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Article

Removal of heavy metals, nutrients and sediment by a stormwater treatment train; a southeast Queensland, medium-density residential case study.

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Abstract: Urban stormwater runoff from a medium-density residential development in southeast Queensland has been monitored in the field since November 2013. A treatment train installed on the site includes rainwater tanks collecting roofwater, 200-micron mesh baskets installed in grated gully pits and two 850 mm high media filtration cartridges installed in an underground 4 m^3 vault. A monitoring protocol developed by research partners, Queensland University of Technology (QUT), guided the monitoring process over a 4.5-year period. Heavy metals were included in the list of analytes during the monitoring period as the catchment is within 1 km of the environmentally-sensitive Moreton Bay, Queensland. Removal efficiencies observed at this site for the regulated pollutants; total suspended solids (TSS), total phosphorus (TP) and total nitrogen (TN) for the pit baskets were 61%, 28% and 45% respectively. The cartridge filters removed 78% TSS, 59% TP, 42% TN, 40% total copper and 51% total zinc. As the measured influent concentrations to the cartridge filters were low when compared to industry guidelines, the dataset was merged with international field results for TSS (n=39) and TP (n=32) but truncated within anticipated guideline levels. The combined dataset for the media filter demonstrates performance at 89% TSS, 66% TP and 42% TN.

The total gross pollutant generation rate from the medium-density residential catchment was observed to be 0.24 m^3/Ha/year, with a corresponding air-dried mass of 142.5 kg/Ha/year. Less than 2% of the gross pollutant mass was anthropogenic.

The findings of this research suggest that the treatment train, and in particular the media filter, holds promise for the removal of total copper and total zinc, in addition to TSS, TP and TN, from urban stormwater runoff. Based on a maximum, low risk trigger TN concentration of 1.5 mg/L, the field test data from 4.5 years of operation and standard maintenance, suggests a 5.5-year replacement interval for the media filters.

Keywords: stormwater; monitoring; gross pollutant generation rates; suspended solids; nitrogen; phosphorus; heavy metals

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1. Introduction

Sustainable urban drainage system (SuDS) national standards and statutory approval bodies (SABs) were mandated in the United Kingdom by the Flood and Water Act in 2010 [1]. Planning policies in Australia since 2000 have sought to implement similar treatment systems, termed water sensitive urban design (WSUD), to achieve typical annual pollutant load reductions of 80% for total suspended solids (TSS), 60% for total phosphorus (TP) and 45% for total nitrogen (TN) [2, 3]. The EU Water Framework

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Directive (2000/60/EC) requires that all emissions to water be identified, quantified and managed [4]. Several authors have identified that heavy metals, originating from road runoff and roof surfaces, are also parameters of concern in urban waterways [5-7].

A manufactured stormwater treatment train was implemented within a medium-density urban residential development at Ormiston, Southeast Queensland. A series of field-based tests were performed on the system, including flow-weighted water quality sampling, measurement of annual gross pollutant loads and nutrient content analysis of captured pollutants. Data from over 4.5 years of field monitoring have been collated. The treatment train incorporates rainwater tanks, pit basket inserts, and media filters inside a detention tank, however monitoring has focussed on the performance of the pit basket inserts and the media filters. Initially investigating the reduction of TSS, TP and TN, the monitored parameters were expanded during the study to include heavy metals for the media filters. A suite of metals including arsenic, cadmium, chromium, copper, nickel, lead, zinc and mercury was tested, however, most were below detection limits, or within analytical variability levels. Copper and zinc were the most readily observed metals in stormwater runoff from this site.

2. Site Details

A stormwater treatment train was monitored over a 4.5-year period at a townhouse complex at Ormiston, about 28 km east of Brisbane, the capital city of Queensland. The site is within 1km of Moreton Bay, a regionally sensitive waterbody. The monitored site has a total area of 2028 m^2, with approximately 1140 m^2 of roof area (56%), 500 m^2 of concrete driveway (25%) and the remaining 388 m^2 (19%) of landscaped area. Roofwater is initially captured by rainwater tanks which supply water for internal and external townhouse use, with overflows plumbed into the underground drainage upstream of the filter vault, entering the system beneath the pit baskets. Grated inlets (catch basins) capture surface runoff from the site, carrying it to an underground vault containing the media filter cartridges after passage through inlet pit basket inserts via the same underground drainage system receiving rainwater tank overflows. The concrete filter vault also provides a detention function prior to release of treated stormwater to Council drainage. The site, monitoring setup and protocol is described in earlier publications [8]. A schematic cross-section of the monitoring installation is shown in Figure 1, and a schematic of the site and stormwater network is shown in Figure 2.

