COPPER AND ZINC CONCENTRATIONS FROM AN ARTIFICIAL TURF FIELD

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ABSTRACT

This study reports copper and zinc concentrations in stormwater runoff from a third-generation artificial turf field. Comparison is made between two different stormwater flow paths and metal concentrations. Third-generation turf fields are different from previous generation fields because crumb rubber is used as a shock absorber. Crumb rubber is typically sourced from recycled vehicle tyres and has been identified as a potential source of metals and organic contaminants. Contaminants are introduced during the tyre manufacturing process as plasticisers, vulcanisers and antioxidants. Two recent meta-reviews reported that there had been few studies of crumb rubber washoff in the field. This study set-out to monitor heavy metal concentrations in runoff from a newly installed third generation artificial turf field.

Automatic flow monitoring and water quality sampling equipment was installed in April 2013 and maintained for a 28-month period. The sampler was positioned to collect samples from a combination of surface runoff from the field and surrounding concrete path (hereafter 'runoff' flow) and subsurface field drainage ('infiltration' flow). Flow weighted samples were taken during storm events. The water samples were collected and transported to an accredited laboratory where they were analysed for total copper and zinc.

Over the monitoring period copper concentrations exceeded ANZECC 80% survival thresholds for 87% of samples and zinc thresholds for 26% of samples (sample n = 561). Zinc showed greater intra-event variability in concentration. Copper and zinc yield from the artificial turf field for the first three months was comparable to a heavily trafficked road (>20,000 vpd). Thirty-four events were sampled for Mass First Flush (MFF). Both metals demonstrated a range of MFF values, with zinc having a stronger overall response than copper. High MFF was observed when peak flow was high and the peak one-hour rainfall intensity was high. High rainfall intensity, high peak flows and high pollutant concentrations were linked to runoff. Infiltration flow had lower concentrations. Thus, redesign of the artificial turf field to reduce runoff flow could reduce pollutant yield.

KEYWORDS

Artificial turf, stormwater contaminants, copper, zinc, mass first flush

PRESENTER PROFILE

Ed Clayton is an environmental scientist at Pattle Delamore Partners. This paper presents some findings from his recently completed MSc thesis.

1 INTRODUCTION

Artificial turf fields are on the rise around the world as they provide more playable hours than traditional natural turf fields. It is estimated that one ATF can provide up to 3000 hours of playing time annually compared to 680 hours for a traditional grass pitch (Cheng et al, 2014). Third generation artificial turf is distinguished by the use of crumb rubber as an infill shock absorbing layer, replacing the sand used in second generation fields. The crumb rubber is usually sourced from recycled vehicle tyres (Cheng and Reinhard, 2010).

In Auckland, New Zealand, the local government authority has undertaken a program to build 32 ATF fields before 2021 to accommodate an increase in demand for sports facilities fueled by an increasing population (Auckland Council, 2017). This paper describes a study that investigated Cu and Zn concentrations observed during a 28 month study of an ATF field installed at Michaels Avenue Sports Field, Ellerslie, Auckland.

2 ARTIFICIAL TURF FIELDS AND CONSTITUENT MATERIALS

In 2008, it was estimated that 3500 of the third generation ATFs exist in the USA, with around 900-1000 new fields being developed every year (Li et al, 2010). If crumb rubber is used on these fields it constitutes around 26% of the annual "waste" tyre stockpiles in the USA. Cheng et al (2014) calculated that this added up to around 180,000 tonnes of tyre rubber being used on fields every year (figure for the year 2009).

There are questions about the suitability of tyres to be recycled for other uses as they are made from a variety of materials. The main constituent is rubber in the form of differing blends of styrene butadiene rubber, polybutadiene and natural rubber together with carbon black or silica as a reinforcing agents and fillers (Magnusson and Mácsik, 2017). Four to five kg of crumb rubber can be sourced from a standard car tyre (Rhodes et al, 2012). Heavy metals are one of the leachates from tyres that pose a risk to receiving environments (Bocca et al, 2009; Li et al, 2010; Cheng et al, 2014). Zn is a primary concern because it is one of the more toxic components and is relatively abundant. It is used in the tyre as an additive in the vulcanisation process as ZnO, contributing up to 2.5% of tyre tread formulations (Councell et al, 2004; Gualtieri et al, 2005), although truck tyres can contain higher Zn content than car tyres (Kruger et al, 2012). The main effect of this is to make tyres harder and reduce wear. The amount of Cu in tyres varies between makes and models (Li et al, 2010; Sadiq et al, 1989). Cu in tyres helps dissipate heat.

Tyre debris toxicity increases with decreasing particle size and longer exposure time (Rhodes et al, 2012) Given the high surface to volume ratio of the small crumb rubber particles, they are also more prone to ozone attack (Cheng et al, 2014). As tyres age there is understood to be an increase of toxic leachates through chemical and physical degradation (Bocca et al, 2009; Rhodes et al, 2012; Cheng et al, 2014). Multiple processes work together to accelerate the breakdown of crumb rubber in the environment. Climate plays an important part. Heat and sunlight accelerate the breakdown through oxidative degradation. Wetting promotes the loss of any protective coatings and the leaching of constituent materials while abrasion provides a physical breakdown of the particles (Cheng et al, 2014).

In addition to crumb rubber, third generation ATFs have a number of other constituent materials, usually composing of three layers. Grass fibres are simulated using polyethylene / nylon blends; a carpet of polyurethane, polypropylene and polyamide-6 blends is used as a backing material; crumb rubber is added after installation (Figure 1 (a)) (Cheng et al, 2014). The base course over which the field components are laid is a rock aggregate on top of geotextile and clay liners. Perforated pipes run through the base course to provide drainage functions (Figure 1 (b)) (Cheng et al, 2014).

