NUTRIENTS AND SOLIDS REMOVAL BY AN ENGINEERED TREATMENT TRAIN

Field evaluation of a gully pit insert and cartridge media filter

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Abstract

The performance claims for individual stormwater treatment devices is often open to debate, as much of the data available has not been subjected to robust scrutiny and/or the claims are unable to be replicated. The following article summarises the results from a field trial of two such devices: an EnviroPod® and a StormFilter®, arranged in series (or a 'treatment train') treating runoff from a small road catchment on Streets Creek, Kuranda, west of Cairns in Far North Queensland.

This field trial complements an earlier research project undertaken on the same system by James Cook University. Data was collected from six storm events, predominantly during the dry seasons of 2008 and 2009, and includes simultaneous sampling of both the flow rate and water quality on the inflows to, and outflows from, the treatment train for a suite of particulate and soluble stormwater pollutants. Influent concentrations for both Phosphorus and Nitrogen were found to be half to one-third of concentrations reported in the literature as typical for urban catchments in Australia.

One storm was also analysed for an expanded suite of nitrogen analytes, which determined that more than half the load was in soluble form. Furthermore, results from the field trial and research project indicated that this treatment train system has the potential to achieve meaningful load reductions of Suspended Solids (up to 99%), Phosphorus (up to 70%) and Nitrogen (up to 45%) through the use of conventional screening, filtration and ion-exchange removal technologies.

Introduction

Livingston and McCarron (1992) identified that pollution loads (gross pollutants, sediment and nutrients) in stormwater increase proportionally with the degree of urbanisation in the catchment. Most consent authorities in Australia have established pollution removal efficiencies to be achieved prior to discharge from the urban catchment (eg, NSW Department of Environment and Climate Change (DECC) 2007 recommends Suspended Solids (SS) 85%, Total Phosphorus (TP) 65%, and Total Nitrogen (TN) 45%) and/or Event Mean Concentrations (EMCs) in any stormwater discharged into natural ecosystems (e.g. ANZECC 2000 recommends turbidity 2-15 Nephelometric Turbidity Units (NTU), TP 0.01 mg/L and TN 0.15 mg/L for river systems in tropical Australia).

In general, each pollutant is removed from the water column using a specific physical, chemical or biological process. Arranging these processes in sequence provides a treatment train approach that addresses and treats the whole pollutant load. There is, however, a paucity of published peer-reviewed scientific information validating the removal efficiency of each element or device used within a treatment train – let alone the performance of the treatment train itself. The research referred to herein provides information to validate the performance claims of an EnviroPod® gully trap and a StormFilter ® cartridge arranged in series as a treatment train.

