DEVELOPING A RAINFALL CONTAMINANT RELATIONSHIP MODEL FOR CHRISTCHURCH URBAN CATCHMENTS

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ABSTRACT

Stormwater quality is receiving increased scrutiny in order to reduce ecological degradation of urban waterways. This involves its appropriate characterization and treatment before resource consents can be renewed or approved for surface water management. This study developed a rainfall-contaminant relationship (RCR) model to ascertain the degree of relationships from stormwater contaminant loads with antecedent dry period, time to peak rainfall intensity, magnitude of peak rainfall intensity, and total rainfall. Rainfall and key contaminant (TSS, Zn, Cu and Pb) data sets for a University carpark collected between 2007-2008 were used as input parameters for the model. A distinct contaminant first flush was observed within 30 minutes for each storm event while the relative metal abundance showed a pattern of Zn>Cu>Pb attributed to the high vehicle intensity use. The RCR model indicated a strong positive relationship between antecedent dry period and both Zn and Cu concentrations. Lead had a positive relationship with total rainfall. Results also showed that TSS concentrations were largely controlled by antecedent dry period and total rainfall but not by time to peak rainfall intensity. This model is being refined to provide end-users with a useful tool for estimating contaminant loads and their appropriate management in Christchurch urban catchments.

KEYWORDS

Rainfall, contaminant loads, model, Christchurch, urban catchment

PRESENTER PROFILE

Daniel Wicke recently finished his PhD in Environmental Engineering at the Technical University Berlin, Germany. He has expertise in investigating the fate of contaminants in various aqueous systems (e.g. PAH in biofilm systems, pharmaceuticals during bank filtration, heavy metals in stormwater systems). His interests include the modelling of contaminant transport in urban catchments from stormwater runoff.

1 INTRODUCTION

In recent years, urban stormwater discharge is increasingly considered a major contributor to the pollution of many receiving waters. Zinc, copper and lead are generally the most common metal contaminants found in urban stormwater runoff and receiving streams in New Zealand (Zanders, 2005; Suren and Elliot, 2004). Vehicle wear (dust from tyres and brake linings) contains high concentrations of zinc, copper and lead that is deposited on roads and washed off during rainfall events into waterways via stormwater collection systems (Moores and Pattinson, 2008; Zanders, 2005). Our measurements of urban stormwater runoff during the past years raised concern, because levels of heavy metals (esp. Zn and Cu) in stormwater runoff were consistently above the 80% levels of protection of aquatic species as defined in the ANZECC guidelines (Adams et al. 2007; Hutchinson and Funnell, 2008). This data provided impetus for this study to develop a model that predicts contaminant loadings valid for the local conditions based on local data. Regional (e.g. Environment Canterbury) and local authorities also increased their attention regarding the need for stormwater contaminant mitigation due to the pressure on receiving waterways (ECan 2008). This includes surface water management requirements (e.g. 75% reduction of TSS for discharged stormwater runoff) for Resource Consents for new and retrofitted sub-catchments.

The small urban catchment investigated in this study is a carpark located on the University of Canterbury (UC) campus. The runoff that drains to the nearby Avon River was sampled, analysed and the data was used as input parameters to develop the rainfall-contaminant relationship model (RCR). The outcomes are compared to a contaminant load model developed by the Auckland Regional Council (ARC CLM). This simple, Excel-based model is currently being used to predict pollutant discharge from urban catchments. However, the CLM is specific to the local climate and hilly topography typical of Auckland catchments, and is not directly applicable to the flat plains of the Canterbury region, whereas the RCR model is more suitable for local conditions in Christchurch.

2 METHODS

In this study a small urban catchment in Christchurch (University of Canterbury carpark with 650 parking lots, about 1.5 ha and with daily traffic of 300-1000 vehicles per day) was investigated regarding stormwater runoff and related pollutants. Runoff was sampled for contaminants known to be present and relevant in urban stormwater. A simple relationship model was developed and fitted to the experimental data to reveal relationships between storm event parameters and contaminant concentrations.

