Evaluation of bioswale efficiency in consideration of climate and design features: A case study in Hong Kong

Season S Chen[1], Yuqing Sun[1], Liang Chen[1], Mingjing He[1], Albert Chiu[2], William Cheung[2] and Daniel C W Tsang[1]

[1] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, People's Republic of China

[2] Drainage Services Department, the HKSAR Government, Hong Kong, People's Republic of China

ABSTRACT

Sustainable drainage systems (SuDSs) have been increasingly implemented to mitigate the stress of urbanisation, climate change, and water scarcity. However, SuDS construction in densely populated metropolitan cities with a subtropical monsoon climate such as that of Hong Kong may encounter challenging field conditions and site constraints. This field-scale study aimed to verify the performance of bioswale for flood resilience and water quality improvement under various simulated rainfall scenarios with different intermittency and intensity. In the six simulated rainfall events, the results showed that metal removal and flow attenuation were excellent under minor and moderate rainfall events, while the system performance was compromised during intensive rainfall events. The removal of turbidity and nutrients from the runoff was moderate owing to the low contaminant levels in the synthetic stormwater. The dry state of soil media led to more fluctuating results for water quality control. To further enhance the treatment capability under practical site constraints, the addition of appropriate soil amendments and the integrated use of different SuDS measures are recommended in order to achieve sustainable development goals and resilient water management.

KEYWORDS Bioswale; stormwater management; sustainable drainage systems; sustainable development goals; wastewater treatment
CONTACT Daniel C W Tsang dan.tsang@polyu.edu.hk
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1. Introduction

Worldwide urbanisation continues to result in more impervious surfaces, decreasing groundwater recharge, and increasing surface runoff (Grebel et al., 2013; Hering et al., 2013; Roy-Poirier et al., 2010), which are worsened by climate change. For instance, the Hong Kong Observatory has recorded an increasing average rainfall intensity from 88.4 mm to 145.5 mm at daily peak hours from 1885 to 2017, and a 700–900 mm rise of sea level is projected by the year 2100 (HKO, 2021). Conventional stormwater management measures primarily aim at flood mitigation, while water quality control is not taken into account, thereby limiting the use of stormwater as a resource to alleviate water scarcity (Luthy and Sedlak, 2015; Luthy et al., 2019). Sustainable drainage systems (SuDSs) have been designed to restore hydrology and improve the water quality of a developed area close to its pre-construction conditions by mimicking natural processes (Charlesworth and Booth, 2017; Davis, 2008). A combination of biophysical processes such as detention, infiltration, storage, and biological pollutant uptake are designed in SuDSs to reduce surface flow and remove major pollutants such as suspended solids, metals, nutrients, organics, and pathogens in the runoff, thereby improving both the quantity and quality of surface runoff. The typical types of SuDSs include bioswale, rain gardens, porous pavements, green roofs, retention ponds, constructed wetlands, and so on (CIRIA, 2015).

Modification and performance verification of SuDSs under different climates are necessary. Earlier field studies evaluating the SuDS performance in flow reduction and pollutant removal were mainly conducted in the temperate regions of the USA (DeBusk and Wynn, 2011; Dietz and Clausen, 2005; Passeport et al., 2009), Australia (Hatt et al., 2009; Mangangka et al., 2014), and New Zealand (Trowsdale and Simcock, 2011). In recent years, more field studies in cold regions such as Canada and tropical regions such as Singapore have also confirmed the flexibility of SuDSs to accommodate various climates with modified designs and local guidelines (Ding et al., 2019; Wang et al., 2017, 2019). Nevertheless, there is an information gap regarding the competence of SuDSs in subtropical regions with a monsoon climate where storm events of varied intermittency and intensity occur.

However, the construction of SuDSs in densely populated cities such as Hong Kong encounter more complicated and unpredictable situations. For example, even though the SuDS designs are more likely to be incorporated into an existing non-greenfield infrastructure, the original drainage functions and operation efficiencies of the site should not be compromised. The installation of the SuDS features often face challenges of congested and unknown ground utilities such as dual water supply systems, sewerage system, power cables, and gas pipelines. As a result, the design dimensions may not fully comply with the recommended values in the guidelines due to construction feasibility and site constraints, e.g., shallower depth of the underground functioning layers. A recent study of 70 cases in the Netherlands highlighted that 40% of SuDS failures were identified at the interface between

SuDSs and other urban systems (De Bilt et al., 2021). Thus, it is important to understand the city-specific challenges in SuDS performance and evaluate the system efficiencies in terms of pollutant removal and flow attenuation in field studies.

This study conducted a field-scale performance evaluation of an on-site bioswale at Stonecutters Island Sewage Treatment Works (SCISTW). Bioswales are vegetated swales incorporated into bioretention systems, which provide stormwater runoff treatment with a designed gentle gradient and extended detention to facilitate infiltration. The fine particles and nutrients are then removed by filter media and taken up by plants and microbes, respectively. The filtered water collected by perforated subsoil pipes can be reused on site or conveyed downstream for water quality improvement (Chen et al., 2018). The field tests aimed at: (i) examining the relationships between the system hydrology and pollutant removal under different rainfall scenarios; and (ii) identifying the key design factors to provide guidance on informed decisions for future SuDS engineering and deployment.

2. Materials and methodology

2.1. Study field and synthetic stormwater

The bioswale is located at the SCISTW in Hong Kong. The surface treatment and catchment area of the bioswale are 49 m^2 and 303 m^2, respectively. In view of the similar average temperature and annual rainfall of Singapore and Hong Kong, the SuDS guideline of Singapore was adapted for this study. Due to the site constraints and minimisation of retrofit construction at SCISTW, a transition layer and a submerged zone were not included in the bioswale design. The bioswale was constructed in late 2016 consisting of a vegetated open channel to convey and treat stormwater flows through dense vegetation (Table A1) with a gentle slope as well as infiltration through the filter media (i.e., 300 mm planting soil layer) (Figure 1(a)). To enhance the permeability of the system, a 150-mm gravel layer and a perforated pipe (with a diameter of 150 mm) were installed in the bioswale. However, preliminary evaluation of the bioswale at SCISTW during three intensive rainfall events from June to September 2017 exhibited inconsistent performance in regard to water quality control, i.e., low or negative pollutant removal efficiencies (i.e., outflow concentrations of total suspended solids (TSS), total phosphorous (TP), and total nitrogen (TN) were larger than those in the inflow). In addition, road-deposited sediments contributed to a major portion of metal loadings in stormwater runoff. Metals including chromium (Cr), copper (Cu), cadmium (Cd), lead (Pb), nickel (Ni), and zinc (Zn) were among the key pollutants in stormwater (HK DSD, 2014; Le Fevre et al., 2015; Sun et al., 2020). Therefore, in this study, synthetic stormwater composed of six commonly reported metals and various inorganic salts (Table 1) was prepared according to relevant field studies in Hong Kong (Li et al., 2001; Milik and Pasela, 2018; Zafra et al., 2017;). The chemicals, namely NaCl, $CaCl_2$, $MgCl_2$, Na_2SO_4, $NaHCO_3$, $NaNO_3$, NH_4C_l, Na_2HPO_4, $Zn(NO_3)_2$, $Pb(NO_3)_2$, $Cu(NO_3)_2$, $Cd(NO_3)_2$, $Ni(NO_3)_2$, and CrO were of reagent grade and used without further purification.

