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REMOVAL OF HEAVY METALS FROM STORMWATER RUNOFF BY A PASSIVE MULTI-BARRIER TREATMENT SYSTEM

FIELD EVALUATION AT GLENCORE'S BULK STORAGE FACILITY IN PORT OF TOWNSVILLE

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ABSTRACT

A series of white papers and articles published in international peer-reviewed journals has focused on the challenge of evaluating stormwater runoff quality, and the ability of commercially available stormwater runoff devices to successfully control runoff and its pollutants. This paper summarises the results from a field trial of GHD's StormDMT™ device, treating stormwater runoff generated at a bulk storage facility in the Port of Townsville.

The aim of the trial was to assess the performance of StormDMT technology, a passive multi-barrier stormwater treatment system, against critical stormwater runoff parameters such as storm event pollutograph, runoff quality and pollutant phase distribution (particulate, dissolved and colloidal). Flow-based stormwater quality data were obtained from six major storm events during the wet season of 2012 and 2013.

It was found that the major pollutant in stormwater runoff was zinc, with a minimum event mean concentration of 2.7 mg/L, a maximum of 12 mg/L and an average of 4.9 mg/L. The phase distribution of zinc concentration in the stormwater runoff was almost equally divided between particulate (46.2%) and dissolved (53.8%). The event mean copper concentration in stormwater runoff varied from 0.23 to 1.3 mg/L, with the average at 0.55 mg/L and a phase distribution of 60% particulate and 40% dissolved. The event mean lead concentration fluctuated between 0.44 and 1.2 mg/L, with the average at 0.61 mg/L. As expected, the phase distribution of lead concentration was dominated by the particulate phase (79.1%).

The StormDMT multi-barrier filter has demonstrated an event mean copper concentration removal efficiency of approximately 87% in regard to total copper concentration and 91% for dissolved, with average copper concentrations at the outlet of the filter at 0.07 and 0.02 mg/L, respectively.

The StormDMT multi-barrier filter event mean lead concentration removal efficiency was approximately 80% for total and 83% for dissolved, with average event mean lead concentrations of 0.12 and 0.02 mg/L respectively in the outlet of the filter.

Regarding zinc, the StormDMT multi-barrier filter removal efficiency was approximately 76% for total zinc and 70% for dissolved, with average event mean concentrations of 1.1 and 0.8 mg/L respectively in the outlet of the filter.

Considering the site-relevant stormwater runoff pollutant rates, the StormDMT filtration unit demonstrated a minimum maintenance life of one year (i.e. the filter medium is designed to last a minimum of one year).

INTRODUCTION

In 2007 the Australian Prime Minister's Science, Engineering and Innovation Council (PMSEIC, 2007) declared that Australia needed a diverse portfolio of water supply options and stormwater should be viewed as a potential resource rather than a waste product. This decision was a major shift from the original approach of stormwater being considered a nuisance requiring immediate drainage from urban areas. However, stormwater is also considered to be one of the major environmental risks to receiving waterways that increasingly degrade as urban population densities increase (Livingston and McCarron, 1992).

To address this the principle of Water-Sensitive Urban Design (WSUD) was developed in Australia. Similar principles have been developed in the US (Low Impact Development (LID)) (USEPA, 2000) and in the UK (Sustainable Urban Drainage Systems (SUDs)) (Eriksson *et al*., 2007).

Typical WSUD structures used in stormwater management are swales, bio-retention systems and constructed wetlands. These systems can achieve significant reductions of Total Suspended Solids (TSS 70–80%), Total Nitrogen (TN 40–50%) and Total Phosphorus (TP 50%), mainly due to the removal of the particulate bound contaminants.

The load reduction of NOx, PO43- and dissolved heavy metals is effective only in constructed wetlands, albeit with inconsistent performance (Fisher and Acreman, 2004). In addition, these systems require significant land surface area, one to two per cent of the catchment area for a bio-retention basin and five to six per cent for a constructed wetland. This is a major issue when the available land is at a premium.

To fill this gap a range of engineered Stormwater Quality Improvement Devices (SQIDs) is available from various commercial vendors. However, a protocol to allow the evaluation of the performance claims made by vendors is still not in place in Australia.

BACKGROUND

The bulk storage facility is located in the Port of Townsville in North Queensland (see Figure 1) and the catchment area is approximately 4.6 hectares in size. The percentage of impervious area at the site has been estimated as relatively high in line with industrial land use (hard surfaces like pavements, compacted earth, roads and buildings) and, therefore, 100% impervious fraction for the site is assumed.

