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Article

Pollutant Removal and Hydraulic Reduction Performance of Field Grassed Swales during Runoff Simulation Experiments

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Abstract: Four different field swales were tested in this study, using 24 standardised synthetic runoff simulation experiments to evaluate their performance in removing Total Suspended Solids (TSS), Total Nitrogen (TN) and Total Phosphorous (TP) from stormwater runoff. Hydraulic reduction capability of the swales was also assessed. The study demonstrated that a swale's TSS removal performance is highly dependent on the inlet TSS concentrations. Results showed that between 50% and 80% of the TSS was generally removed within the first 10 m of the swale length. The study found no reduction in TN concentrations due to treatment by the swales. However, it did demonstrate a reduction in measured TP levels of between 20% and 23% between the inlet and the outlet. The study results demonstrated that swales can be successfully used to attenuate peak stormwater flow rates, reduce runoff volumes and to improve the quality of stormwater runoff, particularly in runoff with high concentrations of TSS and TP. The results from this study will assist designers to estimate the appropriate length of swale required to achieve specific TSS and TP pollution reductions in urban stormwater runoff and to reduce downstream runoff volumes.

Keywords: swales; stormwater pollution; total suspended solids (TSS); particle size distribution (PSD); stormwater treatment train

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1. Introduction

Grassed swales are increasingly being used in a variety of engineering applications to transport polluted stormwater runoff to downstream catchments in an efficient, economic and aesthetically pleasing way. In addition, swales reduce runoff pollutants, require little maintenance, and can be easily incorporated in projects that require a cost-effective stormwater conveyance system. This can often make swales a better choice than traditional curb-and-gutter systems [1]. It has been demonstrated that grassed swales minimise stormwater runoff pollution levels [2] by reducing stormwater flow velocities, which decreases peak outlet discharges and allows filtering and sedimentation processes to occur within the swale.

Research has shown swales can be used as stormwater runoff pre-treatment systems which reduce the need for downstream treatment facilities [3]. Water Sensitive Urban Design (WSUD) guidelines recommend cost-effective and sustainable non-point-source stormwater pollution treatment options. These can include incorporating swales into urban catchments for treating polluted stormwater runoff prior to discharge into receiving waters [4]. WSUD is about integrating water cycle management into urban planning and design. The principles of WSUD are similar to those of Sustainable Urban Drainage System (SUDS) design in Europe and Low Impact Development (LID) in America [5].

Despite significant literature sources reporting the benefits of grassed swales to treat urban stormwater runoff, a fully comprehensive understanding of the design and performance characteristics of swales is still not apparent [6]. This investigation builds on previous swale research with a particular focus on swale length, and how it influences the stormwater attenuation and pollution removal capabilities of grassed swales.

2. Previous Research

Numerous researchers have reported that swales substantially reduce runoff volumes. Ackerman and Stein [7] demonstrated that grassed swales reduce mean runoff volume by approximately 52.5%. Barrett [8] reported that swales may have the potential to infiltrate up to 50% of the runoff volume, provided the soil is permeable and the initial moisture content of that soil is low. Fassman and Liao [3] monitored field swales in New Zealand under natural storm conditions and concluded that, on average, 73.6% of the peak flow discharge was dampened by swales, while 63.7% of the total volume was captured. Bäckström *et al.* [9], and Fassman and Liao [3] noted complete capture of runoff by swales when rainfall events of less than 2 mm occurred. Yousef *et al.* [10] and Deletic [11] also reported significant runoff reduction by swales. Barrett [8] concluded that the reduction in runoff volume also meant that the total pollutant constituent load was reduced, including nutrient loads, which generally exhibit little change in concentration due to treatment by swales. Increased stormwater retention time, and reduced peak flow rates by swales has the potential to significantly improve the quality of stormwater runoff [7,8].

Previous research agrees that swales remove pollutants through the processes of sedimentation, filtration by grass blades, infiltration into the subsurface zone and bio-chemical processes [2,6,12]. Previous research also reports that swale length, slope, vegetation cover and soil type, all factor into pollution removal performance. Pollutant properties, such as the sediment particle size distributions

(PSD) and concentrations, and the amount of particulate bound pollutants also directly affects the pollutant treatment efficiency of swales [1,13,14].

Due to their ability to trap sediments, and consequently pollutant constituents attached to particulate matter, many researchers have measured the pollution reducing efficiency of swales based on total suspended solids (TSS) removal. A summary of previous studies on the TSS removal performance of grassed swales is listed in Table 1.

Table 1. Previous studies on the Total Suspended Solids (TSS) removal performance of swales.

Literature Source	TSS Removal Performance of Grassed Swales (%)		Remarks
	Range	Mean (Median)	
Ackerman and Stein (2008) [7]	41–84	70.6 (72)	* Review of ten different swales studies
	80–99	89 (87)	* Review from five different peer reviewed swale study sources; ** TSS load reduction
Barrett *et al.* (1998) [2]	85–87	86	* Studied two field swales of 1055 m and 356 m long tested under real runoff events (n = 34); ** TSS concentration (EMC) reduction
Deletic and Fletcher (2006) [15] (review section)		72 (76)	* Review of 18 swale study sources
Deletic and Fletcher (2006) [15]	61–86		* A 6.2 m field grass channel studied with runoff simulation; ** TSS concentration (EMC) reduction
		69	* A 65 m long field swale with runoff simulation; ** TSS load reduction
Bäckström (2002) [13]	79–98		* Simulation study on nine different swales of 5–10 m long; ** TSS concentration (EMC) reduction
Yu *et al.* (2001) [12]	67.2–94		* From two field swale studies, one with a 30 m long swale using runoff simulation and other swale of 274.5 m with real time events (n = 4); ** mass sediment removal
Lloyd *et al.* (2001) [16]		74	* A 35 m long swale tested with runoff simulation; ** TSS load removal
Bäckström *et al.* (2006) [9]		15	* Field swale of 110 m long under real storm events (n = 7); ** TSS EMC removal; *** *few negative TSS removals were also observed in the study*
Kaighn and Yu (1996) [1]	29.7–49		* Results from two 30 m long field swales studied under real storm events (n = 8); ** TSS EMC removal
Scheuler (1994) [17]	65–98		* Results from three 61 m long field swales tested under real storm events; *** *one swale showed negative TSS removal due to erosion, which was not given in the range). This finding was verified by Winston et al. (2012) [18] who also found that erosion within a swale caused negative percent reductions for TSS.*
Stagge *et al.* (2012) [6]	44.1–82.7		* Two field swales of 198 m and 138 m long tested with different configurations under real events (n = 45); ** mass TSS removal
Mean	***61.3–86.4***	***67.9 (78.3)***	***Arithmetic mean of the listed literature performance data***

Notes: * type of swales used in the study and experimental method used and number of real storm events (n) sampled; ** TSS measurement method employed in the respective study; *** any specific observations noted; blank cells mean relevant data wasn't available; EMC—event mean concentration of pollutants.