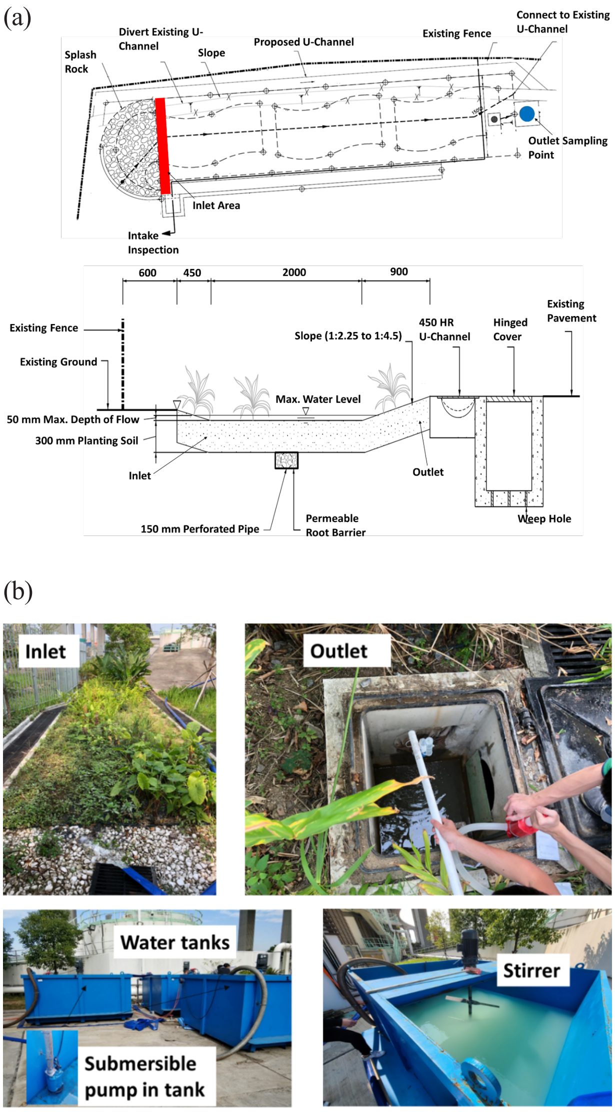


Figure 1. Overview of the (a) bioswale; and (b) on-site setup.

Table 1. Constituents of the synthetic stormwater.

Salts	Concentrations (mM)
NaCl	5.1
$CaCl_2$	0.75
$MgCl_2$	0.0075
Na_2SO_4	0.33
$NaHCO_3$	1.0
$NaNO_3$	0.072
NH_4Cl	0.072
Na_2HPO_4	0.016
Metals	**Concentrations (mg L^{-1})**
Zn	4.4
Pb	2.4
Cu	0.9
Cd	0.8
Ni	0.5
Cr	0.1

2.2. Simulated rainfall events

Hong Kong has a subtropical climate, and the average annual rainfall ranges from 1400 mm to over 3000 mm from Peng Chau to Tai Mo Shan (HKO, 2021). About 80% of the precipitation falls during May to September, and June and August usually receive most rainfalls, while January and December are usually the driest months. To mimic various rainfall events, annual recurrence interval (ARI) from a 2-year to 50-year return period was adopted in the simulated rainfall tests. Moreover, Hong Kong is subjected to frequent storm events within short intervals as well as extreme rainstorms during typhoons (Chen et al., 2021). These rainfall scenarios were considered in the simulated rainfall tests (Table 2). The rainfall scenarios included: (Scenario A, minor rainfall event) a storm with a 2-year return period; (Scenario B, minor rainfall event) another storm with a 2-year return period on the next day following Scenario A; (Scenario C, moderate rainfall event) a storm with a 10-year return period; (Scenario D, intensive rainfall event) a storm with a 50-year return period; (Scenario E, intensive rainfall event) a storm with a 50-year return period with a shorter duration; and (Scenario F, intensive rainfall event) a consecutive storm with a 50-year return period after one-hour drainage following Scenario E.

A concentrated stormwater stock solution was prepared in the laboratory on the same day prior to the field test. Three steel water tanks (volume of 10 m^3) with a submersible pump (Tsurumi) fixed at the bottom and an electric blender stainless steel stirrer in the centre (Figure 1(b)) were used to completely mix and dilute the concentrated stock solution to prepare synthetic stormwater on site right before the field-scale simulated rainfall tests. The solution homogeneity of the synthetic stormwater was checked by using a portable ProDSS water quality meter (YSI) at different locations and depths in the water tank. The synthetic stormwater was pumped to the bioswale through an external pipe at the designated flow rates (Table 2). The effective pumping time varied from 15 minutes to 1 hour, representing the scenarios of different return periods and frequent storm events in a wet season in Hong Kong. Outflow samples were collected at the bioswale outlet (Figure 1(a)) at different time intervals. A 50-mL sample was taken at each time interval and 30–50 samples were collected for each test. The sampling time and total data points may vary in view of the discrepancies of outflow rates among Scenarios A to F.

Table 2. Simulated rainfall events.

Test date	Scenario	Simulated rainfall event	Average pumping rate (m^3 min^{-1})	Total pumping amount (m^3)
16/03/2020	A	Storm with a 2-year return period for 120 minutes	0.1	12
17/03/2020	B	Storm with a 2-year return period on the consecutive day for 120 minutes	0.1	12
14/04/2020	C	Storm with a 10-year return period for 60 minutes	0.3	18
16/04/2020	D	Storm with a 50-year return period for 30 minutes	0.6	18
27/04/2020	E	Storm with a 50-year return period for 15 minutes	0.6	9
27/04/2020	F	Storm with a 50-year return period for 15 min after a 1-hour break from Scenario E	0.6	9

2.3. Water quality and quantity analyses

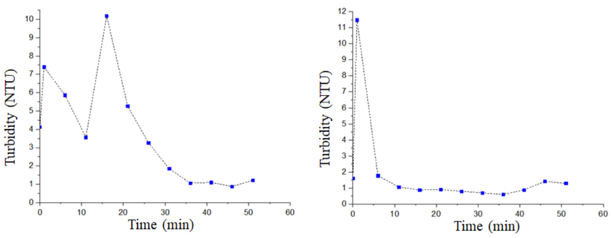
The pH value of the initial synthetic stormwater in the water tank and outflow of the bioswale was measured by using a ProDSS water quality meter after on-site calibration. The turbidity of the samples was also measured on site by using the Turbidimeter (Hach) as a proxy of TSS, where the two parameters were in a linear relationship. To determine the metal concentrations in the influent and effluent samples, the collected samples were first digested by using concentrated nitric acid and then measured by an Inductively Coupled Plasma Optical Emission Spectrophotometer (ICP-OES) in the laboratory. For the analysis of nutrients, TN was analysed by a TOC-L/TN analyser (Shimadzu Corporation), and TP was measured using the PhosVer 3 method with phosphate reagent powder pillows, and the concentrations were determined by a colourimeter (Hach). Each sample was divided into three portions to reduce analytical errors. The time-weighted average outflow rate of the bioswale was estimated by recording the time needed to collect 50 mL of samples.

