied significantly with V_p in the range 60–100% ((Figure 3((b-2) and (c-2)) and Figure 4(c)).

Moreover, TN and TP had a similar variation with respect to V_p. When V_p varied between 60 and 90%, the influent and effluent EMCs (Figure 3(a-3 and a-4) and (b-3 and b-4)) and their removal efficiencies (Figure 3(c-3 and c-4) and Figure 4(d and e)) were similar to the true values. Generally, as V_p increased, the removal efficiencies still changed with accepted extents, demonstrating that sampling for nutrient assessment can be completed as the inflow volume accounted for 60% of the total storm runoff.

Based on the above, the inflow EMCs were subjected to more pronounced variations than the outflow EMCs with the change in V_p partly because the removal performance is better for higher pollutant concentration. In comparison, TSS and turbidity EMC rather than COD, TN and TP EMCs in the inflow possibly fluctuated significantly with variation in V_p. The change in the EMC with V_p demonstrates the characteristics of the transport of pollutant mass related to the runoff flow. Several studies have investigated this characteristic of the stormwater from urban and agricultural areas (Bertrand-Krajewski *et al.* 1998; Luo *et al.* 2009; Kato *et al.* 2009; Lee *et al.* 2002; Vaze & Chiew 2004). Sheng *et al.* (2008) investigated the change in the cumulative mass of suspended sediment, TSS, volatile suspended sediment, TCOD, dissolved COD, and particulate COD with urban stormwater volume, indirectly indicating that the EMC did not change remarkably for V_p >50%. According to the study by Kato *et al.* (2009), pollutant species (dissolved or particle related) determine the change in EMCs with stormwater flow, and for V_p >60%, the inflow EMC did not change significantly. In this study, even though the EMC was closely related to the inflow volume for the specific event, the removal efficiencies were almost similar or equal to the true values. Therefore, the removal efficiencies were subjected to very limited variation. Usually, in practice, as manual sampling is used, it is almost impossible to wait and continue sampling until the flow rate becomes equal to the base condition because of exponential decrease after the peak flow. This study indicates that the available removal efficiency before the inflow attained the base condition was useful in estimating BMP performances. Hence, it is possible to terminate the sampling before stormwater reaches the flow rate prior to the rainfall. As for automatic sampling, we can exclude some samples and do not need to spend time and money on analyzing their water quality. Also, we can stop the sampling earlier based on the rainfall condition and historical data.

Stormwater wetlands are required to treat a water quality volume, which is generally defined as the storage required to capture runoff from a specific rainfall depth, associated with specific pollutant reduction (Wong *et al.* 1998; PUB 2011); e.g. in Singapore, the wetland is required to treat 90% rainfall events together with 80% removal or less than 10 ppm for TSS, 45% removal or less than 1.2 ppm for TN, and 45% removal or less than 0.08 ppm for TP (PUB 2011). Therefore, these findings will improve the sampling strategy for the performance of BMP assessment. However, this study has its limitations. The conclusion was obtained only based on five rainfall events. Because few rainfall events are expected to introduce more variability, we have had to make conservative estimates and therefore suspect that our recommendation would be applied. A second limitation was our ability to extrapolate our conclusions to another watershed. If the water quality changes, or if the relationship between water quality and flow were to differ, our conclusions may not be applicable. Therefore, further investigation into this study is necessary.

Occurrence between two consecutive rainfall events

The occurrence of two consecutive rainfall events was investigated, as shown in Figure 5, to pursue the design of a proper strategy for dry day sampling. Over the dry days, the hydrological condition was stable.

It was observed that TSS concentrations were stable but little higher in the outflow than in the inflow (Figure 5(b)) during dry days, indicating that particulate matter went out of the wetland. The concentrations of the TSS among the wetland components with respect to time indicated that they were partly related to the previous rainfall event during the initial several hours. Most of the time, however, the increased outflow TSS concentrations were related to the increase in the aeration pond, which was mainly attributed to the resuspension of sediments caused by the turbulence during the aeration, and this was verified by a previous study from Yu *et al.* (2012). Moreover, the increase