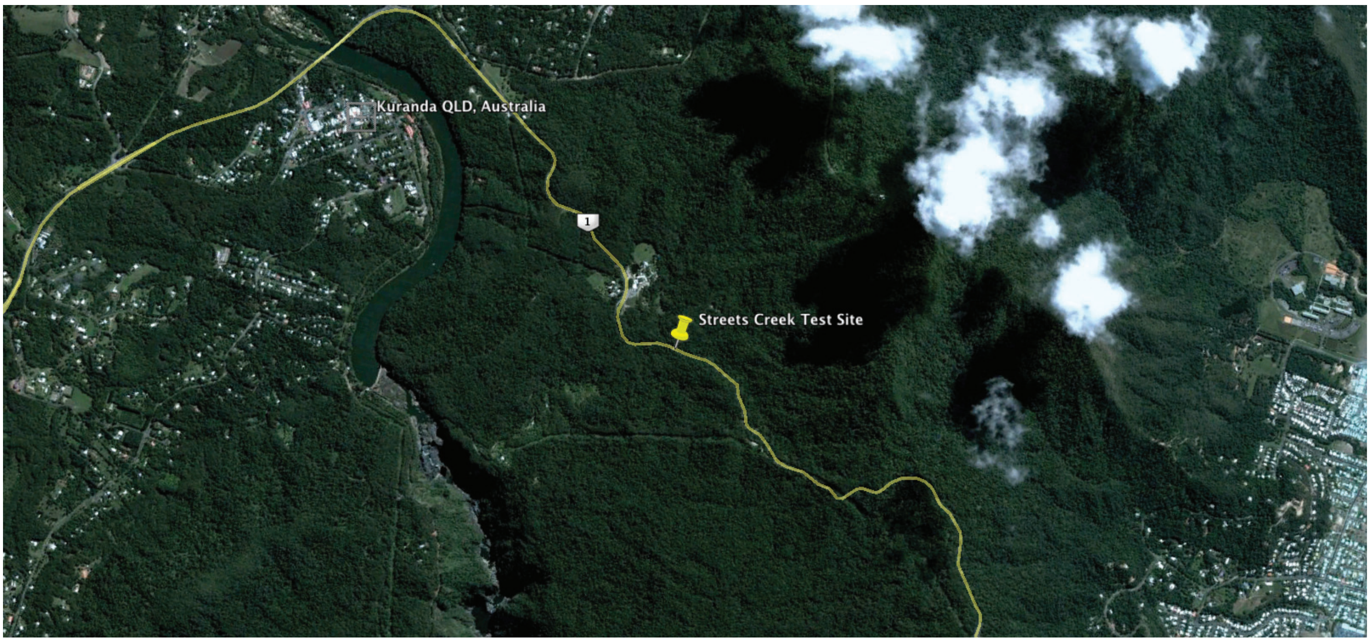

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Figure 1. Location of the Kuranda Test Site.

Background

This field trial follows a previous research project undertaken by the School of Earth and Environmental Sciences, James Cook University (JCU), as part of a wider investigation into the impacts of road runoff on the Kuranda Range Road watershed, near Cairns (Munksgaard and Lottermoser, 2008), which discharges into the sensitive environment of Streets Creek. JCU reported on the quality of the watershed's receiving waters, the chemical characterisation of the road runoff and the performance of the system over four runoff events.

JCU found that the system "had a high retention capacity for suspended sediment and by implication particulate metals". Conversely, they reported that the "treatment train" had only a "modest retention capability for dissolved (filtered) metals". In addition, JCU identified that the treatment train system was, in fact, responsible for a significant net export of zinc. On the basis of their data, nutrient levels in the road runoff were low, and do not constitute a water quality concern at Streets Creek. However, they also reported significant retention of both TN and TP. The JCU study, which, in their own words "do[es] not constitute a full evaluation of the EnviroPod/StormFilter treatment system", found the system achieved substantial removal of Total Nitrogen (45%), Total Phosphorus (70%), Total Aluminium (71%), Total Nickel (73%), Total Lead (60%) and Total Copper (58%). On the other hand, it identified potential releases of Suspended Solids under 500 microns, as well as dissolved zinc and copper.

One explanation for the above-mentioned releases is that they could be related to the anaerobic conditions present in either the standing water within the wet-sump or, in the case of zinc, corrosion of the exposed galvanised protection on the steel components. Given the substantial removal of suspended solids, nutrients and total metals, it appears unlikely that the dissolved copper and zinc, observed in the outflows, was associated with a release of the under-500 micron sediment fraction.

It was largely to address these issues and better understand the sources of these copper and zinc releases that Stormwater360 undertook a further field evaluation of the treatment train system, which is the subject of this evaluation.

