

CONTAMINANT SOURCES, TRANSPORT, AND FATE IN STORMWATER RUNOFF IN CHRISTCHURCH

Dr. Daniel Wicke, Dr. Tom Cochrane,
and Dr. Aisling O'Sullivan

University of Canterbury, Department of Civil and Natural Resources Engineering, Private Bag 4800,
Christchurch 8140, New Zealand,

Corresponding author: Dr. Tom Cochrane, Tel: ++ 64-3-364 2378, email: Tom.Cochrane@canterbury.ac.nz

Abstract

Stormwater quality is receiving increased scrutiny to reduce ecological degradation of urban waterways. In order to predict the fate of key contaminants in stormwater runoff, a model applicable to the local conditions in Christchurch is necessary. We are developing a model to estimate contaminant sources, transport and fate, which will help decision makers ascertain best structural and management practices to reduce contaminant loading to urban waterways. Necessary input parameters include coefficients for contaminant build-up and wash-off functions that describe the deposition during antecedent dry days and dislodgement during a rain event. To derive these parameters, we constructed thin boards of different street materials (e.g. asphalt, concrete), which were exposed at various locations within a University of Canterbury carpark over a nine day period before being placed under a rainfall simulator to collect surface runoff. Our experimental results showed that asphalt retains more contaminant particles compared to concrete surfaces. Spatial variability of contaminant distribution within the carpark was high. First flush TSS wash-off concentrations from concrete boards, for example, ranged from 63 to 164 mg/L. Similar variability was also observed for copper and lead concentrations from both concrete and asphalt boards. Variation was attributed to factors such as the number and type of vehicles parking over the boards. The application of this experimental data to parameterize our initial model resulted in predictions that seemed realistic and are comparable to measured TSS and copper concentrations in stormwater.

Key Words: stormwater modelling, heavy metals, urban runoff

1. INTRODUCTION

Urban waterways are an important part of Christchurch's aesthetic attractiveness and serve the practical purpose of draining excess storm runoff from urban areas. The city's urban drainage system has been designed to efficiently transport water to the nearest stream or river (e.g. Okeover, Avon, and Heathcote). Unfortunately, pollutants carried by water in the form of sediment, particulate and soluble heavy metals, and other contaminants, are also transported efficiently, causing adverse environmental impacts in those waterways.

The three most common metal contaminants impacting urban waterways in Christchurch and around New Zealand are zinc, copper, and lead (CCC 2003, Zanders, 2005; Suren and Elliot, 2004; Adams et al, 2007). The main source of these contaminants are dust from vehicle tyres (e.g. Zn) and brake linings (e.g. Cu), which accumulate on paved surfaces and are washed off during rainfall events into nearby waterways (Moores and Pattinson, 2008; Zanders, 2005). Sampling of untreated stormwater runoff from car parks draining into waterways at the University of Canterbury has recently raised concern about the level of these contaminants. Heavy metal concentrations for Zn and Cu were found to be consistently higher than recommended 90% ANZECC (2000) guidelines for the protection of aquatic species in waterways (Adams, et al., 2007; Hutchinson and Funnell, 2008).

Although direct stormwater sampling is an ideal way to quantify total contaminant loading from a specific area during a given storm event, it is expensive and time consuming. Data obtained from sampling events is therefore limited and generally insufficient to construct robust models for

predicting stormwater behaviour. Furthermore, direct sampling of runoff masks the potential spatial variability in contaminant accumulation. Given inherent variability in natural rainfall events, it is also difficult to construct contaminant build-up and wash-off functions from sampling events for modelling purposes. In order to more accurately quantify sources of urban contaminants, determine the extent of spatial variability of contaminant build-up, and easily obtain large data sets to develop stormwater contaminant models, a unique experimental system for capturing contaminants on different surfaces was developed. This paper reports on initial results from applying the unique experimental system and determining contaminant build-up and wash-off functions for modelling purposes. Initial modelled results are also presented that compare modelled scenarios with data from monitored storm events.

2. METHODOLOGY

Our experimental system deploys constructed asphalt and concrete boards (75 cm L x 75 cm W x 3 cm D) to capture contaminants accumulating over time on these surface types in an urban catchment (roads, paths, or carparks). Spatial variability in contaminant accumulation and wash-off functions were investigated by placing 8 boards (4 smooth asphalt, 4 (3 mm) concrete) on different parking of a 1.5 ha carpark at the University of Canterbury, New Zealand spaces (see Fig. 1) for 9 days (16.6.2009-25.06.2009).

