The influence of external conditions on runoff quality control of grass swale in Beijing and Shenzhen, China

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Abstract

This study focused on the effects of external conditions on the performance of grass swales installed to improve stormwater runoff quality. Four grass swales in Beijing and Shenzhen with different underlying surface characteristics, antecedent dry weather period (ADWP), transport within the grass swales, and rainfall characteristics, were compared during 16 rainfall events in Beijing and six in Shenzhen, and were evaluated over two years. The results revealed that the impervious fraction of the catchment's surface below the swales influenced inlet pollutant concentrations, resulting in variations in their efficiency. ADWP, transport within the swales, and rainfall characteristics all had important effects on their efficiency in removing pollutants. With high pollution loads, long ADWP, and concentrated influent, the swales reduced pollutant concentrations significantly, particularly suspended solids.

Key words: antecedent dry weather period (ADWP), grass swale, pollutant removal efficiency, rainfall characteristics, surface characteristics

INTRODUCTION

Urban stormwater problems have become increasingly complicated as urbanization has modified the hydrologic cycle. Conventional stormwater management, which relies on rapid drainage, cannot reduce runoff volume or pollution effectively. Many new stormwater management techniques have therefore been developed worldwide, and low impact development (LID) has been recommended as an innovative solution for stormwater management (Baek et al. 2015; Hu et al. 2017; Montalto et al. 2007; Palhegyi 2010). The use of grass swales is an LID practice applied widely to reduce runoff volumes and the impact of non-point source pollution from stormwater runoff on the environment. Grass swales have increasingly been used to provide primary treatment for road runoff and been integrated into existing project retrofits, and represent a simple, aesthetically pleasing technique for conveying runoff along a linear system (Davis et al. 2012; Leroy et al. 2016; Li et al. 2016).

Grass swales are shallow, grass-lined, typically flat-bottomed channels that produce positive results in stormwater runoff improvement by filtration, infiltration, and biological processes (Li et al. 2016). Several studies have shown that they can remove suspended solids (SS) successfully. However, intense rainfall with the potential to re-suspend settled particles can increase SS concentrations in

the discharge from grass swales. Investigations of the effects of grass swales on total phosphorus (TP) and nitrogen (TN) show that pollutant removal efficiency can be influenced by both the vegetation and its fertilization, which can increase nutrient loads in grass swale effluent while decreasing the pollutant removal efficiency (Li et al. 2016; Line et al. 2008; Luell et al. 2011; Stagge et al. 2012).

The effectiveness of grass swales depends on many factors, including design parameters (longitudinal slope, side slope, and length), underlying surface characteristics, antecedent dry weather period (ADWP), and rainfall characteristics (rainfall duration and intensity, and total rainfall depth). Of these, ADWP is key in determining grass swale infiltration capacity and the pollutants deposited on the underlying surface. Rainfall characteristics are directly associated with the efficiency of washing pollutants from the underlying surface and variations in the discharge from grass swales. The underlying surface characteristics, the manner that runoff flows into the swales, and the transport of runoff within them, can all create different pollutant loads and pollutant removal efficiencies that affect receiving waterways and water bodies. Accordingly, the effects must be studied of all four factors on pollutant concentrations in grass swale outlets and overall removal efficiency.

Previous studies have shown that the underlying surface characteristics are one of the most important factors influencing urban stormwater quality (Gunawardena et al. 2010; Liu et al. 2012; Liu et al. 2014), and influence pollutant removal efficiency by grass swales. The underlying surface characteristics' primary impact is on the surface pollutant loads washed off by the runoff. Some studies have indicated that increasing the pervious fraction of grass swale catchment can reduce pollutant concentrations, while enhancing the efficiency of pollutant removal by grass swales (Charlesworth et al. 2012; Bouchard et al. 2013; Leroy et al. 2017). Liu et al. (2013) demonstrated that different underlying surface characteristics led to different pollutant removal efficiencies, and also reported lower removal efficiency for TSS in residential areas than industrial areas.

The duration of an ADWP is unpredictable and varies naturally between storm events. It is another important factor influencing grass swale efficiency in pollutant removal. ADWPs can influence the grass swale topsoil's runoff holding capacity so that pollutant removal efficiency differs between long and short ADWPs (Stovin 2010). With longer ADWPs, grass swale influent pollutant concentrations are higher, resulting in greater pollutant removal efficiency (Tiefenthaler et al. 2003; Bian 2009). However, the relationship is not always obvious (Li et al. 2007).

The manners by which runoff flows into and is transported within grass swales may influence pollutant removal efficiency. The pollutant concentration in stormwater runoff transported into swales can be affected by the presence and degree of longitudinal and side slopes, and the length of grass. Some studies have shown that long swales with gradual slopes remove pollutants more effectively due to the increased time available for settling and the greater number of infiltration sites (Storey et al. 2009; Hood et al. 2013).

Rainfall characteristics can also influence pollutant removal efficiency. Shaw et al. (2010) noted that, in relatively low intensity rainfall events, only a fraction of the pollutants will be removed as stormwater runoff moves through a grass swale. In the initial phase of rainfall, pollutant removal is closely related to rainfall depth and duration, whereas, in later phases, it is influenced primarily by rainfall intensity (Alias et al. 2014). The first flush can significantly influence pollutant removal efficiency (Bach et al. 2010).

Although the effects of the first flush and design parameters on grass swale performance in improving runoff quality have been widely demonstrated, only a few studies have considered the effects of the underlying surface characteristics, ADWP, the manner that runoff enters and is transported within the swales, and rainfall characteristics, on the efficiency of pollutant removal in residential areas and parks. Moreover, although grass swale performance has previously been studied in China, few studies have focused on the influence of these conditions on pollutant removal efficiency. This study was designed to evaluate the efficiency of pollutant removal by grass swales in Beijing and Shenzhen,

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China, while considering the influences of underlying surface characteristics, ADWP, the ways in which runoff enters and is transported within grass swales, and rainfall characteristics.

MATERIALS AND METHODS

Study sites

Four grass swales in two areas of Beijing and Shenzhen, China were investigated. The first is in the Oriental Sun City Swale (OS), Beijing, which receives most of its runoff from residential roadways. It has greenbelt on both sides and is in the northeastern section of a residential building district. The other three swales, designated NS-a, NS-b and NS-c, are in New District Park, Guangming New District, Shenzhen, Guangdong. They receive runoff from comparable roadway areas.

Residential land use in Oriental Sun City comprises townhouses, roads, roofs, driveways, and greenbelt, with gentle slopes and pervious areas near the grass swales. The road surfaces are relatively flat and traffic volumes are relatively high.

Land use in New District Park consists of roads, hills and greenbelt, with the roads and hills corresponding to the grass swales. Traffic volumes are high and the road surfaces relatively steep. The swale parameters are given in Table 1.

