sustainability

Article

Field and Evaluation Methods Used to Test the Performance of a Stormceptor® Class 1 Stormwater Treatment Device in Australia

Peter Nichols [1,*,†], Terry Lucke [1,†] and Darren Drapper [2,†]

Received: 22 October 2015; Accepted: 3 December 2015; Published: 8 December 2015
Academic Editor: Ken Tamminga

[1] Stormwater Research Group, University of the Sunshine Coast, Sippy Downs Drive, Sippy Downs QLD 4556, Australia; tlucke@usc.edu.au
[2] Drapper Environmental Consultants, 12 Treetops Ave, Springfield Lakes QLD 4300, Australia; darren@drapperconsultants.com
* Correspondence: pnichols@usc.edu.au; Tel.: +61-7-5420-8727
† These authors contributed equally to this work.

Abstract: Field testing of a proprietary stormwater treatment device was undertaken over 14 months at a site located in Nambour, South East Queensland. Testing was undertaken to evaluate the pollution removal performance of a Stormceptor® treatment train for removing total suspended solids (TSS), total nitrogen (TN) and total phosphorous (TP) from stormwater runoff. Water quality sampling was undertaken using natural rainfall events complying with an *a priori* sampling protocol. More than 59 rain events were monitored, of which 18 were found to comply with the accepted sampling protocol. The efficiency ratios (ER) observed for the treatment device were found to be 83% for TSS, 11% for TP and 23% for TN. Although adequately removing TSS, additional system components, such as engineered filters, would be required to satisfy minimum local pollution removal regulations. The results of dry weather sampling tests did not conclusively demonstrate that pollutants were exported between storm events or that pollution concentrations increased significantly over time.

Keywords: stormwater pollution; testing protocols; nitrogen; phosphorus; suspended solids

1. Introduction

The increase in impervious surface area associated with urban development has resulted in increased stormwater runoff volumes and increased pollution loads for downstream receiving waters [1,2]. The management of stormwater in urban areas has therefore become a priority issue during the planning, construction and maintenance of urban developments [3].

A wide range of best management practices (BMPs) have been implemented over the last few decades to remove pollution from stormwater runoff [4–7]. These include sediment basins, swales, rain gardens, wetlands and biofilters. These devices primarily function by filtering and removing the sediment contained within stormwater runoff. Supplementary biochemical treatment processes that remove nutrients from urban runoff may also occur within the media and plants used in various BMPs [8]. To prolong the useful life of these devices, periodic removal of the trapped sediment is required. However, removal of the sediment can often be difficult and costly to achieve in practice, and this can limit their application [9]. The size of some of the BMPs can also restrict their use in dense urban environments.

Proprietary stormwater treatment devices (PSTDs) have also been widely implemented in urban areas over the last few decades to manage stormwater by reducing peak flows and downstream pollution loads [10–12]. Compared to complex treatment trains and large surface area basins, PSTDs are designed for easy installation and maintenance and are becoming more popular in Australia, as well as in the rest of the world [13,14]. There has been a range of studies that have focused on the performance and evaluation of conventional BMPs. However, much less is known about the pollution removal performance of PSTDs [14,15].

This paper reports on the pollution removal performance results of a series of field-based tests undertaken on a PSTD (Class 1 Stormceptor®; Figure 1). The PSTD, located on the Sunshine Coast, Australia, was subjected to a series of natural rainfall events over a period of 14 months. Water quality tests were undertaken to determine the levels of removing total suspended solids (TSS), total nitrogen (TN) and total phosphorous (TP) removed by the system during rainfall events and dry weather for potential leaching evaluation. Most pollutants from urban areas are transported during wet weather conditions rather than dry, which is why this testing was undertaken during rainfall events.

Figure 1. Aerial photograph of the subject site (property boundary shown by the yellow line).

In particular, the system has been designed to specifically remove TSS; removal of TP and TN has been regarded as an added bonus. The suitability of the performance evaluation calculation methods used has also been discussed.

2. Methodology

Testing was undertaken over a period of 14 months at a commercial-zoned site in Nambour, approximately 100 km north of Brisbane, Australia. The site comprised a total area of 2800 m^2, with approximately 1848 m^2 of roof area (66%), 924 m^2 of impervious concrete driveway (33%) and 28 m^2 (1%) of landscaped area.

2.1. Treatment Train Approach

The stormwater treatment train (Figure 2) included an underground rainwater tank (roof water capture and reuse), gully pits and surface drains, as well as the PSTD. Roof water from the site was firstly directed to an underground rainwater tank (shown as a blue dot in Figure 1), which then overflowed to the PSTD (shown as a red rectangle in Figure 1) once the tank was full. The surface runoff from the carpark area was drained directly to the PSTD via a series of gully pits, surface drains and underground pipes.

A schematic of the treatment train and flow paths from the site is presented in Figure 2. Once treated, stormwater was discharged to the municipal stormwater drainage system and eventually into

Petrie Creek, a sub-catchment of Maroochy River, which is comprised of predominantly low-land freshwaters within partly-confined valleys. Petrie Creek supports rare and threatened species and diverse invertebrate and fish populations [16].