In-situ ATF’s have been subject to occasional manual sampling for water quality effects (Moretto, 2007; Bristol and McDermott, 2008; Lim and Walker, 2009; Connecticut DEP, 2010; Cheng and Reinhard, 2010) and artificial turf has been subject to laboratory testing of constituent materials (Bocca et al, 2009; Rhodes et al, 2012; Li et al, 2010). The information on lifecycle effects from installed fields is sparse however. Cheng et al (2014) identified a gap in the knowledge regarding the potential for cumulative effects over the functional lifespan of an ATF.

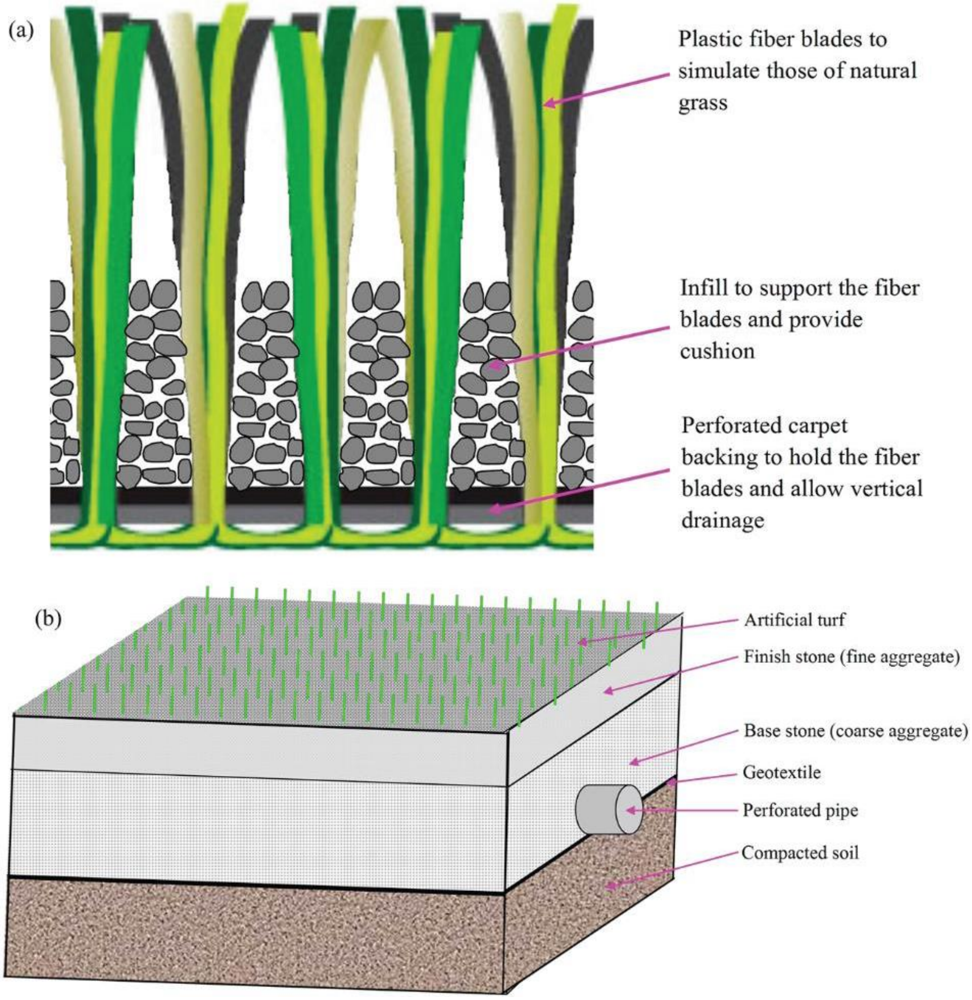


Figure 1. The illustration of a typical third generation artificial turf field: (a) crumb rubber infill and major constituent parts, and (b) the base course and drainage system. (From Cheng et al, 2014, p.2116)

3 METHODOLOGY

The Michaels Ave catchment is dominated by the ATF surface (9,200 m^2) (Figure 2). A small concrete path runs around the outside of the field (600 m^2) and an adjacent grassed bank contributes runoff during high intensity events. Water percolates through the ATF surface and into the sub-surface drains, or enters the catchpits built into the path as surface flow. These flows then combine to flow into a manhole riser and past the monitoring equipment.

Data used in the study was gathered from monitoring equipment positioned in the drainage system of the ATF. This was installed in the manhole riser where all sub-surface field drains converged (Plate 1 and Figure 2). The datalogger and sampler were placed in a locked chain-link enclosure adjacent to this (Plate 2).

Figure 2. Contributing catchments for the Michaels Ave ATF (aerial photo from Auckland Council)

Plate 1 (left): View inside the manhole where monitoring equipment was located. Exit pipe orifice is top left, one sub-surface drain can be seen entering at top right.

Plate 2 (right): Datalogger, raingauge and sampler equipment one week after installation

The equipment installed on site was standard monitoring equipment used to measure stream water level, flow and rainfall. It consisted of a HyQuest Solutions 350FX datalogger, HyQuest Solutions TB3 tipping bucket raingauge (0.5mm resolution), INW Aquistar PT2X pressure transducer (0-3m range, 0.01% full-range resolution) and ISCO 3700 Sampler. Flow was derived using a rating that applied to the orifice of the exit pipe.