Table 1 | Grass swale parameters

Grass swales	Length (m)	Top width (m)	Bottom width (m)	Depth (m)	Catchment area (m^2)	Side slopes	Longitudinal slope (%)
OS	69	1.30	0.25	0.30	384	1:2	0.5
NS-a	51	1.14	0.30	0.32	230	1:1.3	0.2
NS-b	67	1.11	0.30	0.30	256	1:1.3	0.4
NS-c	44	1.00–1.20	0.25–0.30	0.34	310	1:1	0.2

Beijing is in northern China, with a mean annual precipitation of 600 mm and mean annual evaporation exceeding 1,600 mm. About 75% of the rainfall occurs from June to August. However, Shenzhen is in southern China with a mean annual precipitation of 1,933 mm and evaporation of 1,614 mm. The majority of Shenzhen's precipitation falls from April to September.

All grass swales were planted with tall fescue, and the topsoil used in the swales was classified as sandy loam and clay loam in the Beijing and Shenzhen areas, respectively.

Sampling protocol and analytical methodology

Sampling at OS was conducted between June 2012 and October 2013, and 16 rainfall events were monitored. The NS sites were monitored from June to September 2012, when six rainfall events occurred. Of the 16 events in Beijing, four produced a measurable discharge from OS, the water from the other events was completely captured by the swales. Details of the rainfall events and selected parameters for all grass swales are summarized in Table 2.

Rainfall data for Shenzhen and Beijing were recorded using a WatchDog 1120 (Spectrum Technologies, Aurora, IL, USA) and a HOBO Data Logging Rain Gauge (0.2 mm) (Onset, Bourne, MA, USA), respectively. Runoff samples from OS and NS-c were collected at the grass swale inlets and outlets, and at the mid-point of the grass swales for the other sites. Sample collection was manual using 500 mL bottles, with a sequence of 3, 5, 10, 15, 20, 30, and then 60 minutes. There were approximately 14 samples from each swale for each rainfall event, and TSS, chemical oxygen demand (COD), TP,

Table 2 | Event characteristics

Location	Date	Rainfall Duration (min)	Total Rainfall Depth (mm)	Maximum Rainfall Intensity (mm/min)	ADWP (days)
OS	21/7/2012	797	223.0	12.0	1
	2/9/2012	574	43.6	0.5	1
	28/6/2013	104	16.0	1.3	3
	4/9/2013	135	17.8	1.1	7
NS-a	17/6/2012	42	4.4	0.4	0
	6/8/2012	44	20.9	1.3	0
NS-b	21/6/2012	389	70.4	5.4	2
	5/8/2012	41	5.4	0.3	1
	6/8/2012	44	20.9	1.3	0
NS-c	30/6/2012	43	10.6	1.2	3
	21/7/2012	131	10.4	1.8	1
	25/7/2012	665	65.6	0.4	0

and TN, were determined. Laboratory analyses were conducted according to the Chinese Standard Methods (Table 3).

Table 3 | Analytical methods for determination of pollutant concentrations

Parameter	Standard Methods	Detection limit (mg/L)
TSS	Gravimetric method (GB 11901–89)	–
COD	Fast digestion-spectrophotometric method (HJ/T 399–2007)	15–1,000
TP	Ammonium molybdate spectrophotometric method (GB 11893–89)	0.01–0.6
TN	Alkaline potassium persulfate digestion UV spectrophotometric method (HJ 636–2012)	0.05

Study method

Because it was difficult to measure the flow rate through a grass swale, the pollutant load could not be calculated. Pollutant removal efficiency was calculated, therefore, based only on pollutant concentrations, and was defined as (inlet concentration – outlet concentration)/inlet concentration. It did not reflect the pollutant load removal rate and can only be used as a guide.

RESULTS AND DISCUSSION

Influence of underlying surface characteristics

The variability of TSS, COD, TP, and TN concentrations with rainfall duration for OS was evaluated (Figure 1). Most TSS, COD, and TN concentrations in the OS outlet were lower than those from nearby roads and roofs, but the TP concentrations were higher, regardless of rainfall duration (Figure 1(c)). The influent at this swale came from nearby roads and roofs. The swales were shown to have some removal efficiency for TSS, COD, and TN, but were less effective removing TP. The higher TP concentrations at the OS outlet could be due to the treatment mechanisms, which include sedimentation, adsorption, and interception by the underlying soil. When TP concentrations in the swale runoff were low or the underlying soil was TP-saturated, adsorbed phosphorus could be released from the underlying soil, increasing its concentration in the swale runoff. Leroy et al. (2016) also presented evidence that swales did not remove TP efficiently from highway runoff.
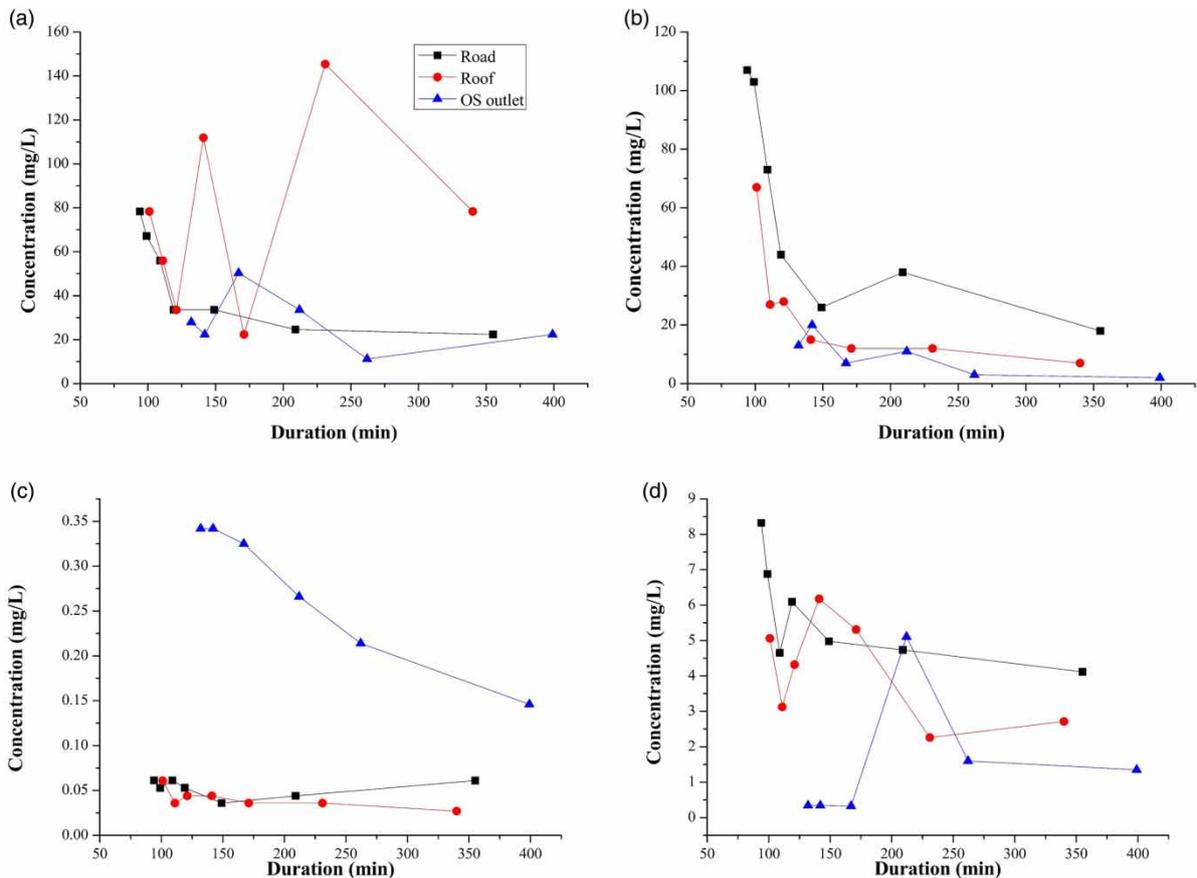
Figure 1 | Differences in underlying surface pollutant concentrations at OS with varying rainfall durations (a) TSS, (b) COD, (c) TP, and (d) TN.