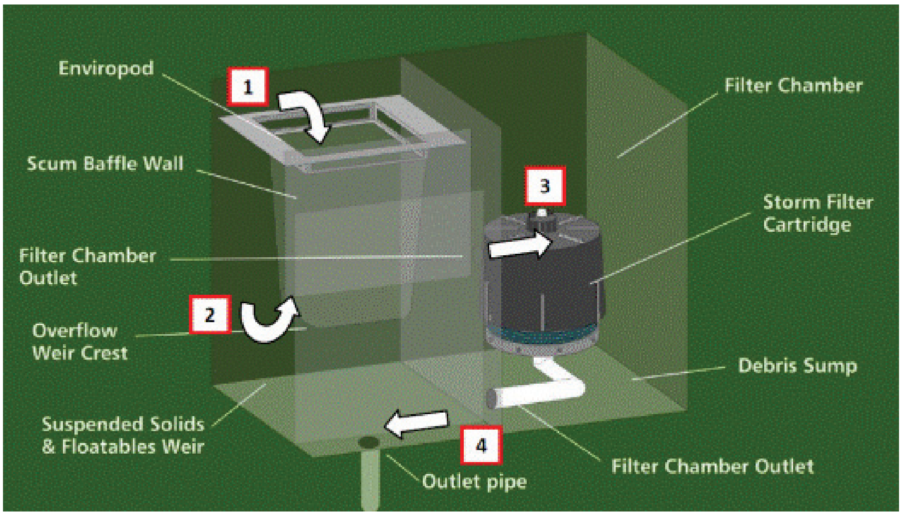

Figure 2. Schematic of the SYSTEM treatment train.

Table 1. Water quality analytical parameters.

Parameter	Abbreviation	Analytical Method*	Units	Limit of Reporting	Analysed by
Electrical Conductivity	EC	APHA 2510B	µS/cm	1	Cairns Water
pH	pH	APHA 4500-H+	-	0.1	Cairns Water
Suspended Solids above 500 microns	SS > 500 micron	500 micron sieve & APHA 2540B	mg/L	1	Cairns Water
Volatile Suspended Solids above 500 microns	SS Vol. > 500 micron	500 micron sieve & APHA 2540E	mg/L	0.1% Dry Solids	Cairns Water
Suspended Solids below 500 microns	SS < 500 micron	APHA 2540B; equiv. ASTM D-3977-97	mg/L	1	Cairns Water
Volatile Suspended Solids below 500 microns	SS Vol. < 500 micron	APHA 2540E	mg/L	0.1% Dry Solids	Cairns Water
Suspended Solids	SS	Calculated	mg/L	-	-
Volatile Suspended Solids	SS Vol.	Calculated	mg/L	-	-
Total Phosphorus	TP	APHA 4500-P	mg/L P	0.02	Cairns Water
Total Nitrogen	TN	APHA 4500-N	mg/L N	0.05	Cairns Water
Total Kjeldahl Nitrogen	TKN	Calculated	mg/L N	-	-
Ammonia Nitrogen (Ammonium Nitrogen)	NH3-N	APHA 4500-NH3	mg/L N	0.05	Cairns Water
Nitrate/Nitrite (Total Oxidised Nitrogen)	NO3-/NO2--N	APHA 4500-NO3	mg/L N	0.01	Cairns Water
Total Organic Carbon	TOC	APHA 5310-B	mg/L	1	ALS
Dissolved Organic Carbon	DOC	APHA 5310-B	mg/L	1	ALS
Particle Size Distribution (Laser Diffraction)	PSD	Malvern Mastersizer S	micron	0.05	QUT

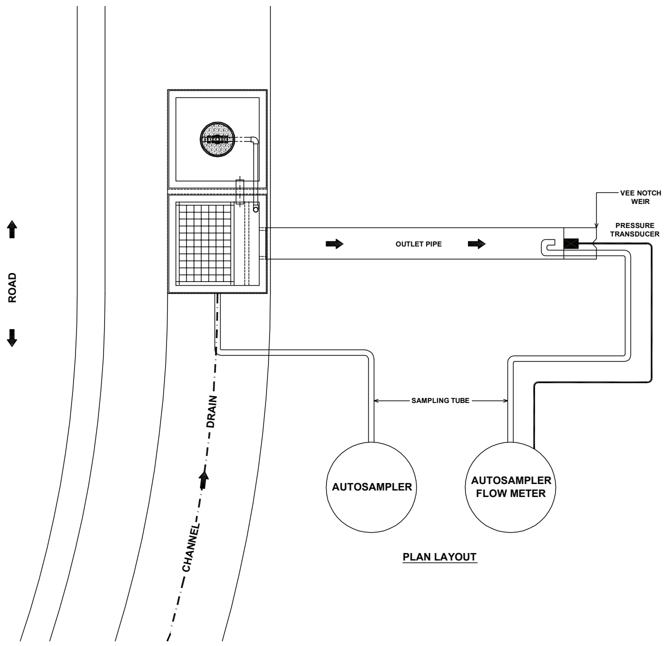

Figure 3. Schematic of the sampling location.

