# SAMPLING ROAD RUNOFF TO ESTIMATE LOADS OF COPPER AND ZINC

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**ABSTRACT**

A review of previous research on copper and zinc in New Zealand road runoff suggested that loads, expressed in terms of vehicle emission factors (VEFs), are highest where roads are subject to relatively high rates of brake and tyre wear (Moores and Pattinson, 2008). A subsequent programme of road runoff sampling at four sites in the Auckland region is investigating variations in VEFs of copper and zinc in relation to traffic characteristics. The sites range from a rural highway to the frequently congested Northern Motorway. Sampling of runoff at a pond inlet and outlet at one site has allowed the reduction in copper and zinc loads due to this device to be estimated. At two of the other sites samples of runoff discharged from a vegetated swale and an open roadside drain are being collected, allowing assessment of their effectiveness for contaminant removal. The results of the programme will provide New Zealand's stormwater and roading managers with guidance in two ways: firstly, to assist with the identification of priority areas for treatment of road runoff; and secondly, to provide information on the suitability of different types of treatment for different parts of the road network.

**KEYWORDS**

**Roads, runoff, zinc, copper, vehicle emission factor, treatment efficiency**

**PRESENTER PROFILE**

Jonathan Moores is an Urban Aquatic Scientist with NIWA in Auckland. His areas of expertise include environmental hydrology, water resource management and, more recently, stormwater research. He is currently leading a number of field-based and modelling studies into the sources, fate and treatment of stormwater contaminants.

## 1 INTRODUCTION

Copper and zinc are important constituents in brake linings and tyres respectively and both are classified as priority pollutants by the US Environmental Protection Agency (Kennedy, 2003). Braking and tyre wear results in the emission of brake pad and tyre debris containing these metals to the road surface. Through chemical processes associated with wetting and drying of the road surface, these metals pass into solution and may bind with particulate matter deposited on the road (Macaskill and Williamson, 1994). Following rainfall, they are conveyed via road drainage systems to receiving water bodies.

Moores and Pattinson (2008) presented a review of previous international and New Zealand studies to quantify copper and zinc loads in road runoff. This included estimates derived from NIWA field programmes over the period 2006-07. The review provided the basis for the design and implementation of a current programme of road runoff sampling funded by the New Zealand Transport Agency (NZTA) and Auckland Regional Council (ARC). The study has the objectives of investigating:

- vehicle emission factors (VEFs) of copper and zinc for different types of road; and
- the effectiveness of existing contaminant control measures at the selected sampling locations.

This paper provides a description of the methods employed in the sampling programme, results obtained to date and further work to be completed. While the project also includes investigation of Total Petroleum Hydrocarbon (TPH) in road runoff, those results are not discussed here. Findings on all aspects of the study are to be reported to NZTA on completion of the project.

# 2 METHODS

## 2.1 SAMPLING LOCATIONS

Four sampling locations were selected to represent road types at which VEFs may be expected to differ in relation to traffic behaviour. All are located on the State Highway network in the Auckland region. Table 1 lists the sites along with a measure of their congestion calculated in accordance with a method developed by Gardiner and Armstrong (2007).

*Table 1: Road runoff sampling locations and traffic characteristics*

| Site name and location | Road description | Traffic volume[a] (vpd) | Indicator of congestion[b] (AADT/Capacity) | Road runoff treatment investigated |
|---|---|---|---|---|
| SH 18 @ Westgate, east of northwestern motorway interchange | Two lane arterial road, urban fringe | 36455 both directions | 1.39 | None |
| SH 1 (Northern motorway) @ Northcote, north of Esmonde Rd interchange | Four lane urban motorway (northbound lanes only) | 41636 northbound | 0.66 | Vegetated swale |
| SH 16 @ Coopers Creek, north of Huapai | Two lane rural highway | 12702 both directions | 0.47 | Open roadside drain |
| SH 1 (Northern motorway) @ Redvale, north of Oteha Valley Rd interchange | Four lane rural motorway | 42115 both directions | 0.40 | Pond |