The pollutant concentrations at the OS and NS-c inlets and outlets are shown in Figure 2. To investigate the influence of underlying surface characteristics on the pollutant removal efficiency of grass swales, samples with similar ADWP and rainfall depth were analyzed. As shown in Figure 2, the NS-c inlet and outlet concentrations generally exceeded those at OS, but NS-c removal efficiency was lower than OS. The OS catchment has a relatively low impervious fraction (84.2%) that at NS-c is higher (96.2%). The pollutant removal efficiency of the grass swales seems to decrease as the impervious surface fraction increases, which differs from the conclusions of other studies (Winston *et al.* 2010; Winston *et al.* 2011). However, it should be noted that the two rainfall events used for analysis have different rainfall durations. Rainfall duration may affect the pollutant removal efficiency of the grass swales as well as the impervious surface fraction, which may lead to deviations in monitoring results. During the monitoring period, there were no rainfall events with similar rainfall depth, rainfall duration and ADWP in Beijing and Shenzhen. Therefore, in Section 3.4 of this paper, there is an analysis of the impact of rainfall duration on the pollutant removal efficiency of grass swales. Unlike the other pollutants, the removal efficiencies of TP and TN were less obviously influenced by differences in the impervious fraction around the grass swales (Figure 2(c) and 2(d)).

ADWP influence

Runoff pollutant concentrations at the OS inlet and outlet are plotted against time for four events in Figure 3. The TSS and COD concentrations follow similar trends following a relatively long ADWP. When the ADWP was from three to seven days, the TSS and COD concentrations decreased with the increased rainfall duration, but TP and TN were relatively stable. When the ADWP was one day, there
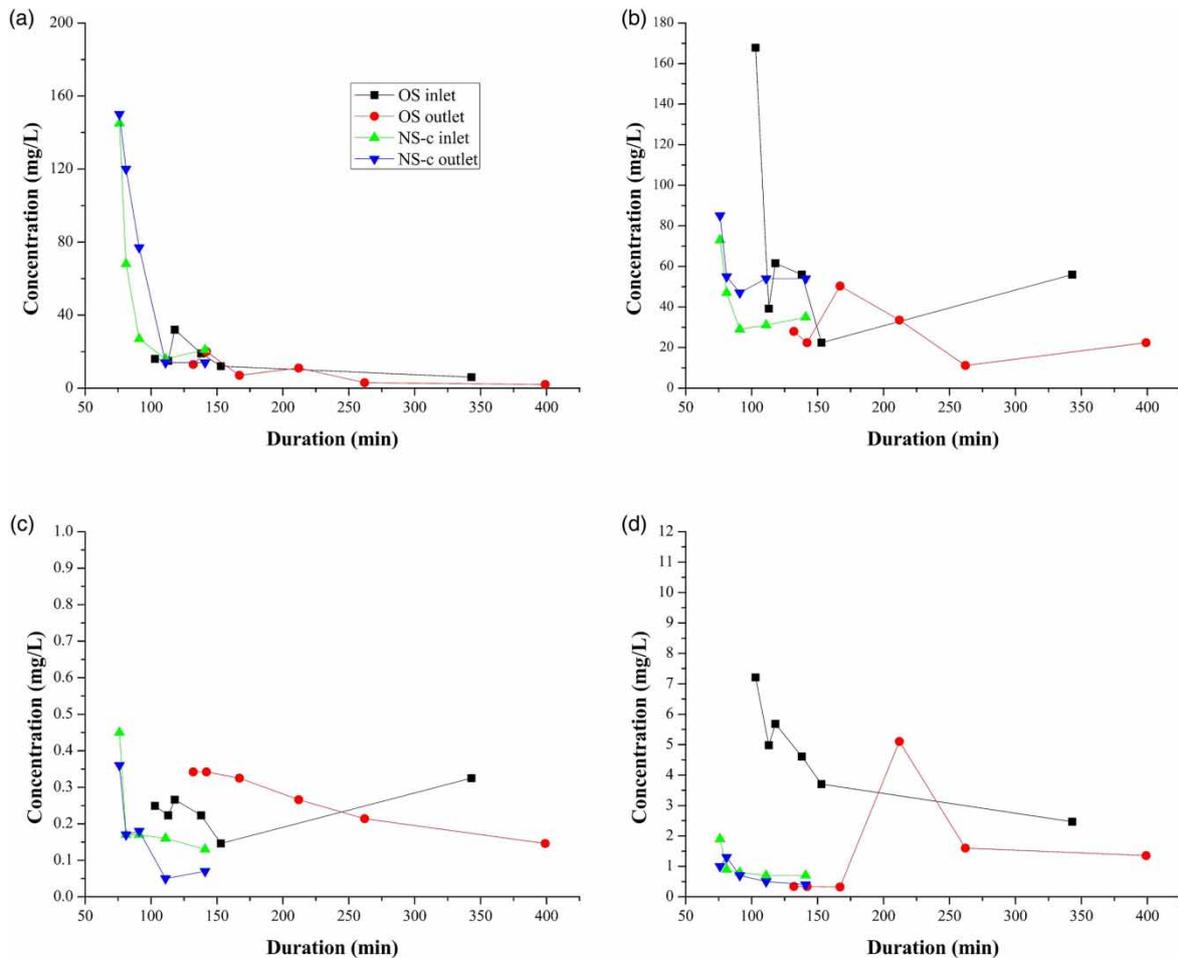
Figure 2 | Grass swale inlet and outlet pollutant concentrations at OS and NS-c (a) TSS, (b) COD, (c) TP, and (d) TN.

was no obvious COD or TSS concentration trend. ADWPs of seven, three, one and one day(s) occurred at OS on September 4, 2013, June 28, 2013, July 21, 2012, and September 2, 2012, respectively, and the grass swale influent TSS concentrations were about 500, 300, 30, and 20 mg/L. Lower concentrations were found for ADWPs of less than 1 day. Higher TSS and COD concentrations were found in the grass swale inlet after the relatively long ADWPs of September 4, 2013 and June 28, 2013, particularly in the initial rainfall phase, which led to higher pollutant removal efficiency.