2.1 STORMWATER SAMPLING

Stormwater runoff from a University carpark (Clyde Carpark) was obtained via a Sigma900 series automatic sampler that was located in a secure manhole in the Clyde Carpark. During 2007 and 2008, the untreated carpark runoff of six known storm events was sampled and analyzed. The sampler was programmed to start sampling at a rainfall intensity of 1 $mm{\cdot}hr^{-1}$, which was triggered by a rain gauge attached to a nearby building. Samples were taken for 3 hours (2007) and 6 hours (2008) with a first flush programme for the first 30 minutes (composite sample: 300 mL every five minutes, 3 samples per bottle) followed by a consecutive sampling programme (composite sample: 200 mL every 23 minutes, 4 samples per bottle). Additional samples were further combined to obtain two composite samples per rain event: one from the first flush (first 30 minutes) and one from 90 minutes after triggering until end of sampling. The preserved samples were sent to the International Accreditation New Zealand (IANZ) certified laboratory, Hill Laboratories Limited, for analysis for the following contaminants: total suspended solids (TSS), Zinc, Copper and Lead (total and dissolved concentrations for all heavy metals). Metal samples were analysed using inductively coupled plasma mass spectrometry (ICP-MS) while dissolved metals were analysed by APHA Method 312B (APHA 2005). All sampling was conducted following a strict sampling and handling regime to reduce potential sampling error. Sampler bottles were acid washed (5% nitric acid solution) prior usage to remove potential metal contamination.

2.1.1 EVENT MEAN CONCENTRATIONS

For the purpose of comparing results, and in order to simplify the inputs for the models, the event mean concentrations (EMC) were calculated for each of the contaminants as the weighted average concentration over the storm event, according to equation 1:

$$EMC = \frac{1}{6} C_{FF} + \frac{5}{6} C_{Storm} \qquad (1)$$

with C_{FF}=first flush concentration and C_{Storm}=post first flush concentration.

2.2 MODELLING

2.2.1 RAINFALL CONTAMINANT RELATIONSHIP (RCR) MODEL

The contaminant data from the six storm events were used to determine simple relationships between the key contaminants of concern and four chosen rainfall variables; total rainfall (TR), antecedent dry days (AD), time to peak (TtP) and peak intensity (PI). A summary of these values is presented in Table 1. The underlying concept assumes that the concentration of a contaminant is a linear, first order function of the above variables (equation 2). The RCR model was developed in this manner due to constraints of limited data and high variability in the contaminant concentration results.

$$X = \alpha + a \cdot TR_{\%} + b \cdot AD_{\%} + c \cdot TtP_{\%} + d \cdot PI_{\%} \qquad (2)$$

Where: X = *contaminant concentration in* $mg \cdot L^{-1}$ *for TSS,* $\mu g \cdot L^{-1}$ *for Cu, Zn and Pb*
α = *arbitrary constant concentration with the same units as X*
a, b, c and d = scaling factors, with the same units as X
$TR_{\%}$, $AD_{\%}$, $TtP_{\%}$ *and* $PI_{\%}$ = *dimensionless input variables*

Excel Solver was employed to determine the five unknown parameters, α, a, b, c and d, by fitting Equation 2 to the data from the six storms (minimizing the product of variance and sum of differences between measured and modelled data). Before attempting to solve Equation 2, the units of the variables were adjusted (normalised) so that they were all on the same order of magnitude to reduce potential bias. For this data set, the range of all variables was between 0.17 and 17 when the units for TR, TtP, PI and AD were in millimetres, hours, millimetres per hour and days, respectively.

2.2.2 AUCKLAND REGIONAL COUNCIL CONTAMINANT LOAD MODEL (ARC CLM)

The contaminant load model (version May 06, developed by the Auckland Regional Council) is an empirical spreadsheet model to estimate annual yields of TSS, zinc, copper and petroleum hydrocarbons from different land area types and the efficiencies of various management options. The model is simple and straightforward, requiring only source areas and knowledge of the management systems. In this study it has been employed to derive mean annual contaminant loads for TSS, zinc, and copper and compare these with the outcome of the RCR model.