Notes
a. Annual average daily traffic - AADT (Transit NZ, 2007).
b. After Gardiner and Armstrong (2007)

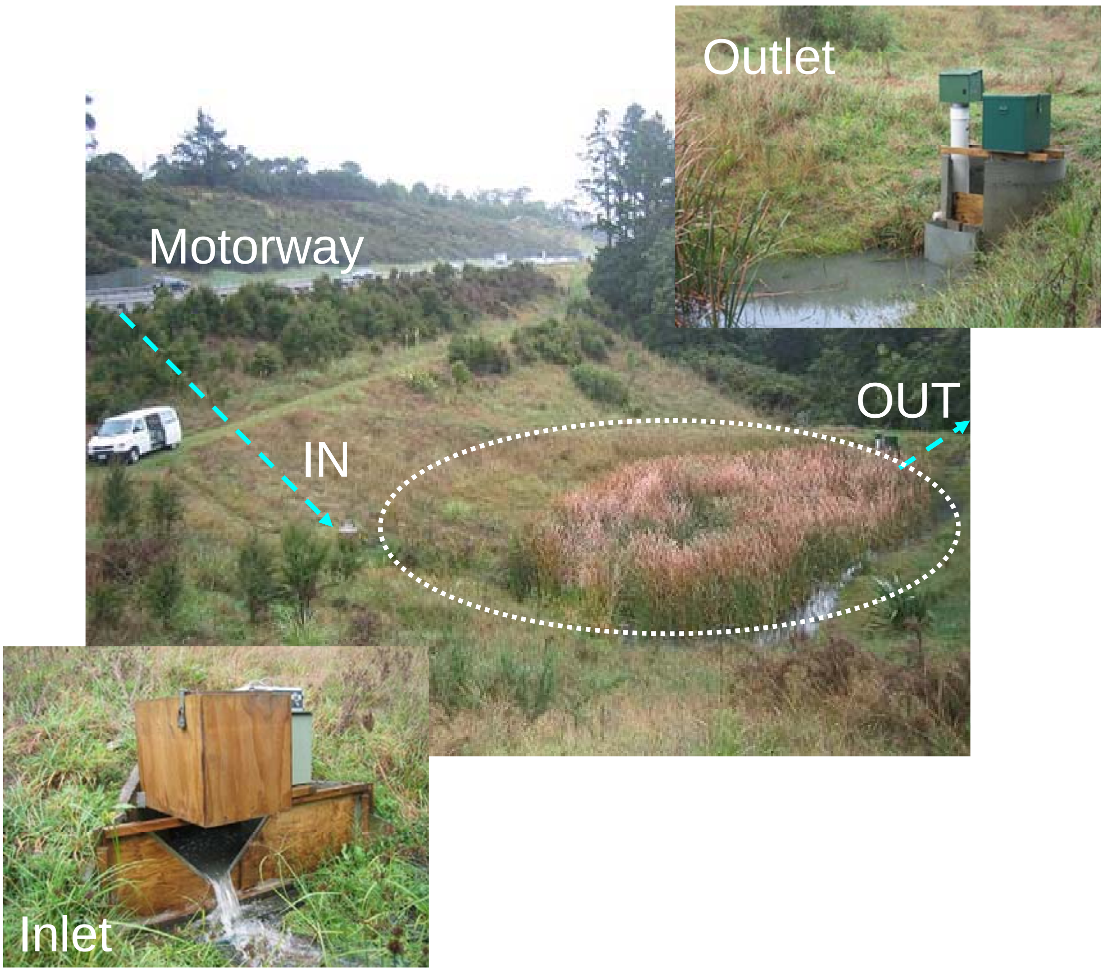
Of the four sites, SH 18 @ Westgate is the most congested. This site is located close to the current western end of Auckland's northwestern motorway and is subject to particularly heavy peak hour use. The remaining three sites are all classed as subject to 'interrupted' traffic flows (AADT / Capacity between 0.35 and 0.7) according to Gardiner and Armstrong's (2007) system, although the SH16 @ Coopers Creek and SH1 @ Redvale sites have substantially lighter traffic flows relative to capacity than does the SH1 @ Northcote site.