The observations described above show that TSS removal efficiency fell as the ADWP decreased. Bäckström (2002, 2003) showed that rainfall events with long ADWP could generate grass swale influent TSS concentrations exceeding 100 mg/L with TSS removal efficiencies over 50%. When influent TSS concentrations at OS were below 40 mg/L, pollutant concentrations increased after the stormwater moved through the grass swale, resulting in increased effluent pollutant concentrations and decreasing pollutant removal efficiency. In Figures 2(a) and 4(c) the influent TSS concentrations at NS-c were 147 and 8 mg/L following ADWPs of one and zero days, respectively. Effluent concentrations following the two rainfall events were generally high. The pollutant removal efficiency of the swales following a one-day ADWP was higher than when the ADWP was zero. This is in agreement with previous studies, which also indicated that ADWP length could influence pollutant removal (Miguntanna *et al.* 2013). This can be attributed to longer ADWPs generating higher pollutant accumulations on the catchment's underlying surface, and raising pollutant concentrations in the grass swale influent. Moreover, Abuzreig *et al.* (2003) indicated that an important factor influencing the efficiency of pollutant removal by grass swales is the vegetation and infiltration into underlying
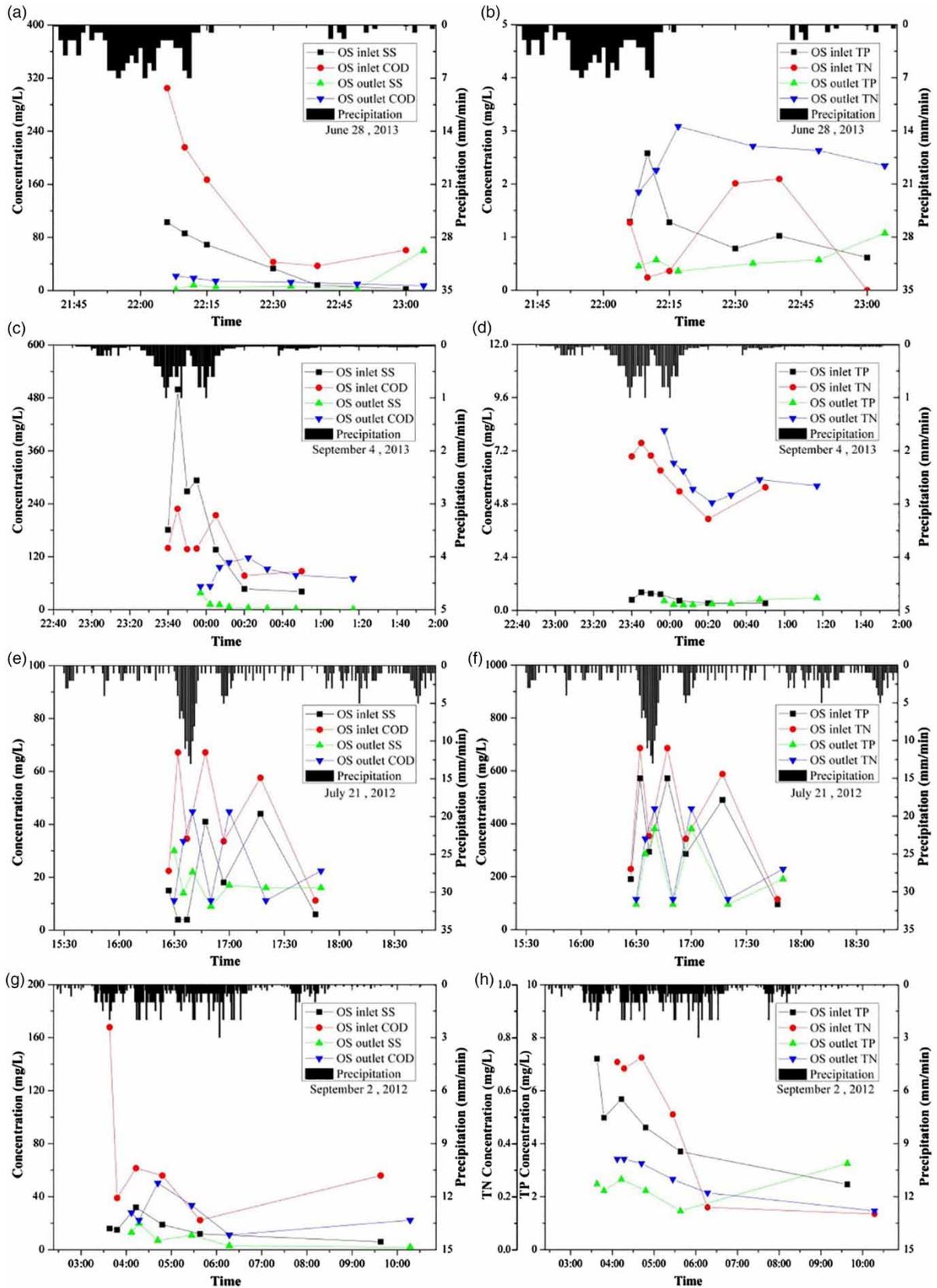
Figure 3 | Grass swale pollutant concentrations for four rainfall events at OS. (a), (c), (e) and (g) show TSS and COD; (b), (d), (f) and (h) TP and TN.
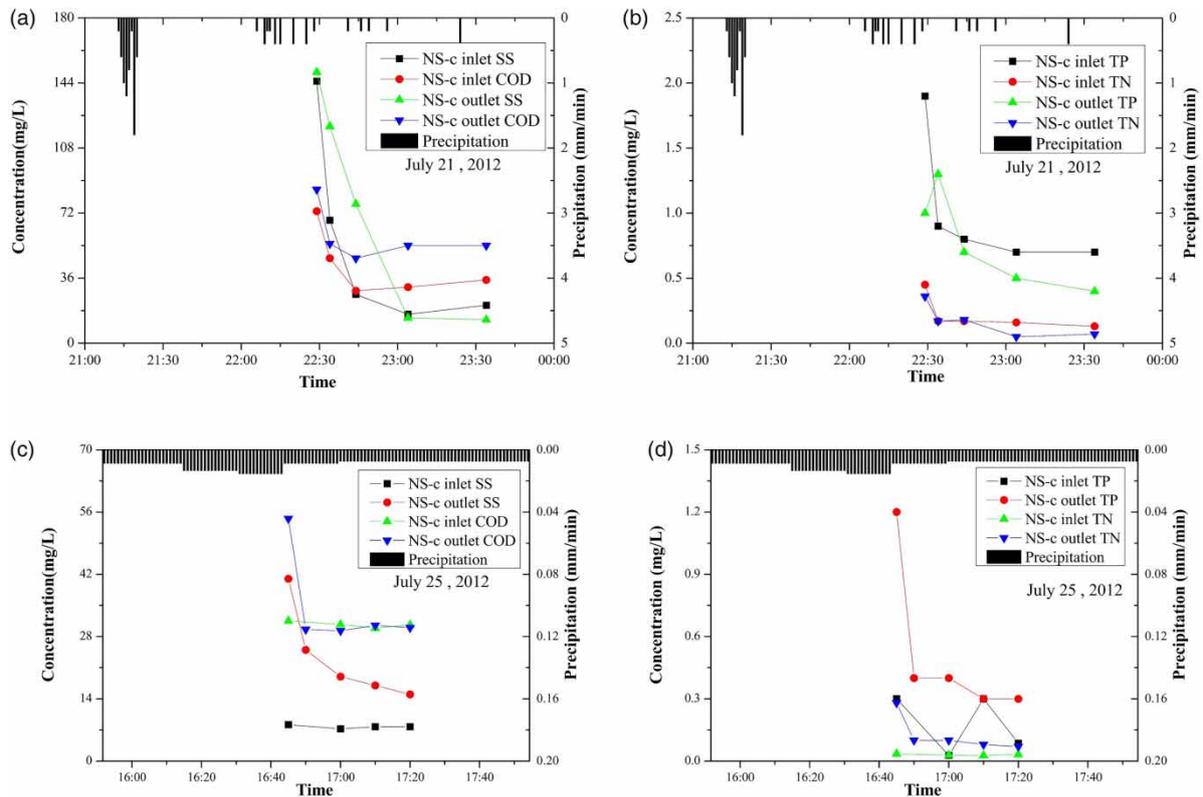
Figure 4 | Grass swale runoff pollutant concentration at NS-c inlet and outlet for rainfall events on July 21 and 25, 2012. (a) and (c) SS and COD, and (b) and (d) TP and TN.