The bulk storage facility handles magnetite, copper and zinc concentrates, as well as ammonium sulfate fertiliser. The total catchment area is broken down into sub-catchments with the field trial installed in sub-catchment D4 with a surface area of 3,005m^2. D4 sub-catchment was selected after assessing historical available water quality data of the catchment's generated stormwater runoff, indicating the highest site pollutant concentrations in regard to heavy metals.

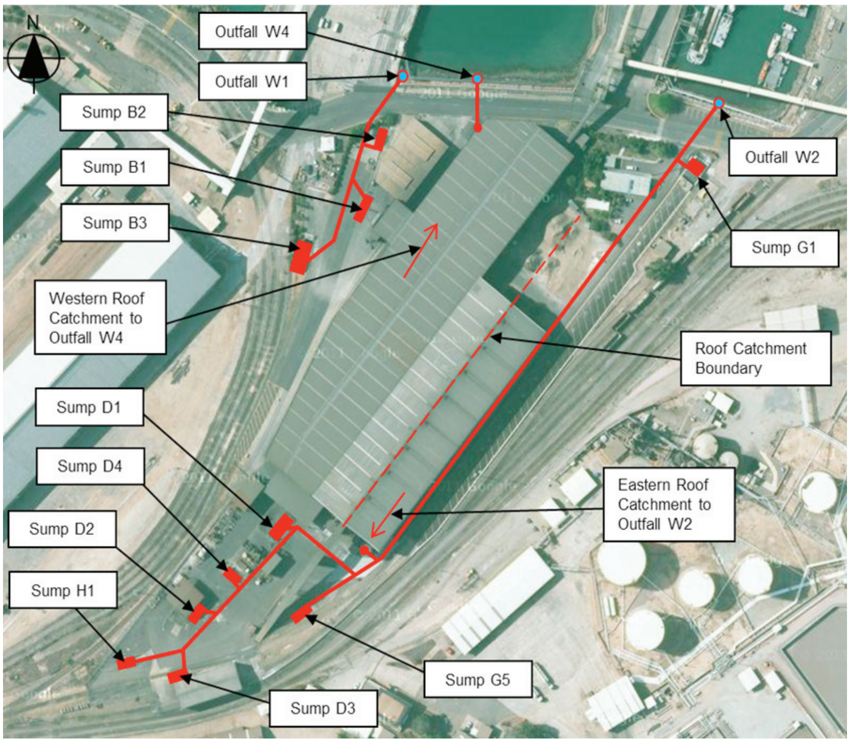

Figure 1. The bulk storage facility in the Port of Townsville.

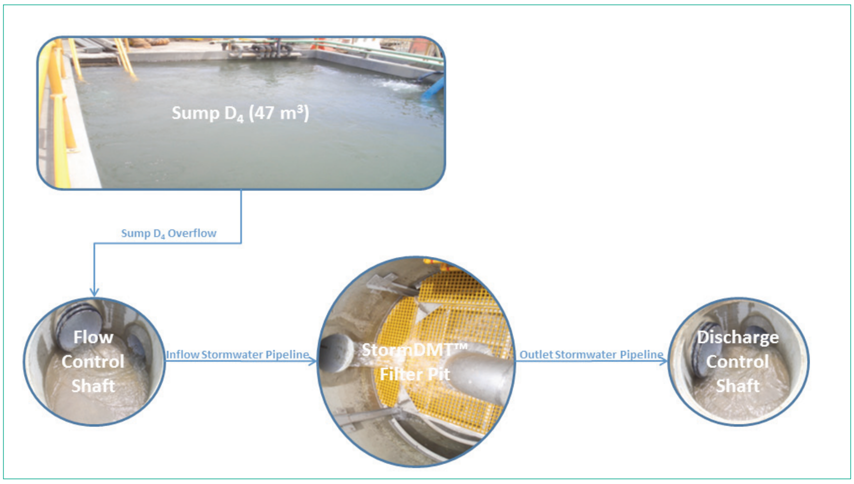

Figure 2. Field trial infrastructure configuration.

Field Trials Description

Figure 2 illustrates the StormDMT field trial configuration. In a rainfall event Sump D4 captures approximately the first 15mm (47m^3) of stormwater runoff generated across the sump's catchment area while the additional runoff overflows the existing weir. Downstream of the weir the flow is directed into the StormDMT multi-barrier filter pit and, after cross-flowing through the filter, is discharged via a penstock into the existing stormwater pipeline network system.

DRAINS software program Version 2010 (Rational Method Steady Flow Module) was used. The Intensity Frequency Duration (IFD) rainfall data were sourced from the BoM Online IFD facility. This data was used to generate storm patterns for the catchment hydraulic capacity analysis. Following critical review of the size, extents, land use and catchment slopes with the critical storm duration at each node in the model, modelling indicates that the Q100 peak outflow generated from the D4 catchment was approximately 0.28 m^3/s.