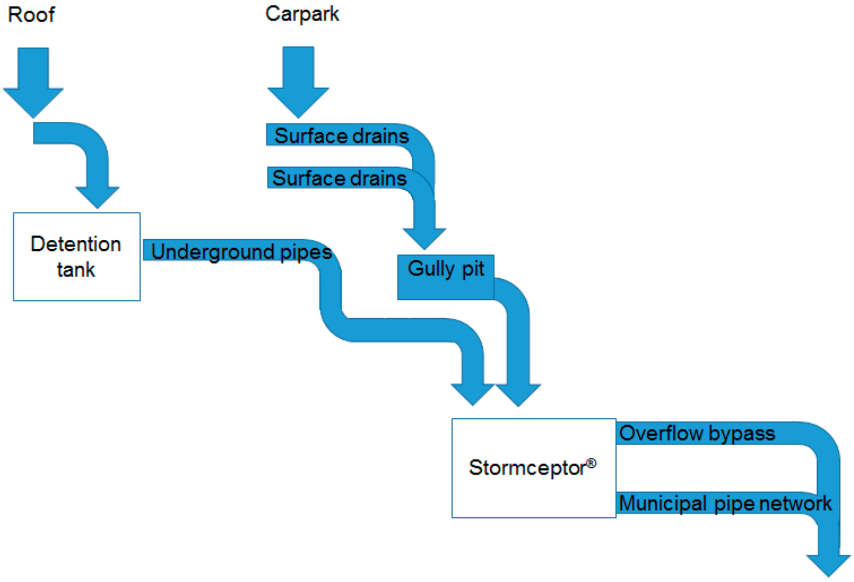


Figure 2. Schematic of the proprietary stormwater treatment device (PSTD) treatment train.

The hydraulic design of this device facilitates a minimum four-minute retention period that provides conditions within the secondary (offline) chamber, promoting the separation of total suspended solids (TSS), hydrocarbons (TPH) and other pollutants (nitrogen and phosphorous) through the coalescer unit (Figure 3). Incorporated into the hydraulic flow of the unit, the coalescer is a polyethylene, oleophilic matrix that filters and then repels hydrocarbons from water.

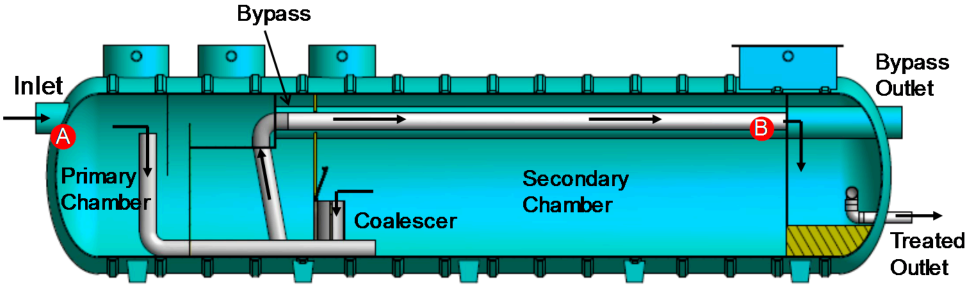


Figure 3. Design schematic of the study PSTD and monitoring equipment setup.

The arrows in Figure 3 show the flow path that the treated stormwater takes through the PSTD. The primary chamber of the PSTD is designed to trap gross pollutants and sediment greater than 0.2 mm in diameter, and the coalescer in the secondary chamber is designed to separate immiscible liquids (oil and grease) from water. The maximum treatment capacity of the PSTD used in this study was 20 L/s. This flow volume was referred to as the treatable flow rate (TFR), and it is from these flows that auto-samplers located at Points A and B (Figure 3) collected water samples for analysis. In particular, the study evaluated the ability of the PSTD to remove TSS contained in stormwater effluent to the levels specified by the Queensland State Planning Policy [17]. This policy is intended to control stormwater pollution through the development and approvals process. The policy specifies that pollution emanating from development sites must be reduced by 80% for total suspended solids (TSS), 60% for total phosphorus (TP) and 45% for total nitrogen (TN) [17].

The manufacturers recommend that the PSTD should generally be maintained at least annually. However, this is also dependent on observed pollution loads. Maintenance includes sediment removal from the gross pollutant trap (GPT) section of the unit via a suction hose. The coalescer is subjected to a low pressure wash during maintenance, with the resultant wash-off also being removed via a suction hose. No maintenance of the unit was required or undertaken during the 14-month study test period.

2.2. Sampling Protocol

A sampling protocol (Table 1) was developed based on the Auckland Regional Council Proprietary Device Evaluation Protocol [18] and Washington State Department of Environment Stormwater BMP Database protocols [19]. The protocol was developed specifically to provide sufficient numbers of valid sampling events and water quality samples for analysis, in order to clearly demonstrate the pollution removal performance of the PSTD under an appropriate range of natural rainfall conditions. Much of the adopted protocol is also included in the Stormwater Australia Stormwater Quality Improvement Device Evaluation Protocol draft [20].

Table 1. Field testing protocol requirements for Nambour. TSS, total suspended solids.

