Enhancing the control of contaminants from New Zealand's roads: results of a road runoff sampling programme

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Abbreviations and acronyms

ARC	Auckland Regional Council
EMC	event mean concentration
FRST	Foundation for Science, Research and Technology
LoS	level of service
LRF	load-reduction factor
mg/veh/km	milligrams per vehicle per kilometre
NIWA	National Institute of Water & Atmospheric Research
NZTA	New Zealand Transport Agency
PAHs	polycyclic aromatic hydrocarbons
TPHs	total petroleum hydrocarbons
TSS	total suspended solids
VCLM	vehicle contaminant load model
VEF	vehicle emission factor
VPD	vehicles per day

Contents

Executive summary

Overview

Road runoff contains the metals copper and zinc, and a range of hydrocarbon compounds. These contaminants can be harmful when discharged to aquatic receiving environments. Roading and stormwater managers have expressed the need for guidance in relation to the identification of roads, or parts of roads, that generate these contaminants in sufficient quantities to require stormwater treatment.

This research, funded by the New Zealand Transport Agency (NZTA) and Auckland Regional Council (ARC), sought to address this need. The objective of this study, which was conducted in the Auckland Region from February 2008 to June 2009, was to enhance the control of contaminants on New Zealand's roads by quantifying and providing guidance on:

1 representative contaminant loads for different types of road

2 the effectiveness of existing contaminant control measures.

The aim was to provide roading managers with an improved ability to prioritise road runoff treatment needs and to select appropriate contaminant control measures.

In order to meet these goals, the study has firstly, investigated and provided guidance in relation to Vehicle Emission Factors (VEFs) for copper and zinc in road runoff. This report provides guideline VEF estimates for copper and zinc in untreated road runoff for two categories of road: roads subject to normal traffic flows, and congested roads/intersections.

Secondly, the research has investigated and provided guidance on the performance of three systems for treating road runoff: a stormwater pond, a grass swale and a roadside drainage channel. While the latter drainage system is not designed or constructed specifically for runoff treatment, it is common to roads throughout New Zealand and on that basis, investigation of its potential to treat road runoff was warranted. Guideline load-reduction factors (LRFs) are provided that can be used to estimate loads of copper and zinc discharged to aquatic receiving environments from each of these three types of treatment systems.

Review of previous studies

The reporting of contaminant VEF estimates in the international literature is limited. However, several previous studies in New Zealand have estimated VEFs and others have yielded data from which it was possible to derive VEF estimates for copper and zinc. These estimates appear to fall into two groups, defined on the basis of traffic behaviour rather than traffic volumes. Relatively high VEF estimates (greater than, or equal to, 0.12mg/veh/km for copper and 0.87mg/veh/km for zinc) largely coincide with roads on which brake and tyre wear are likely to be greater than elsewhere. Low- to mid-range estimates (less than 0.086mg/veh/km for copper and 0.45mg/veh/km for zinc) largely coincide with roads on which traffic may be generally expected to move freely.

The international literature covers a range of devices that have been employed to treat stormwater, with two broad categories common for the treatment of road runoff: vegetated filter systems, such as swales and buffer strips, and detention systems such as ponds and wetlands. The performance of these types of device is reported to vary widely. While few previous studies have assessed performance

against treatment targets, the results of many of them indicate that vegetated systems, ponds and wetlands can be considered effective contaminant control measures when compared against water quality trigger values or criteria. Previous studies of the effectiveness of ponds and swales for treating road runoff in New Zealand are limited, but show a similar range of performance to that reported internationally.

Field programme

For this research, a field programme, comprising the measurement of road runoff volume and the collection and analysis of runoff samples, was conducted at four sites. Sites were selected on the basis of traffic characteristics, road drainage characteristics and the nature of the stormwater treatment systems present. The sites were: SH18 @ Westgate (most congested, no treatment); SH1 Northern Motorway @ Northcote (congested, treatment by grass swales); SH16 @ Huapai (freely flowing traffic, drained by a roadside drainage channel); and SH1 Northern Motorway @ Redvale (freely flowing traffic, treatment by a pond).

The study sites were instrumented to measure and record water levels for the estimation of discharge (flow) and to collect water samples during storm events. Water samples were collected during storm events by automatic water samplers installed at points of discharge from the road and treatment devices (where present) at each site. Samples were analysed for total suspended solids (TSS), particulate and dissolved copper and zinc, and total petroleum hydrocarbons (TPHs).

Eight rainfall events were sampled at each of the Redvale and Huapai sites, seven at Northcote and six at Westgate. Rainfall depths during the events sampled varied from 7 to 75mm, while the duration of sampling events ranged from 3 to 83 hours. The majority of sampling events followed several days of dry weather, with the longest being a 20-day dry period.

Concentrations of particulate and total copper and zinc in water samples of untreated runoff were highest at Westgate, followed by Huapai and Redvale, while concentrations of TSS fell within a similar range at all three sites. Dry-weight copper and zinc concentrations in road sediments were also higher at Westgate than at these other two sites, which is in keeping with the expectation of higher rates of brake pad and tyre wear at the more congested site.

Concentrations of TSS, particulate metals and total metals were much lower at Northcote than at any of the other three sites. In contrast, dissolved metal concentrations at Northcote were relatively high, and more copper and zinc was in the dissolved phase than the particulate phase at this site, while the reverse was true at the other three sites. The most likely reason for these results is the resealing of the road surface at this location with open-graded porous asphalt (OGPA) in early 2008. OGPA is relatively permeable when new and allows road sediments (and associated particulate metals) to be deposited in voids in the road surface.

Concentrations of TSS and particulate and total copper and zinc were markedly lower in samples of treated runoff than in untreated runoff samples collected at Huapai and Redvale. At Northcote, TSS concentrations were higher in treated runoff samples than in untreated samples, but dissolved metal concentrations were lower, and this resulted in lower total metal concentrations in treated runoff than in untreated runoff samples at this site.

TPHs were measured above the detection limit in only eight samples, seven of which were collected at Westgate and one at Huapai. The absence of TPHs in water samples does not appear to be an artefact of sampling methodology, but rather reflects the generally free movement of traffic at these sites,

limiting the potential for hydrocarbon spills and leaks. As a result of the absence of detectable concentrations of TPHs in the majority of samples, no attempt was made to estimate TPH loads or the efficiency of their removal by road runoff treatment.

Estimation of VEFs

VEFs for copper and zinc were calculated from the data collected at the four sampling sites by two different methods, depending on the way in which the contaminant loads had been estimated.

'Event-based' estimates were calculated from the measured runoff volumes and sample contaminant concentrations associated with each storm event that was sampled. This method is subject to considerable uncertainty, particularly in terms of the sensitivity of the estimates to the characteristics of the storm events sampled.

The second method sought to reduce this uncertainty by deriving estimates from the entire period of flow record at each site through the application of a contaminant accumulation/wash-off model (STORMQUAL) fitted to the measured data.

VEF estimates produced by the event-based method were generally higher than those resulting from the modelling of contaminant loads. This indicates that the events sampled were relatively effective at removing contaminants from the road. Less-effective events, such as those characterised by low rainfall depths and intensities, were under-represented in the sampling programme. The modelled VEF estimates were less sensitive to the characteristics of individual storm events, and so these are likely to be a better estimate of the long-term contaminant load discharged from the road at each site.

Modelled copper and zinc VEFs were highest at Westgate, followed by Huapai, Redvale and Northcote. The ranking of the first three sites was consistent with expectations in relation to levels of congestion, while the low VEF estimates for Northcote reflected the relatively low metal concentrations in runoff samples collected at this site. A source of uncertainty in the VEF estimates for Westgate and Redvale is the fact that runoff samples at these sites were collected at pipe outlets discharging from roadside catchpits. As the catchpits retain road sediments and associated particulate metals, the VEFs for these sites may be underestimates of the true (pre-catchpit) VEFs by a value in the range 5–15%.

Allowing for an upwards adjustment of 10% in the VEF estimates for these two sites, the modelled VEF estimates for each of the sites were:

Site	Copper (mg/veh/km)	Zinc (mg/veh/km)
SH18 @ Westgate	0.08	0.5
SH1 @ Northcote	0.011	0.04
SH16 @ Huapai	0.054	0.28
SH1 @ Redvale	0.039	0.28

These estimates fell within the range of low- to mid-range estimates from previous New Zealand studies, with the exception of the zinc VEF for Westgate (slightly higher), and both copper and zinc for Northcote (lower). Both copper and zinc VEFs for Westgate were comparable with previous upper mid-range estimates, but were markedly lower than certain other previous estimates. Taking account of the different sources and degrees of uncertainty associated with several of the previous estimates, the VEF estimates for Westgate appear to provide a reasonable basis for arriving at representative VEFs for sites with relatively high brake and tyre wear, while those for Huapai and Redvale can be considered representative of roads subject to 'normal' driving conditions.

The following guideline VEFs are provided for the estimation of loads of copper and zinc discharged in untreated runoff from New Zealand's roads.

Traffic characteristics	Total copper (mg/veh/km)	Total zinc (mg/veh/km)
Normal traffic	0.047	0.28
Congested traffic & intersections	0.095	0.62

Performance of road runoff treatment

The performance of road runoff treatment at the Northcote, Huapai and Redvale sites was assessed in terms of the efficiency of contaminant load removal and by comparison with water quality trigger values and criteria. The roadside drainage channel at Huapai was most effective at TSS removal, with the total TSS load discharged from the drain 96% lower than at the road edge. Similarly high removal rates of particulate and total copper and zinc were achieved at this site. The results indicate that, while not specifically designed or constructed as systems for the removal of contaminants, these drainage systems do retain TSS, copper and zinc discharged in road runoff. Where such systems are present (most rural roads), the estimation of loads discharged to receiving water bodies should take account of their contaminant retention capacity.

The vegetated swale at Northcote was less effective than the Huapai drainage channel at reducing TSS loads, but removed more than 90% of copper and zinc, including high removal rates of both metals in the dissolved phase. The removal rates of total copper and total zinc loads were similar to those for the most effective vegetative buffers and swales reported in the international literature.

The performance of the stormwater pond at the Redvale site was relatively poor, removing 71% of TSS, 40% of total copper and 67% of total zinc. The low removal efficiency for copper reflects the ineffectiveness of the pond at removing dissolved metals and the relative importance at this site of copper in the dissolved phase, compared with zinc.

The concentrations of total and dissolved copper in the treated runoff samples from all three sites exceeded minimum ANZECC guideline values for a 95% level of protection. Whether or not these copper concentrations would exceed ANZECC trigger values once discharged to a receiving water body would be dependent on the hardness of the water and the extent of dilution. Concentrations of total zinc in treated runoff samples also exceeded the ANZECC trigger values for a 95% level of protection for waters of low hardness, but not for waters of moderate to extreme hardness. Dissolved zinc concentrations were mostly below ANZECC guideline trigger values. While concentrations of dissolved copper and zinc in treated runoff samples were generally below USEPA water quality criteria, total copper concentrations in around a quarter to half the samples collected at each site exceeded the USEPA Criterion Continuous Concentration for this metal.

The following guideline LRFs are provided as a basis for estimating loads of copper and zinc discharged following treatment by swales, roadside drainage channels and ponds.

Treatment type		Load-reduction factor		
		TSS	Total copper	Total zinc
Vegetated swales and open roadside drains		0.6	0.8	0.8
Stormwater ponds	More vegetation ↕ Less vegetation	0.7 ↕ 0.5	0.5	0.65 ↕ 0.55

Application of the results of this study

The results of this study can be used to provide input data for relatively detailed assessments of the effects of road runoff discharges using relatively sophisticated tools that have been developed elsewhere. Alternatively, roading and stormwater managers can apply the four-step approach presented here in order to undertake a 'first cut' at identifying those parts of a road network most in need of treatment or requiring further, more detailed, investigations.

- **Step 1** of the method involves using the VEFs recommended in this report to determine the loads of copper and zinc in untreated road runoff.
- **Step 2** then involves estimating the copper and zinc loads discharged following treatment of road runoff, by application of the recommended LRFs.
- In **Step 3**, the relative importance of contaminant discharges from different parts of the road network is assessed with reference to existing information on the values of the receiving environment. Where there is little or no existing information on these values, the comparison of loads can be used to prioritise those areas where investigations to gather further information should focus.
- Step 4 simply involves iteration of steps 2 and 3 to compare the extent to which alternative treatment measures will achieve the desired environmental outcome.

Abstract

This study provides guidance on Vehicle Emission Factors (VEFs) for loads of copper and zinc discharged in road runoff, and the performance of stormwater treatment devices for removing these metals and total suspended sediments (TSS).

Between February 2008 and June 2009, a field programme comprising the measurement of road runoff volumes and the collection and analysis of runoff samples was conducted at four sites, of differing traffic characteristics, in the Auckland Region. Concentrations of copper and zinc were higher at a congested site than at two sites at which traffic generally moved freely. Substantially lower TSS and metal concentrations were measured at a moderately congested site, counter to expectations and possibly reflecting the recent resealing of the road surface at this location with open-graded porous asphalt (OGPA). VEFs estimated using a contaminant accumulation/wash-off model provided the basis for determining a set of guideline copper and zinc VEF values for (1) congested roads and intersections and (2) 'normal' roads.

The performances of a stormwater pond, a grass swale and a roadside drainage channel for treating road runoff were assessed in terms of contaminant removal efficiencies and comparisons of treated runoff quality with water quality guideline values and criteria. The roadside drainage channel was the most effective method and the pond was the least, because of its ineffectiveness at removing dissolved metals. The results provided a basis for determining a set of guideline load-reduction factors (LRFs) for the removal of contaminants by these types of system.

1 Introduction

1.1 Background

Metal and hydrocarbon contaminants derived from vehicle component wear and emissions are conveyed via road drainage systems to receiving water bodies. The loads of these contaminants discharged to the receiving environment vary with a number of factors, including: vehicle numbers, vehicle types, traffic behaviour and the design of road drainage systems. Loads can be expected to be highest on busy roads carrying a high proportion of heavy traffic; in braking and acceleration zones; and where road runoff is 'untreated' on its way to the point of discharge from the road corridor.

Through the Road Controlling Authorities (RCA) Forum Stormwater Group, roading managers have expressed concern at the uncertainty surrounding road runoff treatment requirements. In particular, some authorities fear that the treatment requirements appropriate to busy urban roads may, in the future, be imposed elsewhere, such as through consent processes, without evidence of any real need for this. Results from an RCA Forum survey (Knight and Newman 2006) also show that roading managers currently have little information as to the extent to which stormwater treatment devices that have been installed are achieving the desired results.

Through its industry-generated research funding programme, the New Zealand Transport Agency (NZTA) funded the National Institute of Water & Atmospheric Research (NIWA) to undertake this programme of research, aiming to build on existing information and improve the ability to:

- identify which parts of the New Zealand road network are likely to require some form of stormwater contaminant control
- quantify the effectiveness of existing stormwater contaminant controls
- give guidance on appropriate control measures, where they are required.

This project, which was undertaken in the Auckland Region between February 2008 and June 2009, included:

- a review of previous work
- a field programme to characterise variations in road runoff quantity
- an evaluation of this data
- reporting the study findings (this document).

Additional cofunding for the project was provided by Auckland Regional Council (ARC).

1.2 Key concepts

1.2.1 Contaminants of interest

The contaminants of particular concern in highway runoff include a number of metals and a range of hydrocarbon compounds. This study focuses on the metals copper and zinc, and on Total Petroleum Hydrocarbons (TPHs).

Copper and zinc are important constituents in brake linings and tyres respectively, and both are classified as priority pollutant elements 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 the wetting and drying of the road surface, particles of these metals pass into solution and/or bind with other particulate matter deposited on the road (Macaskill and Williamson 1994). Previous studies have reported a wide range of results on the ratio of dissolved to particulate zinc and copper in highway runoff, with 25–71% of total copper and 24–95% of total zinc in the dissolved form (Marsalek et al 1997; Preciado and Li 2005; Sansalone and Buchberger 1997; Timperley et al 2005). The phase of these metals is of particular importance for the effectiveness of contaminant control, because the more commonly employed treatment systems function through removal of suspended solids.

A large number of hydrocarbon compounds are emitted to the road surface from oil, grease and fuel leakages and spills, and from exhaust emissions. These hydrocarbons may become adsorbed on to road sediments, be conveyed in dissolved form, or float on top of runoff discharging from the road (Williamson 1993). The analysis of road runoff for total petroleum hydrocarbons (TPHs) provides a non-specific but overall measure of all hydrocarbon compounds present.

Polycyclic aromatic hydrocarbons (PAHs) are a subgroup of TPHs comprising mainly toxic (including some carcinogenic) compounds that are present in vehicle oils and fuels. They are emitted from both tailpipe and non-tailpipe sources (Kennedy et al 2002). Most are poorly soluble in water and so are transported in the particulate matter conveyed by road runoff (Williamson 1993). While this project sought to characterise hydrocarbon contamination of road runoff solely in terms of TPHs, the review of previous studies (chapter 2) records values of PAHs reported by others in order to provide a context on the scope of previous work to characterise road runoff quality.

1.2.2 Vehicle emission factors

Vehicle emission factors (VEFs) are a means of characterising the load of a contaminant conveyed in road runoff[1]. They are expressed in terms of the mass of the contaminant per vehicle per unit of road length travelled. This report adopts the unit 'milligrams per vehicle per kilometre' (mg/veh/km).

The estimation of a VEF requires information on the load of the contaminant discharged from a known length of road carrying a known volume of traffic. In this study, contaminant loads were estimated from the measurement of runoff volumes and contaminant concentrations in runoff samples.

1 Vehicle emission factors are also used elsewhere to characterise vehicle emissions to air. However, the VEFs presented here are a measure of the contaminant load conveyed solely in road runoff.

Information on the number of vehicles contributing to the contaminant load was gathered from traffic count data. This data was used to estimate VEFs for each location studied.

VEFs estimated at a given location may be adopted as a representative value from which contaminant loads discharged elsewhere in the roading network can be estimated. This approach relies on transferability of VEFs from one location to another. This is valid providing that, on average, the quantities of contaminants discharged from the road per individual vehicle are similar. For example, a single VEF for zinc emissions could be applied to estimate zinc loads discharged from two highways, one conveying 100,000 vehicles per day (vpd) and the other conveying 50,000vpd, provided that they were similar in all other respects. Whilst the total load from the former road would be expected to be twice that of the latter, the load per vehicle would be expected to be the same, all other things being equal.

However, there are a number of factors that influence the rate at which vehicles emit contaminants, and VEFs can be expected to vary accordingly. The emission of zinc and copper, for instance, might be expected to be higher in zones of heavy tyre wear and frequent braking. It follows that higher zinc and copper VEFs may occur at intersections rather than on straight sections of highway. One of the aims of this study was to investigate the extent to which such expectations are supported by field data.

1.2.3 Treatment performance

Stormwater treatment involves the conveyance of water through a device designed to remove contaminants prior to the point of discharge to a natural water body. Most forms of stormwater treatment function through the removal of solids, involving one or more of the following three processes: physical interception of solids (filtration); infiltration of runoff; or a reduction in the velocity of runoff resulting in the deposition of suspended sediments. Systems for treatment of road runoff employ all of the above methods: vegetated systems, such as swales and buffer strips, remove contaminants by filtration and infiltration; catchpits and ponds provide for settlement of solids as a result of a reduction in velocity.

The effectiveness of treatment devices is commonly assessed in terms of the efficiency of contaminant removal. This involves comparing the concentrations or loads of a contaminant entering the device with those leaving, and is typically reported as a percentage removal efficiency. Alternatively, efficiency can be expressed as the fraction of contaminant removed, in which case it is often termed a load-reduction factor (LRF).

A second approach for evaluating the performance of a treatment device involves assessing the extent to which discharges of contaminants from the device are (or could potentially be) harmful to the aquatic receiving environment. This can involve comparison of contaminant concentrations in effluent (water discharged at the device outlet), or in water and sediment samples taken from the receiving water body, against water and sediment quality guidelines or criteria.

1.3 Objectives

The objective of this research programme was to enhance the control of contaminants on New Zealand's roads by quantifying and providing guidance on:

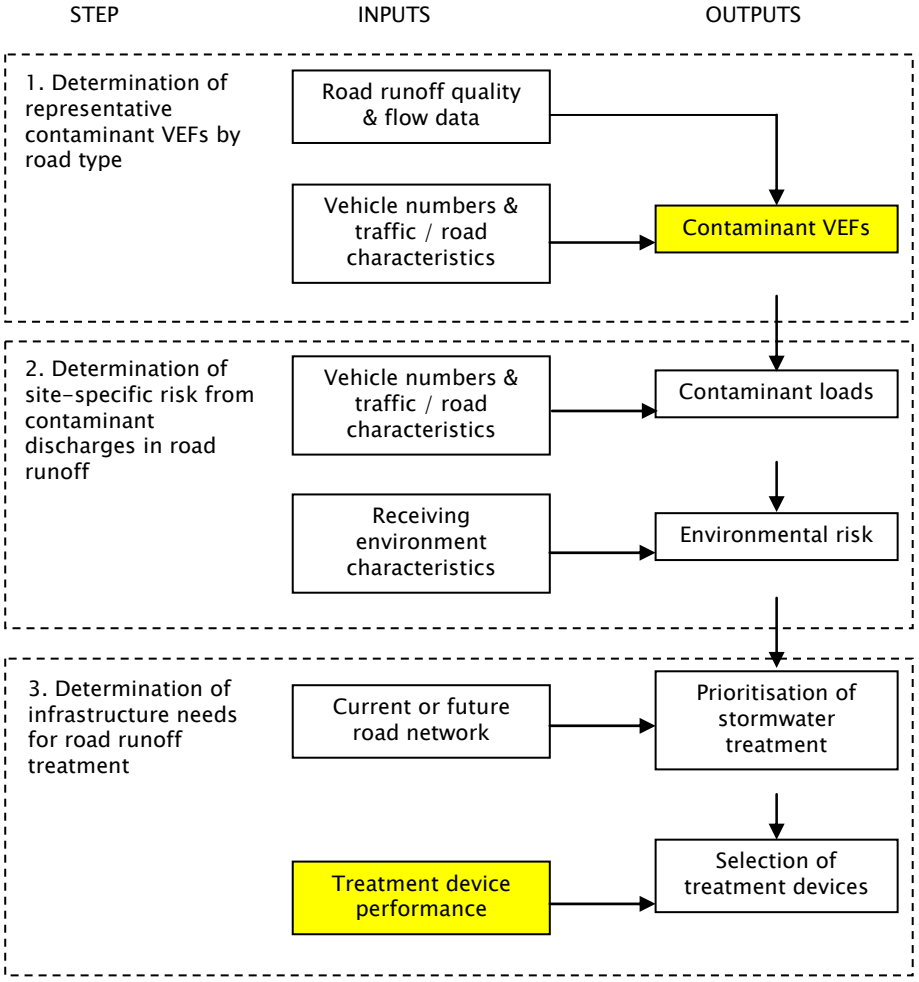
1 representative contaminant loads for different types of road

2 the effectiveness of existing contaminant control measures.

The aim was to provide roading managers with an improved ability to prioritise road runoff treatment needs and to select appropriate contaminant control measures.

Figure 1.1 provides an overview of information requirements and the way in which this information needs to be evaluated in order to prioritise the control of road runoff contaminants discharged to aquatic receiving environments. It provides the context within which the objectives of this study were set.

Figure 1.1 Overview of information requirements and evaluation process for determining contaminant control requirements in relation to road runoff. Yellow text boxes indicate the areas relating to the objectives of this study.



The process of information gathering and evaluation involves three sequential stages:

1 *Characterising contaminant discharges – determination of representative contaminant VEFs by road type*:
It is clearly impractical to measure contaminant loads discharged from every part of the road network. As noted in section 1.2.2, a more realistic approach is to attempt to determine representative values (in the form of VEFs) that can be used to estimate contaminant loads throughout the road network on the basis of road and traffic characteristics. The determination of VEFs can be by measurement, modelling or a combination of the two. As noted above, the

determination of representative contaminant VEFs in road runoff was the first objective of this study.

2 *Applying the information – determination of site-specific risk from contaminant discharges in road runoff*:
Given information on traffic volumes and road characteristics, contaminant loads discharged at any point in a road network can be estimated using the VEFs from (1) above. The extent to which the discharge of these loads represent a problem then needs to be evaluated. This involves an assessment of the values of the aquatic receiving environment and an evaluation of how these values may be affected as a result of the discharge of contaminants from each point in the road network.

Gardiner and Armstrong (2007) developed a Geographic Information System (GIS)-based screening tool that enables a risk-based evaluation of the effects of road-derived contaminant discharges in relation to the sensitivity of receiving environments, with the method demonstrated for Porirua Harbour in the Wellington Region.

Moores et al (2009a) described the linking of models that firstly, predict the generation of contaminant loads from urban areas (including roads) and secondly, simulate their distribution and accumulation in receiving environments. These methods have been applied to predict the future accumulation of copper and zinc in Auckland's Waitemata and Manukau Harbours.

It was not an objective of this study to undertake any assessments of the values of receiving environments, nor to develop a sophisticated tool such as those described above. However, this study should be seen as being complementary to these previous studies, in that the results presented here provide input data that can be used to improve on contaminant loads estimated by these (and other) methods.

3 *Prioritising the response – determination of infrastructure needs for stormwater treatment*:
From an assessment of the type described in (2), roading managers can compare the contaminant loads generated in different parts of a road network and identify those areas in which contaminant discharges may result in the greatest threat to receiving environments. This then provides a basis for identifying priority areas for installing or improving runoff controls (ie stormwater treatment devices) and assessing the optimum configuration of devices to meet treatment targets. This assessment requires information on the effectiveness of the types of treatment devices under consideration.

As noted above, investigation of the effectiveness of devices commonly employed to treat contaminants in road runoff was the second objective of this study.

1.4 Study overview and outputs

In order to meet objective 1, the first step was to complete a review of previous international and New Zealand information. This informed the design of the study field programme, which comprised the measurement of road runoff and collection, and analysis of runoff samples, at four locations. The locations were selected with the aim of characterising road runoff quality in relation to differences in traffic behaviour.

Estimates of copper and zinc VEFs were made from the results of the field programme, using two different approaches. These estimates provide the basis for a set of guideline VEF values that can be used to estimate loads of copper and zinc in untreated road runoff at locations elsewhere in the New Zealand road network.

As part of the selection of road runoff sampling locations, sites were chosen that allowed sampling of both untreated and treated runoff. The sampling sites included three different types of treatment system: a wet pond, a grass swale and a roadside drainage channel. While the latter was not designed or constructed specifically for runoff treatment, it represents a drainage system that is common throughout New Zealand, and an assessment of its influence on contaminant loads discharged to the receiving environment was warranted solely on that basis. Estimates of the efficiency of each of these systems were made through comparing contaminant loads before and after treatment. These estimates provide the basis for a set of guideline LRF values that can be used to estimate treated loads of copper and zinc generated at locations elsewhere in the New Zealand road network. Treatment performance was also evaluated by comparison of sample effluent quality with guideline values.

In summary, and in accordance with the study objectives, the key output of this research is the provision of the following guidance information for roading and stormwater managers:

1 recommended VEFs for the estimation of contaminant loads discharged in road runoff

2 recommended LRFs by which the contaminant loads in treated road runoff should be adjusted.

A relatively simple method by which these recommended values can be applied is described in section 6.3.1 of this report.

1.5 Structure of this report

Chapter 2 of this report describes previous estimates of contaminant VEFs in road runoff that have been reported in international and New Zealand literature, and presents additional estimates derived from unpublished data held by the authors. Potential sources of variation in VEF estimates are discussed.

Chapter 3 describes the study field programme, including the process by which sampling sites were selected, methods of runoff measurement, and methods of sample collection and analysis. Results for copper, zinc and TPH concentrations in the runoff are presented and differences in runoff quality between sites are discussed.

Chapter 4 presents two methods by which VEF estimates have been made and describes the results of each. The reasons for differences between the two sets of results are discussed and a comparison provided with the estimates from previous studies reported in chapter 2. A set of VEFs is recommended for the estimation of copper and zinc loads in untreated road runoff elsewhere in the New Zealand road network.

Chapter 5 describes the performance of the selected three treatment systems, evaluated in terms of percentage contaminant removal efficiency and by comparison with water quality guideline values. The results are also compared with the findings of previous studies reported in chapter 2. A set of LRFs is recommended for the estimation of copper and zinc loads in treated road runoff, using these devices, elsewhere in the New Zealand road network.

The key findings of the study and the ways in which they can be applied are summarised in chapter 6, including recommendations for further work associated with areas of uncertainty arising from the results described in chapters 3, 4 and 5.

2 Review of previous studies

2.1 Introduction

Several authors have previously reported on road runoff contaminants of concern for New Zealand's receiving environments. Macaskill and Williamson (1994) provided an assessment of contaminants and their impacts on water quality as part of a Ministry of Transport (MoT) study of the environmental effects of land transport. As part of a more recent suite of studies for MoT, Kennedy (2003) provided a comprehensive description of contaminants, their sources, transport and environmental effects. O'Riley et al (2002) and Kouvelis and Armstrong (2004) reviewed information on road runoff quality and its treatment as part of previous studies funded by one of the NZTA's predecessors, Transfund. More recently, the NZTA (as Land Transport New Zealand, LTNZ) funded research on the development of a methodology to identify sensitive receiving environments that may be at risk from contaminants in road runoff (Gardiner and Armstrong 2007).

To avoid replication of those studies, the focus of this review was on meeting the following three objectives:

1 To report on estimates of vehicle emission factors (VEFs) for selected contaminants in road runoff, both reported in published literature and derived from analysis of previously unpublished data held by NIWA, and to consider the applicability of these estimates for the New Zealand roading network.

2 To report on the effectiveness of selected stormwater treatment measures to control contaminants in road runoff, based on a review of the published literature and with reference to previously unpublished data held by NIWA.

3 Having met objectives (1) and (2), to identify critical knowledge gaps and determine the design of the field component of this study (see chapter 3).

2.2 Vehicle emission factors

2.2.1 Introduction

This section reports on estimates of VEFs for selected contaminants in road runoff and considers the applicability of these estimates to the New Zealand roading network. The review considers:

- results reported in the published literature
- VEFs estimated in this research from previously published data on road runoff quality
- estimates derived from relevant unpublished data held by NIWA.

These VEFs are compared below and their differences and the extent to which they may be considered representative are discussed.

2.2.2 International literature

Despite the existence of an extensive body of work to characterise road runoff worldwide, estimates of VEFs in the published literature are limited. Whilst some authors have provided loads and traffic volume data that allows calculation of VEFs (Harrison et al 1985; Hewitt and Rashed 1992; Legret and Pagotto 1999), of the international examples given in table 2.1, only Hoffman et al (1985) presented results in the form of a VEF.

Some authors have reported loads in units of contaminant mass discharged from a unit area of road surface per unit time period (eg Stotz 1987). Moy et al (2003) reported on contaminant event loads from six comprehensively monitored highway sites in southern England. Copper and zinc event loads were in the range 11.2–153.2mg/1000m^2 and 38.7–371.7mg/1000m^2 respectively. However, although vehicle numbers were given, these loads cannot be converted to VEFs without information on the average vehicle count per event, and on the width of road monitored, to allow conversion from road area to road length.

There is considerable variability in the VEF estimates reported by, or derived from, these sources (see table 2.1). Hoffman et al (1985) reported that zinc loads were high compared with other studies, and this is reflected in their high VEF for zinc, which is up to two orders of magnitude higher than other estimates presented in table 2.1.

Table 2.1 VEFs reported in, or estimated from, road runoff loads published in (a) international literature and (b) New Zealand literature

Source	Location	Traffic volume (vpd)	VEFs (mg/veh/km)			
			Cu	Zn	TPHs	PAHs
(a) International literature						
Hoffman et al 1985	Rhode Island, USA	101,500	1.0	22.0	24.0	0.058
Harrison et al 1985	M6, UK	30,000	0.33[a]	-	-	-
Hewitt & Rashed 1992	M6, UK	37,600	0.19[a]	-	-	0.005[a]
Legret & Pagotto 1999	Nantes, France	11,800	0.067[a]	0.56[a]	-	-
(b) New Zealand literature						
Macaskill & Williamson 1994	NZ, based on international literature	-	0.16	4.0	15.0	0.015
Kennedy & Gadd 2003	Waitakere City	65 to 38,178	0.017[b]	0.049[b]	-	0.004[b]
			0.16[c]	0.18[c]	-	0.014[c]
			0.5[d]	1.0[d]	-	0.059[d]
	NZ average fleet as modelled by VFEM-W	-	0.086[e]	1.2[e]	-	0.079[e]
			0.12[f]	2.3[f]	-	0.098[f]
Timperley et al 2005	Richardson Rd, Auckland	17,000	0.078	0.45	-	-
Gardiner & Armstrong 2007	VCLM source model prediction for Richardson Rd, Auckland	17,354	0.05[g]	0.23[g]	-	-
			0.15[h]	1.6[h]	-	-
Moores et al 2008	SH1 Northern Motorway, Silverdale	21,124	0.08	0.45	-	-
	SH1/SH17 interchange, Silverdale	33,500	0.13	0.87	-	-

Notes:

a) Calculated for this study from the authors' published loads and traffic volumes

b) Lower quartile

c) Median

d) Upper quartile

e) Normal driving conditions

f) Congested driving conditions

g) Freely flowing traffic and 'average' (ie partially filled) catchpit treatment (Timperley et al 2005)

h) Interrupted (more congested) flow and average catchpit treatment

2.2.3 New Zealand literature

Based on a review of international literature, Macaskill and Williamson (1994) estimated deposition rates of various contaminants to New Zealand roads[2]. Their estimates of VEFs for copper and PAHs are within the ranges reported in subsequent New Zealand-based studies, but that for zinc is much higher.

As part of a suite of studies for MoT, Kennedy and Gadd (2003) estimated VEFs based on road dust sampling at sites throughout Waitakere City. They reported median emission factors of 0.16mg/veh/km copper, 0.18mg/veh/km zinc and 0.014mg/veh/km PAHs on roads carrying traffic volumes in the range 65 to 38,178vpd.

More recently, Timperley et al (2005) estimated VEFs for copper and zinc respectively from sampling and subsequent modelling of contaminant discharges at Richardson Rd, an urban arterial road in Auckland City. The Richardson Rd study did not include investigation of the quantities of copper and zinc retained in roadside catchpits, although the authors made allowance for this in estimating VEFs, using the concept of an Auckland-wide 'average' catchpit, partially filled with sediment, which retained around 30% of particulate zinc and copper. A new sampling programme was completed in 2009 in the same location, in order to better estimate the influence of catchpits (Moores et al 2009b). That study also involved analysis of samples for TPHs to provide estimates of VEFs for this group of contaminants. Other than an estimate derived from a review of international data (Macaskill and Williamson 1994), there are no published VEF estimates of TPHs in runoff from New Zealand roads.

As part of a study (funded by the Foundation for Science, Research and Technology – FRST) into the dispersion of particulate metals emitted from vehicles, Moores et al (2008) estimated VEFs for copper and zinc based on runoff sampling at Auckland's Northern Motorway (SH1 @ Redvale) and at a nearby state highway interchange (SH1/17 near Silverdale). VEFs estimated for the interchange were 62% and 93% higher, for copper and zinc respectively, than VEFs for the open-road site[3]. The VEF estimates for the open-road site were very similar to those estimated by Timperley et al (2005) from the Richardson Rd study.

Other authors have estimated VEFs based on modelling of contaminant sources. Kennedy and Gadd (2003) reported emission factors estimated with the Vehicle Fleet Emissions Model – Water (VFEM-W)

2 These estimates are VEFs by another name, being expressed in the same units of mg/veh/km.

3 Note that sampling at the open-road site was continued as part of the present study (see section 3.2.2).

for both normal and congested driving conditions. The VFEM-W factors were derived from an assessment of existing data in the international literature on emissions from individual contaminant sources, such as brake wear, tyre wear and exhaust emissions (Kennedy et al 2002). Although the VFEM-W emission factors for copper are similar to those based on the road dust sampling programme, the VFEM-W emission factors for zinc and PAHs are comparatively high.

Gardiner and Armstrong (2007) developed a vehicle contaminant load model (VCLM) that allowed prediction of vehicle emissions to runoff for copper, zinc, TSS and PAHs, based on 11 attributes including road type, level of service[4], vehicle numbers, fleet composition, topography and type of treatment device. Model predictions using field data from the original Richardson Rd study, and assuming freely flowing traffic conditions, gave VEFs that are comparable with those estimated by Timperley et al (2005) from runoff sampling at the same site. Model predictions assuming interrupted traffic flow conditions are around two and four times higher, for copper and zinc respectively, than those estimated from runoff sampling. The authors commented that owing to considerable uncertainty in model source data, their predictions should be treated as 'order of magnitude' estimates (Gardiner and Armstrong 2007).

2.2.4 Estimation of VEFs from published contaminant concentrations

As noted in section 2.2.2, there has been a substantial international research effort to investigate and characterise contaminants in stormwater from roads. Authors commonly publish results in terms of contaminant event mean concentrations (EMCs), examples of which are summarised in table 2.2. There is substantial variation between studies, with average EMCs falling in the ranges 0.003–1.2g m^{-3}, 0.01–4.27g m^{-3} and 0.0016–18.2g m^{-3} for copper, zinc and PAHs respectively. As a number of authors have found (eg Driscoll et al 1990), these variations do not necessarily correspond with measures of road usage such as vehicle numbers. The factors that influence concentrations of contaminants in road runoff are discussed further in section 2.2.6 of this report.

EMCs alone do not provide a basis for the estimation of VEFs. For the calculation of VEFs, information is required on contaminant loads. In order to estimate loads, information on both EMCs and runoff volumes is required.

A number of New Zealand studies have reported concentrations of metals and TPHs in road runoff but have not reported loads or VEFs. However, it was possible to produce estimates of VEFs from this data because relevant information was readily available from other sources to allow estimates of annual runoff and traffic volumes to be made. In these circumstances, VEFs were calculated as follows:

$$VEF = \frac{\text{Mean contaminant concentration x mean annual runoff from 1km road}}{\text{Mean annual traffic volume}} \quad \text{(Equation 2.1)}$$

Where:

mean contaminant concentration was taken as the EMC value reported in the literature

mean annual runoff = mean annual rainfall x width of road sampled x 1000 metres

mean annual traffic volume = published AADT[5] x 365.

4 Freely flowing, interrupted or congested (see also section 3.2.1).

5 Average annual daily traffic.

Table 2.2 EMCs of contaminants in road runoff reported in the international literature

Location	Road type	Traffic volume (vpd)	Copper (g m^{-3})		Zinc (g m^{-3})		PAHs (g m^{-3})		Reference
			Average	Variability	Average	Variability	Average	Variability	
Combined international	Various	-	0.003–1.2[a]	-	0.01–1.2[a]	-	1.86–18.2[a]	-	Grant et al 2003
US various	Urban highways	-	-	-	0.42[b]	-	-	-	Shelley et al 1987
California, US	3 urban highways	>260,000	0.092[b]	0.015–0.92[d]	0.42[b]	0.042–8.15[d]	-	-	Han et al 2006
British Colombia	Urban highway	156,000	0.062[b]	0.033–0.11[d]	0.36[b]	0.22–0.66[d]	-	-	Preciado & Li 2005
Cinncinati, US	Urban highway	150,000	0.135[b]	0.043–0.325[d]	4.27[b]	0.46–15.2[d]	-	-	Sansalone & Buchberger 1997
London, UK	2 sites, urban motorway	140,000	0.27, 0.25[b]	-	0.21, 0.19[b]	-	-	-	Hares & Ward 1999
Minnesota, US	Urban highway	114,000	0.046[b]	0.003–0.78[d]	0.17[b]	0.01–1.2[d]	-	-	Thomson et al 1996
Ontario, Canada	Highway bridge	92,000	0.14[b]	0.023–0.28[e]	0.34[b]	0.06–0.78[e]	-	-	Marsalek et al 1997
Osaka, Japan	Urban highway	75,000	0.066[b]	0.039–1.0[d]	0.65[b]	0.43–1.19[d]	0.0016[b]	0.0007–0.0024[d]	Shinya et al 2000
Texas, US	Urban highway	58,000	0.037[c]	-	0.222[c]	-	-	-	Barrett et al 1998
Multiple sites, US	Urban highways	>30,000	0.054[c]	-	0.4[c]	-	-	-	Driscoll et al 1990
Multiple sites, US	Rural highways	<30,000	0.022[c]	-	0.08[c]	-	-	-	Driscoll et al 1990
US various	Rural highways	-	-	-	0.12[b]	-	-	-	Shelley et al 1987
Portugal	Rural highways	6,000	0.024[b]	0.015-0.033[f]	0.31[b]	0.12–0.49[f]	-	-	Barbosa & Hvited-Jacobsen 1999
Texas, USA	Residential roads	9,000	0.007[c]	-	0.044[c]	-	-	-	Barrett et al 1998

Notes:

a) Range of means from studies reviewed

b) Mean

c) Median

d) Range

e) 10–90 percentile range

f) ±1 standard deviation

This approach assumed that the EMCs reported in the literature are representative of the mean concentration in all runoff discharged over a year. Mean annual runoff was crudely estimated as the mean annual rainfall falling on a 1km length of road, assuming no losses and no minimum rainfall required to trigger runoff. Given that there are errors associated with both these assumptions, the VEFs estimated by this method can only be considered approximate values. However, care was taken to correctly identify the width of road sampled (for instance, from aerial photographs) to allow estimation of runoff volumes and to determine whether to use single- or dual-direction traffic count data.

This approach was used to estimate VEFs from the contaminant concentrations in runoff samples collected from the following three sites on State Highway 1:

- Auckland's Southern Motorway at Otahuhu (from unpublished ARC data reported in Kennedy 2003)
- Auckland's Northern Motorway at Silverdale (Larcombe 2003)
- Johnsonville–Porirua Motorway at Tawa (Sherriff 1998).

The VEFs estimated from this data are presented in table 2.3.

Table 2.3 VEFs estimated from contaminant EMCs reported in the New Zealand literature

Source	Location	Traffic volume (vpd)	VEFs (mg/veh/km)[a]			
			Zn	Cu	TPHs	PAHs
ARC, unpublished (reported in Kennedy 2003)	SH1 Southern Motorway, Otahuhu	90,000	0.17	0.06	-	0.02
Larcombe 2003	SH1 Northern Motorway, Silverdale	17,990	0.19	0.06	2.19	-
Sherriff 1998	SH1 Motorway, Tawa, Wellington	19,750	0.07	0.08	-	-

Note:

a) Approximate values – refer to text for assumptions made.

The VEF estimates for zinc, copper and PAHs are similar to the low to median values estimated from Waitakere City road dust sampling (Kennedy and Gadd 2003). While the VEF estimates for Cu are also similar to those reported by Timperley et al (2005) from the Richardson Rd study, the zinc VEFs in table 2.3 are relatively low compared with those derived from that study.

Other New Zealand studies reporting contaminant concentrations from which it may be possible to calculate VEFs include Pandey et al (2005), O'Riley et al (2002) and Taylor et al (2004), subject to availability of information on runoff volumes, catchment road length and width, and relevant traffic

volumes. This additional information was not included in the above-mentioned publications and was not otherwise readily available at the time of this review.

2.2.5 Estimation of VEFs from unpublished data

NIWA holds additional data on concentrations of copper and zinc in road runoff. This data was collected during 2006 and 2007 under a FRST-funded programme of research into the effects and mitigation of particulate metals originating from vehicle emissions. While Moores et al (2008) used some of these datasets to investigate the effectiveness of different stormwater treatment methodologies (see section 2.3.3), the data itself has not previously been published in the form presented here. Although the data had not been specifically collected for the purpose of determining VEFs, it was possible to manipulate it to provide estimates for comparison with published VEFs.

2.2.5.1 Metal concentrations

As part of the FRST study described by Moores et al (2008), samples of untreated road runoff were collected at three sites (in addition to the two Northern Motorway sites reported in section 2.2.3):

- two on SH17 north of Auckland
- one at East Coast Rd in North Shore City.

Road runoff samples were collected manually at equal time intervals during runoff sampling events at each of these locations, and composite samples were analysed for total copper and zinc concentrations to provide an estimate of the EMC of each metal for each event. Table 2.4 below summarises the concentrations of the mean and range of copper and zinc EMCs in samples collected at each of these three sites.

Table 2.4 Total zinc and total copper EMCs in road runoff samples (FRST-funded research 2006–07)

Location	Traffic volume – AADT[a] (vpd)	Copper (g m^{-3})		Zinc (g m^{-3})	
		Mean	Range	Mean	Range
SH17 (nr Horseshoe Bush Rd), Dairy Flat	6,387	0.038	0.035–0.041	0.207	0.188–0.226
SH17 (nr Green Rd), Dairy Flat	6,387	0.152	0.099–0.185	0.910	0.53–1.090
East Coast Rd, North Shore City	20,040	0.071	0.053–0.089	0.448	0.391–0.498

Note:

a) Source: Transit NZ (2007)

Note that there is considerable uncertainty around the extent to which these EMC estimates can be considered representative. The range of events sampled was limited to relatively short-duration events of small rainfall depths. The concentrations presented in table 2.4 for each site may not be representative of contaminant concentrations associated with all rainfall events, as greater dilution of

contaminants can be expected during longer and heavier rainfall[6]. The long-term mean and minimum concentrations of copper and zinc at these sites are likely to be lower than those reported in table 2.4.

The concentrations of metals in samples collected at the SH17 (Green Rd) site were noticeably higher than elsewhere, including the sampling sites on SH1 (Northern Motorway) reported in section 2.2.3. These high metal concentrations corresponded with elevated TSS concentrations at the Green Rd site and resulting high particulate metal concentrations in these samples[7]. The road at this location was notably dirtier than elsewhere. Tyre tracks on the road indicated that a nearby property, occupied by a quarry and landfill, was the source of this material.

2.2.5.2 VEF estimates

VEFs were estimated from the unpublished data described above, using the following method:

For each sampling event, the loads of copper and zinc were estimated from the EMC and the event runoff volume, which were estimated from flows measured during each event. The contaminant loads from each sampling event were summed to give the total load over all the events sampled (Σ CL).

The vehicle movements over the antecedent dry period and during each sampling event were derived from vehicle counts in the case of East Coast Rd, and from published mean traffic count data in relation to the SH17 sites (Transit NZ 2007). The estimate of vehicle counts for each event included all movements since the preceding rainfall event[8]. The vehicle counts preceding and during each event were summed to give the total vehicle counts (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 was then estimated by:

$$VEF = (\Sigma CL / \Sigma VM) \times (1000 / L) \quad \text{in units of mg/veh/km} \qquad \text{(Equation 2.2)}$$

Table 2.5 presents the estimated VEFs for each of these three locations.

Table 2.5 VEF estimates for copper and zinc (FRST-funded research 2006-07)

Location	Traffic volume (vpd)	VEF Cu (mg/veh/km)	VEF Zn (mg/veh/km)
SH17 (nr Horseshoe Bush Rd), Dairy Flat	6387	0.06	0.33
SH17 (nr Green Rd), Dairy Flat	6387	0.29	1.64
East Coast Rd, North Shore	20,040	0.02	0.15

The SH17 (near Green Rd) VEFs are similar to the high end of the range of estimates reported by Kennedy and Gadd (2003), whilst the East Coast Rd VEFs fall towards the lower end of their estimates.