The hydraulic capacity of the StormDMT multi-barrier filter (driven by gravity) was considered to be nominally in the range 160–180 L/s. Sumps overflow in excess of the pilot plant hydraulic capacity was to overflow via a weir directly into the existing stormwater network system.

First-flush water captured in sump D4 from either rainfall events or catchment washdown cleaning schedule (process water) was tested for pH, dosed with lime if necessary to raise the pH to 8.3 and then pumped to the StormDMT filter to remove remaining contaminants.

The conducted field trials involved treatment of:

- Stormwater runoff beyond the first-flush capacity of Sump D4;
- Lime-treated first-flush water stored in Sump D4; and
- Lime-treated process water stored in Sump D4 from the catchment washdown cleaning schedule.

OBJECTIVES

The StormDMT field trial was designed to assist in:

- Evaluating the performance of the proposed multi-barrier treatment system in regard to:
  - Hydraulics
  - Stormwater runoff metal removal efficiency; and
  - Influence of metal phase distribution (particulate, dissolved and colloidal).
- Defining the presence and the impact of the so-called first-flush effect;
- Defining operation and maintenance requirements.

Figure 3. StormDMT multi-barrier filter cartridge.

StormDMT Multi-Barrier Filter

The StormDMT multi-barrier filter trial unit (see Figure 3) comprises three filtration media that have been designed to remove fine solids, particulate, colloidal-bound and dissolved contaminants such as heavy metals and nutrients. The filter cartridge had a height of 1.8m, a diameter of 1.45m and an internal discharge pipe of DN350.

The first media is a porous polypropylene/polyethylene mixture. This material removes oil and grease and fine particulate matter not captured in Sump D4, and which may foul subsequent media (Matsui *et al*., 2003). The second media is chemically conditioned clinoptilolite (Athanasiadis and Helmreich, 2005). This material removes dissolved positively charged contaminants such as heavy metals (Athanasiadis *et al*., 2004; Athanasiadis *et al*., 2007; Sansalone and Buchberger, 1997) and nitrogen (Hankins *et al*., 2004) in the form of NH4 -N. The third media, laterite, also removes dissolved contaminants, including negatively charged heavy metals such as arsenic, and nutrients such as phosphate and nitrate (Wood and McAtamney, 1996).

Monitoring Process

Samples were taken by two flow-based auto samplers sampling from two different tube intake strainers installed at the following sampling points (see Figure 2 for details):

- The inflow stormwater pipeline to the StormDMT multi-barrier filter pit; and
- The outlet stormwater pipeline of the StormDMT multi-barrier filter pit.

Both auto-samplers were programmed to sample on the same flow basis. They initiated sampling once the flow rate in the inflow stormwater pipeline to the StormDMT multi-barrier filter pit was greater than two L/s measured by the installed flowmeter. While the flow remained above two L/s, sampling continued at a rate of one sample every three minutes. The auto-sampler contained 24 x 1L bottles, and a 500mL sample was taken every three minutes and two samples composited into a single sample bottle by the auto-sampler. Samples would continue to be taken for up to a maximum of 144 minutes of a rainfall event (three-minute intervals * two samples per sample bottle * 24 bottles). The auto-sampler was able to log all flows from the flowmeter whether sampling was occurring or not.

The auto-samplers used were Isco 6712 full-size portable samplers equipped with an Isco 750 area velocity doppler ultrasonic 500 kHz flow module. In addition, for each rain event sampled, grab samples of the stored first-flush water in Sump D4 were also collected. All samples were analysed by NATA-accredited ALS Group Laboratory, Environmental Division in Brisbane. Analytical parameters, methods and limits of reporting are illustrated in Table 1.

RESULTS AND DISCUSSION

Six rain events were sampled during the 2012/2013 wet season. The profile of the rain events and of the sampling upstream and downstream of the StormDMT multi-barrier filter is illustrated in Table 2.

During the same wet season, the following two additional trials were conducted:

- Treatment of process washdown water ($29m^3$) following storm event number 3; and
- Treatment of first-flush water ($30m^3$) stored in Sump D4 generated by storm event number 4.