3 RESULTS AND DISCUSSIONS

3.1 EXPERIMENTAL DATA

Details from the storm events 2007-2008 (dates, total rainfall, number of antecedent dry days, peak intensity, and time to peak) are listed in Table 1.

Table 1: Details for investigated rain events: antecedent dry days (AD), total rainfall (TR), peak intensity (PI) and time to peak (TtP)

	28/03/07	29/06/07	4/09/07	24/08/08	4/09/08	18/09/08
AD (days)	9	3	17 (4)*	5	8	9
TR (mm)	3.8	2.4	3	13.2	4.8	4.2
PI (mm·hr^{-1})	9.6	2.4	2.4	7.2	4.8	4.8
TtP (minutes)	35	10	10	240	345	280

*17 days without daily precipitation > 2 mm, 4 days without any precipitation

Table 2 shows the measured contaminant concentrations in the carpark runoff. As expected, first flush concentrations for heavy metals (total and dissolved) as well as suspended solids are higher compared to the subsequent samples (post first flush). For example, total copper concentrations in the first flush composite sample range from 11.8 – 46 µg·L^{-1} in contrast to 5.6 – 11 µg·L^{-1} in the composite sample collected after the first flush. Event mean concentrations (EMC) determined for all storm events are also listed in Table 2 and provide an overall indication of the contaminant concentrations throughout the storm duration.

Table 2: Concentrations of TSS and total/dissolved heavy metals from carpark runoff from the six rain events (EMC: event mean concentration, FF: first flush)

		TSS [mg L^{-1}]	***Diss. Cu*** [µg L^{-1}]	***Total Cu*** [µg L^{-1}]	***Diss. Pb*** [µg L^{-1}]	***Total Pb*** [µg L^{-1}]	***Diss. Zn*** [µg L^{-1}]	***Total Zn*** [µg L^{-1}]
28/03/07	*First Flush*	*38*	*11.5*	*16.5*	*0.7*	*5.4*	*50.0*	*75.0*
	Post FF	*12*	*9.5*	*11.0*	*0.8*	*2.0*	*39.0*	*41.0*
	EMC	*16*	*9.8*	*11.9*	*0.8*	*2.6*	*40.8*	*46.7*
29/06/07	*First Flush*	*19*	*10.7*	*11.8*	*0.6*	*2.3*	*95.0*	*96.0*
	Post FF	*5*	*5.7*	*6.9*	*0.3*	*1.8*	*36.0*	*40.0*
	EMC	*7*	*6.5*	*7.7*	*0.4*	*1.9*	*46*	*49*
4/09/07	*First Flush*	*29*	*13.9*	*16.7*	*0.4*	*1.0*	*76.0*	*84.0*
	Post FF	*18*	*7.5*	*10.9*	*0.2*	*2.2*	*34.0*	*51.0*
	EMC	*20*	*8.6*	*11.9*	*0.2*	*2.0*	*41*	*57*
24/08/08	*First Flush**	*120*	*2.2*	*36.0*	*0.1*	*52.0*	*15.0*	*160.0*
	Post FF	*11*	*4.4*	*5.6*	*0.6*	*1.8*	*13.0*	*16.0*
	EMC	*29*	*4.0*	*10.7*	*0.5*	*10.2*	*13*	*40*
4/09/08	*First Flush*	*62*	*5.0*	*14.0*	*0.1*	*5.8*	*19.0*	*45.0*
	Post FF	*17*	*5.0*	*7.6*	*0.1*	*2.7*	*22.0*	*33.0*
	EMC	*25*	*5.0*	*8.7*	*0.1*	*3.2*	*22*	*35*
18/09/08	*First Flush*	*25*	*n.s.*	*46.0*	*n.s.*	*2.2*	*n.s.*	*73.0*
	Post FF	*31*	*7.7*	*11.0*	*1.5*	*6.2*	*110.0*	*130.0*
	EMC	*30*	*6.4*	*16.8*	*1.3*	*5.5*	*92*	*121*

n.s. – no sample * sample possibly influenced by construction involving earthworks