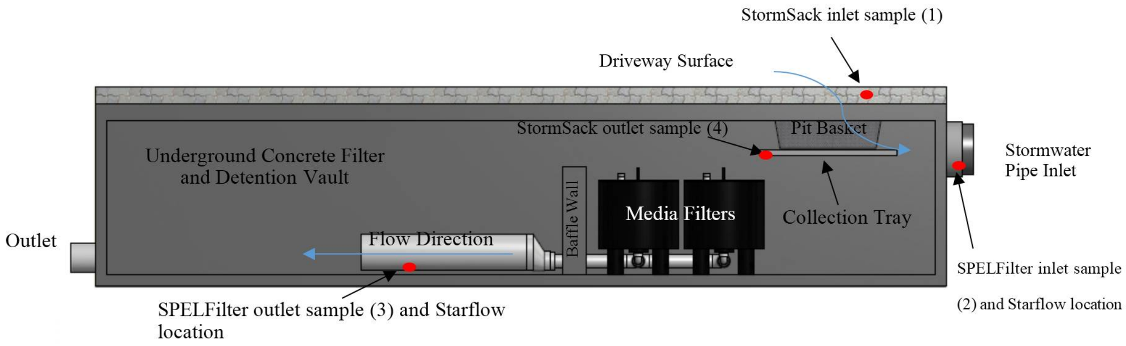

Figure 1. Schematic cross section of the field monitoring system and detention vault (not to scale).

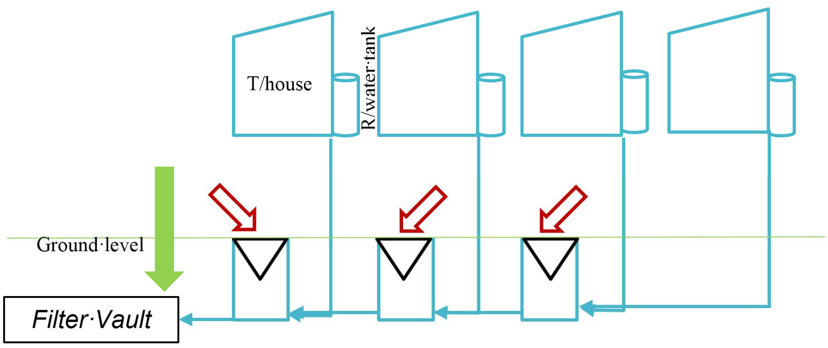

Figure 2. Schematic of the flowpaths at Ormiston. Red arrows indicate surface runoff entering the pit baskets. Blue arrows represent the stormwater drainage. The monitoring location is shown by the green arrow.

3. Methodology

Several international standards were consulted to formulate a protocol to deliver a robust, scientifically defensible, outcome [9-11]. The protocol was collaboratively formulated with research partners Queensland University of Technology (QUT) and Griffith University (GU). It is in alignment with Stormwater Australia's draft Stormwater Quality Improvement Device Evaluation Protocol (SQIDEP) [12].

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Composited, flow-weighted water sampling from the inlet and outlet points of the treatment devices provided Event Mean Concentrations (EMC) for each location. Samples were independently collected and analysed in National Association of Testing Authorities (NATA) registered laboratories. To provide an annual estimate of gross pollutant and coarse sediment loads generated on the site, quarterly maintenance of the pit baskets was deferred for a 12-month period in 2014. Gross pollutant and sediment samples from the pit baskets and filter vault were collected after 12 months operation for weighing and nutrient analyses by GU. Samples were air-dried, sieved and anthropogenic materials were manually separated. A sub-sample of the solids from both the pit basket and vault were then analysed by the laboratory for TN and TP. Reports on the findings were prepared by the respective universities [13,14]. Average Concentration Removal Efficiency (Av. CRE) and Efficiency Ratio (ER) of the analysed pollutants in runoff samples are discussed in this paper.