To better evaluate the effect of pollutant concentration fluctuations on the performance of a retention facility such as the StormDMT and on receiving water bodies, the use of the Event Mean

Table 1. Stormwater quality analytical parameters.			
Parameter	Units	Analytical Method	Limit of Reporting
PH	-	APHA 4500 H+	0.01
Electrical Conductivity (EC)	µS/cm	APHA 2510B	1.0
Total Suspended Solids (TSS)	mg/L	APHA 2540D	5.0
Total Metals	mg/L	APHA 3125, USEPA SW846-6020	0.0001–0.005
Dissolved Metals	mg/L	APHA 3125, USEPA SW846-6020	0.0001–0.005
Particle Size Distribution (PSD)	µm	Coulter LS230	0.05

Table 2. Profile of rain events and sampling.					
Storm event	Antecedent dry weather period (d)	Fluctuation of average flow rates during sampling (L/s)	Volume of stormwater runoff entering StormDMT™ filter (m^3)	Number of samples taken from stormwater runoff entering and exiting StormDMT™ filter	Portion of sampled storm event (%)
1	0.5	12.5–27.9	155.2	10	55.5
2	17	3.5–6.3	61.5	24	71.7
3	10	4.0–6.2	23.8	14	94.9
4	21	2.0–8.9	12.3	6	78.8
5	18	2.3–10.6	45.6	14	94.5
6	0.5	2.8–7.8	26.1	10	90.4

Concentration (EMC) is introduced. The EMC (Charbeneau and Barrett, 1998; Sansalone and Buchberger, 1997) represents a flow-weighted average concentration computed as the total pollutant mass divided by the total stormwater runoff volume, for an event of duration t_r.

$$EMC = \frac{M}{V} = \frac{\int_0^{t_r} C_t Q_t dt}{\int_0^{t_r} Q_t dt} \cong \frac{\sum C_t Q_t \Delta t}{\sum Q_t \Delta t}$$

where EMC is the event mean concentration (mg/L); M is the total mass of pollutant over the entire storm event duration (g); V is the total volume of the flow over the entire storm event duration (m^3); t is the time (min); Ct is the time variable concentration (mg/L); Qt is the time variable flow (m^3/min); and Δt is the discrete time interval (min). The EMC is computed for the entire stormwater runoff duration.

The Total Suspended Solids Event Mean Concentration (EMCTSS) of stormwater runoff entering the StormDMT filter was in the range of 5.0 to 38.8 mg/L, with the median EMCTSS at 8.4 mg/L and the average at 14.5 mg/L (see Figure 4). These concentrations are much lower than that reported in the Australian Runoff Quality manual (*Australian Runoff Quality: A Guide to Water Sensitive Urban Design*, 2006) for industrial land use (45 to 490 mg/L) and is mainly due to the following reasons:

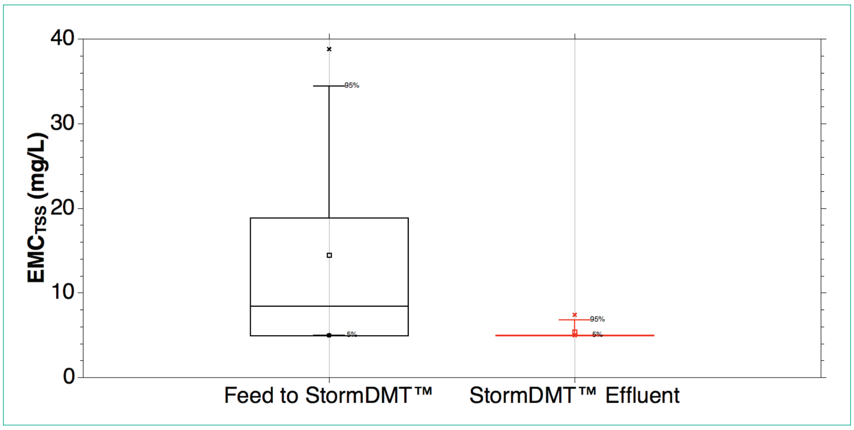

Figure 4. Total suspended solids.

- Available Sump D4 capacity to capture the first 15mm of the generated catchment stormwater runoff during a rain event;
- 100% impervious catchment area; and
- Site's thorough cleaning maintenance schedule (daily dry cleaning; three times a week a washdown of the catchment area).

The average TSS concentration of the first 15mm of the stormwater captured in Sump D4 for all stormwater events was 20.7 mg/L. This indicates that the stormwater runoff quality exiting Sump D4 in regards to TSS was reaching the average concentration much earlier than the 15mm storage rain capacity. Thus a reduction of the storage capacity down to 5mm may not significantly affect the stormwater runoff quality entering the StormDMT filter.

The extended 15mm first-flush storage capacity is only contributing to the attenuation of the flows.