Bäckström [13] found sedimentation of the coarse particles (>25 µm) within the first few metres of the swale length was the most significant factor in removing TSS from runoff, followed by filtration by grass blades predominantly in shallower flow regimes that often correspond to low to moderate intensity rainfall events. Bäckström [13] also reported that laboratory tests on swales generally performed better than field swale tests in sediment trapping. Five metre long field swales showed efficient removal of particles coarser than 25 µm. However, when the lengths of the swales were doubled, particles smaller than 25 µm were also trapped. Bäckström *et al.* [9] confirmed his earlier findings of sediment trapping using a 110 m long roadside grassed swale in Södra Hamnleden, Sweden, under different real rainfall and runoff events. This study revealed that particles larger than 25 µm were effectively trapped by the swale. However, this study found that sediments finer than 25 µm were not retained, and were transported out of the swale, which was in contrast to the earlier study results [13]. Bäckström *et al.* [9] attributed the export of finer sediment to higher flow rates that occurred under real runoff conditions. They concluded [9] that further studies are needed to improve the understanding of the capacity of swales to trap finer particles. Deletic's [14] experimental study on swales concluded that a substantial proportion of sediment particles larger than 57 µm in size were trapped by grassed swales. She also found that the removal efficiency of grassed swales was very low for particles smaller than 5.8 µm.

Previous studies have also looked into the nutrient removal performance by swales. Nutrients such as nitrogen and phosphorous were mostly considered in those studies due to their impact on urban waterways. Removal of total nitrogen (TN) in swales was found to be variable [15–17]. Other researchers reported that the removal of TSS particles finer than 150 µm would increase removal of total phosphorous (TP), because approximately 70% of the TP present in urban runoff is bound to particulates [6]. It has been suggested that relevant chemical or biological processes need to take place to significantly remove these nutrients, particularly the dissolved components [12]. However, it is unclear whether swale systems provide adequate Hydraulic Retention Time for these processes to occur [18]. Tables 2 and 3 list previous research results on the TN and TP removal performance by swales respectively.

It appears from the literature reviewed above that there are significant knowledge gaps relating to the ability of swales to remove pollutants from stormwater runoff. This study investigated the pollutant removal performances of field swales under simulated runoff conditions. As swales convey runoff to downstream water bodies, the main focus of the study was to investigate the level of pollution removal performance that can be expected from grass swales used to treat stormwater runoff before it reaches receiving waters. The study focussed on the three most common pollutants of concern to WSUD practitioners, namely: TSS, TN and TP. The particle size distributions (PSD) of the sediment trapped by the swales, runoff volume reduction, and peak discharge attenuation were also investigated in the study.

Table 2. Previous studies on the Total Nitrogen (TN) removal performance of swales.

Literature Source	TN removal performance of grassed swales (%)		Remarks
	Range	Mean (Median)	
Deletic and Fletcher's [15] review (2006)		45 (50)	* Review of 13 swale study sources
Deletic and Fletcher (2006) [15]		56	* A 65 m long field swale with runoff simulation; ** TN load reduction
Yu *et al.* (2001) [12]	13.8–23.1		* From two field swale studies, one with a 30 m long swale with runoff simulation and other swale of 274.5 m with real time events (n = 4); ** mass TN removal
Lloyd *et al.* (2001) [16]		Nil	* A 35 m long swale tested with runoff simulation; ** TN load removal
Scheuler (1994) [17]	(−X)–46.5		*Results from three 61 m long field swales tested under real storm events; (*** *one swale showed TN export of a certain negative percentage*)
Stagge *et al.* (2012) [6]	(−25.6)–85.6		* Two field swales of 198 m and 138 m long tested with different configurations under real events (n = 45); ** mass TN removal
Yousef *et al.* (1987) [10]	(−7)–11		* From two field swales of 53 m and 170 m long under simulated runoff events; ** EMC reduction
Mean	***−6.3–41.2***	***33.7 (50)***	***Arithmetic mean of the listed literature performance data***

Notes: * type of swales used in the study and experimental method used and number of real storm events (n) sampled; ** TN measurement method employed in the respective study; *** any specific observations noted; −X is an unknown negative value; blank cells mean relevant data wasn't available; EM—event mean concentration of pollutants.

Table 3. Previous studies on the Total Phosphorous (TP) removal performance of swales.

Literature Source	TP removal performance of grassed swales (%)		Remarks
	Range	Mean (Median)	
Barrett *et al.* (1998) [2]	34–44	39	* In two field swales of 1,055 m and 356 m long + tested under real runoff events (n = 34); ** TP concentration (EMC) reduction
Deletic and Fletcher's [15] review (2006)		52 (55)	* Review of 20 swale study sources
Deletic and Fletcher (2006) [15]		46	* A 65 m long field swale with runoff simulation; ** TP load reduction
Yu *et al.* (2001) [12]	28.8–98.6		* From two field swale studies, one with a 30 m long swale with runoff simulation and other swale of 274.5 m with real time events (n = 4); ** mass TP removal
Lloyd *et al.* (2001) [16]		55	* A 35 m long swale tested with runoff simulation; ** TP load removal
Kaighn and Yu (1996) [1]	(−0.4)–33		* Results from two 30 m long field swales tested under real storm events (n = 8); ** EMC removal
Scheuler (1994) [17]	18–41		* Results from three 61 m long field swales tested under real storm events
Stagge *et al.* (2012) [6]	(−49.6)–68.7		* Two field swales of 198 m and 138 m long tested with different configurations under real events (n = 45); ** mass TP removal
Yousef *et al.* (1987) [10]	3–25		* From two field swales of 53 m and 170 m long under simulated runoff events; ** EMC reduction
Mean	***5.6–51.7***	***48 (55)***	***Arithmetic mean of the listed literature performance data***

Notes: * type of swales used in the study and experimental method used and number of real storm events (n) sampled; ** TP measurement method employed in the respective study; *** any specific observations noted; blank cells mean relevant data wasn't available; EMC—event mean concentration of pollutants.