6 See section 2.2.7.

7 Particulate metal concentrations are calculated as the product of TSS concentrations and the dry-weight metal concentrations on the suspended solids. In samples collected at this site the dry-weight metal concentrations were similar to those at other sites on SH17, but the TSS concentrations were substantially higher.

8 Ignoring discontinuous rainfall showers of 1mm or less.

The VEF estimates for the SH17 (near Horseshoe Bush Rd) site are reasonably similar to estimates for Richardson Rd (Timperley et al 2005) and the Northern Motorway (Moores et al 2008).

As described above, the sampling programme at these sites was restricted to a relatively narrow range of rainfall events of short duration and limited depth. As a consequence, there is considerable uncertainty associated with these VEFs estimates. They could quite conceivably be either:

- overestimates, in the event that the metal concentrations used to estimate loads are an overestimate of the long-term EMCs at these sites
- underestimates, in the event that the runoff volumes used to estimate loads under-represent the long-term mean event runoff.

2.2.6 Factors influencing VEFs

As noted in section 2.2.2, there has been limited reporting of VEFs in the international literature. In contrast, there have been many studies characterising road runoff quality in terms of contaminant concentrations, of which a number have explored the relationship between concentrations and a range of influencing factors. These studies provide a starting point from which the factors that could influence VEF estimates can be considered.

Previous studies have reported a relationship between traffic volumes (eg AADT) and contaminant concentrations in highway runoff. Caltrans (2003a) and Kayhanian et al (2003) reported on the results of a substantial state-wide monitoring programme in California. Sites with higher AADTs had higher concentrations of nearly every contaminant evaluated. Driscoll et al (1990) reported differences in contaminant concentrations in samples from urban versus non-urban roads based on a 30,000 AADT threshold (see table 2.2).

However, these and other studies involving analyses of large datasets generated from road runoff characterisation studies have found that, taken on their own, traffic volumes are not necessarily a good, or the only, indicator of contaminant concentrations in road runoff (Caltrans 2003a; Drapper et al 2000; Driscoll et al 1990; Kayhanian et al 2003; Moy et al 2003; Stotz 1987). They have identified a number of other factors, independent of traffic volume and occurring over a range of temporal and spatial scales, which could influence contaminant concentrations. These are grouped below as factors influencing the accumulation of contaminants and factors influencing their wash off.

2.2.6.1 Factors influencing contaminant accumulation

Contaminant concentrations in road runoff at a single site vary on a temporal basis, reflecting differences in contaminant accumulation. Higher contaminant concentrations are associated with longer antecedent dry periods prior to an event (Kayhanian et al 2003), reflecting the greater accumulation of contaminants on the road surface. The relationship is not necessarily linear, however, because of removal of some of the accumulated contaminants by other processes such as wind. The effect of this is a reduction in the rate of accumulation with time (Timperley et al 2005).

Contaminant concentrations also reflect spatial (site-to-site) influences on accumulation rates. In particular, variations in traffic behaviour at different points in a road network can influence accumulation rates. Kennedy et al (2002) reported differences in the estimated emissions from brake linings in relation to braking behaviour. Intense brake use was estimated to result in the emission of around four times as much brake lining material as low brake use. In a study of 21 sites in southeast

Queensland, Drapper et al (2000) reported higher copper concentrations at sites collecting motorway off-ramp runoff compared with those from the motorway itself. This could have been indicative of greater copper emissions from vehicles that were braking as they left the motorway. Muschack (1990) also reported higher contaminant concentrations in runoff derived from zones of braking and acceleration, whilst a number of studies have reported higher concentrations of contaminants in road sediments collected from intersections compared with other roads (Charlesworth et al 2003; Kennedy and Gadd 2003).

Driscoll et al (1990) described factors relating to the design and construction of the road itself that could influence contaminant accumulation. They found that a design that favoured greater wind dispersal of road sediments, such as an elevated section of road, could be expected to result in lower concentrations of particulate contaminants than a sheltered section of road through a cut or tunnel.

Adjacent land use may also influence contaminant concentrations. Kayhanian et al (2003) found statistically significant differences between contaminant concentrations in highway runoff relating to land-use type, but noted that additional data was needed to establish the ways in which land use could influence runoff quality. Driscoll et al (1990) found differences between urban and rural land uses to be more significant than traffic volumes, and reported that general atmospheric quality differences are the most important influence on road runoff quality. This reflects differences in the production and contribution of contaminants from different types of land use, either by airborne deposition or transported to the road on the wheels of vehicles.

Land use may also influence the composition of the vehicle fleet – for example, there can be a higher proportion of heavy commercial vehicles (HCV) on roads though industrial areas compared with residential streets. Depending on the number of wheels, wear rates of brakes and tyres have been reported to be up to 7 and 31 times greater, respectively, for HCVs than for passenger cars (Kennedy et al 2002). Accordingly, the emissions of contaminants associated with vehicle component wear will also vary by vehicle type.

2.2.6.2 Factors influencing contaminant wash off

Factors influencing road contaminant wash off may be grouped as those relating to the generation of road runoff and factors that influence contaminant transport.

Runoff from a road is a function of rainfall, catchment area and road surface permeability. Given a fixed contaminant load, contaminant concentrations can be expected to decrease as the magnitude of a rainfall event (rainfall depth) increases, reflecting the greater dilution of contaminants by larger runoff volumes.

Kayhanian et al (2003), Caltrans (2003a) and Kim et al (2005) reported statistically significant negative relationships between contaminant concentrations and rainfall measures such as total event rainfall, storm duration, maximum or average rainfall intensity and cumulative seasonal rainfall (ie rainfall accrued since the onset of a wet season). However, not all contaminants followed this pattern. A statistically significant positive relationship was reported between particulate zinc concentrations and maximum rainfall intensity, suggesting the greater mobilisation of particulate matter during heavier rainfall (Kayhanian et al 2003).

While an increase in road catchment area yields a greater runoff volume from a given rainfall event, this would not be expected to affect contaminant concentrations, providing that the load to be washed off varies proportionally to the road catchment area. Caltrans (2003a) reported the results of multiple

regression analyses that support the lack of a relationship between road catchment area and contaminant concentration.

In contrast, road surface construction and condition can be expected to influence contaminant concentrations through their effects on both the generation of runoff and the extent to which the transport of contaminants may be inhibited. A more permeable road surface, whether through design or disrepair (cracking etc), will result in lower runoff volumes and provide for contaminant deposition (especially particulate matter) prior to the point of discharge. This could conceivably result in either greater contaminant concentrations associated with the reduction in runoff volumes, or lower concentrations associated with the deposition of solids prior to the point of discharge. However, Driscoll et al (1990) reported there being no evidence in their data, or that of Stotz (1987), that quantified any effect of road surface type or condition on runoff quality[9].

2.2.6.3 Relevance for VEFs

As noted in section 2.2.5, differences in contaminant concentrations are not necessarily indicative of differences in loads, which are the basis for estimation of VEFs. There can be differences in contaminant concentrations from site to site simply as a result of differences in runoff volumes, whilst the total load and VEF may be identical. The extent to which the factors described above may influence VEFs is therefore a function of the extent to which they influence the quantity of material emitted per vehicle and removed in runoff, as opposed to loss by other mechanisms.

Traffic volumes, taken on their own, are not expected to influence VEFs. Given an identical fleet composition and driving conditions, the total contaminant load should vary in relation to vehicle numbers but the VEF should not. Under these circumstances a doubling of the number of vehicles would result in a doubling of the total vehicle-derived contaminant load, while the VEF would remain constant.

However, in some situations, differences in traffic volume result in differences in traffic behaviour, and then VEFs can be expected to vary. Gardiner and Armstrong (2007) modelled contaminant loads from a hypothetical suburban road, with all attributes held constant other than the average daily traffic volume and level of service (a measure of congestion[10]). A doubling of the traffic volume, and change in level of service from freely flowing to congested, resulted in a 29-fold and 7-fold increase in zinc and copper loads respectively. Allowing for the increased traffic volumes, VEF estimates for the congested scenario were substantially higher than those for freely flowing conditions.

Relatively high VEFs are also expected where road characteristics promote relatively high brake and tyre wear, such as intersections, bends, hills, roundabouts and highway on- and off-ramps. Gardiner and Armstrong (2007) compared modelled contaminant loads generated from a hypothetical rural road with all attributes held constant other than the terrain. With an increase in gradient and bends, copper loads increased by around a third, whilst zinc loads doubled.

VEFs can also be expected to vary with fleet composition, with higher values associated with roads carrying a greater proportion of large vehicles such as heavy commercial vehicles and buses. Given

9 However, the results of this research do appear to provide evidence of the influence of road surface characteristics and age on road runoff quality (see section 3.5).

10 See section 3.2.2.

identical driving conditions and vehicle numbers, the VEF from a motorway, central urban road or rural highway might be expected to be higher than that for a residential street.

At the scale of the individual vehicle, component composition may also influence the load of contaminants emitted. Kennedy et al (2002) reported that there could be more than 400 types of brake pads and linings in use in New Zealand. However, differences in the influence of component composition influence are unlikely to be reflected in overall traffic VEFs, providing that the use of different brands and types is evenly distributed.

Of the other factors considered above, road design may have some influence on differences in VEFs from site to site. The localised VEF in a sheltered cutting or tunnel may be greater than that on an exposed bridge. Again, however, unless a road is particularly sheltered or exposed, these differences can be expected to even out. Given that highways are typically constructed with a cut-to-fill balance, this can be expected to be the case for major roads.

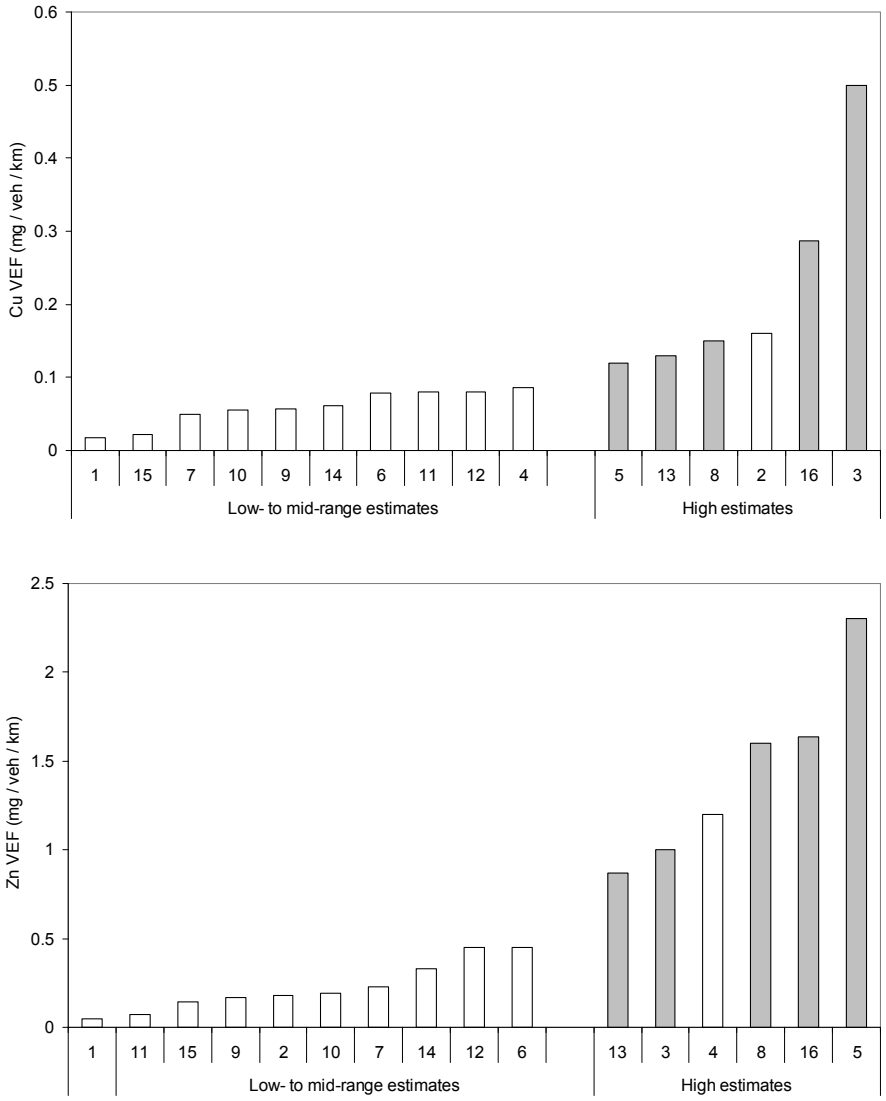
Other factors also contribute to variability in VEFs, but at temporal rather than spatial scales. Rainfall event characteristics and antecedent conditions, both of which influence contaminant concentrations, can also be expected to result in differences in VEFs from one event to the next. Frequent heavy 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 removed by wind between rainfall events. Hewitt and Rashed (1992) reported a strong correlation between the length of antecedent dry period and loads of some contaminants removed during runoff events. Other authors, however, including Ellis et al (1986), have reported that length of antecedent dry period is unimportant compared with runoff volume and storm duration.

Over the longer term (for instance, on an annual basis) these inter-event variations can be expected to even out, giving a representative VEF that is independent of the particular sequence of weather events. This holds true for roads subject to the same long-term climatic conditions. However, substantial differences between regional climates do have the potential to influence VEFs. Roads in regions enjoying relatively low and infrequent rainfall can be expected to lose a relatively greater proportion of contaminants by atmospheric processes rather than as a result of runoff. This would result in a lower VEF for runoff-conveyed contaminants.

2.2.7 Discussion

As described in section 2.2.3, three previous studies in New Zealand have resulted in the estimation of copper and zinc VEFs from sampling of road runoff or road sediments (Kennedy and Gadd 2003; Timperley et al 2005; Moores et al 2008). Kennedy and Gadd (2003) and Gardiner and Armstrong (2007) have also reported emission rates estimated from the source-based models using published data on emissions from individual vehicle components (Kennedy at al 2002). Copper and zinc VEFs have also been estimated and reported here from road runoff data collected for other purposes. These include data reported by others (ARC (unpublished) in Kennedy 2003; Larcombe 2003; Sherriff 1998) and unpublished data collected under a current FRST-funded programme of research. Comparison of these VEFs estimates suggested that they could be placed into two groups (see figure 2.1): a group of six relatively high estimates; and a group of ten low- to mid-range estimates for both copper and zinc.

Figure 2.1 VEF estimates of total copper and total zinc in New Zealand. Estimates associated with situations in which high rates of brake and tyre wear are considered likely are shaded.



Key					
1	Kennedy & Gadd 2003	Waitakere City (lower quartile)	**9**	ARC unpublished	SH1 Southern Motorway, Otahuhu
2	Kennedy & Gadd 2003	Waitakere City (median)	**10**	Larcombe 2003	SH1 Northern Motorway, Silverdale
3	Kennedy & Gadd 2003	Waitakere City (upper quartile)	**11**	Sheriff 1998	SH1, Tawa
4	Kennedy & Gadd 2003	VFEM-W (normal)	**12**	Moores et al 2008	SH1 Northern Motorway, Silverdale
5	Kennedy & Gadd 2003	VFEM-W (congested)	**13**	Moores et al 2008	SH1/SH17 intersection (Silverdale)
6	Timperley et al 2005	Richardson Rd	**14**	NIWA unpublished	SH17 (nr Horseshoe Bush Rd)
7	Gardiner & Armstrong 2007	VCLM freely flowing	**15**	NIWA unpublished	East Coast Rd, North Shore
8	Gardiner & Armstrong 2007	VCLM interrupted	**16**	NIWA unpublished	SH17 (nr Green Rd)

2.2.7.1 Relatively high estimates

These are VEF estimates greater than, or equal to:

- 0.12mg/veh/km for copper
- 0.87mg/veh/km for zinc.

They include:

- modelled VEFs reported by Kennedy and Gadd (2003) for congested driving conditions and, in the case of zinc, normal driving conditions
- modelled VEFs reported by Gardiner and Armstrong (2007) for interrupted driving conditions at Richardson Rd
- Kennedy and Gadd's (2003) upper range and, in the case of copper, median estimates from road dust sampling
- estimates reported by Moores et al (2008) for the SH1/17 interchange at Silverdale
- SH17 (near Green Rd) on a route conveying quarry/landfill traffic.

Most, but not all, of these estimates correspond with situations in which traffic could be congested or where higher-than-average braking and tyre wear occurs. In the case of the SH17 (near Green Rd) site, the relatively high VEFs might reflect not just driving conditions, but also the fleet composition.

2.2.7.2 Relatively low- to mid-range estimates

These estimates are less than, or equal to:

- 0.086mg/veh/km for copper
- 0.45mg/veh/km for zinc.

They include:

- estimates based on the Richardson Rd study (Timperley et al 2005)
- estimates reported by Moores et al (2008) for SH1 (Northern Motorway) at Silverdale
- Kennedy and Gadd's (2003) lower range and median estimates from road dust sampling (except copper)
- modelled VEFs reported by Gardiner and Armstrong (2007) for freely flowing driving conditions at Richardson Rd
- estimates reported in this research programme for SH17 (near Horseshoe Bush Rd)
- estimates reported in this research programme from roadwash experiments for East Coast Rd, North Shore
- in the case of copper, modelled VEFs reported by Kennedy and Gadd (2003) for normal driving conditions, and estimates reported in this research programme based on data from the SH1 Southern Motorway (ARC unpublished), SH1 Northern Motorway at Silverdale (Larcombe 2003) and SH1 Motorway at Tawa (Sherriff 1998)

- in the case of zinc, estimates reported in this research programme based on data from the SH1 Southern Motorway (ARC unpublished), SH1 Northern Motorway at Silverdale (Larcombe 2003) and SH1 Motorway at Tawa (Sherriff 1998).

These estimates largely correspond with roads on which traffic is generally likely to move freely and are subject to lower brake and tyre wear than those falling into the 'relatively high' group of estimates. Among the lowest VEF estimates are those reported in this research programme from roadwash experiments for East Coast Rd, North Shore. These VEFs were calculated from roadwash experiments that may not have removed as great a proportion of the load off the road as would be the case during natural rainfall events (see section 2.2.5).

This grouping of copper and zinc VEFs is largely in accordance with expectations, with traffic behaviour appearing to be a good predictor of the loads of these metals generated in road runoff. It suggests that it may be appropriate to characterise copper and zinc loads generated in zones of high brake and tyre wear separately from those on roads subject to 'normal' driving conditions. Sites at which relatively high VEFs can be expected include intersections, motorways conveying high traffic volumes subject to regular congestion, and other roads subject to relatively high brake and tyre wear, such as hill sections. Sites at which mid-range or relatively low VEFs can be expected include freely flowing roads, whether motorways, rural highways or urban roads.

However, while the results of previous New Zealand studies point to a relationship between copper and zinc VEFs and traffic characteristics, there is clearly considerable variability within each of the 'high' and 'low-to-mid' groups of estimates presented in this report. This variability is likely to reflect differences not only in study site characteristics but also in the methodologies by which these estimates were derived.

The extent to which traffic characteristics alone are a key factor is a critical knowledge gap. One of the principal objectives of this study, therefore, was to derive a set of VEF estimates based on a consistent, field-based approach at roads characterised by different traffic behaviour. This objective guided the design of the subsequent phase of the study, the road runoff sampling programme. The process by which sampling sites were selected to investigate the relationship between traffic characteristics and VEF variations is described in section 3.2.1.

2.3 Treatment of road runoff

2.3.1 Introduction

This section reports on the findings of previous studies on the effectiveness of selected stormwater treatment devices employed to control contaminants in road runoff.

Several published guidelines describe the applicability of a range of systems for treating stormwater contaminants. Whilst reference is made to certain of these documents in section 2.3.2, this review deliberately sought to avoid replicating their detailed guidance on device selection, design and operation. Instead, emphasis was placed on examining the extent to which devices that have been employed in the field meet expectations – for instance, in terms of treatment efficiency or compliance with environmental standards.

The review focused on studies into the effectiveness of two broad categories of stormwater treatment devices:

- vegetated filter systems, such as swales and buffer strips
- detention systems, such as wet ponds and wetlands.

Although a range of other devices can be employed to treat stormwater, swales and ponds are among the most widely employed to treat highway runoff, and their effectiveness is relatively well reported in the international literature.

2.3.2 Guidelines for treatment of road runoff

Guidelines for the selection of stormwater treatment devices typically provide information on:

- factors that influence the selection of devices
- treatment options available
- device effectiveness.

Several guidelines (ARC 2003; Austroads 2003; Kouvelis and Armstrong 2004; USEPA 2002a) have outlined the factors that influence the suitability of a device, including:

- the objectives of the treatment, reflecting the characteristics of the receiving environment and any environmental or regulatory requirements to be met – eg whether or not runoff volumes are to be controlled and the nature of the contaminants to be removed
- physical factors, such as catchment land use, influencing the generation of contaminants
- physical factors influencing the transport of the contaminants – eg catchment size, shape and percentage imperviousness, all of which affect runoff volumes and response to rainfall
- site factors at the point of treatment, including site area, topography, soil type and drainage characteristics.

When considering the selection of devices to remove contaminants conveyed in road runoff, the following factors are reasonably well defined:

- The objective of treatment includes the removal of solids, from gross pollutants to the finest sediment fraction, and metals and hydrocarbons in both particulate and dissolved forms. In some places, local regulatory standards or guidelines specify the target percentage of these contaminants that are to be removed (see section 2.3.3).
- The land cover in a road drainage catchment characteristically comprises the area of road seal itself and adjacent paved or vegetated areas. However, road runoff can also include non-vehicle-derived contaminants, contributed via stormwater discharged to the road drainage system from, for example, neighbouring properties or by air-dispersed particulate matter deposited on the road.
- Road drainage catchments are relatively small compared with urban stormwater drainage catchments and, although they tend to have a high percentage of imperviousness, runoff volumes and peak flows are accordingly comparatively small. Devices can be sized accordingly.

- Finally, the sites available for treatment of road runoff are typically within close proximity to the road itself – eg within the road reserve. This can be either a constraint, or an opportunity not present in the management of stormwater from other land uses. For example, space constraints are more likely to be a factor in the retrofitting of treatment systems in existing urban road networks than in the construction of new highways.

Given these characteristics, the treatment measures that have been reported as appropriate for treating road runoff are listed in table 2.6. Combinations of these can be used to provide a treatment train, with each component designed to deal with a target group of contaminants (ARC 2003, USEPA 2002a).

Table 2.6 Treatment devices for the control of contaminants in road runoff (ARC 2003; Austroads 2003; Kouvelis and Armstrong 2004; USEPA 2002a)

Treatment	Target contaminants	Road types/locations
Infiltration (non-vegetative)		
Porous pavements	Suspended sediments, particulate metals and hydrocarbons, dissolved metals	Large impervious areas subject to low traffic volumes and light-weight vehicles, eg car parks, driveways
Filtration (non-vegetative)		
Sand filters	Suspended sediments, particulate metals and hydrocarbons	Local road systems, arterial roads and highways[a]
Media filters	Suspended sediments, particulate metals and hydrocarbons, dissolved metals	Local road systems, arterial roads and highways[a]
Vegetative filtration and infiltration		
Raingardens, infiltration and bioretention systems	Suspended sediments, particulate and dissolved metals and hydrocarbons	Large impervious areas eg car parks, local road systems[b]
Vegetated buffer strips	Suspended sediments, particulate metals and hydrocarbons	Local road systems[b], arterial roads and highways
Vegetated swales	Litter, suspended sediments, particulate metals and hydrocarbons	Large impervious areas eg car parks, local road systems[b], arterial roads and highways
Storage		
Catchpits, gully traps and related screens and inserts	Litter, large organic matter, coarse sediments	Large impervious areas eg car parks, local road systems
Oil and grease separators, multichamber systems	Oil and grease, other hydrocarbons, coarse sediments	Areas with high pollution risk, large impervious areas eg car parks, local road systems[a]
Sediment traps/basins/forebays	Coarse suspended sediments, particulate metals and hydrocarbons	Prior to 'end-of-line' treatments (eg ponds) from local road networks, arterial roads and highways[c]
Infiltration basins/ponds	Suspended sediments, particulate metals and hydrocarbons, dissolved metals, nutrients	'End-of-line' treatment from local road networks, arterial roads and highways[c]
Wet ponds and wetlands	Suspended sediments, particulate metals and hydrocarbons, dissolved metals, nutrients	'End-of-line' treatment from local road networks, arterial roads and highways

Notes:

a) Subject to pre-treatment for litter and coarse sediments

b) Subject to space constraints

c) Subject to soil permeability

Most forms of stormwater treatment are designed to function through the removal of solids, either by physical interception, infiltration of runoff, or by reducing the velocity of runoff resulting in deposition of suspended sediments. As a high proportion of contaminants in road runoff are associated with the particulate fraction, removal of solids also reduces the loads of other contaminants discharged to receiving environments.

However, treatment devices designed to remove solids are less effective for the removal of dissolved contaminants, which, as noted in section 1.2.1 of this report, can contribute a large part of the total load of metallic contaminants. In recognition of this gap, several researchers have investigated the effectiveness of various filter media as a means of removing dissolved contaminants from stormwater, including New Zealand studies of their effectiveness in treating road runoff (Pandey et al 2005; Taylor et al 2004).

2.3.3 Device effectiveness

2.3.3.1 Measures of effectiveness

Two approaches[11] used to evaluate the effectiveness of a stormwater treatment system are:

- assessment of effluent contaminant concentrations against a water quality standard or guideline
- assessment of contaminant removal efficiency against a target.

Whilst the former approach involves a relatively straightforward comparison of the contaminant concentration in the discharge against a relevant acceptable concentration, identification of the acceptable concentration itself can be relatively complicated. For example, it may involve having to make an assessment of the environmental values of the receiving water body to be protected, deciding on an appropriate level of protection and determining management goals (ANZECC 2000).

In contrast, the assessment of contaminant removal efficiency does not require reference to any water quality threshold (although measures of efficiency can incorporate them) but relies upon a comparison between the water quality characteristics of the influent entering, and effluent exiting, a treatment device.

However, as yet there is no single accepted measure of device efficiency, reflecting the fact that stormwater contamination can be characterised in a number of ways (Lenhart 2007). USEPA (2002b) summarised 10 alternative methods of assessing the effectiveness of treatment devices in removing contaminants. The most common is the calculation of an efficiency ratio that involves comparison of inlet and outlet contaminant **concentrations** (using EMCs). An alternative common practice is the summation of loads approach, which compares total inlet and outlet contaminant **loads** over the period of monitoring.

Lenhart (2007) described the limitations of using simple percentage removal measures of both contaminant concentrations and loads. He noted that most contaminants in freshwater had a background concentration or 'irreducible concentration', and when concentrations in influent waters are close to this background level, they cannot be reduced much further. Based on comparison of inlet and outlet EMCs, a device would appear to be achieving a poor percentage removal in such

11 Other ways of assessing the effectiveness of a treatment device (eg by monitoring sediment quality or biological indicators in the receiving environment) are not discussed here.

circumstances. On the other hand, the evaluation of efficiency in terms of percentage removal of total loads can obscure the fact that a device is effective in meeting water quality guidelines during individual events: this information could be important when considering the acute (rather than chronic) contamination of a receiving water body.

There are measures of efficiency that aim to address these issues, for instance by either factoring in the 'irreducible concentration' or relevant water quality standards in the estimation of percentage removal (USEPA 2002b). An alternative approach is to graphically define a threshold for the effectiveness of a device that reflects the reduction in percentage removal at lower influent concentrations. These thresholds have been termed 'lines of comparative performance' or 'performance expectation functions' (Lenhart 2007; USEPA 2002b). The effectiveness of a device is assessed on the basis of whether its performance at a particular influent concentration plots above or below the threshold. Other methods involve statistical analyses, such as linear or multivariate regression, and fitting probability distributions to test for statistical differences between influent and effluent concentrations (USEPA 2002b).

2.3.3.2 Water quality standards and treatment targets

In New Zealand the discharge of water and contaminants to water is controlled under the Resource Management Act 1991 (RMA). The RMA does not require road runoff or any other discharges of water to meet specific water quality standards. Instead, it provides a framework by which regional councils can prepare and implement regional plan provisions to avoid, remedy or mitigate the adverse effects of discharges on receiving environments. Whilst the Third Schedule of the Act does set out optional standards for a range of water quality classes, these do not specify target contaminant concentrations, but describe the effects to be avoided by discharges to receiving waters.

Six of New Zealand's regional councils and unitary authorities have operative or proposed regional plans containing rules relating to stormwater discharges from roads (L Hopkins, pers comm 2007). Three of these specify minimum water quality standards for concentrations of suspended solids and hydrocarbons in receiving waters, whilst one also specifies minimum standards for concentrations of copper and zinc.

The ANZECC water quality guidelines (ANZECC and ARMCANZ 2000) set out receiving environment trigger levels for each of a large number of contaminants at a range of levels of protection. Table 2.7 summarises those that are most relevant to this study. Note that these are not statutory water quality standards. In some overseas jurisdictions, water quality standards are required by law – for example, in the US, standards are set at the state level under the Clean Water Act (USEPA 2002a). The US Environmental Protection Agency (USEPA) publishes recommended water quality criteria to provide guidance to states. These criteria are also shown in table 2.7 for comparison with the ANZECC trigger values. However, whilst the setting of water quality standards in the US is mandatory, regulation of stormwater discharges to achieve compliance with specific water quality criteria is not. As of the year 2000, only 11% of state authorities responsible for water quality management had numeric limits for TSS or other indicators of effluent water quality (USEPA 2002a).

As with water quality standards, in New Zealand there are no national statutory standards relating to contaminant removal efficiencies. ARC's TP10 guidelines (ARC 2003) set an objective for stormwater

treatment in the Auckland Region of 75% removal of total suspended solids (TSS)[12]. This target has been adopted as a condition of rules providing for stormwater discharges by both ARC and Environment Canterbury in their relevant proposed regional plans (ARC 2005; ECan 2004). In the US, 24% of relevant state authorities have set a requirement for percentage reduction of solids, with 80% removal of TSS in stormwater being the most commonly adopted standard (USEPA 2002a).

Table 2.7 ANZECC trigger values and USEPA national recommended water quality criteria for concentrations of selected contaminants in freshwater (ANZECC and ARMCANZ 2000; USEPA 2006). All units µg l^{-1}.

Contaminant	ANZECC trigger values				USEPA recommended water quality criteria	
	Level of protection[a]					
	99%	95%	90%	80%	CMC[b]	CCC[c]
Copper[d,e]	1.0[f] (2.5–9.0)	1.4[f] (3.5–13)	1.8[f] (4.5-16)	2.5[f] (6.3–23)	13.0[g]	9.0[g]
Zinc[d,e]	2.4[f] (6–22)	8.0[f] (20–72)	15[f] (38–140)	31[f] (78–250)	120[g]	120[g]
PAHs	ID[h,i]	ID[h,i]	ID[h,i]	ID[h,i]	NS[j]	NS[j]
Oils & petroleum hydrocarbons	ID[h]	ID[h]	ID[h]	ID[h]	Narrative statement	

Notes:

a) Percentage of species protected.

b) Criteria Maximum Concentration: an estimate of the highest concentration to which an aquatic community can be exposed briefly without resulting in an unacceptable effect.

c) Criterion Continuous Concentration: an estimate of the highest concentration to which an aquatic community can be exposed indefinitely without resulting in an unacceptable effect.

d) ANZECC (2000) trigger values are for comparison with total metal concentrations followed by, in the event of exceedance, comparison with dissolved metal concentrations.

e) USEPA criteria are for dissolved metal concentrations.

f) Trigger values for low hardness (30mg/L $CaCO_3$): for moderately to extremely hard waters, these trigger values are multiplied by a factor in the approximate range 2.5 to 9 (giving the range of values shown in brackets).

g) Criteria corresponding with hardness of 100mg/L $CaCO_3$.

h) ID = insufficient data to derive a reliable trigger value.

i) ANZECC trigger values available for naphthalene (a specific PAH), but not generically for PAHs or other specific PAHs.

j) NS = not specified.

The following sections report on the extent to which a selection of previous studies to evaluate treatment device performance (specifically vegetative filters and ponds/wetlands) have assessed their effectiveness against measures such as the water quality criteria and percentage removal guidelines discussed above.

12 Targets for contaminant removal efficiency typically focus on the removal of TSS since it is relatively easily measured. It is common practice for TSS removal to be considered a surrogate measure for the removal of other contaminants, despite evidence to the contrary (eg see table 2.8).

2.3.3.3 Effectiveness of vegetative filters

Studies of vegetated swales and buffer strips have reported their performance in terms of percentage removal of suspended solids and, in some cases of other contaminants such as metals (see table 2.8). Of the studies listed in table 2.8, only Han et al (2005) reported on the extent to which relevant standards for water quality or treatment efficiency had been met.

The comments on the other studies summarised in table 2.8 reflect a comparison of the published results against the relevant water quality criteria and treatment targets of those described above in section 2.3.3. There are substantial variations in the reported effectiveness of swales and other vegetated treatment systems. This variability is likely to reflect not only differences in the design and maintenance of these systems, but also the experimental design of the studies reviewed. The USEPA reported that 'differences in monitoring strategies and data evaluation alone contribute significantly to the range of [device] "efficiency" that has been reported in the literature to date' (USEPA 2002b). It is therefore important to exercise a degree of caution when seeking guidance from the results of studies into device efficiency and, in particular, an understanding should be gained of the experimental design upon which results are based.

Some of the results indicate that swales and buffers can, on their own, be effective contaminant control measures in terms of meeting the water quality or efficiency targets cited. Several authors provide guidance on the design, construction and maintenance of swales to optimise the effectiveness of these systems (eg Austroads 2003; Ellis 1999; Caltrans 2003b; Larcombe 2003). In some locations, lower device performance may be acceptable, as vegetative treatments are often used in conjunction with other devices. It should be noted that the comments on device performance in table 2.8 do not reflect the cumulative treatment that could be achieved by a treatment train.

As part of NIWA's FRST-funded study into the dispersion of particulate metals from vehicle emissions (see section 2.2.3), runoff samples were also collected at the outlets of roadside drainage channels adjacent to SH17 north of Auckland (Moores et al 2008). The objective of sampling in these locations was to compare total suspended solids (TSS) and particulate metal concentrations at the drain outlets with influent concentrations in samples collected at the respective road edges. Of the two roadside drains sampled at SH17, one was vegetated whilst the other was lined with a rock riprap matrix within which vegetation had become established. Particulate copper and zinc loads were reduced by 87–95% in runoff discharged from the drains as compared with untreated road runoff. Although based on relatively limited sampling, these results suggest that roadside drainage channels can provide stormwater treatment despite not being specifically designed for this purpose.

Table 2.8 Effectiveness of vegetative filters reported in the published literature

Reference	System and location	Effluent water quality (Cu and Zn)	Treatment efficiency	Comments on performance
Barrett et al 2004, Caltrans 2003b	Eight vegetated buffers, California	Median concentrations from all eight sites: Total copper: 0.009 mg l^{-1} Total zinc: 0.025 mg l^{-1}	Percentage removal[b] in the ranges 77–97% for TSS, 76–98% for total copper and 87–99% for total zinc.	Median concentrations did not exceed USEPA water quality criteria[c]. Seven of eight sites achieved common US requirement of 80% TSS removal.
Deletic & Fletcher 2006	Trial swales, Aberdeen (UK) and Brisbane	Not reported	Percentage TSS removal[a] in the range 61–86% (Aberdeen) and average load reduction[b] 69% (Brisbane)	Not compared with a relevant water quality standard or treatment target.
Han et al 2005	Vegetated filter strip, North Carolina	Not reported	Mean percentage removal of TSS of at least 89%[a] and 91%[b]	Author commented on state requirement of 85% TSS removal being met.
Karamalegos et al 2005	Two vegetated filter strips, Austin, Texas	Not reported	Percentage TSS removal[a] 98% and -32%	One site achieved common US requirement of 80% TSS removal.
Kaighn & Yu 2006	Two swales, Virginia	Not reported	Mean percentage removal[a] (2 swales): TSS: 49/29.7% Dissolved zinc: 13/11%	Did not achieve common US requirement of 80% TSS removal.
Larcombe 2003	Motorway swale, SH1, Silverdale, NZ	Mean EMCs (2 swale lengths): Total copper: 0.012/0.011mg l^{-1} Total zinc: 0.016/0.025 mg l^{-1} TPHs: 0.52/0.52mg l^{-1}	Mean percentage removal[a] (2 swales of lengths (i) 100 and (ii) 50 metres): TSS: (i) 36% and (ii) 25% Total copper: (i) 60% and (ii) 63% Total zinc: (i) 82% and (ii) 78% TPHs: (i) 38% and (ii) 55%	Mean effluent concentration did not exceed ANZECC 80% to 95% trigger value[c]. However, ARC guideline for TSS removal not met.
Moores et al 2008	Motorway swale, SH1, Silverdale, NZ	Median sample concentrations: Particulate copper: 0.015mg l^{-1} Particulate zinc: 0.068 mg l^{-1}	Median percentage removal[a]: TSS: 58% Particulate copper: 71% Particulate zinc 73%	Median effluent concentration did not exceed ANZECC 80% to 90% trigger value[c, d].

Reference	System and location	Effluent water quality (Cu and Zn)	Treatment efficiency	Comments on performance
Walsh et al 1997	Two vegetated filter strips, Austin, Texas	Mean concentrations (2 filter strips): Total zinc: 0.032/0.032mg l^{-1}	Mean percentage removal[a] (2 filter strips): TSS: 87/85% Total zinc: 91/75% Mean percentage removals[b] (2 filter strips): TSS: 89/87% Total zinc: 93/79%	Achieved common US requirement of 80% TSS removal.
Yousef et al 1987	Two swales, Orlando, Florida	Mean concentrations (2 swales): Dissolved copper: 0.005/0.024mg l^{-1} Dissolved zinc: 0.003/0.053mg l^{-1}	Mean percentage removal[b] (2 swales): Dissolved copper: 70/49% Dissolved zinc: 93/77%	Mean concentrations at one site exceeded USEPA water quality criteria[c]. TSS reduction not reported.

Notes:

a) Percentage removal based on influent and effluent EMCs.

b) Percentage removal based on total influent and effluent loads.

c) Depending on water hardness.

d) Comparison made on basis of particulate metals only – total metals would be expected to be higher.

2.3.3.4 Effectiveness of ponds and wetlands

As with studies of vegetated treatment systems, the results from studies of ponds and wetlands are most commonly presented in terms of percentage removal of TSS and other contaminants, rather than in terms of whether or not effluent contaminant concentrations meet a water quality standard. Results from a number of studies are summarised in table 2.9. Again, the comments on performance are mainly based on a comparison with New Zealand and US water quality and treatment standards, except where otherwise indicated. Note that each of these studies evaluated the performance of a pond or wetland specifically employed for the treatment of highway runoff rather than stormwater from other land uses.

The results summarised in table 2.9 indicate that there are considerable variations in pond effectiveness. Some of the factors that influence pond effectiveness are described in ARC (1999), while guidance on pond and wetland design and maintenance is given in Revitt et al (1999), Shutes et al (1999) and Austroads (2003). As noted in relation to swales, the variations in results may also be partly due to differences in experimental design as well as pond design and operational criteria. It is important to take account of study methods when seeking guidance from the results of previous studies.

Other than Moores at al (2008), the New Zealand literature appears to be restricted to studies of ponds treating stormwater from mixed land use urban and industrial sites (eg Larcombe 2002, Leersnyder 1993, McKergow 1994), rather than ponds treating road runoff. Moores et al (2008) found relatively low removal efficiencies of 56%, 50% and 55% for TSS[13], total copper and total zinc, respectively. However, pond efficiency during individual events varied considerably, with TSS, particulate copper and particulate zinc removal in the ranges 47–71%, 51–81% and 59–82%, respectively. While the pond did not meet the ARC target for removal of 75% TSS, effluent water quality compared well with ANZECC trigger values for copper and zinc.

13 TSS removal efficiency is not published in Moores et al (2008) but is available from the dataset collected for that study.

Table 2.9 Effectiveness of ponds and wetlands reported in the published literature

Reference	System and location	Effluent water quality	Treatment efficiency	Comments on performance
Griffin et al 2003	Highway bridge discharging to wet pond, Louisiana	Median EMC: TPHs: 0.0mg l^{-1}	Mean percentage removals[a]: TSS: 85% TPHs: 100%	Achieved common US requirement of 80% TSS removal. Met USEPA narrative standard for TPHs. Authors noted compliance with regulations.
Hares & Ward 1999	Wetland and dry pond, M25, London	Mean sample concentration during initial storm stages, wetland: Total copper: 0.024mg l^{-1} Total zinc: 0.028mg l^{-1} Mean sample concentration during initial storm stages, dry pond: Total copper: 0.034mg l^{-1} Total zinc: 0.034mg l^{-1}	Mean percentage removal during initial storm stages, wetland[a]: Total copper: 93% Total zinc: 87% Mean percentage removal during initial storm stages, dry pond[a] Total copper: 88% Total zinc: 84%	Effluent concentrations were 1.4–6.8 times higher than 'background' concentrations reported by authors.
Hossain et al 2005	Highway discharging to wet pond, Washington State	Not reported	Mean percentage removal[a]: TSS: 84% Total copper:65% Total zinc: 62%	Achieved common US requirement of 80% TSS removal. Author noted lower efficiencies associated with lower influent concentrations.
Mitchell et al 2002	Highway discharging to natural wetland, Ohio	Not reported	Mean percentage removal[a]: Total zinc: 67%	Not compared with a relevant water quality standard or treatment target.
Moores et al 2008	Pond receiving runoff from state highway intersection, Silverdale, Auckland	Median EMCs: Particulate copper: 0.0048mg l^{-1} Particulate zinc: 0.032mg l^{-1}	Median percentage removal[b]: TSS[d]: 56% Particulate/total copper: 60/50% Particulate/total zinc: 69/55 %	Median effluent EMC did not exceed ANZECC 80% to 95% trigger value[c] However, ARC guideline for TSS removal not met.

Reference	System and location	Effluent water quality	Treatment efficiency	Comments on performance
Moy et al 2003	Highways discharging to wet ponds, SE England		Mean percentage removal, two ponds[a]: TSS: 73% and 62% Metals: 11% and 35% PAHs: 99% and 50%	Authors reported that UK water quality standards were exceeded in certain highway runoff samples.
Pettersson 1998	Urban road intersection discharging to wet pond, Gotëburg, Sweden	Range of event EMCs: Total zinc: 0.01 to 0.07mg l^{-1}	Mean percentage removal[b]: TSS: 58% Total zinc: 36%	Not compared with a relevant water quality standard or treatment target.
Sriyaraj & Shutes 2001	Natural wetland, M25, London.	Range of sample concentrations: Total copper: 0.00005 to 0.0009mg l^{-1} Total zinc: 0.0012 to 0.0019mg l^{-1}	Not reported	Author reported that effluent concentrations were considerably lower than UK water quality standards.
Stotz 1990	Highways discharging to three detention basins, Germany	Range of sample concentrations: Total copper: 0.027 to 0.082mg l^{-1} Total zinc: 0.18 to 0.37mg l^{-1}	Range of percentage removal[a]: TSS: 45 to 85% Total copper: 13 to 73% Total zinc: 24 to 50%	Not compared with a relevant water quality standard or treatment target.
Yu et al 1997	Eight pond systems receiving highway drainage, Virginia, USA	Not reported	Range of percentage removal[a]: TSS: -67 to 57% Total zinc: -33 to 87% Range of percentage removal[b]: TSS: 30 to 66% Total zinc: 29 to 62%	No ponds achieved common US requirement of 80% TSS removal.

Notes:

a) Percentage removal based on influent and effluent EMCs.

b) Percentage removal based on total influent and effluent loads.

c) Depending on water hardness.

2.3.4 Discussion

The results reported in the international literature provide a considerable resource of information on the effectiveness of stormwater treatment devices. Although there is considerable variability between studies, many devices such as swales, ponds and wetlands are reported to be effective in the removal of suspended solids and particulate metals.

However, this review has shown that many studies do not evaluate the extent to which device performance meets objectives such as water quality standards or targets for percentage removal. Whilst many authors have reported on the efficiencies achieved, few appear to have interpreted the results or to have assessed whether or not device performance was acceptable.

This is a critical knowledge gap, especially in New Zealand where assessments of the effectiveness of systems treating road runoff have been relatively limited. Larcombe (2003) and Moores et al (2008) appear to be the only studies specifically investigating the effectiveness of the more common methods of road runoff treatment in relation to water quality guidelines. While this review did not consider other treatment systems, it is worth noting that studies of innovative treatments, such as various filter media and catchpit filters, have been reported in the New Zealand literature (Pandey et al 2005, Butler et al 2004). Given the variability of results reported in the international literature, the lack of interpretation as to whether water quality objectives are being met, and the limited number of local studies, the general finding of this review is that it is difficult to make even a broad assessment of the effectiveness of road runoff treatment systems in New Zealand.

However, while limited in extent, the results of previous New Zealand studies provided a starting point from which the effectiveness of ponds, swales and roadside drainage channels could be investigated further. The design of the field programme comprising the next stage of this study therefore sought to incorporate sampling that would allow the effectiveness of a pond, swale and roadside drain to be assessed. The site selection process, and characteristics of each of the sampling sites, are given in section 3.2.

3 Road runoff sampling programme

3.1 Introduction

This chapter describes the programme of road runoff sampling and measurement that was undertaken after the review of previous studies was complete. The objectives of the sampling programme were to measure road runoff quantity and concentrations of TSS, copper, zinc and TPHs in samples collected at three or more sites, in order to allow an estimation of:

1 VEFs for selected roads with particular traffic behaviour and road characteristics

2 the effectiveness of selected treatment or road drainage systems for the removal of these contaminants.

3.2 Sampling locations

3.2.1 Selection process

The selection process for sampling locations was driven by three factors:

- traffic and road characteristics
- road drainage characteristics
- type of stormwater treatment present.

The influence of each of these factors is described below.

3.2.1.1 Traffic and road characteristics

The discussion in section 2.2.7 of this report identifies examples of road types at which, firstly, relatively high VEFs and, secondly, low- to mid-range VEFs may be expected based on traffic and road characteristics. Sites at which relatively high VEFs might be expected include:

- motorway interchanges
- motorways conveying high traffic volumes subject to regular congestion
- highways subject to relatively high brake and tyre wear (eg hill sections, intersections or congested sections).

Sites at which mid-range or relatively low VEFs might be expected include:

- motorways subject to less frequent (or no) congestion
- rural highways subject to relatively low brake and tyre wear (eg straight sections)
- urban roads not subject to frequent congestion (eg residential streets).

While the objectives set out in section 3.1 would best be met by undertaking road runoff sampling at sites representing all (or more) of these road types or situations, a sampling programme of that scale

was beyond the scope of, and resources available to, this project alone. The original proposal for this work envisaged sampling at three sites.

