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Evaluation of Active, Beautiful, Clean Waters Design Features in Tropical Urban Cities: A Case Study in Singapore

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Abstract: In Singapore, active, beautiful, clean waters design features (ABCWDFs), such as rain gardens and vegetated swales, are used as a sustainable approach for stormwater management. Field monitoring studies characterising the performance of these design features in the tropical region are currently limited, hampering the widespread implementation of these systems. This study characterised the performance of individual ABCWDFs in the tropical climate context by monitoring a rain garden (FB7) and a vegetated swale (VS1) that were implemented in a 4-ha urban residential precinct for a period of 15 months. Results showed that total suspended solids (TSS), total phosphorus (TP) and total nitrogen (TN) concentrations were low in the new residential precinct runoff, leading to poor removal efficiency despite the effluent concentrations of individual ABCWDFs that were within the local stormwater treatment objectives. Average TSS, TP and TN EMCs of four sub-catchment outlets were lower (23.2 mg/L, 0.11 mg/L and 1.00 mg/L, respectively) when compared to the runoff quality of the major catchments in Singapore, potentially demonstrating that the ABCWDFs are effective in improving the catchment runoff quality. Findings from this study can help to better understand the performance of ABCWDFs receiving low influent concentrations and implications for further investigations to improve stormwater runoff management in the tropics.

Keywords: urban stormwater runoff management; field monitoring; ABC Waters design features; water quality; bioretention; swales

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1. Introduction

In an urban landscape, the high percentage of impervious surfaces often results in a greater volume of surface runoff [1,2]. Flood risks are higher due to an intense storm that generates a higher volume of surface runoff that exceeds the drainage design capacity. Deterioration of stormwater runoff quality inevitably occurs as catchments become more developed and stormwater runoff washes accumulated pollutants deposited on the impervious surfaces [3]. With increasing future urban developments, the level of imperviousness is likely to increase and deposition of pollutants would also increase with more development activities. Thus, it is essential to have an effective stormwater management solution that is built into the developments to capture, detain and treat the runoff before channeling it to downstream water bodies through drains or canals in order to maintain good water quality in the reservoirs.

Key blue–green infrastructures such as bioretention systems and vegetated swales are widely used in stormwater management solutions due to their effectiveness in the management of stormwater peak flow, runoff volume and stormwater pollution [4,5]. Bioretention systems are effective solutions for the removal of pollutants in stormwater runoff, such as suspended solids [6,7], nutrients [8–10] and heavy metals [11,12]. Vegetated swales were also reported to improve stormwater runoff quality [13–15]. However, the performance of vegetated swales in nutrient removal varies in different studies. Yu et al. [15] reported a decrease in stormwater phosphorus and nitrogen mass loadings after going through the grassed swale, while others reported an increase in nutrient concentration [14,16,17]. This variation can somewhat be attributed to the different characteristics of the runoff in terms of speciation and concentration in these studies.

In Singapore, the Active, Beautiful, Clean Waters (ABC Waters) Programme is a sustainable stormwater management approach that seamlessly integrates the environment, water bodies and the community. This creates new community spaces and lifestyles around developments where runoff is generated during wet weather whilst improving the water quality of urban runoff [18]. Where appropriately designed, ABC Waters design features (ABCWDFs) utilise blue–green systems that could manage stormwater quality and peak runoff before it is discharged into the downstream drainage system [18,19]. ABCWDFs use natural systems such as plants and soil to detain and treat stormwater runoff before discharging the cleansed runoff into the drainage system. Biodiversity and living environment are also supplemented with the implementation of ABCWDFs, which include bioretention basin (rain garden), bioretention swales, vegetated swales, constructed wetlands and sedimentation basins. The ABC Waters design guidelines were originally referenced from temperate countries such as Australia [20] and were adapted to Singapore's context. However, Singapore being a tropical country has different meteorological conditions such as rainfall, temperature, humidity and evapotranspiration rate [21]. Guidelines applicable to temperature contexts might not be suitable in Singapore. The difference in rainfall characteristics implies systems need to be sized larger in terms of surface area and storage capacity in tropical climates. Pollutant generation differs between the two rainfall regimes with a high annual mean rainfall typically leading to lower stormwater runoff pollutants concentration [22]. The runoff pollutant concentration can affect the assessment of the performance of stormwater management features [23,24]. Lintern et al. [23] reported that the influent pollutant (nutrients) concentration was found to be strongly correlated with the effluent coming out from the stormwater management systems. Thus, the results from these temperate field studies might not be adopted as the actual performance of stormwater management features in such tropical countries [21]. Present field-scale studies were also evaluated based on actual rain events. Few studies provided a simulation of water features under extreme weather conditions. With the advent of global climate changes, extreme weather conditions such as prolonged dry and wet periods would be increasingly common. Harsh conditions such as prolonged antecedent dry period (ADP) were reported to affect runoff retention and pollutants removal performance [25–27]. Batalini de Macedo et al. [25] found that soil moisture largely affected runoff retention efficiency during a dry period while rainfall depth and intensity is the primary factor during the wet period. On a smaller laboratory scale, Zinger et al. [10] reported that ADP affects changes in hydraulic conductivity of bioretention systems that affect solids and nutrient removal.

Herein, this paper aims to evaluate the performance of the ABCWDFs in a tropical urban context. A residential precinct-scale study spanning for a period of 15 months was conducted in Singapore and used as a case study, facilitating further improvements to existing stormwater management systems. To keep up with global climate changes, the performance of the ABC design was also assessed under challenging operational conditions (e.g., simulated events with prolonged dry periods and higher pollutant concentrations). Hence, the effectiveness and feasibility of these design features can be better understood in terms of managing stormwater runoff from more polluted sources. This paper serves to supplement the knowledge with regards to the field performance of ABCWDFs (in terms of water quantity and quality improvements) in the tropical setting. This field monitoring study also aims to determine whether water quality targets can be achieved at the catchment scale with the implementation of ABCWDFs.

2. Materials and Methods

2.1. Study Area

The study area is a 4-ha pilot urban residential project (Figure 1) named Waterway Ridges, in collaboration with Singapore's Water Agency (PUB) and the Housing Development Board of Singapore (HDB). The study area is an urbanised residential precinct of around 4 ha. Various ABCWDFs were built in the entire precinct (21 bioretention basins or rain gardens, 4 vegetated swales and 2 gravel swales) and the precinct is divided into 4 sub-catchment areas (Figure 1) with 4 distinct sampling outlets (SP1–SP4). Detailed design for each design feature can be found in the hydraulic modelling study by Yau et al. [28]. For the purpose of this study, a representative rain garden and vegetated swale was monitored. The rain garden (FB7) was selected due to its close proximity to the central location of the precinct whereas the vegetated swale (VS1) was selected due to its close proximity to the main road. The 4 catchment outlets of the residential precinct were also monitored for water quantity and quality. Detailed design characteristics of the monitored ABCWDFs and precinct outlets are summarised in Table 1.

Table 1. Characteristics of the monitored ABCWDFs and the 4 catchment outlets of the monitored precinct.