3. Study Objectives

The main goal of this study was to evaluate the overall performance of grass swales in improving urban stormwater runoff quality and mitigating runoff quantity. Four different grassed swales on the Sunshine Coast in Australia were studied using controlled stormwater runoff simulation experiments to evaluate their pollution removal performance. The specific objectives of this research project were to:

- Correlate the overall TSS removal efficiency of the swales to their length;
- Determine the relationship between the trapping efficiency of various sediment size fractions and swale length;
- Evaluate the nutrient removal performance of swales relative to their length;
- Understand the effects of varying influent pollutant concentrations on the swale pollution removal performance; and
- Evaluate the hydrological control characteristics of swales.

4. Experimental Methodology

The stormwater pollutant removal performance of four different field swale installations was monitored during 24 controlled field runoff simulation experiments. Controlled field runoff simulations were selected for the study because of their reliability and the difficulties in sampling real time precipitation runoff events. The experiments were designed to compare selected water quality parameters in the influent and effluent runoff. Three different pollutants were tested, namely: TSS, TN and TP. TSS was sampled every 5 m along the swale length and the nutrients TN and TP were tested every 10 m. Four different pollutant concentrations were used in the experiments as shown in Table 4. The reduction in flow rates due to infiltration along the swales was also measured. It must be noted that the pollution loads for the C and D tests are much higher than typical nutrient and sediment concentrations in stormwater runoff in Australia and these were included to ensure that differences in results could be measured.

Table 4. Synthetic runoff pollutant constituents and test types used in simulation experiments.

Pollutant constituents	Test types and design pollutant mix concentrations (mg/L)				Concentrations observed at swale inlets (mg/L)			
	Test A (TA)	Test B (TB)	Test C (TC)	Test D (TD)	Test A (TA)	Test B (TB)	Test C (TC)	Test D (TD)
Total suspended solid (TSS)–Silica	0	150	750	1500	0–19	67–96	283–451	511–1211
Total nitrogen (TN)–KNO_3	0	1.000	5.000	10.000	0.115–0.209	1.120–1.270	4.926–5.384	9.495–10.520
Total phosphorous (TP)–KH_2PO_4	0	1.000	5.000	10.000	0.088–0.261	0.947–1.245	3.868–5.145	8.570–11.650

Three of the swales tested were located on the campus of the University of the Sunshine Coast (identified as USC, IC, and CPB in Table 5). The fourth swale was located in Caloundra, Sunshine Coast (identified as SC in Table 5). The swale size, shape, length and slope are also given in Table 5.

The four swales were between 30 and 35 m in length. Figure 1 shows the CPB swale that was used in simulation experiments. All four study swales had similar characteristics with the grass type of kikuyu (*Pennisetum clandestinum*). Experiments were performed in swales within seven days of mowing, and the grass heights were varied between 10 and 60 mm.

Table 5. Study swale characteristics.

Swale Name	Swale characteristics				
	Length (m)	Shape	Dimensions (m)	Slope (%)	Grass type and grass height (mm)
USC Engineering (USC)	35	Triangular	b = 4.0, h = 0.16	<1	Kikuyu, 10–60
Sports Complex (SC)	35	Triangular	b = 6.1, h = 0.44	<1	Kikuyu, 10–60
Innovation Centre (IC)	35	Triangular	b = 3.0, h = 0.35	1	Kikuyu, 10–60
Car Park–B (CPB)	30	Triangular	b = 4.3, h = 0.49	1	Kikuyu, 10–60

Notes: * b—top width of swales in metres; h—mid height of swales in metres; all swales were tested under recently mowed conditions (within seven days of mowing) under which grass heights were varying between 10 and 60 mm.

Figure 1. Car Park-B (CPB) swale used in simulation experiments.

Experiments were conducted in 2012 and 2013, identified as R1 (Round 1) and R2 (Round 2) in Table 6. The experiments were conducted at least one day apart in order to allow the soil moisture to stabilise between tests. A runoff simulation approach similar to that used by Deletic and Fletcher [15] was employed in this field study. Each round (R1 and R2) had 12 individual experimental runs. To simulate the rainfall events, a 2000 L tank filled with clean water was used. The first set of experiments in 2012 (R1) were conducted using an average inflow rate of approximately 1.6 L/s for 21 min. The selected flow rate and the duration were limited by the capacity of the tank. However, this flow rate was considered to be appropriate to simulate a one year, 21 min, average recurrence interval (ARI), naturally occurring storm event (rainfall intensity = 29.3 mm/h) typically experienced on the Sunshine Coast.

Table 6. Experimental arrangements and tested parameters.

Test Name	Swale Name	Experiment	Inflow	IVMC (%)	Outflow (%)	WQ Tests
Round—R1 (Experiments performed in 2012)	USC Engineering (USC)	R1-USC-TA	2000 L of runoff delivered into the swales at an approximate average flow rate of 1.6 L/s (simulating 21 min runoff events)	NM	NM	TSS, TN & TP (Samples collected at every 5 m along swales and analysed for these WQ parameters)
		R1-USC-TB				
		R1-USC-TC				
		R1-USC-TD				
	Sports Complex (SC)	R1-SC-TA				
		R1-SC-TB				
		R1-SC-TC				
		R1-SC-TD				
	Innovation Centre (IC)	R1-IC-TA				
		R1-IC-TB				
		R1-IC-TC				
		R1-IC-TD				
Round—R2 (Experiments performed in 2013)	USC Engineering (USC)	R2-USC-TA	2000 L of runoff delivered into the swales under varying flow rates of 0.5–2.0 L/s (simulating 30 min runoff events)	39.5	NM	TSS, TN, TP & PSD (TSS and PSD analysis performed on samples collected at every 5 m along swales and nutrient tests were performed with every 10 m samples)
		R2-USC-TB		45.6	NM	
		R2-USC-TC		10.2	46.5	
		R2-USC-TD		34.3	53.5	
	Sports Complex (SC)	R2-SC-TA		47.2	NM	
		R2-SC-TB		27.6	NM	
		R2-SC-TC		11.3	0	
		R2-SC-TD		19.5	0	
	Car Park–B (CPB)	R2-CPB-TA		35.0	42.1	
		R2-CPB-TB		52.0	68.1	
		R2-CPB-TC		48.5	75.0	
		R2-CPB-TD		52.3	88.3	

Notes: * IVMC—initial volumetric moisture content of swales; Outflow—outflow measured as a percentage of inflow; NM—not measured; WQ tests—water quality tests performed in respective experiments; experiment names should be read as Round#-Swale name-Test type as shown in Table 5 (e.g., R1-USC-TA).