Sampling Procedure and Equipment

A graphical representation of the system is shown in Figure 2. The direction of flow through the gully pit insert (EnviroPod®) and into the cartridge media filter (StormFilter®) is shown in sequence from 1 to 4. The gully pit insert is intended to treat most flows and filter solids above 100 µm while containing contaminants in a dry state.

After treatment by the gully pit insert, water is filtered radially through the media cartridge (outside to inside). The media cartridge had a nominal flow rate of 0.95 L/s (at 46 cm head, when the cartridge is primed) and a peak flow rate of *ca.* 1.3 L/s (at maximum 0.88 m head prior to bypass). The ZPG™ media used was a proprietary blend containing perlite (50%), granular activated carbon (GAC, 10%) and zeolite (40%).

The system samples were collected using automated influent and effluent samplers (Figure 3), collecting continuous flow and precipitation data and water quality simultaneously. The influent sampler was programmed to send an SMS alert to Stormwater360, via the GSM cellular network, when the sampling program was triggered. A dial-up connection was then made to each sampler to download data for analysis.

To qualify as a representative sample, the following criteria were specified.

I. Collection of at least three simultaneous influent and effluent samples per storm;

II. Samples must have been collected while the treatment system operated within design flow rates (not in bypass);

III. The sampled portion of the storm event must represent at least 60% of the storm total flow volume;

IV. A minimum of six data sets must be collected for a full performance evaluation.

Antecedent dry period was not identified as a constraint, due to the impervious nature of the catchment and the absence of a base flow; however, at least a three-day antecedent dry period was preferred. If the storm was deemed to qualify, Stormwater360 would inform Cairns Water and Waste Laboratory Services (Cairns Water, NATA accreditation # 14204) that samples required collection and analysis. Analysis was performed by Cairns Water and Waste Laboratory Services, ALS Laboratory Group – Brisbane (ALS, NATA accreditation # 825). All water quality parameters for qualifying storms were sent to an independent peer reviewer at Queensland University of Technology (QUT), ensuring transparency of data. Test methods for water quality analysis used for this study are provided in Table 1.

Gross pollutants were not monitored as part of this study, although significant quantities were captured. Previous monitoring by White *et al*. (2001) demonstrated that the Enviropod® filter retained all (100%) litter up to an approach flow of 100L/sec.

Results and Discussion

The system was installed at the Streets Creek site in March 2006 and remained an active treatment and sampling site for four years until being decommissioned in March 2010. Stormwater360 monitored the system from April 2008 to December 2009. During this time, the unit was maintained annually, prior to the onset of each dry season. Complete maintenance involved removing all sediments and debris from the system, gully pit insert and replacing the cartridge media. The gully pit insert required additional manual maintenance approximately once per year.

Maintenance frequencies for the study were conducted in line with the systems standard operational lifecycle. Due to the nature of the catchment and size, there was an absence of a base flow or dry weather flows. Potential pollutant leaching of soluble contaminants was, however, still accounted for; organic debris left within the system was allowed to break down between maintenance periods and permitted to be sampled by the effluent sampler during storm events.

A summary of the principal analytes sampled is contained in Table 2.

Suspended Solids

ANZECC (2000), DECC (2007) and Fletcher *et al*. (2004) have identified suspended solids as a stressor of aquatic ecosystems. In addition, many of the other pollutants, such as metals, hydrocarbons etc, are transported attached to the suspended solids and sediment. The system achieved an SSC

Table 2. Summary of results.