soils. As ADWP gets longer, the removal efficiency of TSS, COD and TP increases. However, TN showed a strong fluctuation trend. The reason for the increase in removal efficiency of TSS, COD and TP was the increase in soil infiltration, water retention, and adsorption and interception capacities with the increase of ADWP. As for TN, although adsorption and interception by the soil still affected nitrogen. Total nitrogen includes various proteins as well as inorganic nitrogen – e.g., NO_3^-, NO_2^- and NH_4^+. Its cycle is complicated and these four rainfall events cannot be used for regularity analysis. In addition to the rainfall characteristics, soil type also affects the TN concentration in the effluent, so the relationship of the change in TN with ADWP is not obvious.

Comparing the rainfall events on June 28, 2013 and September 2, 2012 at OS, with those of July 21 and 25, 2012 at NS-c, shows that TSS removal efficiency at OS was higher than at NS-c. TSS removal efficiency differences following similar ADWPs may be caused by the different grass swale topsoil conditions in Beijing and Shenzhen. Sorption by topsoil could be the most significant mechanism for removing particulates from urban stormwater runoff (Borst *et al.* 2008). The soil moisture in Beijing was relatively lower than that in Shenzhen, so that at OS has higher water holding capacity and TSS removal efficiency.

Influence of runoff entry and transport within grass swales

The manner of stormwater entry to grass swales influences pollutant removal efficiency. At OS, runoff enters as a concentrated influent, while at NS-c it enters along the length of the swale. During rainfall, all runoff at OS travels the full length of the swale. The runoff route length at NS-c varies, however, with some runoff traveling only a short distance, with little interaction with the swale system. As a result, pollutants cannot be removed efficiently at NS-c. This is clear in Figures 3(a), 3(b), 3(g) and 3(h) and 4(a)–4(d), which show that removal efficiency at OS was higher than at NS-c, particularly for TSS and COD.

The longitudinal and side slopes of grass swales also influence pollutant removal efficiency. The pollution concentration changes with the timing of rainfall events at NS-a, NS-b, NS-c and OS are shown in Figures 5–8, respectively. TSS concentrations were lower at NS-b than NS-a or NS-c (Figures 5(a) and 6(a)), but this was not true for other pollutants. This may be attributable to the runoff depths in the grass swales, as NS-b has steeper longitudinal slopes than NS-a and NS-c. However, as shown in Figure 6(b) and Table 1, NS-b has a gentler side slope but steeper longitudinal slope than NS-a, so, runoff depth in NS-a is shallower than in NS-b. For the August 6, 2012 events, the TSS removal efficiency of NS-a was higher than NS-b because shallow runoff in grass swales improves pollutant removal efficiency. Pitt *et al.* (2008) presented percentage reductions for TSS data relating to three experimental flow depths and confirmed that flow depth is one of the most important factors affecting sediment capture. The TSS removal mechanisms of grass swales include sedimentation and filtration within the grass layer (Stagge *et al.* 2012). Shallow runoff can result in more TSS sedimentation and filtration than deep runoff.
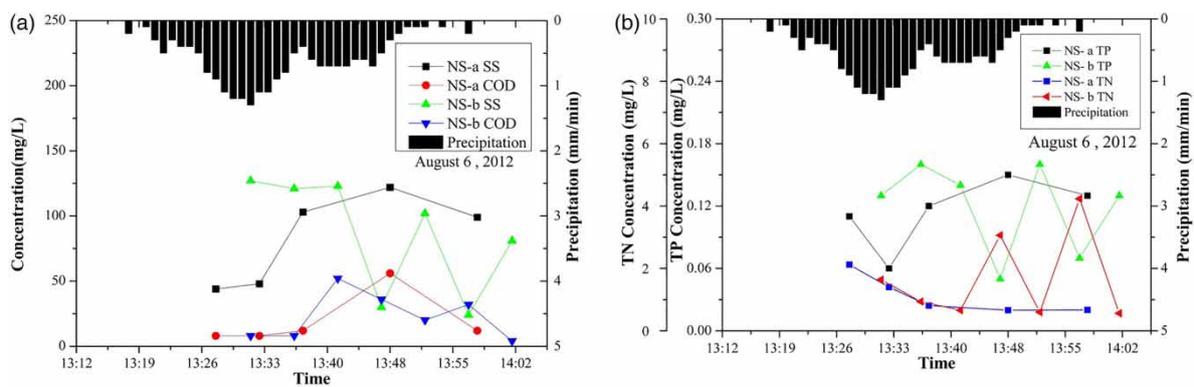