However, by coordinating this project with others, it was possible to conduct sampling at a broader range of sites than originally intended. As described in section 2.2.3, road runoff from sites on the Northern Motorway and at the SH1/17 interchange north of Auckland was previously sampled under a FRST-funded programme of research (Moores et al 2008). Sampling at one of the former sites (SH1 @ Redvale) was continued and expanded on as part of this study, with the addition of sampling at the outlet of a stormwater pond located at this site (refer to section 3.3.1 below). This decision was made because the site satisfied required conditions relating to traffic characteristics (low congestion), road drainage (see below) and the presence of one of the study's target treatment devices (a pond). It also meant that the programme could aim to characterise road runoff at four locations, rather than the original three.

Concurrently with this study, NIWA conducted a sampling programme for ARC to collect road runoff samples and catchpit solids at Richardson Rd. The results of that field programme have recently been reported (Moores et al 2009) and it is anticipated that ARC's analyses of the results will yield refined VEF estimates for the urban road setting.

Given the availability of data from the SH1/17 intersection, the decision to continue sampling at SH1 @ Redvale, and the existence of the ARC-funded Richardson Rd study, the selection of three further sampling sites was driven by the need to collect runoff samples at:

- motorway and highway straight sections subject to frequent congestion
- non-motorway sites that are not subject to frequent congestion (with SH1 @ Redvale representing the equivalent low, or no, congestion on a motorway).

In order to aid site selection, a measure of congestion was calculated for each site considered, in accordance with a method developed by Gardiner and Armstrong (2007). This method, which varied for motorways and single-lane roads, compared traffic volumes (as measured by AADT) with road capacity (again, in terms of a daily volume) to calculate the road Level of Service (LoS). AADT data was taken from the most recently published traffic count data available at the time (Transit NZ 2007). Data for road capacity, as a function of factors such as numbers of lanes, width, terrain and the proportion of trucks, was provided by NZTA staff for each site of interest. Gardiner and Armstrong (2007) classified roads with an LoS of <0.35 as freely flowing, 0.35–0.7 as interrupted, and >0.7 as congested. An alternative measure, provided in LTNZ (2007), uses a similar approach but based on peak traffic volumes. The LTNZ measure adopts a value of 0.7 as a threshold above which 'traffic interactions are significant' and notes the occurrence of 'bottleneck' or 'over-saturation' delays when the ratio between traffic volume and capacity is in excess of 1.

3.2.1.2 Road drainage characteristics

The road drainage characteristics of each site considered were examined carefully in order to determine whether or not the following critical requirements were met:

- Sites had a clearly defined road catchment area that excluded any non-road sources of stormwater.
- Runoff from the road was sufficiently concentrated at the point of measurement to allow flow measurement and the collection of samples at the road edge.

Assessments of each site were made from both drainage plans and careful inspections in the field. The latter approach often revealed aspects of site drainage systems that were not discernible from the drainage plans. Several favoured sites were ruled out simply because it was too difficult to establish with any certainty the true source of all stormwater inputs and the extent to which treatment may have occurred prior to the point of sample collection.

Sites that best met these requirements were characterised by kerb-and-channel drainage discharging concentrated runoff to either a pipe network or a clearly identifiable location on the road edge. At such sites, discharge measurement and sample collection were feasible, either at the outlet from the drainage network[14] (eg at the inlet to a stormwater pond) or at the road edge itself. While kerb-and-channel drainage systems are less common on rural roads, suitable sites were located, such as those adjacent to road cuttings.

3.2.1.3 Stormwater treatment

The selection of sites was also guided by the objective of building upon existing data on the treatment effectiveness of ponds, wetlands, swales or roadside drainage channels. As noted above, the presence of a stormwater pond at the SH1 @ Redvale site influenced the decision for continued sampling at that location.

Much of Auckland's motorway network drains to vegetated swales and so, in the investigation of suitable motorway sites, consideration was given to the potential to sample discharge at a swale outlet as well as at the road edge. Successive sections of the motorway draining to, firstly, kerbed (no swale) and, secondly, unkerbed (with swale) drainage provided the best opportunity to investigate the effectiveness of swales.

A similar approach was taken in the selection of sites on rural highways. As noted above, rural highways are less frequently drained by kerb-and-channel systems, more typically discharging to open roadside drainage channels. As noted in section 2.3.3, while such drains are not engineered as stormwater treatment devices, on the evidence of limited sampling, Moores et al (2008) found that they could have the capacity to reduce contaminant loads being discharged to receiving waters in much the same way as a true vegetated swale. The selection of rural highway sites therefore provided the opportunity to sample discharge at the outlet of a roadside drainage channel in close proximity to a sampling site collecting runoff from a kerbed length of road. Because the characteristics of the road (and the traffic it carried) had to be similar for the comparison to be valid, opposite or successive sections of the same road provided the best opportunity for locating such sites.

3.2.1.4 Other characteristics

Although not of fundamental importance in the site selection process, a range of other road characteristics had the potential to have some bearing on road runoff quality. These included road design and construction, adjacent land use and the nature of the road surface. While it was beyond the scope of this study to attempt to characterise the influence of these variables on contaminant loads, it was important that all relevant site characteristics were identified and recorded in order to provide subsequent consideration of their potential influence on the results of the sampling programme.

14 Noting that in such cases, stormwater may have first passed through catchpits before sampling occurs and it is necessary to make allowance for this in the estimation of contaminant loads (refer to section 4.4.4).

Details on a broad range of road characteristics were provided by NZTA from the New Zealand Road Asset Maintenance and Management system (RAMM).

3.2.2 Description of study sites

Four sampling locations were selected through the process described above. All were located on the state highway network in the Auckland region. Figure 3.1 shows the location of each site, while table 3.1 describes their key characteristics, including the level of congestion as estimated in accordance with Gardiner and Armstrong's (2007) method. Sites are ranked from most to least congested.

Figure 3.1 Location map of sampling sites (source of base map *www.transit.govt.nz/content_files/maps/PDF/Auckland.pdf*)

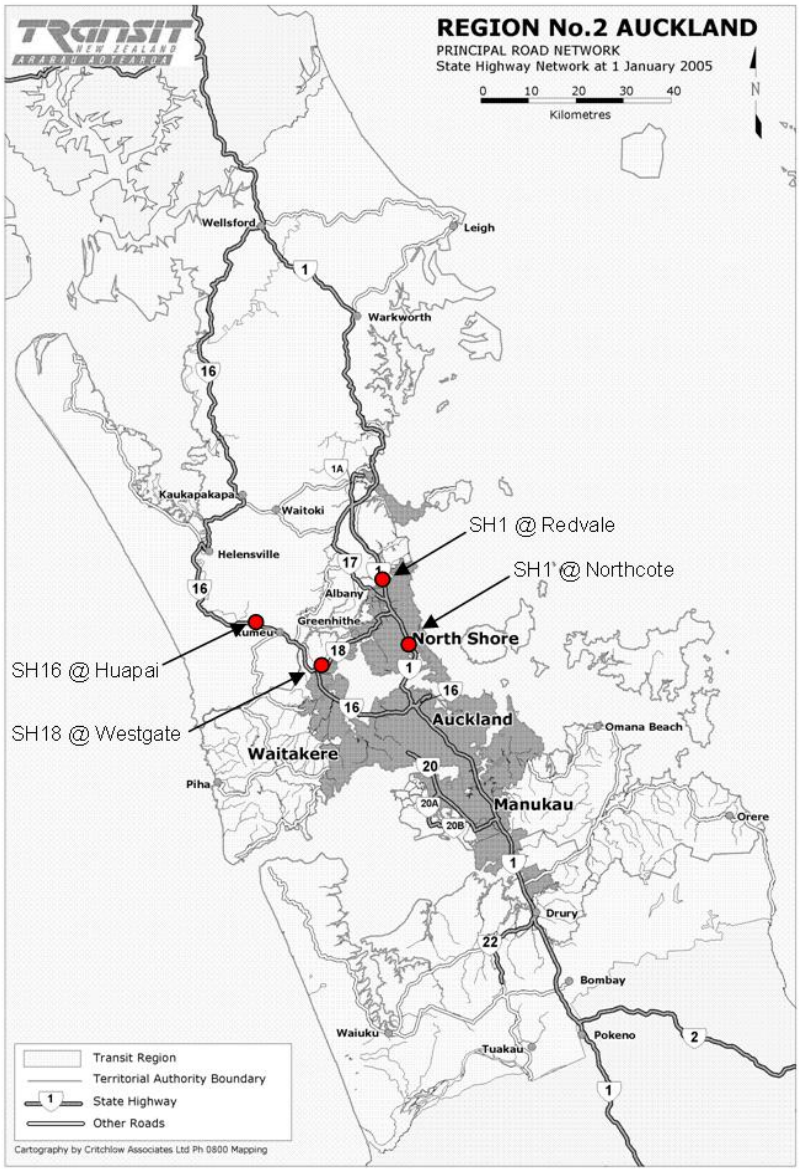


Table 3.1 Characteristics of road runoff sampling locations

Site name and location	Road description	Traffic volume[a] (vpd)	Congestion[b] (AADT/capacity)	Stormwater treatment	Road catchment area (m^2)	Road length to discharge point (m)
SH18 @ Westgate, east of North-western Motorway interchange[c]	2-lane arterial road, urban fringe	36,088 both directions	1.38	None	600	80
SH1 (Northern Motorway) @ Northcote, south of Northcote Rd interchange	7-lane urban motorway (4 northbound lanes monitored)	50,849 northbound	0.81	None	1980	100
				Vegetated swale	6480	360
SH16 @ Huapai, west of Trigg Rd	2-lane rural highway	13,866 both directions	0.52	None	1640	140
				Open roadside drain	2325	230[d]
SH1 (Northern Motorway) @ Redvale, north of Oteha Valley Rd interchange	4-lane rural motorway	41,541 both directions	0.40	None	13,475	550
				Pond	13,475	550

Notes:

a) Annual average daily traffic – AADT (NZTA 2009).

b) After Gardiner and Armstrong (2007).

c) Sampling completed prior to the current works to extend the Northwestern Motorway.

d) Mean of westbound (370m) and eastbound (90m) lanes draining to discharge point.

3.2.2.1 Traffic characteristics

Of the four sites, SH18 @ Westgate was the most congested. This site was located close to the current western end of Auckland's Northwestern Motorway and was subject to particularly heavy peak-hour use. SH1 @ Northcote was also classed as congested, while the remaining two sites had 'interrupted' traffic flows (AADT/capacity between 0.35 and 0.7) according to Gardiner and Armstrong's (2007) system.

3.2.2.2 Drainage characteristics and stormwater treatment

Figure 3.2 shows the roads at each site and various details of their drainage characteristics. The roads at all four sites were drained, in whole or part, by kerb-and-channel systems. At SH18 @ Westgate and SH1 @ Redvale, the sections of the road discharged to catchpits. Stormwater discharged from a single catchpit draining only the eastbound lane at Westgate ended up in an adjacent paddock (figure 3.2b). Runoff from the westbound lane was not sampled.

At Redvale, untreated stormwater was collected at several catchpits on both sides of the motorway and piped to a stormwater pond (figure 3.2d). The pond had a water surface area of approximately 350m^2, an estimated permanent water volume of 260m^3, and discharged through a 50mm slot weir in a 1.6m diameter concrete manhole riser. The pond outlet discharged treated runoff to a tributary of Okura River. The pond was densely vegetated with emergent reed beds. Aerial photographs from 2001 showed the pond to be unvegetated at that time. While the pond was designed and constructed under resource consents for the ALPURT B1 extension of the Northern Motorway, it was not known whether the pond's current operation was consistent with guidelines such as ARC's TP 10 (ARC 2003).

A kerbed northbound section of motorway at SH1 @ Northcote delivered a point discharge of road runoff onto a vegetated roadside margin. This provided a collection point for the sampling of untreated runoff (see section 3.3.1). Further north, the road was unkerbed and discharged to a grass swale (figure 3.2f). The section of swale that was monitored was approximately 360m long, draining to two sumps spaced 130m apart on a gradient of up to 5 degrees. The swale invert was approximately 1.5m wide with its midpoint 4m from the motorway edge. While these specifications were consistent with guidelines in ARC's TP10 (ARC 2003), it was not known whether other design criteria, such as maximum water depth and velocity of the water conveyed by the swale, were met. Both the kerbed section and the swale at Northcote drained only the northbound lanes of the motorway and discharged to stormwater ponds, which in turn, discharged to a tidal reach of the Hillcrest Creek. The creek drained to Shoal Bay in Auckland's Waitemata Harbour.

The kerbed section of road at SH16 @ Huapai drained the eastbound lane and delivered untreated runoff onto a concrete-reinforced road embankment. Runoff from the opposite side of the road discharged to a roadside drainage channel (figure 3.2h). The drain was approximately 370m long with its bed approximately 1.75m from the road edge and 0.9m below the road surface. The bed of the drain comprised a mix of road aggregate and soil and was vegetated with low grass and weeds during the period of sampling. At the Huapai site, both untreated road runoff from the eastbound lane and treated runoff (ie runoff conveyed by the drainage channel) from the westbound lane discharged to Coopers Creek, a tributary of the Kaipara River. Further details of the pond at Redvale, the swale at Northcote and the drainage channel at Huapai are given in Appendix A.

Figure 3.2 Road and drainage characteristics at each sampling site:

a) SH18 @ Westgate, showing part of road draining to sampling location

b) SH18 @ Westgate – catchpit outlet

c) SH1 @ Redvale, showing part of road draining to sampling location

d) SH1 @ Redvale stormwater pond

e) SH1 @ Northcote, showing part of road draining to sampling location

f) SH1 @ Northcote, grass swale

g) SH16 @ Huapai, showing part of road draining to sampling location

h) SH16 @ Huapai roadside drainage channel

3.2.2.3 Other characteristics

As noted above, other characteristics that could influence road runoff quality are road design and construction, adjacent land use and the nature of the road surface. All sites drained straight sections of road, apart from the kerbed section of the SH16 @ Huapai site, which was on a slight bend. Site gradients were gently to moderately sloping – the maximum was 6 degrees, at Huapai (NZTA 2008)[15].

The Westgate site was located on Auckland's western urban fringe, with residential land use to the south of the road and pasture to the north. At the time of writing, the road network in this area was undergoing major redevelopment as part of the extension of the Northwestern Motorway, although those works post-date the sample collection undertaken as part of this study. The Huapai and Redvale sites were both surrounded by rural land use, including orchards and vineyards at the former, and areas of bush and scrub at the latter. Although the Northcote site was the only urban site, it, too, was close to relatively large areas of open space, including a bush block adjacent to part of the swale section.

NZTA (2008) provided the data on road surface types and age. The road surface at Westgate and Huapai was described as two-coat seal (Bitumen 80/100 binder and chip sizes 2 & 4 aggregate). It was last resealed in 2005. The road surface at Redvale and Northcote was described as open-graded porous asphalt (OGPA) (Bitumen 60/70 binder and chip size 14 aggregate). These sections were last resealed in 2002 and 2008, respectively.

3.3 Methods

3.3.1 Instrumentation and data collection

3.3.1.1 Overview

The study sites were instrumented to measure and record water levels for the estimation of discharge (flow) and to collect water samples during storm events. Temporary plywood sharp-crested V-notch weirs were installed at points of discharge from (a) the road surface and (b) treatment devices, including at culvert outlets, in pond drop structures, in roadside drains and in manholes. Each weir V was fitted with a 2mm thick stainless steel strip to produce the required 'sharp crest'. A 'zero stage' datum (comprising an aluminium strip, level with the invert of the weir V-notch) was built into each side of the weir, allowing accurate stage measurements to be taken during periods when the weir was flowing. Further details in relation to individual sites are provided below.

The water level upstream of each weir was measured by a float and counterweight-driven recorder, except at one site where there was insufficient space and a pressure transducer was employed (see below for details). Water levels were recorded to a stage resolution of 1mm at one-minute intervals during sampling events and at five-minute intervals when not sampling. Each logger was programmed with a customised rating equation relevant to the weir at the site, allowing the calculation of instantaneous and cumulative discharge, in order to trigger the collection of flow-proportional water samples.

15 Sloping sections were deliberately chosen to ensure that sufficient runoff depths and velocities were generated for discharge measurement and runoff sampling to be feasible.

An ISCO automatic water sampler was housed in a secure cabinet at each site (pre- and post-treatment). Sampler intakes were located so as to ensure samples were collected from freely flowing, well-mixed waters. The water samplers were set up for sampling before forecasted rainfall events by stocking them with 12 pairs of plastic and glass acid-washed sampling bottles. Plastic bottles were used to collect samples for metal analyses, to avoid the potential contamination associated with the use of glass, which contains traces of metallic elements (Batley 1989). Conversely, glass bottles were used for the collection of samples for TPH analysis to avoid potential contamination from the organic impurities that can accumulate in plastics (Liess and Schulz 2000) and to reduce sorption of TPH to the plastic walls of the bottle.

The samplers were 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 were 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 continued beyond the anticipated sampling period, the sampler was restocked with additional bottles and reprogrammed to continue sampling. Once returned to the laboratory, sample bottles were stored in the dark at 4°C until processed (usually within 48 hours).

During each visit to set up or collect samples, water level data was collected by unloading the logged measurements onto a laptop computer. Regular additional visits were made to collect this data at times when the samplers were not activated. During each visit to the site, field staff inspected 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 were recorded in a log book.

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

Note that rain gauges were not installed at any of the sites. Telemetred rainfall information was available from nearby gauges operated by Auckland Regional Council[16]. This data provided a near-real time check on the progress of events at each sampling site, while also allowing characterisation of the rainfall depths and durations associated with each event sampled. Details of the rainfall sites used are given below.

3.3.1.2 SH18 @ Westgate

As described in section 3.2.2, road runoff at Westgate discharged from a pipe outlet to a paddock. A plywood weir box was constructed around the pipe outlet (see figure 3.3) and this was instrumented and operated in accordance with the description above. The weir box was screened to avoid clogging with debris from overhanging vegetation and had baffles fitted internally to reduce the turbulence of the influent stormwater, to allow the accurate measurement of water level. Rainfall data was taken from Whenuapai (ARC site number 647601), located approximately 3.5km to the north-east.

16 http://maps.arc.govt.nz/website/maps/map_hydrotel.htm

3.3.1.3 SH1 @ Northcote

Untreated runoff from the kerbed section of the motorway at the Northcote site was directed into a submerged collection box, and from there through an approximately 5m long, 300mm diameter PVC pipe to a weir box (see figure 3.4a). The need to locate the collection box in soft ground required extension of the kerbing with a length of timber. A small piece of timber was also fitted approximately perpendicular to the road edge at the downstream edge of the collection box, in order to ensure that runoff was directed into the box. A screen was fitted to the weir box to prevent debris clogging the weir V. The site was instrumented and operated in accordance with the description above.

Figure 3.3 SH18 @ Westgate: weir, instrumentation for water level measurement and automatic sampler cabinet

Treated runoff from the swale section of the motorway at the Northcote site entered two concrete sumps, with water from the upstream sump piped to the lower sump. A weir was constructed in the downstream sump, below the point of entry of water from the upstream sump (see figure 3.4b). The sump was also fed by subsurface drainage discharged from the outlet of a 100mm novacoil pipe and this water was included in the measurement of swale flow. Owing to space limitations, the water level at this site was measured by a Greenspan PS 1000 pressure transducer connected to a NIWA hydrologger. Rainfall data was taken from Oteha (site number 647727) located approximately 5km to the north-west.

3.3.1.4 SH16 @ Huapai

As described in section 3.2.2 untreated runoff from the kerbed section of the highway at Huapai drained to an erosion-protected embankment. A plywood weir was constructed at the margin of the concreted area (see figure 3.5a). Treated runoff, discharged via the roadside drainage channel at Huapai, drained through a corrugated iron half-pipe set in concrete on the upper stream bank of Coopers Creek. A plywood weir was constructed at the outlet of this structure (see figure 3.5b). Both sites were instrumented and operated in accordance with the description above. Rainfall data was taken from Kumeu (site number 647513), located approximately 3.5km to the south-east.

Figure 3.4 SH1 @ Northcote: weir and instrumentation for water-level measurement at (a) kerbed site and (b) inside manhole at swale site

Figure 3.5 SH16 @ Huapai: weir and instrumentation for water level measurement at (a) kerbed site and (b) road drainage channel outlet.

3.3.1.5 SH1 @ Redvale

Untreated runoff at Redvale discharged to the stormwater pond via a concrete outlet structure. A plywood weir was constructed across the concrete apron below the outlet and incorporated baffles fitted internally to reduce the turbulence of the influent stormwater (see figure 3.6a). The pond discharged treated runoff via a manhole riser. A plywood weir was installed across the bed of the outlet structure along with a baffle to reduce turbulence (see figure 3.6b). Both sites were instrumented and operated in accordance with the description above. Rainfall data was taken from Awanohi (site number 646622), located approximately 2km to the north.

Figure 3.6 SH1 @ Redvale: weir and instrumentation for water level measurement at (a) pond inlet (b) pond outlet

3.3.2 Sample processing and analysis

3.3.2.1 Total suspended solids (TSS)

The full volume of each of the plastic bottle samples was agitated by hand and filtered through acid-washed, dried and preweighed polycarbonate membranes (0.4µm) using plastic, acid-washed, vacuum filtration equipment. After filtration, the membranes were redried in the laboratory oven at 60°C and reweighed to give the weight of TSS in the volume filtered.

3.3.2.2 Particulate and dissolved metals

Once reweighed for TSS determination, each membrane was transferred to a 50ml polypropylene vial for acid digestion and analysis of particulate copper, lead and zinc. A 14.5ml subsample was taken from the filtrate of each filtered sample for the analysis of dissolved copper, lead and zinc. The subsample was transferred to a 15ml acid-washed or sterilised plastic vial and acidified with the addition of 0.5ml of nitric acid. The membranes and filtrate subsamples were despatched to Hill Laboratories Ltd in Hamilton for determination of metal concentrations by inductively coupled plasma mass spectrometry (ICP-MS) according to method APHA 3125B.

3.3.2.3 Total petroleum hydrocarbons (TPHs)

The glass bottle samples were despatched to Hill Laboratories Ltd for determination of TPH concentrations following acidification by the addition of 0.5ml sulphuric acid. Hill Laboratories performed the TPH analysis by Gas Chromatography – Flame Ionization Detection (GC-FID) following solvent (hexane) extraction (Hill Labs' in-house method)[17].

3.3.3 Quality assurance

3.3.3.1 Water level measurement and runoff calculations

The float and counterweight recorders used in this study recorded water level to a 1mm resolution, while the pressure transducer employed at one site had a lower accuracy of ±2.5mm. As described in section 3.3.1, during each visit to the site, field staff compared, observed and logged water levels to monitor the accuracy of water level measurement. This was in accordance with standard NIWA hydrometric operating procedures (NIWA 2005).

As part of quality assurance checks, total and event runoff depths were calculated from discharge volumes and estimated site catchment areas. These runoff depths were compared with rainfall recorded at nearby gauges. An additional check on data collected at the Redvale site involved comparing the volumes of water discharged into, and out of, the stormwater pond. These checks revealed some important findings:

- At Northcote, runoff estimated at the kerbed site was around only 35% of that calculated from recorded rainfall for the period 1–22 February 2009. A site inspection detected a leak at the point of runoff collection, due to vehicle damage, which was duly repaired. For the remainder of the record, runoff estimated at the kerbed site was around 65% of recorded rainfall, suggesting systematic losses of runoff (see discussion in section 3.5.1).

17 Based on the American Petroleum Institute 'Method for the characterisation of petroleum hydrocarbons in soil' (P Robinson, pers comm April 2009).

- At Redvale, runoff estimated at the pond inlet varied between 100 and 122% of that calculated from recorded rainfall. This variation was seasonal, being higher in winter than summer, and was indicative of additional groundwater-fed contributions to the point of discharge during periods of wetter weather. Sumps draining the motorway central reservation were the most likely source of this additional runoff.
- The volume of water discharged from the pond during storm events was almost always greater than the volume measured at the pond inlet, by up to 30%. This variation pointed to a probable combination of additional groundwater-fed contributions and direct surface runoff from the depression surrounding the pond during periods of wetter weather, when the ground was saturated.

Note that in each case, the detection of these discrepancies led to a detailed review of water level records and stage-discharge rating curves to ensure that they were not an artefact of errors in water level measurement or the estimation of discharge. No such causes were evident and the findings for the Northcote and Redvale sites were therefore assumed to be real: in other words, the discharge that was measured differed from that estimated from rainfall records based on the assumed catchment area to each point of measurement. A further series of checks was therefore initiated to confirm that catchment areas were correctly defined and sized. Sites were visited during periods of rainfall to delineate flow paths and catchment boundaries. Following that process, some minor adjustments were made to the sizing of catchment areas, but not enough to greatly modify the findings described above, which were therefore accepted as real.

Contaminant loads (from which VEFs are estimated) were calculated from water volumes and contaminant concentrations. In the event that flows were under-recorded (as appears to have been the case at Northcote), contaminant loads will be underestimated. The flow record for the Northcote kerbed site was therefore adjusted to compensate for the losses detected through these quality assurance checks. For the estimation of VEFs (see chapter 4), flows were increased by 65% for the period 1–22 February 2009 and by 35% for the remainder of the record (again, see discussion in section 3.5.1).

There was no such need to make adjustments to the Redvale pond inlet and outlet flow records. While the records were suggestive of additional flows from the central reservation and pond depression, these had the effect of diluting the 'pure' road runoff, but did not affect the calculation of contaminant loads (because the effect of the increased volume was counteracted by the lower contaminant concentration). In arriving at this conclusion, the assumption was made that these additional sources of runoff would not be sources of non-road-related contaminants.

3.3.3.2 Sample processing and analysis

The protocols that NIWA follows for sample collection, storage and filtration are set out in sections 3.3.2. An additional quality control for the estimation of TSS involves frequent checking of the balance calibration with a small gold weight of about 100mg. For the analysis of particulate and dissolved metals, each batch of samples sent for analysis included a procedural blank and a duplicate sample.

Hill Laboratories are accredited by International Accreditation New Zealand for the metals and TPH analysis in conformance with standard NZS/ISO/IEC 17025: 2005. The laboratory undertakes a calibration standard recheck every 15 to 20 samples, and interference check solutions and numerous blanks are analysed in each batch of samples. For the analysis of TPH, solvent blanks are run to check

for contamination and avoid the potential for false positives. Samples are reanalysed if any deviation from the laboratory quality control criteria is detected.

3.3.4 Traffic count data

Traffic count data is available for all four of the sites (Transit NZ 2009). As described in section 3.2.1, this data was used to assess congestion levels at these (and other sites) as part of the site selection process. NZTA routinely monitors traffic flows on the Northern Motorway, and this met the need for traffic count data for VEF estimation at the Northcote and Redvale sites.

Published traffic count data for the SH16 @ Huapai and SH18 @ Westgate sites is based on irregular surveys. Additional surveys were therefore contracted to provide up-to-date data at these two sites. The surveys were not designed to span the entire sampling period at each site, but rather to collect data for a sufficient length of time to provide a reliable estimate of representative traffic flows for the later estimation of VEFs. The surveys of traffic counts were conducted by Traffic Counting Services over the periods 1 Nov–8 Dec 2008 (Huapai) and 30 Nov 2008–16 Feb 2009 (Westgate).

3.4 Results

3.4.1 Characteristics of sampling events

Table 3.2 summarises the characteristics of the storm events sampled at each site. Eight events were sampled at each of the Redvale and Huapai sites, seven at Northcote and six at Westgate. The original proposal for this study set a target of at least five events at each of three sites.

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 pond 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 @ Huapai sites in spring 2008 and was completed in autumn 2009.

Rainfall depths during the events that were sampled varied from 7mm (Event 6, Northcote) to 75mm (Event 1, Redvale) while the duration of sampling events ranged from 3 hours (Event 7, Huapai) to 83 hours (Event 5, Huapai), the latter comprising a series of events over a period of more than 3 days. The average event rainfall depths were similar across all sites other than Redvale, which had a markedly higher mean rainfall depth. Mean event durations were very similar at three of the sites, but substantially longer at Huapai.

The majority of sampling events followed periods of several days of dry weather, with the longest being a 20-day dry period prior to Event 2 at Huapai. Nine events were sampled within 36 hours of the last rainfall, the shortest dry period being 12 hours prior to Event 4 at Redvale. As with rainfall event durations, mean antecedent dry periods were very similar at three of the sites, but substantially longer at Huapai.

Event discharge volumes at each site varied by a factor of 4 to 7, while peak flows varied by a factor of 3 to 8. Event discharge volumes and peak flows were markedly higher at Redvale than at the other three sites, reflecting the much larger road catchment area draining to this site. At the other three

sites, mean event volumes decreased in the order Northcote > Huapai > Westgate, which was consistent with the ranking of road catchment areas. However, mean peak flows decreased in the order Huapai > Westgate > Northcote[18] indicating that other factors may have played an important role in determining the rate at which runoff was delivered to the point of measurement (eg road surface, refer to section 3.5.1).

Table 3.2 Summary of rainfall, discharge and antecedent weather characteristics during and prior to sampling events

Event	Dates	Rainfall depth (mm)	Rainfall duration[a] (hours)	Discharge volume[b] (m^3)	Peak discharge[b] (l/sec)	Antecedent dry period[c]
SH18 @ Westgate						
1	9/5/08	15	23	12	7.9	3 days
2	26/5/08	14	20	8	3.7	6 days
3	16/06/08	24	21	12	3.9	7 days
4	22/6/08	20	8	16	4.8	5 days
5	26/7/08	36	18	42	3.8	2 days
6	6–7/10/08	25	45	29	2.4	4 days
Mean		*22.3*	*22.5*	*19.8*	*4.4*	*4½ days*
SH1 @ Northcote						
1	12/2/09	9	4	18	0.9	2 days
2	20/2/09	41	8	81	7.0	5 days
3	27–28/2/09	42	10	83	3.7	7 days
4	5/3/09	34	16	67	3.9	5 days
5	19–21/4/09	19	24	32	1.6	10 days
6	26–29/4/09	7	76	15	0.9	2½ days
7	1–2/5/09	30	20	62	1.8	2 days
Mean		*26.0*	*22.6*	*51.1*	*2.8*	*5 days*
SH16 @ Huapai						
1[d]	9/12/08	22	16	28	8.7	7 days
2[d]	9–12/2/09	20	80	12	6.0	20 days
3	20/2/09	42	10	86	18.5	6 days
4[d]	19–21/4/09	15	27	21	6.5	10 days
5[e]	25–29/4/09	19	83	39	11.5	5 days
6[e]	1–2/5/09	27	16	56	7.0	2 days
7	30/5/09	13	3	25	9.6	5 days
8	9/6/09	25	11	64	9.0	9 days
Mean		*22.9*	*30.8*	*41.4*	*9.6*	*8 days*

18 This remains the case once the adjustment to flows at Northcote is made (see section 3.3.3).

Event	Dates	Rainfall depth (mm)	Rainfall duration[a] (hours)	Discharge volume[b] (m^3)	Peak discharge[b] (l/sec)	Antecedent dry period[c]
SH1 @ Redvale						
1	22–24/2/08	75	44	1066	61.0	6 days
2	1–2/3/08	23	24	270	76.0	6 days
3	13–14/4/08	47.5	30	546	56.0	10 days
4	15/4/08	35	9	601	148.0	12 hours
5	29/4/08	22	8	300	87.0	1½ days
6	16/6/08	31	18	489	38.0	10 days
7	26/7/08	28	9	771	110.0	1 day
8	6–7/10/08	35	45	523	198.0	6 days
Mean		*37.1*	*23.4*	*570.8*	*96.8*	*5 days*

Notes:

a) Duration over which samples were collected – rainfall was intermittent over this period during some sampling events.

b) Discharge measured at kerbed/inlet sites, prior to treatment.

c) Time elapsed since previous rainfall >1mm depth.

d) Discharge occurred at the kerbed site but not drainage channel outlet.

e) No discharge recorded at drainage channel outlet, possibly because of suspected leakage under the weir.

3.4.2 Runoff quality

The analytical results for each sample collected are given in Appendix B along with summary statistics for each site. Figures 3.7 to 3.13 provide a summary of these results, presenting the median, 10th percentile and 90th percentile values at each site for both untreated and treated[19] runoff of:

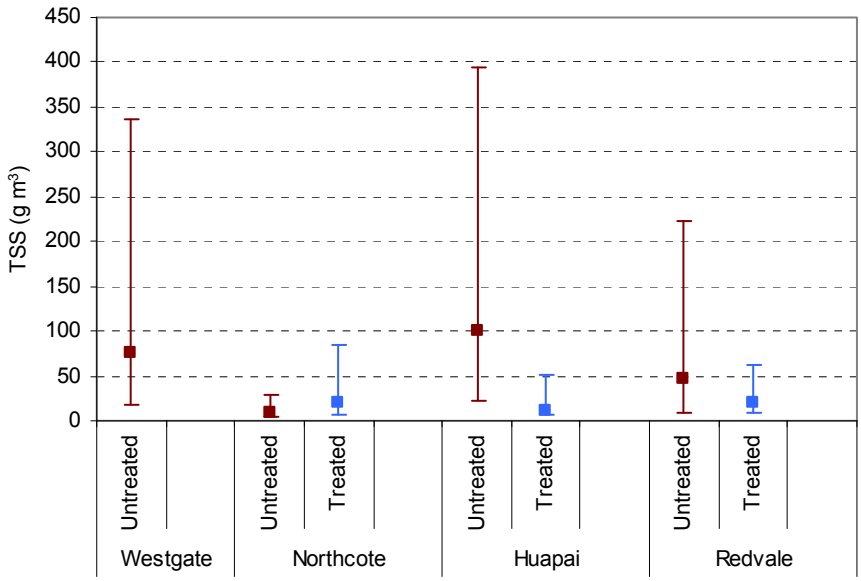
- TSS concentrations
- dry-weight copper and zinc concentrations in suspended sediments
- particulate, dissolved and total copper and zinc concentrations
- partitioning of dissolved and particulate copper and zinc
- total zinc to copper ratios.

3.4.2.1 TSS in road runoff

Median and 90th percentile TSS concentrations in untreated runoff were highest at Huapai (101g m^{-3} and 394g m^{-3} respectively), followed by Westgate and Redvale (figure 3.7). TSS concentrations in untreated runoff were much lower at Northcote (median 9g m^{-3}, 90th percentile 30g m^{-3}) than at the other sites.

19 'Untreated' and 'treated' referring to samples collected before and after conveyance through a stormwater pond, swale or roadside drain, respectively.

Figure 3.7 Median, 10th percentile and 90th percentile concentrations of TSS in samples of untreated and treated runoff



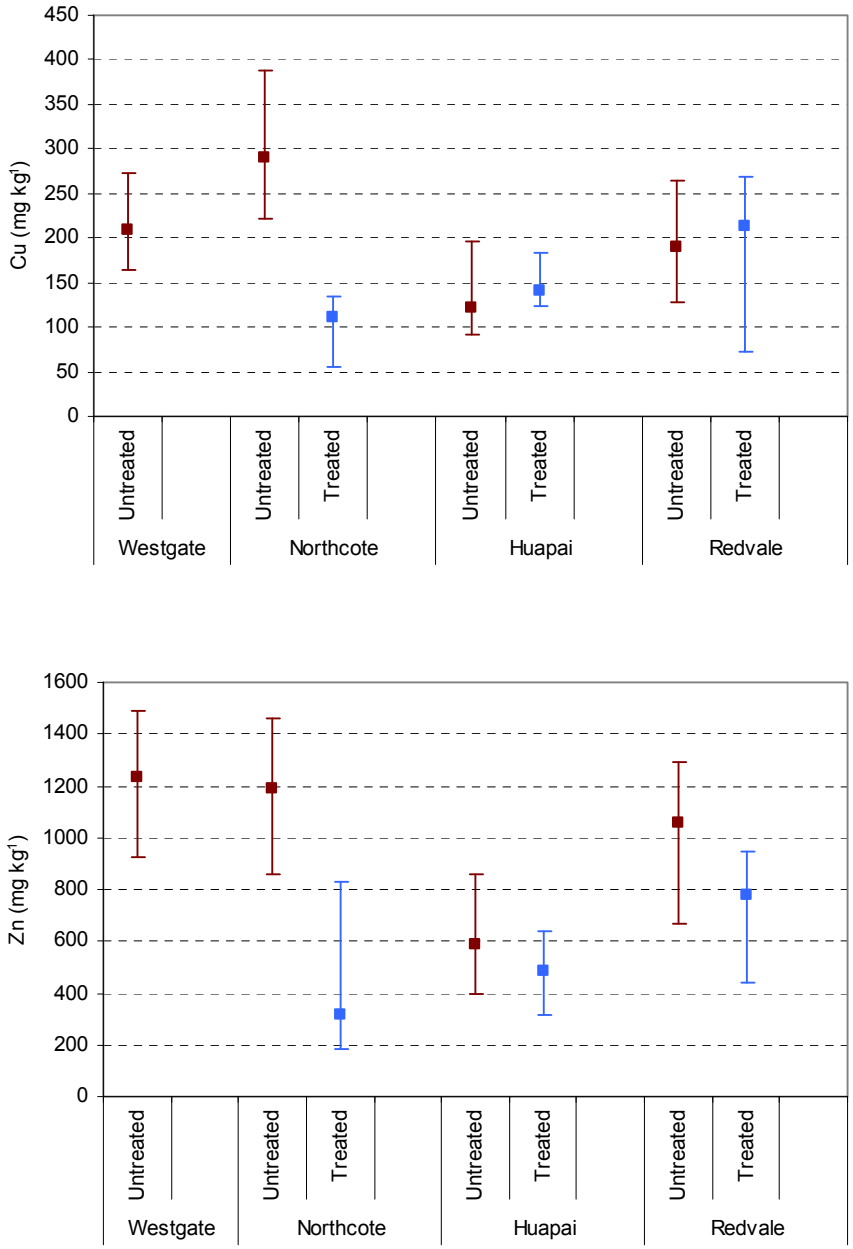
TSS concentrations were markedly lower in treated runoff than in untreated runoff at Huapai and Redvale, with median concentrations lower by 88% and 55%, respectively, at these sites. In contrast, TSS concentrations in treated runoff at Northcote were higher than in untreated runoff, with median and maximum concentrations of 19g m^{-3} and 85g m^{-3}, respectively.

3.4.2.2 Dry-weight copper and zinc in suspended sediments

Dry weight refers to the concentrations of solid copper and zinc in the suspended sediments filtered from runoff samples. Accordingly, it has units of mass per mass (mg kg^{-1}). These differ from the 'particulate' copper and zinc concentrations described below, those being the volumetric concentrations of solid copper and zinc in water samples and which have units of mass per volume (g m^{-3}). The dry-weight concentrations of copper and zinc provide useful information because, combined with TSS, they reveal whether a high particulate metal concentration in a water sample runoff is the result of either: (a) there being a lot of moderately contaminated sediment in the sample; or (b) there being a lesser amount of more highly contaminated sediment in the sample; or a combination of both (a) and (b).

Median and 90th percentile dry-weight copper concentrations in suspended sediments in untreated runoff were highest at Northcote (290mg kg^{-1} and 390mg kg^{-1}), followed by Westgate (figure 3.8). Median and 90th percentile dry-weight zinc concentrations were similar at these two sites (medians of 1190, 1223mg kg^{-1} and 90th percentiles of 1457, 1486mg kg^{-1}). Dry-weight metal concentrations in suspended sediments in untreated runoff were lowest at Huapai, with median values of between 42 and 64% of those at the other sites.

Figure 3.8 Median, 10th percentile and 90th percentile dry-weight concentrations of copper and zinc in suspended sediments in samples of untreated and treated runoff



Dry-weight copper and zinc concentrations were markedly lower in suspended sediments in treated runoff than those in untreated runoff at Northcote, with median concentrations lower by 62% and 74%, respectively, in the treated runoff (figure 3.8). Dry-weight zinc concentrations were also reduced (but not to the same extent) in suspended sediments in treated runoff samples at Huapai and Redvale. In contrast, median dry-weight copper concentrations were higher by up to 15% in road sediments in treated runoff than in untreated runoff at these two sites.

3.4.2.3 Copper in road runoff

Median and 90th percentile concentrations of total copper in untreated runoff were highest at Westgate (0.025g m^{-3} and 0.066g m^{-3} respectively), followed by Huapai and Redvale, then Northcote (figure 3.9). Total copper concentrations were markedly lower in treated runoff than in untreated runoff at all three sites sampled, with median concentrations lower by 40–62%.

Median and 90th percentile concentrations of particulate copper in untreated runoff were also highest at Westgate (0.015g m^{-3} and 0.06g m^{-3} respectively), followed by Huapai and Redvale (figure 3.9). Particulate copper concentrations in untreated runoff were much lower at Northcote (median 0.002g m^{-3}, 90th percentile 0.007g m^{-3}) than at the other three sites. Particulate copper concentrations were markedly lower in treated runoff than in untreated runoff at Huapai and Redvale, but less so at Northcote where the median concentration in treated runoff was only 25% lower than that in the untreated runoff samples.

In contrast to the results described above, median and 90th percentile concentrations of dissolved copper in untreated runoff were highest at Northcote (0.012g m^{-3} and 0.023g m^{-3} respectively) (figure 3.9). Median concentrations at the three other sites were between 30% (Huapai) and 57% (Redvale) of the value for Northcote. Dissolved copper concentrations were markedly lower in treated runoff than in untreated runoff at Northcote (median lower by 56%) and less so at Redvale. In contrast, the median dissolved copper concentration in treated runoff at Huapai was higher than in untreated runoff, with median concentrations of 0.0048g m^{-3} and 0.0037g m^{-3}, respectively.

The partitioning of dissolved and particulate copper in untreated runoff samples was noticeably different at Northcote compared with the other three sites (figure 3.10). At Northcote, copper was predominantly in the dissolved phase (median dissolved proportion of 82%, 90th percentile of 88%). Samples of untreated runoff from Westgate, Huapai and Redvale typically contained more copper in the particulate form (median dissolved proportions of 23–43%), although some samples from these sites did contain more dissolved copper (note the 90th percentile proportions of dissolved copper in excess of 60% at all three sites). Samples of treated runoff from all sites contained more dissolved than particulate copper (median and 90th percentile dissolved proportions of 57–74% and 76–85%, respectively). The dissolved proportion in treated runoff was higher than in untreated runoff at Huapai and Redvale, but not at Northcote.

Figure 3.9 Median, 10th percentile and 90th percentile concentrations of total, particulate and dissolved copper in samples of untreated and treated runoff

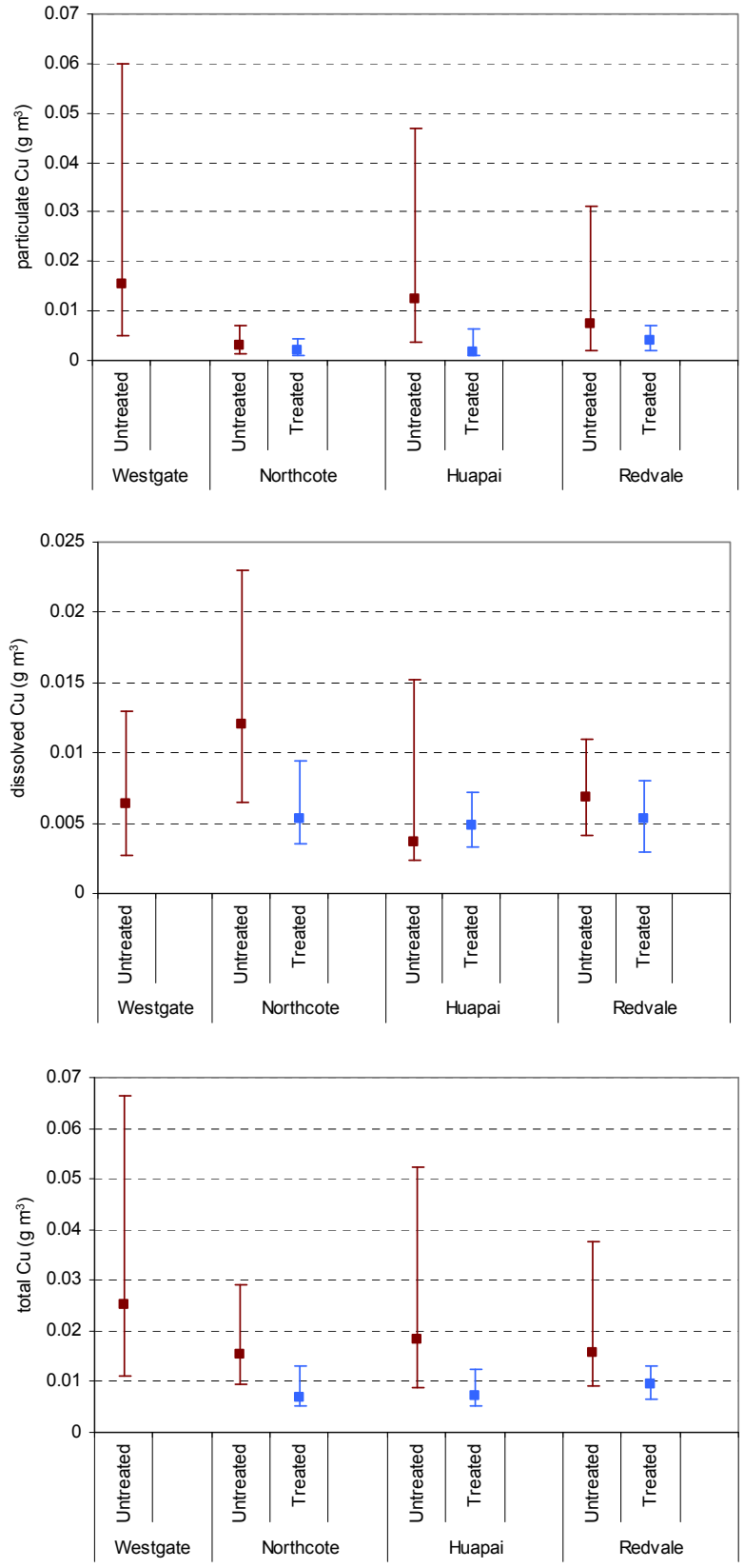
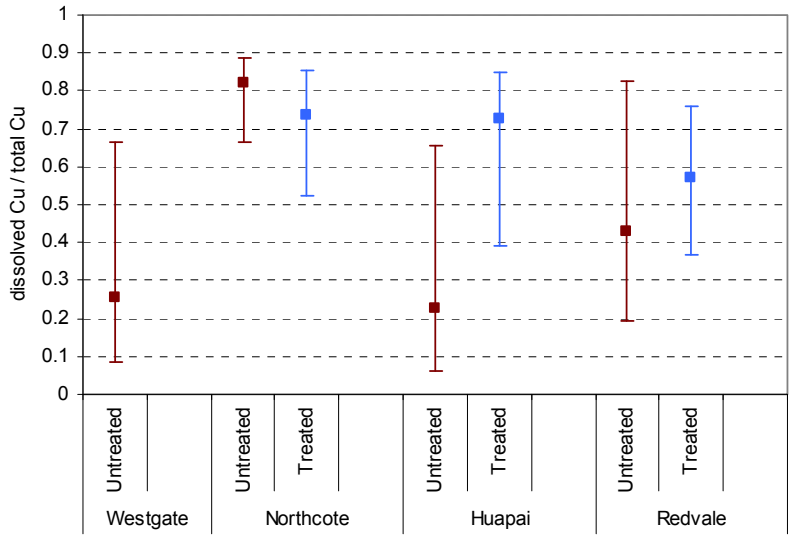


Figure 3.10 Median, 10th percentile and 90th percentile proportions of total copper present in the dissolved phase in samples of untreated and treated runoff



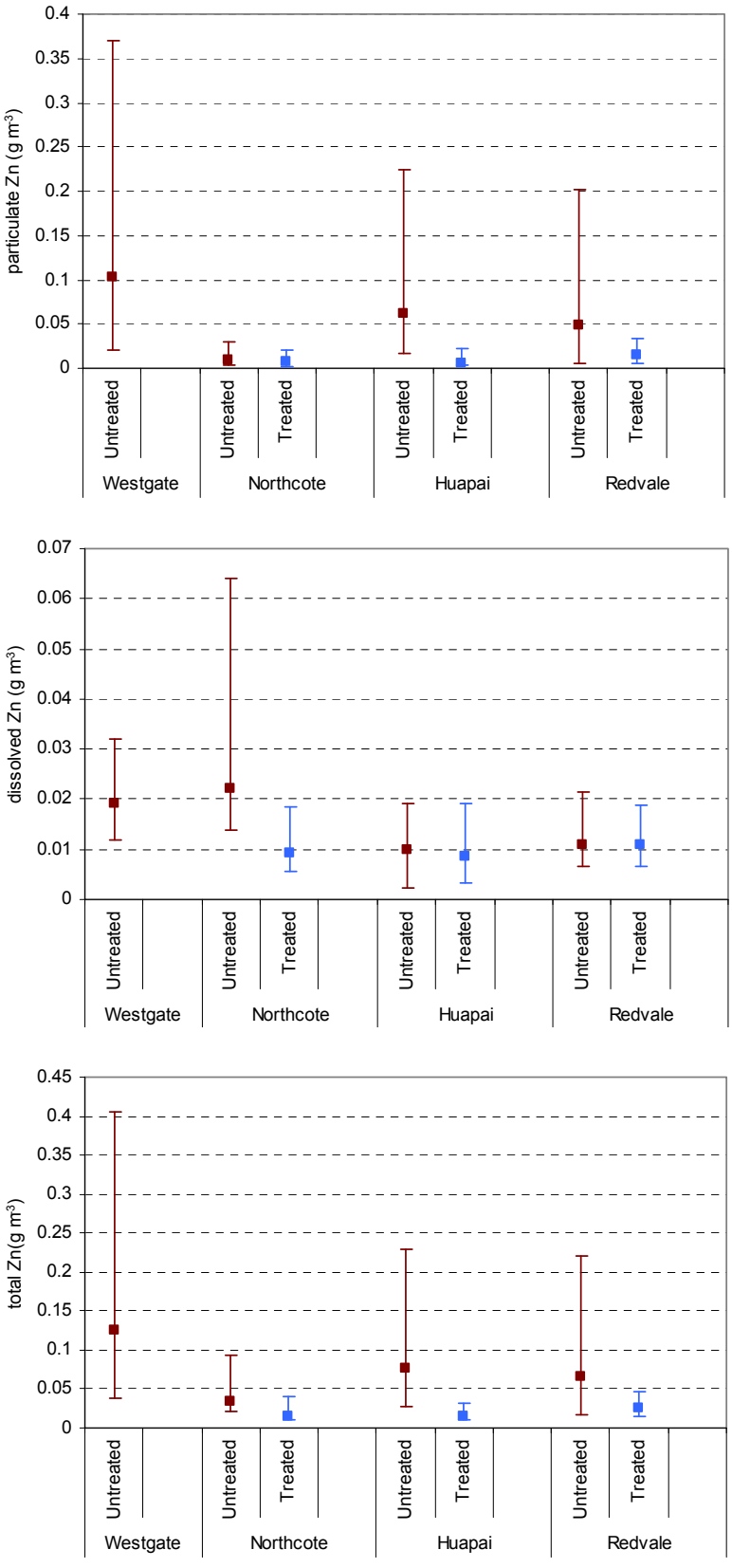
3.4.2.4 Zinc in road runoff

Median and 90th percentile concentrations of <u>total</u> zinc in untreated runoff were highest at Westgate (0.13g m^{-3} and 0.40g m^{-3} respectively), followed by Huapai and Redvale then Northcote (figure 3.11). Total zinc concentrations were considerably lower in treated runoff than in untreated runoff at all three sites sampled, with median concentrations lower by 53–81%.