		Monitored ABCWDFs		
	FB7		**VS1**	
Construction completion	April 2017		April 2017	
Drainage area	572 m^2 (236 m^2—roof, 12 m^2—other impervious, 244 m^2 pervious)		806 m^2 (442 m^2—roof, 81 m^2—other impervious, 163 m^2 pervious)	
Surface area	80 m^2		120 m^2	
Media depth	0.40 m		- [a]	
Number of inlet points	1		2	
		Monitored Sub-Catchments		
	SP1	***SP2***	***SP3***	***SP4***
Catchment area	13,833 m^2	15,713 m^2	2176 m^2	8105 m^2
Impervious fraction	0.69	0.71	0.53	0.69
Area treated (percentage of total area)	32%	57%	62%	88%
ABCWDFs present [b]	Bioretention system (5) Swale system (2)	Bioretention system (11) Swale system (4)	Bioretention system (1)	Bioretention system (4)

[a] there is no filter media depth for vegetated swale. [b] bioretention system includes both bioretention basin and bioretention lawn; swale system includes both vegetated swale and gravel swale.

FB7 is a bioretention basin/rain garden in catchment 2 with a surface area of 80 m^2 and a soil-based filter media depth of 400 mm. The bottom of the rain garden is lined with an impermeable liner and the overflow pit allows a maximum detention depth of 200 mm. This feature received runoff predominantly from the roof of surrounding residential buildings. Both the inlet (*FB7-Inlet*) and outlet of FB7 (*FB7-Outlet*) were monitored for water quantity and water quality.

VS1 is a vegetated swale that is gravel-lined and vegetated with short grass located in catchment 1. It does not have an impermeable liner at the bottom of the gravel-lined layer. It has two inlet points for stormwater runoff. The first inlet point (*VS1-1-Inlet*) is located at the top of the slope while the second inlet point (*VS1-2-Inlet*) is in the middle of the swale. However, only *VS1-1-Inlet* was monitored for water quantity and quality due to instrumental error at *VS1-2-Inlet*. As the catchment characteristics for both inlet points are similar (roof catchment with similar area), the water quality characteristics of both inlet points are assumed to be the same. For a more holistic and accurate assessment of the entire VS1, the water quantity information for *VS1-2-Inlet* was obtained from calibrated model simulation (Model for Urban Stormwater Improvement Conceptualisation, MUSIC V6, for simulation of hydrological model and Water Sensitive Urban Design (WSUD) systems) [29].

The outlet of VS1 (*VS1-Outlet*) was also monitored for both water quantity and quality, where it captures effluent of VS1 that travels through the surface of the swale.

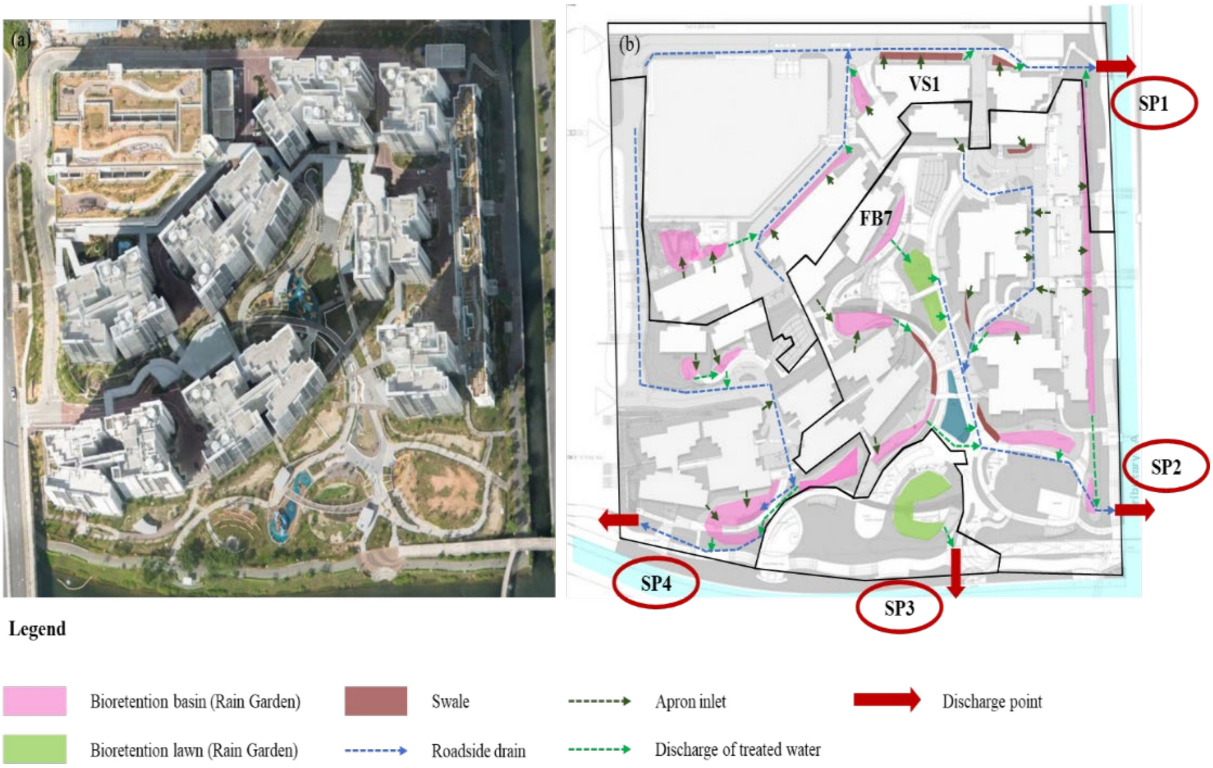

Figure 1. Satellite image of monitored precinct (**a**); Location of monitored ABC water design features (FB7—bioretention system, VS1—swale system) and catchment outlet stormwater drains (SP1–SP4) (**b**).

2.2. Natural Storm Events Monitoring Protocol and Sampling Methodology

The monitoring study spanned a period of 15 months that corresponded to the wet and dry periods in Singapore caused by local monsoon. A pressure transducer (4–20 mA, Heron, ON, Canada) and 90° V-notch weir plate were used to continuously monitor flow depth (interval of 15 s) at the inlet and outlet of the ABCWDFs. Discharge (L/s) and total volume (L) were calculated by incorporating the use of the stage–discharge rating curve Measurements of water level and flow rate at each monitoring point were taken to generate the reliable stage–discharge rating curve. The curve is further refined and calibrated twice throughout the monitoring period). For the discharge at the catchment outlets, area–velocity (AV) sensors (2150, ISCO, Lincoln, NE, USA) were used. Automatic water samplers (3700, ISCO, Lincoln, NE, USA) were set to collect a maximum of 24 water samples using a time-based discrete sampling method. A total of 1 L of stormwater runoff samples were collected at a user-defined interval. Rainfall depth was monitored using a tipping bucket rain gauge (TB3, Hydrological Services, Lakeworth, FL, USA), installed at the high open space within the precinct. Rainfall information from the rain gauge was logged at a 1 min interval.