Analyte	No. of events	Range of Influent EMCs (mg/L)	Median Influent EMC (mg/L)	Range of Effluent EMCs (mg/L)	Median Effluent EMC (mg/L)	Mean Removal Efficiency (Sum of Loads)
SSC	6	75 to 4384	1181	8 to 63	20	99%
SSC < 500 micron	6	48 to 180	105	8 to 62	20	78%
TP	6	0.08 to 0.19	0.123	0.02 to 0.15	0.055	47%
TN	6	0.6 to 1.5	1.045	0.2 to 0.9	0.615	44%
TKN	6	0.6 to 1.2	1.007	0.175 to 0.800	0.515	49%
NH3-N	6	0.05 to 0.15	0.050	0.05 to 0.07	0.050	31%
TOC	6	3 to 16	7	3 to 10	5	32%
DOC	6	3 to 12	7	3 to 11	6	21%

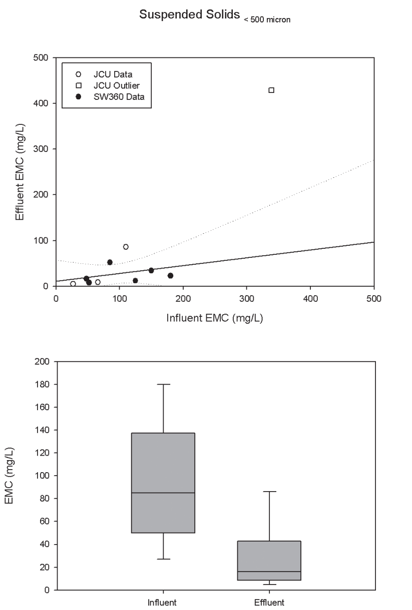

Figure 4. SS <500micron data (JCU + SW360).

aggregate load reduction of 99%. SSC (ie, SSC is defined as the sum of SS <500 micron and SS >500 micron) is 'suspended' in the sense that all these particles were sufficiently suspended to reach the system. However, SS <500 micron represents what is more commonly understood by the term 'suspended solids'. It excludes coarse settleable sediment, which, while being a management issue, does not represent such an acute threat to water quality.

Figure 4 shows influent and effluent data (Stormwater360) for SS <500 micron, together with the results published by JCU. In the scatter plot, the filled-in circles represent data from the trial reported herein, and open circles represent data from the previous JCU's research project. The exception is the JCU outlier represented as an open square, which has not been included in this evaluation. The line of best fit shown as a solid straight line was calculated by a least squares linear regression for all data points except the JCU outlier (intended to be informational only). Its relative slope provides an appreciation of the trend of the removal efficiency for the treatment train. The dotted curves represent the 95% confidence limits for these same data points. The true statistical significance of the regression lines is open to interpretation and requires further investigation, due to the limited number of data points available for this analysis.

Over the six storms analysed by Stormwater360, the influent EMC for SS <500 micron was in the range of 48 to 180 mg/L with a median influent EMC of 105 mg/L. Duncan (1999) literature review determined that the median concentration for most land uses (roofs excepted) lies between 71 mg/L (forested catchments) and 232 mg/L (urban roads). Fletcher *et al*. (2004) recommend using a value of *ca.* 120 mg/L for roads and *ca.* 100 mg/L for most other land uses. Both sources propose a median value of *ca.* 40 mg/L for forested catchments. The influent concentration of Suspended Solids at Streets Creek is within the typical range of average annual EMCs proposed within the literature; however, no data was collected during large wet-season storm events. Consequently, the median influent EMC reported herein should not be regarded as indicative of an annual median value.

Effluent EMCs recorded for SS <500 micron were in the range of 8 to 62 mg/L. The median effluent EMC was 20 mg/L. Mean removal efficiency for SS<500 micron, calculated by aggregate load reduction, was 78%. It is evident from Figure 4 that the Stormwater360 and JCU data sets are in relatively good agreement with each other, with the exception of the JCU outlier, which represents the first storm from JCU's research project. This storm was deemed an outlier for all water quality parameters due to possible sampling errors and has been removed from the analyses. The box plot in Figure 4 shows that the combined dataset is also clustered around an influent EMC of *ca.*100 mg/L and an effluent EMC of *ca.*20 mg/L. In practical terms, 10 mg/L approximates the system's irreducible EMC for under-500 micron suspended solids. The box plot in Figure 4 indicates that, over the course of two trials, the effluent EMCs from the system, were typically within the range of 10 to 40 mg/L.