The drainage characteristics of these sites was a key factor in their selection and they were chosen in preference to many other potential sites which were also considered. Each of the four sites has a clearly defined catchment area comprising only road surface with no additional non-road sources of stormwater. In addition, these sites also provide an opportunity to investigate the effectiveness of different stormwater treatment and drainage systems. Table 1 lists the treatment type investigated at each site.

## 2.2 INSTRUMENTATION AND SAMPLE COLLECTION

The study sites are instrumented to measure and record water levels for the estimation of discharge (flow) and to collect water samples during storm events. Figure 1 shows an example of the instrumentation deployed. Temporary plywood sharp-crested V-notch weirs have been installed at points of discharge from (a) the road surface and (b) treatment devices, including at culvert outlets, in pond drop structures, in road side drains and in manholes. The weirs have been designed and configured specifically for each site. Water level at the weirs is measured by either a float and counter weight driven recorder, where there is sufficient space to construct a stilling well and recorder cabinet, or a pressure transducer in situations where space is limited. Water levels are recorded at 1 minute intervals to a stage resolution of 1 mm. Each logger is programmed with a customised rating equation relevant to the weir allowing the calculation of instantaneous and cumulative discharge in order to trigger the collection of flow-proportional water samples.

*Figure 1: Instrumentation at the inlet and outlet of a stormwater pond, SH1 @ Redvale, showing V notch weirs, sampler cabinets, stilling wells and water level recording cabinets.*



An ISCO automatic water sampler is housed in a secure cabinet at each site (pre- and post-treatment). The water samplers are set up for sampling before forecasted rainfall events by stocking with 12 pairs of plastic and glass acid-washed sampling bottles. Plastic bottles are used to collect samples for metal analyses to avoid potential contamination associated with the use of glass which contains traces of metallic elements (Batley, 1989). Conversely, glass bottles are preferred for the collection of samples for TPH analysis to avoid potential contamination from organic impurities that can accumulate in plastics (Liess and Schulz, 2000).

The samplers are programmed to collect samples on a flow proportional basis, with sampling intervals determined prior to each attempted sampling event based on the forecasted rainfall depth and experience gained during previous events. Samples are collected from the samplers and delivered to the NIWA laboratory as soon as practicable, usually within 24 hours of the first samples being collected. In the event that a rainfall event continues beyond the anticipated sampling period, the sampler is restocked with additional bottles and re-programmed to continue sampling. Once returned to the laboratory, sample bottles are stored in the dark at 4$^{o}$C until they can be processed (usually within 48 hours).

During each visit to set up or collect samples, water level data are collected by unloading the logged measurements onto a laptop computer. Additional visits are made regularly to collect these data at times when the samplers are not activated. During each visit to the site, field staff inspect all instrumentation including comparison of observed and logged water levels, measurement of battery voltages and observation of equipment condition. Measurements, comments and any adjustments made are recorded in a log book.

Water levels collected from the logger are transferred to NIWA's TIDEDA hydrological database. Following the collection of samples, the time series of water levels, discharge and sampling time are reviewed in order to check that the collected samples are well distributed throughout the relevant event hydrograph. Providing that this is the case, all samples from each event are retained for processing and analysis.

### 2.3 SAMPLE PROCESSING AND ANALYSES

The plastic bottle samples are analysed for Total Suspended Solids (TSS) and particulate and dissolved copper and zinc. The samples are filtered through acid-washed, dried and pre-weighed polycarbonate membranes using plastic, acid-washed, vacuum filtration equipment. After filtration, the membranes are re-dried in the laboratory oven and re-weighed to give the weight of TSS in the volume filtered. The dried membranes and filtrate sub-samples are analysed by an external laboratory for particulate and dissolved metals, respectively, using inductively coupled plasma mass spectrometry (ICP-MS).