Water quality samples were collected within 24 h of each storm event and transported in an icebox to SINGLAS-accredited laboratory for water quality testing. For each event, 10 samples were chosen out of the 24 samples for testing based on the hyetograph of the event. The selection of the 10 samples reflected the full spread of rainfall and aimed to capture all the rising and falling limbs of the rainfall. More priority was given to the first few samples to focus on "first flush" concentrations.

Over the monitoring period, water quality data were collected for 12 events. The characteristics of the monitored storm events are given in the supporting document (Table S1).

2.3. Challenge Test Framework and Sampling Methodology

The challenge test framework developed for this study was adapted from prior challenge test study by Zhang et al. [27]. The two ABCWDFs were artificially spiked with synthetic stormwater, with a target pollutants concentration representing the 95th percentile of Singapore's stormwater EMC. Detailed chemicals and target pollutant concentration can be found in Table S2 of supplementary information. Water from the waterway beside the study area was pumped into a mixing tank (1 m^3) and prepared chemicals were mixed using an internal recirculation pump. The mixed-dosed water was then released to the ABCWDFs. The pumping and mixing steps were repeated to attain the event volume for the tests. For sampling, three inflow samples were taken from the outlet hose of the mixing tank and were then composited into a 1 L sample. For the outflow samples, volume-based sampling was conducted (Table S2 in supplementary information). Once the water samples were collected, they were stored in an icebox and delivered to the same laboratory at the end of the challenge test within 8 h for water quality testing.

A total of 4 challenge tests for each ABCWDF (summarised in Table 2) was conducted to study the effects of various antecedent dry period (ADP). Two scenarios were simulated: extreme wet and extreme dry conditions. For extreme wet simulation (simulating back-to-back storm events), 12 h were selected. For extreme dry simulation, the longest antecedent dry period was represented by the 95th percentile of the dry period experienced by the study area, which was found to be 6 days (144 h). This value was estimated using 8 years of rainfall data from the nearest meteorological station from the study area.

Table 2. Summary of challenge test conditions.

ABCWDFs	Challenge Test ID	Date	Antecedent Dry Period (h)	Event Volume (m^3)
FB7	Challenge Test 1 (*FB-CT1*)	28 February 2019	240	14
	Natural Storm Events	[a]	-	-
	Challenge Test 2 (*FB-CT2*)	12 March 2019	16	14
	Challenge Test 3 (*FB-CT3*)	13 March 2019	12	14
	Challenge Test 4 (*FB-CT4*)	20 March 2019	144	15
VS1	Challenge Test 1 (*VS-CT1*)	25 February 2019	168	9
	Challenge Test 2 (VS-CT2)	26 February 2019	12	12
	Challenge Test 3 (VS-CT3)	5 March 2019	144	15
	Natural Storm Events	[b]	-	-
	Challenge Test 4 (*VS-CT4*)	28 March 2019	144	12

[a] 1 rainfall event observed on 11 March 2019 (26.2 mm). [b] 2 rainfall events observed on 11 March 2019 (26.2 mm) and 21 March 2019 (19.6 mm).

For the event volume for extreme wet simulation, 1.1 times the pore volumes of the ABCWDFs were selected as the event volume (Table S2 in supplementary information). For extreme dry simulation, a larger event volume for the challenge tests was needed as more water was needed to fill up the drier pores of the filter media. As such, a MUSIC model was set up for the catchment and the 95th percentile of runoff volume received by the ABCWDFs (simulated by MUSIC) was selected as the event volume. Details of the calculation can be found in Table S2 of supplementary information.

2.4. Water Quality Analysis

For both water samples from natural storm events and challenge tests, testing was conducted in accordance with the Standard Method for the Examination of Water and Wastewater [30]. The tested parameters are listed in Table S4 (supplementary information).

2.5. Performance Assessment and Analysis

In this study, the water quantity and quality data were used to compute the Event Mean Concentration (EMC) of TSS, TP and TN. When the pollutant concentration of the water samples was below the detection limit, half of the lowest detection limit was selected to estimate the EMC [31]. To calculate the efficiency of pollutant removal in ABCWDFs, the efficiency ratio (ER) method was used to assess the performance of these design features [32]. Student *t*-test was conducted to demonstrate the significance of results. A *p*-value of <0.05 is considered significant. The performance of the ABCWDFs was compared with the stormwater treatment objectives in Singapore [18], listed in Table 3 below.

Table 3. Stormwater treatment objectives for Singapore [18].

Pollutants	Stormwater Treatment Objectives
Total Suspended Solids (TSS)	80% Removal or less than 10 mg/L
Total Nitrogen (TN)	45% Removal or less than 1.2 mg/L
Total Phosphorus (TP)	45% Removal or less than 0.08 mg/L

3. Results

3.1. Characteristics of Influent Stormwater Runoff

For FB7-Inlet, water quality data from nine events were measured. TSS influent EMCs ranged from 7.4 to 23.8 mg/L (average of 11.3 mg/L), TP influent EMCs ranged from 0.03 to 0.42 mg/L (average of 0.12 mg/L) and TN influent EMCs ranged from 0.38 to 1.50 mg/L (average of 0.92 mg/L). For VS1-1-Inlet, water quality data from eight events were gathered. TSS influent EMCs for this point ranged from 21.1 to 190.6 mg/L (average of 88.4 mg/L), TP influent EMCs ranged from 0.04 to 0.43 mg/L (average of 0.27 mg/L) and TN influent EMCs ranged from 1.19 to 2.84 mg/L (average of 2.02 mg/L).

Overall, the precinct stormwater runoff (represented by the average of FB7-Inlet and VS1-1-Inlet) in this study had a much lower EMC for TSS, TP and TN when compared to the world data for high urban areas reported by Duncan [22] (Table 4). It is important to note that stormwater runoff concentration depends heavily on land uses [22]. For the precinct in this study, the monitored catchments are predominantly hard roof catchments, which typically have lower levels of pollutant generation compared to other surfaces such as road, pedestrian footpaths and parkland. The TP and TN runoff concentrations observed in this study were also comparable to the observations from another study in Queenstown [33], another urban residential area in Singapore.

Table 4. Runoff water quality of the precinct and comparison with literature studies.