As expected, different amounts of metals were washed off the catchment surface area during all monitored storm events, depending on the preceding dry period between rain events, the site handling schedule of chemical concentrates and the specific operational washdown catchment regime. The major pollutants in stormwater runoff for this catchment were copper, lead and zinc. Concentrations of other metals, such as cadmium and nickel, were of limited significance as they were either not detected or far lower than the regulated discharged limit.

The total copper EMC in stormwater runoff varied from 0.23 to 1.29 mg/L, with the average at 0.547 mg/L (median at 0.44 mg/L). These copper concentrations are up to 6.5 times higher than those reported in the Australian Runoff Quality manual for industrial land use (0.02 to 0.2 mg/L). The copper phase distribution in stormwater runoff was 60% particulate and 40% dissolved, with the minimum EMC at 0.02 and the maximum at 0.564 mg/L.

The total lead EMC in stormwater runoff varied from 0.44 to 1.24 mg/L, with the average at 0.607 mg/L (median at 0.490 mg/L), four times higher than the average lead concentration reported in the Australian Runoff Quality manual for industrial land use (0.04 to 0.5 mg/L). The dissolved lead EMC varied from 0.001 to 0.299 mg/L, with the average EMC at 0.127 mg/L (median at 0.100 mg/L). As expected, the phase distribution of lead was dominated by the particulate phase (Athanasiadis *et al*., 2004) (79.1%).

The total zinc EMC in stormwater runoff varied from 2.7 to 12.0 mg/L, with the average at 4.9 mg/L (median at 3.3 mg/L), 20 times higher than the average zinc concentration reported in the Australian Runoff Quality manual for industrial land use (0.15 to 0.4 mg/L). The dissolved zinc EMC in stormwater runoff varied from 0.518 to 6.4 mg/L, with the average concentration at 2.6 mg/L (median at 1.8 mg/L). The phase distribution of zinc was almost equally divided between the particulate (46.2%) and dissolved phase (53.8%).

These results are of major importance in regards to the successful management of wet weather flows requiring the StormDMT multi-barrier filter to be able to remove equally well the particulate and dissolved contaminants. In regards to particulate contaminants, further investigation was undertaken concerning the particle size distribution. The results are illustrated in Table 3.

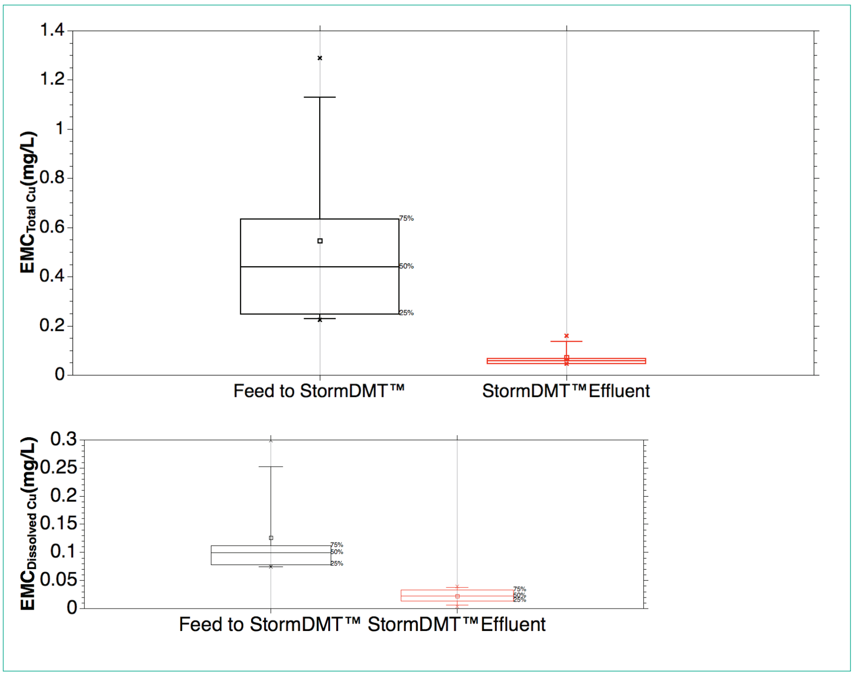

Figure 5. Total and dissolved copper.

Table 3. Particle size distribution in stormwater runoff entering StormDMT™ filter.			
Sample	90th percentile (µm)	50th percentile (µm)	10th percentile (µm)
1	5.35	1.82	0.286
2	18.5	3.88	0.219
3	23.9	4.99	0.325
4	6.92	2.64	0.276
5	21.3	5.67	0.657

It can be seen that the 50th percentile of the particles entering the StormDMT multi-barrier filter were in the range of 1.0 to 5.0 µm and that of the 10th percentile was even in the colloidal phase. Numerous field-scale and laboratory-based studies have documented the importance of colloid facilitated transport in porous media (Saiers and Hornberger, 1996; Roy and Dzombak, 1997; Kersting *et al*., 1999; Schriewer *et al*., 2007). This can have a significant impact on the performance of stormwater treatment devices, especially when extremely low concentrations are required to be achieved.