## 3 RESULTS

### 3.1 CHARACTERISTICS OF SAMPLING EVENTS

Table 2 describes the characteristics of the storm events sampled to date. Sampling commenced at the SH1 @ Redvale and SH18 @ Westgate sites in late 2007 and early 2008, respectively, and was completed at these sites in October 2008. Of the eight events sampled at Redvale, the first two were undertaken as part of a previous project that involved sampling at the wetland inlet only (Moores *et al.* 2008). Instrumentation was added to the pond outlet for the remaining six events sampled as part of this project. Sampling commenced at the SH1 @ Northcote and SH16 @ Coopers Creek sites in spring 2008. At the time of writing (March 2009), sampling is still in progress at these locations.

*Table 2: Summary characteristics of runoff sampling events*

| Site name and location | Period of runoff (flow) monitoring | Number of events sampled | Range of rainfall depths | Range of antecedent dry periods[a] |
|---|---|---|---|---|
| SH 1 (Northern motorway) @ Redvale | November 2007 - October 2008 | 8 | 22 – 75 mm | 12 hours to 10 days |
| SH 18 @ Westgate | April 2008 - October 2008 | 6 | 14 – 36 mm | 2 to 15 days |
| SH 1 (Northern motorway) @ Northcote | September 2008 - (in progress) | 3 | 20 – 42 mm | 2 to 20 dry days |
| SH 16 @ Coopers Creek | October 2008 - (in progress) | 4 | 9 – 42 mm | 2 to 7 dry days |

Notes
a. Time elapsed since previous rainfall > 1 mm depth.

Runoff generated during rainfall events of a range of depths has been sampled. Events sampled range from broken sequences of relatively low intensity showers to continuous rainfall of relatively long duration. There has also been substantial variation in antecedent conditions. While the majority of sampling events have followed dry periods of at least 5 days, a number of events have been sampled after shorter periods of dry weather in order to investigate the influence of antecedent conditions on event contaminant loads.