	Runoff Pollutants EMC		
	Average TSS EMC (mg/L)	**Average TP EMC (mg/L)**	**Average TN EMC (mg/L)**
This study			
FB7-Inlet (9 events)	11.3	0.12	0.92
VS1-1-Inlet (8 events)	88.4	0.27	2.02
Average	**49.9**	**0.2**	**1.47**
Literature			
(Duncan, 1999)			
High Urban Areas	155	0.32	2.63
Roofs	35	0.13	
(Lim, 2003)			
Queenstown high urban residential	100	0.13	1.25

Typically, as the antecedent dry period increases, more pollutants will accumulate and this leads to higher loading or concentration in the stormwater runoff. The first flush analysis was conducted to further verify the relationship between runoff pollutants loading/concentration and ADP. Bertrand-Krajewski [34] proposed that a significant first flush phenomenon arises when 80% of pollutant loads were transported within the first 30% of runoff volume. This signifies that the pollutants were disproportionately high discharge in the beginning stage of a storm event [35]. Using the established criteria from Bertrand-Krajewski [34], there was no presence of the first flush phenomenon for TSS, TP and TN. The dimensionless cumulative pollutant load against the dimensionless cumulative runoff volume (MV curve) for the storm event is shown in Figure S1. From

Figure 2, it is interesting to note that there was no trend being observed between ADP and the EMC/loadings of the stormwater runoff (low R^2 values). This could be attributed to the high frequency and intensity of storm events of the tropical meteorological condition in Singapore. Stormwater pollutants' wash-off happened more often and led to a decrease in pollutant accumulation [36]. Furthermore, the monitored precinct is rather new (construction was completed 1 year prior to the field monitoring), which may lead to a lower accumulation of stormwater pollutants. Overall, this observation of low stormwater runoff concentration was obtained based on 17 samples (11 storm events) with small catchment areas. The results should be further validated by conducting a larger-scale monitoring study with more storm events. Despite Singapore being an urbanised developed country with a high impervious percentage, the runoff quality observation in this study might not be representative of other countries in the tropical region. Furthermore, effective pollutant source management solutions such as strict erosion control practices and routine drainage system maintenance from PUB minimised the presence of urban pollutants within the catchment in Singapore [37].

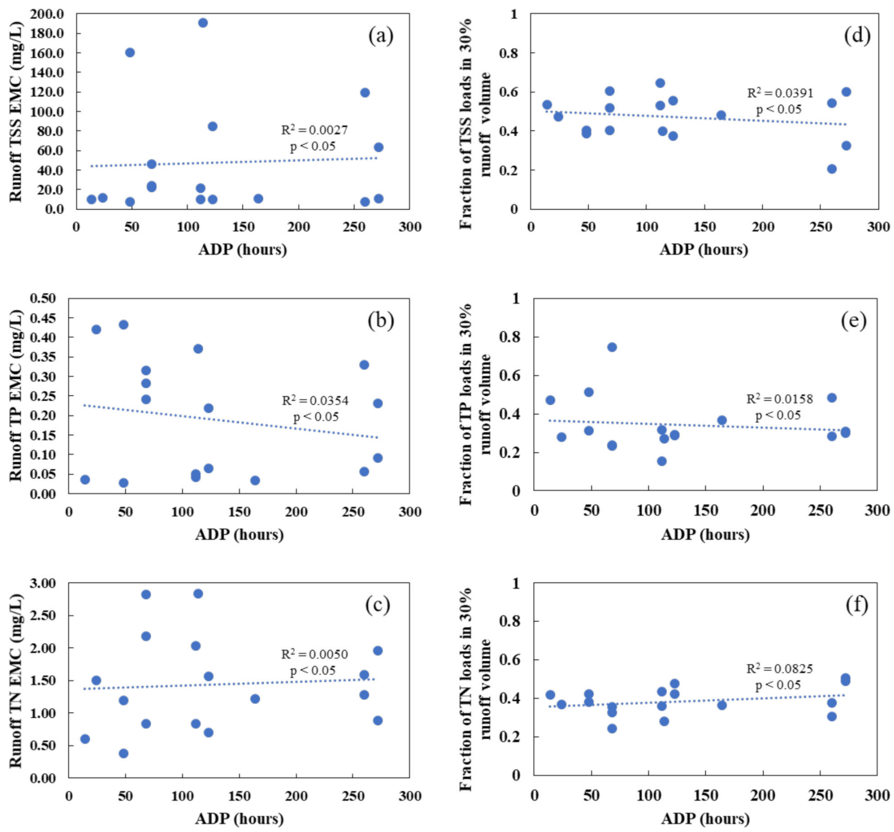

Figure 2. Inflow pollutants EMC against ADP (**a**–**c**); Fraction of pollutants loads in 30% of runoff volume against ADP (**d**–**f**).

3.2. Treatment Performance of Rain Garden

3.2.1. Natural Storm Events

A total of six natural storm events were monitored for the FB7 system (Table 5). Effluent TSS EMCs ranged from 6.3 to 20.7 mg/L (average of 13.4 mg/L), effluent TP EMCs ranged from 0.07 to 0.58 mg/L (average of 0.19 mg/L) while effluent TN EMCs ranged from 0.39 to 1.15 mg/L (average of 0.73 mg/L). Altogether, variation in the inflow concentrations over an event was observed due to the initial spike in pollutant concentration and this was observed for most monitored storm events. On the other hand, pollutant concentrations of the effluent were relatively steadier with minimal fluctuations. An example can be seen from the inflow and outflow TSS, TP and TN pollutographs of FB7 for Event 4 (Figure 3).

Table 5. Pollutant EMC and loads removal for FB7 and VS1 during monitored storm events and challenge tests.

ID	Pollutant EMC								
	TSS			TP			TN		
	Influent (mg/L)	Effluent (mg/L)	Removal (%)	Influent (mg/L)	Effluent (mg/L)	Removal (%)	Influent (mg/L)	Effluent (mg/L)	Removal (%)
Rain garden (FB7) during monitored storm events									
Event 3 [a]	10.9	20.3	−86.4	0.03	0.07	−116.0	1.22	1.15	5.4
Event 4	23.8	6.3	73.4	0.28	0.14	51.6	0.83	0.39	52.8
Event 8	9.8	12.4	−25.7	0.06	0.15	−131.5	0.71	0.73	−3.4
Event 9	7.7	20.7	−168.0	0.06	0.12	−112.7	1.29	0.55	56.9
Event 11	11.7	10.7	8.3	0.42	0.58	−39.1	1.50	0.97	35.6
Event 12	9.8	10.1	−2.5	0.04	0.09	−164.3	0.60	0.59	0.8
Average	**12.3**	**13.4**	**−33.5**	**0.15**	**0.19**	**−85.3**	**1.02**	**0.73**	**24.7**
Rain garden (FB7) during challenge tests									
FB-CT1	32.1	2.3	92.9	0.18	0.04	76.7	3.19	1.93	39.4
FB-CT2	25.1	3.0	87.9	0.23	0.06	73.5	3.20	1.62	49.5
FB-CT3	40.4	6.0	85.2	0.23	0.06	74.5	3.19	1.86	41.6
FB-CT4	44.7	4.2	90.7	0.29	0.07	75.0	3.11	1.88	39.4
Average	**35.6**	**3.9**	**89.2**	**0.23**	**0.06**	**74.9**	**3.17**	**1.82**	**42.5**
Vegetated swale (VS1) during monitored storm events [b]									
Event 7	61.8	145.4	−135.5	0.25	0.12	53.0	2.55	0.89	65.0
Event 8	86.4	70.5	18.4	0.22	0.11	51.9	1.70	0.81	52.4
Event 9	116.8	46.4	60.3	0.44	0.17	60.9	2.00	0.71	64.4
Event 10	180.0	44.8	75.1	0.36	0.07	80.1	2.76	1.25	54.8
Average	**111.2**	**76.8**	**4.6**	**0.32**	**0.12**	**61.5**	**2.25**	**0.92**	**59.1**
Vegetated swale (VS1) during challenge tests									
VS-CT1	39.7	17.8	55.2	0.24	0.23	3.9	3.06	2.78	9.3
VS-CT2	34.5	9.6	72.2	0.15	0.12	16.7	2.93	2.55	12.9
VS-CT3	32.9	13.2	59.9	0.14	0.13	5.3	2.69	2.58	4.2
VS-CT4	44.5	5.8	86.9	0.24	0.21	11.9	3.40	3.17	6.6
Average	**37.9**	**11.6**	**68.6**	**0.19**	**0.17**	**9.5**	**3.02**	**2.77**	**8.3**

[a] accumulation of sediments at the weir plate, causing some inaccurate water level readings. [b] assumed that water quality information for VS1-1-Inlet and VS1-2-Inlet were the same.