To determine the StormDMT reduction performance capacity in regards to pollutant concentration, the following Concentration Removal Efficiency (CRE) equation was used:

$$CRE(\%) = \frac{EMC_{Feed} - EMC_{Effluent}}{EMC_{Feed}}$$

where EMC_{Feed} is the event mean pollutant concentration entering the StormDMT device for each storm event; and $EMC_{Effluent}$ is the event mean pollutant concentration exiting the StormDMT filter for each storm event.

The reduction capacity of the StormDMT multi-barrier filter concerning the TSS concentration was 40.5% (see Figure 4). It was clearly demonstrated that in most cases the TSS concentration exiting the StormDMT multi-barrier filter was lower than 5 mg/L.

Figure 5 illustrates the recorded copper EMC (total and dissolved) entering and exiting the multi-barrier filter.

The StormDMT copper Concentration Removal Efficiency (CRE) was approximately 87% for total copper and 91% for dissolved, with average copper concentrations at the outlet of the filter at 0.073 and 0.020 mg/L respectively, and always lower than the regulated discharged limit of 0.100 mg/L.

The retaining performance capacity (total and dissolved) of the StormDMT multi-barrier filter in regards to copper mass load during the field trial was 72.5 and 85.4% respectively. The total copper mass entering the StormDMT filter was 137.8g, with the filter retaining approximately 100g.

The retention capability of the StormDMT filter in regards to lead EMC (total and dissolved) is illustrated in Figure 6. The StormDMT multi-barrier filter achieved a lead CRE of approximately 80% for total lead and 83% for dissolved lead, with average lead concentrations of 0.119 and 0.022 mg/L respectively in the outlet of the filter. It can be seen that the total lead concentration at the outlet of the StormDMT multi-barrier filter was slightly higher than the regulated discharged limit of 0.1 mg/L. This is mainly due to particulate and colloidal-bound lead migrating through the filter bed (see Figure 6).

The total lead mass load entering the StormDMT multi-barrier filter during the field trial was 212.7g, with the filter retaining approximately 149g, thus achieving a total lead mass removal efficiency of 70%.

The StormDMT multi-barrier filter achieved a CRE of approximately 76% for total zinc and 70% for dissolved zinc, with average zinc concentrations of 1.1 and 0.8 mg/L respectively in the outlet of the filter (Figure 8). It can be seen that the total zinc concentration at the outlet of the StormDMT multi-barrier filter was lower than the regulated zinc discharged limit of 2.0 mg/L, but the dissolved zinc concentration was slightly higher than the regulated zinc discharged limit of 0.5 mg/L. This is mainly due to the saturation of the StormDMT multi-barrier filter in regards to zinc operating sorption capacity by the end of the wet season.

The zinc mass load performance (total and dissolved) of the StormDMT multi-barrier filter for all field trials is illustrated in Table 4.