Figures 1 to 3 illustrate the total and dissolved heavy metal concentrations in the post FF composite samples for all six rain events. Comparison with the 90% trigger value from guidelines of the Australian and New Zealand Environment and Conservation Council (ANZECC 2000) – marked as a solid horizontal line in Figures 1 to 3 – show that copper (Figure 1) and zinc (Figure 3) exceed these values several fold. This is especially remarkable, since the graphs only show the lower post first flush values – initial first flush concentrations are even higher (see Table 2). Average EMC values for the investigated heavy metals are shown in Figure 4. It can be seen that zinc is the predominant metal species associated with the carpark runoff, which is a consistent trend seen in the literature (see Table 3). Nevertheless, copper and lead are also present in alarming concentrations, since the toxicity of these metal species is higher compared to zinc (expressed by the lower ANZECC trigger values seen in figures 1 to 3).

The average EMC values of all six storm events from the carpark are compared to TSS and heavy metal concentration runoff results reported in recent studies (Table 3). Since no data specifically about carpark runoff could be found, values for highway and road runoff are given. It can be seen that the NZ carpark runoff concentrations are in the same order of magnitude, but are also the lowest concentrations compared to the other studies. This could be due to the fact that traffic within this carpark is comparably low (even when all parking lots are used), because most cars arrive in the morning and leave in the evening. Thus, the number of driving vehicles per day is much lower compared to a highway. Although the emissions per car at a carpark are considered to be higher (due to frequent brake usage, engine starting and oil leakage), the total emissions per day are probably lower compared to depositions on a road or highway consequent of less vehicle traffic. Zinc and copper release by cars was linked to driving conditions (e.g. free traffic flow versus braking and acceleration zones) by Moores and Pattinson (2008), supporting these assumptions.