This rating was developed as a rating table from an Auckland Council Stormwater rating used to estimate pipe flows. Water level was recorded as a time-series measured at two-minute intervals. The datalogger read the water level information, converted this to flow using the rating table and then computed the accumulated flow information that governed the ISCO Sampler. The sampling program was set to be flow-proportional with 8m^3 of flow accumulating between sample points. Sampling was set to commence at 20mm and reset at 15mm above the zero datum. Twenty-four 350mm glass bottles were used in the sampler, each collected a single discrete sample. Glass was used as testing was undertaken for organic pollutants as well as Cu and Zn described in this paper.

Flow-proportional (alternatively known as flow-interval) sampling for stormwater pollutants using automatic sampling equipment is considered best practice, and produces less bias than time-interval or random sampling (Leecaster et al, 2002). Multiple samples through events were needed as information was collected to understand MFF and how pollutant concentrations changed during storms. As pollutant load was required it was also crucial that flow was measured (Harmel et al, 2006).

The monitoring period was initially set at 24 months (this was slightly exceeded and reached 28 months before the monitoring ceased). This allowed for the sampling program to be run continuously over different seasons and to study temporal change as the field aged.

Notification of a storm event at Michaels Ave was generated by an automated alarm that sent text and email alerts when the sampling trigger level was exceeded. Once a rain event had ceased, the site was visited within 24 hours to collect the samples. These were capped, labelled and transferred to the council office or straight to the IANZ accredited WaterCare laboratory for analysis. If delivered to the council office they were refrigerated until they could be couriered to WaterCare, usually within 24-48 hours. At WaterCare they were tested for a ‘leachate suite’ of total metals to trace-level accuracy using standard ICP-MS procedures (EPA 2017). Dissolved metals were not tested for due to budgetary limitations.

Analysis of ‘raw’ metal concentrations was done by preparing boxplots of metals over the monitoring period and then by sampling event. This allowed comparison of distributions against guidelines for receiving environment concentrations to look at overall exceedance, and exceedance by event. Visual assessment was used to define trends in event concentration over time. Metal datasets were checked for log-normality using the Kolmogorov-Smirnov test.

First flush for the Michaels Ave ATF was calculated following the Mass First Flush (MFF) ratio developed by Ma et al (2002) (Equation 1). This provides a quantitative assessment of the strength of the first flush at different stages of the event (Barco et al, 2008). Should a MFF_n value be greater than 1, the proportion of contaminant is larger than the proportion of the elapsed event flow, i.e. a MFF_{20} of 3 indicates that 60% of the total volume of a contaminant is transported in the first 20% of runoff volume. It also allows for direct comparison of first flush strength at different stages of the event, rather than a ‘best-fit’ equation such as Bertrand Krajewski et al’s (1998) power law function.

$$MFF_n = \frac{\dfrac{\int_0^{t_1} C(t)Q(t)\,dt}{M}}{\dfrac{\int_0^{t_1} Q(t)\,dt}{V}} \qquad (1)$$

4 RESULTS

4.1 SAMPLING EVENTS

Sampler activity at the Michaels Avenue ATF was linked to storm events and associated site discharge. If a storm event met the following conditions it was called a Sampling Event:

- The water level must have exceeded the trigger level required to commence the sampling program;
- The rise in water level must have been associated with a corresponding rainfall event;
- Five or more samples were collected;
- Sampling must have been active over the period of the event; and
- The water level must have returned below the reset level of the sampling program OR twelve hours must have passed between the finish of event rainfall and the start of the next event rainfall.

Thirty-four Sampling Events were observed during the monitoring period. With the exception of three Sampling Events in a December month, all Sampling Events occurred between April and September (Figure 3). A total of 561 samples were collected, ninety-five percent of all during the months April – September, consistent with seasonal rainfall patterns (Figure 2).