Requirements	Criteria	Details
Minimum qualifying events	15	With the aim to gain sufficient valid data to achieve a statistically-significant difference between influent and effluent. Statistical significance will not, however, be a critical requirement, as this may require hundreds of samples and be financially unviable.
Minimum rainfall depth	1.5 mm	Test and report unless below detectable limits in the influent.
Minimum storm duration	5 min	Required to provide minimum volume of runoff.
Minimum dry antecedent period	6 h	Test and report unless below detectable limits in the influent.
Hydrograph sampled	Minimum 60%	Capture as much as possible, but a minimum of the first 60% of the hydrograph.
Flow rates tested	Range (0% ± 50%)	Minimum 3 events >75% of treatable flow rate (TFR) and 1 >100% of TFR; Magflow flow meter.
Minimum number of sample aliquots	2	Minimum total volume 180 mL; 8 aliquots preferred across the full hydrograph.
Aliquots' (subsamples) volume	200 mL	Minimum sufficient for National Association of Testing Authorities (NATA) testing.
Sample method	ISCO GLS automatic sampler	Composite sample collection, ISCO GLS auto-sampler
Flow-weighted samples	Every 1000 L	To provide for the calculation of an event mean concentration (EMC). EMC is the concentration measured in the sample.
Rainfall monitoring	0.2-mm intervals	Waterlog automatic pluviometer.
TSS	APHA [1] (2005) 2540 D [10]	HDPE [2] or glass bottles, cool to 4 °C, maximum hold time 24 h.
Total nitrogen	APHA (2005) 4500 N	HDPE or glass bottles, cool to 4 °C, collect ASAP, maximum hold time 48 h.
Total phosphorous	APHA (2005) 4500 P	HDPE or glass bottles, cool to 4 °C, collect ASAP, maximum hold time 48 h.
Particle size distribution	Laser diffraction (Malvern Mastersizer)	Continuously stirred, without chemical dispersion nor sonication.
Laboratory certification	NATA registered	
QA/QC	Random duplicates and blanks	In accordance with the relevant Australian Standard and by NATA registered laboratory.

Note: [1] APHA: American Public Health Association; [2] HDPE: High density polyethylene.

2.3. Sampling Equipment and Timing

The output signals from all of the monitoring equipment installed on the PSTD in the study were logged using a CR800 Campbell Scientific datalogger. Flow-weighted subsamples (200 mL) were taken after a stormwater volume of 1000 L had passed through the MJK Magflux® flow meter installed at the treated flow outlet pipe (Figure 1). A Starflow ultrasonic probe was located in the bypass outlet. A water volume of 1000 L was chosen as the sampling flow interval, as this was approximately equal to the runoff generated by 0.5 mm of rainfall over the site, assuming zero losses. All subsamples collected during runoff events were composited within the automatic samplers in 9-L bottles. For sampling events where insufficient volume was collected for the suite of subsequent chemical analyses to be undertaken (listed in Table 1), the event was discarded and recorded as non-qualifying.

The antecedent dry period was initially set at 72 h between rainfall events [21,22]. However, to increase the number of qualifying events, the antecedent dry period was reduced to 6 h unless the influent pollutant concentrations were below the limits of detection (LOD). The minimum event rainfall trigger for sampling was set to 1.5 mm.

2.4. Performance Metrics

A number of calculation methodologies was used to determine pollution removal performance metrics. These include: event mean concentration (EMC) (Equation (1)), concentration removal efficiency (CRE) (Equation (2)) and the efficiency ratio (ER) (Equation (3)). Prior to statistical testing, concentrations of all pollutants were log-transformed (Equation (4)) to achieve normality (Shapiro–Wilks $p > 0.05$ alpha). One-sided confidence intervals (95%) were calculated using Equation (5).

Event mean concentration (EMC) was calculated using Equation (1):

$$EMC = \frac{\sum_{i=1}^{n} V_i C_i}{\sum_{i=1}^{n} V_i} \tag{1}$$

where:

- V_i = volume of flow during period i;
- C_i = concentration associated with period i;
- n = total number of aliquots collected during the event.

Average concentration removal efficiency (CRE) was calculated using Equation (2):

$$Avg.\ CRE = \frac{\sum \left[\frac{\{EMCin - EMCout\}}{EMCin} \right]}{no.\ of\ events} \tag{2}$$

The efficiency ratio (ER) was calculated using Equation (3):

$$ER = 1 - \frac{Mean\ EMCout}{Mean\ EMCin} \tag{3}$$

Log-transformation was undertaken using Equation (4):

$$X' = \log_{10}(X + 1) \tag{4}$$

Confidence intervals (95%) were calculated using Equation (5):

$$\bar{x} \pm 1.96 \left(\frac{\sigma}{\sqrt{x}} \right) \tag{5}$$

Q-Q plots were used to compare the two datasets using a non-parametric approach to compare their underlying distributions. Q-Q plots are generally used to provide a graphical assessment of the "goodness of fit". Q-Q plots (log) were used in this study to compare the shapes of observed sample distributions and to provide a graphical view of how properties, such as location, scale and skewness, are similar or different in the two distributions.