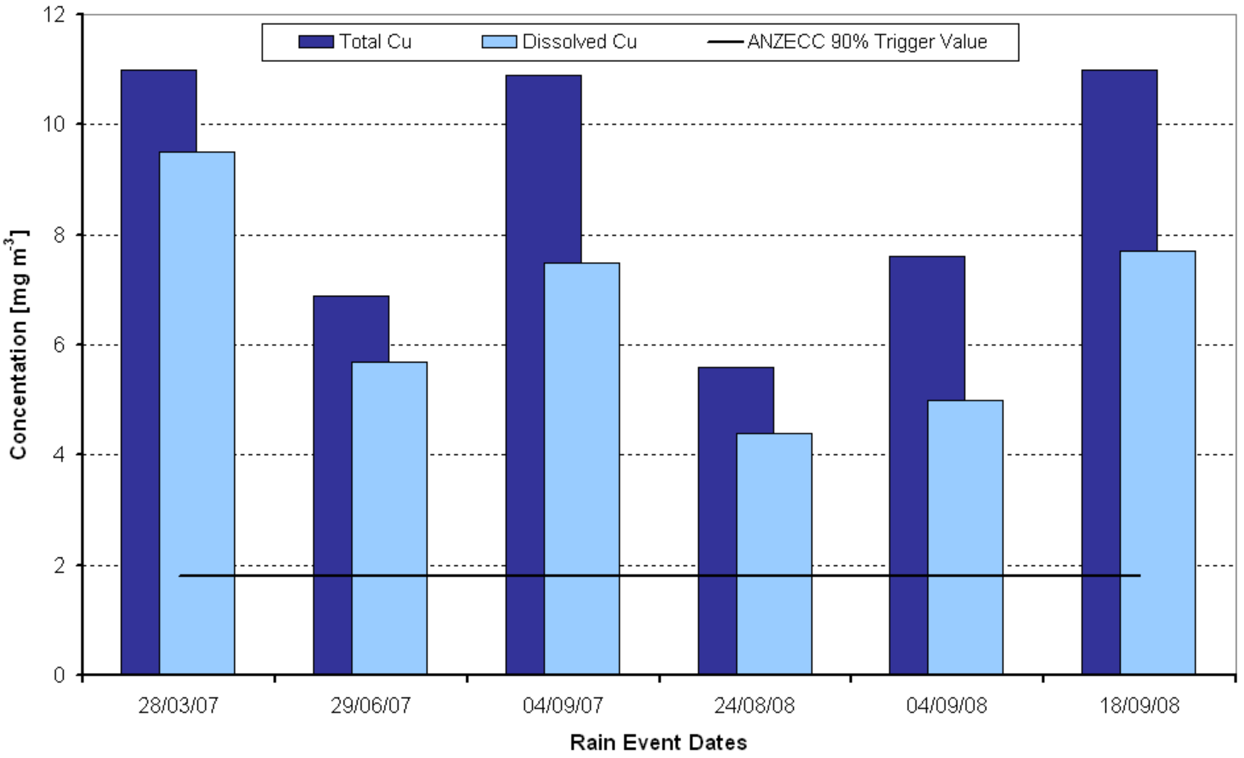

Figure 1: Concentration of total and dissolved copper in UC carpark runoff (post first flush composite) in comparison with ANZECC guidelines

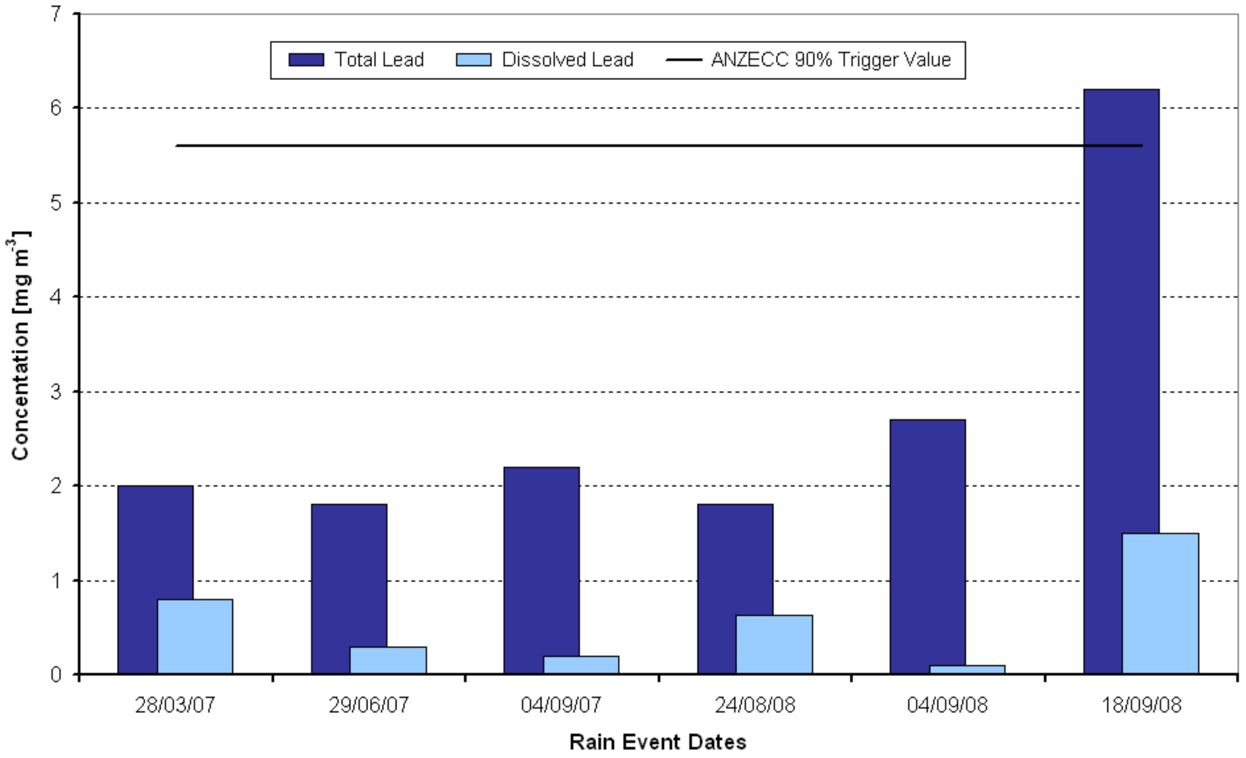

Figure 2: Concentration of total and dissolved lead in UC carpark runoff (post first flush composite) in comparison with ANZECC guidelines