3. Results and discussion

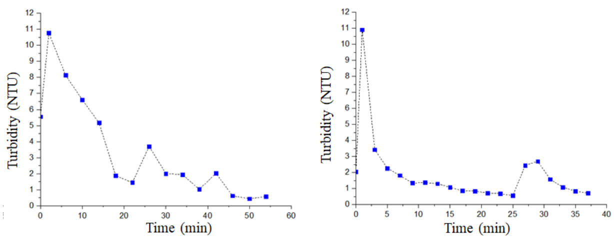
3.1. Turbidity and pH of the treated runoff

The turbidity of runoff was both time- and scenario-dependent. An apparent increase of turbidity in the effluent samples was found at the beginning of all tested rainfall events (Figure 2 and Table A2). This phenomenon was probably due to the fine particles or detachable colloids from the soil media at a dry state being perturbed and washed out by the incoming stormwater. When the antecedent dry period was short and the soil moisture was high in Scenarios B and F (Figure 2(b) and (f)), the turbidity could readily reach a stable level. The effect of sedimentation and filtration in the bioswale system was indicated by a reducing turbidity along with the breakthrough time. Compared to the initial pH of the synthetic stormwater ranging from 7.4 to 7.8, the pH values of collected effluents at the bioswale outlet were generally stable (7.2–8.0) along with the breakthrough time. Various rainfall scenarios had little effect on the pH patterns (Figure A1), where acidity/alkalinity-induced leaching of contaminants was negligible.

(a) (b)



(c) (d)



(e) (f)

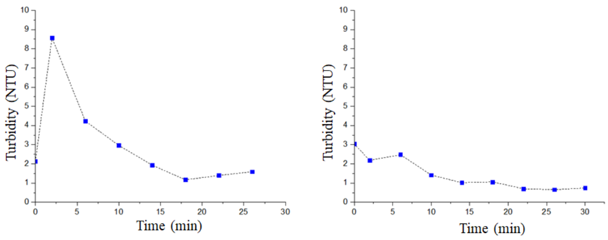


Figure 2. Turbidity changes at the bioswale outlet during simulated rainfalls in (a) Scenario A; (b) Scenario B; (c) Scenario C; (d) Scenario D; (e) Scenario E; and (f) Scenario F.

It is believed that the presence of vegetation not only screens the large particles in the runoff but also increases the stability of soil media in the swale, thereby enhancing the removal of TSS from the runoff. There has not been a local guideline on stipulated TSS removal by SuDSs in Hong Kong (Chen et al., 2021), while a removal efficiency of 80% is generally recommended by different design guidelines (PUB, 2018; Water by Design, 2014). However, in this study, the turbidity removal was far below 80%, indicating a low TSS removal efficiency (Figure 2), which should be attributed to the low level of turbidity in the synthetic stormwater. This phenomenon has also been documented in other field studies with a relatively clean runoff (Goh et al., 2019; Wang et al., 2017). Therefore, in addition to removal percentage, the values for TSS in the treated runoff (e.g., 10 mg L^{-1}) should be recommended to adequately evaluate the performance and functionality of the bioswale (PUB, 2018). From an engineering point of view, filtration has been demonstrated to be an effective means of TSS removal in other studies (Purvis et al., 2018). To enhance the runoff treatment efficiency in the bioswale system, outlet configuration with an orifice fitting could facilitate active storage and detention of runoff (Toronto and Region Conservation Authority, 2018).

3.2. Metal removal

Primary sources of metals in urban stormwater include vehicle components, building materials, and industrial operations, etc. Under minor and moderate rainfall events, most metal removal efficiencies were greater than 85% (Figures 3 and A2(a)-(c)), except for Cr and Cu. Metal contaminants in the surface runoff often exist in particulate form or dissolved form, which can be removed via sedimentation, filtration, and adsorption onto soil particles such as clay minerals and soil organic matter. The field test results showed that the current bioswale system demonstrated a good capability to remove most of the metal contaminants in urban surface runoff. The poor removal efficiency of Cr was probably due to the much lower Cr content in the synthetic stormwater compared to other metals, while the moderate removal of Cu may reflect that the soil media in the bioswale system may not be selective for Cu adsorption.

When the runoff intensity increased, the removal efficiencies of Cd, Ni, Pb, and Zn decreased to approximately 70% and Cu removal efficiency was ~50% (Figure 3 and A2(d)-(f)). Intensive runoff significantly shortened the residence time in the bioswale, which allowed insufficient time for incoming metal contaminants to adsorb onto the soil media, thus diminishing the metal removal efficiencies. At present, there is no regulation regarding the metal contents in SuDS runoff in Hong Kong. It should be noted that the current approach aimed at understanding the efficiency of a bioswale system in response to various types of rainfall events; therefore, the initial state of metal uptake in plants and soil was beyond the scope of this field study. To enhance the metal removal efficiency in the SuDS, several widely available amendments such as biochar (Peng et al., 2021b; Sun et al., 2019), zero-valent iron (Sun et al., 2017), zeolite (Jéssica et al., 2019), and fly ash (Zhang et al., 2021) can be incorporated and homogeneously mixed in the filter media in view of their large surface area and abundant functional groups for metal sequestration.

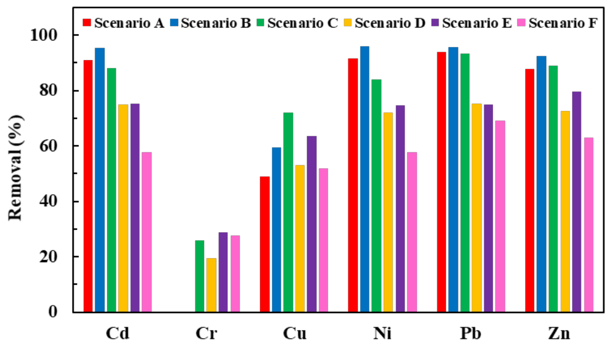


Figure 3. Metal removal by bioswale during field tests (Cr was not added in Scenarios A and B due to experimental error).