Apart from quantifying the potential spatial variation in contaminant build-up, it was also hypothesised that there would be differences in the ability of the different surfaces to retain and release contaminants due to their surface roughness. Visual representations of the roughness for the asphalt and concrete boards was therefore assessed by a surface laser scanner as described in Darboux et al. (2003) and is shown in Fig. 2. Heights are represented by the differences in grey levels with dark tones showing lower elevations.



Fig. 1: Position of boards placed on the carpark: A1-A4 – asphalt boards, C1-C4: concrete boards. Main carpark entrance is in the upper right corner.

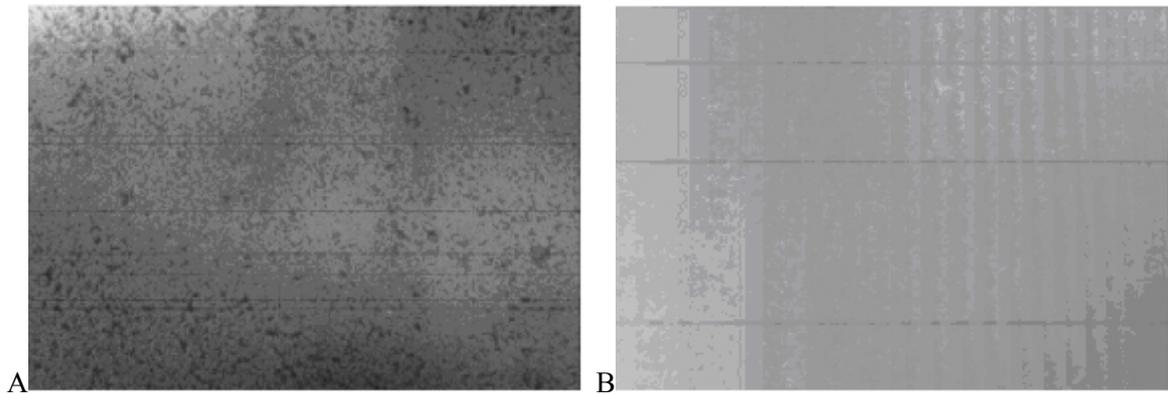


Fig. 2: Images of boards derived from a surface laser scanner. A: asphalt surface; B: concrete surface. Heights are represented in grey levels with darker tones represented by lower elevations.

During the experimental period, the boards were exposed to considerable car traffic and to a few rainfall events. Rainfall events and their intensity during that period are shown in Fig. 3. After 9 days, boards were then placed under a rainfall simulator to quantify contaminant wash-off rates and determine the contaminant accumulation amounts. A two-nozzle (Veerjet 80100) Norton type rainfall simulator (Herngren et al. 2005) was used to wash contaminants off the boards at a rainfall intensity of 22 mm/hr. Runoff samples from the boards were collected at 0, 15, 30, 60 and 90 minutes in accordance with typical sampling regimes. Samples were measured instantaneously for pH (calibrated YSI Model 60 pH field meter), conductivity (calibrated Hach sension 156 multiparameter meter) and turbidity (calibrated Hach Model 2100P portable turbidimeter). Total suspended solids (TSS) were measured within 24 hours in our environmental engineering laboratory following APHA (2005) Method 2540D. Total metal concentrations (Zn, Cu and Pb) taken at 0, 15 and 30 min. were analysed by inductively coupled plasma mass spectrometry (ICP-MS) through an accredited laboratory following APHA Method 3125B with HNO₃ digestion (APHA, 2005).