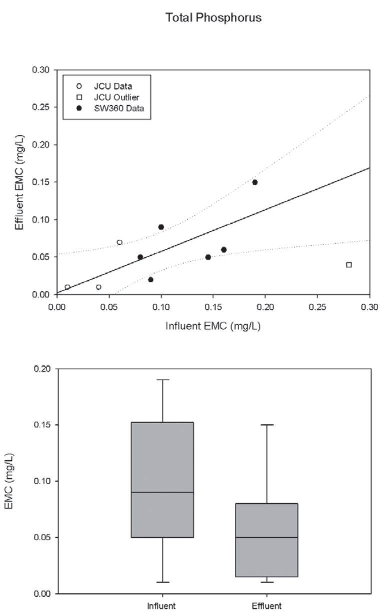

Figure 5. Total Phosphorus (SW360 and JCU combined).

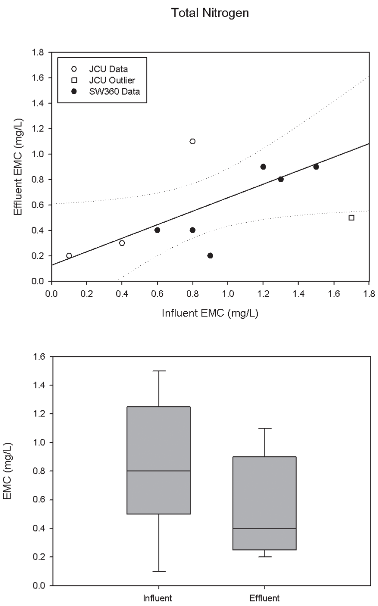

Figure 6. Total Nitrogen (SW360 and JCU combined).

Particle size distribution (PSD) by laser diffraction was performed for the SS <500 micron fraction for three storms during the Stormwater360 evaluation. Inspection of the three cases analysed consists of particles between *ca.* 10 microns and 200 microns in diameter. There is substantial variation between the three events.

- Storm 2 influent PSD centred at *ca.* 20 microns for a removal efficiency of approximately 65%;
- Storm 3 influent PSD centred at *ca.* 100 microns for a removal efficiency of approximately 85%;
- Storm 6 influent PSD centred at *ca.* 35 microns for a removal efficiency of approximately 75%.

Generally, the higher removal efficiency would be expected for the coarser samples, and this was the case for all three storms sampled.

Total Nutrients

The system achieved an aggregate load reduction for total phosphorus (TP) of 47% (note, JCU recorded a load reduction of 70%), the median influent and effluent EMCs for TP were 0.123 mg/L and 0.055 mg/L respectively (refer to Table 2). Duncan (1999) and Fletcher *et al.* (2004) recorded EMCs within a similar range and Fletcher (2004) recommends mean TP concentrations of between 0.25 and 0.50 mg/L for most land uses. Similarly, BMP Database (2010) suggests that a typical range for TP concentrations in stormwater is from 0.11 to 0.38 mg/L, across a range of land uses. In this context it is apparent that the influent TP concentration at the Kuranda site is towards the very low end of published data. Consequently, the 47%

Table 3. Nitrogen results from Storm 6.