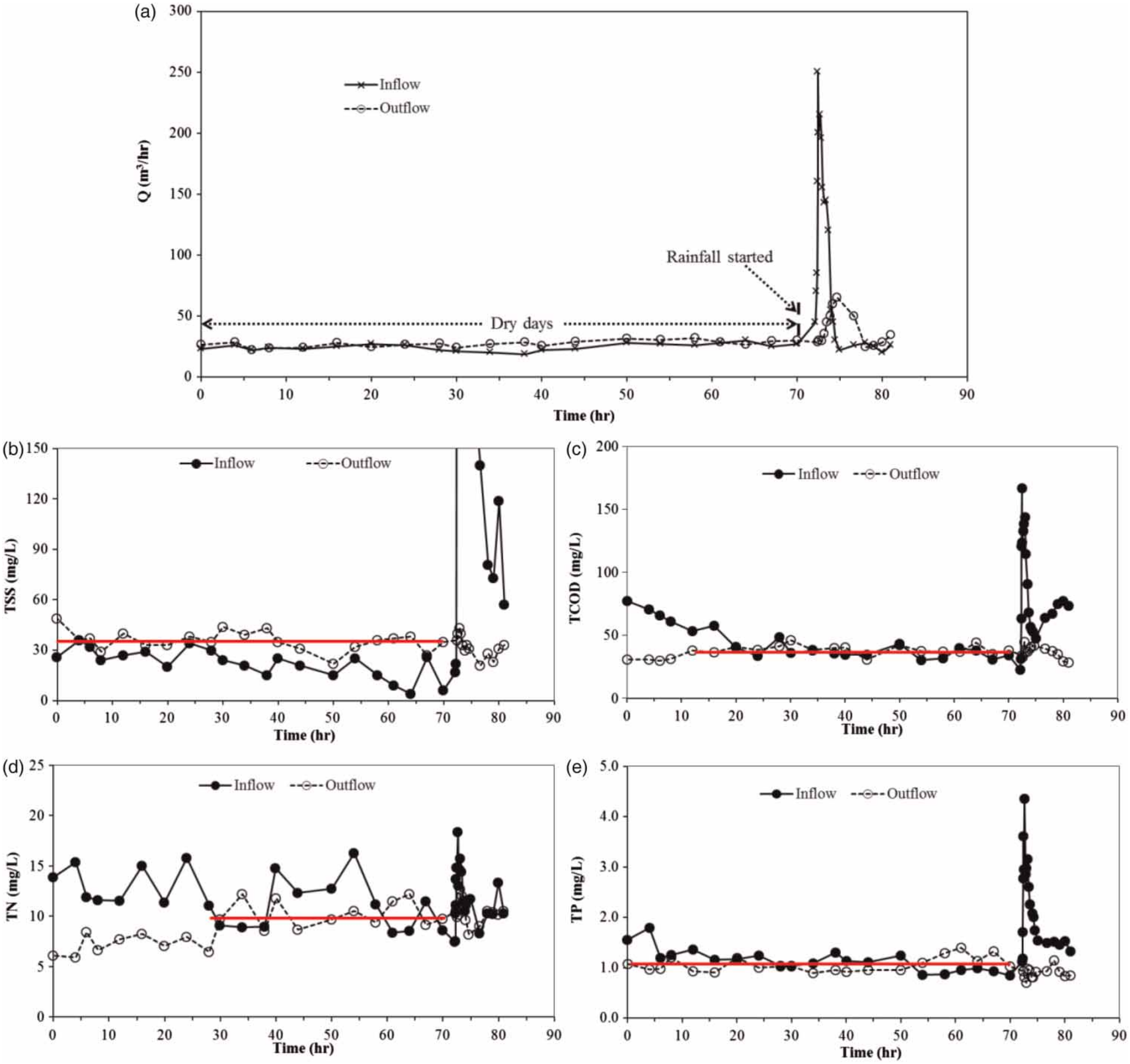

Figure 5 | Hydrological condition and selected pollutants in the inflow and outflow during the period between storm events (the time when the inflow rate reached the base flow value was set as 0).

in TSS concentration was also likely to be related to algal growth in wetlands (Li *et al.* 2009). In this study, the TSS in the wetland had a significant relationship with Chlorophyll-a (Chl-a) ($r = 0.524$, $p = 0.001$). During the studied period, as for TSS, the TP concentrations in the outflow were almost stable (Figure 5(e)). This is because the phosphorus was remarkably related to the TSS ($r = 0.840$, $p = 0.001$). Considering the variation in TSS and TP concentrations in the outflow was very small, the sampling to assess wetland performance in trapping TSS and phosphorus can be undertaken at any time during the dry days.

However, the outflow TCOD concentration first increased and then became stable during the first 10 h (Figure 5(c)). Comparing the TCOD distribution in different wetland components with respect to time, the increase in the outflow TCOD likely occurred because of the resuspension of particulate TCOD in the aeration pond and the growth of algae in the marsh pond. This can be demonstrated by the relationships between the TCOD and TSS ($r = 0.456$, $p = 0.006$) and between TCOD and Chl-a ($r = 0.409$, $p = 0.012$). So, this result suggests that the sampling for treatment performance evaluation over dry days should be carried out after 1 day of the rainfall event.

Similar to TCOD, the outflow TN concentrations also gradually increased and then was stable after around 30 h (Figure 5(d)), and the variation in the TN concentrations in the wetland components followed a similar trend. This increase in outflow TN concentration was mainly attributed to the continuous high nitrogen input and the limited denitrification in the dry days. For the denitrification process, a significant inhabitation appeared when dissolved oxygen (DO) >0.09 mg /L (Oh & Silverstein 1999). However, in the wetland, the DO concentration ranged from 2.5 to 5.5 mg/L, resulting in a suppressed denitrification, which can be confirmed by the change of NH_4-N and NO_3-N concentrations. Consequently, the sampling toward the wetland capacity in terms of nitrogen conversion should be conducted after 30 h.

This analysis shows that the change in the outflow TSS, TCOD, TN and TP concentrations between two consecutive rainfall events mainly took place during the initial 30 h after the rainfall events. As a result, the sampling result during the first day after the rainfall event may not be representative of dry day performance; and dry day sampling should be carried out at least 1 day after the rainfall event. It should be noted that the retention time is around 6 days.

CONCLUSIONS

This study was performed to investigate the effect of sampling duration on the performance evaluation of a stormwater wetland. Based on the results, we can draw the following conclusions.

As the cumulative percentage stormwater volume to the total event water volume varied between 60 and 100%, the EMC might change significantly, especially for particle-associated pollutants, whereas removal efficiency did not vary significantly, indicating that it is possible to shorten the sampling duration, because the performance of stormwater is usually estimated based on removal efficiencies rather than the pollutant concentrations. Moreover, consistent with previous studies, during the dry days between two consecutive rainfall events, the pollutant concentrations probably changed significantly within the initial 30 h; therefore, dry day sampling should be carried out after at least 1 day following a rainfall event. However, these results were obtained just based on the investigation on of several rainfall events. Therefore, further study for detailed investigation and to figure out how to decrease the rainy sampling duration should be undertaken.

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