3.3. Nutrient removal

Excess nutrients such as nitrogen and phosphorus are typical pollutants found in the surface runoff in rural areas due to agricultural practices or wastewater discharge, which can pose potential risks to aquatic life and compromise human health (Paerl et al., 2016; Whitehead et al., 2009). In this study, the nitrogen source in the synthetic stormwater came from NH_4Cl (Table 1). As shown in Figure 4 and Table A2, the TN in the runoff (*ca.* 4 mg L^{-1}) decreased moderately after passing through the bioswale system. The removal of TN was more effective when the flow rate was relatively small (Figure 4(a) and (b)). Under a mild runoff, the nitrogen could be better captured by the vegetation near the surface layer, and a longer retention time in the bioswale system was also beneficial for nitrogen removal. When the runoff was more intensive (Figure 4(c)-(e)), the average TN in the treated runoff was ~3 mg L^{-1}. Nitrogen removal capacity was compromised when frequent rainfall events occurred (Figure 4(b) and (f)), which may pose additional challenges to SuDSs in subtropical regions.

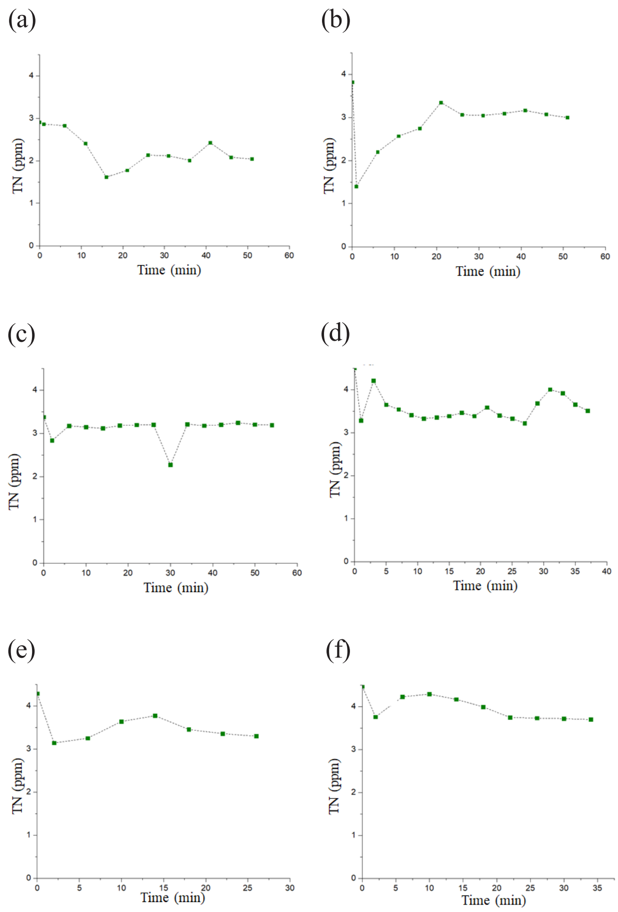
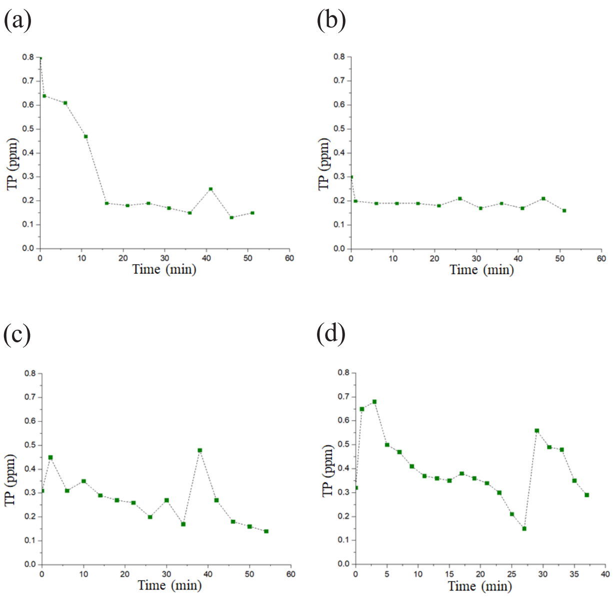


Figure 4. Total nitrogen (TN) changes at the bioswale outlet during simulated rainfalls in (a) Scenario A; (b) Scenario B; (c) Scenario C; (d) Scenario D; (e) Scenario E; and (f) Scenario F.

The recommended TN removal efficiency was 45% or less than 1.2 mg L^{-1} in the treated runoff (PUB, 2018). In this study, the TN removal did not meet the guideline in terms of either percentage or absolute value, which could be partly due to the relatively low TN level in the influent stormwater that could be close to the background TN content in the soil media. In view of the construction constraints that limited the soil media depth of bioswale, supplementary biochar amendment in the soil media would be a feasible measure to enhance TN removal. Biochar placed near the top of the system improved the water retention and total porosity in the vadose zone, which enhance the ammonium removal by adsorption and improve the nitrate removal via denitrification in an anoxic condition. In addition, placing biochar close to the saturated zone would enrich the microbial community to facilitate nitrate removal via denitrification where biochar could serve as an electron donor (Luo et al., 2020; Marvin et al., 2020; Xiong et al., 2019).

The amount of TP in the synthetic stormwater was less than 0.8 mg L^{-1} which was lower than the recommended value in the treated runoff by SuDSs (PUB, 2008). Hence, phosphorus was considered as a minor pollutant in the synthetic stormwater. Although the initial concentration of TP was low in the surface runoff, the TP value in the bioswale treated effluent could be further reduced to nearly 0.1 mg L^{-1} in the Scenarios representing 2-year and 10-year return periods (Figure 5(a)-(c) and Table A2). These results confirmed that the bioswale presented a good capability to remove phosphorus from the surface runoff. When the rainfall was intensive with a high flow rate, the outlet TP level tended to fluctuate more (Figure 5(d)-(f) and Table A2). The challenge for pollutant removal efficiency under intensive rainfall events was also suggested by the pollutant removal curves as a function of bioswale area and catchment area derived from the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) (PUB, 2018). The occasionally higher TP content in the treated runoff during the test indicated potential leaching of phosphorus source from the soil media. Similar to TN removal, possible introduction of amendment materials such as biochar (Peng et al., 2019, 2021a), water treatment residuals (i.e., alum sludge), and other mineral-rich adsorbents into the soil media could enhance TP removal from the runoff (Chen et al., 2021; Qiu et al., 2019). It should also be noted that nutrient uptake by plants plays an important role in SuDSs. In the wet season, plants can utilise nutrients which have accumulated in the system, while the nutrients can be released back into the system due to plant decomposition, where seasonal plant harvesting would be advisable (Li and Davis, 2014).



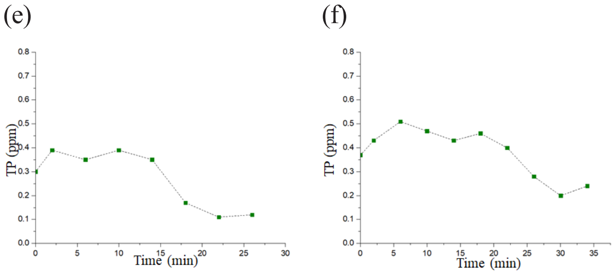


Figure 5. Total phosphorus (TP) changes at the bioswale outlet during simulated rainfalls in (a) Scenario A; (b) Scenario B; (c) Scenario C; (d) Scenario D; (e) Scenario E; and (f) Scenario F.