Median and 90th percentile concentrations of <u>particulate</u> zinc in untreated runoff were also highest at Westgate (0.10g m^{-3} and 0.37g m^{-3} respectively), followed by Huapai and Redvale (figure 3.11). Particulate zinc concentrations in untreated runoff were much lower at Northcote (median 0.01g m^{-3}, 90th percentile 0.03g m^{-3}) than at the other three sites. As with particulate copper, particulate zinc concentrations were markedly lower in treated runoff than in untreated runoff at Huapai and Redvale. However, concentrations of particulate zinc in untreated and treated runoff at Northcote were similar, with median concentrations of 0.0096g m^{-3} and 0.0073g m^{-3}, respectively.

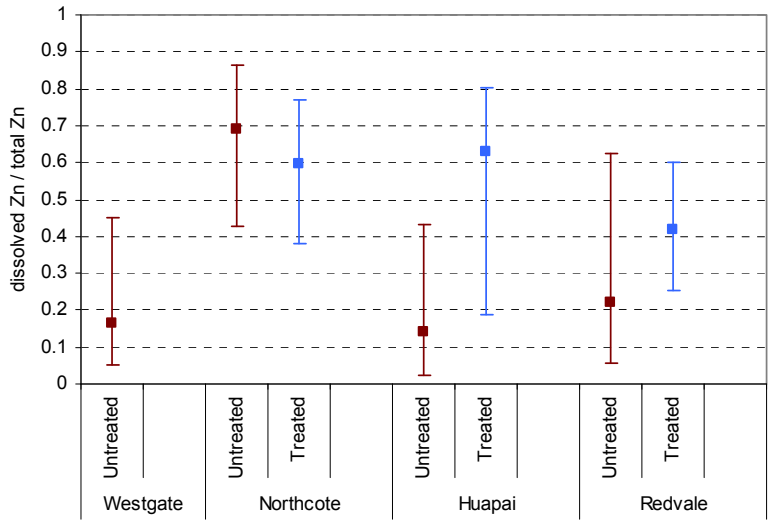
As with copper, median and 90th percentile concentrations of <u>dissolved</u> zinc in untreated runoff were highest at Northcote (0.022g m^{-3} and 0.064g m^{-3} respectively) (figure 3.11). Dissolved zinc concentrations were also relatively high at Westgate, but much lower at Redvale and Huapai, with median concentrations of 86%, 50% and 45% of the value for Northcote, respectively. While dissolved zinc concentrations were markedly lower in treated runoff than in untreated runoff at Northcote (median lower by 57%), there was little difference between dissolved zinc concentrations in untreated and treated runoff samples from both Huapai and Redvale.

Figure 3.11 Median, 10th percentile and 90th percentile concentrations of total, particulate and dissolved zinc in samples of untreated and treated runoff



The partitioning of dissolved and particulate zinc in untreated runoff samples was again noticeably different at Northcote than at the other three sites (figure 3.12). At Northcote, zinc was predominantly in the dissolved phase (median dissolved proportion of 69%, 90th percentile of 87%). Samples from the remaining three sites typically contained more zinc in the particulate form (median dissolved proportions of 14–22%), and only rarely did samples from these sites contain more dissolved than particulate zinc (note the lower 90th percentile proportions of dissolved zinc than that for dissolved copper). Samples of treated runoff from Northcote and Huapai generally contained more dissolved than particulate zinc, but the reverse was true in the majority of treated runoff samples from Redvale (median percentile dissolved proportion of 42%). The dissolved proportion in treated runoff was higher than in untreated runoff at Huapai and Redvale, but not at Northcote.

Figure 3.12 Median, 10th percentile and 90th percentile proportions of total zinc present in the dissolved phase in samples of untreated and treated runoff



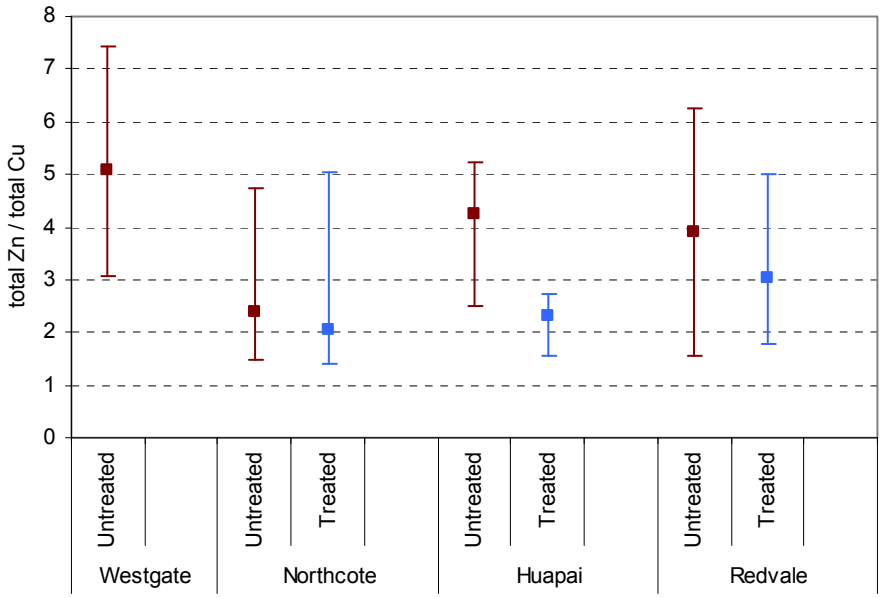
3.4.2.5 Zinc to copper ratios

Median total zinc:total copper ratios in untreated runoff were within the range 4:1 to 5:1 at all sites except Northcote, which had a lower median ratio of 2.4:1 (figure 3.13). Median zinc:copper ratios in treated road runoff were within the range 2:1 to 3:1 at the three sites sampled.

3.4.2.6 TPHs

TPHs were measured above the detection limit of 0.7g m^{-3} in only eight samples, seven of which were collected at Westgate and one at Huapai. TPH concentrations in the Westgate samples ranged from 0.84 to 3.9g m^{-3}, while the single sample at Huapai had a concentration of 0.77g m^{-3}.

Figure 3.13 Median, 10th percentile and 90th percentile ratios of total zinc:total copper in samples of untreated and treated runoff



3.5 Discussion

3.5.1 Variations in TSS

The key feature of the results of the sampling programme was the difference in road runoff quality at Northcote compared with the three other sites. Samples of untreated road runoff collected at Westgate, Huapai and Redvale contained much higher TSS concentrations than samples collected at Northcote. Samples from the first three sites contained more particulate than dissolved copper and zinc, while the reverse was true at Northcote. In essence, there appeared to have been a plentiful supply of road sediments to which the metals could bind at all sites other than Northcote.

Possible reasons for the lack of road sediments in runoff at Northcote included the following:

1 Road sediments were present in greater concentrations than detected, but the sampling methodology failed to collect representative samples.

2 Road sediments were generated and deposited on the road surface, but were more effectively removed by non-wash-off processes (eg atmospheric dispersion) than at the other sites.

3 Road sediments were generated and transported in runoff, but were trapped or deposited prior to the point of sampling.

4 The generation of road sediments occurred at much lesser rate than at other sites, because of, for example, the nature of the road surface, surrounding land use and traffic characteristics.

There was no evidence that the sampling methodology employed at Northcote (or at any of the other sites) was not collecting representative samples. Runoff was well mixed at the point of sampling and there was no evidence of excessive deposition of sediments either adjacent to the motorway kerb or in the roadside collection box within which the sampler intake was located (refer to section 3.3.1). Observations of the road surface and kerbside gutter appeared to confirm that this was a relatively 'clean' section of road compared to other sites.

Of the remaining possible reasons for the absence of road sediments at Northcote, a credible explanation was provided by the properties of the road surface at this site. As noted in section 3.2.2, the road surface at Northcote is open-graded porous asphalt (OGPA). While OGPA is widely used to improve the drainage characteristics of roads by allowing water to infiltrate its porous structure, the surface voids have the potential to become clogged with road debris or dust, thus compromising its ability to drain water (Lane 2008). Lane's study (for Transit NZ) assessed the effectiveness of high-pressure cleaning of OGPA to rejuvenate the permeability of the surface. Of relevance here is the finding that permeability prior to cleaning appeared to be strongly linked to the age of the road surface. Following cleaning, the permeability of surfaces that were three to six years old improved markedly, while there was little change for surfaces that had been laid within the two years prior to the study. Samples of the cleaning water recovered during the study were high in metals and an 'oily sludge'.

Sections of motorway in New Zealand are typically resealed with OGPA every six to eight years. The section of the motorway draining to the Northcote sampling site was sealed relatively recently, in early 2008[20]. On the basis of the trial results reported by Lane, it would be expected that this surface would be relatively permeable. The flow record for this site was consistent with this expectation: around only two-thirds of total rainfall appeared to have contributed to the runoff measured at the kerb (see section 3.3.3), suggesting that the remaining third drained by infiltration through the road surface. Associated with this infiltration, it was likely that at least some fraction (and perhaps the main part) of road sediments were deposited in the voids in the road surface. The results of the trial described by Lane suggested that, over time, the road surface at Northcote would become less permeable and, in that event, it might be expected that road runoff quality would gradually deteriorate.

The results from the same motorway at Redvale provided further support for this explanation. While the road surface at that location was also OGPA, it was last resealed in 2002 and so was likely to have relatively low permeability as a result of clogging of surface voids. Certainly, there was no evidence of 'missing' runoff in the Redvale flow record, and the broad similarity of the runoff quality with that sampled at the Huapai and Westgate sites suggested that contaminants deposited on the road were largely being discharged in runoff.

While the nature of the road surface at Northcote does provide a reasonable explanation for the substantially lower TSS concentrations in samples collected at this site, without further data (eg on permeability at this site in relation to others), at the time of writing, this explanation remains speculative. Accordingly, the extent to which the results obtained in this study are truly representative of contaminant loads discharged from the site, or are transferable to other roads of similar characteristics, is uncertain. Any application of the results from Northcote requires the use of considerable caution. However, the results do support further investigation of the 'treatment' characteristics of OGPA.

20 P Mitchell, Auckland Motorway Alliance, pers comm June 2009.

3.5.2 Evidence of variations in emission rates of copper and zinc

Putting aside questions over the lack of road sediments in samples collected at Northcote, other aspects of the sampling programme were more in keeping with expectations. Dry-weight concentrations of copper and zinc would be expected to be high at sites subject to frequent braking and acceleration. The relatively high dry-weight metal concentrations at Northcote and Westgate could have been indicative of these sites experiencing higher rates of brake pad and tyre wear than was the case at the Huapai and Redvale sites. These results corresponded well with the differences in levels of congestion.

3.5.3 Variations in copper and zinc concentrations in road runoff

High total metal concentrations in untreated road runoff at Westgate and Huapai reflected the relatively high TSS concentrations (and, in the case of Westgate, the high dry-weight concentrations of copper and zinc noted above) at these sites. The low total metal concentrations at Northcote reflected the very low TSS and corresponding low particulate metal concentrations at this site.

However, it is interesting to note that the total metal concentrations in samples collected at Northcote were not as low as might have been anticipated from the TSS results alone, because the 'missing' particulate copper and zinc was, to some extent, compensated for by relatively high concentrations of both metals in the dissolved phase. Northcote was the only site from which samples routinely contained higher concentrations of dissolved, rather than particulate, metals. This was less marked for zinc than copper, a result that was consistent across all sites: a greater proportion of total copper was in the dissolved phase than was the case for zinc.

3.5.4 Effect of treatment

Judged on the basis of sample TSS and total metal concentrations alone, the three treatment systems sampled were clearly effective at removing contaminants from road runoff. In the case of the Redvale pond and the Huapai drainage channel, this was achieved through the removal of TSS and particulate metals. Note that in both cases, the dry-weight concentrations of copper (but not zinc) on sediments in treated runoff were higher than in untreated road runoff, indicating the effect of preferential removal of coarser solids. Despite this, the substantial reduction in TSS concentrations in treated samples translated into a similar reduction in particulate and total metal concentrations. This was not the case for dissolved copper and zinc, which were present at similar concentrations in both treated and untreated samples. Given that the proportion of zinc present in the particulate form was generally greater than was the case for copper, treatment appears to have been slightly more effective for the removal of zinc than for copper.

At Northcote, the results were again quite different. In this case, the improvement in water quality due to treatment was because of a reduction in dissolved metal concentrations in the treated runoff samples. The mechanism for this reduction in dissolved metal concentrations was probably both vegetative filtration and infiltration, as swale flow at the point of sampling comprised both overland flow along the swale invert, and shallow groundwater flow discharged from subsurface drains. Another unique aspect of the results at Northcote was the fact that TSS concentrations were slightly higher in the swale flow than in the untreated road runoff. This appeared to indicate the addition of 'clean' sediments from areas other than the road surface, because dry-weight metal concentrations in the sediments contained in runoff samples collected at the swale outlet were much lower than those in the

untreated road runoff. Drainage from a mulched area that ran alongside the swale for much of its length could have been the source of this additional 'clean' sediment (See figure 3.2f).

3.5.5 Zinc to copper ratios

The similarity of zinc:copper ratios at three of the sites is suggestive of a consistent relationship between rates of tyre and brake wear at these three sites. The lower ratio at Northcote could be interpreted as indicating relatively low rates of tyre wear at this site as a consequence of, for example, the characteristics of the road surface or traffic behaviour. An alternative explanation is that this result reflects the importance of dissolved metals at this site and, as described above, the fact that more copper was present in the dissolved form than was zinc. In other words, less zinc was removed from the road surface because it has a greater tendency to bind to the particulate matter that for some reason did not find its way to the point of sample collection (eg became trapped in voids in the road surface).

3.5.6 Absence of TPHs

The non-detection of TPHs in the majority of runoff samples could have been the result of either a genuine absence of hydrocarbons on the road surface, or a failure of the sampling methodology to adequately collect representative samples. The potential for the latter arises where flow at the point of sampling is not well mixed, allowing floating hydrocarbon compounds to bypass the submerged entry point to the automatic water sampler intake.

Moores et al (2009b) reported a similarly low rate of detection of TPHs in samples collected at Richardson Rd in Auckland. As part of that study, grab samples[21] were collected in order to check that the apparent absence of TPHs in runoff samples was not a result of sampling methodology. Grab samples were taken at the entry to the catchpit, in the weir pond and at the weir outlet, with flow appearing to be well mixed in all three locations. A TPH concentration of 0.8g m^{-3} (slightly higher than the reporting limit) was measured in the sample collected at the catchpit entry. TPH concentrations in the remaining two grab samples were below the reporting limit and were consistent with concentrations in samples collected around the same time by the auto sampler. The results suggested a possible reduction in TPH concentrations as runoff passed through catchpits, but did not point to any undermeasurement of TPHs in post-catchpit flows because of sampling methodology (Moores et al 2009b).

Given that the same sampling methodology was adopted here, the results of this study appear to genuinely indicate that TPHs are rarely present in detectable concentrations at these sites. Their occasional detection at Westgate may reflect the more frequent congestion at this site, giving rise to greater potential for the accumulation of hydrocarbon spills and leaks on the road surface from stationary or slow-moving traffic. An additional factor allowing the detection of TPHs at Westgate may have been the relatively high TSS concentrations in road runoff at this site. The samples in which TPHs were detected tended to have elevated TSS concentrations (a mean of 332g m^{-3} compared with an overall mean of 131g m^{-3}). TPHs are found in elevated concentrations in samples of road sediments collected from catchpits (Depree 2008, Moores et al 2007), indicating that TPHs deposited on the road

21 Water samples collected manually by submersion of a sample bottle into the water body of interest.

surface that are not lost to the atmosphere by volatilisation tend to bind to road sediments and be removed in runoff.

While TSS concentrations were slightly higher at Huapai than at Westgate, and lower at Redvale, traffic generally moved freely at these sites, limiting the potential for accumulation of hydrocarbon spills and leaks in the road catchment. At Northcote, there was greater potential for hydrocarbon losses from congested traffic, but TSS concentrations in runoff samples were extremely low. If, as suggested in section 3.5.1, road sediments are accumulating in voids on the road surface at this site, then it is conceivable that hydrocarbon losses are trapped by this same process. Over time, there may be increased likelihood of detectable TPH concentrations in runoff discharged at this site.

Because of the absence of detectable concentrations of TPHs in the majority of samples collected as part of this study, no attempt has been made to estimate TPH loads, or the efficiency of their removal by road runoff treatment, in the following chapters.

4 Vehicle emission factors

4.1 Introduction

This chapter describes the estimation of vehicle emissions factors (VEFs) of copper and zinc in road runoff from the results of the sampling programme described in chapter 3. The calculation of a VEF requires information on contaminant load, vehicle numbers and the length of road discharging to the point of sampling.

VEFs were calculated by two different methods, depending on the way in which the contaminant loads had been estimated:

1 event-based estimates, calculated from the contaminant load and vehicle number estimates associated with each storm event sampled

2 longer-term estimates, derived from modelling contaminant loads over the entire period of flow measurement at each site.

At the project scoping stage, it was proposed that VEFs be estimated according to the former method. This same method was used to estimate VEFs from previously unpublished data held by NIWA, as described in section 2.2.5. The strength of the method is that VEFs are derived solely from loads estimated from measured data. Loads are calculated for each storm event, based on recorded water volumes and contaminant concentrations in samples. There is no extrapolation to periods of time for which no data is collected. VEFs are then calculated from these loads and the estimated traffic numbers preceding each sampled event.

However, this method has a number of weaknesses:

- It is difficult to quantify the extent to which VEFs estimated from the storm events sampled are representative of the long-term emission rate of contaminants.
- It is likely that estimates derived in this manner are sensitive to storm event characteristics.
- There can be uncertainty regarding the length of the period preceding each storm event during which the number of vehicles contributing to the load should be counted.

These issues were identified in section 2.2.7 of this report as being some of the temporal factors that can influence VEF estimates.

In recognition of the potential uncertainty in VEF estimates derived by the event-based method, the decision was made to also derive estimates by another method: modelling contaminant loads over a longer time period. This involved using an existing contaminant accumulation/wash-off model that has been developed specifically for the estimation of contaminant loads from roads and other pervious surfaces. While this approach provided the potential to overcome short-term variability in VEF estimates associated with individual storm events, it relied on extrapolation of contaminant loads over the whole period of record (6–10 months, depending on the site).

Section 4.2 describes each of the two methods in more detail, while results and discussion are provided in sections 4.3 and 4.4, respectively.

4.2 Methods

4.2.1 Event-based method

The event-based method for estimating VEFs involved, firstly, estimating the event load (EL) of copper and zinc from measured sample concentrations and the volume of flow between successive samples. The event load for an individual event is given by:

$$EL = \sum_{i=1}^{n-1} \frac{(C_i + C_{i+1})}{2} \bullet q_i$$

(Equation 4.1)

where

c_i = contaminant concentration in sample i

q_i = runoff volume between sample i and sample i+1.

The event loads from each sampling event were summed to give the total contaminant load (Σ EL) of copper and zinc during all sampled storm events at each site.

The vehicle movements corresponding with each sampling event were estimated from traffic counters deployed at each site, or from published traffic data (see section 3.3.4). The number of vehicle movements for each event included all preceding movements since the previous runoff-generating event (ignoring showers of up to 1mm rainfall depth, which typically fail to generate runoff), and vehicle movements during the event. This involved multiplying the AADT by the number of antecedent dry days and the number of days in the sampled storm event. The vehicle movements associated with each event were then summed to give the total vehicle movements (Σ VM) associated with all sampled storm events.

The length of road (L, in metres) discharging to the sampling point was estimated from a combination of field observations and analysis of aerial photographs.

The vehicle emission factor for either copper or zinc was given by:

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

(Equation 4.2)

VEF estimates calculated by this method are referred to below as 'event-based aggregate' estimates. VEFs for individual sampling events were also calculated from the loads and vehicle numbers associated with each event, to provide an indication of variability around the aggregate estimates for each site.

4.2.2 Modelling contaminant loads

Contaminant loads in runoff over the full period of flow measurement at each site were estimated by application of a contaminant accumulation/wash-off model, STORMQUAL. This model was developed and first applied for the estimation of contaminant loads from data collected from runoff sampling at Richardson Rd, Auckland in the early 2000s (Timperley et al 2003 and 2005). The method involves

fitting modelled contaminant loads to those derived from measured sample concentrations and runoff volumes by adjusting four parameters that control the modelled rate of contaminant accumulation and wash-off. The model can then be used to predict contaminant loads for storm events that were not sampled.

4.2.2.1 Model description

Contaminant loads are estimated for each five-minute timestep as follows (Timperley et al 2003):

- Wash-off intensity (I), equivalent to runoff depth, is estimated as the volume of flow (Q_t) over each five-minute period (t) divided by the catchment area (A).
- The wash-off fraction (F) is the proportion of the contaminant load present on the road surface that is washed off during time period (t). The wash-off fraction is calculated as:

$$F = 1 - e^{-(SI)^B}$$

(Equation 4.3)

where

S is a slope coefficient, and

B is an exponent.

The gross accumulation (GM_t) at the end of each time step is the contaminant load available for wash-off. It is calculated as:

$$GM_t = ((tRA) + NM_{t-1}) \bullet (1 - D)$$

(Equation 4.4)

where

R is the contaminant accumulation rate

NM_{t-1} is the net accumulation at the end of the previous timestep.

D is a non-wash-off coefficient (representing contaminant removal by other processes such as atmospheric dispersion).

Net accumulation at the end of each timestep is the load remaining on the road after wash-off has occurred. It is given by:

$$NM_t = GM_t \bullet (1 - F)$$

(Equation 4.5)

The load washed off in each timestep (L_t) is the difference between gross and net accumulation, ie:

$$L_t = GM_t - NM_t$$

(Equation 4.6)

4.2.2.2 Model optimisation

Modelled five-minute loads were fitted to loads derived from measured sample concentrations and measured flow by adjusting the values of R, D, S and B. The values of these parameters were optimised by minimising the sum of differences and absolute sum of differences between modelled and measured loads. Optimisation was aided by the use of graphs to check the linear regression relationship between modelled and measured loads (aiming for a slope of 1) and of the time series of modelled and measured loads during each sampled event. Once optimised, a final check was run by extracting the modelled loads for each of the events sampled and comparing these with the loads calculated from the measured sample concentrations and flow data.

Figure 4.1 provides an example of the fit between 'modelled' and 'measured' loads during two storm events sampled at the SH18 @ Westgate site. Table 4.1 shows the comparison of modelled loads and loads that were derived from measured sample contaminant concentrations for each event, and for each site in total. The loads estimated by the two methods generally agreed well, with differences explained to some extent by the timing of sample collection. For instance, where samples were collected either side of periods of peak flow, event loads estimated from sample concentrations are likely to be underestimated because the concentrations themselves are not representative of the period of more intense runoff. In one case, Event 7 at Huapai, the modelled loads were significantly lower than those estimated from sample concentrations. This event was an anomaly, with TSS (and consequently particulate metal) concentrations sustained at high levels throughout the event. While the reasons for this are not clear, the model was unable to replicate the load estimated from sample contaminant concentrations when run with the parameter set that produced optimum results for the other seven events. The decision was made to fit the model to those seven events and accept underestimation of the Event 7 load, rather than to use suboptimal parameter values, which would likely result in an overestimation of loads in seven of the events and over the period of record as a whole. Plots from all the six to eight events sampled at each site, along with the optimised parameter values and descriptors of model goodness of fit, are contained in Appendix C.

4.2.2.3 VEF estimation

Once optimised, the total copper and zinc loads (TL) over the entire period of flow monitoring at each site (6–11 months) were estimated by summing the values of L_t. The total number of vehicle movements (VM) over the period of record was estimated by multiplying the AADT by the number of days of record. The length of road (L) was known from the analysis undertaken for the event-based method.

The vehicle emission factor for either copper or zinc was then given by:

$$VEF = TL/(VM \times 1000/L) \qquad \textit{in units of mg/veh/km}$$

(Equation 4.7)

Figure 4.1 Time series of total zinc load estimates derived from measured runoff volumes and sample concentrations ('measured') compared with loads predicted from contaminant accumulation/wash-off modelling ('modelled'), SH18 @ Westgate, 26–27 July 2008

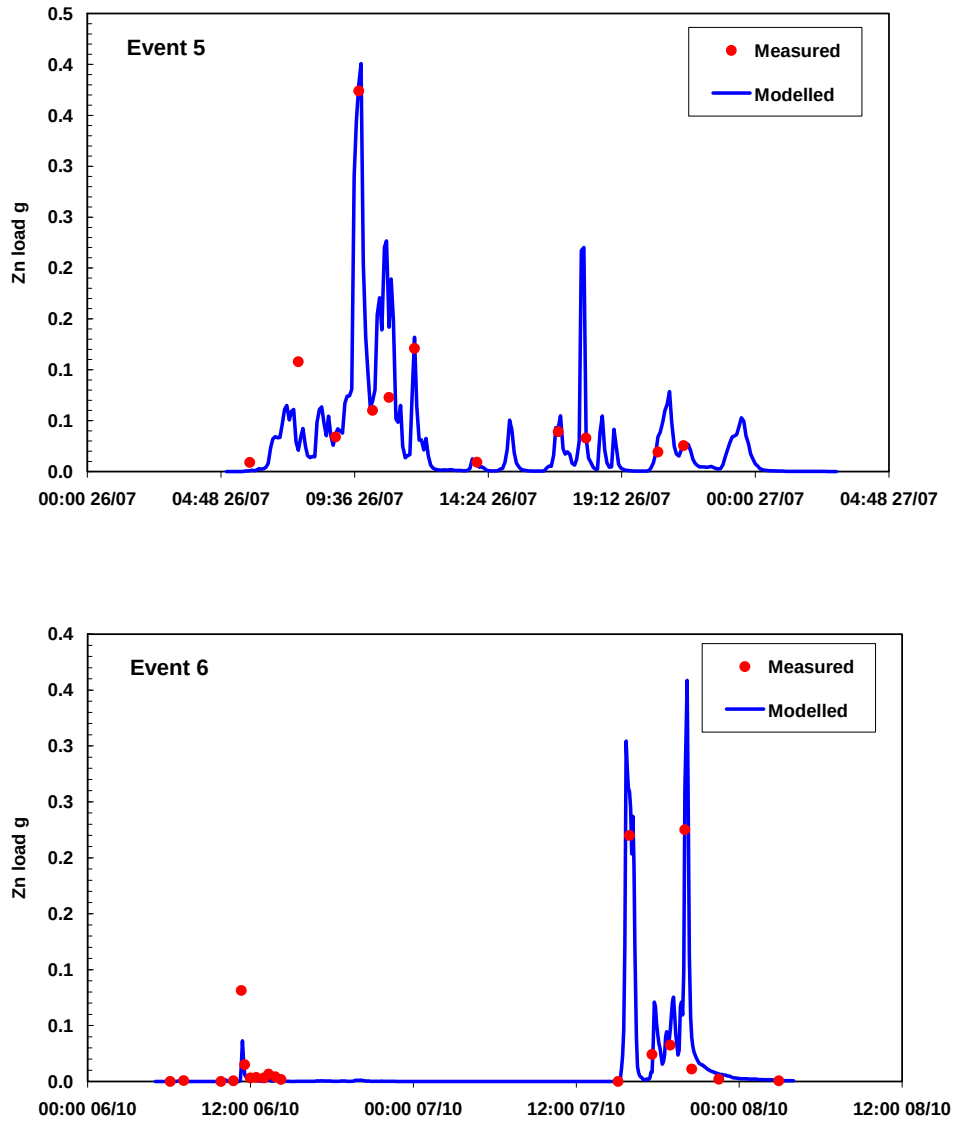


Table 4.1 Comparison of total copper and total zinc load estimates derived from measured runoff volumes and sample concentrations ('measured') with loads predicted from contaminant accumulation/wash-off modelling ('modelled')

Event	Total copper load (g)		Total zinc load (g)	
	Measured	Modelled	Measured	Modelled
Westgate				
1	0.39	0.27	2.3	1.6
2	0.18	0.19	1.3	1.2
3	0.72	0.62	4.9	3.8
4	0.27	0.76	1.8	4.7
5	1.5	1.3	8.1	8.0
6	0.96	0.94	8.5	5.7
Total[a]	*4.1*	*4.1*	*26.8*	*25.0*
Northcote				
1	0.67	0.24	1.1	0.8
2	1.4	1.4	3.6	6.6
3	0.98	0.96	6.2	3.4
4	0.82	0.72	1.7	2.4
5	0.69	0.36	1.1	1.1
6	0.33	0.09	0.8	0.3
7	0.88	0.87	2.4	3.1
Total[a]	*5.7*	*4.6*	*17.0*	*17.5*
Huapai				
1	0.89	0.47	3.5	1.8
2	0.25	0.16	0.53	0.55
3	1.9	1.8	8.5	9.9
4	0.60	0.34	3.2	1.3
5	0.66	1.4	3.3	5.8
6	0.64	0.55	2.8	2.7
7	1.3	0.34	5.3	1.3
8	1.6	1.1	6.6	5.34
Total[a]	*7.8*	*6.2*	*33.7*	*28.7*
Redvale				
1	16.0	19.0	77.0	120.0
2	6.6	4.3	18.0	28.0
3	9.7	8.1	45.0	44.0
4	21.0	16.0	150.0	110.0
5	3.3	6.7	11.0	43.0
6	7.4	5.6	32.0	29.0
7	9.4	7.8	50.0	51.0
8	14.0	9.8	83.0	58.0
Total[a]	*87.0*	*77.0*	*470.0*	*480.0*

Notes:

a) Sum of individual event totals

4.3 Results

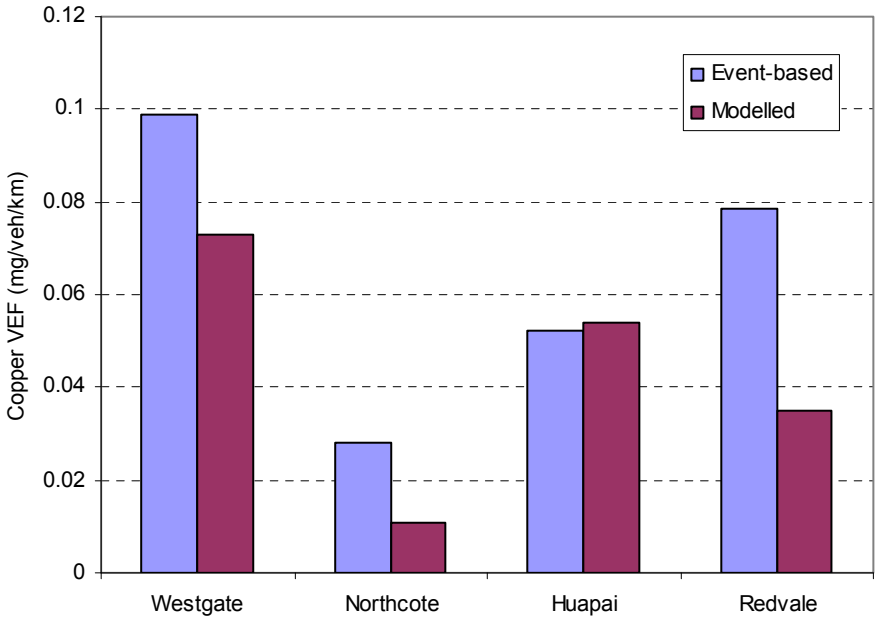
VEF estimates for total copper and total zinc at each of the four sites are presented in figure 4.2 and table 4.2. The table includes estimates made by the event-based method based on the aggregated load and vehicle numbers from all sampled events combined, and the range of VEFs estimated for individual events.

Copper and zinc VEF estimates calculated by both methods were highest for Westgate and lowest for Northcote. VEF estimates (event-based aggregates and modelled) for Westgate were between 3.5 and 11 times those for Northcote. The ranking of the two intermediate sites differed according to the method: VEFs estimated by the event-based method were higher for Redvale than Huapai, while the reverse was true for modelled VEFs. Copper and zinc VEFs (event-based aggregates and modelled) estimated for these sites were between 41% and 78% of the estimated values for Westgate.

Modelled VEF estimates were lower than event-based aggregate estimates by 20–61% for all sites other than Huapai. For Huapai, modelled estimates were higher than event-based aggregates by 4% for copper and 22% for zinc.

VEFs estimated by the event-based method for individual events were extremely variable. The range of estimates was greatest for Redvale, with maximum VEFs 77 and 39 times larger than minimum estimates for zinc and copper, respectively. The range was least for Northcote, with maximum VEFs only 8 and 5.5 times larger than minimum estimates for zinc and copper, respectively.

Figure 4.2 Total copper and total zinc VEFs for the four sampling sites: comparison of event-based aggregates and modelled estimates



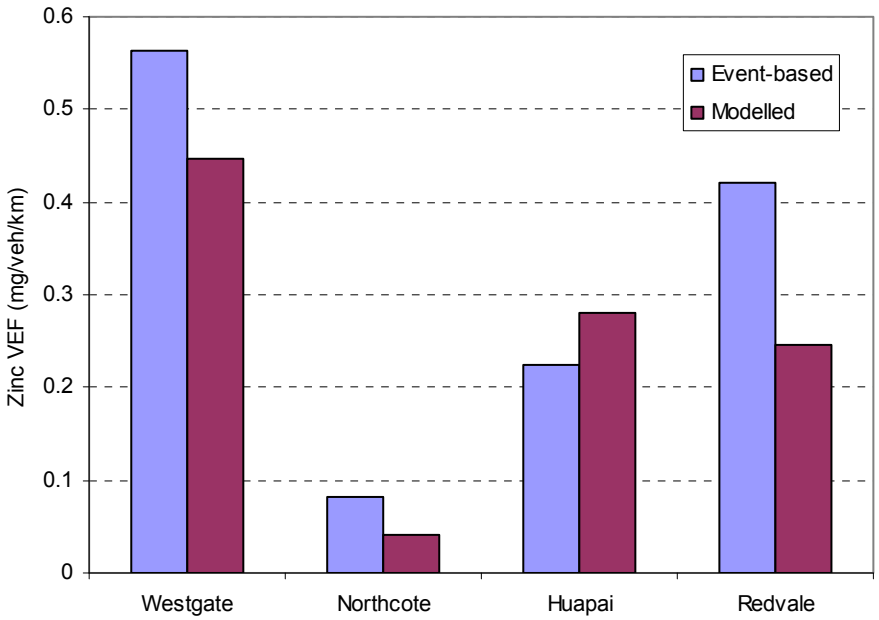


Table 4.2 Total copper and total zinc VEF estimates for the four sampling sites: comparison of event-based aggregates and ranges for individual events with modelled estimates

Site	Congestion[a] (AADT/ capacity)	Copper (mg/veh/km)			Zinc (mg/veh/km)		
		Event-based		Modelled	Event-based		Modelled
		Aggregate, all events	Range, individual events		Aggregate, all events	Range, individual events	
SH18 @ Westgate	1.38	0.099	0.021–0.45	0.073[b]	0.56	0.15–2.31	0.45[b]
SH1 @ Northcote	0.81	0.028	0.012–0.066	0.011	0.08	0.019–0.16	0.04
SH16 @ Huapai	0.52	0.052	0.005–0.15	0.054	0.23	0.011–0.66	0.28
SH1 @ Redvale	0.40	0.078	0.030–1.16	0.035[b]	0.42	0.11–8.5	0.25[b]

Notes:

a) After Gardiner and Armstrong (2007).

See section 4.4.4 for adjusted values to compensate for the effect of catchpits

4.4 Discussion

4.4.1 Variations in VEF estimates between sites

Consistent with the results of the sampling programme described in section 3.4, VEF estimates for Northcote were low compared with those for the other three sites. For the reasons noted in section 3.5.1, and in particular the relative newness and porosity of the road surface, the results for Northcote are unlikely to be representative of actual vehicle emissions at this site.

Setting the estimates for Northcote aside, there was a distinction between the VEF estimates for the most congested site (Westgate), and the least congested sites (Huapai and Redvale). The difference between Westgate and Huapai was more marked on the basis of the event-based aggregate estimates, with copper and zinc VEFs of 0.099 and 0.56mg/veh/km respectively for Westgate and 0.052 and 0.23mg/veh/km for Huapai. However, on the basis of the modelled estimates, the difference between Westgate and Redvale was greater, with copper and zinc VEFs of 0.073 and 0.35mg/veh/km respectively for Westgate and 0.045 and 0.25mg/veh/km for Redvale. In both cases, there appeared to be a relationship between traffic behaviour, as measured by congestion levels, and emission factors of copper and lead.

4.4.2 Variability in VEF estimates for each site

VEFs estimated from individual event data varied by an order of magnitude (see table 4.2). Clearly, there was substantial variation in the relationship between the accumulation of contaminants on road surfaces and their removal in road runoff: as noted in section 2.2.7, contaminants do not simply accumulate and wash off at a constant rate. Antecedent weather conditions and rainfall event intensity, duration and frequency are important factors driving these variations (Ellis et al 1986; Hewitt and Rashed 1992). Frequent heavy rainfall of long duration is likely to promote 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 in between rainfall events.

A specific example illustrates the way in which these factors influenced the event-based VEFs shown in table 4.2. Event 3 at Redvale followed a 10-day dry period. The event removed an estimated 45g of zinc from the road, and the resulting VEF estimate (based on 275 hours of vehicle movements) was 0.17mg/veh/km. Just 12 hours later Event 4 was sampled. While this event was of lesser depth (35mm compared with 47.5mm) it was more intense (duration nine hours compared with 30) and was more effective in moving sediments and metals off the road. The event removed an estimated 154g of zinc from the road, and the resulting VEF estimate (based on just 20 hours of vehicle movement) was 8.5mg/veh/km. While this was a somewhat extreme example, with only one other event at Redvale having an estimated zinc VEF of more than 1.0mg/veh/km, it clearly illustrates the influence of antecedent dry period and event characteristics.

These interevent variations in VEFs are important: they indicate the uncertainty in extrapolating a long-term VEF from only a small number of sampling events. Aggregated VEF estimates derived from predominantly high-intensity rainfall events following short periods of dry weather are likely to be higher than estimates derived from lower-intensity rainfall events following long dry periods.

4.4.3 Comparison of event-based with modelled VEF estimates

The influence of the characteristics of the sampling events helps to explain the differences between the event-based and modelled VEF estimates shown in figure 4.2 and table 4.2. Event-based aggregate estimates were higher than modelled estimates at Westgate, Northcote and Redvale. This implies that the events sampled at these sites yielded higher loads of copper and zinc per unit of time than was the case over the longer period from which the modelled estimates were derived (181, 198 and 322 days at Westgate, Northcote and Redvale, respectively). In other words, the events sampled at these sites were relatively effective at removing contaminants from the road. Less effective events, such as those characterised by low rainfall depth and intensity, were under-represented in the sampling programme. Evidence of this came from a comparison of the daily rainfall depths during the sampling events with those on all rain days (ie any day on which rain was recorded) over the period of monitoring as a whole. For example, sampling at Westgate occurred on days on which the average rain day rainfall depth was 19mm, compared with 5.6mm over the period of runoff monitoring as a whole.

The difference between event-based and modelled VEF estimates was greatest for Redvale, which implies that the events sampled at this site were the least representative of runoff events over the longer term. The events sampled at Redvale did indeed have a higher mean rainfall intensity (depth/duration, from table 3.2) than at the other sites: 1.6mm/hr, compared with 1.0mm/hr at Westgate and 1.2mm/hr at Northcote. Redvale had the highest single event rainfall of 75mm, and five events with depths more than 30mm, compared with only one at Westgate and three at Northcote.

In contrast with the other sites, modelled VEF estimates for Huapai (from 223 days of runoff measurement) were higher than the event-based aggregates, although differences between the two sets of estimates were not great, particularly for copper. This implies that the sampled events at Huapai were reasonably representative of the contaminant removal effectiveness of events over the longer term. Compared to the other sites, events sampled at Huapai had a lower mean rainfall intensity (0.7mm/hr) and included only one event with more than 30mm rainfall depth. Two of the events at Huapai were characterised by relatively long durations (80 and 83 hours) over which rain fell intermittently.

As noted in section 4.4.2, the extent to which the VEF estimates derived from the event-based method are representative of the long-term VEF at each site is subject to considerable uncertainty because of the influence of individual sampling event characteristics. It can be expected that as the number and type of rainfall events sampled increases, the event-based aggregate VEF estimates would gradually tend towards a stable value. However, these results suggest that this point has not been reached with the small number of events (six to eight) monitored at each site.

As a result, modelled VEFs estimated over the entire period of runoff 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. This conclusion is made on the basis that the level of agreement between 'modelled' and 'measured' loads was considered satisfactory for the storm events sampled at each of the four sites.

4.4.4 Adjustment for catchpits

An additional source of uncertainty in the VEF estimates for Westgate and Redvale was the fact that runoff samples at these sites were collected at pipe outlets discharging from roadside catchpits. It was likely that the TSS and metal concentrations in these samples (and hence loads calculated from these concentrations) were reduced from those in untreated road runoff, although this reduction could have been relatively limited, as discussed below.

Semadeni-Davies (2008) reviewed a number of studies of catchpit performance, including that of Pitt and Field (2004), who reported that a well-designed and well-maintained catchpit could retain up to 35–40% of the annual sediment load in stormwater. However, the sediments retained tend to be coarse-grained, typically in the 250–2000µm size range, while copper and zinc tend to be associated with finer sediment fractions. Kennedy and Gadd (2003) analysed road dust samples collected in Waitakere City and reported median copper and zinc concentrations of 149mg/kg and 326mg/kg, respectively, on <2mm fraction, and 297mg/kg and 431mg/kg, respectively, on <63µm fraction. Ding et al (1999) reported on a study that found that 93% and 95% of the total copper and zinc load, respectively, was associated with sediments <100µm.

Semadeni-Davies (2009) has developed performance rules for catchpits as part of the development of a Catchment Contaminant Annual Load Model (C-CALM). These rules link catchpit performance to the particle size distribution of sediments conveyed in runoff. Based on the 2008 literature review reported above, the rules assume that catchpits do not remove any sediments (or associated metals) smaller than, or equal to, 96µm). Depending on the particle size distribution of sediments, this results in a reduction in TSS due to treatment by catchpits by around 10% at best, and in particulate metals by less than this.

An alternative estimate derived from New Zealand data (Timperley and Skeen n.d.) suggested that catchpits were slightly more effective, removing 20% of TSS. Associated estimates of removal rates of total zinc and total copper were 11% and 15% respectively (M Timperley, pers comm 2009). A recent study by NIWA for ARC collected 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 these estimates (Moores et al 2009b). At the time of writing, the results of the analyses of this latest data were not yet available.