Dry weather samples were taken on consecutive days after rainfall events to determine whether nutrients were exported over time. The dry weather samples were collected manually as grab samples. Inflow grab samples were taken from the primary chamber and outflow grab samples from the secondary chamber of the PSTD. Calculations of the changes in pollution concentrations were made using Equations (1)–(3).

3. Results and Discussion

During 14 months of monitoring, 59 rainfall events (>1.5 mm) were recorded at the study location. Of these, 18 events were characterised as qualifying events according to the agreed sampling protocol (Table 1). When any of the results were less than the limits of detection (LOD) for that particular test, they were shown as 50% of the LOD in Table 1.

The measured pollution removal performance (ER) of the PSTD was 83% for TSS, 11% for TP and 23% for TN over the 14-month study period (Table 2). Being specifically designed to remove TSS, the system has successfully achieved this objective. Although not unexpected, the removal of TP and TN from outflows was found to be minimal and not achieving the minimum specified by the regulations. Additional components would need to be added to the treatment train to fully satisfy the specific Queensland Government regulations in terms of TP and TN pollution removal.

Table 2. Measured pollution removal performance. TP, total phosphorus; TN, total nitrogen; CRE, concentration removal efficiency.

Parameter	**TSS**		**TP**		**TN**	
Event	**In (mg/L)**	**Out (mg/L)**	**In (mg/L)**	**Out (mg/L)**	**In (mg/L)**	**Out (mg/L)**
LOD (mg/L)	**1**		**0.005**		**0.1**	
27 March 2014	6	1	0.069	0.075	0.203	0.223
30 May 2014	54	7	0.052	0.071	0.694	0.651
21 June 2014	121	15	0.126	0.041	1.25	0.633
16 July 2014	207	19	0.151	0.016	1.59	0.7
22 July 2014	27	4	0.029	0.005	1.29	0.772
9 August 2014	20	4	0.035	0.033	1.02	0.703
22 August 2014	5	0.5	0.005	0.005	0.399	0.462
28 November 2014	35	4	1.04	1.13	0.55	0.36
8 December 2014	16	8	0.38	0.6	0.49	0.62
11 December 2014	7	5	0.77	0.49	0.27	0.38
18 December 2014	25	3	0.47	0.47	1	0.59
27 December 2014	21	6	0.47	0.6	0.4	0.35
3 January 2014	24	6	0.72	0.45	0.58	0.82
12 January 2015	8	4	0.55	0.4	0.23	0.57
20 January 2015	9	9	0.42	0.47	0.25	0.46
22 March 2015	21	4.4	0.0025	0.0025	0.6	0.7
1 April 2015	9.3	4.3	0.19	0.0025	1	0.4
7 April 2015	18	3.4	0.0025	0.0025	0.9	0.4
Average Concentration	35.2	6.0	0.305	0.270	0.25	0.20
Median Conc.	20.5	4.35	0.1705	0.073	0.13	0.15
Efficiency Ratio (Average)		83%		11%		23%
Efficiency Ratio (Median)		79%		57%		2%
Average CRE		71%		17%		0%
CRE 95% confidence interval		±12%		±20%		±25%

Notes: LOD = limit of detection.

Even though the calculation methods for both the ER and CRE metrics use the same data, these results were found to vary substantially (Table 2). This is the result of the two calculation methods using different mathematical logic. Results near the limits of detection, such as those for rainfall events on 22 March 2015 and 7 April 2015 (Table 2), skewed the average CRE metric by producing individual event CREs of 0%. Exclusion of these outliers produced substantially different results, increasing the average TN CRE result to 15% (up from 0%).

The PSTD has a designed treatable flow rate (TFR) of 20 L/s. Eleven of the 18 events were >75% of the TFR (Table 3) and were >100% of the TFR. Performances (CRE) for treatable flow rates between 75% and 100% were found to be highly variable for each pollutant measured (TSS, 0%–90%; TN, 0%–99%; TP, −148%–60%). This variability appears to be more related to the low influent concentrations than the flow rate.

Table 3. Rainfall and flow data in relation to event CRE.

Parameter Event	Rainfall Depth	Peak Flow Rate	CRE (%)		
LOD (mg/L)	(mm)	(L/s)	TSS	TN	TP
27 March 2014	101	32.8	83	−9	−10
30 May 2014	21.6	36.6	87	−37	6
21 June 2014	8	7.89	88	67	49
16 July 2014	5.6	7.64	91	89	56
22 July 2014	4	7.51	85	83	40
9 August 2014	3.6	7.74	80	6	31
22 August 2014	21.8	32.7	90	–	−16
28 November 2014	18	36.9	89	−9	35
8 December 2014	21.6	32.4	50	−58	−27
11 December 2014	67.6	31.7	29	36	−41
18 December 2014	40.4	39.7	88	0	41
27 December 2014	15.4	16.5	71	−28	13
3 January 2014	8.4	6.5	75	38	−41
12 January 2015	23.8	35.8	50	27	−148
20 January 2015	564.4	34.9	0	−12	−84
22 March 2015	36.8	22.3	79	0	−17
1 April 2015	66.2	33.5	54	99	60
7 April 2015	2.6	5.1	81	0	56

PSTD measured performances over total flow volumes (sum of loads) were found to be variable and, although high for TSS, included a calculated export of TN (Table 4). The sum of loads (SoL) has been calculated according to Equation (6).