3.4. Hydrologic performance

Peak flow rate reduction, peak outflow delay, and runoff storage can be used to evaluate the hydrologic effectiveness of the SuDS in managing stormwater runoff. In this field test, the bioswale proved to be effective for flow attenuation and peak delay under a minor rainfall event (i.e., a 2-year return period), where over 85% of flow could be retained by the system (Figure 6). The hydrologic effectiveness under consecutive rainfall events (Scenario B) could also be well maintained, and the flow rate was even more stable during the consecutive rainfall events. The larger variation in flow rate during the first rainfall event was probably attributed to the dry state of the soil media as no rainfall event occurred in the past 10 days prior to the first test (HKO, 2020), which indicated the possibility of preferential paths in the unsaturated soil. Homogeneous mixing of the filter media during the construction stage could help to minimise the preferential flows (Chen et al., 2017).

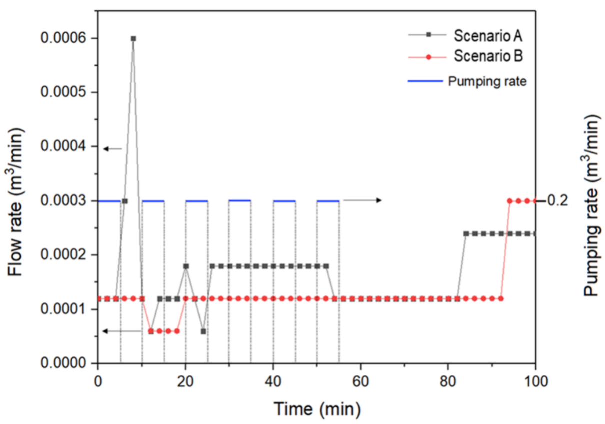


Figure 6. Flow rate change with time during field tests in bioswale (Scenarios A and B).

During the other simulated rainfall events, overflow of surface runoff was observed before reaching the maximum retention capacity of the bioswale because of the large inflow. It was experimentally difficult to determine the flow reduction and peak flow delay during the intensive rainfalls because the site constraints ruled out accurate quantification of the overflow under the current bioswale setting. In this study, the ratio of surface treatment area to catchment area was about 18%, which was much larger than the conservative values (2–5%) recommended in the Singapore guideline (PUB, 2018). Therefore, insufficient storage capacity should not be an issue but the early overflow was probably attributed to the insufficient filtration rate of the soil media in the face of intensive rainfalls. Since the hydrologic performance highly depends on the basin area, ratio of treatment area to catchment area, and rainfall intensity, it is suggested to formulate criteria for the future design of basin size based on targeted rainfall events and specific hydrologic objectives in the local district.

3.5. Current challenges and recommendations for SuDS design in Hong Kong

Due to site constraints, there were some major differences in the design details of the bioswale in SCISTW compared to those in the guidelines (Table A3). The maximum depth of flow allowed in the bioswale in SCISTW was much shallower than suggested (50 mm vs. 300 mm). Increasing the maximum depth of flow above the bioswale basin can expand the capacity to retain more runoff under intensive rainfall events. Moreover, although the transition layer is not mandatory, its presence can minimise migration of soil particles to the drainage layer. The additional incorporation of a submerged zone can also prolong retention, improve nitrogen removal, and provide water retention for plants during dry periods.

Water quality volume (WQV), defined by runoff volume captured by the system, and water quality depth (WQD), defined by WQV divided by catchment area, have been recommended for the design of storage capacities in tropical cities (Chen et al., 2021; Wang et al., 2017). To improve the system efficiency under intensive rainfall events, a WQD value of between 10 and 30 mm is recommended according to the long-term monitoring project in Singapore over 96 storms. It should be noted that strict implementation of WQV or WQD parameters in populated cities may not always be feasible, as space availability is one of the most challenging issues in the design process (Chen et al., 2021).

To improve water quantity and quality performance in view of the available space, the modification of filter media with low-cost, locally available, and high-performance amendments (e.g., wood waste biochar, food waste compost, and alum sludge) are recommended to enhance the establishment of complex root networks and enriched microbial communities in the soil media, which could facilitate nutrient capture and pollutant removal. More detailed mechanisms regarding biochar application for pollutant removal have been documented in our recent studies (Chen et al., 2021; He et al., 2022). It should, however, be noted that the use of various amendments requires careful engineering design and instructed operation to minimise potential leaching and desorption of pollutants from the systems under variable field conditions.

Despite the construction and space limits on site in this case, the field-scale bioswale system could still demonstrate satisfactory metal and turbidity removal capabilities with good hydrologic management during the minor and moderate rainfall events. It is also worth noting that since the operation in 2017 and during this field study in 2019, no clogging or other failure was observed in the bioswale system. These results suggest the resilience of SuDS features over a reasonable period of time. Simulation models could be used in the design and monitoring stages to shed light on the relationships between SuDS performance and other features including rainfall events and system configurations, etc. For example, the Storm Water Management Model (SWMM) and MUSIC have been commonly explored in the decision-making stage to optimise the SuDS design in view of different site-specific objectives (Yang and Chui, 2018; PUB, 2018). Considering that the space constraint is a common issue in densely populated metropolitan areas, decision makers should bear in mind that a series of hierarchical SuDS designs can be implemented together (rather than relying on a single measure) to achieve efficient and sustainable water management.

4. Conclusions

Various rainfall events representing locally relevant field scenarios were simulated to evaluate the field-scale performance of the bioswale in Hong Kong. The water quantity and quality control of the bioswale performance were associated with rainfall intensity and intermittency. Total nitrogen and total phosphorus removal was moderate due to the low pollution level in the synthetic stormwater. The dry state of the soil media and intensive rainfall events also led to the variation of nutrient and turbidity removal. Nevertheless, the bioswale demonstrated satisfactory removal efficiency of Cd, Ni, Pb, and Zn under minor and moderate rainfall events. At the same time, the bioswale could retain most surface runoff under minor rainfall events, while overflow was observed during intensive rainfalls because of limited overflow depth and insufficient filtration rate of the soil media. While the site constraints may limit the design depth of soil media, possible addition of appropriate amendments such as biochar and compost may enhance the pollutant removal efficiency and increase the infiltration rate. This field study validated the performance of a field-scale bioswale in Hong Kong although the design features were restrained by the site conditions. Long-term monitoring under actual storm events and innovative engineering designs with respect to local conditions are recommended for future research and SuDS deployment in Hong Kong.

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Appendices

Table A1. Vegetation in the bioswale.

Scientific name	Chinese name	Amount
[#] Alocasia Macrorrhizos	海芋	70
Canna X Generalis	大美人蕉	90
Cyperus Involucratur	風車草	90
Hedychium Coronarium	薑花	120
Iris Pseudacorus	黃菖蒲	100
[#] Nephrolepis Auriculata	腎蕨	400
Pilea Cadierei	花葉冷水花	180
Strelitzia Reginae	天堂鳥	45
[#] Paspalum Vaginatum	海雀稗	23 m^2

[#] Native species

Table A2. Summary of turbidity, TN, and TP removal by bioswale during the field tests.