Phase	Analyte	Influent EMC (mg/L)	Effluent EMC (mg/L)	Mean Removal Efficiency (Sum of Loads)
Total (dissolved and particulate)	TN	0.8	0.4	50%
	TKN	0.8	0.34	58%
	NH3-N	0.15	0.07	53%
	Org-N	0.65	0.27	58%
	NO3-/NO2--N	0.01	0.06	-500%
Dissolved	TN	0.4	0.3	25%
	TKN	0.39	0.23	41%
	NH3-N	0.16	0.073	54%
	Org-N	0.23	0.157	32%
	NO3-/NO2--N	0.01	0.07	-600%
Particulate (by calculation)	TN	0.4	0.1	75%
	TKN	0.41	0.11	73%
	NH3-N	0	0	N/A
	Org-N	0.41	0.11	73%
	NO3-/NO2--N	0	0	N/A

reduction recorded in the Stormwater360 trial could be related to the difficulty in removing TP at very low influent EMCs, and a much higher removal rate (similar to the 70% recorded by JCU) could be expected as the influent EMC increased.

The system achieved an aggregate load reduction for total nitrogen (TN) of 44%, while the median influent and effluent EMCs for TN were 1.045 mg/L and 0.615 mg/L respectively (Table 2). Again, this influent EMC is low with respect to most of the published data and, according to Duncan (1999), it correlates well with the median for data from forested catchments (0.95 mg/L), but is significantly lower than the median for roads (2.2 mg/L) or urban catchments (2.5 mg/L). Fletcher *et al*. (2004) recommends using a typical total nitrogen value of at least 2 mg/L for most land uses, with the exception of forested catchments.

The total nitrogen results from JCU and SW360 are presented in Figure 6. The spread of influent EMCs is broad, but removal efficiency appears relatively consistent and substantial. This is in spite of the low influent concentrations. TN is generally considered to be predominantly soluble, which is best removed by biological uptake or denitrification (in an anaerobic environment). Consequently, the consistent removal of TN exhibited by the system deserves further consideration. The majority (*ca.* 95%) of the total nitrogen load at Kuranda is TKN and a breakdown of TN species is contained in Table 3.

A small proportion of this TKN load (*ca.* 5%) is ammonia nitrogen, which implies that *ca.* 90% of the total nitrogen load is present as organic nitrogen, in either soluble or particulate forms. An expanded nitrogen suite analysis was conducted for Storm 6, and filtered (0.45 micron) and unfiltered samples were processed in order to establish whether the removal processes, for this event, involved particulate removal or removal of dissolved species. Essentially, the entire TN load was present as TKN and *ca.* 20% of this was ammonia-N (Table 3).

The entire ammonia-N load was soluble, and the treatment train system achieved 54% removal of this species. The remainder (*ca.* 80%) of the TN/TKN load was present as organic nitrogen, of which *ca.* 35% was dissolved. Overall, 73% removal of particulate organic nitrogen and 32% removal of dissolved organic nitrogen was achieved.

Given the removal efficiency for suspended solids, the high removal of particulate organic nitrogen is understandable. Removal mechanisms for dissolved organic nitrogen are less obvious. It is possible that there is some adsorption to the 'schmutzdecke' (bio-film) that develops on the cartridge; another possibility is removal under the anaerobic conditions within the standing water within the wet-zones, being the wet-sump and around the base of the cartridge.

When runoff first enters the StormFilter®, it initially displaces the standing water in the wet-zones. Any pollutants in the standing water are sampled by the effluent sampler (once they have passed through the StormFilter® cartridge), but they are not sampled by the influent sampler. Furthermore, the last of the runoff to enter the cartridge during a storm event does not necessarily pass through the filter cartridge during that event and may be retained within the wet-sump until the next storm event, whereupon it is displaced. When the (particulate or dissolved) organic nitrogen converts to ammonia in the anaerobic wet sump, it can be removed as ammonia-N by the zeolite.

Table 4. Grab samples from wet sump.