Figure 5 | Grass swale runoff pollutant concentrations for the rainfall event on August 6, 2012. (a) SS and COD at the NS-a and NS-b inlets and outlets, and (b) TP and TP.
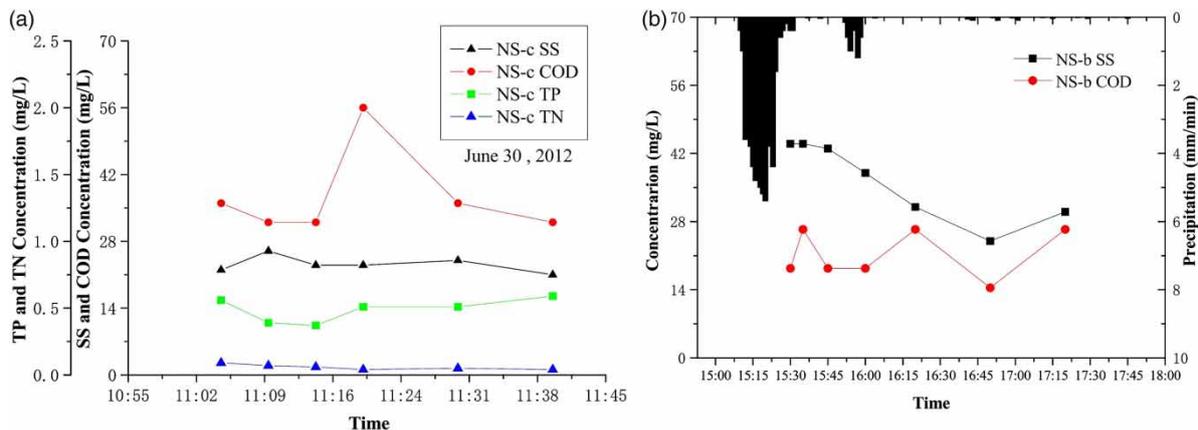

Figure 6 | Grass swale runoff pollutant concentrations at NS-b and NS-c for the rainfall events on June 21 and 30, 2012. (a) The SS, COD, TP, and TN for the NS-c inlets and outlets, and (b) SS and COD for the NS-b inlets and outlets.

Influence of rainfall characteristics

Whether there was a first flush can influence pollutant removal efficiency. TSS concentrations at OS on September 4, 2013 and at NS-b on June 21, 2012 are shown in Figures 3(c) and 6(b). TSS concentrations were very high when it began raining. This agreed well with observations in previous studies,
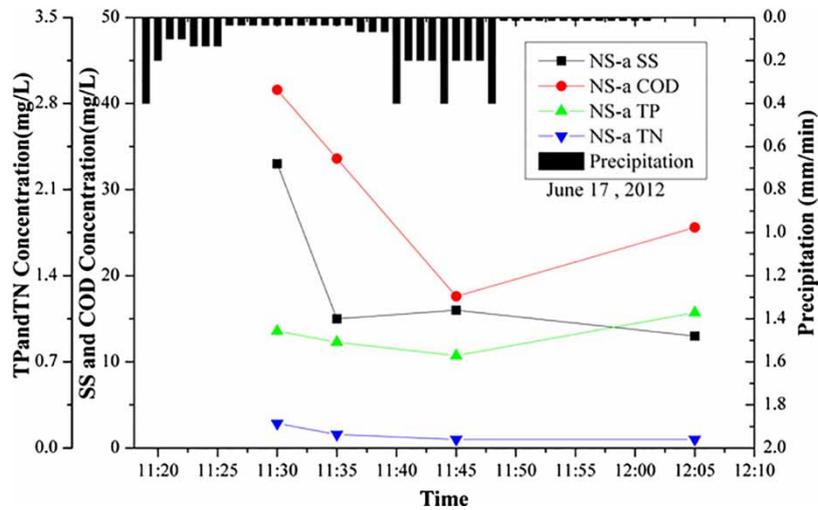
Figure 7 | Grass swale runoff pollutant concentration at NS-a for the rainfall event on June 17, 2012.
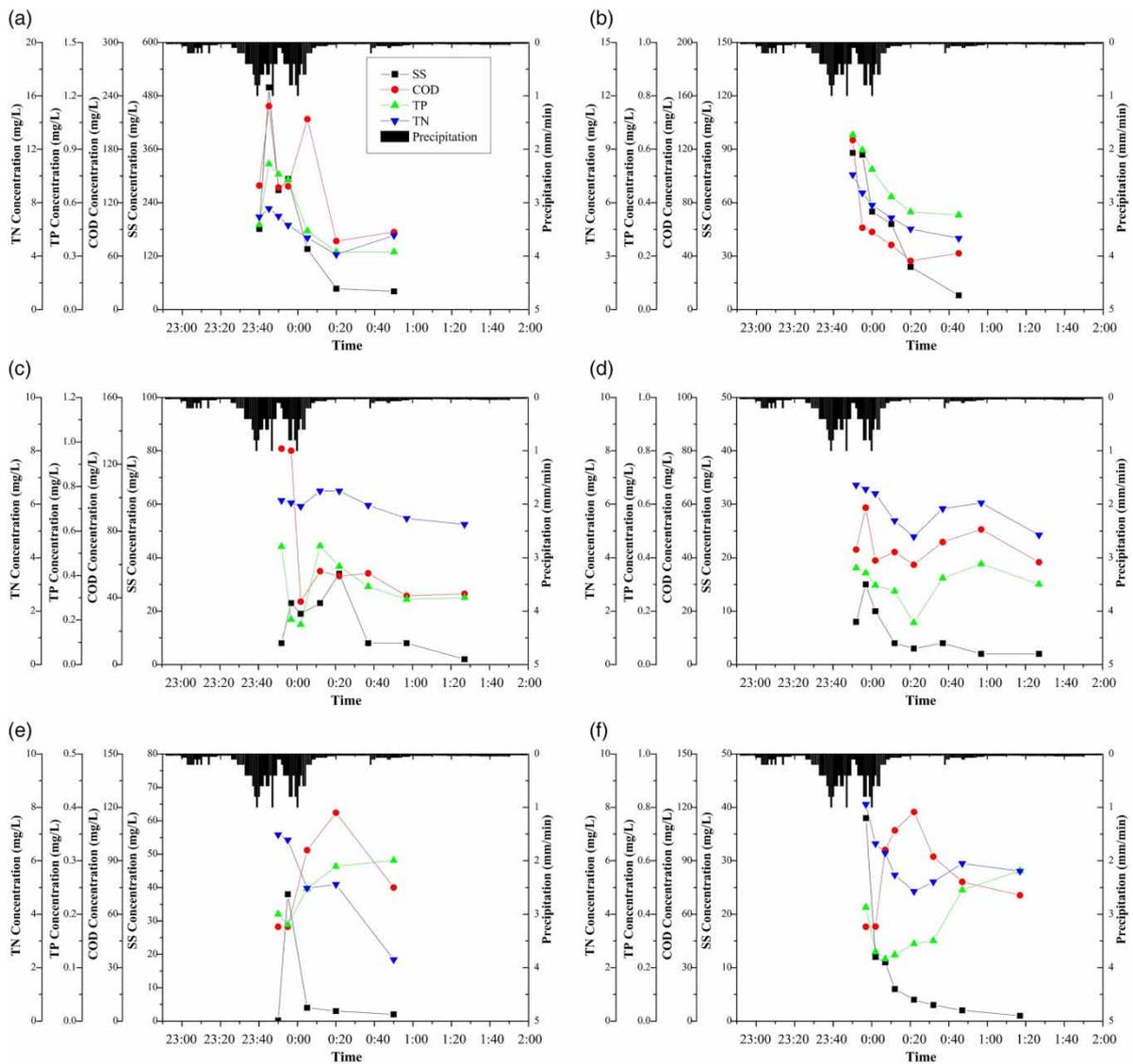