In the interim, the VEF values for Westgate and Redvale, presented in table 4.2, were considered to be underestimates of the true (pre-catchpit) VEFs by a value in the range 5–15%. Upwards adjustment of

the modelled estimates by the mid-range value of 10% gives the following pre-catchpit VEF estimates for these sites:

- Westgate:
  - copper: 0.08mg/veh/km
  - zinc: 0.5mg/veh/km.
- Redvale:
  - copper: 0.039mg/veh/km
  - zinc: 0.28mg/veh/km.

4.4.5 Comparison with previous estimates

The review of previous studies summarised VEF estimates as falling into one of two groups (see section 2.2.6):

a) Relatively high estimates, ie previous VEF estimates greater than or equal to:
   - 0.87mg/veh/km for zinc
   - 0.12mg/veh/km for copper.

b) Relatively low- to mid-range estimates, ie less than or equal to:
   - 0.45mg/veh/km for zinc
   - 0.086mg/veh/km for copper.

The modelled VEF estimates reported in this research (as adjusted for the influence of catchpit retention) for all sites fell within the range of low- to mid-range estimates from previous studies, with the exception of the zinc VEF for Westgate, which was slightly higher than the upper mid-range value from previous studies (see figure 4.3). However, both copper and zinc VEFs for Westgate, the most congested site sampled in this study, were substantially lower than the previous estimates for sites associated with high rates of tyre and brake wear.

There are plausible reasons why some of the previously reported VEFs for these types of road could overestimate the true VEF. Estimates for Silverdale interchange (Cu VEF of 0.13mg/veh/km and Zn VEF of 0.87mg/veh/km) were derived using the event-based method described in section 4.2.1, based on six storm events (Moores et al 2008). Given the apparent tendency for the event-based method to overestimate loads, these VEFs could reasonably be expected to be overestimates of a similar magnitude to the difference between event-based and modelled estimates presented in table 4.2. Based on the differences observed in this research between modelled and event-based VEFs, an adjusted estimate for the Silverdale interchange gives VEFs of 0.08–0.11mg/veh/km for copper and 0.54–0.73mg/veh/km for zinc. These adjusted values are more similar to those reported here for Westgate, the most congested site in this study. Of the other previous 'high' estimates, that for SH17 (near Green Rd) was derived from a limited sampling programme and related to a road noted for its high heavy-vehicle numbers (refer to section 2.2.5). Kennedy and Gadd's (2003) VEFs estimated by the VFEM-W method could also have been systematically high, based on a comparison of their estimates for normal traffic relative to others for non-congested sites.

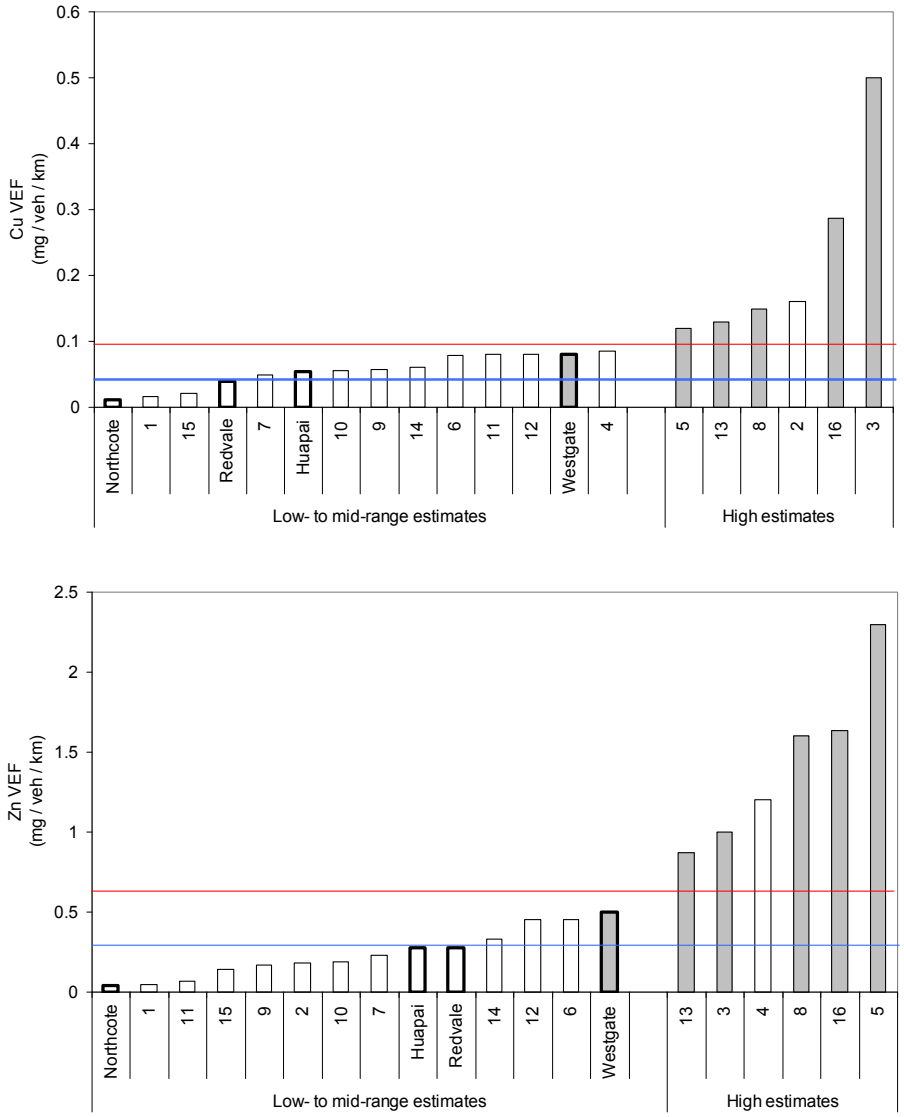
Similarly, there are a number of reasons why certain of the mid-range VEFs similar to the values estimated for Westgate in this study could have been overestimates of representative copper and zinc VEFs for normal driving conditions. Of these previous estimates, that of Timperley et al (2005) was based on the most comprehensive programme of road runoff sampling but, as the authors noted, there was uncertainty about their adjustment for the loads of metals retained in catchpits. Timperley et al adjusted their zinc and copper VEFs derived from the sampling programme upwards by 23% and 42%, respectively, to account for catchpit retention of metals. This compares with an adjustment of only 10% in this study. The estimates reported by Moores (2009) for the Northern Motorway at Silverdale were derived using the event-based method described in section 4.2.1 and, for the reasons described above, are likely to be overestimates[22]. The estimates derived from the EMC data reported by Sherriff (1998) are subject to substantial uncertainty (see section 2.2.5).

The VEF estimates for Huapai and Redvale were similar to the mid- (zinc) to low-ranked (copper) estimates from previous studies. These previous estimates were all associated with 'normal' or freely flowing driving conditions. Although it is tempting to draw on the similarity with these previous estimates as support for the Huapai and Redvale estimates, it should be noted that other than the findings from Gardiner and Armstrong (2007), those previous estimates (from EMC data and/or limited sampling) are subject to the same sources of uncertainty described above.

The VEF estimates for Northcote were lower than any previous estimates and substantially lower than estimates for congested roads. Although these may truly represent the loads of copper and zinc discharged from the motorway under the particular circumstances at the study site at the time of sampling, it seems unlikely that these estimates are truly representative of long-term emission rates from congested sections of New Zealand's motorways.

22 These VEFs were estimated using the event-based method from the first five of the eight sampling events at Redvale reported in this document. They are considered to have been superceded by the results presented here for the Redvale site.

Figure 4.3 Comparison of VEFs of total copper and total zinc estimated for sites sampled in this study, with the previous estimates summarised in section 2.2.6. Estimates associated with situations in which high rates of brake and tyre wear are considered likely are shaded. Estimates from this study are shown with a bold outline. Guideline VEFs recommended in section 4.4.6 are shown by the blue (normal traffic) and red (congested traffic and intersections) horizontal lines.



Key					
1	Kennedy & Gadd 2003	Waitakere City (lower quartile)	9	ARC unpubl.	SH1 Southern Motorway, Otahuhu
2	Kennedy & Gadd 2003	Waitakere City (median)	10	Larcombe 2003	SH1 Northern Motorway, Silverdale
3	Kennedy & Gadd 2003	Waitakere City (upper quartile)	11	Sheriff 1998	SH1, Tawa
4	Kennedy & Gadd 2003	VFEM-W (normal)	12	Moores et al 2008	SH1 Northern Motorway, Silverdale
5	Kennedy & Gadd 2003	VFEM-W (congested)	13	Moores et al 2008	SH1/SH17 intersection (Silverdale)
6	Timperley et al 2005	Richardson Rd	14	NIWA unpubl.	SH17 (nr Horseshoe Bush Rd)
7	Gardiner & Armstrong 2007	VCLM freely flowing	15	NIWA unpubl.	East Coast Rd, North Shore
8	Gardiner & Armstrong 2007	VCLM interrupted	16	NIWA unpubl.	SH17 (nr Green Rd)

4.4.6 Guideline VEFs

Guideline VEFs for copper and zinc are presented in table 4.3 on the following basis:

- While the results of this study have been evaluated in the light of previous estimates, the guideline VEFs provided here were solely derived from data collected as part of this research or held by the report's authors.
- The guideline VEFs are those derived from modelling copper and zinc loads over the period of runoff measurement, these being preferred to the estimates derived by the event-based method, which appear to be strongly influenced by the characteristics of individual sampling events[23].
- The estimates from which these guideline VEFs have been derived have been adjusted by an increase of 10% for the retention of particulate metals in catchpits, where relevant.

Table 4.3 Guideline VEFs for total copper and total zinc

Traffic characteristics	Total copper (mg/veh/km)	Total zinc (mg/veh/km)
Normal traffic	0.047	0.28
Congested traffic & intersections	0.095	0.62

The VEFs for normal traffic characteristics are the mean of values for Huapai and Redvale (for zinc, the values for these two sites were the same once the value for Redvale had been adjusted for the influence of catchpit retention). It may be appropriate to revisit these guideline values once ARC's analysis of data from the most recent Richardson Rd study has been completed.

The guideline VEFs for congested traffic and intersections are the mean of the values for Westgate (this study) and the Silverdale interchange (Moores et al 2008), subject to downward adjustment of the latter values to 0.08 and 0.11mg/veh/km for copper and zinc, respectively, in line with the minimum difference between modelled and event-based VEF estimates reported in section 4.3. This approach was adopted because, firstly, while the VEF estimates for Westgate are clearly not as high as those resulting from several previous studies, they are substantially higher than our own estimates from sites associated with 'normal' driving conditions. However, it is recognised that the Westgate values are at the lower end of VEF estimates for congested roads and, on the basis of other results (eg Silverdale interchange – Moores et al 2008), a higher VEF estimate may better represent a range of road types subject to frequent congestion, braking and acceleration. Noting that the published estimates for the Silverdale intersection could well be overestimates due to the event-based method used, they were adjusted downwards as described above.

23 With the exception that we have included our previous event-based estimates for the SH1/SH17 intersection at Silverdale (Moores et al 2008), these being the only estimates available for that site.

The application of the guideline values in table 4.3 as a basis for estimating loads of copper and zinc discharged in the runoff from any road is simple, subject to availability of the following information:

- the traffic characteristics of the road (eg congested or normal, following the method developed by Gardiner and Armstrong (2007)[24])
- a measure of the traffic volumes (eg AADT)
- the length of road (L) draining to the discharge point.

The daily contaminant load (CL) can be estimated from this data as follows:

$$CL\ (mg) = VEF\ (mg/veh/km) \times AADT\ (vpd) \times L\ (km)$$

(Equation 4.8)

Section 6.3.1 describes the way in which these VEF values can be applied as part of a 'first-cut' method for identifying those parts of a road network most in need of treatment or requiring further, more detailed, investigations.

24 Gardiner and Armstrong (2007) provided three LoS classes: congested, interrupted and normal. For the purpose of distinguishing VEFs by traffic characteristics, normal and interrupted roads have been grouped here as a single class.

5 Performance of road runoff treatment

5.1 Introduction

Differences in runoff quality of samples collected pre- and post-treatment at the Northcote, Huapai and Redvale sites were described earlier in section 3.4.2. The objective of this chapter is to assess these differences in terms of the measures of treatment performance described in section 2.3.3, and to provide guideline load-reduction factors (LRFs) associated with each device for the estimation of contaminant loads discharged to aquatic receiving environments.

5.2 Methods

5.2.1 Treatment efficiency

Treatment efficiencies for the removal of TSS and particulate, dissolved and total copper and zinc were estimated using the summation of loads method (refer to section 2.3.3). Efficiencies for each individual sampling event were also calculated. The calculation of contaminant removal by the Redvale stormwater pond involved comparison of the loads discharged into and out of the pond. For the assessment of contaminant removal by the Northcote swale and Huapai roadside drainage channel, an additional step was necessary. At these sites, samples of untreated and treated runoff were collected from adjacent sections of the road at each site. However, the loads of contaminants discharged in the untreated and treated runoff at the sample collection points at each site were not directly comparable because of a difference in the area of road catchments (see table 3.1). The catchment areas discharging to the points of untreated and treated runoff sample collection were 1980m^2 and 6480m^2, respectively, at Northcote; and 1640m^2 and 2325m^2, respectively, at Huapai. In order to calculate the efficiency of contaminant removal at these sites, untreated and treated loads were therefore first divided by the respective catchment areas (ie converted to yields) to allow for their comparison.

5.2.2 Treated runoff quality

Concentrations of copper and zinc in treated runoff samples were compared with the water quality trigger values and criteria summarised in table 2.7 (ANZECC and ARMCANZ 2000; USEPA 2006).

5.3 Results

5.3.1 Treatment efficiency

Table 5.1 presents the treatment efficiencies achieved at each of the three sites, along with a comparison of pre- and post-treated runoff volumes and peak discharges.

Table 5.1 Percentage removal of aggregated TSS, copper and zinc loads and mean percentage reduction in event runoff volumes and peak discharges due to treatment at Northcote, Huapai and Redvale. Values in brackets are the ranges of reductions in loads, runoff volumes and peak discharges associated with individual sampling events.

Site	Treatment	TSS	Copper			Zinc			Reduction in event runoff volumes[d]	Reduction in event peak discharge[d]
			Particulate	Dissolved	Total	Particulate	Dissolved	Total		
SH1 @ Northcote[a]	Vegetated swale	59% (17–90%)	87% (76–96%)	93% (88–97%)	91% (85–96%)	90% (83–96%)	93% (88–96%)	92% (89–96%)	84% (79–87%)	84% (52–94%)
SH16 @ Huapai[b]	Open roadside drain	96% (91–98%)	95% (90–97%)	50% (-20–30%)	87% (76–86%)	96% (92–98%)	53% (-121–62%)	93% (87–92%)	63% (7–100%)	68% (28–100%)
SH1 @ Redvale[c]	Wet pond	71% (41–91%)	63% (20–78%)	-19% (-153–16%)	40% (18–59%)	77% (39–89%)	-3% (-136–47%)	67% (27–82%)	-14% (-27–1%)	66% (45–89%)

Notes:

a) Results based on sampling results from six of seven events (the automatic water sampler at the swale outlet failed during Event 3).

b) Results based on sampling results from six of eight events (weir leakage was suspected at the drainage channel outlet during Events 5 & 6). Of these six events, runoff was discharged from the roadside drain during only three events (Events 3, 7 and 8), with all runoff in the drain apparently lost by infiltration during Events 1, 2 and 4 (all in summer to early autumn).

c) Results based on sampling results from six of eight events (pond outlet not instrumented for Events 1 and 2).

d) Based on comparison of runoff volumes and peak discharge scaled by catchment area at each site.

The information on runoff volumes and peak discharge is useful because it provides an indication of the mechanisms by which treatment occurred.

The roadside drainage channel at Huapai was most effective at TSS removal, with the total TSS load discharged from the drain 96% lower than at the road edge. Similarly high removal rates of particulate copper and zinc (95% and 96% respectively) and total copper and zinc (87% and 93% respectively) were achieved at Huapai, reflecting the fact that these metals were predominantly in the solid phase at this site (see section 3.4.2). The removal of dissolved metals was much more variable but had little influence on the overall results for removal of total metals. It is worth noting that during three of the six events upon which these results were based, no runoff was discharged from the roadside drain: ie there was a volume reduction (and consequently a treatment efficiency) of 100% due to infiltration (see table 5.1). Event runoff volumes discharged from the drainage channel were, on average, 63% lower than those at the kerb, while peak discharges were reduced by, on average, 68%.

The vegetated swale at Northcote was less effective than the Huapai drain at reducing TSS loads (total 59% removal), but performed similarly in relation to particulate metals (87% copper and 90% zinc removed). As noted in section 3.4.2, the dry-weight metal concentrations in sediments in treated runoff were much lower than those in untreated runoff at Northcote, suggesting that those discharged from the swale were 'clean' (ie deriving from less contaminated roadside soils rather than from sediments deposited on the road surface). This explains why a higher removal rate was achieved for particulate metals than for TSS. The removal rate of dissolved metals was also very high at Northcote (93% for both metals) and, because a greater proportion of copper and zinc were in the dissolved phase at this site, this resulted in the total metal removal (91% for copper and 92% for zinc) being slightly higher than for particulate metals. Event runoff volumes and peak discharges were, on average, 84% lower than those at the kerb.

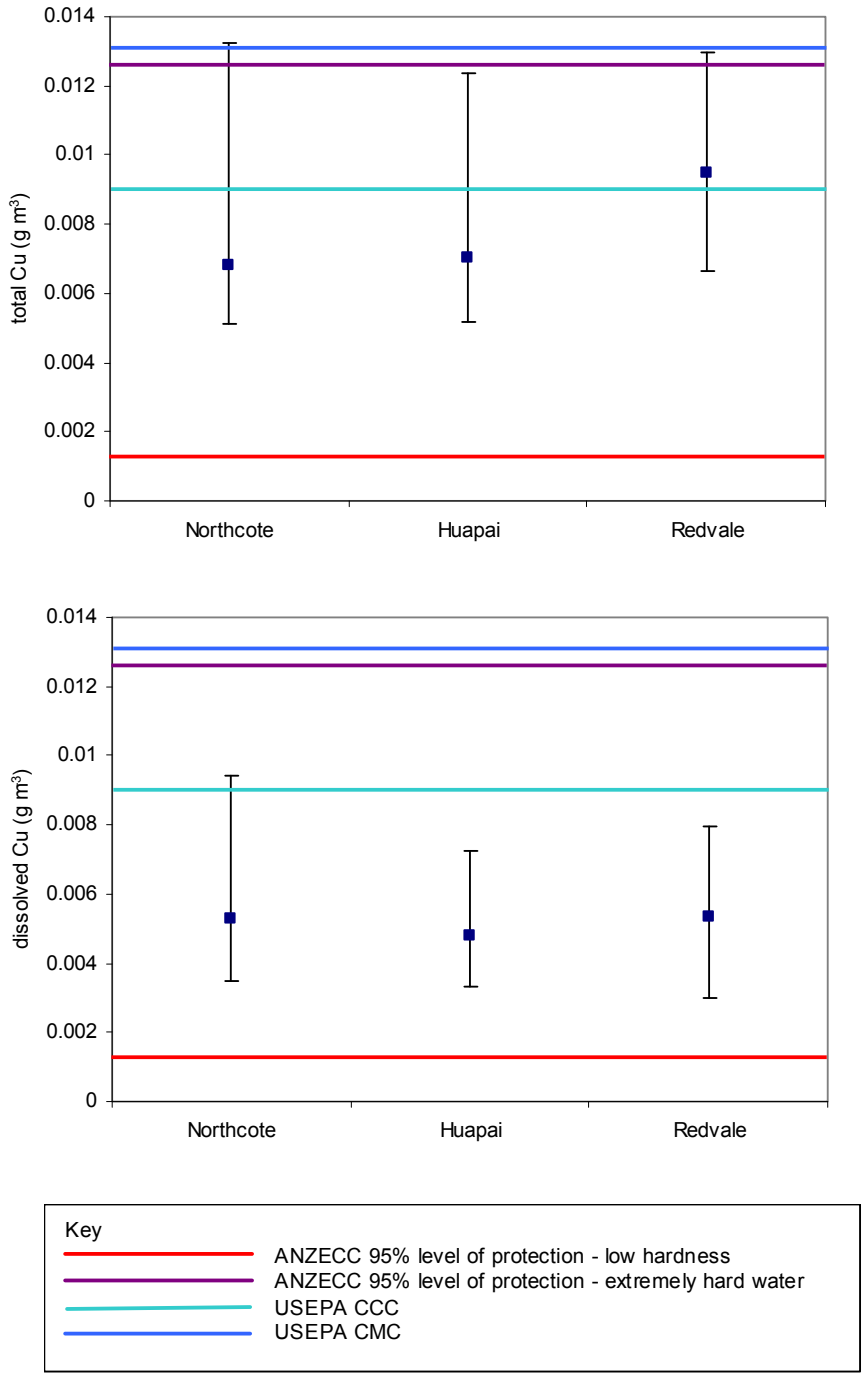
The Redvale pond was the least effective device, removing 71%, 63% and 77% of incoming TSS, particulate copper and particulate zinc, respectively. The removal efficiency of total metals was lower than for particulates, at 40% for total copper and 67% for total zinc. The particularly poor performance for copper removal reflects the ineffectiveness of the pond at removing dissolved metals and the relative importance of copper in the dissolved phase. Loads of dissolved copper and zinc metals discharged from the pond were slightly greater than those entering the pond in road runoff overall, and by more than double in one event. Because over half of the copper load discharged from the pond was in the dissolved phase, compared with around a third of the zinc load, the inability of the pond to remove dissolved metals had a greater influence on overall efficiency of the pond in relation to total copper than to total zinc. While event runoff volumes discharged from the pond were mostly greater than volumes measured at the pond inlet, because of additional inputs (see section 3.3.3), the pond did attenuate flows, with a mean reduction in peak flows of 66%.

5.3.2 Treated runoff quality

Figures 5.1 and 5.2 show median, 10th and 90th percentile concentrations of total and dissolved copper and zinc in samples of treated road runoff from Northcote, Huapai and Redvale. Concentrations are compared with the range of ANZECC guideline trigger values for a 95% level of protection (low

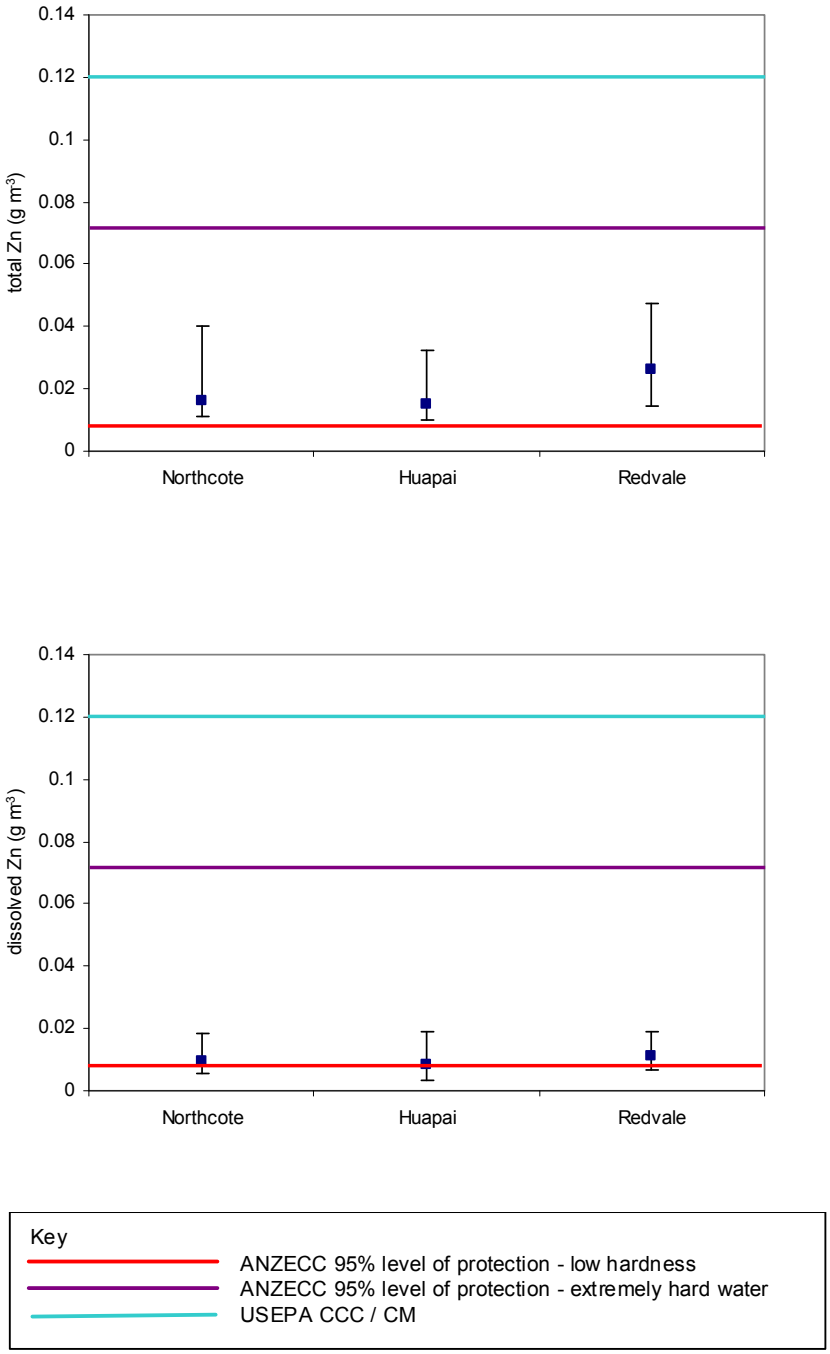
hardness to extremely hard water) and with USEPA Criteria Maximum Concentrations (CMC) and Criterion Continuous Concentrations (CCC)[25].

Figure 5.1 Median, 10th percentile and 90th percentile concentrations of total and dissolved copper in treated runoff samples from Northcote, Huapai and Redvale compared with ANZECC guideline values and USEPA water quality criteria



25 These values were presented earlier in table 2.7, section 2.3.3.

Figure 5.2 Median, 10th percentile and 90th percentile concentrations of total and dissolved zinc in treated runoff samples from Northcote, Huapai and Redvale compared with ANZECC guideline values and USEPA water quality criteria



The concentrations of total and dissolved copper in the treated runoff samples from all three sites exceeded minimum ANZECC guideline values for a 95% level of protection. Median total copper concentrations were below the trigger value for extremely hard waters but above the trigger value for low hardness. Median dissolved copper concentrations were closer to the value for low hardness, but consistently exceeded the trigger value. Whether or not these copper concentrations would exceed

ANZECC trigger values once discharged to a receiving water body is clearly very dependent on the hardness of the water, as well as the extent of dilution. In waters of low hardness, these copper concentrations would exceed ANZECC trigger values even at the 80% level of protection (trigger value 0.0025g m^{-3}).

While concentrations of copper were generally below USEPA water quality criteria, total copper concentrations exceeded the CCC in more than half of the samples of treated runoff from Redvale and in about a quarter of the samples from each of Northcote and Huapai. Dissolved copper concentrations at Huapai and Redvale were below the CCC at all times, whereas the 90th percentile value for dissolved copper at Northcote exceeded these criteria.

Concentrations of total zinc in treated runoff samples also exceeded the ANZECC trigger values for a 95% level of protection for waters of low hardness, but not for waters of moderate to extreme hardness. Dissolved zinc concentrations were below ANZECC guideline trigger values, except for waters of low hardness, with the median concentrations similar to the low-hardness trigger value at all three sites. At lower levels of protection (80 and 90%), zinc concentrations were generally below ANZECC trigger values, other than for waters of the lowest hardness. Total and dissolved zinc concentrations were very much lower than the USEPA criteria at all three sites.

5.4 Discussion

5.4.1 Effectiveness of contaminant removal

5.4.1.1 Swale at Northcote

The removal rates of total copper and total zinc by the swale at Northcote were similar to those for the most effective vegetative buffers and swales reported in the international literature (Barrett et al 2004; Caltrans 2003b; Han et al 2005; Walsh et al 1997), and higher than the efficiencies reported previously by Larcombe (2003) and Moores et al (2008) for swales on the Northern Motorway at Silverdale[26] (see table 2.8). Treatment appeared to have been primarily the result of infiltration rather than filtration, with greatly reduced event runoff volumes discharged from the swale compared with the road edge (see table 5.1).

However, the contaminant concentrations in samples of untreated runoff collected at Northcote were lower than those in untreated samples reported by these previous New Zealand studies. Larcombe (2003) reported median EMCs in untreated road runoff at two sampling sites on the Northern Motorway at Silverdale of 119–124g m^{-3} TSS, 0.03g m^{-3} total copper and 0.09–0.117g m^{-3} total zinc. Larcombe's concentrations were approximately double the maximum TSS concentration measured in this study at Northcote (67g m^{-3}) and similar to 90th percentile concentrations of total copper and zinc (0.03 and 0.09g m^{-3}). Concentrations reported by Moores et al (2008) were substantially higher, with medians of 869g m^{-3} TSS, 0.069 particulate copper and 0.267g m^{-3} particulate zinc. It is worth noting, however, that their results were based on limited sampling during the initial stages of runoff events. While the removal efficiencies reported by these two previous studies were not clearly related to contaminant concentrations in untreated runoff, their results do suggest that if the loads of TSS and metals

26 Noting that these two previous New Zealand studies reported efficiencies in terms of TSS and metal concentrations, rather than loads.

discharged at the road edge at Northcote were to increase over time (as suggested by the discussion in section 3.5.1), the removal efficiency of the swale could decrease somewhat.

Another feature of the performance of the swale at Northcote was the high removal rate of dissolved copper and zinc (93%). These results were not without precedent: Yousef et al (1987) reported mean removal rates of 70% and 93% for dissolved copper and dissolved zinc, respectively. Clearly, the results of this study support the use of swales as a treatment method for reducing TSS, copper and zinc loads discharged in road runoff. A recommended load-reduction factor, based on the results presented in this research, is given in section 5.4.3.

5.4.1.2 Roadside drainage channel at Huapai

The removal rates of TSS, total copper and total zinc loads by the roadside drainage channel at Huapai were similar to those reported by Moores et al (2008), which were based on limited sampling at sites on SH17 north of Auckland. The results indicate that, while these drainage systems are not specifically designed or constructed as systems for the removal of contaminants, TSS, copper and zinc discharged in road runoff are retained by them to some extent. Again, infiltration appears to have been the primary mechanism by which treatment occurred, most notably in the three events during which there was no outflow from the drainage channel.

Where such systems are present (most rural roads) the estimation of loads discharged to receiving water bodies should take account of this retention, although there are likely to be variations in removal efficiency in relation to factors such as slope, substrate and vegetation. A steep, unvegetated, soil-lined drain is more likely to be subject to scouring, and hence loss of sediments and associated metals, than a low-gradient, well-vegetated drain constructed with a highly permeable bed material such as rock rip-rap. While such factors introduce considerable uncertainty, in the absence of a more comprehensive investigation of rural road runoff quality, a single load-reduction factor is provided in this study for the estimation of contaminant loads discharged through roadside drainage channels (see section 5.4.3).

5.4.1.3 Pond at Redvale

The removal rates of TSS, total copper and total zinc loads by the stormwater pond at Redvale were similar to middle-ranked results reported in the international literature (eg Hossain et al 2005; Mitchell et al 2002). The Redvale pond was more effective at removing TSS and total zinc, but less effective at removing total copper, compared with a pond located adjacent to the Silverdale interchange on the same motorway (Moores et al 2008). The Silverdale pond achieved removal rates of 56%, 50% and 55% for TSS, total copper and total zinc, respectively. The poorer performance of the Redvale pond in relation to total copper reflects the increase in the dissolved copper load discharged from this pond, relative to the influent load to the pond. In contrast, at Silverdale around a third of the dissolved copper load was removed by the pond.

The differences in the performance of the two ponds may be in some part attributable to differences in their characteristics. While the ponds were a similar size, emergent aquatic vegetation was well established in the Redvale pond but not in the pond at Silverdale. Vegetation is likely to enhance the removal of particulate matter and metals bound to it as occurs in wetland treatment systems (Semadeni-Davies 2008). This may occur through bio-accumulation of dissolved metals by basin vegetation and micro-organisms.

The increased loads of dissolved metals discharged from the Redvale pond were counter to expectations, given the presence of emergent vegetation. However, previous studies have found that changes in metal partitioning between the dissolved and particulate phases can also occur depending on water chemistry (notably pH) – in acidic ponds or wetlands, there is likely to be a general increase in the dissolved metal fraction (Dempsey et al 1993; Sansalone et al 1996; Sansalone and Buchberger 1997). While the pH of the Redvale pond was not measured in this research, in a study of the performance of a stormwater wetland in Auckland, Larcombe (2002) reported a slight reduction in pH in effluent samples compared with those of influent samples. However, without further investigating the chemistry of the Redvale and Silverdale ponds, it is not possible to explain differences in their performance with any certainty.

While the results from the Redvale site indicated that ponds treating highway drainage were able to achieve close to the TP10 target removal of 75% of TSS (ARC 2003), the Silverdale results suggested that this was not the case where ponds were largely unvegetated. In either situation, removal rates for total copper and, to a lesser extent, total zinc, were lower than for TSS, and this appeared to be strongly influenced by the proportion of the total metal load that was in the dissolved phase. Despite the different characteristics of the two ponds described here, both were relatively ineffective for the removal of dissolved metals.

Of course, as well as the extent of vegetation, many other aspects of pond design and operation can influence their performance. Factors such as pond size and shape, outlet design, and the presence or absence of forebays can contribute to the hydraulic regime of a pond and so influence the extent to which suspended sediments settle out (ARC 2003; USEPA 2002a). While it was beyond the scope of this study to investigate the influence of variations in pond design and operation, it is noted that a relatively short residence time may be one factor limiting the effectiveness of treatment at the Redvale pond. Data collected at the weir installed in the pond outlet showed that it was flowing 99% of the time. This indicates that the pond's water level was almost always maintained above the invert of the outlet between storms, probably because of the contribution of groundwater inflows. Although there was a marked attenuation of flows discharged from the pond during rainfall events, there was little delay between the timing of the onset of runoff entering the pond and a rise in the rate of discharge at the pond outlet. It would be interesting to compare the performance of this pond with others that allow for greater residence time of influent stormwater.

5.4.2 Effects on receiving environments

Although the treatment systems evaluated at all three sites removed substantial loads of copper and zinc, the concentrations of both metals in treated runoff remained above certain ANZECC guideline trigger values. While the exceedance of zinc trigger values was limited, particularly for the dissolved phase, this was not the case for copper. Total copper concentrations (and only very rarely, dissolved copper) also exceeded the USEPA CCC value. As noted earlier in section 5.3.2, the extent to which these copper concentrations would exceed ANZECC trigger values, once discharged to a receiving water body, depends on dilution and the hardness of the receiving water. At the Huapai and Redvale sites, treated runoff was discharged to freshwater streams. In each case the stream catchments were rural in character and sufficiently large to give a reasonable degree of confidence that road runoff would be well diluted, resulting in copper concentrations below ANZECC trigger values.

At Northcote road, runoff was discharged from the swale to a stormwater pond, and from there to a tidal creek of the Waitemata Harbour that drains a mainly urbanised catchment. In this situation, discharges of road runoff could conceivably contribute to exceedance of ANZECC trigger values,

depending on the concentrations of copper and zinc in stormwater discharged at other locations in the catchment. Monitoring stream water quality upstream and downstream of road runoff discharge points would provide a basis for quantifying the contribution of road runoff to the contamination of urban streams.

While stormwater treatment results in reduced loads and volumetric concentrations of metals in road runoff, it can have the opposite effect on metal concentrations in sediments. As noted in section 3.5.4, this can occur through the preferential removal of coarser sediments, which typically have lower dry-weight metal concentrations than the finer fractions, which are less effectively removed. This would explain the higher dry-weight copper concentrations on suspended sediments in treated runoff at Huapai and Redvale than on sediments in untreated runoff (section 3.4.2). The dry-weight concentrations of both copper and zinc on road sediments in treated runoff from all three sites were in excess of representative background values for soils in the Auckland region (ARC 2001). This could lead to metal accumulation in depositional environments over time, depending on the extent to which dilution by 'clean' sediments occurred.

Moores et al (2008) sampled roadside soils, stormwater pond sediments and stream bed sediments below discharge points from the Northern Motorway at Silverdale, and found no evidence of any metal accumulation in the stream bed over the five-year period since the opening of the motorway. In contrast, they found that metal concentrations in roadside (swale) soils and stormwater pond sediments were markedly higher than background soils concentrations, indicating that metal accumulation was concentrated in these locations. However, they reported one anomaly suggesting the localised accumulation of zinc in stream sediments below a point of discharge of untreated road runoff. Reed at al (2008) investigated the metal contamination of sediments at five locations receiving discharge from state highways (and other land uses) in the Waitemata and Manukau Harbours. While their study confirmed copper and zinc contamination above guideline values at three of the sites, the authors were unable to determine the relative contribution of road runoff compared to other sources of stormwater contaminants.

Clearly, the extent to which road runoff contributes to the contamination of both water and sediments in receiving environments in New Zealand needs to be established and quantified. While there are modelling approaches that allow an estimation of the road-derived proportion of sediment, copper and zinc loads discharged to receiving environments, such as ARC's Contaminant Load Model (Timperley and Skeen n.d.), field validation of the road-derived contaminant signal is essential. The extent to which treatment influences the rate of contaminant accumulation (eg by the removal of 'clean' coarser sediments) is integral to further investigations in this area.

5.4.3 Guideline load-reduction factors

Guideline LRFs for TSS, copper and zinc are presented in table 5.2 on the following basis:

- While the results of this study have been evaluated in the light of previous estimates of treatment efficiency, the guideline LRFs were solely derived from the results of this study and previous data collected by the authors.
- A single set of guideline LRFs for swales and open roadside drainage channels are provided. Although the results of this study suggest that higher efficiencies may be achieved by the drainage channels, there is currently insufficient information to establish whether these higher efficiencies are also achieved by drains having differing characteristics from those investigated here. A

relatively cautious approach has therefore been taken in assigning the same LRF values to drainage channels as to swales.

- For ponds, a range of guideline LRFs are suggested in relation to the extent of emergent vegetation, based on the results for the Redvale and Silverdale ponds described above.
- In the absence of other information or further research into the influence of variations in device design on treatment performance, these guidelines should only be applied to devices that are similar in design, construction and operation as those studied here (refer to section 3.2.2).

The guideline LRFs for swales and roadside drains are approximate mid-range values of the swale efficiencies estimated from the results of this study and those reported by Moores et al (2008)[27]. The guideline LRFs for total zinc are consistent with previous estimates from the Northern Motorway reported by Larcombe (2003), while the LRF for copper is around 30% higher. The guideline LRF for TSS removal is double that reported by Larcombe (2003).

Table 5.2 Guideline load-reduction factors for treatment of road runoff by vegetated swales, roadside drainage channels and stormwater ponds. These guidelines should only be applied to devices that are similar in design, construction and operation as those studied here (refer to section 3.2.2).

Treatment type		Load-reduction factor		
		TSS	Total copper	Total zinc
Vegetated swales and open roadside drains		0.6	0.8	0.8
Stormwater ponds	More vegetation ↕ Less vegetation	0.7 ↕ 0.5	0.5	0.65 ↕ 0.55

The TSS and total zinc LRFs for ponds are approximately the same as efficiencies estimated for the ponds at Redvale (more vegetation) and Silverdale (less vegetation). A single guideline LRF is recommended for total copper because there is insufficient information or understanding to provide a sound basis for adopting the result from the Redvale pond (40% total copper removal) for vegetated ponds.

The application of these values as a basis for estimating loads of copper and zinc discharged in **treated** runoff from any road is straightforward: estimate the **untreated** metal load according to the method described in section 4.4.6, and then multiply that estimate by (1–LRF) for the drainage or treatment system in place. Section 6.3.1 describes the way in which these values can be applied as part of a 'first-cut' method for identifying those parts of a road network most in need of treatment or requiring further, more detailed, investigations.

27 Swale removal efficiency of 58%, 71% and 73% for TSS, copper and zinc, respectively.

6 Conclusions

6.1 Vehicle emission factors

The results of this research were consistent with the expectation that there would be a relationship between traffic behaviour and the rates at which copper and zinc were discharged in road runoff, reflecting higher rates of brake pad and tyre wear at locations subject to greater traffic congestion. While not as high as some estimates reported in previous studies, copper and zinc VEFs were highest at the most congested of the four sampling sites (Westgate). VEF estimates were markedly lower at Huapai and Redvale, roads on which traffic generally flowed freely.

However, copper and zinc VEFs estimated from data collected at the second most congested site (Northcote) were much lower than any of those for the other three sites. The most likely reason for these results is the resealing of the road surface at this location with open-graded porous asphalt (OGPA) in early 2008. OGPA is relatively permeable when new and allows road sediments (and associated particulate metals) to be deposited in voids in the road surface. Evidence reported by other researchers has indicated that this permeability decreases over time as voids become choked with road dust and debris. This would explain why the road runoff quality at the Redvale site, which was last resealed with OGPA in 2002, was similar to that of sites sealed with other materials.

While there appears to be a relationship between traffic behaviour and VEFs, and there is a credible explanation for the results at Northcote, the extent to which differences between the estimates for each site are due to other factors is uncertain. Factors such as road design, exposure to wind, adjacent land use and fleet composition have been reported to influence road runoff quality (see section 2.2.7), and the results of this study have also shown the strong influence of sampling event characteristics on VEFs (see section 4.4.2). VEF estimates derived from individual events at a single site could vary by up to an order of magnitude, resulting in considerable uncertainty in the extrapolation of long-term VEFs from only a small number of sampling events. Modelled VEF estimates are less sensitive to the characteristics of individual storm events and so these are likely to be a better estimate of the long-term contaminant load discharged from the road at each site.

Despite these sources of uncertainty, comparison with VEF estimates previously reported provides a measure of confidence that the guideline VEF estimates presented here do provide a reasonable basis for the estimation of loads of copper and zinc discharged in untreated road runoff at locations elsewhere in the New Zealand road network. As the results of further studies become available, it may be appropriate to revise these guideline values.

6.2 Performance of road runoff treatment

This study evaluated the performance of a stormwater pond, grass swale and roadside drainage channel for the removal of TSS, copper and zinc. While the roadside drainage channel was highly effective at removing TSS, both the swale and the pond failed to meet guideline targets for TSS removal (ARC 2003; USEPA 2002a), albeit by a small margin for the pond. Both the roadside drainage channel and the swale achieved very high removal rates of copper and zinc. The stormwater pond was less effective at removing metals, reflecting the relative importance of the dissolved phase and the ineffectiveness of the pond at removing dissolved metals. The quality of runoff discharged to receiving

water bodies from all three systems was either below water quality trigger values or criteria, or was likely to have been once dilution was taken into account.

The extent to which the performance of each of these systems reflect site-specific or sampling event-specific factors is uncertain. Factors such as device design, the quality of the untreated road runoff and the characteristics of sampling events are likely to have influenced results.

However, comparison with previous results on the performance of treatment devices provides a measure of confidence that the guideline LRFs presented here do provide a reasonable basis for the estimation of loads of copper and zinc discharged in treated runoff at locations elsewhere in the New Zealand road network. As the results of further studies become available, it may be appropriate to revise these guideline values.

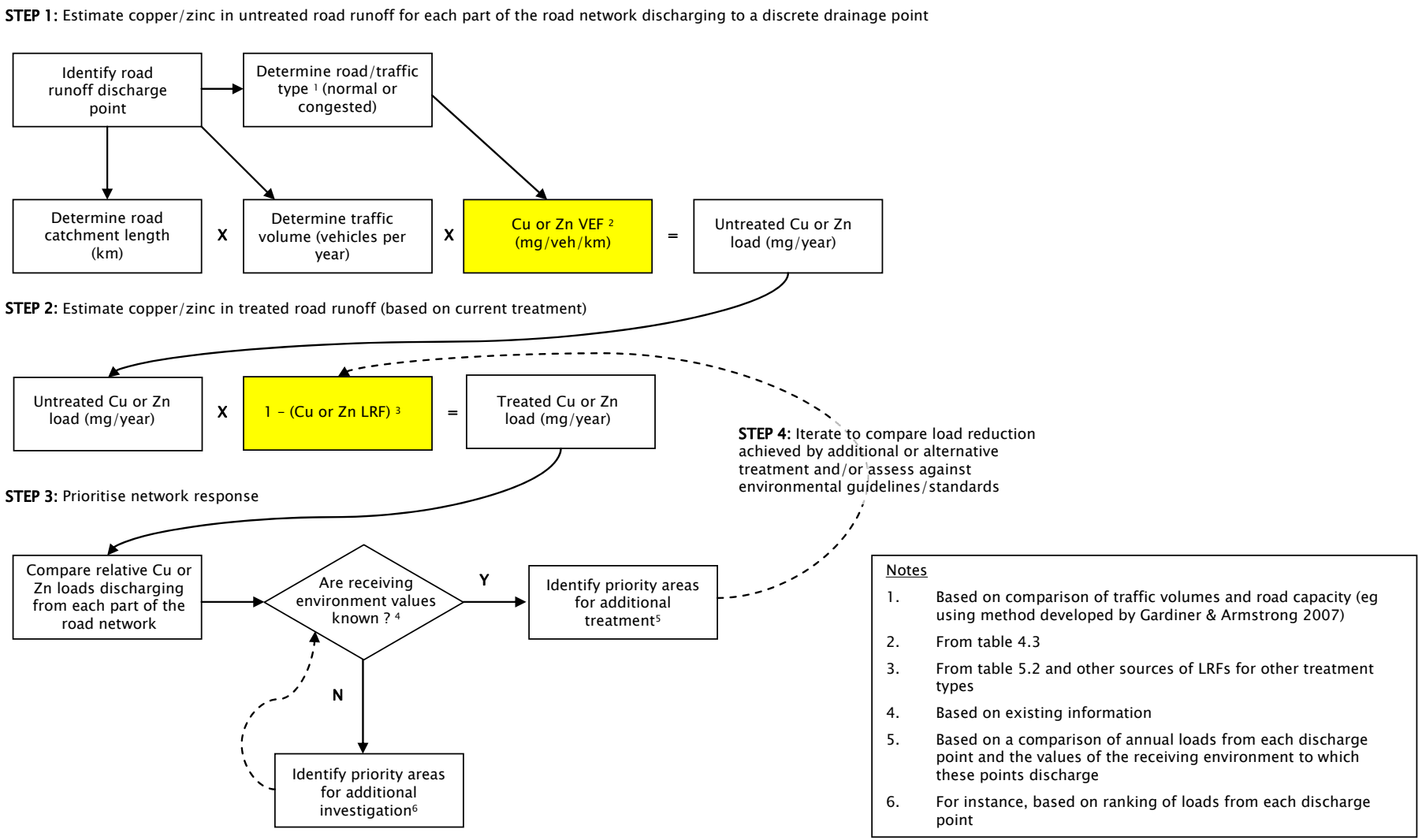
7 Recommendations

7.1 Application of the results of this study

Section 1.3 of this report provided an overview of the information requirements, and the way in which this information would need to be evaluated, in order to decide how to prioritise the control of road runoff contaminants discharged to aquatic receiving environments. It was noted that the extent to which the discharge of contaminants in road runoff presents a problem requires an assessment of both the loads discharged and the values of the aquatic receiving environment. As noted in section 1.3, some relatively sophisticated methods have been developed for evaluation of the effects or risk of contaminant discharges to receiving environments (Gardiner and Armstrong 2007; Moores et al 2009a). One way in which the results of this study can be used is to provide input data for relatively detailed assessments of the effects of road runoff discharges, using these types of tools. The VEFs and LRFs recommended here can be used as an alternative to current values, subject to due consideration being given to the origin and applicability of competing data sources.