Date	Antecedent Dry Period (days)	Report #	Diss. Cu (mg/L)	Diss. Zn (mg/L)	DOC (mg/L)	Diss. N (mg/L)	Diss. NH3-N (mg/L)	Diss. NOx--N (mg/L)
07/07/2008	8	40627	0.011	0.053	17	-	-	-
20/02/2009	6	42998	0.001	0.016	-	2.4	2.39	<0.01
06/05/2009	19	43826	0.005	0.082	16	7.2	5.85	0.72
21/07/2009	79	44703	0.004	0.083	20	3.4	2.24	0.025

Periodic grab samples from the wet-sump indicate that most of the TN load in the standing water is present as ammonia-N at concentrations that are two orders of magnitude higher than typical influent ammonia-N concentrations. As such, ammonia-N is, possibly, generated in the wet-zones by anaerobic decomposition of organic nitrogen in the inter-storm event periods. This has two important implications: 1): the load of ammonia-N passed to the StormFilter® cartridge is significantly higher than is suggested by the influent EMC, which implies that the removal rates for ammonia-N removal may be an under-estimate; and 2): by converting organic nitrogen to ammonia-N in the wet-zones and then removing this ammonia, the system has the potential to remove soluble organic-N.

Discussion

The results for Storm 6 represent a snapshot of one storm, and should not be considered as comprehensive; they do suggest, however, that the main TN removal pathways for the treatment train is the efficient removal of particulate organic nitrogen, complemented by the sorptive removal of soluble ammonia-N and organic-N.

Very often TN removal is treated as a key performance benchmark for stormwater treatment practices. This is potentially problematic, given the apparent variation in the nature of the TN load. In a comprehensive study of nitrogen composition in Melbourne (Taylor *et al*., 2005), *ca.* 25% of the load was present as particulate organic nitrogen. The remainder was soluble and, of these species, oxidised nitrogen predominated over dissolved organic nitrogen and ammonia-N.

Taylor *et al*. (2005) inferred that either 'removing' the water by infiltration or denitrification (ie, in the anaerobic zone of bio-retention practices) would be necessary to achieve significant TN reduction. Fletcher *et al*. (2004) reported that the TN composition measured in wet weather samples for various land uses in the Sydney and Illawarra regions was extremely variable. For urban catchments, median oxidised nitrogen concentrations were in the range 0.09 to 0.42 mg/L, while the median TN concentration range was 0.65 to 2.32 mg/L.

The oxidised nitrogen represents a much smaller proportion of the TN load than was observed by Taylor *et al*. (2005) for Melbourne data. In a study of nutrient build-up on urban roads in the Gold Coast, Miguntanna *et al*. (2010) found that oxidised nitrogen comprised only *ca.* 10% of the TN load, across three different land uses, and most of the TN load was present as TKN and a significant proportion of this was particulate in nature. Consequently, the measured TN load from the Gold Coast catchments is similar to that measured at the Streets Creek, Kuranda site, providing applicability of Nitrogen removals to various urban land uses.

Conclusions

The results from this field trial generally correlate well with an earlier study at this site by JCU (Munksgaard and Lottermoser, 2008). The data collection from this study has been based on a rigorous and technically demanding monitoring program, which adds further credibility of the results (Goonetilleke, 2010). From an operational perspective, the system captured an appreciably large sediment load requiring annual cleaning to maintain its operational effectiveness.

The EnviroPod®/StormFilter® treatment train achieved 78% removal for suspended solids under 500 microns, which approximates the long-term environmental target recommended by NSW DECC (2007), QLD DERM (2010) for South East Queensland (SEQ) and consistent with the 80% reduction target of many consent authorities in the US.

The runoff at Streets Creek contained very low levels of phosphorus and nitrogen. Total Phosphorus removal was between 45% and 70% respectively in both the Stormwater360 field trial and the JCU research project, which approximates the NSW DECC (2007) and QLD DERM (2010) SEQ long-term environmental targets of 65% and 60% respectively, and is better than expected given the low influent EMCs. Total Nitrogen removal was consistent, substantial and in agreement with the NSW DECC (2007) and QLD DERM (2010) SEQ 45% long-term environmental target, despite the proximity of the influent EMC to the irreducible concentration of the treatment train. The removal of nitrogen was particularly noteworthy, given that the debris captured and stored within the treatment train was not included in the influent load into the system, but may have been sampled as a soluble leachate by the effluent sampler.

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