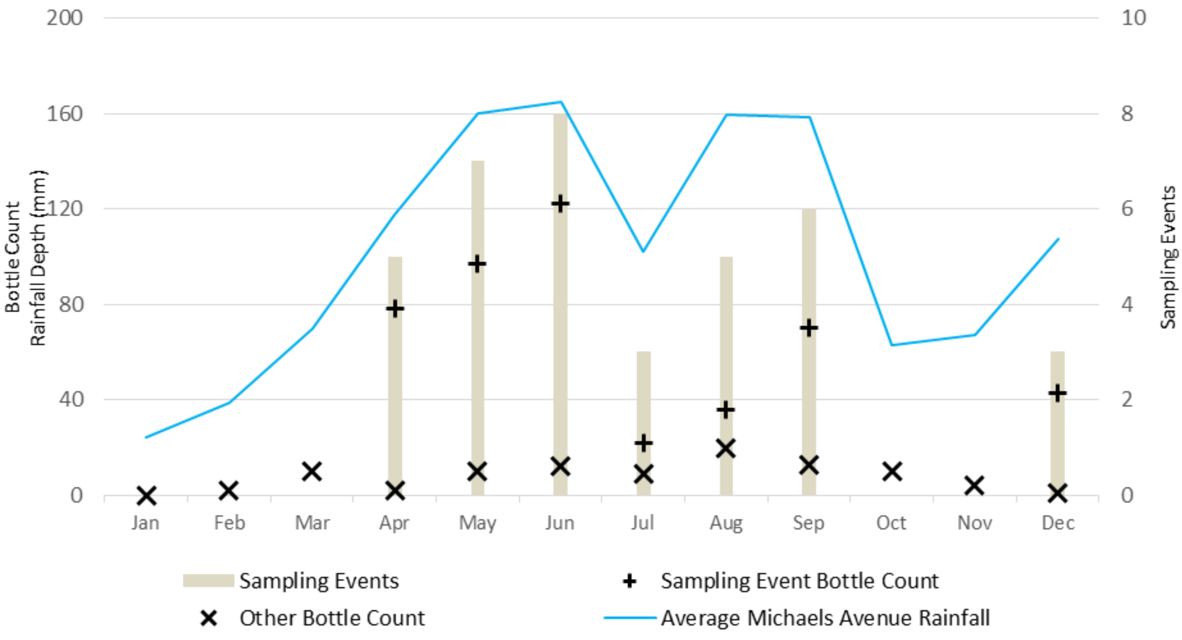


Figure 3. Sampling Event occurrence, number of samples collected and rainfall depth observed at Michaels Avenue by calendar month

4.2 CU AND ZN CONCENTRATIONS AND CRUMB RUBBER MASS TRANSPORT

Observed Cu and Zn concentrations at the Michaels Ave ATF varied markedly during the monitoring period, both showing a three order-of-magnitude range. Both distributions were log-normal with mean concentrations greater than medians. When compared to ANZECC 80% species survival thresholds, 87% of Cu samples and 26% of Zn samples exceeded guidelines (Figure 4).

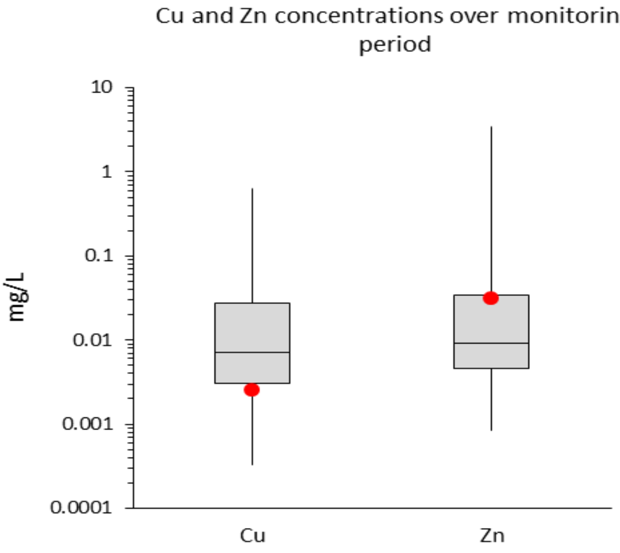


Figure 4. Cu and Zn concentrations over the monitoring period (box plots) with respective ANZECC 80% species survival marked (red dot). Box plots indicate maximum, minimum, median and upper and lower quartile values.

Two different patterns of concentration over time emerged from plotting boxplots of Sampling Event concentrations. Cu had low intra-event concentrations, with a steady decreasing trend over time (Figure 5). A similar trend was noticed for Zn, however greater intra-event variability was observed (Figure 6).

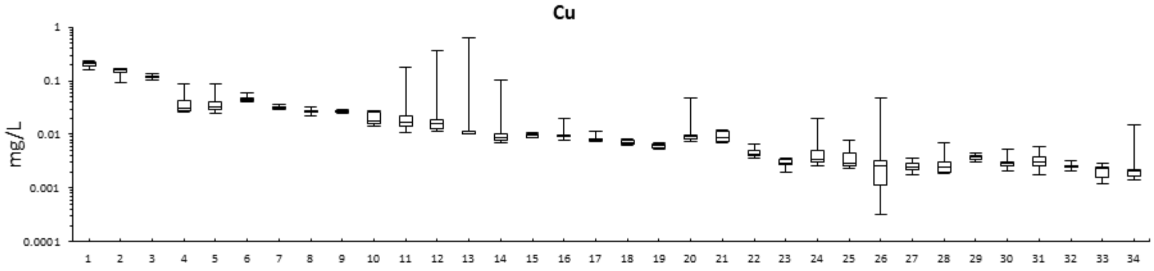


Figure 5. Cu concentrations by Sampling Event. Box plots indicate maximum, minimum, median and upper and lower quartile values

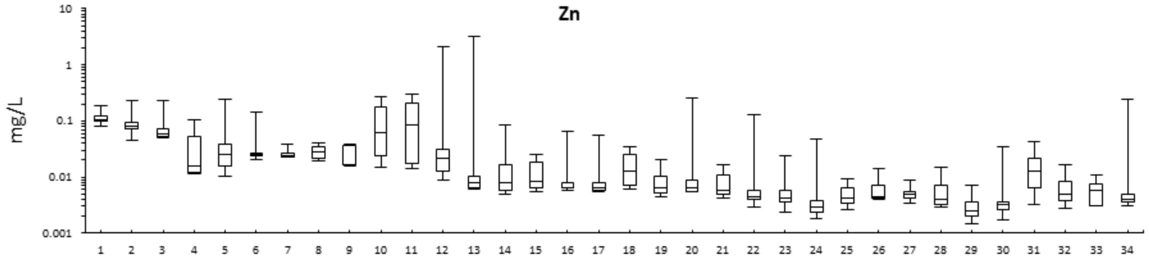


Figure 5. Zn concentrations by Sampling Event. Box plots indicate maximum, minimum, median and upper and lower quartile values

Entrainment of crumb rubber from the ATF surface was observed, with large deposits of crumb rubber noticed within catchpit Enviropod filters (Plates 3-6). Observations of the crumb rubber deposition distribution within the filter bags and overflows indicated that when high volumes of runoff flow occurred, a proportion of the flow would have bypassed the filter.