Scenarios		Turbidity (NTU)	TN (mg L^{-1})	TP (mg L^{-1})
A	Inlet	4.1	2.9	1.1
	Outlet	3.8	2.2	0.3
	Removal [std] (%)	8.5 [0.2]	24.1 [0.4]	74.8 [0.2]
B	Inlet	1.6	3.8	0.3
	Outlet	2.0	2.8	0.2
	Removal [std] (%)	-23.6 [3.0]	27.0 [0.5]	37.6 [0.0]
C	Inlet	5.6	3.4	0.3
	Outlet	7.2	3.1	0.3
	Removal [std] (%)	-30.1 [13.9]	8.3 [0.3]	12.4 [0.1]
D	Inlet	2.1	4.5	0.3
	Outlet	1.9	3.5	0.4
	Removal [std] (%)	6.6 [2.3]	21.4 [0.3]	-26.6 [0.1]
E	Inlet	2.1	4.3	0.3
	Outlet	3.1	3.4	0.3
	Removal [std] (%)	-45.9 [2.6]	20.3 [0.2]	10.5 [0.1]
F	Inlet	3.0	4.5	0.4
	Outlet	1.2	3.9	0.4
	Removal [std] (%)	60.1 [0.7]	12.3 [0.3]	-2.7 [0.1]

Outlet: average value in effluent samples
Removal (%): calculated by average outlet value and inlet value
[std]: standard deviation

Table A3. Design details with reference to the Singapore guideline.

Design details	SCISTW bioswale	[a] Singapore bioretention system
Catchment area (m^2)	~ 303	N/A
SuDS size (m^2)	~ 49	N/A
Ratio of treatment area to equivalent impervious area	[b] 18%; [c] 27%	3–5%
Soil saturated hydraulic conductivity (mm h^{-1})	180 (by design)	100–300
Side slope	1:1.25 to 1:4.5	1:4 to 1:10
Maximum depth of flow (mm)	50	300
Soil type	Planting soil	Sandy loam or sandy clay loam
Soil layer (mm)	300	600–1000 (min. 400 accepted with caution)
Transition layer (mm)	N/A	100
Submerged zone	N/A	300–400
Gravel (mm)	150	150 (> 50 mm above drainage pipes)
Perforated pipe size (mm)	150	100 (maximum)
Perforated pipe above ground (mm)	N/A	N/A

[a] PUB (2018). Active, Beautiful, Clean Waters Design Guidelines (4th edition)
[b] Assuming that the catchment area is 90% impervious
[c] Assuming that the catchment area is 60% impervious

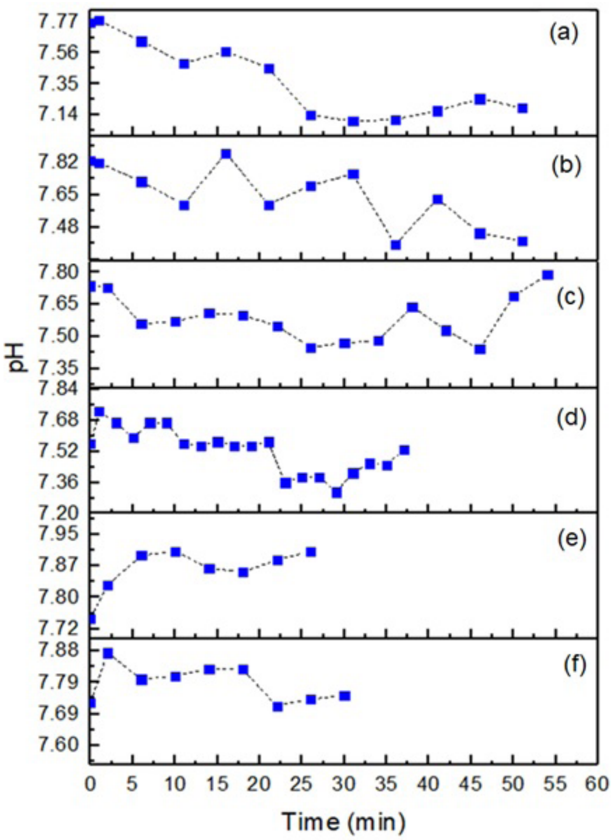

Figure A1. pH changes at the bioswale outlet during the simulated rainfalls in (a) Scenario A; (b) Scenario B; (c) Scenario C; (d) Scenario D; (e) Scenario E; and (f) Scenario F.

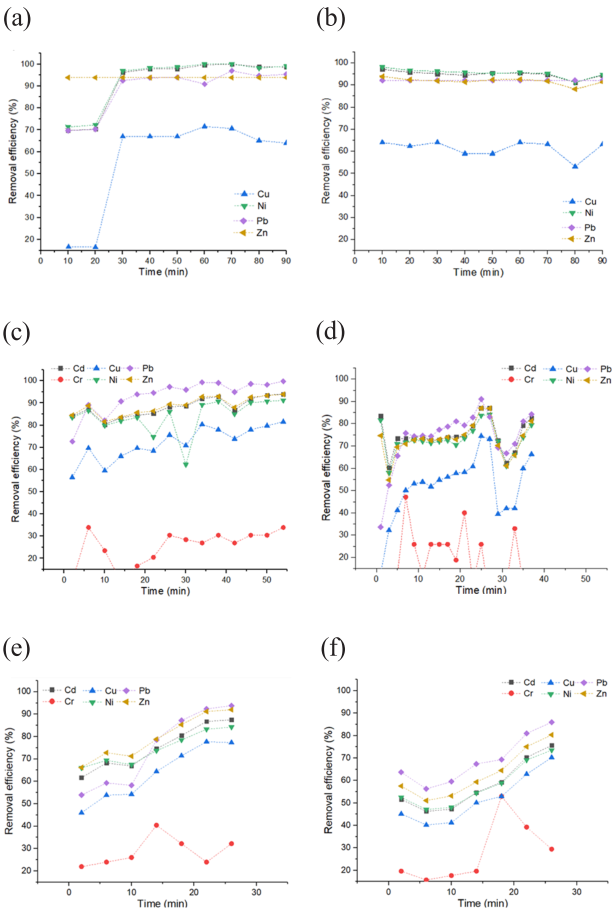

Figure A2. Metal removal by bioswale during the field tests: (a) Scenario A; (b) Scenario B; (c) Scenario C; (d) Scenario D; (e) Scenario E; and (f) Scenario F.

Notes on contributors

Dr Season Chen is an Assistant Professor at Tsinghua Shenzhen International Graduate School. She received her Ph.D. degree from The Hong Kong Polytechnic University (HK) under the supervision of Prof Dan Tsang. She is a Fulbright Scholar at Iowa State University and RGC Postdoc Fellow at City University of Hong Kong. Her research interests include valorisation of waste materials to valuable resources and environmental remediation. Dr Chen has published 50+ journal publications in top 10% journals with an h-index of 31 (Scopus).