Average Concentration Removal Efficiency (CRE) is calculated from Equation 1:

$$Avg.CRE = \frac{\sum\left[\frac{\{EMCin - EMCout\}}{EMCin}\right]}{no.of\ events} \quad \text{(Eqn. 1)}$$

Efficiency Ratio (ER) is calculated from Equation 2:

$$ER = 1 - \frac{Mean\ EMCout}{Mean\ EMCin} \quad \text{(Eqn. 2)}$$

4. Results

Following more than 4.5 years of monitoring, 31 events qualifying with the protocol have been tested for the pit basket insert, and 22 events for the media filter. As is typical of environmental monitoring, the difference between the qualifying events for the two technologies is a result of flow volume, compliance with the testing protocol (e.g. aliquot numbers) and occasional equipment error.

Table 1 summarises the water quality data presented by the final report for the pit basket [13]. The results indicate that the pit basket has efficiency ratios of 61% of TSS, 28% TP and 45% TN. Both metrics for the pit basket are converging to within 3%, indicating that the dataset is not unduly influenced by anomalous outliers.

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Table 1. Pit Basket Water Quality Results [13].

Pollutant	**TSS**		**TP**		**TN**	
LOD (mg/L) [1]	**5**		**0.01**		**0.1**	
Statistics	**In (mg/L)**	**Out (mg/L)**	**In (mg/L)**	**Out (mg/L)**	**In (mg/L)**	**Out (mg/L)**
Minimum	10	2.5[2]	0.05	0.02	0.20	0.20
Maximum	543	253	2.45	1.92	3.85	2.20
Average	93.3	36.2	0.34	0.24	1.59	0.88
ER	61%		28%		45%	
Average CRE	62%		30%		43%	

[1]Limit of Detection

[2]Results reported as below LOD were substituted with 50% of the LOD concentration in statistical analysis.

Filter cartridge results are summarised in Table 2. The data indicates that the filters are receiving relatively low inflow concentrations of TSS, TP and TN in comparison with industry guidelines [15]. Even so, ERs of 78%, 59% and 42% for TSS, TP and TN respectively are observed from the qualifying events. CRE and ER metrics for the media filters are within 8% of each other.

Table 2. Media Filter Cartridge Water Quality Results.

Pollutant	**TSS**		**TP**		**TN**		**Cu**		**Zn**	
LOD (mg/L)	**5**		**0.01**		**0.1**		**0.001**		**0.005**	
Statistics	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**
Minimum	8.00	0.5[1]	0.01	0.005[2]	0.31	0.05	0.006	0.005	0.041	0.012
Maximum	66	20	0.38	0.16	1.50	1.10	0.022	0.014	0.138	0.067
Average	28	6	0.07	0.03	0.74	0.41	0.013	0.008	0.07	0.03
ER	78%		59%		42%		40%		51%	
Average CRE	73%		51%		38%		36%		49%	

[1] One qualifying event was tested to a TSS LOD of 1 mg/L and produced a <LOD result.

[2]Results reported as below LOD were substituted with 50% of the LOD concentration in statistical analysis.

The observed pollutant concentrations entering the treatment train are low in comparison with those anticipated historically [16]. In the context of the relatively low influent concentrations observed at this site, the media filter dataset was combined with the slightly higher influent concentration results from

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comparable US field testing and truncated to comply with the upper limit of the SQIDEP concentrations [17,12]. The combined results are summarised in Table 3.

Table 3. Combined USA and Australian Field Results for Media Cartridges, truncated to comply with SQIDEP maximum concentrations.

Pollutant	**TSS**		**TP**	
LOD (mg/L)	**5[1]**		**0.01**	
n	**39**		**32**	
Statistics	**In (mg/L)**	**Out (mg/L)**	**In (mg/L)**	**Out (mg/L)**
Minimum	7	0.5[1]	0.01	0.01
Maximum	279	25	0.47	0.16
Average	53	6	0.13	0.04
ER	89%		71%	
Average CRE	81%		62%	

[1] One qualifying event was tested to a TSS LOD of 1 mg/L and produced a <LOD result. The minimum is therefore presented as 50% of the lower LOD.