Figure 8 | Observed pollutant concentrations from 0 to 60 m along the OS inlet during the event on September 4, 2013 (a) 0 m, (b) 10 m, (c) 20 m, (d) 30 m, (e) 40 m, and (f) 60 m.

in which successful removal of SS occurred during the first flush, particularly following a long ADWP (Davis *et al.* 2012; Graceson *et al.* 2013). As noted, all variables (first flush, and rainfall duration and intensity) were found to be significant factors influencing pollutant removal efficiency by grass swales, and it is generally agreed that SS removal by grass swales is attributable to the initial capture of large amounts during the first flush, resulting in peak concentrations at the beginning of rainfall events (Fenner 1999; Lee *et al.* 2002; Sansalone & Cristina 2004; Bach *et al.* 2010).

The timing of the peak rainfall intensity influenced pollutant removal efficiency. During the event on August 6, 2012, the highest SS and TN concentrations were 106 and 4.23 mg/L, respectively, at NS-a (Figure 5(a) and 5(b)). In contrast, at the same location on June 17, the highest SS and TN concentrations were 18 and 1.1 mg/L, respectively (Figure 7). Clearly, pollutant removal efficiency on June 17, 2012 exceeded that on August 6, 2012. This arose because the relatively higher peak rainfall intensity on June 17 resulted in more pollution being transported (Kleinman *et al.* 2006). The events on June 28, 2013 and July 25, 2012 each had one peak. For these, the earlier the peak intensity arrived, the higher the pollution removal efficiency of the grass swale (Figures 3(a) and 3(b), and 4(c) and (d)). The rainfall events on September 4, 2013 and July 21, 2012 both had two peaks. For these, although the first rainfall peak influenced pollutant removal efficiency, the second peak had a stronger influence; pollutant removal efficiency was higher when the second rainfall peak arrived earlier. A shorter time between the peaks also increased pollution removal efficiency (Figure 3(c)–3(f)).

For rainfall events with similar intensities and total rainfall depths, the longer the duration, the higher the efficiency of pollutant removal by grass swales. As shown in Figures 3(c) and 5(a), the rainfall events on September 4, 2013 at OS and August 6, 2012 at NS-b had similar intensities and rainfall depths. The pollutant wash-off was higher at OS than at NS-b. This indicates that longer rainfall duration gave increased time during which pollutants could be washed-off, resulting in the removal of more pollutants at OS on September 4, 2013. However, the removal efficiency at NS-c on July 25, 2012 differed little from that on July 21, 2012, despite the longer rainfall duration – Figure 4. This indicates that in addition to rainfall duration, factors such as rainfall depth and rainfall intensity also affect pollutant removal efficiency. The pollutant removal efficiency of grass swales is affected not only by the single external factor of rainfall duration but also other rainfall characteristics such as rainfall depth, rainfall intensity and ADWP. Liu *et al.* (2013) also reported that the influence of rainfall duration on pollutant removal during low-intensity events was minimal.

CONCLUSIONS

The influence of the underlying surface characteristics, ADWP, runoff entry into and transport within grass swales, and rainfall characteristics on grass swale performance and stormwater runoff quality in Beijing and Shenzhen, was investigated. It was concluded that:

(1) The grass swale pollutant removal efficiency varies significantly with the proportion of the underlying surface that is impervious. A higher proportion of impervious surface leads to higher pollutant removal efficiency.

(2) ADWP can affect soil infiltration capacity and the influent pollutant load. Grass swales had better pollutant removal efficiency after longer ADWPs.

(3) Pollutants can be removed effectively during transport through grass swales. Issues affecting this include variations in swale length and slope, and how runoff enters the swale. Shallow runoff depths in grass swales lead to higher pollutant removal efficiency, as does longer swale length. Pollutant removal efficiency is also higher for concentrated influent at the end of the swale rather than when runoff enters along the swale's length.

(4) Pollutant removal efficiency by grass swales varies with rainfall characteristics, including first flush, the timing of peak rainfall intensity and rainfall duration. Higher pollutant removal

efficiency was associated with earlier second intensity peaks, as was longer rainfall duration, unless intensity was low.

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REFERENCES

Abuzreig, M., Rudra, R. P., Whiteley, H. R., Lalonde, M. N. & Kaushik, N. K. 2003 Phosphorus removal in vegetated filter strips. *Journal of Environmental Quality* **32**, 613.

Alias, N., Liu, A., Goonetilleke, A. & Egodawatta, P. 2014 Time as the critical factor in the investigation of the relationship between pollutant wash-off and rainfall characteristics. *Ecological Engineering* **64**, 301–305.

Bach, P. M., Mccarthy, D. T. & Deletic, A. 2010 Redefining the stormwater first flush phenomenon. *Water Research* **44**, 2487.

Bäckström, M. 2002 Sediment transport in grassed swales during simulated runoff events. *Water Science & Technology* **45**, 41–49.

Bäckström, M. 2003 Grassed swales for stormwater pollution control during rain and snowmelt. *Water Science & Technology* **48**, 123–132.

Baek, S.-S., Choi, D.-H., Jung, J.-W., Lee, H. J., Lee, H., Yoon, K. S. & Cho, K. H. 2015 Optimizing low impact development (LID) for stormwater runoff treatment in urban area, Korea: experimental and modeling approach. *Water Research* **86**, 122–131.

Bian, B. 2009 Effect of antecedent dry period on water quality of urban storm runoff pollution. *Environmental Science* **30**, 3522.

Borst, M., Struck, S. D., Muthukrishnan, S., Selvakumar, A. & O'Connor, T. 2008 Swale performance for stormwater runoff. *American Society of Civil Engineers (ASCE)* 182–190. https://doi.org/10.1061/41007(331)16.

Bouchard, N. R., Osmond, D. L., Winston, R. J. & Hunt, W. F. 2013 The capacity of roadside vegetated filter strips and swales to sequester carbon. *Ecological Engineering* **54**, 227–232.

Charlesworth, S. M., Nnadi, E., Oyelola, O., Bennett, J., Warwick, F., Jackson, R. & Lawson, D. 2012 Laboratory based experiments to assess the use of green and food based compost to improve water quality in a Sustainable Drainage (SUDS) device such as a swale. *Science of the Total Environment* **424**, 337–343.