In 2013 (R2), the Innovation Centre (IC) swale was replaced by Car Park-B (CPB) swale for field simulation experiments due to non-accessibility to the IC swale. For the second set of experiments (R2) conducted in 2013, the swale inflow rates were varied from between 0.5 and 2.0 L/s based on the hydrograph from a one year, 30 min ARI rainfall event. Inflow rates were regulated using an electromagnetic flow meter to measure and a valve at the 2000 L tank outlet. The PSD of the water sample sediment was also analysed. In R2, initial swale moisture contents of swales were measured, and swale outflow measurements were also performed (Table 6). The moisture content of the swale soil profile was measured at different locations using a moisture probe that records volumetric moisture content of the soil matrix. The average measured moisture value can be seen in Table 6 in the

IVMC column. The flow rate at the outlet was measured continuously throughout the event using a sharp edged V-notch weir during R2 experiments.

Synthetic pollutant constituents were used in the experiments to simulate runoff pollutant levels, which allowed finer control of their concentration levels. Both R1 and R2 experiments were designed with different pollutant concentrations in order to help understand the performance of swales under varying pollutant discharges. This can be related to conditions occurring during the "first flush" phenomenon events, as well as typical pollutant loads. Each swale was tested under four different inlet pollutant loading conditions referred to as TA, TB, TC and TD as in Table 4.

Test-A (TA) was a control experiment, with no added pollutants, to determine the background concentration of the pollutant constituents in each swale tested. All other test runs were carried out with the addition of pollutants as shown in Table 4. Test-B (TB) was designed to simulate urban runoff pollutant concentrations typically found in Australian urban catchments [15,19]. Commercially available silica powder, which closely resembled the PSD of sediment found in urban runoff, was used as the synthetic TSS constituent in the simulated stormwater inside the tank. Chemical reagents KNO_3 and KH_2PO_4 were used to simulate the TN and TP loads respectively. Test-C (TC) and Test-D (TD) were comprised of pollutant concentrations five times and ten times higher than typical Australian urban stormwater pollutant concentrations.

To ensure a relatively homogeneous water column inside the tank, and to maintain constant concentrations of influent pollutant concentrations at the swale inlet, a stirring system using a submersible pump was used inside the 2000 L tank. Synthetic runoff water inside the tank was mixed for 30 min before each experiment, and during each runoff simulation.

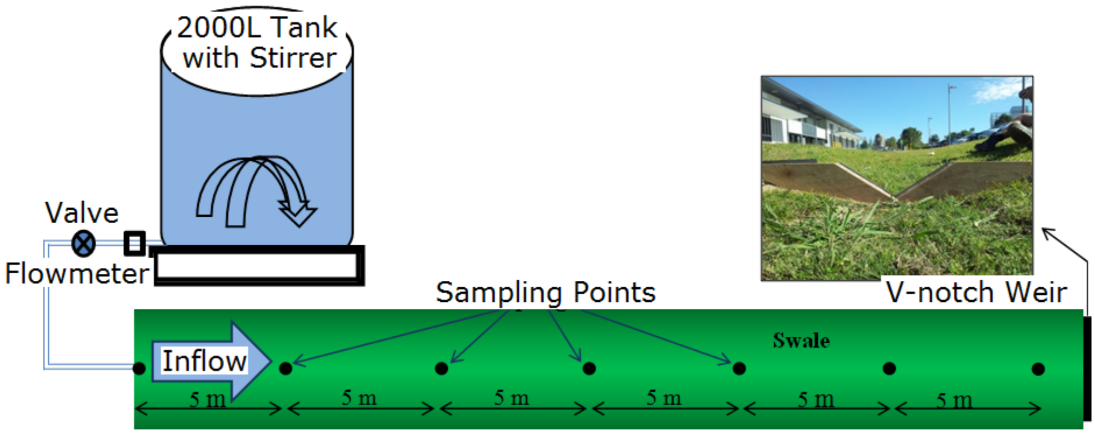
Marginal variations in the swale inlet TN and TP concentrations could be attributed to the compound effect of nutrients attached to settled sediments within the tank, and from residual nutrients inside the tank or water (Table 4). Swale inlet pollutant concentrations found during Test-A experiments represent the background pollutants present in the clean water. Samples from the tank outlet every five minutes revealed that outflow concentrations of TSS could vary by up to ±10% during simulations, possibly due to settling of larger particles in the tank.

The release of runoff into the swale was adjusted to different inflow hydrographs and took place for 21 min in R1 experiments and for 30 min in R2 experiments.

Manual grab samples were collected at selected sampling points located along the length of the swales. Figure 2 shows the conceptual swale testing setup and typical swale testing locations. Water samples were collected at the inlet, the outlet and at every either 5 m (for TSS, TN & TP in R1 and for TSS in R2) or 10 m (for TN & TP in R2) along the length of the swale (Table 5, Figure 2). Three individual samples of 300 mL were collected at each of the sampling locations at between 10 and 15 min intervals during the experiments. The three samples were later mixed together to form composite samples for each sampling point. Sampling was undertaken carefully to avoid disturbing the swale bed.

Collected samples were taken to the USC analytical lab within three hours of the field collection. Each water sample was preserved in accordance with the Standard Methods for the Examination of Water and Wastewater and then analysed for TSS, TN and TP according to APHA/AWWA/WEF [20]. Each sample was analysed for PSD of the suspended solid contents using a laser particle sizer—Malvern Mastersizer 3000 [21].

Figure 2. Conceptual swale testing setup.