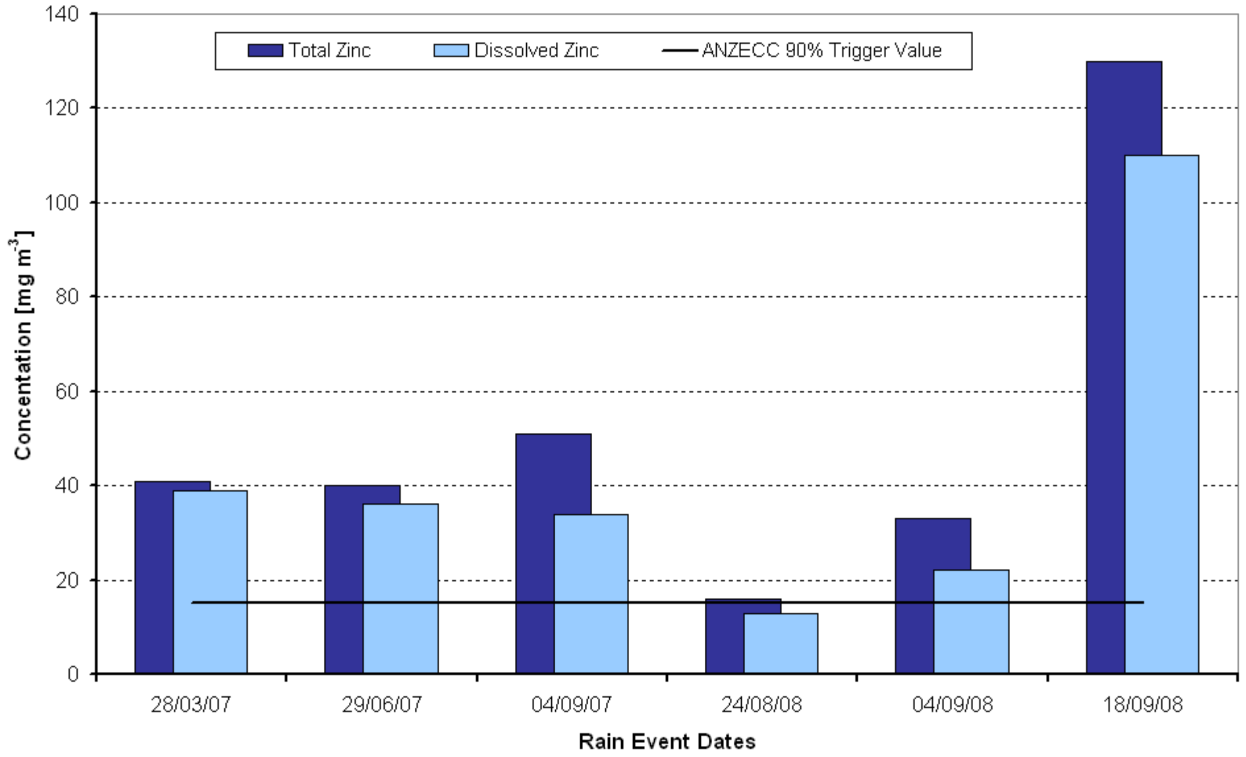

Figure 3: Concentration of total and dissolved zinc in UC carpark runoff (post first flush composite) in comparison with ANZECC guidelines