Dr Yuqing Sun is an Assistant Professor at Sun Yat-Sen University (China), received her Ph.D. degree from The Hong Kong Polytechnic University (HK) under the supervision of Prof Dan Tsang, and continued her research as a Post-doc Fellow in Dan's group. Her research covers the customised design and application of engineered biochar in green and sustainable wastewater treatment. Dr Sun has published 50+ publications in top 10% journals including 15 Highly Cited Papers (Web of Science) with 4,200+ citations and an h-index of 36 (Scopus). Dr Sun was selected as Highly Cited Researcher 2022 (i.e., top 0.1%) in the academic field of Cross Field.

Dr Liang Chen is a Postdoctoral Fellow at The Hong Kong Polytechnic University. His research interests include sustainable waste-to-energy technologies, low-carbon hazardous waste treatment, CO_2 sequestration and utilisation in minerals. By Dec 2022, Dr Liang Chen had published more than 20 SCI papers, including two Hot papers, five Highly Cited Papers (Web of Science) with 1,300+ citations and an h-index of 21 (Scopus).

Ms Mingjing He is now a Ph.D. candidate at The Hong Kong Polytechnic University under the supervision of Prof Dan Tsang with the support of the Hong Kong Ph.D. Fellowship Scheme. She received her Master's Degree from Delft University of Technology with cum laude. Her research focused on the hydrothermal carbonisation of biomass for energy and environmental application. Ms He has published 21 top SCI journal articles with 700+ citations and an h-index of 13 (Scopus).

Mr Albert Chiu previously worked at Drainage Services Department, The Government of the Hong Kong Special Administrative Region (HKSAR) of the People's Republic of China. He was responsible for the Research and Development Project "Sustainable Drainage System (SuDS) at Stonecutters Island Sewage Treatment Works".

Mr William Cheung previously worked at Drainage Services Department, The Government of the Hong Kong Special Administrative Region (HKSAR) of the People's Republic of China. He was responsible for the Research and Development Project "Sustainable Drainage System (SuDS) at Stonecutters Island Sewage Treatment Works".

Prof Dan Tsang is a Professor and M.Sc. Programme Leader at The Hong Kong Polytechnic University. Dan strives to develop low-carbon engineering solutions to ensure sustainable urban development and attain carbon neutrality. His research interests include valorisation of biomass waste and emerging biochar design/application. Prof Tsang has published 500+ publications in top 10% journals and received 36,000+ citations with an h-index of 103 (Scopus). Dan was selected as Highly Cited Researchers 2022 (i.e., top 0.1%) in the academic fields of Engineering as well as Environment and Ecology.

References

[1] Charlesworth SM and Booth CA (2016). *Sustainable surface water management: a handbook for SuDS*. United States: John Wiley & Sons.

[2] Chen SS, Sun Y, Tsang DCW, Graham NJD, Ok YS, Feng YJ and Li XD (2017). Insights into the subsurface transport of As (V) and Se (VI) in produced water from hydraulic fracturing using soil samples from Qingshankou Formation, Songliao Basin, China. *Environmental Pollution*, 223, pp. 449-456.

[3] Chen SS, Tsang DCW, He M, Sun Y, Lau LSY, Leung RWM, Lau ESC, Hou D, Liu A and Mohanty S (2021). Designing sustainable drainage systems in subtropical cities: Challenges and opportunities. *Journal of Cleaner Production*, 280(2), pp. 124418.

[4] CIRIA (2015). *The SuDS manual*. [online report]. Available from: <https://www.ciria.org/ItemDetail?iProductCode=C753&Category=BOOK&WebsiteKey=3f18c87a-d62b-4eca-8ef4-9b09309c1c91>. [Accessed on 15 June 2021].

[5] Davis AP (2008). Field performance of bioretention: Hydrology impacts. *Journal of Hydrologic Engineering*, 13(2), 90-95.

[6] De Bilt V, Nieuwenhuis E, van de Ven F and Langeveld J (2021). Root causes of failures in sustainable urban drainage systems (SuDS): an exploratory study in 11 municipalities in The Netherlands. *Blue-Green Systems*, 3(1), pp. 31-48.

[7] DeBusk KM and Wynn TM (2011). Stormwater bioretention for runoff quality and quantity mitigation. *Journal of Environmental Engineering*. 137(9), pp. 800-808.

[8] Dietz ME and Clausen JC (2005). A field evaluation of rain garden flow and pollutant treatment. *Water, Air, & Soil Pollution*, 167, pp. 123-138.

[9] Ding B, Rezanezhad F, Gharedaghloo B, Van Cappellen P and Passeport E (2019). Bioretention cells under cold climate conditions: effects of freezing and thawing on water infiltration, soil structure, and nutrient removal. *Science of the Total Environment*, 649, pp. 749-759.

[10] Goh HW, Lem KS, Azizan NA, Chang CK, Talei A, Leow CS and Zakaria NA (2019). A review of bioretention components and nutrient removal under different climates-future directions for tropics. *Environmental Science and Pollution Research*, 26(15), pp. 14904-14919.

[11] Grebel JE, Mohanty SK, Torkelson AA, Boehm AB, Higgins CP, Maxwell RM, Nelson KL and Sedlak DL (2013). Engineered infiltration systems for urban stormwater reclamation. *Environmental Engineering Science*, 30(8), pp. 437-454.

[12] Hatt B, Fletcher TD and Deletic A (2009). Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. *Journal of Hydrology*, 365(3-4), pp. 310–321.

[13] He M, Xu Z, Hou D, Gao B, Cao X, Ok YS, Rinklebe J, Bolan NS and Tsang DCW (2022). Waste-derived biochar for water pollution control and sustainable development. *Nature Reviews Earth & Environment*, 3(7), pp. 444-460.

[14] Hering JG, Waite TD, Luthy RG, Drewes JE and Sedlak DL (2013). A changing framework for urban water systems. *Environmental Science & Technology*, 47(19), pp. 10721−10726.

[15] HK DSD (2014). *An integrated approach in flood prevention and water reclamation in a densely populated metropolitan: will the innovation work?* Paper Presented at the DSD International Conference 2014.

[16] HKO (2020). *The Weather of March 2020*. Available at: <https://www.weather.gov.hk/en/wxinfo/pastwx/mws2020/mws202003.htm>. [Accessed on 30 August 2022].

[17] HKO (2021). *Climate of Hong Kong*. Available at: <https://www.hko.gov.hk/en/cis/climahk.htm>. [Accessed on 17 January 2021].

[18] Jéssica AO, Felipe AC and Luís AMR (2019). Synthesis of zeolite from sugarcane bagasse fly ash and its application as a low-cost adsorbent to remove heavy metals. *Journal of Cleaner Production*, 229, pp. 956-963.

[19] Le Fevre GH, Paus KH, Natarajan P, Gulliver JS, Novak PJ and Hozalski RM (2015). Review of dissolved pollutants in urban storm water and their removal and fate in bioretention cells. *Journal of Environmental Engineering*, 141(1), pp. 04014050.