Plates 3-6. Above, a catchpit grate on the concrete path (left, Plate 3) and the Enviropod filter bag (right, Plate 4). Below, crumb rubber deposited within the Enviropod filter bag overflow (left, Plate 5) and in the bottom of the bag (right, Plate 6)

5 DISCUSSION

5.1 COMPARISON TO OTHER ATF STUDIES AND ANZECC GUIDELINES

The concentrations of Cu and the frequency of ANZECC guideline exceedance was not expected. For studies of crumb rubber derived from tyres and artificial turf fields, Zn is the metal most often associated with ecosystem toxicity and contaminant release (Cheng et al 2014). This is due to tyre wear releasing large volumes of Zn, attributed to the use of ZnO as a catalyst in the vulcanisation process (Councell et al 2005). While the Michaels Ave ATF did release slightly greater concentrations of Zn than Cu, the relative toxicity of Cu is greater (ANZECC 2000) and therefore lower concentrations will have a disproportionately higher effect on receiving ecosystems.

Comparison to other ATF studies shows that although observed maximum concentrations at Michaels Avenue exceeded the values recorded during other field studies, laboratory studies of Cu and Zn concentrations in crumb rubber were closer to the peak values at Michaels Avenue (Table 1). Most concentrations at Michaels Avenue (minimum to upper-quartile range) were similar to previous field studies. With maximum concentrations for Cu and Zn being observed within the first 3 month period it is possible that other field studies underestimated the concentration of pollutants due to different field ages and sampling methodologies.

Table 1. Concentrations of metals in Artificial Turf studies (µg/L)

Study	Cu	Zn	No. of samples	Age of field/ crumb rubber
This study			561	0-2 years
- Minimum	0.33	0.84		
- Lower Quartile	3.06	4.63		
- Median	7.22	9.29		
- Upper Quartile	27.2	34.7		
- Maximum	635	3,492		
Other artificial sports field studies				
Bristol & McDermott (2008)	Not tested	<2.0 - 36	8	1-2 years
Lim & Walker (2009)	5.4	59.5	1	2 years
Connecticut DEP (2010)	1.5 – 5.0	10 – 260	8	2-4 years
Cheng & Reinhard (2010)	1.0 – 34	130 – 470	4	1 year
Moretto (2007)*	0.1 – 10	1 – 500	7	0-11 months
Laboratory studies of crumb rubber				
Bocca et al (2009) (pH 5.0 artificial leachate)	0.2 – 216	2.0 – 62,120	32	Unknown
Rhodes et al (2012) (pH 5.0 artificial leachate)	Not tested	100-2,700	Unknown	Fresh crumb rubber
Li et al (2010)	0.31 – 9.5	220 – 13,000	9	0-2 years

5.2 COMPARISON TO LOCAL CONTAMINANT SOURCES

Understanding the significance of the Cu and Zn loads from the Michaels Avenue ATF necessarily means a comparison to other local urban sources. To do this, the data were divided into four different categories: the first three months, first six months, first year and second year of the ATF lifespan. For comparison, data were compared to the widely used Contaminant Load Model (CLM) (Auckland Regional Council 2010a, 2010b) through flow weighting samples, accumulating the pollutant yield over the appropriate time step and then weighting the results according to field area. As the CLM is used to predict annual loads from a number of urban sources, the yield from the first three months and first six months were annualised by simply multiplying by four and two respectively.

The 3-month and 6-month periods showed the highest concentration for both Cu and Zn (Table 2). These sample periods included the highest measured concentrations and also a high volume of site discharge including the wettest month. This combination of high concentrations with high flow means a large mass of pollutants would have been discharged.

For the first three months, the values for both metals during this period are comparable to a heavily trafficked road. In Auckland, a road with a daily traffic load of more than 10,000 vpd is classified as a High Contaminant Generating Activity where contaminant and flow management requirements need to be implemented. Total Cu and Zn effluent loads from a BMP device should be reduced to 0.010 mg/L and 0.030 mg/L respectively (Auckland Council 2013). Over time, the yield decreased substantially, with yield from the second year lower than a minor suburban road. Under Auckland Council (2013) requirements, a yield of this magnitude would not have to be treated.

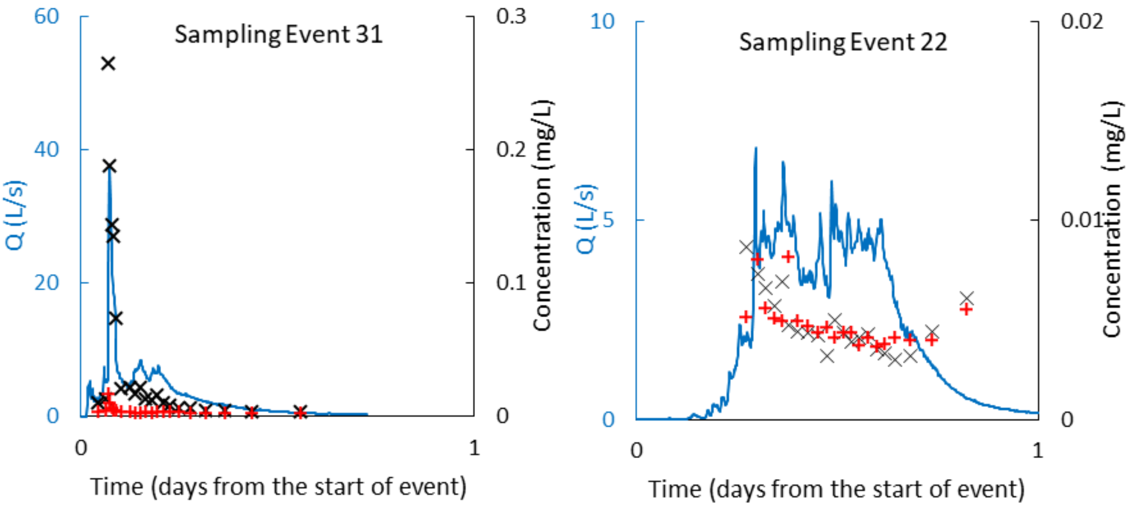
Table 2. Annual loads, units g m^{-2}a^{-1}. All data not from this study sourced from the Auckland Council Contaminant Load Model (Auckland Council 2010a), figures reduced to four decimal places. Selection of CLM classifications used for brevity. Vpd = vehicles per day.