FB7 generally performed well in TSS removal with the average effluent TSS EMCs similar to the treatment objectives of 10.0 mg/L as stipulated in the ABC Waters design guidelines. However, if the system is assessed based on the percentage removal efficiency, poor efficiency (−34%) was obtained due to the low influent TSS EMCs [38]. Various field studies in the temperate region reported a similar range of bioretention effluent TSS concentration [39,40], but positive removal efficiency due to higher influent TSS concentration. Similar to the TSS removal performance of another rain garden in the tropics, previous field monitoring studies of Balam estate rain garden [19] showed lower TSS EMC removal efficiency of 57%, caused by the low influent TSS concentration. Both effluent concentration and removal efficiency ratios should be considered for practical and effective stormwater runoff management practices. This also highlights the importance of considering inflow pollutants concentration when assessing the performance of ABCWDFs, especially in a catchment with low pollutant generation sources.

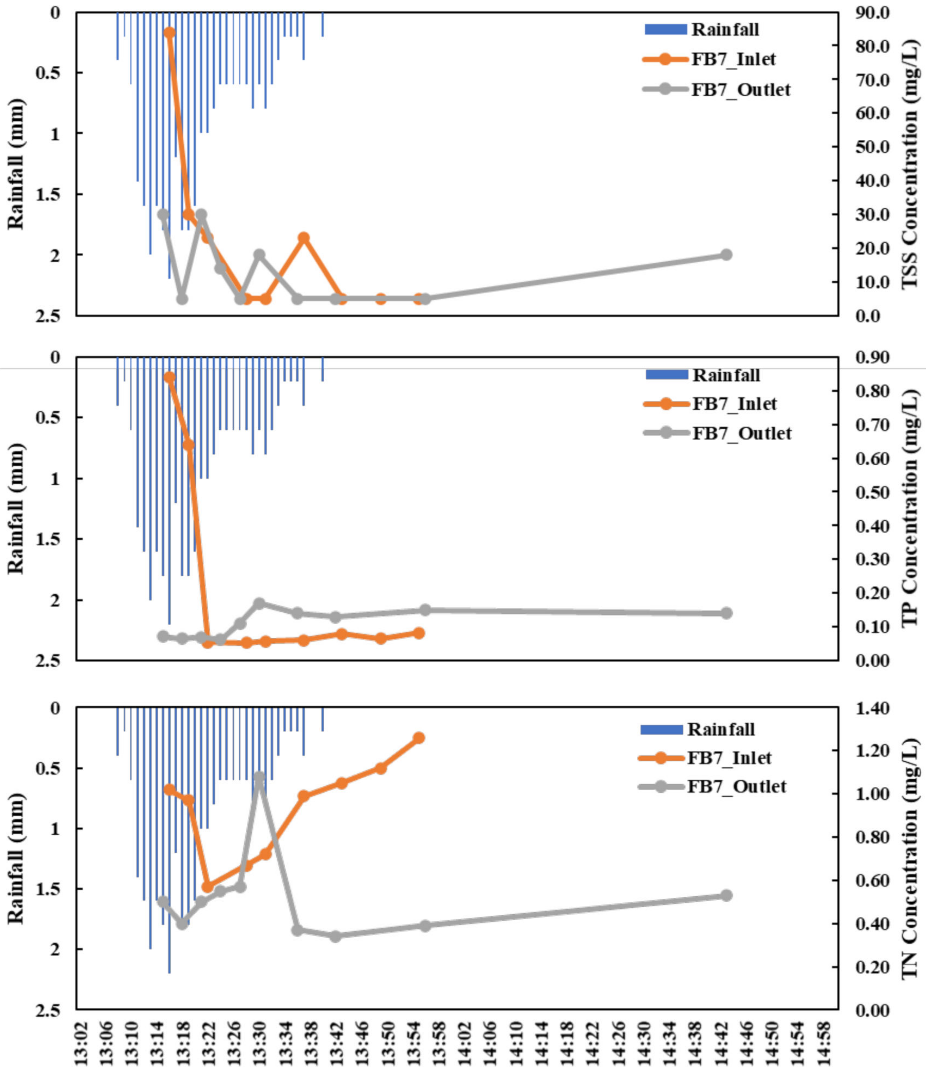

Figure 3. FB7 TSS, TP and TN pollutographs for Event 4.

Similarly, for TP, negative percentage removal efficiency (−85%) was obtained due to low influent TP EMCs. A total of four out of six monitored events had TP influent EMC that was lower than the stormwater quality objectives of 0.08 mg/L. The low influent TP EMC could be due to little phosphorus loading from the rooftop catchment areas (which are not accessible to the general public and hence have fewer anthropogenic activities), in addition to the fact that the development is relatively new. A similar observation was found in the monitoring studies of the Balam estate rain garden [19], where only 27% of TP removal was noted for the rain garden due to the low TP influent EMC.

Likewise, due to the low influent TN EMCs, the average removal efficiency of 25% was observed although the effluent TN EMCs were below the stormwater quality objectives of 1.2 mg/L for all monitored events. TN removal efficiency fluctuated between −3% and 57%. Given that FB7 does not have designed components for denitrification such as a submerged layer or carbon source additives, the TN removal was expected and similar to some of the bioretention studies (without submerged zone and additives) in the literature [40,41].

3.2.2. Challenge Tests

When subjected to higher pollutant loading (in comparison with the natural storm events), clear pollutant reduction patterns for the bioretention system were observed for all four challenge tests. The pollutant removal efficiency of TSS, TP and TN were comparable between the four challenge tests conducted (Table 5). For TSS and TP, all four challenge tests for FB7 showed good EMC removal efficiency for TSS and TP (average of 89% and 75%, respectively). The high TSS performance of the system ($p < 0.05$) demonstrates efficient physical filtration. As phosphorus is closely associated with sediment removal of stormwater runoff (Wu et al., 1998), the high and significant TP removal ($p < 0.05$) is not surprising. High TP removal was also observed in other biofiltration studies [39,42]. Effluent TSS and TP EMCs for all four tests were below the stormwater quality objectives, highlighting the effectiveness of the rain garden in removing stormwater pollutants.