[20] Li J and Davis AP (2016). A unified look at phosphorus treatment using bioretention. *Water Research*, 90, pp. 141-155.

[21] Li X, Poon CS and Liu PS (2001). Heavy metal contamination of urban soils and street dusts in Hong Kong. *Applied Geochemistry*, 16 (11-12), pp. 1361-1368.

[22] Luo Y, Yue X, Duan Y, Zhou A, Gao Y and Zhang X (2020). A bilayer media bioretention system for enhanced nitrogen removal from road runoff. *Science of the Total Environment*, 705, pp. 135893.

[23] Luthy RG and Sedlak DL (2015). Urban water-supply reinvention. *Daedalus*, 144, pp. 72–82.

[24] Luthy RG, Sharvelle S and Dillon P (2019). Urban stormwater to enhance water supply. *Environmental Science & Technology*, 53(10), pp. 5534–5542.

[25] Mangangka IR and Liu A (2014). Performance characterization of a stormwater treatment bioretention basin. *Journal of Environmental Management*, 150, pp. 173-178.

[26] Marvin JT, Passeport E and Drake J (2020). State-of-the-art review of phosphorus sorption amendments in bioretention media: A systematic literature review. *Journal of Sustainable Water in the Built Environment*, 6(1), pp. 03119001.

[27] Milik J and Pasela R (2018). Analysis of concentration trends and origins of heavy metal loads in stormwater runoff in selected cities: A review. *E3S Web Conferences*, 44, pp. 00111.

[28] Paerl HW, Scott JT, McCarthy MJ, Newell SE, Gardner WS, Havens KE, Hoffman DK, and Wilhelm SW and Wurtsbaugh WA (2016). It takes two to tango: When and where dual nutrient (N & P) reductions are needed to protect lakes and downstream ecosystems. *Environmental Science & Technology*, 50(20), pp. 10805–10813.

[29] Passeport E, Hunt WF, Line DE, Smith RA, Brown RA, (2009). Field study of the ability of two grassed bioretention cells to reduce stormwater runoff pollution. *Journal of Irrigation and Drainage Engineering*, 135(4), pp. 505-510.

[30] Peng Y, Sun Y, Fan B, Zhang S, Bolan NS, Chen Q and Tsang DCW (2021a). Fe/Al (hydr)oxides engineered biochar for reducing phosphorus leaching from a fertile calcareous soil. *Journal of Cleaner Production*, 279, pp. 123877.

[31] Peng Y, Sun Y, Tsang DCW, Hanif A, Shang J, Shen Z, Hou D, Zhou Y, Chen Q and Ok YS (2021b). Design and fabrication of exfoliated Mg/Al layered double hydroxides on biochar support. *Journal of Cleaner Production*, 289, pp. 125142.

[32] PUB (2018). *Active, beautiful, clean waters design guidelines. 4th edition*. [online report]. Available at: <https://www.pub.gov.sg/Documents/ABC_Waters_Design_Guidelines.pdf>. [Accessed on 21 January 2021].

[33] Purvis R, Winston RJ, Hunt WF, Lipscomb B, Narayanaswamy K, McDaniel A, Lauffer MS and Libes S (2018). Evaluating the water quality benefits of a bioswale in Brunswick County, North Carolina (NC), USA. *Water*, 10(2), pp. 134.

[34] Qiu F, Zhao S, Zhao D, Wang J and Fu K (2019). Enhanced nutrient removal in bioretention systems modified with water treatment residuals and internal water storage zone. *Environmental Science: Water Research & Technology*, 5, pp. 993-1003.

[35] Roy-Poirier A, Champagne P and Filion Y (2010). Review of Bioretention System Research and Design: Past, Present, and Future. *Journal of Environmental Engineering*, 136(9), pp. 878-889.

[36] Sun Y, Chen SS, Lau AYT, Tsang DCW, Mohanty SK, Bhatnagar A, Rinklebe J, Lin KYA and Ok YS (2020). Waste-derived compost and biochar amendments for stormwater treatment in bioretention column: Co-transport of metals and colloids. *Journal of Hazardous Materials*, 383, pp. 121243.

[37] Sun Y, Lei C, Khan E, Chen SS, Tsang DCW, Ok YS, Lin DH, Feng YJ and Li XD (2017). Nanoscale zero-valent iron for metal/metalloid removal from model hydraulic fracturing wastewater. *Chemosphere*, 176, 315-323.

[38] SunY, Yu IKM, Tsang DCW, Cao XD, Lin DH, Wang LL, Graham NJD, Daniel, SA, Michael K, Ok YS, Feng YJ and Li XD (2019). Multifunctional iron-biochar composites for the removal of potentially toxic elements, inherent cations, and hetero-chloride from hydraulic fracturing wastewater. *Environment International*, 124, pp. 521-532.

[39] Toronto and Region Conservation Authority (2018). Effectiveness of retrofitted roadside biofilter swales – County court Boulevard, Brampton. [online report]. Available at: <https://sustainabletechnologies.ca/app/uploads/2020/11/CC-Bioswale-Tech-brief-2018-FINAL.pdf>. [Accessed on 29 August 2022].

[40] Trowsdale SA and Simcock R (2011). Urban stormwater treatment using bioretention. *Journal of Hydrology*, 397(3-4), pp. 167-174.

[41] Wang J, Chua LHC and Shanahan P (2017). Evaluation of pollutant removal efficiency of a bioretention basin and implications for stormwater management in tropical cities. *Environmental Science: Water Research & Technology*, 3(1), pp. 78-91.

[42] Wang J, Chua LHC and Shanahan P (2019). Hydrological modeling and field validation of a bioretention basin. *Journal of Environmental Management*, 240, pp. 149-159.

[43] Water by Design (2014). *Bioretention technical design guidelines*. [online report]. Available at: <https://waterbydesign.com.au/download/bioretention-technical-design-guidelines>. [Accessed on 21 January 2021].

[44] Whitehead P, Wilby R, Battarbee R, Kernan M and Wade AJ (2009). A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal*, 54(1), pp. 101-123.

[45] Xiong J, Ren S, He Y, Wang XC, Bai X, Wang J and Dzakpasu M (2019). Bioretention cell incorporating Fe-biochar and saturated zones for enhanced stormwater runoff treatment. *Chemosphere*, 237, pp. 124424.

[46] Yang Y and Chui TFM (2018). Optimizing surface and contributing areas of bioretention cells for stormwater runoff quality and quantity management. *Journal of Environmental Management*, 206, pp. 1090-1103.

[47] Zafra C, Temprano J and Suárezc J (2017). A simplified method for determining potential heavy metal loads washed-off by stormwater runoff from road-deposited sediments. *Science of the Total Environment*, 601-602, pp. 260-270.

[48] Zhang Y, Wang L, Chen L, Ma B, Zhang Y, Ni W and Tsang DCW (2021). Treatment of municipal solid waste incineration fly ash: State-of-the-art technologies and future perspectives. *Journal of Hazardous Materials*, 411(5), pp. 125132.