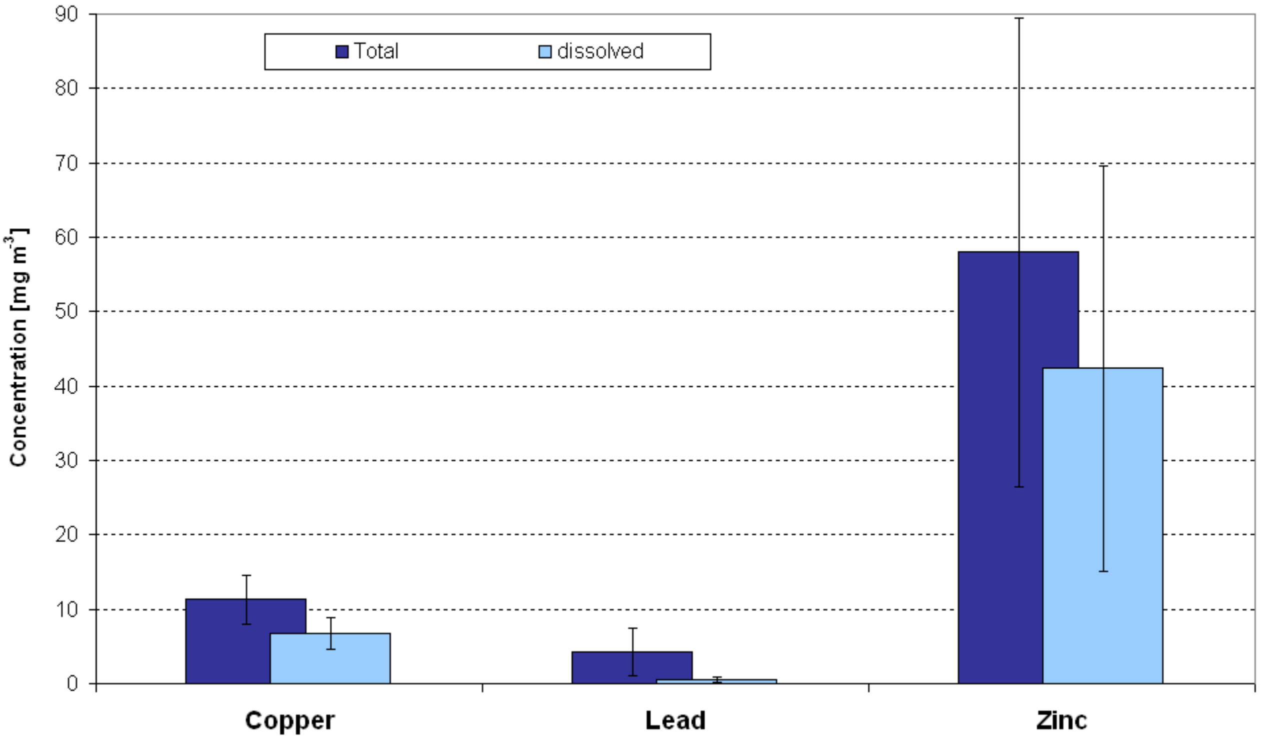

Figure 4: Event mean concentrations of the investigated heavy metals (all storm events: mean ± S(x)) from carpark runoff

Table 3: Comparison of TSS and heavy metal concentration runoff results from paved surfaces.

	Runoff source	TSS [mg L^{-1}]	Zinc [µg L^{-1}]	Copper [µg L^{-1}]	Lead [µg L^{-1}]
This Study[a]	NZ Carpark	**21** ± 9	**58** ± 32	**11** ± 3	**4** ± 3
Kayhanian et al. 2007[b]	US Highways	**59** ± 189	**111** ± 200	**21** ± 32	**13** ± 151
Drapper et al. 2000[c]	Roads, Brisbane	**175** ± 189	**380** ± 271	**75** ± 59	**200** ± 118
Gnecco et al. 2005[a]	Roads, Genoa (IT)	**140** ± 115	**81** ± 33	**19** ± 20	**13** ± 6

[a] EMC mean conc. [b] EMC median conc. [c] first flush median conc.

Comparison of dissolved and total metal concentrations show that zinc and copper are predominant in the dissolved state, whereas lead is mainly associated with suspended particles, also expressed by the log K_D-values listed in Table 4. Since the particulate concentration is not known from laboratory analysis, it was derived from the concentration difference of the total and dissolved fractions and the associated concentrations of total suspended solids (TSS) according to equation 3:

$$C_{Particulate} = \frac{(C_{Total} - C_{Dissolved})}{TSS} \quad (3)$$

Table 4: Partition coefficients for heavy metals in carpark runoff

Log K_D		
Copper	***Lead***	***Zinc***
4.5 ± 0.39	5.9 ± 0.59	4.3 ± 0.59

3.2 MODELLING

The solution parameters for the RCR model (see equation 1) are shown in Table 5. The values indicate which variables have the greatest impact on each of the investigated contaminants. For instance, the highest numbers for TSS are parameters *a* (15.9) and *b* (14.3), indicating that total rainfall TR (represented by *a*) and antecedent days (represented by *b*) are the main parameters controlling the TSS runoff concentrations. The parameter α expresses the relative significance of each of the contaminants, showing that zinc (48.9) has a much higher concentration level followed by copper (8.4) and lead (2.2) – see also Figure 4, which is well reported in the literature on urban pollutants.