Table 4. Total flow volume and Sum of Loads (SoL).

Total Event	Sum of Loads Removal (%)		
flow (kL)	TSS	TP	TN
606.55	75	18	−9

Although somewhat counter-intuitive because the unit is a closed system, this may be a result of the number of non-qualifying events that passed through the system contributing to the overall pollution load in subsequent events.

Particle Size Distribution (PSD) analysis revealed variable results between inflow and outflow (Table 5). The particle sizes at which the different percentages of mass were observed all increased after treatment. Although all size groups were shown to increase after treatment, these results do not represent substantial differences in sizes (especially in the D_{10} and D_{90}). These results may have been affected by unusually non-spherical shapes of the particles measured, which affects the accuracy of the automated laser measurement technology. Alternately, these average results presented below could be influenced by the mathematical averaging across all events.

Table 5. Averaged particle size distribution (PSD) analysis across all events.

PSD	Inflow (µm)	Outflow (µm)
D_{10}	143	185
D_{50}	386	542
D_{90}	860	973

Influent concentrations for TSS and TN at the study site (Table 6) were significantly lower (TSS $p < 0.001$, TN $p < 0.001$) than the typical values for Australian commercial catchments reported by Duncan [23] and those recommended by industry for use in Australian pollution modelling studies and used within the software tool, Model for Urban Stromwater Improvement (MUSIC) [24].

Table 6. Comparison of Nambour surface water quality results with Brisbane MUSIC Guidelines for urban residential areas.

Parameter	MUSIC Guideline Values (Lumped Commercial Catchment) [1]			Nambour Catchment Influent Concentration		
	−1 SD	Mean	+1 SD	−1 SD	Mean	+1 SD
TSS (mg/L)	60.3	145	347	0	35.18	85.68
TP (mg/L)	0.186	0.407	0.891	0	0.305	0.618
TN (mg/L)	1.07	2.34	5.13	0.294	0.706	1.119

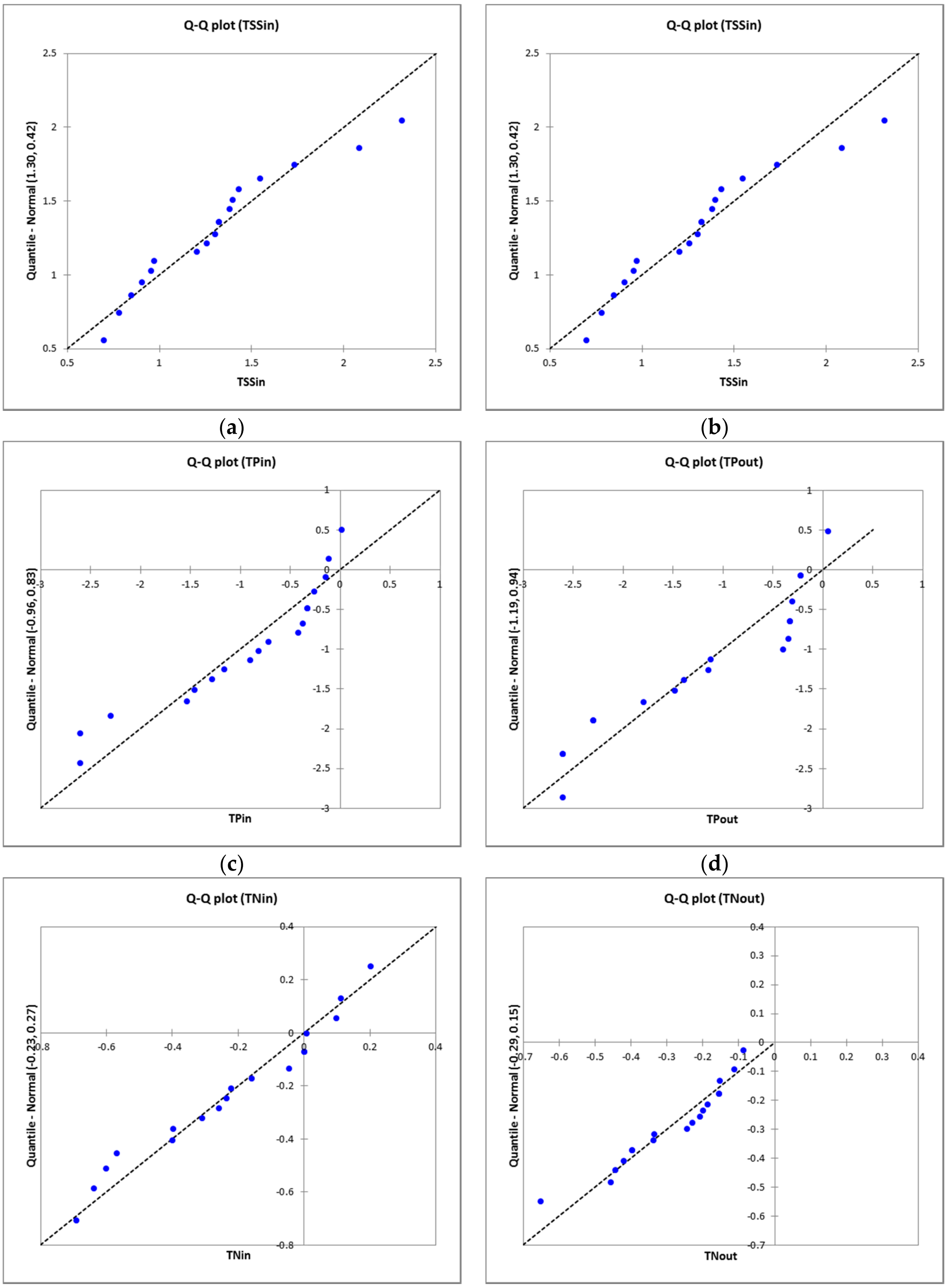
Note: [1] Model for Urban Stromwater Improvement (MUSIC) [24].