Three 20 L buckets of sediment and gross pollutants were collected from the pit baskets, and two 20 L buckets of pollutants were removed from the filter vault in November 2014. The contents of the buckets were homogenised before sub-samples were collected and sent for nutrient analysis. Results of the gross pollutant and nutrient evaluation are presented in Table 4.

Table 4. Gross pollutant & nutrient analysis for Pit Baskets and Filter vault after 12 month's operation.

Parameter	**Pit Baskets**	**Filter Vault**
Total Volume (m^3)	3.19×10^{-2}	1.71×10^{-2}
% Anthropogenic Volume	0.11	0.12
Total Mass (kg)	24.59	4.31
% Anthropogenic Mass	0.31	1.52
TN (mg/kg)	1,070	5,960

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TP (mg/kg)	104	684

Based on the above data, the total gross pollutant and coarse sediment load from this catchment is estimated to be 0.25 m^3/Ha/yr, with a corresponding air-dried mass of 142.5 kg/Ha/yr. Of this total, the calculated anthropogenic litter load is 2.65 kg/Ha/yr.

5. Discussion

Normality testing (Anderson-Darling) of the water quality datasets confirmed that, except for total copper at the filter outlet, all follow log-normal distributions. Paired Student's *t* tests were performed on the log-normal datasets and Wilcoxon rank sign tests were performed on the total copper datasets, to evaluate statistical difference of the datasets. Results in Table 5 confirm that the inflow and outflow water quality datasets from both treatment devices are statistically significantly different for all pollutants. The findings of the field research in both the US and Australia suggest that the stormwater treatment train holds promise for the removal of total copper, total zinc, TSS, TP and TN.

Table 5. Parametric & Non-parametric test results, paired samples, 90% confidence interval.

Treatment Device	***p*-value (Two-tailed) *t* test, log-transformed datasets**				***p*-value (Two-tailed) Wilcoxon signed-rank test**
	TSS	**TN**	**TP**	**Total Zn**	**Total Cu**
Pit basket In vs Out	<0.001	<0.001	<0.001	-	-
Filter cartridge In vs Out	<0.001	0.001	<0.001	<0.0001	0.001

Considering more than half of the Ormiston site is roof area, the gross pollutant generation rate is relatively high in comparison to the 30 kg/Ha/yr previously reported for Australian urban catchments [18]. This is expected to be a function of the fact that previous gross pollutant research constrained evaluated material to be that greater than 5 millimetres, where the technologies tested at Ormiston can capture much smaller particles. Of interest, when the nutrient content of the material from both devices is converted to an annual load, both devices have captured a similar mass, as presented in Table 6.

Table 6. Estimated Annual Pollutant loads captured by Pit Baskets and Filters at Ormiston, Queensland.

Treatment Device	**Annual TN load**	**Annual TP load**	**Annual sediment & litter load**
Units	**kg/Ha.yr^{-1}**	**kg/Ha.yr^{-1}**	**kg/Ha.yr^{-1}**
Pit baskets	0.129	0.0126	121.25
Filter cartridges	0.127	0.0145	21.25

Monitoring has continued at the Ormiston site to provide an indication of the long-term operation of the filter cartridges and to potentially identify whether a pollutant breakthrough occurs, thereby indicating the triggering of a maintenance interval. Annual maintenance has included vacuum removal of captured sediments and litter from the vault. Evaluation of the TSS concentrations at the outlet indicates a very weak (R^2 = 0.0095) trend increasing over the monitored period as shown in Figure 3. Outlet TP concentrations follow a similarly weak trend over time.