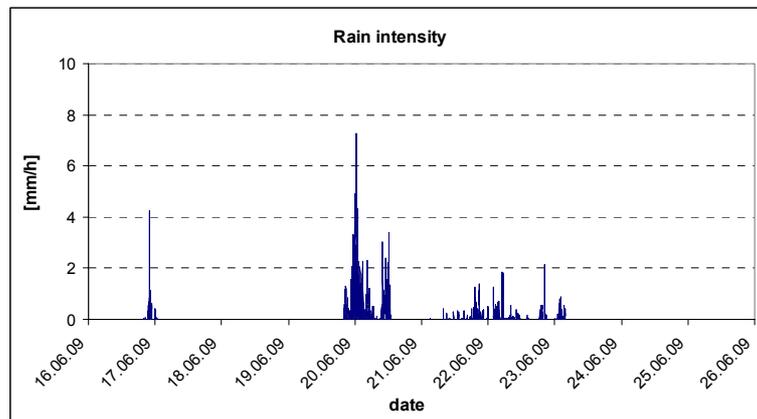


Fig 3: Rain intensity during time of exposure of the boards

2.1 Modelling

Modelling of contaminant runoff from the carpark was conducted using the stormwater management model (SWMM 5.0) developed by the US Environmental Protection Agency (EPA). This hydrologic model uses pollution build-up and wash-off functions to simulate the fate of contaminants associated with stormwater. Coefficients for those functions have to be provided as input parameters and need to be determined experimentally. Results from our experimental system were used to determine appropriate wash-off functions for TSS, copper, and lead for the two different surfaces (concrete and asphalt). Functions for zinc were not determined initially due to contamination from the galvanised fittings in the supplying header tank. A first order decay relationship, as shown in equation 1, was

chosen for our modelling from the available three wash-off functions in SWMM. This was the only non-linear relationship provided, which was closest to the general trend of the observed contaminant behaviour.

$$W = C_1 \cdot q^{C_2} \cdot B \quad (1)$$

where, W – wash-off load [mg/h]

q – runoff rate [mm/h]

B – remaining amount of pollutant [mg]

C_1 – wash-off coefficient

C_2 – wash-off exponent

The parameters C_1 , C_2 and the initial pollutant build-up ($B_{t=0}$) were determined by minimizing the sum of the squared differences between modelled and experimental results. EXCEL solver was used to find the combination of values for C_1 and C_2 that result in a modelled curve with best fit to the experimental values. However, since several mathematical solutions are possible for C_1 and C_2 resulting in the same wash-off curve for our experimental conditions (constant rainfall intensity), but varying under different rainfall intensities, the wash-off exponent C_2 was set to 1 to simplify the problem. A value of $C_2=1$ means that the dependence of the wash-off load (W) from the runoff rate is linear.

The wash-off functions developed from our experiments were then used to simulate runoff concentrations of TSS and total copper and lead from the University carpark for a storm event in August 2008 with 5 antecedent dry days. Parameters for the build-up function (saturation function) used for this simulation were derived from results of carpark runoff measurements as in Wicke et al. 2009 (TSS: C_1 (maximum build-up possible) = 16.9 mg/m², C_2 (half saturation constant) = 7.8 days; Copper: C_1 = 0.0076 mg/m², C_2 = 5.4 days).

3. RESULTS AND DISCUSSION

3.1 Experimental results

Wash-off concentrations of TSS, copper, and lead from the exposed boards under the rainfall simulator are shown in Figure 4. Unfortunately, measurements of concentrations in the water tank supplying the rainfall simulator revealed high contamination of zinc (mainly in dissolved form), presumably from galvanized pump fittings. Therefore, results of zinc measurements (usually being the heavy metal with highest concentrations in urban stormwater runoff) had to be excluded from this study and could not be used for parameter determination and modelling.

The inherent spatial variability of contaminant sources (especially TSS and copper) within the car park is clearly shown in Fig. 4. TSS levels from concrete boards, for example, ranges from 63 to 164 for the first flush despite the close proximity of the boards (Fig. 1). Several factors are believed to contribute to this variability, including number and types (older/newer) of vehicles parked over each board and variability due to rainfall exposure (some boards being covered by cars, others not) leading to some level of wash-off occurring during the exposure period.

Higher concentrations of TSS were measured from concrete boards in comparison to asphalt boards. If we assume that in general the boards were exposed to similar ranges of contaminants, we can then attribute the differences in wash-off concentrations to surface roughness. Deposited particles are easier to be washed off from smoother surfaces such as the concrete, whereas particles deposited on asphalt are likely to be retained in pores and grooves (see Fig. 2). Since the asphalt boards were recently made, the stickiness of fresh asphalt may have also contributed to a greater retention of particles than concrete.

When comparing measured contaminant levels to the 90% Australian and New Zealand Environment and Conservation Council (ANZECC 2000) guidelines the protection of aquatic species exposed to

metal concentrations (black lines in Fig. 4), the data consistently show that copper concentrations are of greater concern than lead. Copper exceeds the ANZECC guidelines throughout the entire sampling period for both asphalt and concrete surfaces. In New Zealand, lead was removed from paints in the mid 1960's and from petrol in 1996 (Zollhoefer 2009) but is still present in older suburbs. Timperely (2008) reported that copper levels were increasing however due to the use of Cu in architectural roofing. Copper (and Zn) in New Zealand are the greatest contaminants in stormwater runoff, predominantly from vehicle traffic and deteriorating roofing (e.g. Zanders 2005, Brown and Peake 2006, Gobel et al. 2007).