The following main trends can be distinguished:

- A strong positive relationship between antecedent days (AD) and both zinc and copper concentrations
- TSS concentrations are largely controlled by total rainfall and the number of antecedent dry days
- Lead has a positive relationship with total rainfall, but none of the other variables

This simple model is only valid at present for the local conditions of the investigated catchment (UC carpark). Due to the small quantity of data points incorporated thus far, its use in its current form should be restricted to events whose variables fall within the range of the investigated storm events (see Table 1). However, it is expected that the accuracy and applicability of the model will improve as more data is incorporated.

Table 5: Model parameters for determining best-fit curves to the storm data

Parameter	***TSS*** [$mg \cdot L^{-1}$]	***Zn*** [$\mu g \cdot L^{-1}$]	***Cu*** [$\mu g \cdot L^{-1}$]	***Pb*** [$\mu g \cdot L^{-1}$]	***Variable scaled***
α	4.4	48.8	8.4	2.2	**-**
a	15.9	6.4	3.1	6.6	***TR***
b	14.3	8.3	4.9	-0.2	***AD***
c	4.8	-18.2	-2.5	-0.3	***TtP***
d	7.9	-6.5	3.1	0.1	***PI***

The RCR model was then applied to an average storm event for Christchurch to obtain estimates of the annual contaminant yields flowing from the carpark. The parameters of this average event were derived from annual rainfall (648 mm) and number of wet days (85) reported for Christchurch, as well as average values of the six investigated storm events: total rainfall TR=7.6 mm, antecedent dry days AD=3.3 days, time to peak

TtP=4.2 h, and peak intensity PI=2.5 mm·h^{-1}. The annual contaminant yields derived from this average storm event using the rainfall contaminant relationship (RCR) model are shown in Table 6 and were also compared to the predicted annual yields using the CLM model. As can be seen, all contaminant values are relatively comparable, which supports the validity of the RCR-model derived values and its assumptions for estimating contaminant runoff loads.

Table 6: Annual yields of contaminants from the carpark using different models

	TSS *[kg·ha^{-1}]*	***Zn*** *[g·ha^{-1}]*	***Cu*** *[g·ha^{-1}]*
RCR	142	253	65
ARC CLM	213*	215	70

* An updated TSS yield value of 21.3 g·m^{-2}·a^{-1} was applied, recently published by the author of the CLM model (Timperley & Reed, 2008)

4 OUTLOOK

Sampling of UC carpark runoff is being continued to obtain more water quality data for further model developments. Our sampling regime includes sampling before and after a recently installed treatment device (Hynds Upflow Filter) aimed to reduce suspended solids and associated metal concentrations. An additional automatic sampler was recently installed to collect roof runoff and incorporate this data into model calculations.

Further investigations include the use of the SWMM programme developed by the US Environmental Protection Agency (EPA). This model can be used to calculate catchment runoff through stormwater drainage systems and is capable of incorporating water quality parameters to simulate contaminant concentrations in the runoff. To predict contaminant yields with SWMM, parameters for the build-up (e.g. maximum build-up and build-up rate constants) and wash-off functions of the contaminants have to be determined. Currently, investigations with 0.5 m^2 thin boards constructed from different materials (e.g. concrete and asphalt) are being carried out to determine those parameters. The boards will be exposed at different urban locations impacted by traffic for different durations, before being placed under a rainfall simulator to collect surface runoff. Results will be valuable to relate urban stormwater contaminant runoff to road surface usage and characteristics, which is necessary to improve contaminant runoff modelling in urban catchments.

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