Similarly affected PSTD performance results have been observed by the authors from other field evaluation sites [25]. Results from these other studies have been shown to differ by up to 30% for TN and 20% for TP, where low influent concentrations result in 0% or negative CRE. In some cases, calculations have resulted in a theoretical export of pollutants. Large negative CRE can have an impact on the average CRE value, and so, for this reason, it is suggested that when influent concentrations are close to the LOD, CRE on its own is not an appropriate metric. Where low influent concentration are observed, the calculated ER may be a more accurate reflection of the PSTD pollution removal performance.

Even though large datasets may be required, statistical validation (paired *t*-test) of data is recommended by some international protocols to confirm significant differences between the influent and effluent sample sets [18]. TP and TSS influent pollution concentrations (log-normally distributed) were found to be significantly different between the Nambour study site and the MUSIC guidelines ($p > 0.05$) (Table 7, Figure 3). The Q-Q plots of the log-transformed datasets confirm visually the results of the statistical tests that the data are closely aligned to a log-normal distribution and that therefore further statistical tests can be performed (Figure 4).

Table 7. Shapiro–Wilks normality tests (log-transformed) (significant *).

PSTD	*p*-Value					
	TSS in	TSS out	TP in	TP out	TN in	TN out
Stormceptor®	0.202 *	0.052 *	0.026	0.015	0.400 *	0.164 *



(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

Figure 4. Q-Q plots of log-normal distributions: (**a**) TSS inflow; (**b**) TSS outflow; (**c**) TP inflow; (**d**) TP outflow; (**e**) TN inflow; (**f**) TN outflow.

3.1. Statistical Significance Tests

Both the Student *t*-test and the Mann–Whitney (Wilcoxon) rank-sum test revealed that TSS outflow concentrations were significantly lower than inflow concentrations (Tables 8 and 9).

Table 8. Student's *t*-tests (log-transformed).

Treatment Device	TSS *p*-Value (Two-Tailed)	TP *p*-Value (Two-Tailed)	TN *p*-Value (Two-Tailed)
PSTD Results	<0.0001 *	0.078	0.293

Note: * Significant.

Table 9. Wilcoxon–Mann–Whitney rank-sum tests (raw data).

Treatment Device	TSS *p*-Value	TSS *p*-Value	TSS *p*-Value
PSTD Results	<0.05 *	0.636	0.459

Note: * Significant.

Previous PSTD testing studies that have produced highly variable data have suggested that the confirmation of statistical significance may require extensive testing; however, they conceded that this may not be achievable in all circumstances [23]. An estimation of the number of samples required for a statistically-significant, paired comparison for the current dataset (Equation (6)) as recommended by Burton and Pitt [26] suggests that eight samples would be required for accurate TSS analysis. However, 333 samples would be required for TP and 280 samples for TN. Collecting this number of samples would not generally be viable for most studies.

$$n = 2\left[\frac{Z_{1-\alpha} + Z_{1-\beta}}{\mu_1 - \mu_2}\right]^2 \sigma^2 \tag{6}$$

where n = the number of sample pairs needed; α = the false positive rate ($1 - \alpha$ is the degree of confidence; a value of α of 0.05 is usually considered statistically significant, corresponding to a $1 - \alpha$ degree of confidence or 95%); β = the false negative rate ($1 - \beta$ is the power, if used; a value of β of 0.2 is common, but it is frequently ignored, corresponding to a β of 0.5); $Z_{1-\alpha}$ = Z score (associated with the area under the normal curve) corresponding to $1 - \alpha$; $Z_{1-\beta}$ = Z score corresponding to a $1 - \beta$ value; μ_1 = the mean of dataset one; μ_2 = the mean of dataset two; σ = the standard deviation (same for both datasets, assuming a normal distribution).

It has been the authors' experience during this and other, similar studies that only approximately 25% of events sampled fully satisfy the criteria needed to be considered as qualifying events. The remainder of the samples are discarded for non-conformance with strict sampling protocols. Continuation of a monitoring program to achieve the 280 qualifying events required for statistical certainty in this study (>750 events overall) was found to be financially prohibitive for this research program. The authors' suggest that this would be the case for many field evaluation studies. The authors therefore recommend that the current industry-accepted methodology used in Australia to calculate pollution removal performance of proprietary stormwater quality improvement devices should be modified to accept contingencies, such as those that have been experienced in this study.