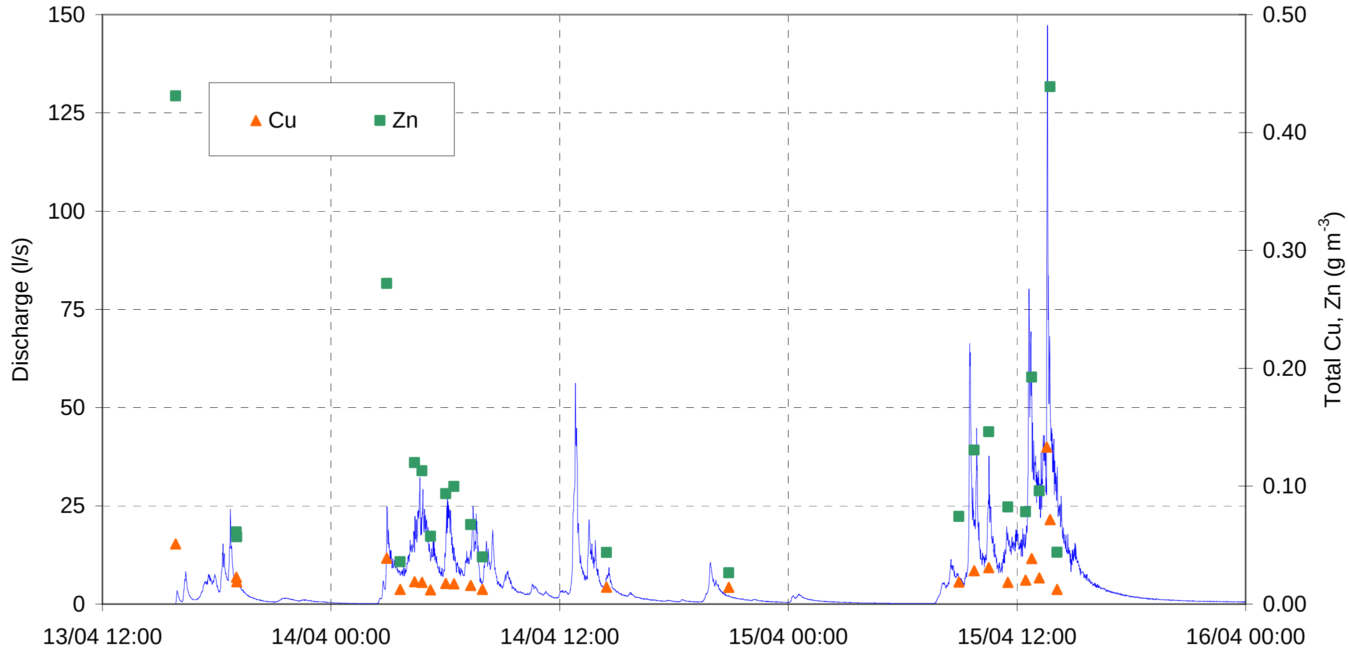
## 3.2 VEHICLE EMISSION FACTORS

VEFs are a means of characterising the load of a vehicle-derived contaminant that is generated in the road corridor and which ends up being conveyed in road runoff. They are expressed in terms of the mass of the contaminant per vehicle per unit of road length travelled, typically in units of mg/veh/km.

The calculation of a VEF requires information on contaminant load, vehicle numbers and length of road discharging to the point of sampling. VEFs have been calculated from the results of sampling at the SH1 @ Redvale and SH18 @ Westgate sites using the following approach (at the time of writing, estimates have not yet been made for the other two sites given that sampling is not yet complete).

Figure 2 provides an example of the data resulting from sample collection and flow measurement during one event at the SH1 @ Redvale site. For each sampling event, the loads of dissolved, particulate and total Cu and Zn have been estimated from sample concentrations and runoff volumes between samples. The contaminant loads from each sampling event have been summed to give the total load ($\Sigma$ CL) over all events sampled for each site.

*Figure 2: Discharge and concentrations of total copper and total zinc in samples collected at the SH1 @ Redvale pond inlet, 13-16 April 2008.*




The vehicle movements during the antecedent dry period up to and including each sampling event have been estimated from published AADT data for SH1 @ Redvale (Transit NZ, 2007) and traffic count survey data collected specifically for this study at SH18 @ Westgate. The estimate of vehicle movements for each event includes all movements since the preceding rainfall event, ignoring showers of up to 1 mm rainfall depth (which typically fail to generate runoff). The vehicle movements preceding and during each event are summed to give the total vehicle movements associated with all events sampled (Σ VM).

The length of road (L) in metres discharging to each respective sampling point was measured in the field and/or from aerial photographs. The estimated vehicle emission factor for any contaminant is then given by:

$$VEF = (\Sigma\ CL / \Sigma\ VM) \times (1000 / L) \quad \text{in units of mg/veh/km} \quad (1)$$

Table 3 lists the VEFs for total copper and total zinc estimated by this method, along with the range of VEFs estimated for each individual event. The VEF estimates from combined event data for the SH18 @ Westgate site are slightly higher than those for the SH1 @ Redvale. While this ranking is in accordance with levels of congestion at the two sites (See Table 1), the difference in the VEFs estimated for each of the two sites is small. The estimates for copper and zinc at both sites are similar to upper mid-range estimates previously estimated from New Zealand data (Moores and Pattinson, 2008).

There are two important areas of uncertainty to note in relation to these estimates. Firstly, VEFs estimated from individual event data vary by an order of magnitude (see Table 3). Clearly, there is substantial variation in the relationship between the accumulation of contaminants on road surfaces and their removal in road runoff: contaminants do not simply accumulate and wash-off at a constant rate (Butler and

Davies, 2004). Moores and Pattinson (2008) reported that rainfall intensity and frequency are likely to be key factors driving these variations. Frequent heavy rainfall of long duration promotes the wash off of a higher proportion of contaminants than infrequent light rain of short duration because, in the latter case, a greater proportion of road sediments are able to be removed by wind between rainfall events. Previous studies have found a strong correlation between the length of antecedent dry period and loads of contaminants removed during runoff events (Hewitt & Rashed, 1992). Other authors, for instance Ellis *et al.* (1986), report that runoff volume and storm duration are of greater importance than antecedent conditions.