However, not all roading and stormwater managers necessarily have access to the resources required to apply the methods referred to above. In recognition of this, and with the aim of ensuring that the results of this study are of wider practical value, an alternative four-step method is presented here as a way of using these VEF and LRF estimates in a 'first-cut' approach to identifying those parts of a road network most in need of treatment or requiring further, more detailed, investigations (see figure 7.1).

Figure 7.1 Method for 'first-cut' prioritisation of location of road runoff treatment (yellow text boxes indicate the application of the results of this study)



- **Step 1** of the method involves using the VEFs recommended in table 4.3, and other information on road characteristics, to determine the loads of copper and zinc in untreated road runoff discharged at each discharge point in a road network.
- **Step 2** then involves estimating the copper and zinc loads discharged following treatment of road runoff, by application of the LRFs recommended in table 5.2, or based on values given elsewhere for treatment types other than ponds, swales or road drainage channels.
- In **Step 3**, the relative importance of contaminant discharges from different parts of the road network is assessed with reference to existing information on the values of the receiving environment. Where there is little or no existing information on these values, the comparison of loads can be used to prioritise those areas where investigations to gather further information should focus. If sufficient information on the values of receiving environments exists (eg data on water quality, sediment quality or ecosystem health), then this information provides a context for evaluating the likely impact of discharges of copper and zinc in road runoff, and provides guidance on the priority locations for additional or alternative treatment measures.
- **Step 4** simply involves iteration of steps 2 and 3 to compare the extent to which alternative treatment measures will achieve the desired environmental outcome (eg meeting ANZECC and ARMCANZ (2000) water quality guidelines or the conditions of a rule in a regional plan).

7.2 Further work

While this study has resulted in important progress in the quantification of contaminant loads in road runoff and the performance of road runoff treatment measures, it has also highlighted a number of key areas for further investigation. The recommended priority areas for further research are:

1 The influence of road surface materials on road runoff quality, in particular the effectiveness of materials such as OGPA as a measure for ‘treating’ road runoff, and the extent to which its effectiveness varies in relation to the age and condition of the road surface.

2 The influence of treatment device characteristics on their performance, in particular:

   - the way in which aquatic vegetation influences pond performance – this requires improving our understanding of the physical, chemical and biological processes involved, and developing methods by which pond characteristics can be optimised to improve treatment performance (eg for the removal of dissolved metals)
   - the way in which variations in the characteristics of vegetated swales and roadside drainage channels influence the performance of these systems, including the way differences in vegetation and other characteristics that may influence their erodibility
   - the extent to which the transferability of the results of this study are dependent upon design criteria being met, including assessment of whether or not the devices studied here are themselves compliant with design criteria.

3 The extent to which the discharge of contaminants in road runoff can be detected in receiving environments. This involves:

- sampling water quality in rivers and streams downstream of road runoff discharge points and comparing the results with water quality trigger values or criteria
- sampling sediment quality downstream of road runoff discharge points and comparing the results with sediment quality trigger values or criteria
- developing methods by which the contribution of road runoff to the contamination of freshwater and estuarine systems (water and sediments) can be assessed – eg by the application of contaminant load models
- assessing the effects of contamination from road runoff on the environmental values of freshwater and estuarine systems.

4 The extent to which the non-detection of TPHs in road runoff reported here is widely valid, including reviewing methods of sample collection and analytical detection limits.

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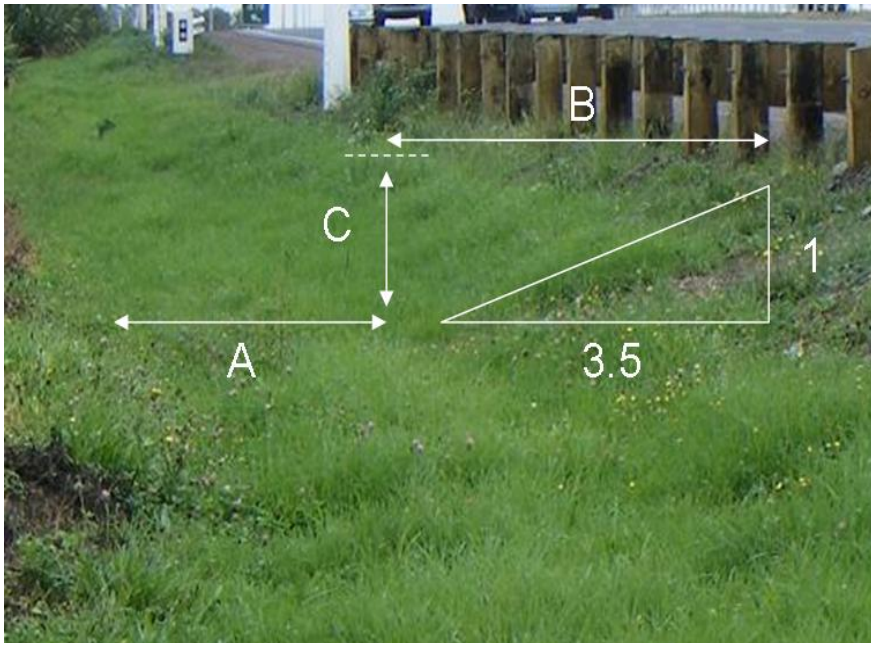
9 Appendices

Appendix A Description of treatment devices

A.1 Swale, SH1 @ Northcote

Longitudinal gradient	5 degrees
Bed width (A)	1.5m
Distance from road edge to swale bed (B)	3.0m
Depth to bed from road edge (C)	0.85m
Side slope	1 in 3.5
Description of vegetation: Dense grass and clover, average blade height 300mm	

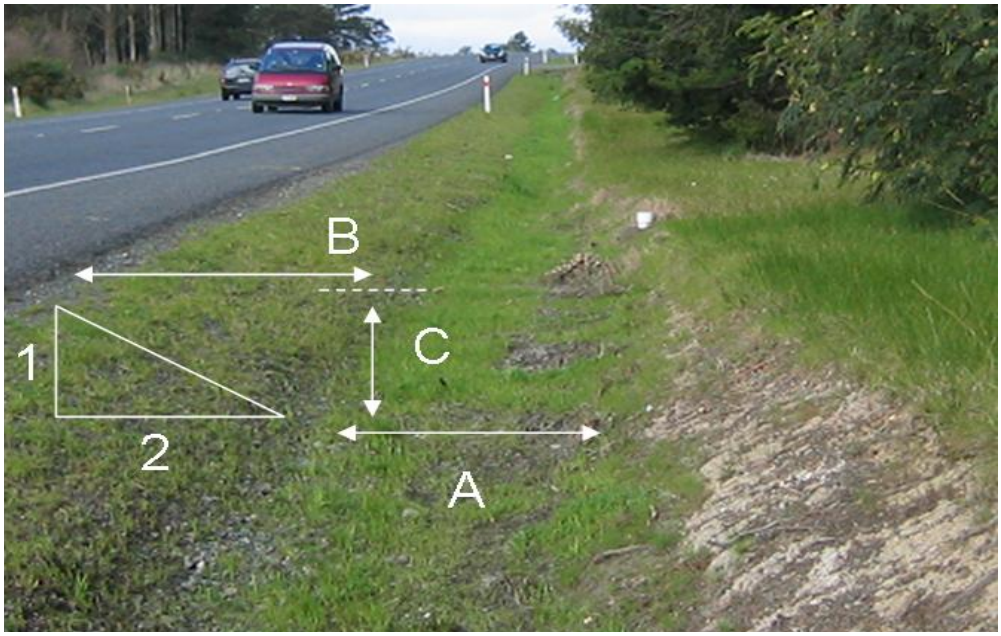
Figure A1 Dimensions of swale, SH1 @ Northcote



A.2 Drainage channel, SH16 @ Huapai

Longitudinal gradient	2 degrees
Bed width (A)	0.8m
Distance from road edge to swale bed (B)	1.75m
Depth to bed from road edge (C)	0.9m
Side slope	1 in 2
Description of vegetation and bed material: Moss and sparse grasses (average height 200mm) growing in approximately 100mm soft sediments over underlying gravel bed.	

Figure A2 Dimensions of drainage channel, SH16 @ Huapai



A.3 Pond, SH1 @ Redvale

Length (A)	30m
Maximum width (B)	13m
Normal surface area	350m^2
Estimated normal volume	260m^3
Side slopes of bank above water level	1 in 1.3
Inlet: 600mm diameter pipe (C) discharging to pond via 2.25m wide concrete apron (D) above a 6m by 4m gabion basket (E), mesh size 60 x 80mm containing average size 300mm diameter rock material.	
Outlet: 1600mm diameter (F) manhole riser fitted with 50mm (G) and 600mm (H) wide weirs, 600mm diameter outlet pipe discharging to stream via 2.25m wide concrete apron above a 1.6m long area of tarseal.	
Description of vegetation: Dense reed bed covering approximately 90% of the water surface.	

Figure A3 Pond, SH1 @ Redvale

Figure A4 Pond inlet, SH1 @ Redvale

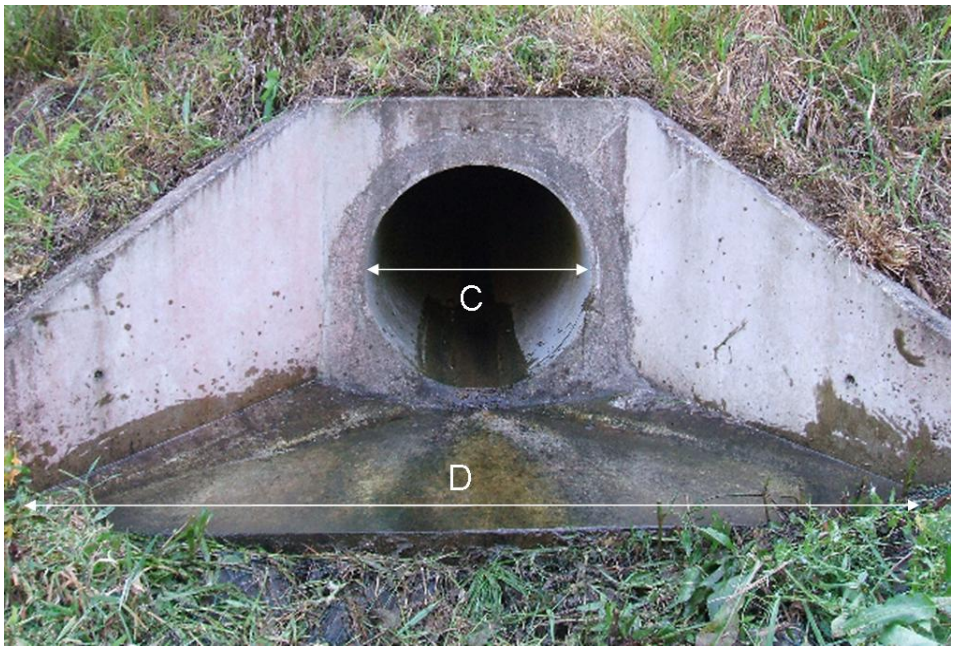


Figure A5 Pond outlet, SH1 @ Redvale

Appendix B Results and summary statistics of road runoff sample analyses

Table B1 Results of analysis of untreated (road edge) runoff samples collected at SH18 @ Westgate

Event	Date & time	TSS (g m^{-3})	Dry-weight Cu (mg kg^{-1})	Dry-weight Zn (mg kg^{-1})	Particulate Cu (g m^{-3})	Particulate Zn (g m^{-3})	Dissolved Cu (g m^{-3})	Dissolved Zn (g m^{-3})	Total Cu (g m^{-3})	Total Zn (g m^{-3})	TPH (g m^{-3})
1	9/05/2008 03:09	114.7	208	955	0.0239	0.1096	0.0063	0.025	0.0302	0.1346	<0.7
	9/05/2008 04:34	17.2	293	943	0.0050	0.0162	0.0074	0.016	0.0124	0.0322	<0.7
	9/05/2008 08:50	647.8	52	375	0.0335	0.2430	0.0041	0.0098	0.0376	0.2528	3.9
	9/05/2008 08:54	445.2	203	1333	0.0904	0.5932	0.0063	0.009	0.0967	0.6022	<0.7
	9/05/2008 09:28	60.3	239	1265	0.0144	0.0763	0.0047	0.017	0.0191	0.0933	2.8
	9/05/2008 15:50	185.8	197	1486	0.0366	0.2761	0.0064	0.02	0.0430	0.2961	1.8
	9/05/2008 16:33	71.5	212	1489	0.0151	0.1064	0.0055	0.017	0.0206	0.1234	<0.7
	9/05/2008 17:35	24.8	249	1355	0.0062	0.0336	0.0049	0.014	0.0111	0.0476	<0.7
	10/05/2008 00:21	4.0	328	936	0.0013	0.0038	0.0028	0.018	0.0041	0.0218	<0.7
2	25/05/2008 23:29	64.1	273	1692	0.0175	0.1084	0.0087	0.032	0.0262	0.1404	<0.7
	26/05/2008 00:00	153.5	196	2320	0.0301	0.3562	0.01	0.058	0.0401	0.4142	<0.7
	26/05/2008 00:24	76.3	161	1863	0.0123	0.1421	0.0071	0.041	0.0194	0.1831	<0.7
	26/05/2008 00:50	39.9	178	1784	0.0071	0.0712	0.0054	0.015	0.0125	0.0862	<0.7
	26/05/2008 06:25	5.8	250	992	0.0014	0.0057	0.0093	0.012	0.0107	0.0177	<0.7
	26/05/2008 09:08	66.0	241	1519	0.0159	0.1003	0.013	0.032	0.0289	0.1323	<0.7
	26/05/2008 14:08	40.7	208	1006	0.0085	0.0410	0.0085	0.029	0.0170	0.0700	<0.7
	26/05/2008 14:48	36.3	256	1475	0.0093	0.0535	0.013	0.03	0.0223	0.0835	<0.7
	26/05/2008 20:11	27.1	246	1395	0.0067	0.0378	0.013	0.021	0.0197	0.0588	<0.7

Table B1 (cont) Results of analysis of untreated (road edge) runoff samples collected at SH18 @ Westgate

Event	Date & time	TSS ($g\ m^{-3}$)	Dry-weight Cu ($mg\ kg^{-1}$)	Dry-weight Zn ($mg\ kg^{-1}$)	Particulate Cu ($g\ m^{-3}$)	Particulate Zn ($g\ m^{-3}$)	Dissolved Cu ($g\ m^{-3}$)	Dissolved Zn ($g\ m^{-3}$)	Total Cu ($g\ m^{-3}$)	Total Zn ($g\ m^{-3}$)	TPH ($g\ m^{-3}$)
3	16/06/2008 10:45	244.3	218	1380	0.0534	0.3371	0.013	0.062	0.0664	0.3991	0.84
	16/06/2008 17:16	172.4	228	1564	0.0393	0.2697	0.008	0.029	0.0473	0.2987	<0.7
	16/06/2008 18:06	136.5	208	1353	0.0284	0.1847	0.0047	0.022	0.0331	0.2067	<0.7
	16/06/2008 18:54	320.6	196	1445	0.0627	0.4632	0.0038	0.027	0.0665	0.4902	<0.7
	16/06/2008 19:17	523.7	186	1326	0.0972	0.6944	0.0003	0.025	0.0975	0.7194	<0.7
	17/06/2008 6:01	56.9	224	1309	0.0128	0.0745	0.0091	0.021	0.0219	0.0955	<0.7
4	22/06/2008 0:46	50.3	286	1401	0.0144	0.0704	0.0071	0.017	0.0215	0.0874	<0.7
	22/06/2008 3:35	13.3	275	1396	0.0037	0.0185	0.013	0.017	0.0167	0.0355	<0.7
	22/06/2008 4:06	106.5	170	1441	0.0181	0.1534	0.0047	0.02	0.0228	0.1734	<0.7
	22/06/2008 4:22	75.1	168	1463	0.0126	0.1099	0.0037	0.019	0.0163	0.1289	<0.7
	22/06/2008 4:30	118.8	176	1331	0.0209	0.1582	0.0023	0.016	0.0232	0.1742	<0.7
	22/06/2008 4:54	134.5	177	1458	0.0239	0.1960	0.004	0.034	0.0279	0.2300	<0.7
	22/06/2008 5:11	49.2	163	1352	0.0080	0.0665	0.0034	0.01	0.0114	0.0765	<0.7
	22/06/2008 5:31	82.1	172	1404	0.0141	0.1153	0.0034	0.018	0.0175	0.1333	<0.7
	22/06/2008 5:37	65.5	170	1233	0.0111	0.0808	0.0023	0.016	0.0134	0.0968	<0.7
	22/06/2008 5:54	35.8	138	885	0.0049	0.0317	0.003	0.012	0.0079	0.0437	<0.7
	22/06/2008 7:59	21.9	228	1218	0.0050	0.0267	0.0068	0.013	0.0118	0.0397	<0.7
	22/06/2008 9:04	18.3	278	1188	0.0051	0.0217	0.0082	0.019	0.0133	0.0407	<0.7

Table B1 (cont) Results of analysis of untreated (road edge) runoff samples collected at SH18 @ Westgate

Event	Date & time	TSS ($g\ m^{-3}$)	Dry-weight Cu ($mg\ kg^{-1}$)	Dry-weight Zn ($mg\ kg^{-1}$)	Particulate Cu ($g\ m^{-3}$)	Particulate Zn ($g\ m^{-3}$)	Dissolved Cu ($g\ m^{-3}$)	Dissolved Zn ($g\ m^{-3}$)	Total Cu ($g\ m^{-3}$)	Total Zn ($g\ m^{-3}$)	TPH ($g\ m^{-3}$)
5	26/07/2008 5:49	188.8	276	1234	0.0521	0.2329	0.008	0.02	0.0601	0.2529	<0.7
	26/07/2008 7:35	535.9	183	1048	0.0983	0.5618	0.0041	0.031	0.1024	0.5928	1.5
	26/07/2008 8:55	121.8	178	1004	0.0217	0.1223	0.0033	0.015	0.0250	0.1373	<0.7
	26/07/2008 9:40	468.1	156	924	0.0730	0.4324	0.022	0.02	0.0950	0.4524	2.1
	26/07/2008 10:13	151.3	171	973	0.0258	0.1472	0.0033	0.016	0.0291	0.1632	<0.7
	26/07/2008 10:47	111.9	204	1057	0.0228	0.1183	0.0022	0.014	0.0250	0.1323	<0.7
	26/07/2008 11:40	179.1	210	1123	0.0375	0.2011	0.0032	0.019	0.0407	0.2201	1.3
	26/07/2008 14:02	43.0	253	1138	0.0109	0.0489	0.0033	0.025	0.0142	0.0739	<0.7
	26/07/2008 16:56	82.5	224	1086	0.0185	0.0896	0.0035	0.033	0.0220	0.1226	<0.7
	26/07/2008 17:57	163.4	209	609	0.0341	0.0994	0.0027	0.014	0.0368	0.1134	<0.7
	26/07/2008 20:28	41.5	205	1179	0.0085	0.0490	0.0024	0.015	0.0109	0.0640	<0.7
	26/07/2008 21:27	80.2	165	896	0.0133	0.0718	0.0024	0.023	0.0157	0.0948	<0.7
6	6/10/2008 6:03	36.0	311	1063	0.0112	0.0383	0.0094	0.018	0.0206	0.0563	<0.7
	6/10/2008 7:07	97.0	200	1219	0.0194	0.1183	0.013	0.022	0.0324	0.1403	<0.7
	6/10/2008 9:50	44.7	208	1162	0.0093	0.0519	0.019	0.041	0.0283	0.0929	<0.7
	6/10/2008 10:45	84.9	198	1269	0.0169	0.1077	0.015	0.022	0.0319	0.1297	<0.7
	6/10/2008 11:20	563.0	170	1116	0.0956	0.6284	0.0088	0.021	0.1044	0.6494	<0.7
	6/10/2008 11:32	126.8	209	1257	0.0265	0.1595	0.0094	0.019	0.0359	0.1785	<0.7
	6/10/2008 11:58	68.1	218	1291	0.0148	0.0879	0.011	0.017	0.0258	0.1049	<0.7
	6/10/2008 12:27	64.3	215	1203	0.0138	0.0773	0.013	0.021	0.0268	0.0983	<0.7
	6/10/2008 13:00	72.4	215	1304	0.0156	0.0944	0.014	0.019	0.0296	0.1134	<0.7

Table B1 (cont) Results of analysis of untreated (road edge) runoff samples collected at SH18 @ Westgate

Event	Date & time	TSS ($g\ m^{-3}$)	Dry-weight Cu ($mg\ kg^{-1}$)	Dry-weight Zn ($mg\ kg^{-1}$)	Particulate Cu ($g\ m^{-3}$)	Particulate Zn ($g\ m^{-3}$)	Dissolved Cu ($g\ m^{-3}$)	Dissolved Zn ($g\ m^{-3}$)	Total Cu ($g\ m^{-3}$)	Total Zn ($g\ m^{-3}$)	TPH ($g\ m^{-3}$)
6 (cont)	6/10/2008 13:21	76.3	222	1396	0.0169	0.1066	0.012	0.021	0.0289	0.1276	<0.7
	6/10/2008 13:49	65.7	225	1404	0.0148	0.0922	0.013	0.021	0.0278	0.1132	<0.7
	6/10/2008 14:15	41.8	221	1366	0.0092	0.0571	0.012	0.018	0.0212	0.0751	<0.7
	7/10/2008 15:06	16.9	243	940	0.0041	0.0159	0.0088	0.011	0.0129	0.0269	<0.7
	7/10/2008 15:57	335.9	194	1133	0.0652	0.3804	0.0074	0.02	0.0726	0.4004	<0.7
	7/10/2008 17:35	227.5	183	977	0.0417	0.2222	0.0099	0.019	0.0516	0.2412	<0.7
	7/10/2008 18:53	128.4	175	919	0.0225	0.1180	0.0061	0.016	0.0286	0.1340	<0.7
	7/10/2008 19:55	335.9	176	1087	0.0590	0.3652	0.0041	0.017	0.0631	0.3822	<0.7

Table B2 Results of analysis of untreated (road edge) runoff samples collected at SH1 @ Northcote

Event	Date & time	TSS (g m^{-3})	Dry-weight Cu (mg kg^{-1})	Dry-weight Zn (mg kg^{-1})	Particulate Cu (g m^{-3})	Particulate Zn (g m^{-3})	Dissolved Cu (g m^{-3})	Dissolved Zn (g m^{-3})	Total Cu (g m^{-3})	Total Zn (g m^{-3})	TPH (g m^{-3})
1	12/02/2009 19:41	66.7	187	567	0.0125	0.0378	0.03	0.052	0.0425	0.0898	<0.7
	12/02/2009 20:51	15.5	243	940	0.0038	0.0145	0.03	0.036	0.0338	0.0505	<0.7
	12/02/2009 23:07	7.6	274	724	0.0021	0.0055	0.038	0.027	0.0401	0.0325	<0.7
2	20/02/2009 6:03	19.3	186	866	0.0036	0.0167	0.019	0.037	0.0226	0.0537	<0.7
	20/02/2009 9:04	8.0	339	1244	0.0027	0.0100	0.016	0.023	0.0187	0.0330	<0.7
	20/02/2009 9:42	8.9	343	1191	0.0031	0.0106	0.015	0.064	0.0181	0.0746	<0.7
	20/02/2009 10:26	7.2	391	884	0.0028	0.0064	0.013	0.025	0.0158	0.0314	<0.7
	20/02/2009 11:08	11.9	244	813	0.0029	0.0096	0.013	0.017	0.0159	0.0266	<0.7
	20/02/2009 12:21	13.3	250	1092	0.0033	0.0145	0.012	0.025	0.0153	0.0395	<0.7
	20/02/2009 12:44	30.3	258	1092	0.0078	0.0331	0.007	0.019	0.0148	0.0521	<0.7
3	27/02/2009 21:48	30.9	223	968	0.0069	0.0299	0.025	0.088	0.0319	0.1179	<0.7
	27/02/2009 23:00	15.3	270	1022	0.0041	0.0156	0.018	0.028	0.0221	0.0436	<0.7
	27/02/2009 23:32	9.0	281	1486	0.0025	0.0133	0.015	0.065	0.0175	0.0783	<0.7
	27/02/2009 23:59	14.2	210	1073	0.0030	0.0152	0.01	0.14	0.0130	0.1552	<0.7
	28/02/2009 0:26	4.7	290	1235	0.0014	0.0058	0.0094	0.051	0.0108	0.0568	<0.7
	28/02/2009 1:03	3.1	356	1349	0.0011	0.0041	0.0084	0.14	0.0095	0.1441	<0.7
	28/02/2009 1:49	2.7	372	1752	0.0010	0.0047	0.0087	0.1	0.0097	0.1047	<0.7
	28/02/2009 2:33	5.7	260	1663	0.0015	0.0094	0.0083	0.08	0.0098	0.0894	<0.7
	28/02/2009 3:14	5.0	243	1244	0.0012	0.0063	0.0069	0.03	0.0081	0.0363	<0.7
	28/02/2009 4:06	3.4	291	1324	0.0010	0.0045	0.0054	0.06	0.0064	0.0645	<0.7
	28/02/2009 5:00	2.8	320	1601	0.0009	0.0044	0.006	0.025	0.0069	0.0294	<0.7
	28/02/2009 6:00	3.1	322	1308	0.0010	0.0040	0.0062	0.02	0.0072	0.0240	<0.7

Table B2 (cont) Results of analysis of untreated (road edge) runoff samples collected at SH1 @ Northcote

Event	Date & time	TSS ($g\ m^{-3}$)	Dry-weight Cu ($mg\ kg^{-1}$)	Dry-weight Zn ($mg\ kg^{-1}$)	Particulate Cu ($g\ m^{-3}$)	Particulate Zn ($g\ m^{-3}$)	Dissolved Cu ($g\ m^{-3}$)	Dissolved Zn ($g\ m^{-3}$)	Total Cu ($g\ m^{-3}$)	Total Zn ($g\ m^{-3}$)	TPH ($g\ m^{-3}$)
4	5/03/2009 18:45	21.3	255	1329	0.0054	0.0283	0.023	0.049	0.0284	0.0773	<0.7
	5/03/2009 23:50	6.7	314	1325	0.0021	0.0088	0.015	0.023	0.0171	0.0318	<0.7
	6/03/2009 0:51	6.1	291	1260	0.0018	0.0076	0.012	0.021	0.0138	0.0286	<0.7
	6/03/2009 1:15	6.8	376	1389	0.0025	0.0094	0.0092	0.018	0.0117	0.0274	<0.7
	6/03/2009 1:42	6.0	292	1308	0.0017	0.0078	0.0086	0.017	0.0103	0.0248	<0.7
	6/03/2009 2:15	6.0	299	1195	0.0018	0.0071	0.0084	0.017	0.0102	0.0241	<0.7
	6/03/2009 2:55	5.3	413	1341	0.0022	0.0071	0.0081	0.015	0.0103	0.0221	<0.7
	6/03/2009 3:49	4.3	298	1016	0.0013	0.0044	0.0083	0.014	0.0096	0.0184	<0.7
	6/03/2009 6:17	3.4	368	997	0.0013	0.0034	0.011	0.015	0.0123	0.0184	<0.7
	6/03/2009 7:36	9.2	312	951	0.0029	0.0087	0.0077	0.018	0.0106	0.0267	<0.7
	6/03/2009 8:21	8.6	287	990	0.0025	0.0085	0.0087	0.013	0.0112	0.0215	<0.7
	6/03/2009 9:00	6.3	326	1025	0.0020	0.0064	0.0065	0.014	0.0085	0.0204	<0.7
5	19/04/2009 21:03	47.1	256	1185	0.0121	0.0559	0.035	0.062	0.0471	0.1179	<0.7
	20/04/2009 7:33	12.7	575	1197	0.0073	0.0152	0.02	0.027	0.0273	0.0422	<0.7
	20/04/2009 8:59	9.0	297	1122	0.0027	0.0101	0.016	0.023	0.0187	0.0331	<0.7
	20/04/2009 10:07	8.1	370	1184	0.0030	0.0096	0.016	0.022	0.0190	0.0316	<0.7
	20/04/2009 11:01	8.8	377	1062	0.0033	0.0093	0.016	0.02	0.0193	0.0293	<0.7
	20/04/2009 12:04	8.7	418	1233	0.0037	0.0108	0.016	0.013	0.0197	0.0238	<0.7
	20/04/2009 14:49	7.5	387	782	0.0029	0.0059	0.018	0.014	0.0209	0.0199	<0.7
	20/04/2009 19:22	7.4	403	1048	0.0030	0.0077	0.015	0.018	0.0180	0.0257	<0.7

Table B2 (cont) Results of analysis of untreated (road edge) runoff samples collected at SH1 @ Northcote

Event	Date & time	TSS ($g\ m^{-3}$)	Dry-weight Cu ($mg\ kg^{-1}$)	Dry-weight Zn ($mg\ kg^{-1}$)	Particulate Cu ($g\ m^{-3}$)	Particulate Zn ($g\ m^{-3}$)	Dissolved Cu ($g\ m^{-3}$)	Dissolved Zn ($g\ m^{-3}$)	Total Cu ($g\ m^{-3}$)	Total Zn ($g\ m^{-3}$)	TPH ($g\ m^{-3}$)
6	26/04/2009 6:42	22.4	237	1284	0.0053	0.0288	0.019	0.032	0.0243	0.0608	<0.7
	26/04/2009 11:53	4.9	319	901	0.0016	0.0044	0.017	0.021	0.0186	0.0254	<0.7
	28/04/2009 18:33	59.7	256	1655	0.0153	0.0988	0.023	0.048	0.0383	0.1468	<0.7
	29/04/2009 1:27	7.2	285	1216	0.0020	0.0087	0.014	0.022	0.0160	0.0307	<0.7
	29/04/2009 5:29	4.5	321	900	0.0015	0.0041	0.016	0.022	0.0175	0.0261	<0.7
7	1/05/2009 22:41	22.2	222	769	0.0049	0.0171	0.021	0.021	0.0259	0.0381	<0.7
	2/05/2009 0:42	15.7	159	491	0.0025	0.0077	0.012	0.04	0.0145	0.0477	<0.7
	2/05/2009 1:43	44.3	222	1275	0.0098	0.0565	0.0081	0.015	0.0179	0.0715	<0.7
	2/05/2009 2:22	20.3	191	1304	0.0039	0.0265	0.0091	0.015	0.0130	0.0415	<0.7
	2/05/2009 3:02	26.5	235	1106	0.0062	0.0293	0.0076	0.015	0.0138	0.0443	<0.7
	2/05/2009 3:46	12.1	295	1452	0.0036	0.0175	0.0087	0.014	0.0123	0.0315	<0.7
	2/05/2009 4:52	6.6	296	1212	0.0020	0.0080	0.0075	0.014	0.0095	0.0220	<0.7
	2/05/2009 6:18	10.3	289	1476	0.0030	0.0151	0.0063	0.014	0.0093	0.0291	<0.7
	2/05/2009 7:26	9.8	405	1339	0.0040	0.0131	0.0084	0.023	0.0124	0.0361	<0.7
	2/05/2009 8:30	16.5	237	1187	0.0039	0.0196	0.006	0.017	0.0099	0.0366	<0.7
	2/05/2009 9:09	29.6	240	1400	0.0071	0.0414	0.0049	0.014	0.0120	0.0554	<0.7
	2/05/2009 9:40	15.6	234	1013	0.0036	0.0158	0.013	0.018	0.0166	0.0338	<0.7

Table B3 Results of analysis of treated (swale outlet) runoff samples collected at SH1 @ Northcote

Event	Date & time	TSS ($g\ m^{-3}$)	Dry-weight Cu ($mg\ kg^{-1}$)	Dry-weight Zn ($mg\ kg^{-1}$)	Particulate Cu ($g\ m^{-3}$)	Particulate Zn ($g\ m^{-3}$)	Dissolved Cu ($g\ m^{-3}$)	Dissolved Zn ($g\ m^{-3}$)	Total Cu ($g\ m^{-3}$)	Total Zn ($g\ m^{-3}$)	TPH ($g\ m^{-3}$)
1	12/02/2009 21:34	30.3	141	796	0.0043	0.0241	0.0098	0.02	0.0141	0.0441	<0.7
	13/02/2009 0:35	29.1	119	335	0.0035	0.0097	0.0061	0.0065	0.0096	0.0162	<0.7
	13/02/2009 7:06	4.8	123	468	0.0006	0.0023	0.0053	0.0094	0.0059	0.0117	<0.7
2	20/02/2009 6:21	21.4	47	1287	0.0010	0.0276	0.0026	0.00096	0.0036	0.0285	<0.7
	20/02/2009 10:44	114.4	53	119	0.0061	0.0136	-	-	-	-	<0.7
	20/02/2009 12:08	18.1	108	257	0.0020	0.0047	0.0056	0.011	0.0076	0.0157	<0.7
	20/02/2009 12:57	395.6	64	184	0.0255	0.0727	0.0067	0.018	0.0322	0.0907	<0.7
	20/02/2009 13:03	101.5	81	183	0.0082	0.0185	0.0088	0.012	0.0170	0.0305	<0.7
	20/02/2009 13:11	50.7	87	209	0.0044	0.0106	0.01	0.013	0.0144	0.0236	<0.7
	20/02/2009 13:20	23.1	112	232	0.0026	0.0054	0.0098	0.011	0.0124	0.0164	<0.7
	20/02/2009 13:29	21.3	114	249	0.0024	0.0053	0.0081	0.0094	0.0105	0.0147	<0.7
	20/02/2009 13:39	18.5	126	279	0.0023	0.0052	0.0082	0.013	0.0105	0.0182	<0.7
	20/02/2009 13:51	22.9	122	270	0.0028	0.0062	0.0086	0.01	0.0114	0.0162	<0.7
	20/02/2009 14:04	15.7	148	319	0.0023	0.0050	0.0098	0.012	0.0121	0.0170	<0.7
	20/02/2009 14:20	13.1	127	330	0.0017	0.0043	0.0068	0.01	0.0085	0.0143	<0.7
4	5/03/2009 22:49	8.7	122	1082	0.0011	0.0094	0.0036	0.014	0.0047	0.0234	<0.7
	6/03/2009 4:10	15.8	101	304	0.0016	0.0048	0.0045	0.015	0.0061	0.0198	<0.7
	6/03/2009 7:27	14.1	92	308	0.0013	0.0043	0.0043	0.0078	0.0056	0.0121	<0.7
	6/03/2009 9:50	15.7	123	293	0.0019	0.0046	0.0054	0.0088	0.0073	0.0134	<0.7
	13/02/2009 7:06	4.8	123	468	0.0006	0.0023	0.0053	0.0094	0.0059	0.0117	<0.7

Table B3 (cont) Results of analysis of treated (swale outlet) runoff samples collected at SH1 @ Northcote

Event	Date & time	TSS ($g\ m^{-3}$)	Dry-weight Cu ($mg\ kg^{-1}$)	Dry-weight Zn ($mg\ kg^{-1}$)	Particulate Cu ($g\ m^{-3}$)	Particulate Zn ($g\ m^{-3}$)	Dissolved Cu ($g\ m^{-3}$)	Dissolved Zn ($g\ m^{-3}$)	Total Cu ($g\ m^{-3}$)	Total Zn ($g\ m^{-3}$)	TPH ($g\ m^{-3}$)
5	20/04/2009 6:47	9.9	154	864	0.0015	0.0085	0.0039	0.0058	0.0054	0.0143	<0.7
	20/04/2009 10:45	68.9	44	124	0.0031	0.0085	0.005	0.0062	0.0081	0.0147	<0.7
	20/04/2009 13:38	20.9	76	239	0.0016	0.0050	0.0053	0.0042	0.0069	0.0092	<0.7
	20/04/2009 17:11	6.8	126	345	0.0008	0.0023	0.0052	0.0053	0.0060	0.0076	<0.7
	20/04/2009 21:42	6.6	127	351	0.0008	0.0023	0.0054	0.0082	0.0062	0.0105	<0.7
6	26/04/2009 11:19	7.7	104	1459	0.0008	0.0112	0.0044	0.013	0.0052	0.0242	<0.7
	28/04/2009 21:15	18.9	80	539	0.0015	0.0102	0.0056	0.026	0.0071	0.0362	<0.7
	29/04/2009 4:49	9.8	100	272	0.0010	0.0027	0.0042	0.019	0.0052	0.0217	<0.7
7	2/05/2009 1:00	19.7	120	724	0.0024	0.0143	0.0028	0.034	0.0052	0.0483	<0.7
	2/05/2009 4:10	58.0	56	190	0.0032	0.0110	0.0035	0.0067	0.0067	0.0177	<0.7
	2/05/2009 7:05	15.9	109	384	0.0017	0.0061	0.0044	0.0057	0.0061	0.0118	<0.7
	2/05/2009 9:22	39.9	78	211	0.0031	0.0084	0.0034	0.0067	0.0065	0.0151	<0.7
	2/05/2009 10:48	30.8	87	281	0.0027	0.0087	0.0057	0.0061	0.0084	0.0148	<0.7
	2/05/2009 12:08	5.3	127	394	0.0007	0.0021	0.0042	0.01	0.0049	0.0121	<0.7
	2/05/2009 13:37	11.5	136	409	0.0016	0.0047	0.0035	0.0057	0.0051	0.0104	<0.7
	2/05/2009 15:38	23.7	131	381	0.0031	0.0090	0.0035	0.0056	0.0066	0.0146	<0.7
	2/05/2009 18:51	126.9	35	530	0.0045	0.0673	0.0057	0.0088	0.0102	0.0761	<0.7

Table B4 Results of analysis of untreated (road edge) runoff samples collected at SH16 @ Huapai

Event	Date & time	TSS ($g\ m^{-3}$)	Dry-weight Cu ($mg\ kg^{-1}$)	Dry-weight Zn ($mg\ kg^{-1}$)	Particulate Cu ($g\ m^{-3}$)	Particulate Zn ($g\ m^{-3}$)	Dissolved Cu ($g\ m^{-3}$)	Dissolved Zn ($g\ m^{-3}$)	Total Cu ($g\ m^{-3}$)	Total Zn ($g\ m^{-3}$)	TPH ($g\ m^{-3}$)
1	8/12/2008 23:22	715.5	105	525	0.0751	0.3757	0.033	0.049	0.1081	0.4247	<0.7
	9/12/2008 1:44	32.4	154	771	0.0050	0.0250	0.0085	0.011	0.0135	0.0360	<0.7
	9/12/2008 2:25	1086.9	73	396	0.0795	0.4305	0.0053	0.012	0.0848	0.4425	<0.7
	9/12/2008 2:32	203.6	110	379	0.0223	0.0771	0.0026	0.0061	0.0249	0.0832	<0.7
	9/12/2008 2:53	46.1	157	569	0.0072	0.0262	0.0042	0.0094	0.0114	0.0356	<0.7
	9/12/2008 3:08	29.5	124	535	0.0037	0.0158	0.0036	0.0067	0.0073	0.0225	<0.7
	9/12/2008 4:07	15.4	200	820	0.0031	0.0126	0.0054	0.0088	0.0085	0.0214	<0.7
	9/12/2008 7:25	41.5	876	3149	0.0364	0.1307	0.0082	0.013	0.0446	0.1437	<0.7
	9/12/2008 9:49	46.8	96	499	0.0045	0.0234	0.019	0.02	0.0235	0.0434	<0.7
	9/12/2008 14:26	177.9	190	950	0.0338	0.1690	0.0083	0.019	0.0421	0.1880	0.77
	9/12/2008 14:37	185.0	130	734	0.0241	0.1357	0.0051	0.011	0.0292	0.1467	<0.7
	9/12/2008 14:55	43.6	187	1059	0.0082	0.0462	0.0075	0.011	0.0157	0.0572	<0.7
2	9/02/2009 21:57	732.5	89	394	0.0649	0.2890	0.017	0.02	0.0819	0.3090	<0.7
	10/02/2009 0:20	58.5	127	491	0.0074	0.0287	0.014	0.013	0.0214	0.0417	<0.7
	10/02/2009 7:13	1.6	319	757	0.0005	0.0012	0.017	0.01	0.0175	0.0112	<0.7
	10/02/2009 19:45	9.2	376	889	0.0035	0.0082	0.026	0.014	0.0295	0.0222	<0.7
	12/02/2009 18:54	162.6	131	395	0.0213	0.0642	0.015	0.015	0.0363	0.0792	<0.7
	12/02/2009 20:46	19.5	196	738	0.0038	0.0144	0.0072	0.013	0.0110	0.0274	<0.7

Table B4 (cont) Results of analysis of untreated (road edge) runoff samples collected at SH16 @ Huapai

Event	Date & time	TSS ($g\ m^{-3}$)	Dry-weight Cu ($mg\ kg^{-1}$)	Dry-weight Zn ($mg\ kg^{-1}$)	Particulate Cu ($g\ m^{-3}$)	Particulate Zn ($g\ m^{-3}$)	Dissolved Cu ($g\ m^{-3}$)	Dissolved Zn ($g\ m^{-3}$)	Total Cu ($g\ m^{-3}$)	Total Zn ($g\ m^{-3}$)	TPH ($g\ m^{-3}$)
3	20/02/2009 3:29	23.1	190	716	0.0044	0.0166	0.02	0.017	0.0244	0.0336	<0.7
	20/02/2009 6:24	40.3	177	848	0.0071	0.0342	0.0062	0.018	0.0133	0.0522	<0.7
	20/02/2009 8:34	85.1	148	739	0.0126	0.0629	0.0037	0.018	0.0163	0.0809	<0.7
	20/02/2009 9:02	117.4	129	620	0.0152	0.0728	0.0031	0.013	0.0183	0.0858	<0.7
	20/02/2009 9:14	224.6	122	640	0.0275	0.1438	0.003	0.0091	0.0305	0.1529	<0.7
	20/02/2009 9:24	383.4	100	449	0.0382	0.1720	0.0025	0.0069	0.0407	0.1789	<0.7
	20/02/2009 9:37	257.5	117	466	0.0300	0.1200	0.0023	0.0082	0.0323	0.1282	<0.7
	20/02/2009 9:49	158.8	100	413	0.0159	0.0656	0.0024	0.011	0.0183	0.0766	<0.7
	20/02/2009 10:13	96.9	102	493	0.0099	0.0478	0.0029	0.017	0.0128	0.0648	<0.7
	20/02/2009 12:05	88.1	133	647	0.0117	0.0570	0.0038	0.03	0.0155	0.0870	<0.7
	20/02/2009 12:26	200.5	108	533	0.0217	0.1069	0.0025	0.032	0.0242	0.1389	<0.7
	20/02/2009 12:34	211.4	84	369	0.0178	0.0781	0.0018	0.0058	0.0196	0.0839	<0.7
4	19/04/2009 21:23	158.5	161	570	0.0255	0.0903	0.031	0.04	0.0565	0.1303	<0.7
	20/04/2009 7:13	316.0	111	857	0.0350	0.2707	0.0056	0.0077	0.0406	0.2784	<0.7
	20/04/2009 7:40	61.0	146	836	0.0089	0.0510	0.0043	0.0094	0.0132	0.0604	<0.7
	20/04/2009 11:33	187.3	138	1139	0.0258	0.2134	0.0059	0.0096	0.0317	0.2230	<0.7
	20/04/2009 23:01	20.3	144	1011	0.0029	0.0206	0.0058	0.0078	0.0087	0.0284	<0.7

Table B4 (cont) Results of analysis of untreated (road edge) runoff samples collected at SH16 @ Huapai

Event	Date & time	TSS ($g\ m^{-3}$)	Dry-weight Cu ($mg\ kg^{-1}$)	Dry-weight Zn ($mg\ kg^{-1}$)	Particulate Cu ($g\ m^{-3}$)	Particulate Zn ($g\ m^{-3}$)	Dissolved Cu ($g\ m^{-3}$)	Dissolved Zn ($g\ m^{-3}$)	Total Cu ($g\ m^{-3}$)	Total Zn ($g\ m^{-3}$)	TPH ($g\ m^{-3}$)
5	25/04/2009 17:24	33.5	125	665	0.0042	0.0223	0.0092	0.013	0.0134	0.0353	<0.7
	25/04/2009 22:33	19.9	159	796	0.0032	0.0158	0.004	0.018	0.0072	0.0338	<0.7
	25/04/2009 22:54	143.1	108	641	0.0155	0.0918	0.0021	0.0096	0.0176	0.1014	<0.7
	26/04/2009 0:11	21.9	330	761	0.0072	0.0167	0.0032	0.012	0.0104	0.0287	<0.7
	26/04/2009 13:48	12.9	210	790	0.0027	0.0102	0.0058	0.017	0.0085	0.0272	<0.7
	26/04/2009 23:57	72.5	122	586	0.0088	0.0425	0.0066	0.028	0.0154	0.0705	<0.7
	28/04/2009 16:25	64.8	94	408	0.0061	0.0265	0.006	0.025	0.0121	0.0515	<0.7
	28/04/2009 17:47	147.0	128	770	0.0189	0.1132	0.0038	0.0093	0.0227	0.1225	<0.7
	28/04/2009 18:02	203.1	139	742	0.0282	0.1506	0.0026	0.0091	0.0308	0.1597	<0.7
	28/04/2009 18:15	118.2	97	458	0.0115	0.0541	0.0029	0.012	0.0144	0.0661	<0.7
	28/04/2009 0:04	166.9	104	584	0.0173	0.0975	0.0027	0.019	0.0200	0.1165	<0.7
	29/04/2009 1:45	83.5	104	595	0.0087	0.0497	0.0025	0.0074	0.0112	0.0571	<0.7
6	29/04/2009 23:37	275.2	114	618	0.0314	0.1699	0.0061	0.01	0.0375	0.1799	<0.7
	1/05/2009 23:43	87.2	133	666	0.0116	0.0581	0.017	0.018	0.0286	0.0761	<0.7
	2/05/2009 0:05	111.5	105	582	0.0117	0.0649	0.0038	0.012	0.0155	0.0769	<0.7
	2/05/2009 0:23	102.7	93	403	0.0096	0.0414	0.0036	0.011	0.0132	0.0524	<0.7
	2/05/2009 0:55	98.9	92	427	0.0091	0.0422	0.0025	0.0069	0.0116	0.0491	<0.7
	2/05/2009 1:24	48.2	88	360	0.0042	0.0173	0.003	0.0081	0.0072	0.0254	<0.7
	2/05/2009 2:21	52.4	93	440	0.0049	0.0231	0.0023	0.0083	0.0072	0.0314	<0.7
	2/05/2009 3:14	49.1	115	496	0.0056	0.0244	0.0025	0.0087	0.0081	0.0331	<0.7
	2/05/2009 5:52	26.8	105	542	0.0028	0.0145	0.0026	0.011	0.0054	0.0255	<0.7
	2/05/2009 8:03	61.0	105	578	0.0064	0.0353	0.0028	0.011	0.0092	0.0463	<0.7