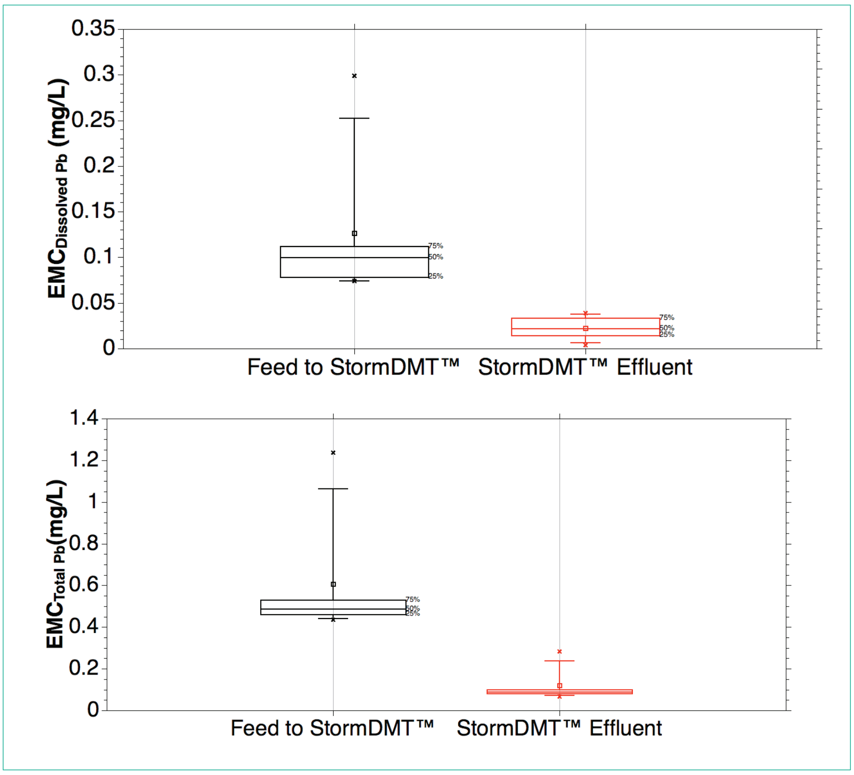

Figure 6. Total and dissolved lead.

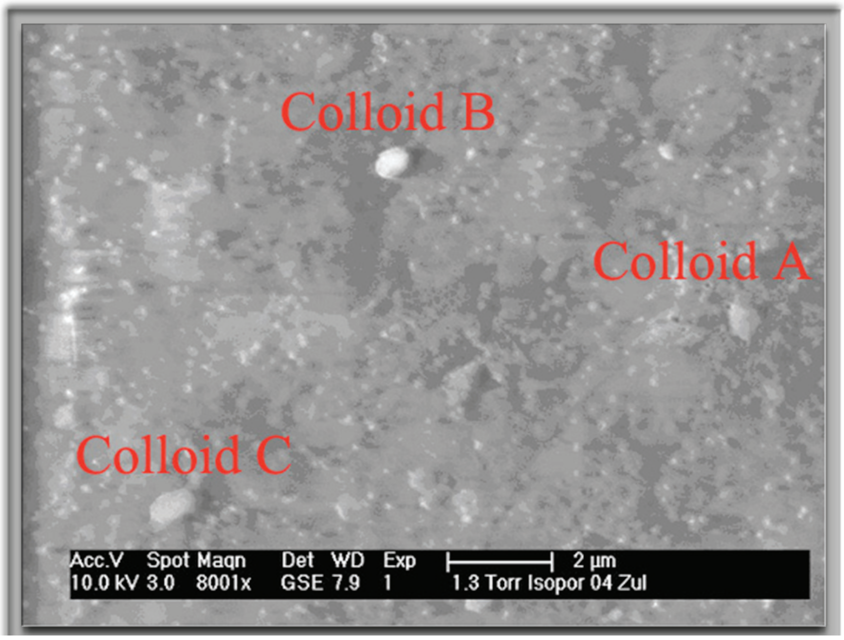

Figure 7. ESEM picture of colloidal particles.

The total zinc mass load entering the StormDMT filter during the field trial was approximately 2.1kg, with the filter retaining approximately 1.1, thus achieving a total zinc mass removal efficiency of 47.6%. This low zinc mass load removal efficiency was due to the saturation of the StormDMT multi-barrier filter.

Table 4 clearly demonstrates that the saturation of the StormDMT filter was due to a failure of the liming process of the first-flush water field trial. The operator reported that the pH of the stored first-flush water in Sump D4 was raised to 8.3 after liming, but left overnight prior to pumping the treated stormwater through the StormDMT filter.

Table 4. Zinc mass load performance.						
Field Trials	Feed to StormDMT™		StormDMT™ Effluent		Mass Load Reduction Efficiency (%)	
	Total Zinc (g)	Dissolved Zinc (g)	Total Zinc (g)	Dissolved Zinc (g)	Total Zinc (g)	Dissolved Zinc (g)
Storm Event 1	432.5	80.4	248.8	35.2	42.5	56.2
Storm Event 2	206.2	106.3	27.2	20.8	86.8	80.4
Storm Event 3	63.9	28.4	12.8	5.6	80.0	80.3
Process Water	20.3	18.3	10.1	4.4	50.2	76.0
Storm Event 4	148.1	78.9	5.4	2.7	96.4	96.6
First-Flush Water	903	795	480	465	46.8	41.5
Storm Event 5	230.9	178.8	109.8	100.5	52.4	43.8
Storm Event 6	83.1	49.5	62.8	40.8	24.4	17.6
Total	**2,088.0**	**1,355.6**	**956.9**	**675**	**54.2**	**49.5**

The laboratory results have reported a feed pH of 6.7, with most of the zinc concentration in dissolved phase. The zinc load contribution to the StormDMT filter of this specific trial was approximately 903g, representing approximately 78% of the load generated by the storm events of the entire wet season.