3.2. Dry Weather Sampling

As the PSTD is located on a relatively small commercial catchment, there is no baseflow through the system during dry weather. TSS and TN concentrations were observed to increase from the first chamber to the second chamber of the device (Table 10). However, it should be noted that the very low inflow concentrations are likely to again be the key factor for any observed increase at the second chamber. For example, typically, the LOD for TSS was 5 mg/L, and had the authors not requested a lower LOD (1 mg/L), the results would have predominantly shown below detectable results on both inlet and outlet samples for TSS. Further, blind duplicate and replicate testing on this and other projects by the authors has demonstrated that the variability of pollutant concentrations on these dry weather samples is within the range of observed variation (±2.8 mg/L TSS, ±0.3 mg/L TN and

±0.02 mg/L TP). Therefore, the authors consider that there is no conclusive evidence that the PSTD releases pollutants during dry weather that could not be attributed to analytical variability. This confirms recent research that also found no significant relationship between nutrient concentrations and length of dry period between events on wet sump devices [27].

Table 10. Dry weather sampling results.

Parameter	**TSS**		**TP**		**TN**	
LOD (mg/L)	**1**		**0.005**		**0.1**	
Event	**In (mg/L)**	**Out (mg/L)**	**In (mg/L)**	**Out (mg/L)**	**In (mg/L)**	**Out (mg/L)**
20 March 2015	2.9	5.2	0.0025	0.0025	0.6	0.7
25 March 2015	1.1	2.7	0.0025	0.0025	0.1	0.3
30 March 2015	1.6	3.3	0.0025	0.0025	0.6	0.5
8 April 2015	1.2	8.9	0.0025	0.0025	0.1	0.3
9 April 2015	2	2.2	0.0025	0.0025	0.2	0.3
10 April 2015	2	3.2	0.0025	0.0025	0.2	0.3

Notes: LOD = limit of detection.

4. Conclusions

The evaluation of proprietary stormwater treatment devices has been performed for decades internationally and appears to be gaining momentum in Australia. While a number of existing guidelines stipulate that the performance of these devices must be demonstrated for local and regional conditions, the guidelines generally do not define how this should be accomplished.

This paper has detailed the evaluation and testing protocol implemented on a Class 1 Stormceptor® at one monitoring site in Queensland, Australia. Results from 18 complying events showed a pollution removal efficiency (ER) of 83% for TSS, 11% for TP and 23% for TN. Based on the analyses, TSS was found to be significantly reduced after treatment by the device. Being specifically designed to remove TSS, the system has successfully achieved this objective. Although not unexpected, the removal of TP and TN from outflows was found to be lower than the minimum specified by Queensland policy. Additional features, such as an engineered filter media, would need to be added to the system to totally comply with the specific Queensland Government policies in terms of TP and TN pollution removal.

Although a reasonably large number of rainfall events were analysed in total, further analysis was found to be required due to the variability in the results, particularly for TP and TN. Because of the large number of samples required (>750) to achieve adequate confidence intervals (>95%) for CRE, it was deemed not financially viable. Dry weather testing of the device demonstrated that the results were within the expected levels of analytical variability, and conclusive evidence that the wet sump exported nutrients during dry weather could not be confirmed.

Low inflow pollution concentrations were found to skew average CRE results, leading to low overall CRE. Exclusion of outliers produced substantially different results. The use of ER in place of CRE evaded the skew effects observed for CRE and provided accurate performance evaluation results.

The study results suggest that when pollution influent concentrations are close to the LOD, CRE may not be an accurate reflection of PSTD performance. In these cases, the calculated ER may be a more accurate reflection of the pollution reduction performance.

The authors recommend that the current industry-accepted methodology used to calculate the pollution removal performance of proprietary stormwater quality improvement devices should be modified to accept contingencies, such as those that have been experienced in this and other similar studies.

Acknowledgments: The authors acknowledge the contribution to this research by staff and students at the University of the Sunshine Coast, including Michael Neilsen, Ronald Kleijn and Brian Pearson.

Author Contributions: All authors have contributed equally to the preparation of this article.

Conflicts of Interest: The research was independently undertaken by USC under a funding agreement with SPEL Environmental.