Table B4 (cont) Results of analysis of untreated (road edge) runoff samples collected at SH16 @ Huapai

Event	Date & time	TSS ($g\ m^{-3}$)	Dry-weight Cu ($mg\ kg^{-1}$)	Dry-weight Zn ($mg\ kg^{-1}$)	Particulate Cu ($g\ m^{-3}$)	Particulate Zn ($g\ m^{-3}$)	Dissolved Cu ($g\ m^{-3}$)	Dissolved Zn ($g\ m^{-3}$)	Total Cu ($g\ m^{-3}$)	Total Zn ($g\ m^{-3}$)	TPH ($g\ m^{-3}$)
7	30/05/2009 13:30	266.5	147	821	0.0391	0.2188	0.013	0.011	0.0521	0.2298	-
	30/05/2009 14:13	383.8	122	584	0.0469	0.2240	0.004	0.0023	0.0509	0.2263	-
	30/05/2009 14:31	481.7	108	520	0.0522	0.2507	0.0025	0.0019	0.0547	0.2526	-
	30/05/2009 14:40	672.5	89	424	0.0596	0.2850	0.0029	0.008	0.0625	0.2930	-
	30/05/2009 14:47	851.6	89	369	0.0759	0.3141	0.0021	0.0014	0.0780	0.3155	-
	30/05/2009 14:52	701.5	82	327	0.0573	0.2292	0.0018	0.0028	0.0591	0.2320	-
	30/05/2009 14:59	545.2	86	373	0.0469	0.2031	0.0019	0.0017	0.0488	0.2048	-
	30/05/2009 15:12	237.0	96	357	0.0228	0.0847	0.0024	0.0022	0.0252	0.0869	-
	30/05/2009 15:52	94.7	118	522	0.0112	0.0495	0.0023	0.0027	0.0135	0.0522	-
8	9/06/2009 3:06	153.5	94	381	0.0144	0.0585	0.0035	0.0027	0.0179	0.0612	-
	9/06/2009 4:06	68.0	110	434	0.0075	0.0295	0.0033	0.0027	0.0108	0.0322	-
	9/06/2009 4:59	124.2	104	498	0.0129	0.0618	0.0019	0.0018	0.0148	0.0636	-
	9/06/2009 5:41	48.4	225	714	0.0109	0.0346	0.003	0.0049	0.0139	0.0395	-
	9/06/2009 7:37	55.7	211	1055	0.0118	0.0588	0.0037	0.0067	0.0155	0.0655	-
	9/06/2009 8:26	94.1	189	890	0.0178	0.0838	0.0036	0.0085	0.0214	0.0923	-
	9/06/2009 9:08	326.0	122	555	0.0399	0.1809	0.0023	0.0017	0.0422	0.1826	-
	9/06/2009 9:16	356.1	111	495	0.0395	0.1763	0.0021	0.0012	0.0416	0.1775	-
	9/06/2009 9:42	118.8	140	632	0.0166	0.0751	0.0029	0.002	0.0195	0.0771	-
	9/06/2009 10:38	260.1	162	740	0.0422	0.1926	0.0039	0.0047	0.0461	0.1973	-
	9/06/2009 11:07	116.3	144	558	0.0168	0.0649	0.0049	0.0037	0.0217	0.0686	-
	9/06/2009 12:15	49.2	171	800	0.0084	0.0394	0.0049	0.004	0.0133	0.0434	-

Table B.5 Results of analysis of treated (drainage channel outlet) runoff samples collected at SH16 @ Huapai

Event	Date & time	TSS (g m^{-3})	Dry-weight Cu (mg kg^{-1})	Dry-weight Zn (mg kg^{-1})	Particulate Cu (g m^{-3})	Particulate Zn (g m^{-3})	Dissolved Cu (g m^{-3})	Dissolved Zn (g m^{-3})	Total Cu (g m^{-3})	Total Zn (g m^{-3})	TPH (g m^{-3})
3	20/02/2009 9:14	6.1	152	597	0.0009	0.0037	0.012	0.023	0.0129	0.0267	<0.7
	20/02/2009 9:24	8.5	147	636	0.0013	0.0054	0.0086	0.014	0.0099	0.0194	<0.7
	20/02/2009 9:30	7.9	149	555	0.0012	0.0044	0.0066	0.025	0.0078	0.0294	<0.7
	20/02/2009 9:37	7.6	163	728	0.0012	0.0056	0.0058	0.0093	0.0070	0.0149	<0.7
	20/02/2009 9:44	8.8	152	533	0.0013	0.0047	0.0053	0.011	0.0066	0.0157	<0.7
	20/02/2009 9:51	7.4	151	623	0.0011	0.0046	0.0054	0.0096	0.0065	0.0142	<0.7
	20/02/2009 9:58	8.6	152	645	0.0013	0.0056	0.0054	0.0095	0.0067	0.0151	<0.7
	20/02/2009 10:07	6.2	175	584	0.0011	0.0036	0.0052	0.0087	0.0063	0.0123	<0.7
	20/02/2009 10:23	4.5	216	595	0.0010	0.0027	0.0053	0.012	0.0063	0.0147	<0.7
	20/02/2009 10:51	3.3	507	841	0.0017	0.0028	0.0071	0.011	0.0088	0.0138	<0.7
	20/02/2009 12:37	13.2	91	330	0.0012	0.0043	0.0065	0.019	0.0077	0.0233	<0.7
	20/02/2009 12:41	7.2	158	652	0.0011	0.0047	0.0049	0.012	0.0060	0.0167	<0.7
5	29/04/2009 6:34	9.8	152	542	0.0015	0.0053	0.0064	0.014	0.0079	0.0193	<0.7
6	2/05/2009 14:32	9.1	128	414	0.0012	0.0038	0.0063	0.0092	0.0075	0.0130	<0.7

Table B.5 (cont) Results of analysis of treated (drainage channel outlet) runoff samples collected at SH16 @ Huapai

Event	Date & time	TSS (g m^{-3})	Dry-weight Cu (mg kg^{-1})	Dry-weight Zn (mg kg^{-1})	Particulate Cu (g m^{-3})	Particulate Zn (g m^{-3})	Dissolved Cu (g m^{-3})	Dissolved Zn (g m^{-3})	Total Cu (g m^{-3})	Total Zn (g m^{-3})	TPH (g m^{-3})
7	30/05/2009 14:41	35.8	126	453	0.0045	0.0162	0.0045	0.0057	0.0090	0.0219	-
	30/05/2009 14:50	68.6	137	430	0.0094	0.0295	0.0048	0.0032	0.0142	0.0327	-
	30/05/2009 14:55	73.0	123	435	0.0090	0.0317	0.0044	0.0033	0.0134	0.0350	-
	30/05/2009 15:01	65.3	126	447	0.0082	0.0292	0.0044	0.0049	0.0126	0.0341	-
	30/05/2009 15:06	66.2	127	437	0.0084	0.0289	0.0038	0.0035	0.0122	0.0324	-
	30/05/2009 15:13	40.7	125	452	0.0051	0.0184	0.0037	0.005	0.0088	0.0234	-
	30/05/2009 15:22	30.8	128	487	0.0039	0.0150	0.0035	0.0043	0.0074	0.0193	-
	30/05/2009 15:36	20.2	125	462	0.0025	0.0093	0.0032	0.0051	0.0057	0.0144	-
	30/05/2009 15:54	11.2	161	551	0.0018	0.0062	0.0034	0.0066	0.0052	0.0128	-
	30/05/2009 16:08	12.2	266	599	0.0032	0.0073	0.0033	0.0052	0.0065	0.0125	-
	30/05/2009 16:21	13.0	141	388	0.0018	0.0051	0.0043	0.005	0.0061	0.0101	-
	9/06/2009 5:07	6.8	137	391	0.0009	0.0027	0.0031	0.0032	0.0040	0.0059	-
	9/06/2009 5:37	9.5	127	397	0.0012	0.0038	0.0028	0.0031	0.0040	0.0069	-
	9/06/2009 8:04	4.7	133	394	0.0006	0.0018	0.0036	0.0048	0.0042	0.0066	-
	9/06/2009 8:41	11.9	154	612	0.0018	0.0073	0.0033	0.0047	0.0051	0.0120	-
	9/06/2009 9:04	15.2	195	622	0.0030	0.0095	0.0034	0.0034	0.0064	0.0129	-
	9/06/2009 9:17	18.2	110	342	0.0020	0.0062	0.0035	0.0034	0.0055	0.0096	-
	9/06/2009 9:35	24.3	142	481	0.0035	0.0117	0.0034	0.023	0.0069	0.0347	-
	9/06/2009 10:02	17.7	143	482	0.0025	0.0086	0.0035	0.0051	0.0060	0.0137	-
	9/06/2009 10:41	21.9	118	172	0.0026	0.0038	0.0072	0.0085	0.0098	0.0123	-
	9/06/2009 11:00	21.0	139	291	0.0029	0.0061	0.0078	0.019	0.0107	0.0251	-
	9/06/2009 11:17	22.2	133	291	0.0030	0.0065	0.0062	0.016	0.0092	0.0225	-
	9/06/2009 11:36	19.0	141	226	0.0027	0.0043	0.0073	0.0095	0.0100	0.0138	-

Table B.6 Results of analysis of untreated (pond inlet) runoff samples collected at SH1 @ Redvale

Event	Date & time	TSS (g m^{-3})	Dry-weight Cu (mg kg^{-1})	Dry-weight Zn (mg kg^{-1})	Particulate Cu (g m^{-3})	Particulate Zn (g m^{-3})	Dissolved Cu (g m^{-3})	Dissolved Zn (g m^{-3})	Total Cu (g m^{-3})	Total Zn (g m^{-3})	TPH (g m^{-3})
1	23/02/2008 03:27	164.4	157	1417	0.0259	0.2329	0.011	0.014	0.0369	0.2469	-
	23/02/2008 03:55	54.4	217	1235	0.0118	0.0671	0.0095	0.014	0.0213	0.0811	-
	23/02/2008 04:52	28.2	157	1239	0.0044	0.0349	0.0091	0.01	0.0135	0.0449	-
	23/02/2008 05:24	42.6	162	1401	0.0069	0.0596	0.0067	0.013	0.0136	0.0726	-
	23/02/2008 05:49	44.2	190	1264	0.0084	0.0558	0.006	0.016	0.0144	0.0718	-
	23/02/2008 06:12	96.0	175	1387	0.0168	0.1332	0.0054	0.0093	0.0222	0.1425	-
	23/02/2008 06:29	220.7	148	1164	0.0327	0.2570	0.0038	0.0034	0.0365	0.2604	-
	23/02/2008 06:48	40.4	196	1208	0.0079	0.0488	0.005	0.012	0.0129	0.0608	-
	23/02/2008 14:52	46.3	165	1061	0.0076	0.0491	0.0048	0.012	0.0124	0.0611	-
	23/02/2008 15:22	46.3	152	1215	0.0070	0.0562	0.0053	0.018	0.0123	0.0742	-
	23/02/2008 15:49	25.7	193	718	0.0050	0.0184	0.0075	0.0076	0.0125	0.0260	-
	23/02/2008 16:20	17.1	188	1103	0.0032	0.0189	0.0059	0.013	0.0091	0.0319	-
	23/02/2008 16:51	8.6	242	805	0.0021	0.0069	0.0092	0.011	0.0113	0.0179	-
	23/02/2008 18:04	6.3	308	805	0.0019	0.0051	0.011	0.012	0.0129	0.0171	-
	23/02/2008 23:01	5.5	350	1007	0.0019	0.0055	0.01	0.012	0.0119	0.0175	-
	24/02/2008 02:31	5.9	318	1059	0.0019	0.0063	0.0082	0.011	0.0101	0.0173	-
	24/02/2008 03:46	4.8	308	976	0.0015	0.0047	0.0061	0.01	0.0076	0.0147	-
	24/02/2008 07:35	4.6	304	997	0.0014	0.0046	0.0076	0.0087	0.0090	0.0133	-

Table B.6 (cont) Results of analysis of untreated (pond inlet) runoff samples collected at SH1 @ Redvale

Event	Date & time	TSS (g m^{-3})	Dry-weight Cu (mg kg^{-1})	Dry-weight Zn (mg kg^{-1})	Particulate Cu (g m^{-3})	Particulate Zn (g m^{-3})	Dissolved Cu (g m^{-3})	Dissolved Zn (g m^{-3})	Total Cu (g m^{-3})	Total Zn (g m^{-3})	TPH (g m^{-3})
2	1/03/2008 06:31	4.3	117	584	0.0005	0.0025	0.0019	0.0053	0.0024	0.0078	-
	1/03/2008 07:17	47.4	232	1060	0.0110	0.0502	0.014	0.016	0.0250	0.0662	-
	1/03/2008 07:52	23.3	222	886	0.0052	0.0206	0.013	0.016	0.0182	0.0366	-
	1/03/2008 08:18	58.7	547	1328	0.0321	0.0780	0.0097	0.014	0.0418	0.0920	-
	1/03/2008 09:10	13.3	249	873	0.0033	0.0116	0.013	0.0093	0.0163	0.0209	-
	1/03/2008 10:01	301.5	175	761	0.0528	0.2294	0.0054	0.0066	0.0582	0.2360	-
	1/03/2008 10:21	106.4	161	836	0.0171	0.0890	0.0086	0.011	0.0257	0.1000	-
	1/03/2008 13:45	11.4	187	611	0.0021	0.0070	0.012	0.0071	0.0141	0.0141	-
	2/03/2008 00:52	9.2	248	739	0.0023	0.0068	0.012	0.0094	0.0143	0.0162	-
	2/03/2008 05:02	5.5	258	712	0.0014	0.0039	0.0093	0.0068	0.0107	0.0107	-
3	13/04/2008 15:51	286.9	143	1426	0.0409	0.4091	0.01	0.022	0.0509	0.4311	<0.7
	13/04/2008 18:12	32.6	204	1264	0.0066	0.0412	0.016	0.02	0.0226	0.0612	<0.7
	13/04/2008 19:03	42.9	182	1105	0.0078	0.0474	0.011	0.0098	0.0188	0.0572	<0.7
	14/04/2008 02:55	225.8	134	1138	0.0304	0.2570	0.0085	0.015	0.0389	0.2720	<0.7
	14/04/2008 03:39	24.9	184	1106	0.0046	0.0276	0.0079	0.0083	0.0125	0.0359	<0.7
	14/04/2008 04:23	88.7	148	1250	0.0132	0.1109	0.0057	0.0091	0.0189	0.1200	<0.7
	14/04/2008 04:47	83.2	170	1226	0.0142	0.1021	0.0042	0.011	0.0184	0.1131	<0.7
	14/04/2008 05:13	33.8	214	1138	0.0072	0.0385	0.0048	0.019	0.0120	0.0575	<0.7
	14/04/2008 06:01	66.1	160	1248	0.0106	0.0825	0.0068	0.011	0.0174	0.0935	<0.7
	14/04/2008 06:28	47.9	247	1164	0.0118	0.0557	0.0053	0.044	0.0171	0.0997	<0.7
	14/04/2008 07:20	32.3	273	1220	0.0088	0.0394	0.0071	0.028	0.0159	0.0674	<0.7
	14/04/2008 07:57	23.1	255	1121	0.0059	0.0259	0.0066	0.014	0.0125	0.0399	<0.7
	14/04/2008 14:28	33.9	209	1011	0.0071	0.0342	0.0072	0.0094	0.0143	0.0436	<0.7
	14/04/2008 20:53	28.4	252	708	0.0072	0.0201	0.007	0.0065	0.0142	0.0266	<0.7

Table B.6 (cont) Results of analysis of untreated (pond inlet) runoff samples collected at SH1 @ Redvale

Event	Date & time	TSS ($g\ m^{-3}$)	Dry-weight Cu ($mg\ kg^{-1}$)	Dry-weight Zn ($mg\ kg^{-1}$)	Particulate Cu ($g\ m^{-3}$)	Particulate Zn ($g\ m^{-3}$)	Dissolved Cu ($g\ m^{-3}$)	Dissolved Zn ($g\ m^{-3}$)	Total Cu ($g\ m^{-3}$)	Total Zn ($g\ m^{-3}$)	TPH ($g\ m^{-3}$)
4	15/04/2008 08:58	62.8	190	1022	0.0119	0.0642	0.0068	0.01	0.0187	0.0742	<0.7
	15/04/2008 09:45	118.3	193	1004	0.0228	0.1187	0.0054	0.012	0.0282	0.1307	<0.7
	15/04/2008 10:32	127.2	197	1054	0.0250	0.1341	0.006	0.012	0.0310	0.1461	<0.7
	15/04/2008 11:31	67.9	190	1092	0.0129	0.0742	0.0054	0.0082	0.0183	0.0824	<0.7
	15/04/2008 12:27	61.5	236	1123	0.0145	0.0691	0.0057	0.0091	0.0202	0.0782	<0.7
	15/04/2008 12:46	239.0	145	771	0.0346	0.1843	0.0041	0.0081	0.0387	0.1924	<0.7
	15/04/2008 13:10	81.7	198	1005	0.0162	0.0821	0.0059	0.014	0.0221	0.0961	<0.7
	15/04/2008 13:34	2039.4	64	832	0.1302	1.6977	0.0029	0.0072	0.1331	1.7049	<0.7
	15/04/2008 13:44	1198.9	57	363	0.0688	0.4358	0.0028	0.0032	0.0716	0.4390	<0.7
	15/04/2008 14:06	97.3	77	386	0.0075	0.0375	0.005	0.0064	0.0125	0.0439	<0.7
5	28/04/2008 23:45	2.3	144	1090	0.0003	0.0025	0.0026	0.0038	0.0029	0.0063	<0.7
	29/04/2008 00:57	27.7	242	969	0.0067	0.0268	0.0047	0.0071	0.0114	0.0339	<0.7
	29/04/2008 02:17	34.2	146	744	0.0050	0.0254	0.0031	0.0058	0.0081	0.0312	<0.7
	29/04/2008 02:50	24.3	115	482	0.0028	0.0117	0.0054	0.0053	0.0082	0.0170	<0.7
	29/04/2008 05:24	9.8	247	911	0.0024	0.0090	0.0055	0.0069	0.0079	0.0159	<0.7
	29/04/2008 06:36	123.9	116	506	0.0144	0.0627	0.0048	0.013	0.0192	0.0757	<0.7

Table B.6 (cont) Results of analysis of untreated (pond inlet) runoff samples collected at SH1 @ Redvale

Event	Date & time	TSS (g m^{-3})	Dry-weight Cu (mg kg^{-1})	Dry-weight Zn (mg kg^{-3})	Particulate Cu (g m^{-3})	Particulate Zn (g m^{-3})	Dissolved Cu (g m^{-3})	Dissolved Zn (g m^{-3})	Total Cu (g m^{-3})	Total Zn (g m^{-3})	TPH (g m^{-3})
6	16/06/2008 07:13	42.7	142	1286	0.0061	0.0549	0.0094	0.023	0.0155	0.0779	<0.7
	16/06/2008 07:56	34.5	197	1591	0.0068	0.0548	0.011	0.026	0.0178	0.0808	<0.7
	16/06/2008 10:00	28.0	226	1309	0.0063	0.0367	0.0095	0.026	0.0158	0.0627	<0.7
	16/06/2008 11:34	142.3	190	1249	0.0270	0.1778	0.0084	0.032	0.0354	0.2098	<0.7
	16/06/2008 12:39	64.9	166	979	0.0108	0.0635	0.0078	0.013	0.0186	0.0765	<0.7
	16/06/2008 14:15	63.1	148	925	0.0093	0.0583	0.0061	0.02	0.0154	0.0783	<0.7
	16/06/2008 16:12	30.5	177	914	0.0054	0.0278	0.0071	0.021	0.0125	0.0488	<0.7
	16/06/2008 17:14	75.8	153	895	0.0116	0.0678	0.0058	0.015	0.0174	0.0828	<0.7
	16/06/2008 17:45	43.1	102	604	0.0044	0.0260	0.0079	0.019	0.0123	0.0450	<0.7
	16/06/2008 18:24	51.9	127	775	0.0066	0.0402	0.0054	0.011	0.0120	0.0512	<0.7
	16/06/2008 18:54	42.0	107	669	0.0045	0.0281	0.0075	0.019	0.0120	0.0471	<0.7
	16/06/2008 19:42	27.1	93	505	0.0025	0.0137	0.0073	0.014	0.0098	0.0277	<0.7
7	26/07/2008 05:09	47.3	124	870	0.0059	0.0412	0.0056	0.015	0.0115	0.0562	<0.7
	26/07/2008 05:57	29.9	165	1000	0.0049	0.0299	0.0047	0.01	0.0096	0.0399	<0.7
	26/07/2008 07:26	111.4	48	330	0.0054	0.0367	0.0036	0.016	0.0090	0.0527	<0.7
	26/07/2008 08:16	67.5	80	586	0.0054	0.0395	0.0043	0.011	0.0097	0.0505	<0.7
	26/07/2008 08:49	134.5	59	419	0.0079	0.0563	0.0036	0.0086	0.0115	0.0649	<0.7
	26/07/2008 09:14	120.8	84	538	0.0102	0.0650	0.0042	0.0084	0.0144	0.0734	<0.7
	26/07/2008 09:32	182.4	82	510	0.0149	0.0930	0.0038	0.012	0.0187	0.1050	<0.7
	26/07/2008 09:46	222.7	48	296	0.0108	0.0659	0.0036	0.0082	0.0144	0.0741	<0.7
	26/07/2008 10:06	120.5	44	315	0.0052	0.0379	0.0036	0.0074	0.0088	0.0453	<0.7
	26/07/2008 10:32	146.0	96	673	0.0140	0.0983	0.0033	0.0085	0.0173	0.1068	<0.7
	26/07/2008 10:44	235.4	50	303	0.0118	0.0712	0.0031	0.0068	0.0149	0.0780	<0.7
	26/07/2008 10:55	204.7	37	231	0.0075	0.0472	0.0029	0.0073	0.0104	0.0545	<0.7

Table B.6 (cont) Results of analysis of untreated (pond inlet) runoff samples collected at SH1 @ Redvale

Event	Date & time	TSS ($g\ m^{-3}$)	Dry-weight Cu ($mg\ kg^{-1}$)	Dry-weight Zn ($mg\ kg^{-1}$)	Particulate Cu ($g\ m^{-3}$)	Particulate Zn ($g\ m^{-3}$)	Dissolved Cu ($g\ m^{-3}$)	Dissolved Zn ($g\ m^{-3}$)	Total Cu ($g\ m^{-3}$)	Total Zn ($g\ m^{-3}$)	TPH ($g\ m^{-3}$)
8	6/10/2008 04:46	1480.1	32	173	0.0471	0.2559	0.0015	0.011	0.0486	0.2669	-
	6/10/2008 06:22	291.5	194	1120	0.0567	0.3267	0.0068	0.017	0.0635	0.3437	-
	6/10/2008 07:15	164.5	194	1045	0.0318	0.1720	0.01	0.016	0.0418	0.1880	-
	6/10/2008 10:25	88.2	215	1148	0.0190	0.1013	0.011	0.014	0.0300	0.1153	-
	6/10/2008 12:45	29.4	252	1206	0.0074	0.0355	0.012	0.014	0.0194	0.0495	-
	6/10/2008 14:16	80.4	207	1185	0.0167	0.0952	0.011	0.015	0.0277	0.1102	-
	6/10/2008 15:55	22.5	308	1099	0.0069	0.0247	0.0096	0.0099	0.0165	0.0346	-
	6/10/2008 18:56	14.9	349	1156	0.0052	0.0172	0.0074	0.012	0.0126	0.0292	-
	6/10/2008 22:40	14.0	321	1232	0.0045	0.0173	0.0071	0.011	0.0116	0.0283	-
	7/10/2008 15:04	18.1	178	1421	0.0032	0.0257	0.0044	0.075	0.0076	0.1007	-
	7/10/2008 16:14	479.3	192	1167	0.0921	0.5592	0.0034	0.024	0.0955	0.5832	-
	7/10/2008 16:49	178.6	11	633	0.0020	0.1131	0.0051	0.078	0.0071	0.1911	-
	7/10/2008 17:58	138.8	191	1207	0.0265	0.1676	0.0054	0.012	0.0319	0.1796	-
	7/10/2008 18:45	48.8	157	964	0.0076	0.0471	0.0066	0.012	0.0142	0.0591	-
	7/10/2008 19:40	31.9	94	682	0.0030	0.0218	0.0055	0.0075	0.0085	0.0293	-
	8/10/2008 01:13	10.7	154	815	0.0017	0.0088	0.0045	0.0053	0.0062	0.0141	-

Table B.7 Results of analysis of treated (pond outlet) runoff samples collected at SH1 @ Redvale

Event	Date & time	TSS (g m^{-3})	Dry-weight Cu (mg kg^{-1})	Dry-weight Zn (mg kg^{-1})	Particulate Cu (g m^{-3})	Particulate Zn (g m^{-3})	Dissolved Cu (g m^{-3})	Dissolved Zn (g m^{-3})	Total Cu (g m^{-3})	Total Zn (g m^{-3})	TPH (g m^{-3})
3	13/04/2008 16:21	6.7	298	489	0.0020	0.0033	0.0077	0.0072	0.0097	0.0105	<0.7
	13/04/2008 21:10	11.2	289	815	0.0032	0.0091	0.011	0.011	0.0142	0.0201	<0.7
	14/04/2008 02:45	7.7	266	761	0.0021	0.0059	0.0091	0.0087	0.0112	0.0146	<0.7
	14/04/2008 04:45	7.7	254	692	0.0020	0.0053	0.0071	0.0073	0.0091	0.0126	<0.7
	14/04/2008 05:28	7.1	296	762	0.0021	0.0054	0.0066	0.0089	0.0087	0.0143	<0.7
	14/04/2008 06:10	9.3	252	863	0.0024	0.0080	0.0056	0.0091	0.0080	0.0171	<0.7
	14/04/2008 06:48	10.0	258	908	0.0026	0.0090	0.0049	0.01	0.0075	0.0190	<0.7
	14/04/2008 07:28	9.5	261	921	0.0025	0.0087	0.0049	0.0096	0.0074	0.0183	<0.7
	14/04/2008 08:06	11.6	252	1186	0.0029	0.0137	0.0059	0.019	0.0088	0.0327	<0.7
	14/04/2008 08:46	13.2	287	1039	0.0038	0.0137	0.0052	0.0096	0.0090	0.0233	<0.7
	14/04/2008 09:33	13.2	571	901	0.0076	0.0119	0.0053	0.01	0.0129	0.0219	<0.7
	14/04/2008 10:35	13.1	269	851	0.0035	0.0111	0.005	0.0095	0.0085	0.0206	<0.7
	14/04/2008 14:52	22.7	260	949	0.0059	0.0215	0.0064	0.013	0.0123	0.0345	<0.7
	14/04/2008 17:04	17.5	236	860	0.0041	0.0150	0.007	0.011	0.0111	0.0260	<0.7
	14/04/2008 21:48	13.5	212	646	0.0029	0.0087	0.0061	0.011	0.0090	0.0197	<0.7
4	15/04/2008 07:11	10.1	230	576	0.0023	0.0058	0.0058	0.011	0.0081	0.0168	<0.7
	15/04/2008 10:45	16.9	230	902	0.0039	0.0153	0.0055	0.014	0.0094	0.0293	<0.7
	15/04/2008 11:23	26.6	263	988	0.0070	0.0263	0.0047	0.013	0.0117	0.0393	<0.7
	15/04/2008 12:15	22.9	260	936	0.0060	0.0214	0.0059	0.014	0.0119	0.0354	<0.7
	15/04/2008 12:46	18.7	232	835	0.0043	0.0157	0.0056	0.012	0.0099	0.0277	<0.7
	15/04/2008 13:22	19.4	227	833	0.0044	0.0161	0.0055	0.012	0.0099	0.0281	<0.7
	15/04/2008 13:44	25.6	243	1043	0.0062	0.0267	0.029	0.037	0.0352	0.0637	<0.7
	15/04/2008 14:02	27.8	256	948	0.0071	0.0263	0.0068	0.019	0.0139	0.0453	<0.7
	15/04/2008 14:20	26.4	234	846	0.0062	0.0224	0.011	0.015	0.0172	0.0374	<0.7

Table B.7 (cont) Results of analysis of treated (pond outlet) runoff samples collected at SH1 @ Redvale

Event	Date & time	TSS ($g\ m^{-3}$)	Dry-weight Cu ($mg\ kg^{-1}$)	Dry-weight Zn ($mg\ kg^{-1}$)	Particulate Cu ($g\ m^{-3}$)	Particulate Zn ($g\ m^{-3}$)	Dissolved Cu ($g\ m^{-3}$)	Dissolved Zn ($g\ m^{-3}$)	Total Cu ($g\ m^{-3}$)	Total Zn ($g\ m^{-3}$)	TPH ($g\ m^{-3}$)
5	29/04/2008 00:27	3.7	240	638	0.0009	0.0024	0.0036	0.0042	0.0045	0.0066	<0.7
	29/04/2008 02:41	14.8	272	886	0.0040	0.0131	0.0027	0.0096	0.0067	0.0227	<0.7
	29/04/2008 03:32	18.4	254	780	0.0047	0.0144	0.0028	0.0057	0.0075	0.0201	<0.7
	29/04/2008 04:44	16.1	214	621	0.0034	0.0100	0.0033	0.0064	0.0067	0.0164	<0.7
	29/04/2008 06:25	14.0	191	531	0.0027	0.0074	0.0074	0.013	0.0101	0.0204	<0.7
	29/04/2008 07:35	13.6	188	617	0.0025	0.0084	0.0041	0.0059	0.0066	0.0143	<0.7
	29/04/2008 09:22	23.5	190	774	0.0045	0.0182	0.0038	0.0062	0.0083	0.0244	<0.7
6	16/06/2008 08:07	7.8	140	700	0.0011	0.0054	0.0025	0.01	0.0036	0.0154	<0.7
	16/06/2008 11:37	23.4	172	945	0.0040	0.0221	0.0045	0.014	0.0085	0.0361	<0.7
	16/06/2008 12:45	23.7	216	1010	0.0051	0.0239	0.0061	0.017	0.0112	0.0409	<0.7
	16/06/2008 13:43	33.5	212	998	0.0071	0.0334	0.0059	0.016	0.0130	0.0494	<0.7
	16/06/2008 14:39	32.4	230	1047	0.0075	0.0339	0.006	0.026	0.0135	0.0599	<0.7
	16/06/2008 15:33	31.6	203	876	0.0064	0.0277	0.0058	0.013	0.0122	0.0407	<0.7
	16/06/2008 16:39	29.9	174	801	0.0052	0.0240	0.0059	0.011	0.0111	0.0350	<0.7
	16/06/2008 17:31	30.2	165	725	0.0050	0.0219	0.0055	0.022	0.0105	0.0439	<0.7
	16/06/2008 18:03	25.8	158	696	0.0041	0.0180	0.0053	0.011	0.0094	0.0290	<0.7
	16/06/2008 18:33	30.0	170	726	0.0051	0.0218	0.0058	0.011	0.0109	0.0328	<0.7
	16/06/2008 18:57	30.2	151	719	0.0045	0.0217	0.0052	0.015	0.0097	0.0367	<0.7
	16/06/2008 19:21	38.5	143	636	0.0055	0.0245	0.0052	0.013	0.0107	0.0375	<0.7

Table B.7 (cont) Results of analysis of treated (pond outlet) runoff samples collected at SH1 @ Redvale

Event	Date & time	TSS ($g\ m^{-3}$)	Dry-weight Cu ($mg\ kg^{-1}$)	Dry-weight Zn ($mg\ kg^{-1}$)	Particulate Cu ($g\ m^{-3}$)	Particulate Zn ($g\ m^{-3}$)	Dissolved Cu ($g\ m^{-3}$)	Dissolved Zn ($g\ m^{-3}$)	Total Cu ($g\ m^{-3}$)	Total Zn ($g\ m^{-3}$)	TPH ($g\ m^{-3}$)
7	26/07/2008 05:56	14.5	91	552	0.0013	0.0080	0.0017	0.012	0.0030	0.0200	<0.7
	26/07/2008 08:24	25.1	128	601	0.0032	0.0151	0.0029	0.01	0.0061	0.0251	<0.7
	26/07/2008 09:13	58.9	74	456	0.0044	0.0268	0.0032	0.029	0.0076	0.0558	<0.7
	26/07/2008 09:42	62.9	74	468	0.0047	0.0294	0.003	0.01	0.0077	0.0394	<0.7
	26/07/2008 10:04	76.3	71	441	0.0054	0.0337	0.0036	0.014	0.0090	0.0477	<0.7
	26/07/2008 10:25	79.7	72	466	0.0057	0.0372	0.0033	0.0094	0.0090	0.0466	<0.7
	26/07/2008 10:45	106.8	66	395	0.0070	0.0423	0.0032	0.0087	0.0102	0.0510	<0.7
	26/07/2008 11:01	117.8	58	334	0.0068	0.0393	0.0033	0.019	0.0101	0.0583	<0.7
	26/07/2008 11:16	115.9	52	334	0.0060	0.0387	0.0031	0.0066	0.0091	0.0453	<0.7
	26/07/2008 11:33	107.1	55	325	0.0059	0.0348	0.0031	0.01	0.0090	0.0448	<0.7
	26/07/2008 11:50	23.3	61	331	0.0014	0.0077	0.0061	0.025	0.0075	0.0327	<0.7
	26/07/2008 12:09	125.9	50	305	0.0063	0.0383	0.003	0.0082	0.0093	0.0465	<0.7
8	6/10/2008 06:01	6.1	181	906	0.0011	0.0055	0.0021	0.0055	0.0032	0.0110	-
	6/10/2008 08:58	7.0	164	839	0.0011	0.0059	0.0021	0.005	0.0032	0.0109	-
	6/10/2008 11:59	15.1	257	920	0.0039	0.0139	0.0073	0.0094	0.0112	0.0233	-
	6/10/2008 14:18	16.7	262	926	0.0044	0.0154	0.0088	0.011	0.0132	0.0264	-
	6/10/2008 15:59	15.2	220	925	0.0034	0.0141	0.0094	0.0092	0.0128	0.0233	-
	6/10/2008 17:49	15.2	224	917	0.0034	0.0139	0.0089	0.012	0.0123	0.0259	-
	6/10/2008 20:05	15.0	263	898	0.0039	0.0135	0.008	0.0077	0.0119	0.0212	-
	6/10/2008 22:43	15.9	214	772	0.0034	0.0122	0.0073	0.0074	0.0107	0.0196	-
	7/10/2008 03:53	12.1	271	883	0.0033	0.0107	0.0063	0.0088	0.0096	0.0195	-
	7/10/2008 15:37	9.9	174	755	0.0017	0.0075	0.0049	0.0072	0.0066	0.0147	-
	7/10/2008 17:17	35.2	227	946	0.0080	0.0333	0.0039	0.011	0.0119	0.0443	-

Table B.7 (cont) Results of analysis of treated (pond outlet) runoff samples collected at SH1 @ Redvale

Event	Date & time	TSS ($g\ m^{-3}$)	Dry-weight Cu ($mg\ kg^{-1}$)	Dry-weight Zn ($mg\ kg^{-1}$)	Particulate Cu ($g\ m^{-3}$)	Particulate Zn ($g\ m^{-3}$)	Dissolved Cu ($g\ m^{-3}$)	Dissolved Zn ($g\ m^{-3}$)	Total Cu ($g\ m^{-3}$)	Total Zn ($g\ m^{-3}$)	TPH ($g\ m^{-3}$)
8 (cont)	7/10/2008 18:17	44.1	194	894	0.0086	0.0395	0.0046	0.013	0.0132	0.0525	-
	7/10/2008 19:07	29.5	156	670	0.0046	0.0197	0.0073	0.018	0.0119	0.0377	-
	7/10/2008 19:55	30.3	139	614	0.0042	0.0186	0.0054	0.014	0.0096	0.0326	-
	7/10/2008 20:57	28.4	116	543	0.0033	0.0154	0.0052	0.011	0.0085	0.0264	-
	7/10/2008 22:50	26.6	92	529	0.0024	0.0141	0.0049	0.0089	0.0073	0.0230	-
	8/10/2008 04:50	25.7	79	408	0.0020	0.0105	0.0044	0.0088	0.0064	0.0193	-

Table B.8 Summary statistics of road runoff sample analyses – SH18 @ Westgate

	Runoff sample type	n	Mean	St Dev	Minimum	10th percentile	25th percentile	Median	75th percentile	90th percentile	Maximum
TSS (g m^{-3})	Untreated	68	131.1	147.0	4.0	17.9	41.3	75.7	151.9	335.9	647.8
Dry-weight Cu (mg kg^{-1})	Untreated	68	207.9	44.8	51.7	164.8	175.8	208.0	228.2	273.3	327.5
Dry-weight Zn (mg kg^{-1})	Untreated	68.00	1218.5	303.9	375.1	922.2	1005.5	1233.5	1395.7	1486.5	2319.6
Particulate Cu (g m^{-3})	Untreated	68	0.0243	0.0241	0.0010	0.0050	0.0091	0.0153	0.0288	0.0601	0.0983
Particulate Zn (g m^{-3})	Untreated	68	0.153	0.158	0.004	0.021	0.051	0.103	0.188	0.370	0.694
Dissolved Cu (g m^{-3})	Untreated	68	0.0073	0.0044	0.0003	0.0028	0.0037	0.0064	0.0095	0.0130	0.0220
Dissolved Zn (g m^{-3})	Untreated	68	0.021	0.010	0.009	0.012	0.016	0.019	0.022	0.032	0.062
Total Cu (g m^{-3})	Untreated	68	0.0316	0.0244	0.0041	0.0110	0.0162	0.0250	0.0361	0.0664	0.1044
Total Zn (g m^{-3})	Untreated	68	0.174	0.161	0.015	0.038	0.075	0.125	0.210	0.405	0.719
Dissolved Cu/Total Cu	Untreated	68	0.33	0.22	0.00	0.08	0.15	0.26	0.47	0.66	0.87
Dissolved Zn/Total Zn	Untreated	68	0.22	0.17	0.01	0.05	0.11	0.17	0.28	0.45	0.83
Total Zn/Total Cu	Untreated	68	5.15	1.75	1.65	3.06	4.07	5.09	6.22	7.42	10.32

Table B9 Summary statistics of road runoff sample analyses – SH1 @ Northcote

	Runoff sample type	n	Mean	St Dev	Minimum	10th percentile	25th percentile	Median	75th percentile	90th percentile	Maximum
TSS (g m^{-3})	Untreated	59	13.8	13.3	2.7	4.2	6.0	8.8	15.6	29.7	66.7
	Treated	36	39.3	68.0	4.8	7.2	12.7	19.3	30.4	85.2	395.6
Dry-weight Cu (mg kg^{-1})	Untreated	59	296.8	72.3	158.6	221.7	243.4	290.8	332.8	387.9	574.6
	Treated	36	102.9	30.9	35.4	54.5	80.9	110.7	125.7	133.8	153.6
Dry-weight Zn (mg kg^{-1})	Untreated	59	1158.6	255.2	490.9	855.1	1005.1	1190.9	1315.9	1457.1	1752.5
	Treated	36	422.4	313.9	119.2	187.1	246.8	313.7	423.9	829.9	1458.9
Particulate Cu (g m^{-3})	Untreated	59	0.0037	0.0029	0.0009	0.0013	0.0019	0.0029	0.0039	0.0071	0.0153
	Treated	36	0.0030	0.0042	0.0006	0.0008	0.0015	0.0021	0.0031	0.0044	0.0255
Particulate Zn (g m^{-3})	Untreated	59	0.016	0.016	0.003	0.004	0.007	0.010	0.016	0.031	0.099
	Treated	36	0.012	0.015	0.002	0.003	0.005	0.007	0.011	0.021	0.073
Dissolved Cu (g m^{-3})	Untreated	59	0.0136	0.0074	0.0049	0.0065	0.0083	0.0120	0.0160	0.0230	0.0380
	Treated	36	0.0057	0.0022	0.0026	0.0035	0.0042	0.0053	0.0068	0.0094	0.0100
Dissolved Zn (g m^{-3})	Untreated	59	0.033	0.028	0.013	0.014	0.017	0.022	0.037	0.064	0.140
	Treated	36	0.011	0.006	0.001	0.006	0.006	0.009	0.013	0.019	0.034
Total Cu (g m^{-3})	Untreated	59	0.0172	0.0091	0.0064	0.0094	0.0105	0.0153	0.0192	0.0291	0.0471
	Treated	36	0.0086	0.0051	0.0036	0.0051	0.0058	0.0068	0.0103	0.0132	0.0322
Total Zn (g m^{-3})	Untreated	59	0.049	0.034	0.018	0.022	0.027	0.034	0.056	0.093	0.155
	Treated	36	0.022	0.018	0.008	0.011	0.014	0.016	0.023	0.040	0.091
Dissolved Cu/Total Cu	Untreated	59	0.79	0.11	0.41	0.66	0.77	0.82	0.86	0.89	0.95
	Treated	36	0.71	0.14	0.21	0.52	0.66	0.74	0.79	0.85	0.90
Dissolved Zn/Total Zn	Untreated	59	0.67	0.17	0.21	0.43	0.59	0.69	0.82	0.87	0.97
	Treated	36	0.56	0.20	0.03	0.38	0.42	0.60	0.70	0.77	0.88
Total Zn/Total Cu	Untreated	59	3.28	2.76	0.81	1.49	1.82	2.39	3.60	4.75	15.19
	Treated	36	2.82	1.95	1.26	1.40	1.70	2.06	2.90	5.05	9.34

Table B10 Summary statistics of road runoff sample analyses – SH16 @ Huapai

	Runoff sample type	n	Mean	St Dev	Minimum	10th percentile	25th percentile	Median	75th percentile	90th percentile	Maximum
TSS (g m^{-3})	Untreated	80	179.8	211.2	1.6	23.0	48.4	100.8	205.5	393.6	1086.9
	Treated	37	19.9	19.1	3.3	6.2	7.9	12.2	21.9	50.5	73.0
Dry-weight Cu (mg kg^{-1})	Untreated	80	145.1	98.6	73.1	91.7	103.8	122.4	149.4	196.1	876.4
	Treated	37	155.5	66.6	91.3	124.0	127.5	141.3	152.5	183.4	506.6
Dry-weight Zn (mg kg^{-1})	Untreated	80	647.7	339.9	326.7	393.1	464.0	583.9	754.2	859.8	3149.4
	Treated	37	489.7	140.9	171.7	314.1	396.6	481.4	596.9	639.6	840.9
Particulate Cu (g m^{-3})	Untreated	80	0.0202	0.0187	0.0005	0.0038	0.0072	0.0124	0.0277	0.0469	0.0795
	Treated	37	0.0027	0.0024	0.0006	0.0010	0.0012	0.0018	0.0030	0.0063	0.0094
Particulate Zn (g m^{-3})	Untreated	80	0.096	0.092	0.001	0.016	0.029	0.062	0.138	0.224	0.430
	Treated	37	0.009	0.008	0.002	0.003	0.004	0.006	0.009	0.023	0.032
Dissolved Cu (g m^{-3})	Untreated	80	0.0061	0.0064	0.0018	0.0023	0.0026	0.0037	0.0060	0.0152	0.0330
	Treated	37	0.0051	0.0019	0.0028	0.0033	0.0035	0.0048	0.0063	0.0072	0.0120
Dissolved Zn (g m^{-3})	Untreated	80	0.011	0.008	0.001	0.002	0.007	0.010	0.013	0.019	0.049
	Treated	37	0.009	0.006	0.003	0.003	0.005	0.009	0.012	0.019	0.025
Total Cu (g m^{-3})	Untreated	80	0.0263	0.0203	0.0054	0.0087	0.0132	0.0183	0.0333	0.0523	0.1081
	Treated	37	0.0079	0.0027	0.0040	0.0052	0.0061	0.0070	0.0092	0.0124	0.0142
Total Zn (g m^{-3})	Untreated	80	0.108	0.093	0.011	0.028	0.043	0.076	0.148	0.230	0.442
	Treated	37	0.018	0.008	0.006	0.010	0.013	0.015	0.023	0.033	0.035
Dissolved Cu/Total Cu	Untreated	80	0.30	0.23	0.03	0.06	0.13	0.23	0.42	0.65	0.97
	Treated	37	0.67	0.18	0.31	0.39	0.53	0.73	0.82	0.85	0.93
Dissolved Zn/Total Zn	Untreated	80	0.19	0.18	0.00	0.03	0.06	0.14	0.28	0.43	0.89
	Treated	37	0.54	0.24	0.09	0.19	0.35	0.63	0.72	0.81	0.86
Total Zn/Total Cu	Untreated	80	4.00	1.20	0.64	2.52	3.24	4.24	4.70	5.22	7.03
	Treated	37	2.29	0.69	1.25	1.57	1.91	2.30	2.52	2.72	5.06

Table B11 Summary statistics of road runoff sample analyses – SH1 @ Redvale

	Runoff sample type	n	Mean	St Dev	Minimum	10th percentile	25th percentile	Median	75th percentile	90th percentile	Maximum
TSS (g m^{-3})	Untreated	98	124.2	278.2	2.3	9.7	27.3	47.4	119.9	223.7	2039.4
	Treated	72	28.8	27.8	3.7	7.9	13.2	21.0	30.0	62.5	125.9
Dry-weight Cu (mg kg^{-1})	Untreated	98	196.4	73.1	57.4	127.4	152.4	189.6	234.1	264.0	546.7
	Treated	72	197.3	84.7	49.8	72.3	148.9	214.2	254.3	268.5	571.1
Dry-weight Zn (mg kg^{-1})	Untreated	98	1010.2	263.1	363.5	669.1	834.5	1054.0	1217.7	1295.3	1591.3
	Treated	72	744.8	209.8	304.5	442.5	610.5	776.7	906.6	949.3	1186.3
Particulate Cu (g m^{-3})	Untreated	98	0.0137	0.0192	0.0003	0.0019	0.0045	0.0075	0.0143	0.0311	0.1302
	Treated	72	0.0042	0.0019	0.0009	0.0020	0.0026	0.0040	0.0056	0.0070	0.0086
Particulate Zn (g m^{-3})	Untreated	98	0.096	0.217	0.002	0.006	0.020	0.049	0.080	0.202	1.698
	Treated	72	0.018	0.010	0.002	0.006	0.009	0.015	0.024	0.034	0.042
Dissolved Cu (g m^{-3})	Untreated	98	0.0073	0.0029	0.0019	0.0042	0.0054	0.0068	0.0093	0.0110	0.0160
	Treated	72	0.0057	0.0034	0.0017	0.0030	0.0038	0.0054	0.0063	0.0080	0.0290
Dissolved Zn (g m^{-3})	Untreated	98	0.013	0.007	0.003	0.006	0.008	0.011	0.015	0.021	0.044
	Treated	72	0.012	0.006	0.004	0.007	0.009	0.011	0.013	0.019	0.037
Total Cu (g m^{-3})	Untreated	98	0.0210	0.0186	0.0024	0.0091	0.0124	0.0158	0.0217	0.0376	0.1331
	Treated	72	0.0099	0.0041	0.0030	0.0066	0.0079	0.0095	0.0113	0.0130	0.0352
Total Zn (g m^{-3})	Untreated	98	0.109	0.216	0.006	0.016	0.032	0.066	0.095	0.220	1.705
	Treated	72	0.030	0.013	0.007	0.015	0.020	0.026	0.039	0.048	0.064
Dissolved Cu/Total Cu	Untreated	98	0.48	0.24	0.02	0.20	0.30	0.43	0.65	0.83	0.89
	Treated	72	0.57	0.14	0.31	0.37	0.47	0.57	0.67	0.76	0.82
Dissolved Zn/Total Zn	Untreated	98	0.28	0.20	0.00	0.06	0.13	0.22	0.42	0.62	0.70
	Treated	72	0.43	0.13	0.15	0.25	0.36	0.42	0.51	0.60	0.76
Total Zn/Total Cu	Untreated	98	3.99	2.03	0.99	1.54	2.42	3.91	4.99	6.24	12.81
	Treated	72	3.16	1.28	1.08	1.78	2.15	3.05	3.77	4.99	7.38