CONCLUSIONS

The following key conclusions can be drawn from the field trial study:

- The stormwater runoff quality is reaching the average contaminant concentration much earlier than the 15mm storage rain event capacity, thus any reduction of the storage sump capacity down to 5mm may not affect the stormwater runoff quality variability.
- The major pollutant in stormwater runoff is zinc with a minimum event mean concentration of 2.7 mg/L, a maximum of 12.0 mg/L and an average 4.9 mg/L for the D4 catchment. The phase distribution of zinc concentration in the stormwater runoff was almost equally divided between particulate (46.2%) and dissolved (53.8%).
- The total copper event mean concentration in stormwater runoff varied from 0.23 to 1.29 mg/L, with the average at 0.547 mg/L (median at 0.44 mg/L). The copper phase distribution in stormwater runoff was 60% particulate and 40% dissolved, with the minimum event mean concentration at 0.02 and the maximum at 0.564 mg/L.

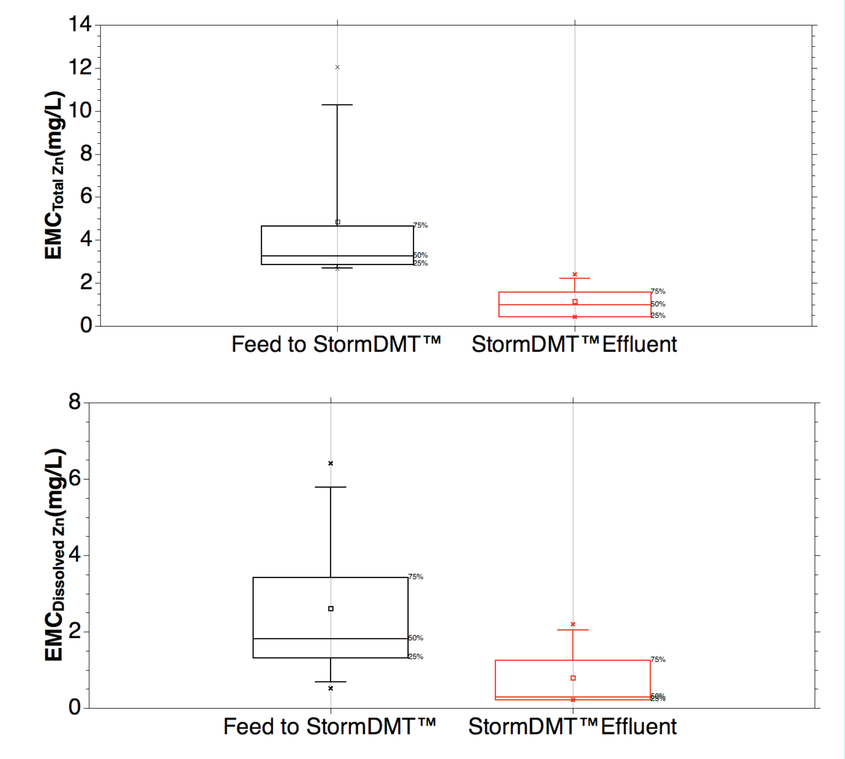

Figure 8. Total and dissolved zinc.

- The total lead event mean concentration in stormwater runoff varied from 0.44 to 1.24 mg/L, with the average at 0.607 mg/L (median at 0.490 mg/L). The dissolved lead event mean concentration varied from 0.001 to 0.299 mg/L, with the average at 0.127 mg/L (median at 0.100 mg/L). As expected, the phase distribution of lead was dominated by the particulate phase (79.1%).
- The StormDMT multi-barrier filter has demonstrated a copper concentration removal efficiency of approximately 87% for total copper and 91% for dissolved copper, with average copper concentrations at the outlet of the filter at 0.073 and 0.020 mg/L, respectively.
- The StormDMT multi-barrier filter lead concentration removal efficiency was approximately 80% for total lead and 83% for dissolved lead, with average lead concentrations of 0.119 and 0.022 mg/L respectively in the outlet of the filter.

- The StormDMT multi-barrier filter has demonstrated a zinc concentration removal efficiency of approximately 76% for total zinc and 70% for dissolved zinc, with average zinc concentrations of 1.1 and 0.8 mg/L respectively in the outlet of the filter.
- The contaminant phase distribution (particulate, dissolved or colloidal) has a significant impact on the performance of the stormwater runoff treatment system.
- Considering the site-relevant stormwater runoff pollutant rates, GHD's StormDMT™ filtration unit demonstrated a minimum maintenance life of one year.

According to these results, the application of StormDMT Filter System as an artificial barrier material appears to be an advanced method of managing stormwater runoff from industrial areas.

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