References

1. Dietz, M.E. Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. *Water Air Soil Pollut.* **2007**, *186*, 351–363. [CrossRef]
2. Lucke, T.; Beecham, S. Field Investigation of Clogging in a Permeable Pavement System. *J. Build. Res. Inf.* **2011**, *39*, 603–615. [CrossRef]
3. Nichols, P.W.B.; White, R.; Lucke, T. Do sediment type and test durations affect results of laboratory-based, accelerated testing studies of permeable pavement clogging? *Sci. Total Environ.* **2015**, *511*, 786–791. [CrossRef] [PubMed]
4. Taylor, A.C.; Wong, T.H.F. *Non-Structural Stormwater Quality: Best Management Practices: A Literature Review of Their Value and Life-Cycle Costs*; CRC for Catchment Hydrology: Melbourne, Australia, 2002.
5. Wong, T.H.F. Water sensitive urban design-the journey thus far. *Aust. J. Water Resour.* **2006**, *10*, 213–222.
6. Braune, M.J.; Wood, A. Best management practices applied to urban runoff quantity and quality control. *Water Sci. Technol.* **1999**, *39*, 117–121. [CrossRef]
7. Taylor, G.D.; Fletcher, T.D.; Wong, T.H.F.; Breen, P.F.; Duncan, H.P. Nitrogen composition in urban runoff—Implications for stormwater management. *Water Res.* **2005**, *39*, 1982–1989. [CrossRef] [PubMed]
8. Hatt, B.E.; Fletcher, T.D.; Deletic, A. Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. *J. Hydrol.* **2009**, *365*, 310–321. [CrossRef]
9. Lucke, T.; Nichols, P. Field Evaluation of Hydrology Performance of Established Bioretention Cells Receiving Street Drainage. *Sci. Total Environ.* **2015**, *536*, 784–792. [CrossRef] [PubMed]
10. Davis, A. Field Performance of Bioretention: Hydrology Impacts. *J. Hydrol. Eng.* **2008**, *13*, 90–95. [CrossRef]
11. Hunt, W.; Smith, J.; Jadlocki, S.; Hathaway, J.; Eubanks, P. Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, N.C. *J. Environ. Eng.* **2008**, *134*, 403–408. [CrossRef]
12. Le Coustumer, S.; Fletcher, T.D.; Deletic, A.; Barraud, S.; Poelsma, P. The influence of design parameters on clogging of stormwater biofilters: A large-scale column study. *Water Res.* **2012**, *46*, 6743–6752. [CrossRef] [PubMed]
13. Hipp, J.A.; Ogunseitan, O.; Lejano, R.; Smith, C.S. Optimization of stormwater filtration at the urban/watershed interface. *Environ. Sci. Technol.* **2006**, *40*, 4794–4801. [CrossRef] [PubMed]
14. Sample, D.J.; Grizzard, T.J.; Sansalone, J.; Davis, A.P.; Roseen, R.M.; Walker, J. Assessing performance of manufactured treatment devices for the removal of phosphorus from urban stormwater. *J. Environ. Manag.* **2012**, *113*, 279–291. [CrossRef] [PubMed]
15. Cates, E.; Westphal, M.; Cox, J.; Calabria, J.; Patch, S. Field evaluation of a proprietary storm-water treatment system: Removal efficiency and relationships to peak flow, season, and dry time. *J. Environ. Eng.* **2009**, *135*, 511–517. [CrossRef]
16. Maroochy Shire. State of Waterways Report, 2005–2007. Available online: http://www.sunshinecoast.qld.gov.au/addfiles/documents/environment/waterways/sow_petrie_ck.pdf (accessed on 25 November 2015).
17. State of Queensland, Department of State Development, Infrastructure and Planning. *State Planning Policy*; State of Queensland: Brisbane, Australia, 2013.
18. Auckland Regional Council. *Proprietary Devices Evaluation Protocol (PDEP) for Stormwater Quality Treatment Devices*; version 3. Auckland Regional Council: Auckland, New Zealand, 2012.
19. Washington Department of Ecology. *Technical Guidance Manual for Evaluating Emerging Stormwater Treatment Technologies*; Technology Assessment Protocol—Ecology (TAPE). Washington Department of Ecology: Washington, DC, USA, 2011.
20. Stormwater Australia. Stormwater Quality Improvement Device Evaluation Protocol (SQIDEP). Available online: http://stormwater.asn.au/images/SQID/SQIDEP_Release_version_December_2014.pdf (accessed on 10 August 2015).
21. Liu, A. Influence of Rainfall and Catchment Characteristics on Urban Stormwater Quality. Ph.D. Thesis, Queensland University of Technology, Brisbane, Australia, 30 October 2011.

22. Parker, N. Assessing the Effectiveness of Water Sensitive Urban Design in Southeast Queensland. Master's Thesis, Queensland University of Technology, Brisbane, Australia, 13 August 2010.
23. Duncan, H. *Urban Stormwater Quality: A Statistical Overview*; Cooperative Research Centre for Catchment Hydrology: Melbourne, Australia, 1999.
24. Water by Design. *MUSIC Modelling Guidelines*; SEQ Healthy Waterways Partnership. Queensland Government: Brisbane, Austrilia, 2010.
25. Drapper, D.; Hornbuckle, A. Field Evaluation of a Stormwater Treatment Train with Pit Baskets and Filter Media Cartridges in Southeast Queensland. *Water* **2015**, *7*, 4496–4510. [CrossRef]
26. Burton, A.; Pitt, R. Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists and Engineers. 2015. Available online: http://unix.eng.ua.edu/~rpitt/Publications/BooksandReports/Stormwater%20Effects%20Handbook%20by%20%20Burton%20and%20Pitt%20book/hirezhandbook.pdf (accessed on 10 August 2015).
27. Millar, G. SQID Wet Sump Nutrient Production—The Reality, Conference Proceedings, Stormwater 2014. In Proceedings of the 3rd National Conference on Urban Water Management, Stormwater Australia, Adelaide, Australia, 13–17 October 2014.