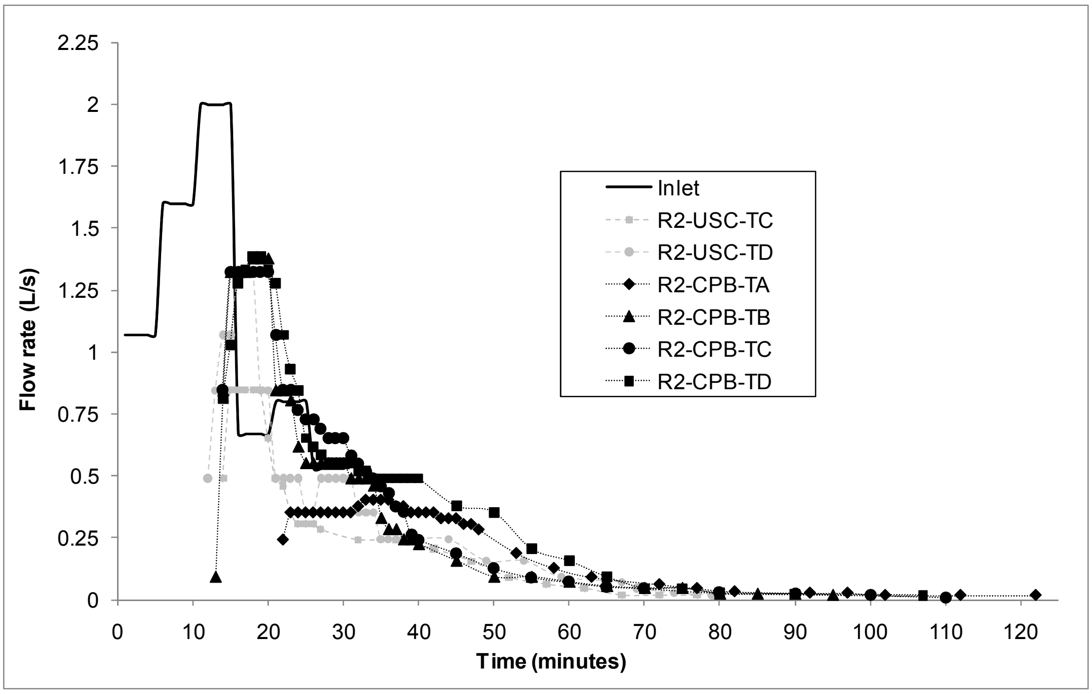


5. Results and Discussion

5.1. Hydraulic Performance of Swales

Figure 3 shows the swale inlet hydrograph, and the outflow hydrographs measured at the swale outlet during the different R2 experiments. Flow rates at the outlet reached a peak after approximately 20 min and then decreased exponentially to nearly zero flow after approximately 80 min. Figure 3 shows that a lag time of approximately 13 min was recorded after the start of the tests before any flow was measured at the outlet. While the flow into the swales ceased after 30 min, trickle flows were recorded at the outlet for up to 120 min after the start of the tests. Flow measurements demonstrated a mean total flow reduction of 52% in the 30 m long swales studied, with a peak flow reduction of 61% occurring in one of the study swales. As expected, more infiltration (and hence greater flow reduction) was observed in swales with low initial soil moisture contents.

Figure 3. Inlet and outlet hydrographs of flow measured experiments in R2.

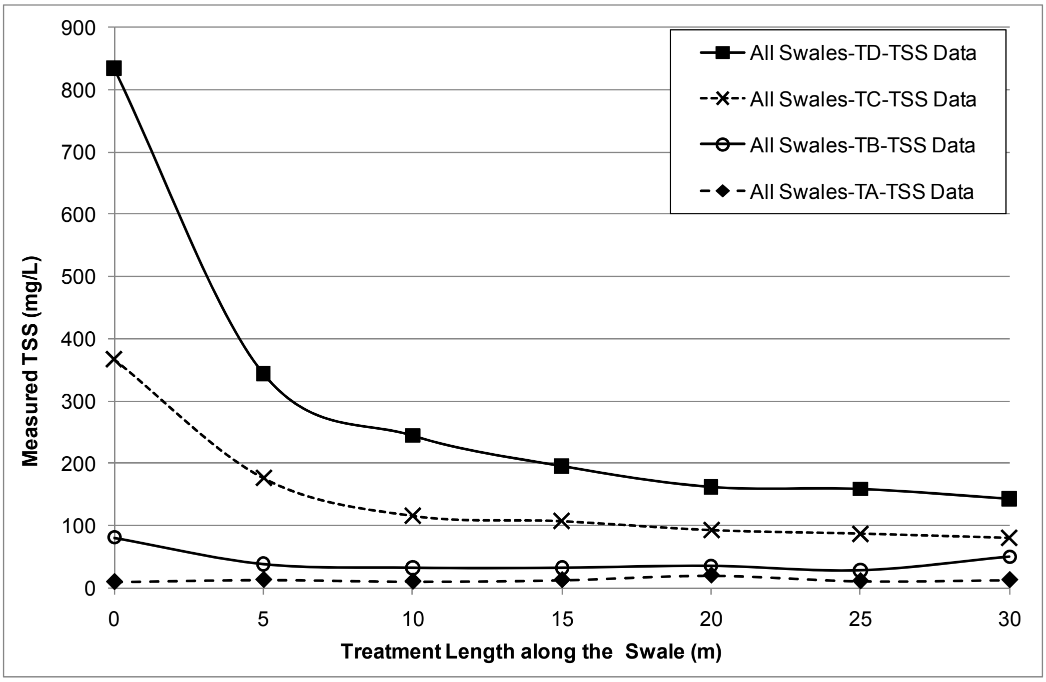


The results in Figure 3 demonstrate that swales can be used successfully to attenuate peak stormwater flow rates and to significantly reduce runoff volumes to downstream water courses. The increased runoff retention and peak flow reduction shown by the swales in this study have also suggested that they have the potential to significantly improve the quality of stormwater.

5.2. TSS Removal Performance of Swales

The average TSS concentrations measured at 5 m intervals for 30 m along the four study swales for tests TA, TB, TC & TD are shown in Figure 4. The figure clearly shows an exponential decay of TSS concentration along the swale, particularly at the higher pollutant loading tests, TC and TD. This trend agrees with previous research by Deletic [14] who reported an exponential decline of TSS concentration corresponding to swale length. Test-B data points also show an exponential decay of TSS concentration along the swale length, although this was less pronounced.

Figure 4. Measured TSS concentrations along the swale length.