These inter-event variations in contaminant VEFs are important: they mean that VEF estimates derived from only a small number of sampling events are subject to considerable uncertainty. Recognising this uncertainty, further work is underway to estimate VEFs based on modeled loads of copper and zinc during all runoff events over the period of runoff monitoring, not just the events sampled. This work is described further in Section 4.

*Table 3: Estimates of VEFs for copper and zinc, SH1 @ Redvale and SH18 @ Westgate*

| Site name and location | VEF – total copper (mg/veh/km) | | VEF – total zinc (mg/veh/km) | |
|---|---|---|---|---|
| | all events combined | range, individual events | all events combined | range, individual events |
| SH 1 (Northern motorway) @ Redvale | 0.08 | 0.03 – 1.1 | 0.4 | 0.1 – 8.4 |
| SH 18 @ Westgate | 0.09 | 0.02 – 0.4 | 0.5 | 0.1 – 2.0 |

Secondly, the VEF estimates presented in Table 3 are based on runoff samples collected at pipe outlets downstream of roadside catchpits. Metal concentrations in these samples (and hence loads calculated from these concentrations) are likely to be reduced from those in untreated road runoff. Based on previous studies in New Zealand Timperley and Skeen (2009) estimate that catchpits remove 20% of TSS. Estimates of removal rates of total zinc and total copper are 11% and 15% respectively (*pers.comm*, M.Timperley, 2009). Semadeni-Davies (2008) has developed performance rules for catchpits as part of the development of a Catchment Contaminant Annual Load Model (C-CALM). These rules allow catchpit performance to vary with the particle size distribution of sediments conveyed in runoff. TSS is predicted to be reduced by around 10% at best, and metals by less than this. A current study by NIWA for ARC is collecting samples of road runoff and catchpit sediments at a site on Richardson Road, Auckland City in order to provide further experimental data on which to refine estimates of catchpit treatment efficiency. In the interim, the VEF values presented in Table 3 should be seen as underestimating the true (untreated) VEFs by around 10-15%.

## 3.3 POND PERFORMANCE

The performance of the pond at the SH1 @ Redvale site has been evaluated by comparing loads of copper, zinc and TSS (the most commonly used indicator of treatment device performance) discharged into and out of the pond during 6 sampling events. The results are summarized in Table 4.

*Table 4: Estimates of percentage removal of TSS, copper and zinc, SH1 @ Redvale pond*

| | particulate | | dissolved | | total | |
|---|---|---|---|---|---|---|
| | all events combined | range, individual events | all events combined | range, individual events | all events combined | range, individual events |
| TSS | NA | NA | NA | NA | 70 % | 26 – 82 % |
| Cu | 62 % | 19 – 78 % | -20 % | -148 – 15 % | 40 % | 16 – 61 % |
| Zn | 76 % | 32 – 89 % | -5 % | -132 – 29 % | 67 % | 19 – 82 % |

The pond removed 70%, 76% and 62% of incoming TSS, particulate zinc and particulate copper over the 6 events sampled. The removal efficiency of total metals was lower than for particulates at 67% for total zinc and 40% for total copper. The poorer performance for copper removal reflects the relative importance of the dissolved phase of this metal, with over half of the copper load discharged from the pond in the dissolved phase compared to around a third of the zinc load. The wetland was ineffective at removing dissolved metals: loads of dissolved metals discharged from the wetland were slightly greater than those entering the pond in road runoff overall, and by more than double in one event. This result is interesting in itself: emergent aquatic vegetation is well established in pond (see Figure 1) and it might be expected that this offers potential for some bio-uptake of dissolved metals.

The results are similar to the results of previous sampling of an un-vegetated pond located adjacent to Silverdale interchange on the same motorway (Moores *et al.*, 2008) Particulate metal loads at that pond were reduced by 69% and 60% for zinc and copper respectively, while total zinc and copper were found to be reduced by 55% and 50%, respectively. Around half of both the zinc and copper load discharged from the Silverdale pond were in the dissolved phase and, again, during some events dissolved metal loads discharged from the pond were grater than those in the incoming road runoff.