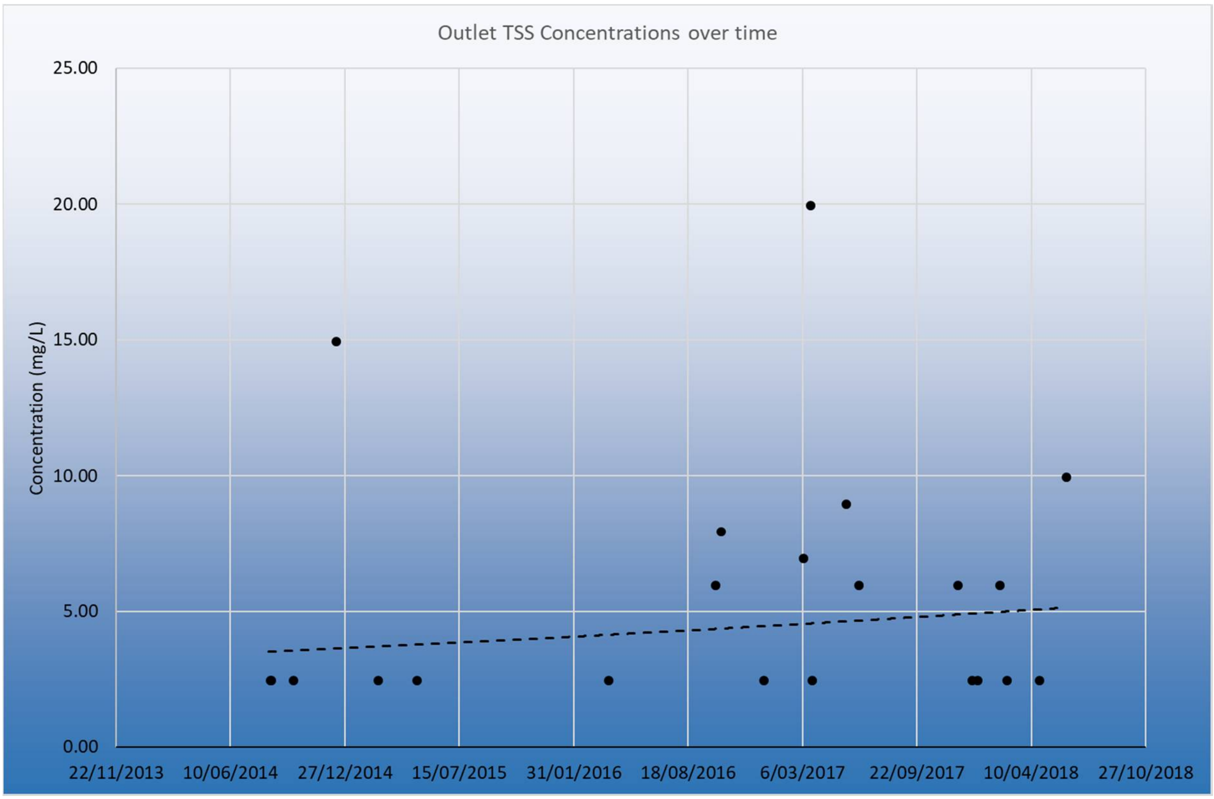

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Figure 3. Filter outlet TSS concentrations over time with a linear trendline.

Evaluation of TN concentrations indicates a stronger upward trend (R^2 = 0.4), though this may be correlated to the upward trend of inlet TN concentrations, also shown on Figure 4. Since the two trendlines appear to diverge, attention has focused on the absolute value of the outlet TN concentration. Water quality guidelines for modified ecosystems in Australia suggest a TN range from 0.5 mg/L to 1.5 mg/L as a low-risk trigger value [19]. Assuming a linear trendline is a reasonable indicator, and a maximum 1.5 mg/L TN as the low risk trigger concentration, it would suggest that the filters should be replaced in August 2019, ~5.5 years after they were installed. Naturally, this will be influenced by the catchment loads produced by each site and the maintenance regime implemented. Further monitoring is continuing to confirm if there will be an occurrence of a pollutant breakthrough.