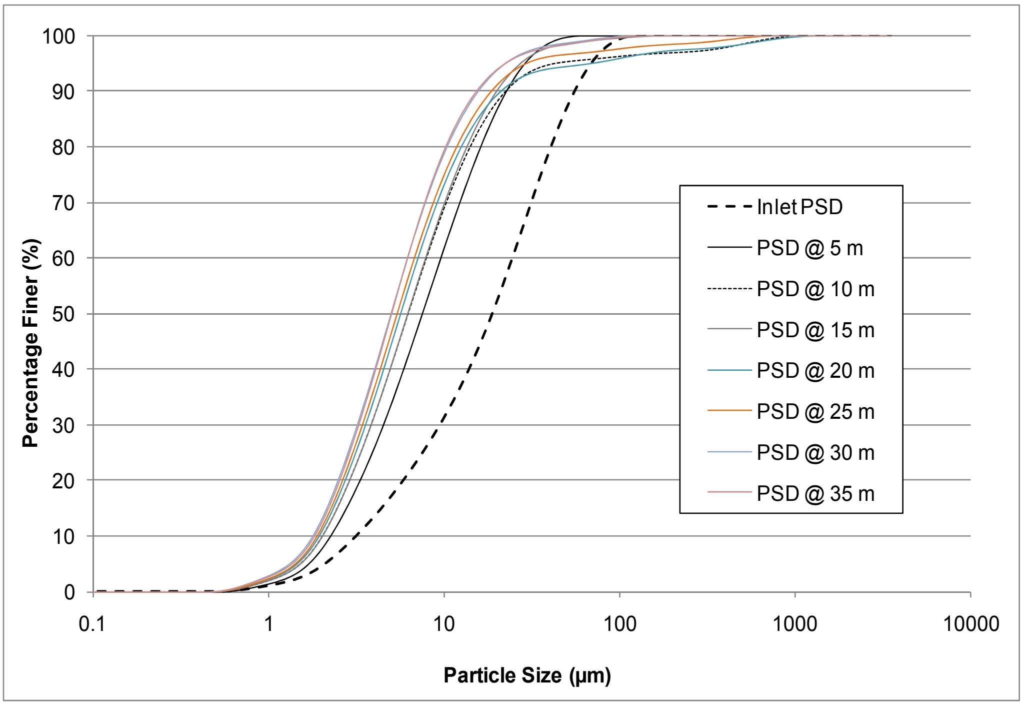
TSS concentrations measured during the TA tests showed that the swales had background TSS concentration values of between 0 and 40 mg/L. This agrees with pervious research finds [15,16,18]. It was hypothesised that these background TSS concentrations may have been due to disturbance of the swale bed during sampling or potential scouring of sediments by the runoff along the swale. Measured TSS concentrations below 40 mg/L for all other tests therefore led to variability in the results with some values showing slight increases along the swale length. The study results demonstrate that a swale's TSS removal performance is highly dependent on the inlet concentrations as was shown in previous research [15,16,18]. Results of TA and TB have demonstrated the difficulty in quantifying the efficiency of stormwater treatment devices with very low inlet pollutant concentrations (<40 mg/L).

Figure 4 demonstrates that the swales tested in the study were effective in reducing the higher TSS concentrations in the TC and TD tests. The results of the TC and TD tests also show that swales can treat higher pollution loads typically associated with the "first flush" phenomenon. Results showed that between 50% and 80% of the TSS was generally removed within the first 10 m of the swales. A further 10% to 20% reduction in TSS concentrations can be expected in swales up to 30 m long. Figure 4 also shows that there was a substantial decline in the TSS removal rate after the initial between 10 and 15 m length of the swales and the removal rate becomes very low from that point on. The results of TSS removal by swales in this study generally agreed with previous research results (Table 1).

5.3. Sediment Particle Size Removal Efficiency of Swales

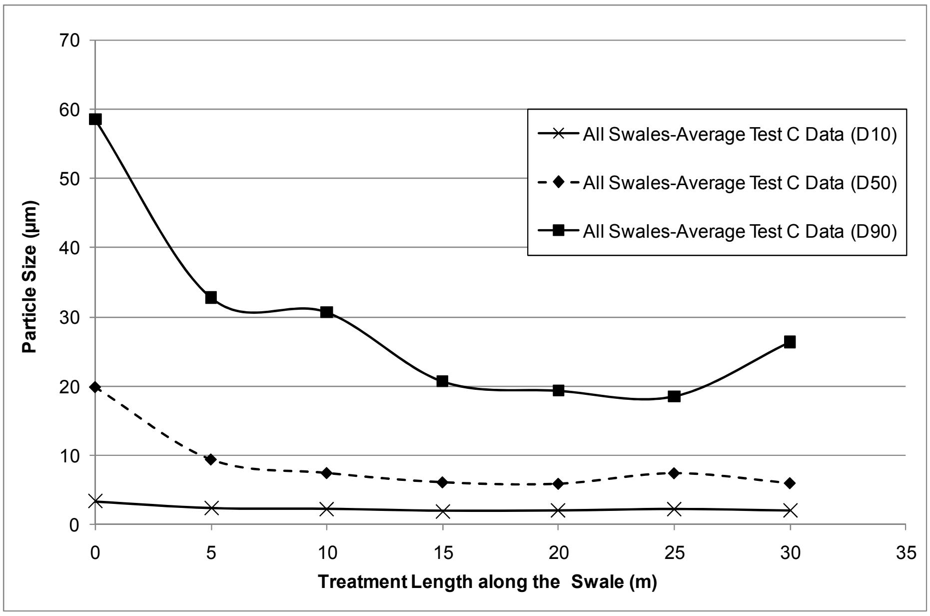
PSDs of the swale synthetic sediment (silica) inlet samples were relatively uniform for all the experiments. Figure 5 shows the variation in PSDs of the samples collected at 5 m intervals along the length of the swale for the R2-USC-TD experiment. There is a substantial difference between the PSD samples collected at the swale inlet and the samples collected within the first five to ten metres suggesting that the larger sediment particles were removed in this initial length. However the PSD of samples collected after 15 m show little difference in size. PSD curves followed a relatively similar pattern for the other R2 experimental runs performed under TB, TC and TD test conditions.

Figure 5. PSD0 of the samples collected during R2-USC-TD experiment.



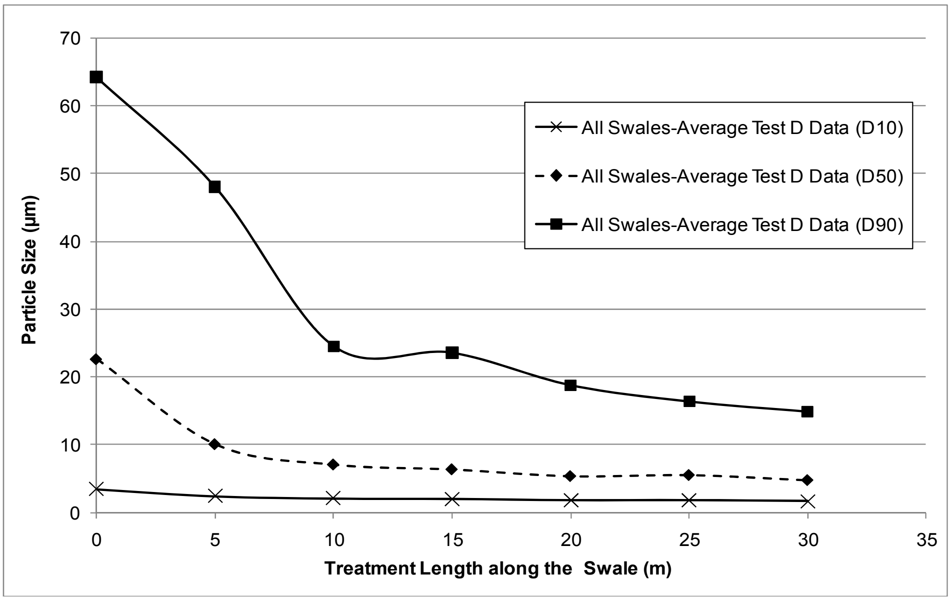
The variation in the D_{10}, D_{50} and D_{90} sediment sizes along the swales under TC conditions is shown in Figure 6. D_{50} and D_{90} values decreased rapidly within the first 10 m of the swale length and then continued to slowly decrease. D_{90} values declined steadily from approximately 58 μm at the inlet, to approximately 18 μm at the 25 m swale length point. It then increased slightly to approximately 27 μm at the 30 m point. The reason for the slight rise was not confirmed. However, it was hypothesised that it may have been due to the soil erosion occurring in the swale, or due to some minor disturbances potentially caused to the swale bed during sampling. No noticeable change was recorded in the D_{10} values along the length of the swale for the TC tests.