The removal mechanisms of nitrogen are much more complicated compared to phosphorus or suspended solids removal. Particulate nitrogen can be trapped by the soil media via sedimentation and filtration, while dissolved nitrogen could be removed via adsorption or biological uptake by plants [43,44]. From the four TN pollutographs of the challenge tests (Figure 4), it was observed that there was a sudden decrease, followed by a gradual increase in the TN pollutant concentration. This is a characteristic of bioretention systems whereby the pore water within the FB7 soil media, which has a better water quality, was purged out by the influent challenge test water. The lower initial TN concentration could also be due to the sorption of nitrate to the active sites of the soil particles when the challenge test water first percolated through the system. When the active sites were all occupied, nitrate was not removed through sorption. Thus, subsequent samples contained higher nitrate concentration (not shown) and TN concentration. All four tests showed a decent average removal efficiency (42.5%), with 39.4% for FB-CT1, 49.5% for FB-CT2, 41.6% for FB-CT3 and 39.4% for FB-CT4 ($p < 0.05$). The nitrogen removal of the challenge tests is similar except for FB-CT2, which had a lower effluent TN EMC (Table 5). This might be caused by the antecedent natural storm event (rainfall depth of 21.0 mm) that occurred before FB-CT2. As mentioned in the previous section, stormwater runoff in the study area has low pollutants concentration and this may lead to cleaner FB7 pore water that reduces the overall effluent TN concentration of subsequent test (FB-CT2).

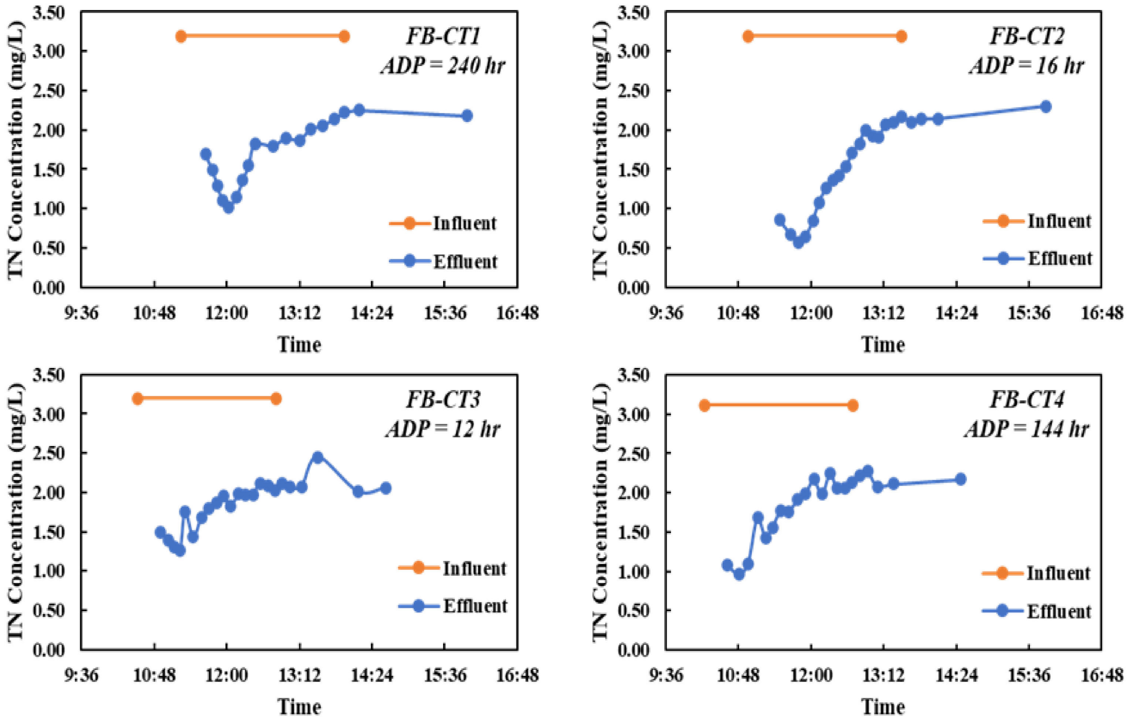

Figure 4. TN pollutographs for FB7 challenge tests.

Hatt et al. [26] found that bioretention effluent nitrate concentration was increased as ADP increased due to the synergistic effect of temperature and moisture (influenced by seasonality and ADP), which may affect the biological processing of nitrogen. Besides that, alternating wetting and drying conditions were shown to affect the soil moisture of the bioretention systems, causing implications to the nitrogen removal performance [44]. However, a tropical country such as Singapore has a minimal seasonality effect. For example, Chui and Tringh [45] found that the average time intervals between consecutive storm events in Singapore were short and this is distinctive as compared to temperate countries. More monitoring studies can be conducted to investigate the relationship between ADP or soil moisture and nitrogen removal in a tropical context.

3.3. Treatment Performance of Vegetated Swale

3.3.1. Natural Storm Events

A total of four water quality datasets for VS1 were obtained. In order to provide a better assessment of VS1, the calculation of inflow pollutant EMC was carried out by dividing the summation of total pollutants load from both VS1-1-Inlet (measured) and VS1-2-Inlet (modelled) with the total event volume.

Influent TSS EMCs ranged from 61.8 to 180.0 mg/L with an average of 111.2 mg/L. Most effluent samples had a lower TSS concentration than the influent, displaying the effectiveness of the swale in reducing solid particles from stormwater runoff (Figure 5). The primary mechanism of TSS removal in the vegetated swale is the sedimentation and filtration process. The removal is influenced by the flow path length, roughness and influent particle size distribution [14]. However, effluent TSS EMCs ranged from 44.8 to 145.4 mg/L (average of 76.8 mg/L), which is higher than the stormwater quality objective of 10.0 mg/L. Throughout the monitoring study, small gravels were found accumulating before the weir plate of VS1-2-Inlet during and after a storm event. Thus, these small gravels were washed off from the landscaping areas (within the contributing catchment) to the swale surface and ended up in the effluent collected at VS1-Outlet.