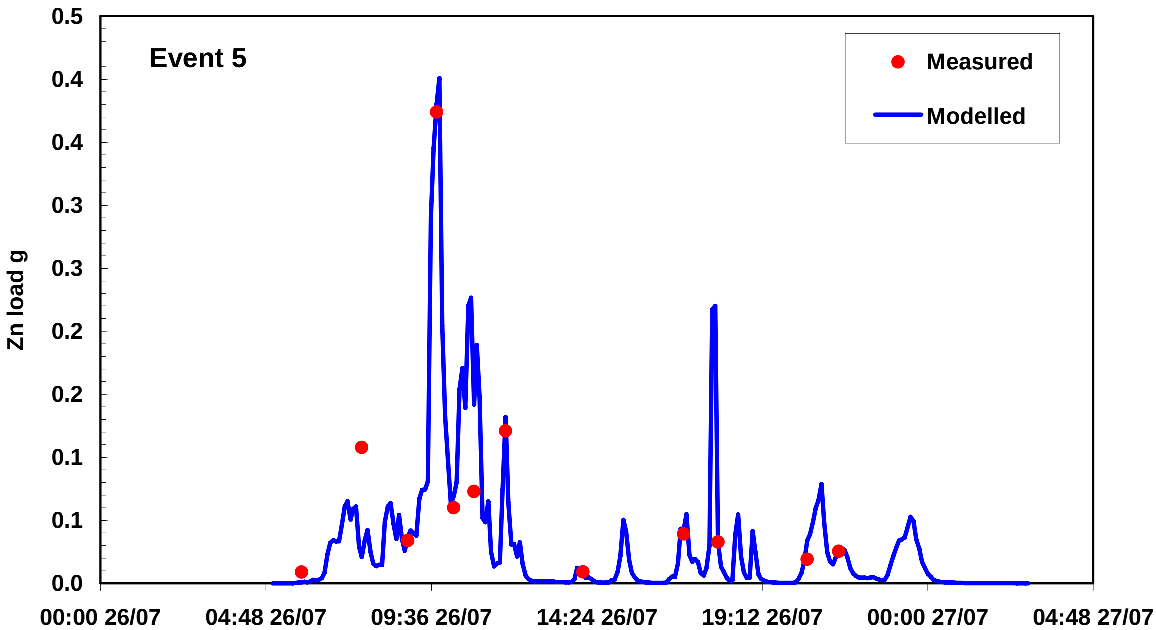
These results indicate that while these ponds are able to achieve close to the TP10 target removal of 75% of TSS (ARC, 2003), this is not the case for copper and zinc. The effectiveness of such devices is evidently limited in situations where substantial proportion of the total metal load is in the dissolved phase. Given the different characteristics of the two ponds described here, their ineffectiveness for the removal of dissolved metals warrants further investigation.