Appendix C Results of STORMQUAL model parameter optimisation

Table C1 Summary of results of STORMQUAL optimisation: model parameter values and measures of goodness of fit between measured and modelled loads of total copper and total zinc

	Accumulation rate (R)	Slope coefficient (S)	Exponent (B)	Non-wash-off removal coefficient (D)	Total measured loads[a]	Total modelled load[a]	Sum of differences[b]	Sum of absolute differences[c]	R^2 value[d]
Units	**g m^{-2} d^{-1}**	**-**	**-**	**-**	**g**	**g**	**g**	**g**	**-**
Copper									
Westgate	0.00025	0.121	2.0	0.0001	0.687	0.686	-0.001	0.212	0.95
Northcote	0.00014	0.17	1.9	0.00033	0.478	0.475	-0.003	0.155	0.86
Huapai	0.00014	0.163	1.9	0.00027	1.504	1.504	-0.0003	0.565	0.69
Redvale	0.00019	0.189	2.2	0.00024	18.472	18.557	0.085	6.262	0.93
Zinc									
Westgate	0.0015	0.121	2.0	0.0001	4.207	4.201	-0.007	1.307	0.95
Northcote	0.00038	0.17	1.9	0.0002	1.773	1.777	0.005	0.949	0.56
Huapai	0.00085	0.12	1.9	0.00027	6.971	6.97	-0.0004	2.865	0.65
Redvale	0.00152	0.19	2.4	0.00023	135.733	136.08	0.347	66.634	0.78

Notes:

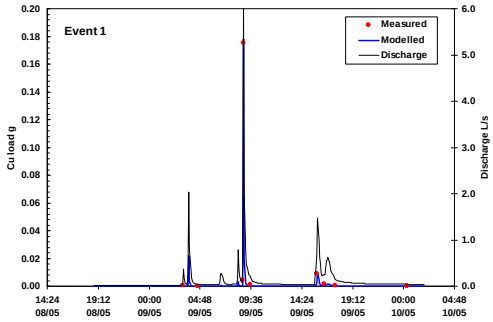
a) Sum of 5-minute loads coinciding with sample collection

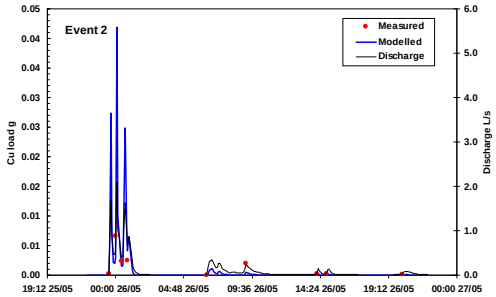
b) Sum of differences between total measured and total modelled loads

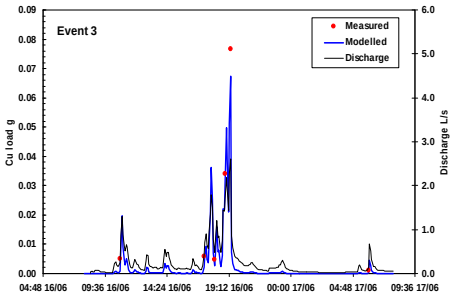
c) Sum of absolute value of differences between total measured and total modelled loads

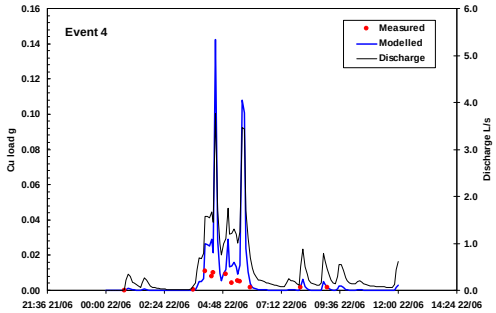
d) Based on least-squares regression of measured and modelled loads (see figures C3, C6, C9 and C12)

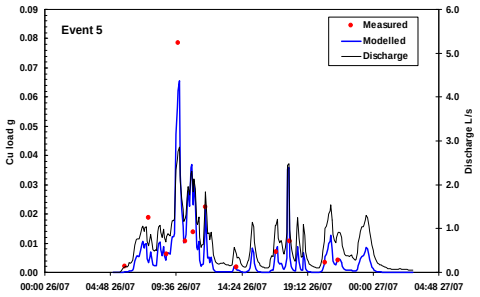
Figure C1 SH18 @ Westgate: comparison of time series of measured and modelled loads of total copper in untreated road runoff, Events 1 to 6











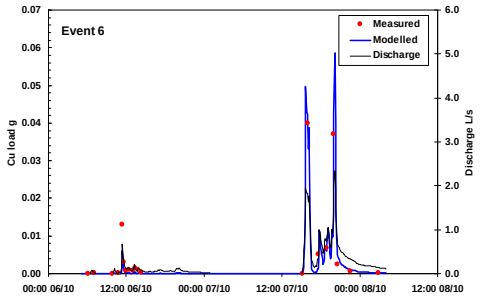
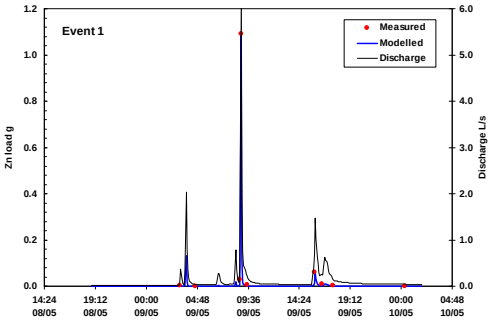
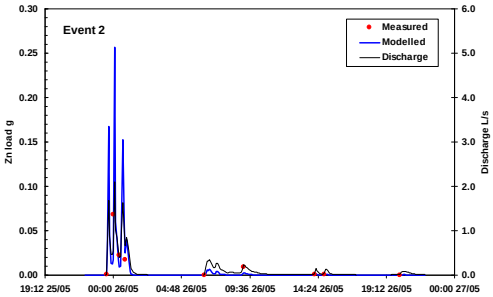
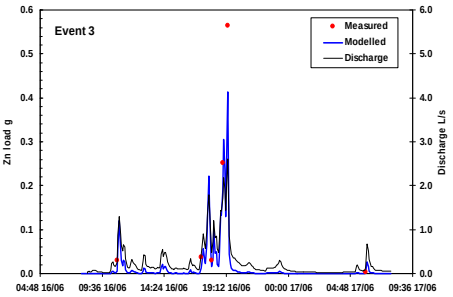
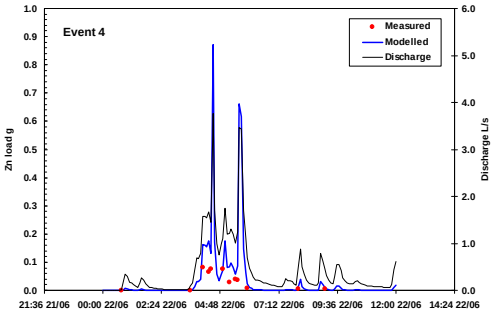


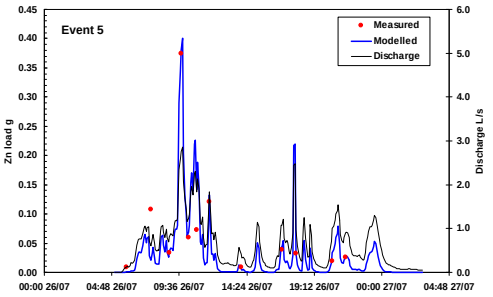
Figure C2 SH18 @ Westgate: comparison of time series of measured and modelled loads of total zinc in untreated road runoff, Events 1 to 6











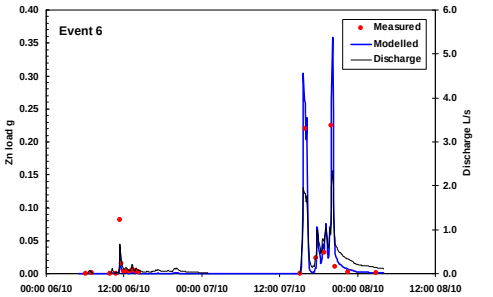
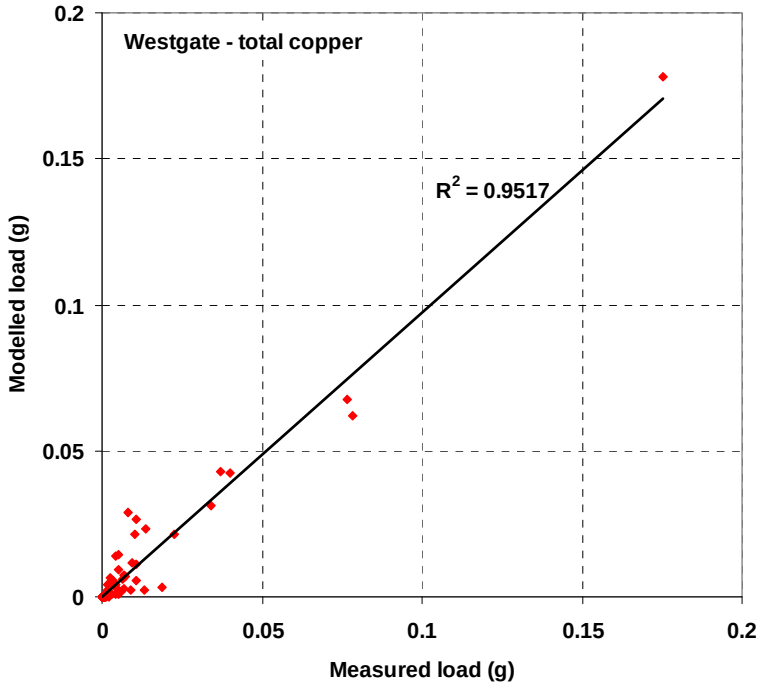


Figure C3 SH18 @ Westgate: scatter plots of measured and modelled loads of total copper and zinc in untreated road runoff



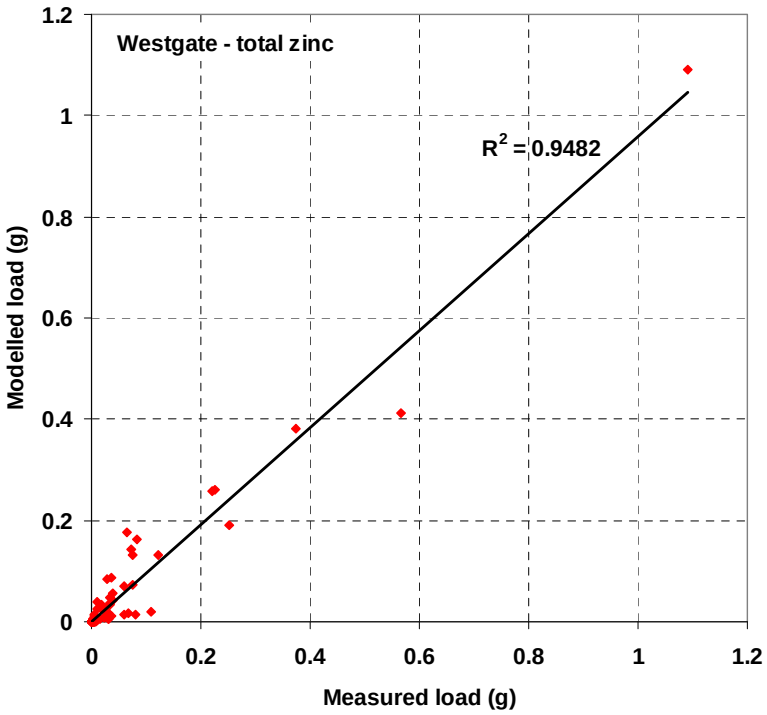
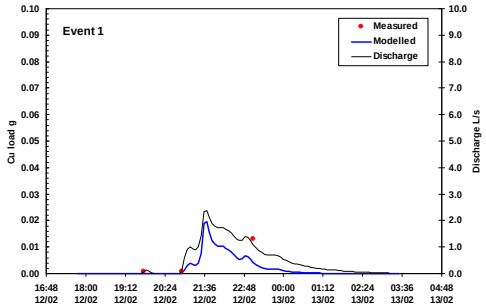
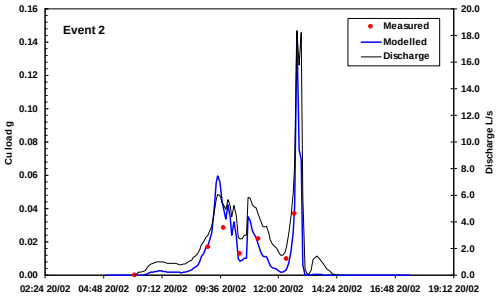
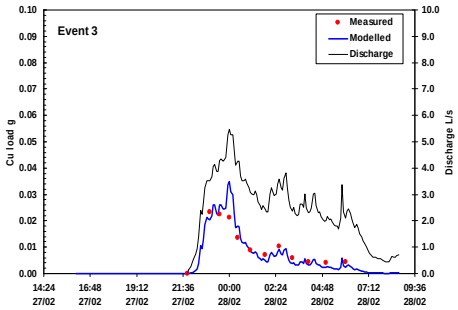
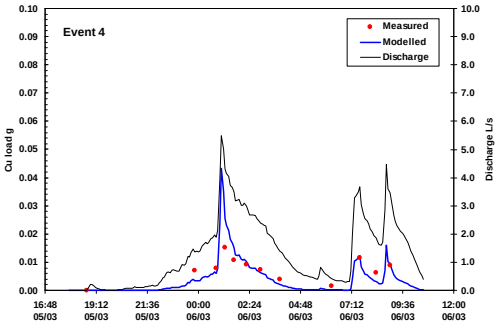


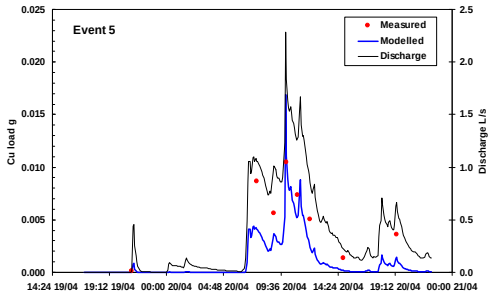
Figure C4 SH1 @ Northcote: comparison of time series of measured and modelled loads of total copper in untreated road runoff, Events 1 to 7

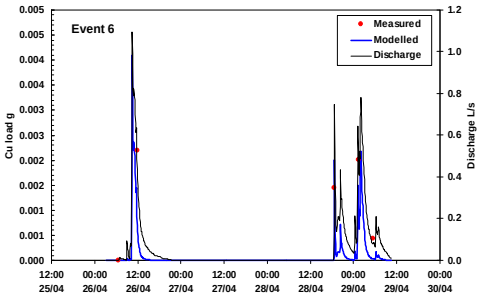












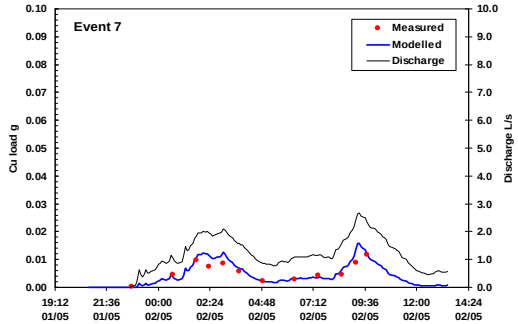


Figure C5 SH1 @ Northcote: comparison of time series of measured and modelled loads of total zinc in untreated road runoff, Events 1 to 7

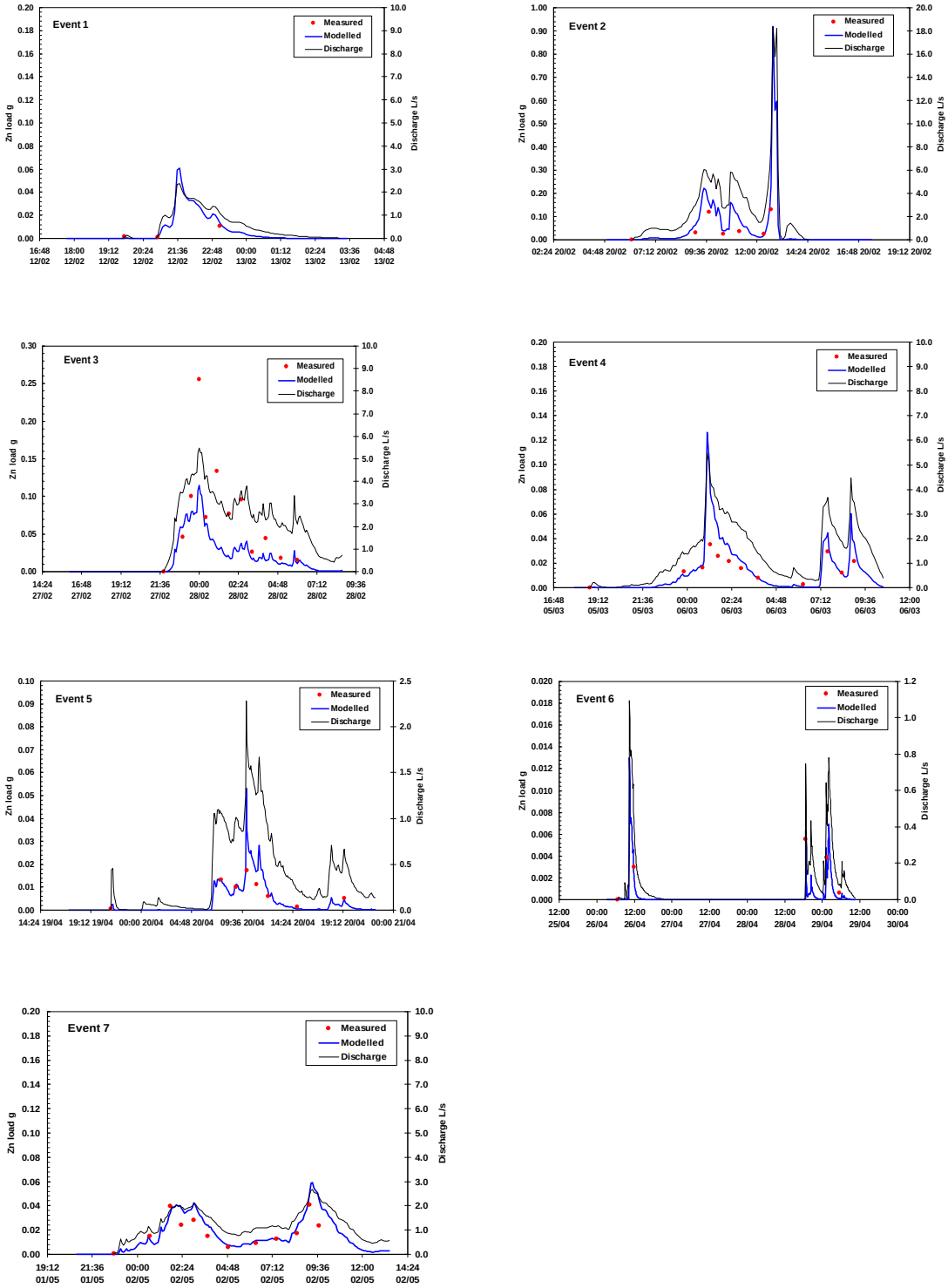
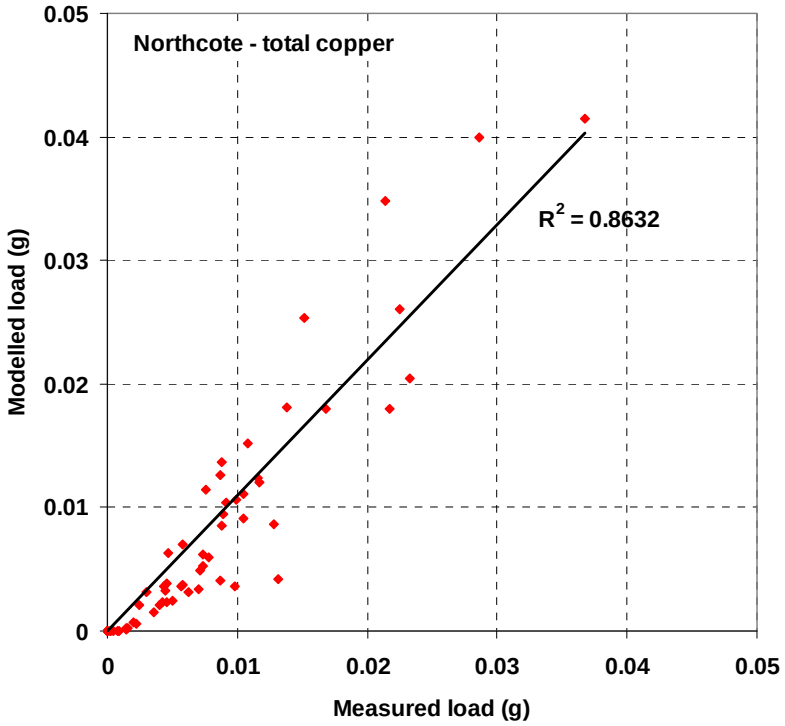
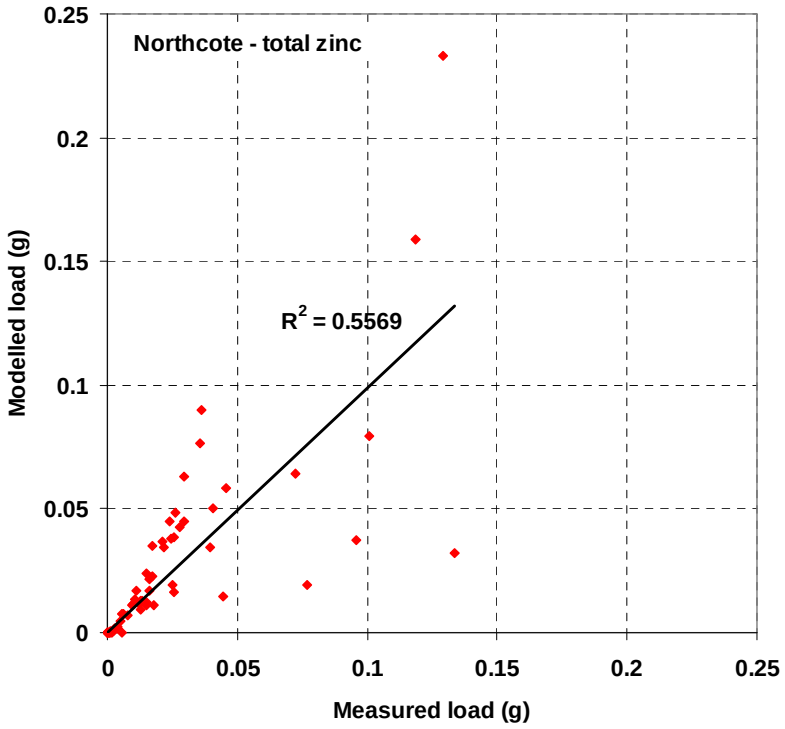


Figure C6 SH1 @ Northcote: scatter plots of measured and modelled loads of total copper and zinc in untreated road runoff





One outlier removed (measured 0.255g, modelled 0.114g)

Figure C7 SH16 @ Huapai: comparison of time series of measured and modelled loads of total copper in untreated road runoff, Events 1 to 8

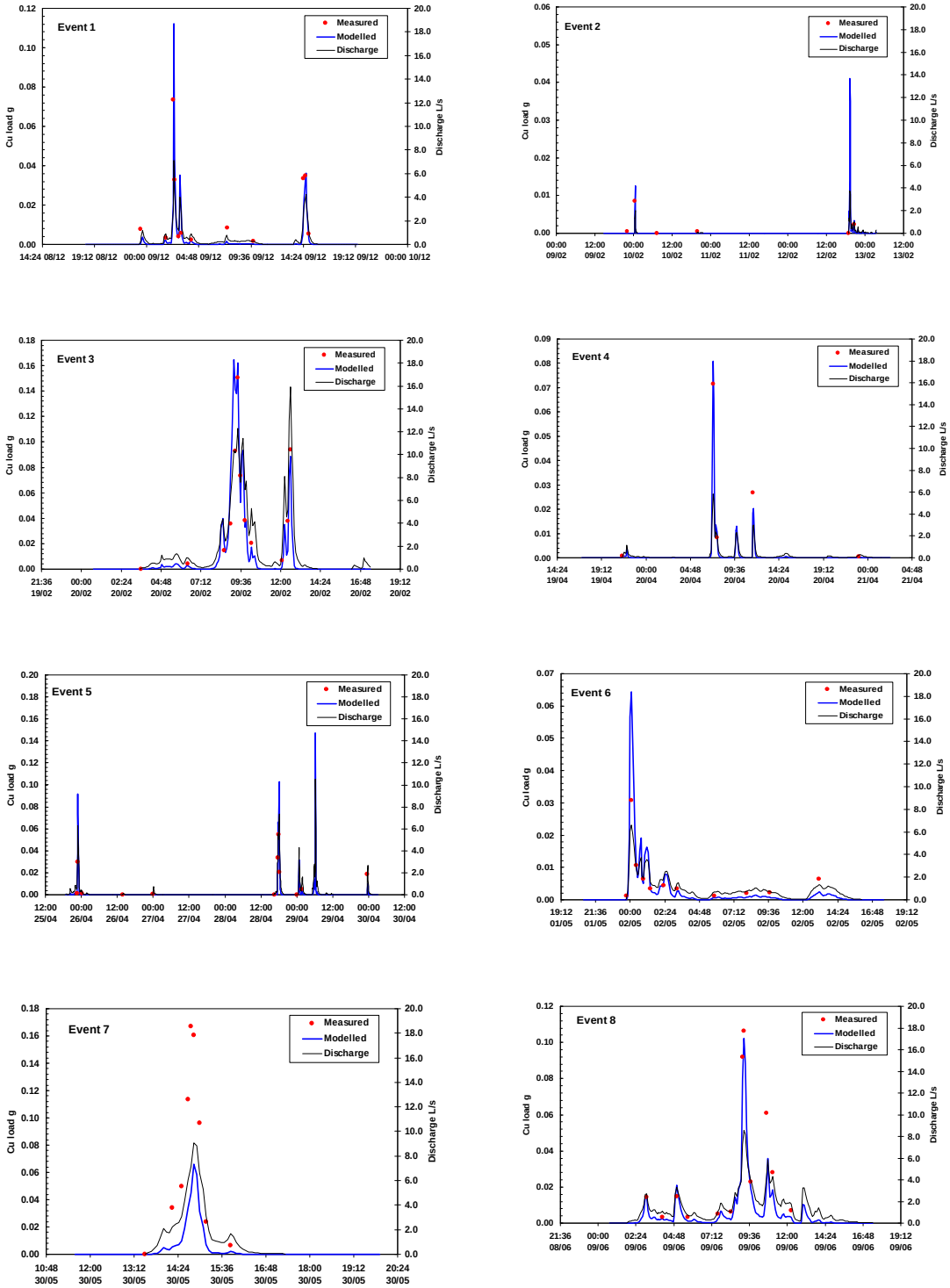


Figure C8 SH 16 @ Huapai: comparison of time series of measured and modelled loads of total zinc in untreated road runoff, Events 1 to 8

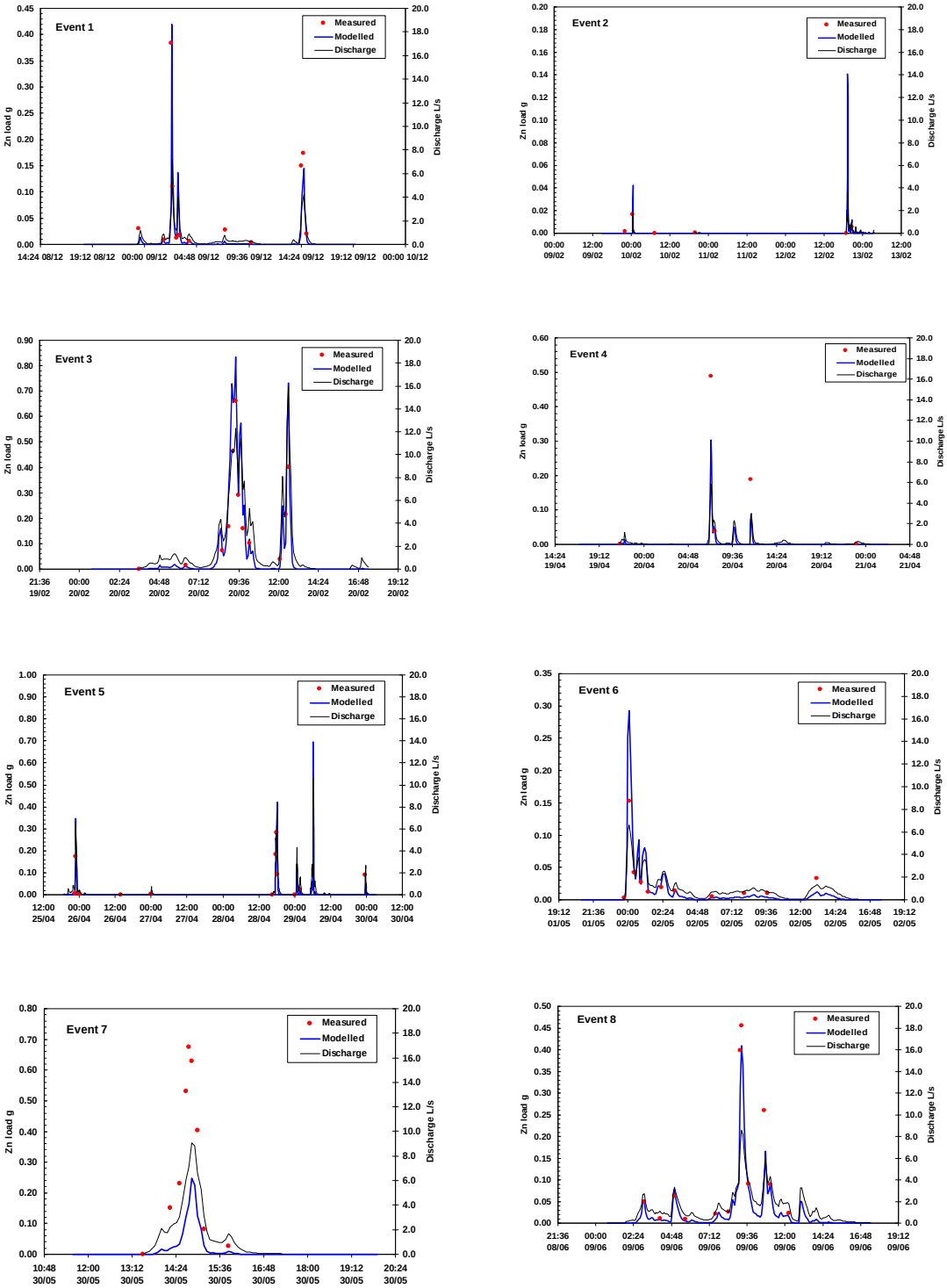
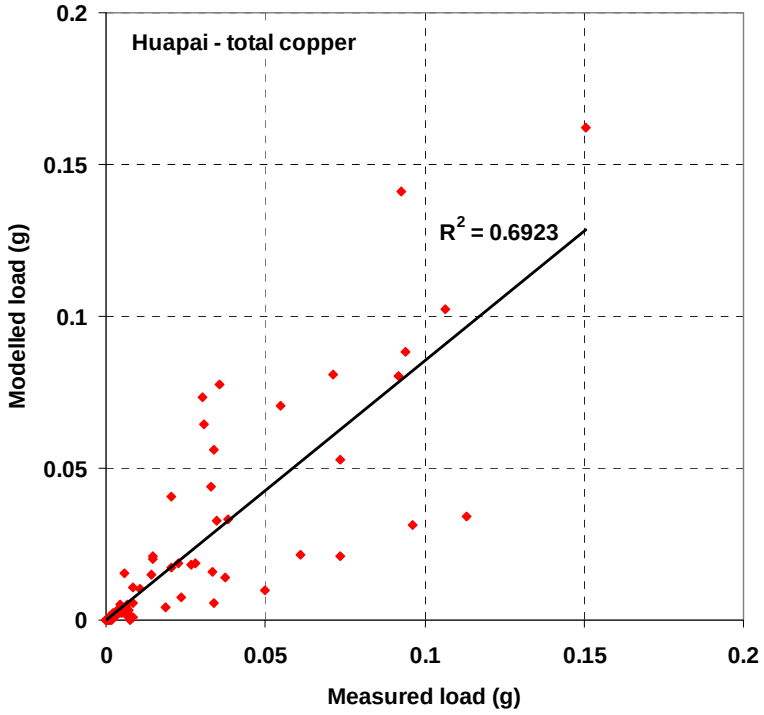
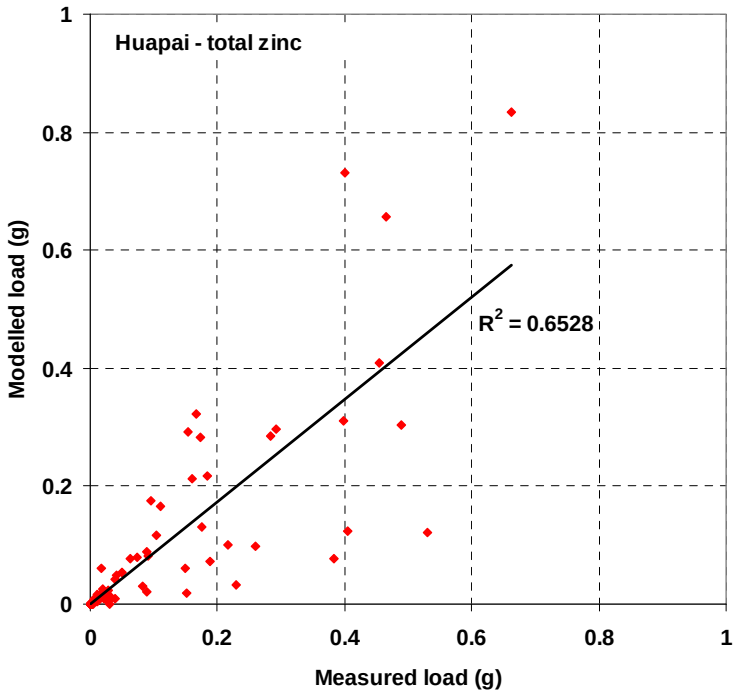


Figure C.9 SH16 @ Huapai: scatter plots of measured and modelled loads of total copper and zinc in untreated road runoff



Two outliers removed (measured/modelled: 0.167/0.045g, 0.161/0.066g)



Two outliers removed (measured/modelled: 0.675/0.162g, 0.63/0.246g)

Figure C10 SH1 @ Redvale: comparison of time series of measured and modelled loads of total copper in untreated road runoff, Events 1 to 8

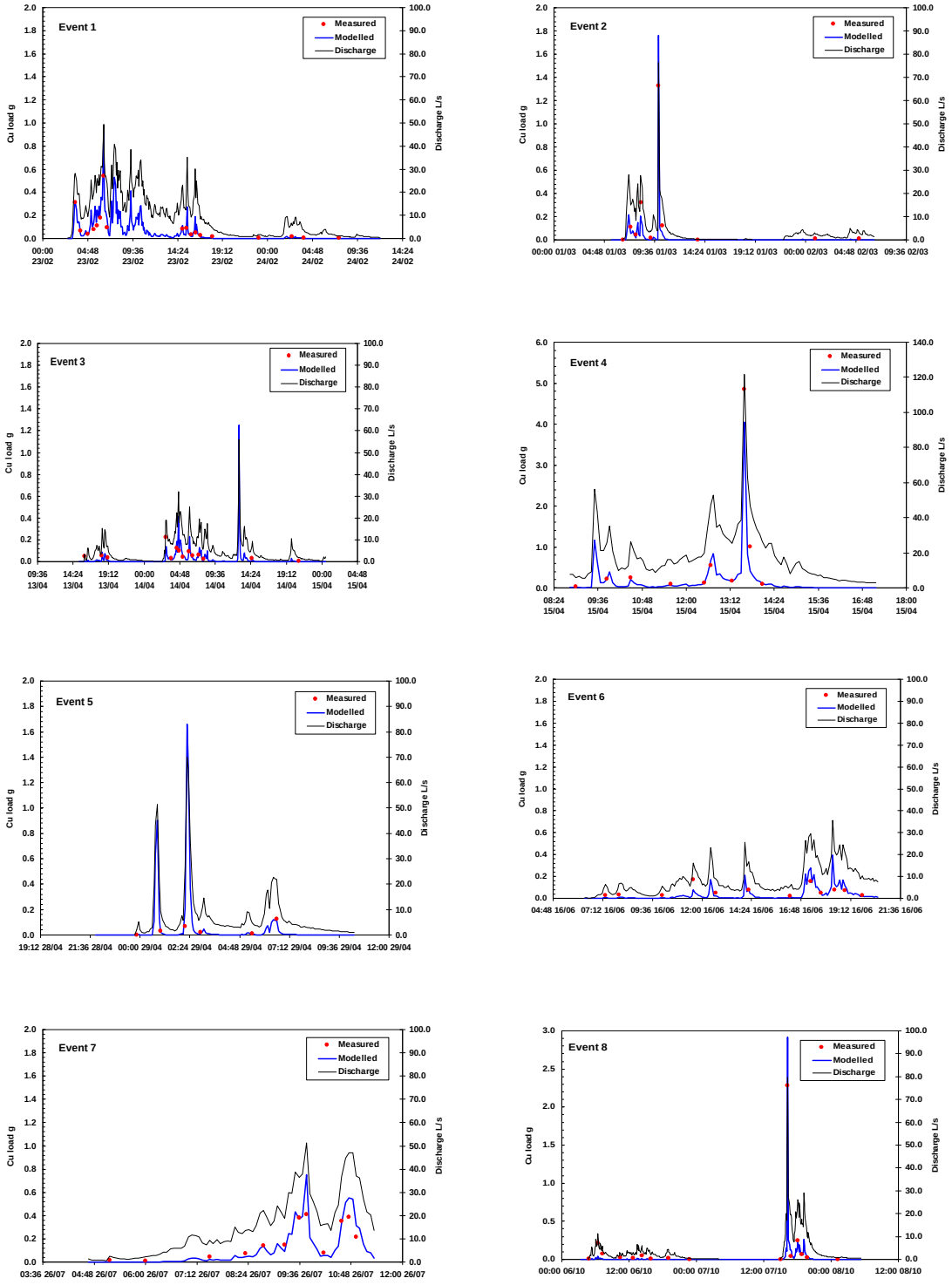


Figure C11 SH1 @ Redvale: comparison of time series of measured and modelled loads of total zinc in untreated road runoff, Events 1 to 8

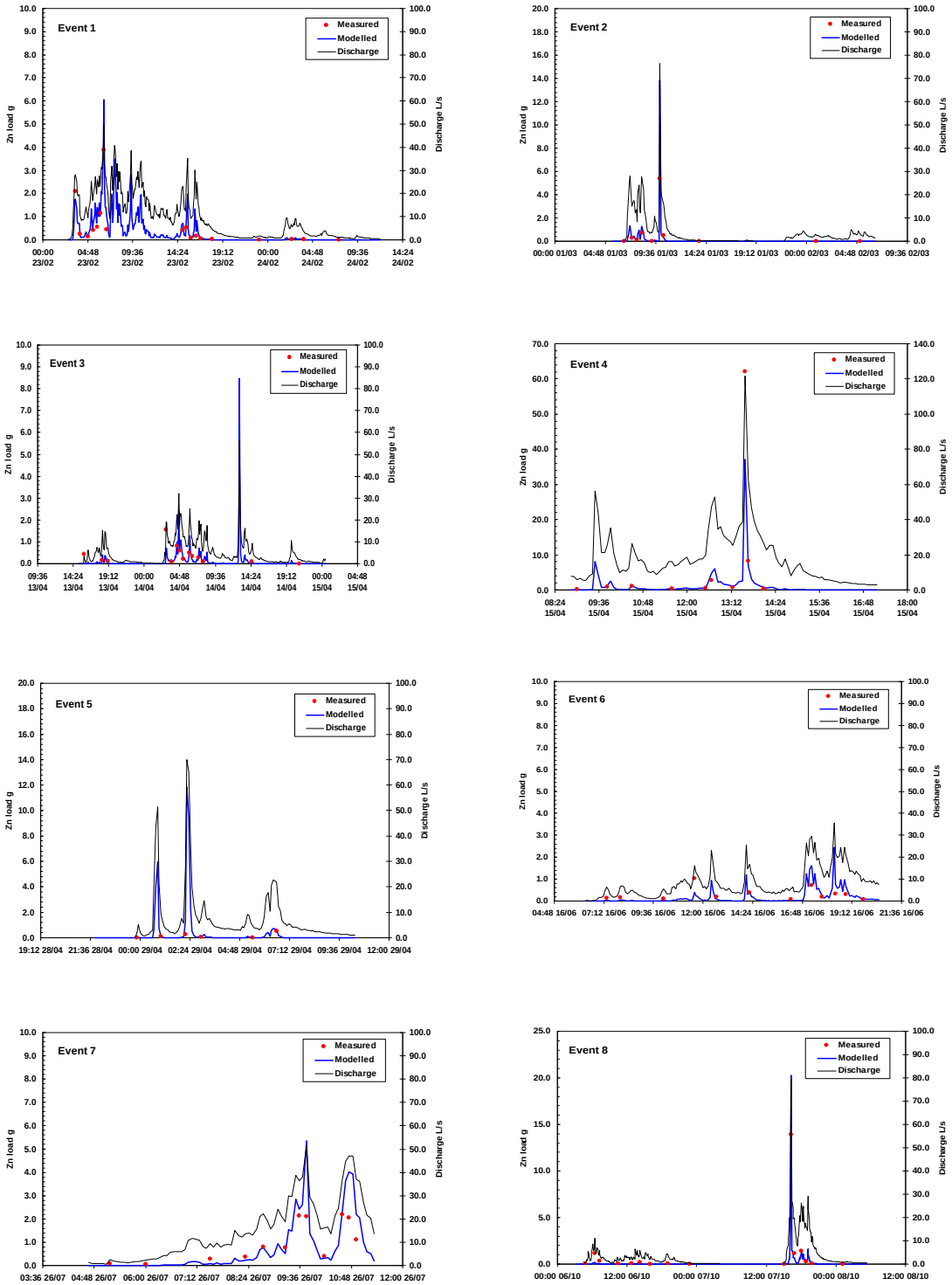
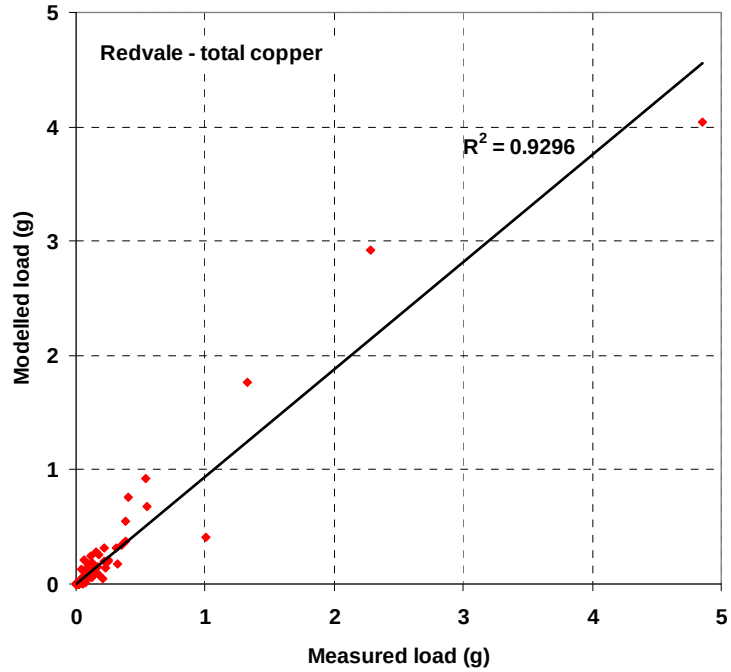
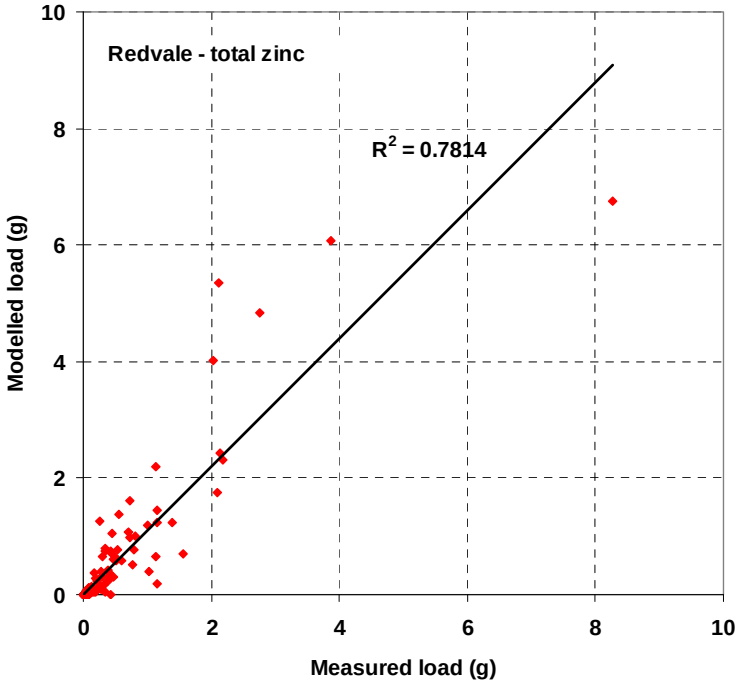


Figure C12 SH1 @ Redvale: scatter plots of measured and modelled loads of total copper and zinc in untreated road runoff





Three outliers removed (measured/modelled: 5.4/13.81g, 62.14/37.09g, 13.92/20.26g)