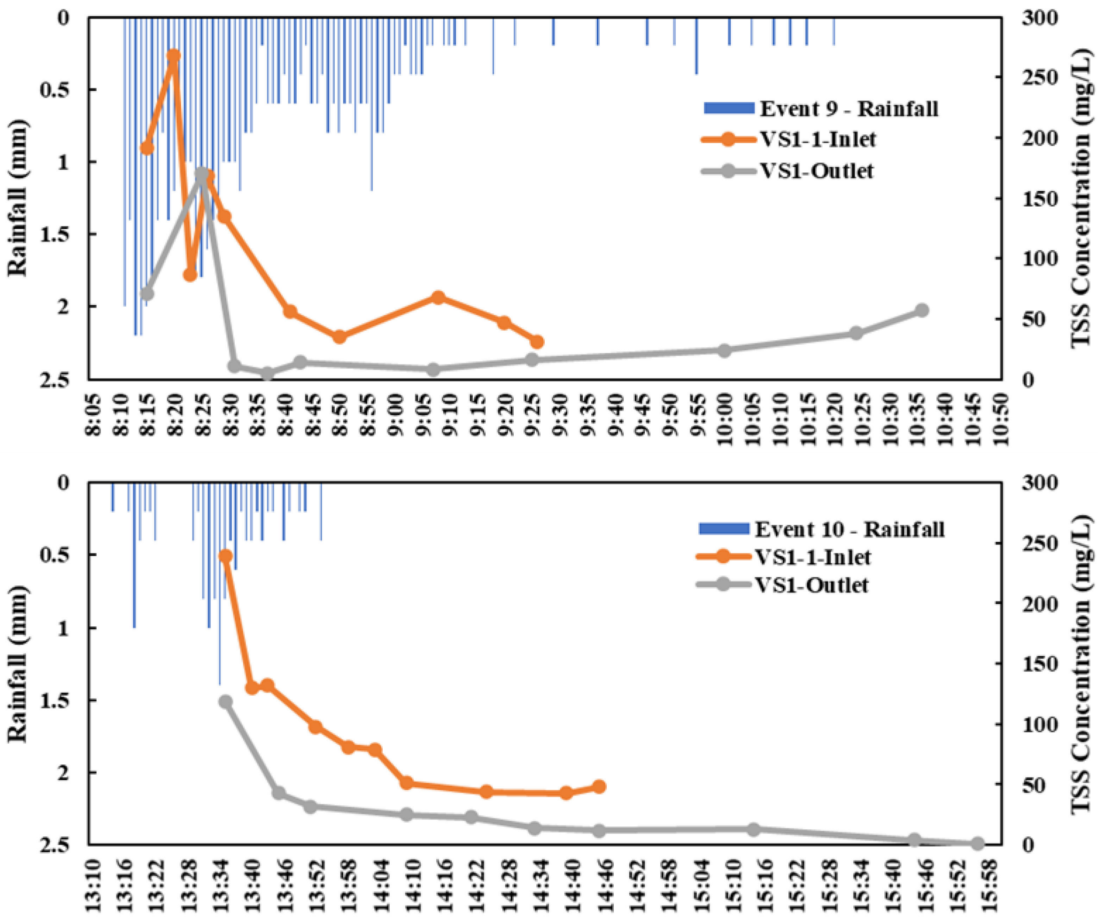

Figure 5. VS1 TSS pollutographs for Event 9 and Event 10.

For phosphorus and nitrogen, influent TP EMCs ranged from 0.22 to 0.36 mg/L (average of 0.32 mg/L) while TN EMCs ranged from 1.70 to 2.76 mg/L (average of 2.25 mg/L). On the other hand, the swale effluent TP EMCs ranged from 0.07 to 0.17 mg/L (average of 0.12 mg/L) while effluent TN ranged from 0.71 to 1.25 mg/L (average of 0.92 mg/L), which were comparable to the stormwater quality objectives of 0.08 mg/L and 1.2 mg/L, respectively (both $p < 0.05$). The low effluent nutrients concentration could again be attributed to two points: (1) the low influent pollutant concentration of the catchment in general; (2) VS1 is unlined and the exfiltration leads to the loss of some TP and TN pollutants, causing a "cleaner" effluent. Fardel et al. [46] analysed swale performance in the literature and found that inflow pollutants concentration was strongly correlated with the pollutants efficiency ratios of the swale system.

3.3.2. Challenge Tests

The four challenge tests for VS1 showed decent removal of TSS with an average removal efficiency of 69.0%, with a range of 55.2% to 86.9% ($p < 0.05$). The effluent of the challenge tests (average of 11.6 mg/L) was just slightly higher than the stormwater quality objectives for TSS. The long-vegetated swale typically conveys the stormwater at a slower speed compared to concrete stormwater drains and this allows better settlement of sediments. Other runoff simulation experiments also reported similar TSS EMC reduction (61%–86% for Deletic and Fletcher [47]; 79%–98% for Bäckström [48]).

For TP and TN, all four tests showed poor removal efficiency with an average of 9.4% and 8.2%, respectively. In terms of effluent concentration, the four tests displayed an average concentration of 0.17 mg/L and 2.77 mg/L for TP and TN, respectively (both $p < 0.05$). The absolute difference in concentration between challenge tests influent and effluent is, however, very small. The results are not surprising as TN and TP removal require adequate retention time (affected by flow velocity) for better pollutant removal [15,49]. It is likely that the nutrient reduction observed in the VS1 challenge tests is attributed to the removal of sediment particles, to which the nutrients are attached [50].

Another thing to take note of is that there were no obvious differences in VS1 pollutant treatment performance between the various operating conditions. The dry duration between consecutive challenge test events did not affect the pollutants removal efficiency since the major factor that affects the water quality improvements of vegetated swale is most likely the swale length and slope ratio [14].

3.4. Water Quality of Entire Precinct

The water quality performance of the entire precinct was monitored and summarised in Table 6.

Table 6. EMCs for the catchment outlets.

	EMC		
	Min–Max (Mean)		
Catchment Outlets	**TSS (mg/L)**	**TP (mg/L)**	**TN (mg/L)**
SP1	16.2–50.3 (32.5)	0.07–0.18 (0.10)	0.63–2.09 (1.26)
SP2	17.4–55.5 (30.7)	0.06–0.22 (0.12)	0.77–1.60 (1.08)
SP3	3.8–48.1 (12.8)	0.04–0.16 (0.10)	0.30–1.02 (0.67)
SP4	8.8–37.3 (16.6)	0.04–0.17 (0.10)	0.69–1.38 (0.99)
Average	**23.2**	**0.11**	**1.00**

SP1 and SP2 are larger catchments in the precinct, and where most residential buildings and common green areas are located. This might explain the higher pollutants concentration for these two catchments. Some of the runoffs from these large catchments (68% of the total catchment area for SP1 and 43% for SP2) were untreated and entered the drainage system directly. On the other hand, SP3 and SP4 are smaller and have a higher percentage of the treated area (62% and 88% respectively), the pollutant concentrations were generally lower. With a higher runoff treatment percentage by ABCWDFs, better water quality can be obtained at the catchment outlets, which is important for downstream urban waterbodies protection.

In terms of meeting stormwater quality objectives, TSS and TP water quality at the catchment outlets were slightly above the guideline value for most monitored events while TN was generally below the guideline value. However, when compared with the runoff pollutant concentration of residential catchment without installation of ABCWDFs in Singapore (Table 4), the three pollutants average EMC at the catchment outlets were either similar or lower, indicating that the ABCWDFs are effective in improving the overall catchment runoff quality. Larger improvements can be seen if compared with worldwide high urban land uses [22].