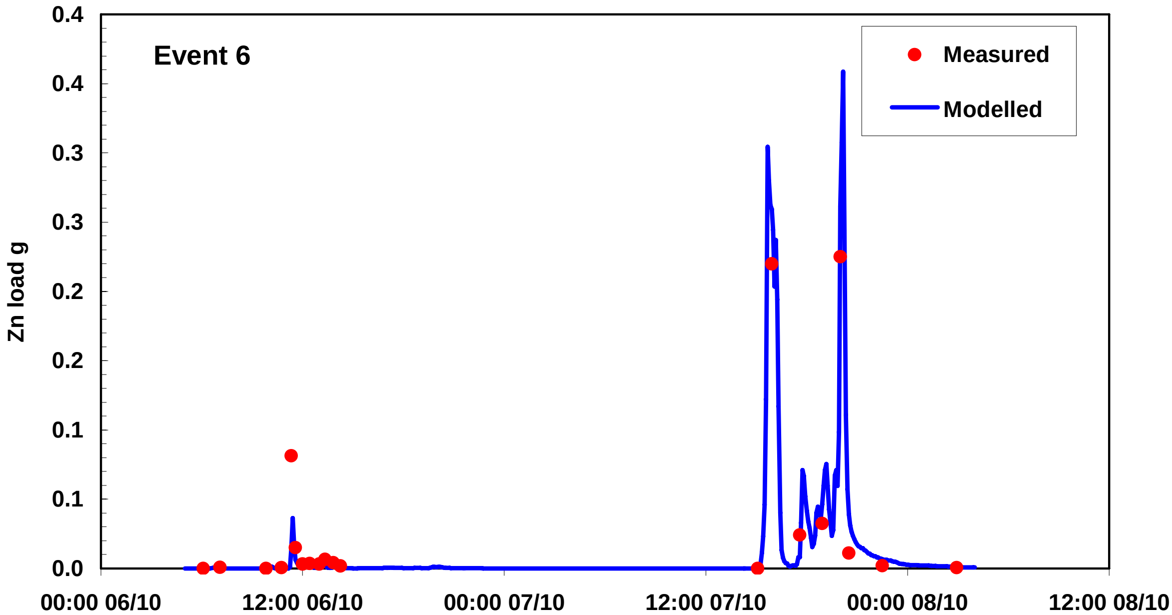
# 4 FURTHER WORK

Sampling at two of the four sites remains in progress at the time of writing. On completion of sampling at those two sites, estimates of copper and zinc VEFs will be made for a relatively free-flowing rural highway and a major urban motorway. Metal loads prior to and following treatment by a vegetated swale and before and after conveyance along an open roadside drain will be compared.

In response to the issue of uncertainty in VEF estimates derived from a small number of sampling events (refer to Section 3.2) a more sophisticated approach to load (and VEF) estimation is being pursued. This approach involves modelling the accumulation and wash-off of contaminants over the entire period of flow measurement, by application of the StormQual model applied previously for estimating loads in road runoff by Timperley *et al*. (2003 and 2005). In this approach, modeled loads are fitted to those derived from measured sample concentrations and runoff volumes by calibrating four parameters which control the modeled rate of contaminant accumulation and wash-off. Figure 3 provides an example of the fit between modeled and 'measured' loads during two storm events sampled at the SH18 @ Westgate site. Providing that a good fit can be achieved, loads estimated over the period of record are likely to be a better estimate of the long term contaminant load discharged from the road than those derived from the measurements taken during a small number of events alone.

*Figure 2: Zinc loads derived from measured runoff volumes and sample concentrations compared to loads predicted from contaminant accumulation / wash-off modelling, SH18 @ Westgate, 26-27 July 2008.*




T ... re 3 s ... eled loads are 0.065 and 0.4 for total copper and zinc, respectively, compared to estimates of 0.09 and 0.5 derived from the event data alone (refer Table 3). The same approach will be adopted for the estimation of loads, VEFs and treatment efficiencies from the remaining data sets.

# 5 SUMMARY

A programme of road runoff sampling at four sites in the Auckland region is investigating variations in VEFs of copper and zinc in relation to traffic characteristics. Based on sampling completed to date, copper and zinc VEFs are higher at a congested arterial road than at a part of the Northern Motorway subject to more freely flowing traffic, although the differences between the two sets of VEFs are relatively small. An important source of uncertainty associated with these estimates is the fact that they have been derived from sampling during a small number of events. Contaminant accumulation and wash-off modelling is in progress to estimate loads over the entire period of the runoff record with the aim of reducing this uncertainty.

Sampling of runoff at a wetland inlet and outlet at one site has allowed the reduction in copper and zinc loads due to this device to be estimated. The removal efficiency of total metals was lower than for particulate metals alone, especially for copper. This reflects the relative importance of the dissolved phase of the two metals, with over half of the copper load discharged from the pond in the dissolved phase compared to around a third of the zinc load.

Sampling at two of the four sites remains in progress at the time of writing. On completion of sampling at those two sites, estimates of copper and zinc VEFs will be made for a relatively freely-flowing rural highway and a major urban motorway. Samples are also being collected at these sites of runoff discharged from a vegetated swale and an open roadside drain, allowing assessment of the effectiveness of these treatment and drainage systems for contaminant removal.

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