Component	**Zn**	**Cu**
This study		
First three months (annualised)	0.1238	0.0449
First 6 months (annualised)	0.0659	0.0243
First year	0.0342	0.0126
Second year	0.0013	0.0007
CLM		
Galvanised steel roof well painted	0.2000	0.0003
Zinc/aluminium unpainted	0.2000	0.0009
Zinc/aluminium coated	0.0200	0.0016
Copper roof	0.0000	2.1200
Concrete roof	0.0200	0.0033
Other roof	0.0200	0.0020
<1000 vpd	0.0044	0.0015
1000-5,000 vpd	0.0266	0.0089
5,000-20,000 vpd	0.1108	0.0369
20,000-50,000 vpd	0.2574	0.0858

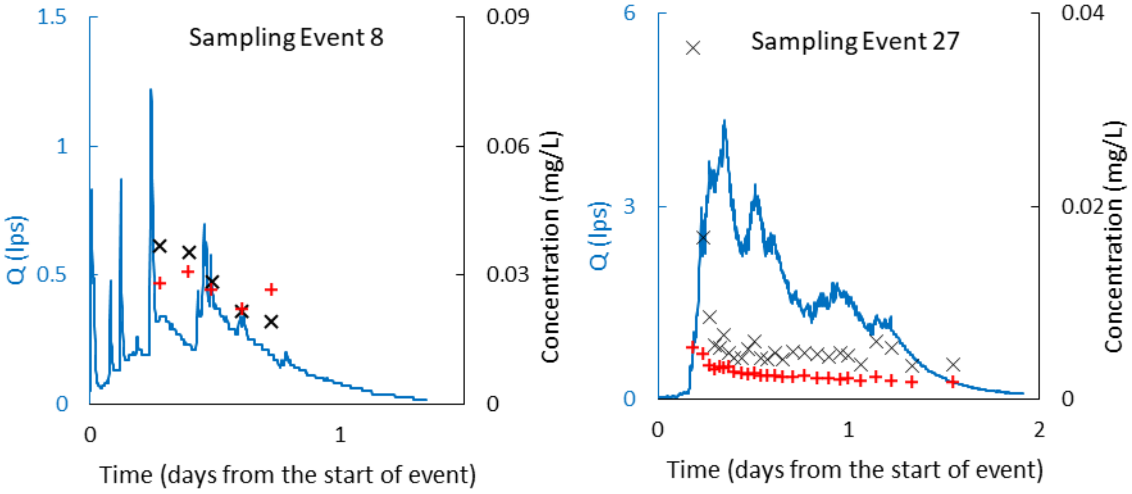
5.3 INFILTRATION AND RUNOFF FLOW

It was observed that site discharge occurs through two different pathways, the first through infiltration through the ATF (infiltration) and the second via surface flow from the surrounding surfaces and infiltration excess from the ATF surface (runoff). Where runoff spikes were sampled, observed Zn concentrations were high. This pattern was not so easily discernible for Cu, where concentrations through an event tended to have smaller ranges (as shown in Sampling Event box plots – Figures 4 & 5). Zn also tended to exhaustion during smaller events where runoff spikes were not sampled.

These differing patterns suggest that pollutant yield for Zn is likely to be source-limited and for Cu flow-limited (Sansalone and Cristina, 2004). The increased Zn concentrations during high rainfall intensities and runoff spikes is symptomatic of urban streams, where increased effective imperviousness is associated with increased concentrations of pollutants (Walsh et al 2005).



Figures 6 – 9: Above, large Sampling Events with a runoff spike (left, Figure 6) and without a runoff spike (right, Figure 7). Below, a small Sampling Event showing Zn exhaustion (left, Figure 8) and a medium Sampling Event showing Zn exhaustion (right, Figure 9), both with no runoff spike sampled. For all Figures flow rates are marked by blue lines, Zn concentrations with black crosses and Cu concentrations with red plus symbols.



5.4 MASS FIRST FLUSH

The differences observed in concentrations during infiltration and runoff flows have impacts on the intra-event mass loading of Cu and Zn to the receiving environment. To assess this, MFF ratios were calculated at two-minute intervals through each event (at the time of flow measurement) through developing and comparing normalised cumulative flow and pollutant yield (as per equation 1). Following the normalised cumulative plots further from previous authors (Bertrand-Krajewski et al, 1997; Ma et al, 2002), Han et al (2006) designed plots of the MFF ratio for each metal at ten percent intervals (MFF_{10}, MFF_{20}, … , MFF_{90}). The current study follows this method for plotting the MFF strength.