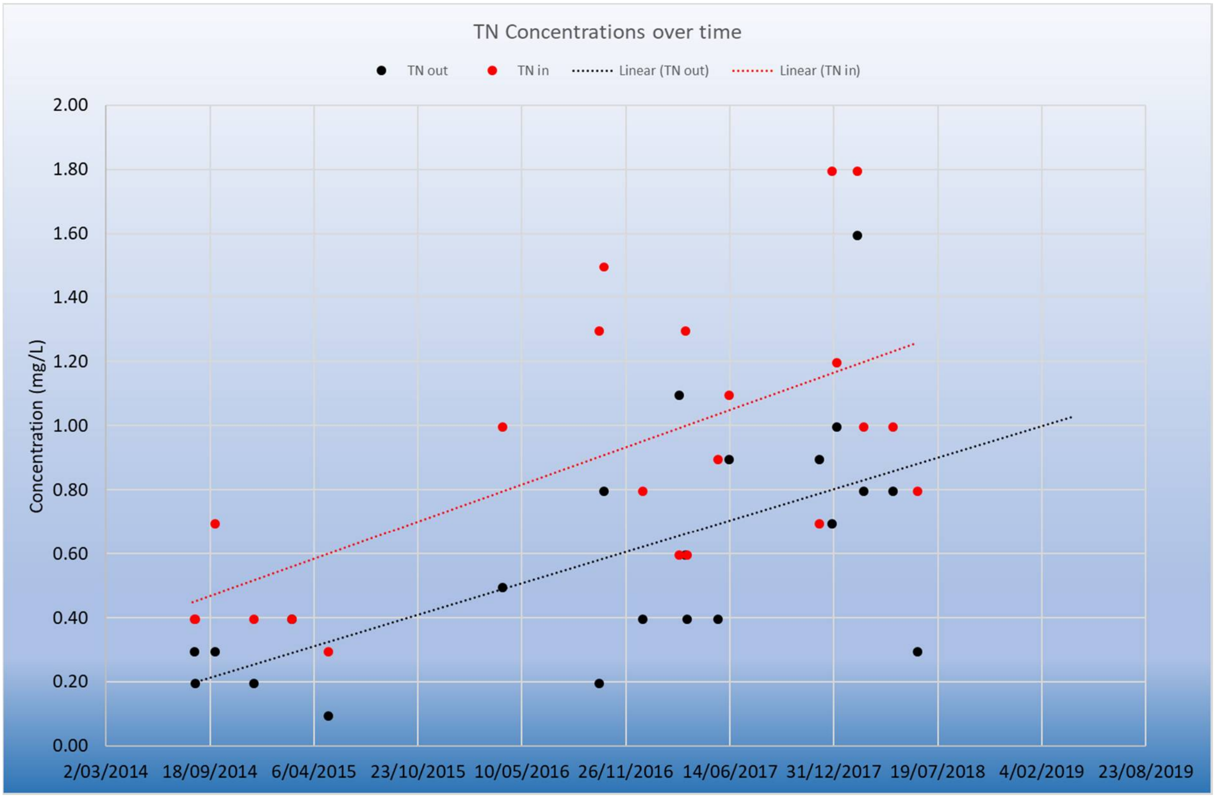

Figure 4. TN concentrations at the filter inlet (red) and outlet (black) over time with linear trendlines.

8. Conclusions

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After 4.5-years of Australian field monitoring, 31 qualifying events for a pit basket insert and 22 qualifying events for media filters were evaluated. The pit basket had removal efficiencies of 61% TSS, 28% TP and 45% TN. The media filters had removal efficiencies of 78% TSS, 59% TP, 42% TN, 40% total Cu, and 51% for total Zn. When combined with international field data, the media filters had removal efficiencies of 89% and 71% for TSS and TP respectively. These results indicate that the stormwater treatment train holds considerable promise for removing Cu and Zn, as well as the regulated pollutants of TSS, TP and TN.

The total gross pollutant and coarse sediment load from the study site was estimated to be 0.25 m^3/Ha/yr with a corresponding air-dried mass of 142.5 kg/Ha/yr. This is higher than previous literature values, potentially due to the treatment measures capturing pollutants >200 microns compared to the previous 5 mm definition of gross pollutants.

Monitoring over the 4.5-year duration has also not shown a defined breakthrough of TSS or TP, with only weak trendlines observed. A stronger trend was observed for TN suggesting that, to comply with a low-risk, maximum outlet trigger concentration of 1.5 mg/L, the replacement interval for the filters is of the order of 5.5 years.

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Research partners QUT, including Prof. Ashantha Goonetilleke, and Dr Prasanna Egodawatta, were integral to the successful delivery of the field monitoring program. Researchers from GU, Lawrence Hughes and Sally Obst provided invaluable support and expertise for the gross pollutant and sediment analyses.

Author Contributions

Darren Drapper was engaged to project manage the research and supervise the ongoing operation of the monitoring system; Andy Hornbuckle is the Asia Pacific Team Leader for SPEL Environmental and pioneered the site selection, approvals, financing and regulator liaison for the project. Both authors have contributed to the preparation of this journal article.

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DECLARATION OF INTEREST

The research was undertaken independently by QUT & GU, project managed by Drapper Environmental Consultants, under a funding arrangement with SPEL Environmental.