Figure 6. Average D_{10}, D_{50} and D_{90} values along the swale length during Test-C experiments.



The variation of the particle size parameters D_{10}, D_{50} and D_{90} along the swales under TD conditions is shown in Figure 7. D_{50} and D_{90} values decreased rapidly within the first 10 m of the swale length and then continued to slowly decrease. D_{90} values declined steadily from approximately 65 µm at the inlet, to approximately 24 µm at the 10 m swale length point. It then continued to decrease slightly along the rest of the swale length to a value of 15 µm at the 30 m point. A slight decrease in the D_{10} values from approximately 3 µm to 2 µm was measured after a length of 5 m, after which time the value remained relatively constant.

Figure 7. Average D_{10}, D_{50} and D_{90} values along the swale length during Test-D experiments.



The trends and variations of PSD along the swale suggested a clear relationship with the TSS removal (Figure 4). Sedimentation processes and removal of larger sediment particles may explain the higher TSS removal rates within the first 10–15 m of the swales (Figure 4). Similarly, the minimal changes in D_{50} and D_{90} after the first 15 m mirrored the TSS reduction occurring in the initial part of the swale. The results shown in Figure 7 also showed that swales evaluated in this study were not effective in capturing particles finer than 20 µm. However, potential scouring and minor disturbances to the soil during sampling may have led to the varying sediment performance shown in the TA and TB experiments.

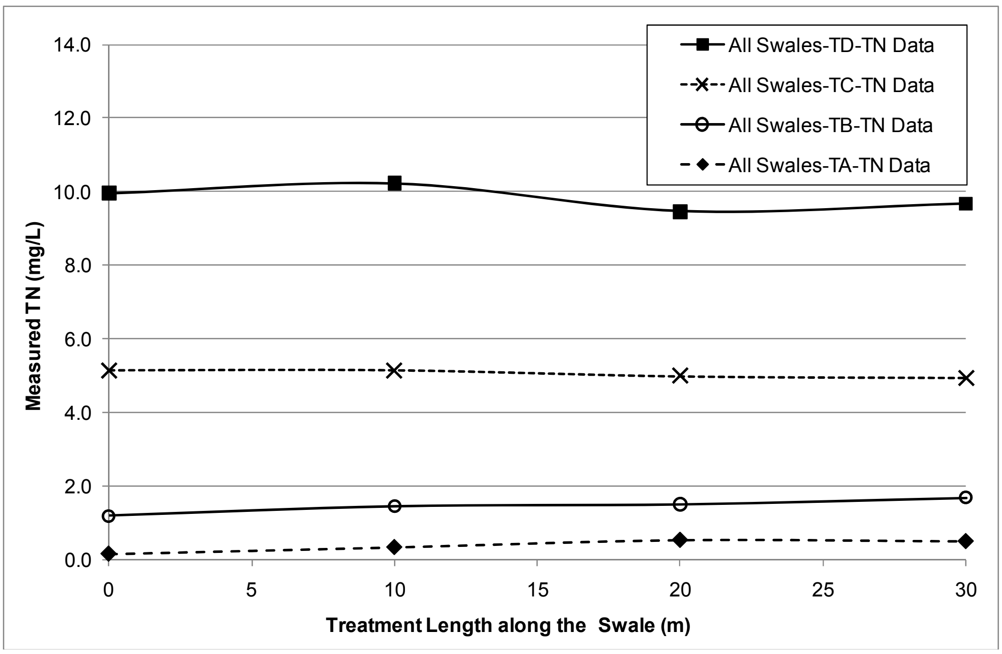
The study has found that swales can be used effectively as a primary treatment measure to remove larger sediment from stormwater runoff. The results showed that the first 15 m of the swale length is the most effective in treating the bulk of the TSS. This suggests that the installation of unnecessarily long swales to treat TSS pollutants may not be the optimal solution.

The selection of swales as a primary stormwater treatment measure could significantly affect the design requirements of downstream (or secondary) treatment systems. As the swales were generally shown to be successful in removing particles larger than 20 µm, this suggests that swales could be used in a stormwater treatment train as a pre-treatment to prevent clogging in downstream treatment systems. Results of this study also confirm that a comprehensive understanding of TSS removal and PSD reduction along the swale length is important in the design and sizing of swales, particularly when planning the construction of an urban stormwater runoff treatment train system.

5.4. Nutrient Removal Performance of Swales

The average TN concentrations measured at 10 m intervals along the four swales during the four tests (TA-TD) are shown in Figure 8. The results demonstrate that there was no reduction in TN levels measured along the length of the swales for any of the four tests. Indeed, for the TB and TA experiments, the TN concentrations appeared to increase. However, the measured TN levels were low in comparison to runoff from other sites such as highways and carparks and it was hypothesised that leaching of nitrogen components from the swales may have caused the TN increases measured during the TA and TB experiments.