On average, Zn could be expected to demonstrate a MFF response for an event (Figure 10). For Cu, only some select events demonstrated MFF, with most events showing limited response (Figure 11). This reinforces that Cu was most likely to demonstrate a non-source (flow) limited discharge pattern (Sansalone and Cristina, 2004).

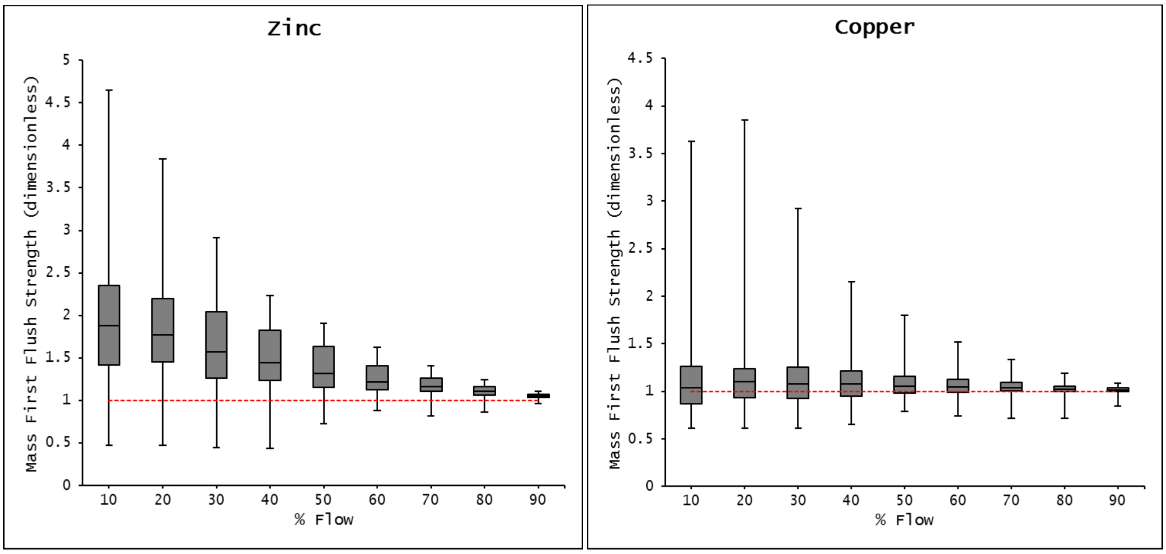


Figure 10 & 11. Left, Zn MFF values (Figure 10). Right, Cu MFF values (Figure 11)

Pearson's Correlation Coefficient was used to investigate the MFF relationships for Al, Cu, Fe and Zn to the site conditions listed below. As the sample size was small (n=34), the significance level was relaxed to 0.1 from the usual 0.05 (Machin et al, 1997). While there was some variation between specific metals and metadata, half of the metadata and statistics were not significant for the sample size (r value under 0.4). For statistically significant correlations that were observed, only weak to moderate positive correlations were seen (Table 3).

For Zn, MFF was positively correlated to peak flow rates (Peak Q) and the maximum one-hour rainfall (Max 1HP and 1H%P). Zn MFF was also more likely to be observed if the event was shorter (Total T) and if the maximum flow rate was observed close to the start of the event (%Q). Cu showed a similar correlation pattern to Zn, with the exception being no correlation to the time of the event where the maximum flow rate was observed.

Table 3. Pearson Correlation Coefficient values for MFF values and Sampling Event statistics. Statistically significant results in bold (greater than 0.4) for sample size n=34, α=0.1, β=0.2. Refer Table 4 for definitions

		Total T	**%Q**	**Peak Q**	**Total P**	**Max 1HP**	**Max 10MP**	**10M%P**	**1H%P**	**ADWP**	**Days**
Zn	**MFF_{20}**	**-0.433**	-0.354	**0.603**	-0.051	**0.492**	0.340	0.324	**0.472**	0.199	-0.164
	MFF_{30}	**-0.488**	**-0.423**	**0.576**	-0.075	**0.540**	0.376	0.342	**0.511**	0.243	-0.182
	MFF_{50}	**-0.491**	**-0.408**	**0.575**	-0.187	**0.434**	0.349	0.353	**0.465**	0.050	-0.235
Cu	**MFF_{20}**	-0.378	-0.313	**0.666**	-0.019	**0.460**	0.257	0.229	**0.409**	0.005	-0.134
	MFF_{30}	**-0.407**	-0.325	**0.624**	-0.050	**0.436**	0.238	0.246	**0.423**	-0.031	-0.139
	MFF_{50}	**-0.407**	-0.303	**0.590**	-0.167	**0.320**	0.211	0.279	0.381	-0.273	-0.102

Table 4. Definition of parameters correlated to MFF

Parameter	**Definition**
Total T	Total event time in minutes
%Q	Point in time where the maximum discharge was measured, expressed as a % of the total event time
Peak Q	Maximum flow discharge in litres per second
Total P	Total rainfall in millimetres
Max 1HP	Maximum one-hour rainfall in millimetres
Max 10MP	Maximum ten-minute rainfall in millimetres
10M%P	The % of event rainfall recorded in the maximum ten-minute rainfall intensity
1H%P	The % of event rainfall recorded in the maximum one-hour rainfall intensity
ADWP	The time in days to the previous significant rainfall (1.5mm in 6 hours)
Day	Count in days from date of installation