Davis, A. P., Stagge, J. H., Jamil, E. & Kim, H. 2012 Hydraulic performance of grass swales for managing highway runoff. *Water Research* **46**, 6775–6786.

Fenner, D. 1999 *Urban Drainage*, David Butler and John W. Davies; E & FN Spon, London, 2000, ISBN 0-419-22340-1. Urban Water, 1, 269.

Graceson, A., Hare, M., Monaghan, J. & Hall, N. 2013 The water retention capabilities of growing media for green roofs. *Ecological Engineering* **61**, 328–334.

Gunawardena, J., Goonetilleke, A., Egodawatta, P., Ayoko, G. & And, K. J. 2010 Urban traffic characteristics and urban stormwater quality: a methodology to measure traffic generated water pollutants. In: *Rethinking Sustainable Development: Urban Management, Engineering, and Design* (Yigitcanlar, T., ed.). IGI Global, United States of America, pp. 168–184.

Hood, A., Chopra, M. & Wanielista, M. 2013 Assessment of biosorption activated media under roadside swales for the removal of phosphorus from stormwater. *Water* **5**, 53–66.

Hu, M., Sayama, T., Zhang, X., Tanaka, K., Takara, K. & Yang, H. 2017 Evaluation of low impact development approach for mitigating flood inundation at a watershed scale in China. *Journal of Environmental Management* **193**, 430–438.

Kleinman, P. J., Srinivasan, M. S., Dell, C. J., Schmidt, J. P., Sharpley, A. N. & Bryant, R. B. 2006 Role of rainfall intensity and hydrology in nutrient transport via surface runoff. *Journal of Environmental Quality* **35**, 1248–1259.

Lee, J. H., Bang, K. W., Ketchum, L. H., Choe, J. S. & Yu, M. J. 2002 First flush analysis of urban storm runoff. *Science of the Total Environment* **293**, 163.

Leroy, M. C., Portet-Koltalo, F., Legras, M., Lederf, F., Moncond'huy, V., Polaert, I. & Marcotte, S. 2016 Performance of vegetated swales for improving road runoff quality in a moderate traffic urban area. *Science of the Total Environment* **566–567**, 113–121.

Leroy, M. C., Marcotte, S., Legras, M., Moncond'huy, V., Le Derf, F. & Portet-Koltalo, F. 2017 Influence of the vegetative cover on the fate of trace metals in retention systems simulating roadside infiltration swales. *Science of the Total Environment* **580**, 482–490.

Li, L. Q., Yin, C. Q., Kong, L. L. & He, Q. C. 2007 Effect of antecedent dry weather period on urban storm runoff pollution load. *Environmental Science* **28**, 2287–2293.

Li, H., Li, K. & Zhang, X. 2016 Performance evaluation of grassed swales for stormwater pollution control. *Procedia Engineering* **154**, 898–910.

Line, D. E., Jennings, G. D., Shaffer, M. B., Calabria, J. & Hunt, W. F. 2008 Evaluating the effectiveness of two stormwater Wetlands in North Carolina. *Transactions of the ASABE* **51**, 521–528.

Liu, A., Goonetilleke, A. & Egodawatta, P. 2012 Inadequacy of land use and impervious area fraction for determining urban stormwater quality. *Water Resources Management* **26**, 2259–2265.

Liu, A., Egodawatta, P., Guan, Y. & Goonetilleke, A. 2013 Influence of rainfall and catchment characteristics on urban stormwater quality. *Science of the Total Environment* **444**, 255–262.

Liu, A., Li, D., Liu, L. & Guan, Y. 2014 Understanding the role of urban road surface characteristics in influencing stormwater quality. *Water Resources Management* **28**, 5217–5229.

Luell, S. K., Hunt, W. F. & Winston, R. J. 2011 Treating Highway Bridge Deck Runoff Using Bioretention and a Swale. In: *World Environmental and Water Resources Congress*. EWRI.ASCE. May 25th, Palm Springs, CA, USA, pp. 364–374.

Miguntanna, N. P., Liu, A., Egodawatta, P. & Goonetilleke, A. 2013 Characterising nutrients wash-off for effective urban stormwater treatment design. *Journal of Environmental Management* **120**, 61–67.

Montalto, F., Behr, C., Alfredo, K., Wolf, M., Arye, M. & Walsh, M. 2007 Rapid assessment of the cost-effectiveness of low impact development for CSO control. *Landscape & Urban Planning* **82**, 117–131.

Palhegyi, G. E. 2010 Designing stormwater controls to promote sustainable ecosystems: science and application. *Journal of Hydrologic Engineering* **15**, 504–511.

Pitt, R., Nara, Y., Kirby, J. & Durrans, S. R. 2008 Particulate transport in grass swales. *American Society of Civil Engineers (ASCE)* 191–204. doi: https://10.1061/41007(331)17.

Sansalone, J. J. & Cristina, C. M. 2004 First flush concepts for suspended and dissolved solids in small impervious watersheds. *Journal of Environmental Engineering* **130**, 1301–1314.

Shaw, S. B., Stedinger, J. R. & Walter, M. T. 2010 Evaluating urban pollutant buildup/wash-off models using a Madison, wisconsin catchment. *Journal of Environmental Engineering* **136**, 194–203.

Stagge, J. H., Davis, A. P., Jamil, E. & Kim, H. 2012 Performance of grass swales for improving water quality from highway runoff. *Water Research* **46**, 6731–6742.

Storey, B. J., Li, M. H., Mcfalls, J. A. & Yi, Y. J. 2009 *Stormwater Treatment with Vegetated Buffers*. National Cooperative Highway Research Program, Transportation Research Board. Project 25–35, Task 53. Texas Transportation Institute, College Station, TX. http://www.doc88.com/p-8791582264598.html.

Stovin, V. 2010 The potential of green roofs to manage Urban Stormwater. *Water & Environment Journal* **24**, 192–199.

Tiefenthaler, L. L., Schiff, K. C., Bay, S. M. & Greenstein, D. J. 2003 Effect of antecedent dry periods on the accumulation of potential pollutants on parking lot surfaces using simulated rainfall. In: *Southern California Coastal Water Research Project 2001–02 Biennial Report* (Weisberg, S. B. & Elmore, D., eds). Southern California Coastal Water Research Project, Westminster, CA, pp. 216–223.

Winston, R. J., Hunt, W. F., Wright, J. D. & Palmer, R. N. 2010 Impacts of roadside filter strips, dry swales, wet swales, and porous friction course on stormwater quality. In *World Environmental and Water Resources Congress. ASCE*, May 16–20, Providence, Rhode Island, USA, pp. 3006–3017.

Winston, R. J., Hunt, W. F., Kennedy, S. G. & Wright, J. D. 2011 *Evaluation of Permeable Friction Course (PFC), Roadside Filter Strips, Dry Swales, and Wetland Swales for Treatment of Highway Stormwater Runoff*. North Carolina Department of Transportation, NC.