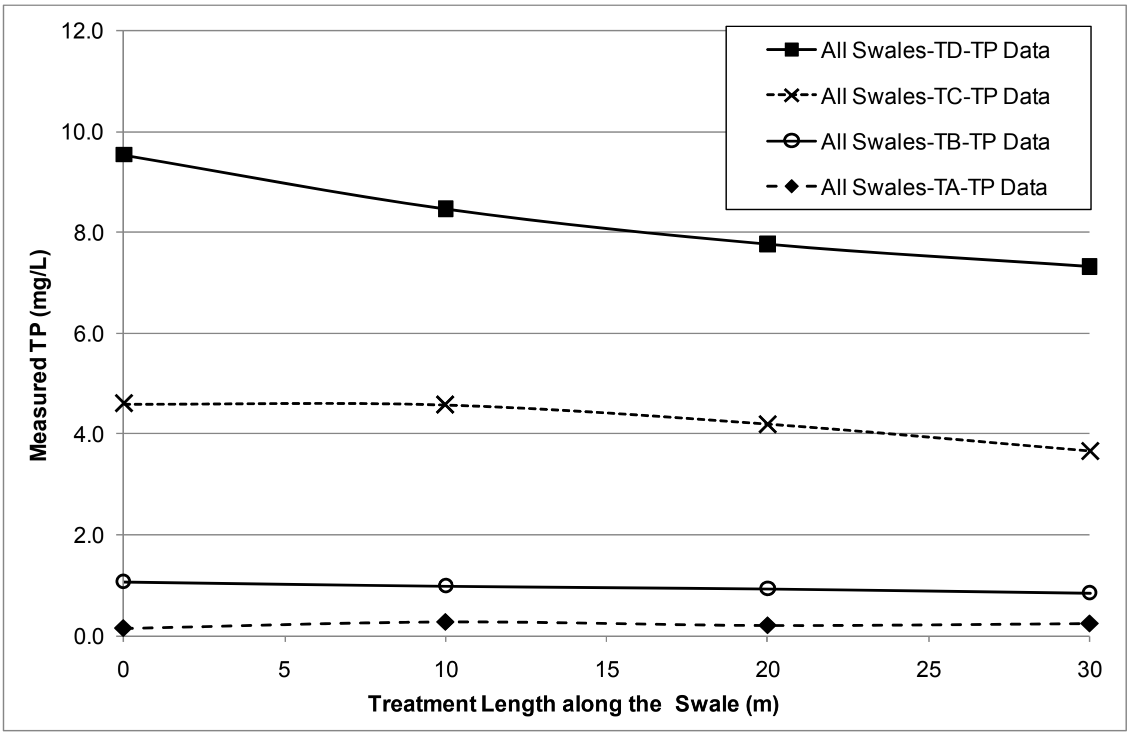
Figure 8. Average TN concentrations for all study swales measured at 10 m intervals.



The experimental results demonstrated that the swales were not effective in removing TN from the synthetic stormwater runoff used in the study. This result is in contrast to a number of previous study results (Table 3). However, the sediment reduction achieved in the swales may also result in a reduction in the overall amount of TN leaving the swales as nutrients are known to attach to sediment particles.

The average TP concentrations measured at 10 m intervals along the four swales during the four tests (TA-TD) are shown in Figure 9. The results show that there was between 20% and 23% reduction in measured TP levels between the inlet and the outlet for the TB, TC and TD tests. The uptake of TP along the swale during the simulation experiments may be attributed to several phosphorous trapping mechanisms that can occur when high TP concentrations are present. Other than direct removal of TP onto the surface of grass and soil within the swale, phosphorous from the simulated runoff may have been adsorbed by finer sediments that settled while flowing in the swales. In addition, the high TSS removal rates shown by swales (Figure 4) may have also assisted in the TP removal performance [6]. However, the results in Figure 9 show there was a substantial increase (61%) in the TP levels between the inlet and the outlet for the TA tests. This was presumably due to leaching of phosphorous components along the swales. The residual of the fertilizers that was used in the tested swales to maintain grass growth may have been contributed to this phosphorous leaching.

Figure 9. Average TP concentrations for all study swales measured at 10 m intervals.



Differences in the nutrient removal performance of the swales used in this study, compared to previous study results may be attributed to a number of causes, including the testing conditions under which the experiments were performed. For example, the synthetic nutrients (*i.e.*, chemical reagents) used in this study to replicate runoff nutrients were fully dissolved in the simulated stormwater. Real stormwater runoff also contains nutrients in particulate form and the methodology used in this study did not account for these pollutant types.

6. Conclusions

Four different field swales were tested during 24 standardised synthetic runoff simulation experiments under varying pollutant loading conditions to evaluate their performance in removing TSS, TN and TP from stormwater runoff. Hydraulic reduction capability of the swales was also assessed by flow measurements carried out at the outlet of the swale during some of the experiments.

Flow measurements demonstrated a mean total flow reduction of 52% in the 30 m long swales studied, with a peak flow reduction of 61%. The initial soil moisture content of a swale was shown to affect infiltration rates, total flow volumes and peak discharges. The study results have demonstrated that swales can be used successfully to attenuate peak stormwater flow rates and to substantially reduce runoff volumes to downstream water courses which can significantly improve the quality of stormwater runoff.

The study has shown that swales were effective in reducing the higher TSS concentrations used in the tests. However, the results demonstrate that a swale's TSS removal performance is highly dependent on the inlet concentrations. Results showed that between 50% and 80% of the TSS was generally removed within the first 10 m of the swales. A further 10% to 20% reduction in TSS concentrations can be expected in swales up to 30 m long. The study also demonstrated that swales can be used to treat higher pollution loads typically associated with the "first flush" phenomenon.

The study has found that swales can be used effectively as a primary treatment measure to remove larger sediment from stormwater runoff. The results showed that the first 15 m of the swale length is the most effective in treating the bulk of the TSS. This suggests that the installation of unnecessarily long swales to treat TSS pollutants may not be the optimal solution. The results suggest that swales could be used in a stormwater treatment train as a pre-treatment to prevent clogging in downstream treatment systems.

The study found no reduction in TN levels in any of the four tests that could be attributed to treatment by the swales. This was in contrast to previous study results. However, the study demonstrated a reduction in measured TP levels of between 20% and 23% between the inlet and the outlet for the TB, TC and TD tests. This reduction is within the range of TP removal reported in previous studies. Differences in nutrient removal performance by swales from this study and other studies may be attributed to the differences in testing conditions and pollutant constituents.

The overall study findings suggest that swales can be used effectively to reduce stormwater runoff pollution, particularly runoff with high concentrations of TSS and TP. Selection of swales as a primary stormwater treatment measure could significantly affect the design requirements of downstream treatment systems. The results from this study will assist designers to estimate the appropriate length of swale required to achieve specific TSS and TP pollution reductions in urban stormwater runoff.

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Author Contributions

This study was undertaken as a collaborative research project by the Stormwater Research Group of the University of the Sunshine Coast in Australia. The experimental design of the project was undertaken by Terry Lucke and Neil Tindale. The majority of the experimental field work was conducted by Mohamed Ansaf Kachchu Mohamed with assistance from Terry Lucke and Neil Tindale. The paper was written by all three authors equally.

Conflicts of Interest

The authors declare no conflict of interest.

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