4. Discussion

This study presents an important field study of ABCWDFs that can guide urban catchment managers for effective stormwater runoff management in tropical countries. Overall, the effluent of both FB7 and VS1 are comparable to the literature studies (Table 7) and these systems can be employed in tropical climates for effective stormwater runoff management. When comparing with other field studies in Singapore, similar information was obtained. Lim et al. [38] observed poor pollutant removal efficiency for a modular bioretention tree system due to low influent runoff pollutant concentration, which may be caused by the high frequency and seasonal severity of storm events. Compared with another ABCWDF by Ong et al. [19], the effluent concentrations were slightly lower in that study. Lower nitrogen concentration in the effluent could be due to the incorporation of the submerged zone in their ABCWDF design. Moreover, the differences in the effluent quality could also be attributed to the difference in volume and runoff characteristics. However, it should be noted that the effluent pollutant EMCs were in accordance with those of previous studies.

Table 7. Comparison of effluent pollutant EMC of this study and literature studies.

Study	Climate	Scope	TSS Effluent (mg/L)	TP Effluent (mg/L)	TN Effluent (mg/L)
		Rain Gardens			
This study, FB7	Tropical	Field monitoring of rain garden in residential precinct, Singapore	13.9	0.19	0.73
Lim et al. [38]	Tropical	Field monitoring of modular bioretention tree system with engineered media, Singapore	4.8	0.04	0.27
Wang et al. [36]	Tropical	Field monitoring of rain garden with submerged zone, Singapore	2.0	0.04	0.61
Ong et al. [19]	Tropical	Field monitoring of rain garden with submerged zone, Singapore	11.3	0.11	0.66
Lopez-Ponnada et al. [9]	Temperate	Field monitoring of modified rain garden, USA	-	-	0.74
Brown and Hunt [41]	Temperate	Field monitoring of rain garden with submerged zone, USA	16.9	0.09	0.43
Davis [39]	Temperate	Field monitoring of rain garden, USA	18, 13	0.15, 0.17	-
		Swales			
This study, VS1	Tropical	Field monitoring of vegetated swale in residential precinct, Singapore	76.8	0.12	0.92
Leroy et al. [17]	Temperate	Field monitoring of vegetated swale in treating road runoff, France	178	-	-
Stagge et al. [14]	Temperate	Field monitoring of vegetated swale, USA	16, 18	0.29, 0.20	2.12, 2.63

With higher inflow pollutants concentration (challenge tests), FB7 could still produce a treated effluent with TSS and TP concentration that achieves the stormwater quality objectives. Long-term TSS accumulation at the rain garden could decrease hydraulic conductivity and affect pollutant uptake capability over time [51,52], but the impact might be lessened due to periodic tropical rain that reduces pollutant build-up. To further enhance phosphorus removal, background TP concentration can be reduced by using media with absorbent to phosphorus such as engineered soil or stringent use of fertilisers for the maintenance of the plants in the ABCWDFs.

No significant difference was noted for the TN removal in the challenge test study (different operational phases). A similar observation was made by Wang et al. [53] where the number of antecedent dry days did not affect TN performance in bioretention column studies. Despite not having a submerged zone [10,54], the TN removal efficiency of this study was still comparable to regional studies of rain gardens. In this study, the rain gardens were able to meet the stormwater quality objectives imposed. Other tropical regions with different runoff characteristics might require more thorough removal of TN, which could be enhanced with submerged zone incorporated rain gardens. Other possible considerations for effective nitrogen removal include additives that could promote denitrification within or below the filter media [55–57]. Moreover, studies have shown that plant species can influence pollutants removal [58,59]. Plant species with dense and fibrous root architecture can perform better in terms of nitrogen removal [60]. Loh [61] also showed that tropical plants, especially native species, could improve the nitrate removal performance of the rain gardens.

The performance of VS1 is similar to the literature studies of temperate climate, where the vegetated swale is effective in slowing down the flow of stormwater runoff as well as removing coarse solids or sediments. In an urban setting, a vegetated swale is a versatile feature that can be installed easily in small catchment areas to convey stormwater runoff as part of a designed drainage system or as a pretreatment feature for other ABCWDFs, such as a rain garden or wetland, which are more expensive and harder to construct in urban environments [49]. The usage of vegetated swale would be justified for residential land use with low stormwater runoff pollutants concentration. From our study, VS1 is able to handle stormwater runoff with low influent pollutant concentrations and produce effluent that meets stormwater treatment objectives. Combining the different functions of these ABCWDFs allows better and innovative ways of managing hydrological and treatment performance during normal and extreme conditions [62]. Besides that, the design of vegetated swales can also be modified further to include check dams, gravel layers (infiltration swales), engineered media (bioretention swales) to enhance the overall pollutants removal performance [63–65]. These modifications have the potential to be further explored.

Future monitoring of ABCWDFs in other land use of Singapore (e.g., industry area, park or business districts) will also provide insights on the performance of the ABCWDFs in removing certain stormwater pollutants such as heavy metals, faecal coliform, TOC, etc., which are more prevalently found in non-residential catchments. Bioretention can be optimised to treat stormwater runoff from commercial, residential and industrial areas [66]. For instance, a previous study was carried out to model the removal of TSS, TN, TP and heavy metal from an industry area [67]. Biochar was recommended in biofilters for treating wastewaters containing hazardous contaminants [68]. Nevertheless, the field application of bioretention or ABCWDFs in industry and business areas is still lacking. Currently, more focus is on the optimisation of engineered media on a laboratory scale to study the factors affecting the removal of industry-associated pollutants, such as organic pollutants and heavy metals [69–71]. Other key design considerations such as catchment characteristics, rainfall pattern and intensities, size of the feature, type of vegetation, soil additives, etc. should be further explored and elucidated to better understand the factors affecting the removal rates of these pollutants.

5. Conclusions

In this study, selected ABCWDFs in an urban residential precinct in Singapore were monitored and assessed in terms of achieving water quality and peak runoff management objectives. The features were monitored for 15 months. During wet events, ABCWDFs such as rain gardens and vegetated swale were able to produce effluent that is within local stormwater treatment objectives. Results showed that total suspended solids (TSS), total phosphorus (TP) and total nitrogen (TN) concentrations were low in the runoff from this new residential precinct. Effluent pollutant (TSS, TP and TN) concentrations at the outlet of the individual treatment systems were within the local stormwater treatment objectives over the monitored storm events. The effluent TSS, TP and TN concentrations are consistent with other field studies in the literature. Through challenge tests with synthetic runoff, a higher removal efficiency of pollutants was observed. Challenge test results displayed that the rain garden performed well even during extreme conditions with clear pollutant reduction. Removal efficiency based on Event Mean Concentration (EMC) in the order of 89%, 75% and 43% for TSS, TP and TN, respectively, were achieved in several simulated storm events, using higher pollutant influent levels. This study provides evidence that ABCWDFs can provide sustainable management of urban stormwater runoff quality in tropical climates.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14030468/s1, Table S1: Summary of monitored natural storm events; Table S2: Target pollutants concentration and dosing volume of challenge tests; Table S3: Number of samples for challenge test events; Table S4: Test methods for water quality parameters; Figure S1: First flush (MV curve) for TSS, TP and TN of FB7 (a–c); VS1 (d–f)

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