These observations are not unusual for studies of first flush. Rainfall intensity has been observed to drive first flush responses in highway runoff as it delivers more energy to entrain pollutants (Sansalone and Cristina 2004). Kang et al (2006) observed that weak intensity rainfall lacking the energy required to sufficiently mobilise pollutants. In an investigation of highway runoff Sansalone and Cristina (2004) drew a link between rainfall intensity and the presence of pollutants in the runoff to determine that high intensity rainfall events would result in a mass limited response (strong first flush) and low intensity rainfall events would mean pollutants would be flow limited (weak first flush). Extremely short duration rainfall doesn't create a first flush as it doesn't have time to exhaust pollutant sources. When long duration events occur, first flush responses can be muted due to the exhaustion of short-term pollutant sources, but then long-term pollutant sources come into play (Kang et al 2008). Antecedent conditions appear to only be relevant to MFF by site. Often, impervious surfaces are more likely to be correlated to antecedent conditions when rates of dry deposition are high, this is true of sites such as road surfaces (Lee et al 2004, Kang et al 2008).

However FF analysis can be applied at time-scales greater than one event. In locations where distinct rainy seasons exist, there is evidence that early season storms can carry a greater pollutant load than storms later in the season. This is known as seasonal first flush (Lee et al, 2004; Tiefenthaler et al, 2008).

Expanding on the work of Lee et al (2004) and Tiefenthaler et al (2008), MFF can be applied across a longer time scale than just seasonal pollutant loads. The raw concentrations of metals at Michaels Ave certainly demonstrate a pattern of decreasing pollutant concentration with time. This visual assessment of concentrations is consistent with concentration based FF methodologies (Sansalone and Cristina 2004). Therefore, adjustment to a MFF over the monitoring period should demonstrate a similar result, but one more quantifiable.

Using the total event yields for pollutants allowed for cumulative flow and pollutant yield to be calculated over the monitoring period for Cu and Zn. Both Cu and Zn show a strong first flush signature (Figure 12, Table 4).

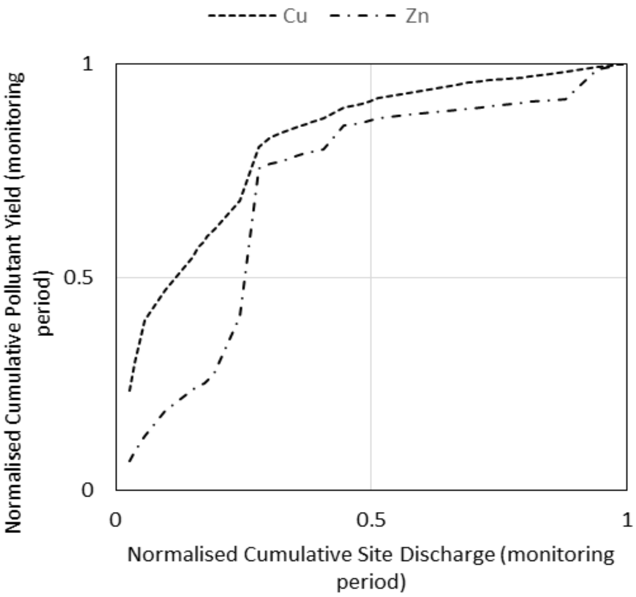


Figure 12: Land-Use First Flush for Cu and Zn

Table 6. Cu and Zn MFF30 values for the monitoring period (Land-Use First Flush)

	Cu	Zn
MFF_{30}	2.759	2.558
% Pollutant Yield at 30% Flow	82.77	76.74

This change in time scale from event MFF shows a change in metal yield pattern for Cu from being flow-limited to source-limited. For the Michaels Ave ATF the entire 28 month dataset demonstrated the majority of contaminant release in the first three months. It is proposed that the term 'Land-Use First Flush' can be applied to this pattern of metal yield.

5.5 CONCLUSION

Three important results were discovered from the Michaels Avenue ATF study. Firstly, the observed concentrations of both Cu and Zn rapidly decreased with time. This is a previously unreported trend for ATF pitches and it is proposed that the term 'Land-Use First Flush' can be used to describe this observation. The Land-Use First Flush may be a result of different field monitoring methodology. Measurement of newly installed ATF pitches has not been reported before. Interestingly, concentrations of Cu and Zn from the Michaels Ave ATF pitch reduced as it aged and became comparable to other studies. It is thus likely that other studies have underestimated the concentration and total load of contaminants washing off the ATF. Pollutant yield was dominated by one or two events where a disproportionate load was produced. There is no evidence that pollutant yield had reached a steady rate by the end of the monitoring period.

The second conclusion is that the two different flow paths from the site, infiltration and runoff, had distinct impacts on the concentrations of metals measured. Runoff flow has higher concentrations of metals than infiltration flow. As runoff flow occurred from surrounding surfaces (and the ATF surface under high intensity events), it would not have been subject to the filtering effect of the ATF sub-surface (through which infiltration percolated). There was evidence in this study that crumb rubber could be entrained in runoff. This finding has consequences for how ATF pitch design could be adapted to use the field surface as a reservoir. Using the ATF structure as a retention device (i.e. eliminating runoff flow) could provide primary treatment for contaminants of concern.

Finally, mass first flush was demonstrated by Zn where moderate to strong MFF responses were observed for a number of events. Cu had a less pronounced MFF response for most events. It is proposed that different transport mechanisms evident in the hydrograph (washoff and runoff flows), and different sources of metals within the ATF structure, were responsible for these two different patterns. At the event scale, Cu was not source-limited. This is different to Zn, where MFF responses indicate that source limitation was an important factor for pollutant transport. When examined at the monitoring scale (over the entire 28 months) Cu concentrations decreased suggesting source limitation.

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