Contaminant concentrations from board experiments were also compared to untreated carpark runoff concentrations (same carpark) measured from actual storm events in 2007 and 2008 as presented in Wicke et al., 2009 (Table 1). First flush concentration ranges are comparable for TSS, copper, and lead between the boards and the 2007 carpark sampling. Copper exceeded the 90% ANZECC guidelines in all runoff samples by at least a magnitude of one, whereas lead exceeded its guidelines value more in concrete than in the asphalt board or asphalt carpark (Table 1).

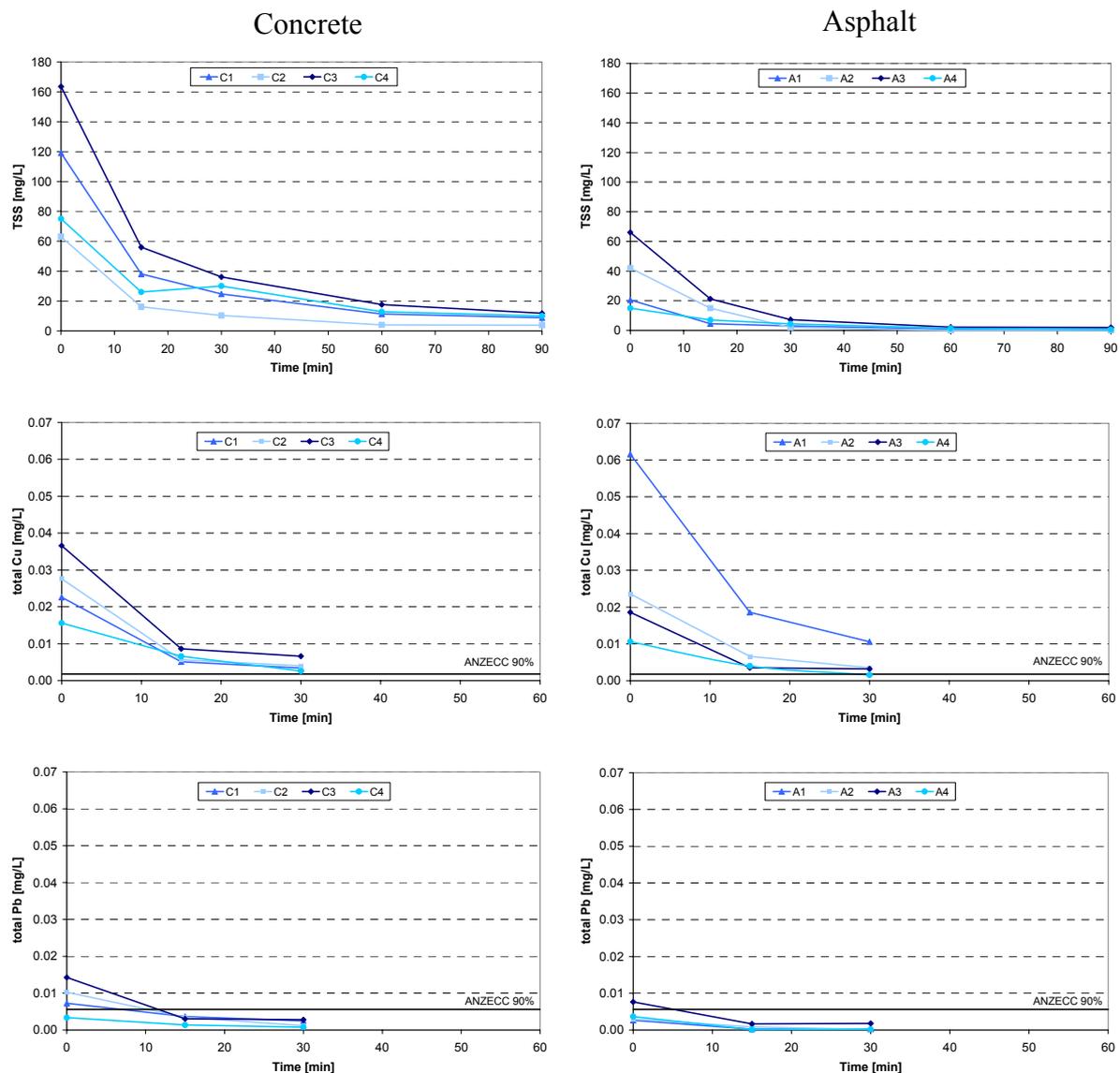


Fig. 4: Measured concentrations of TSS, copper and lead for runoff from concrete and asphalt boards using a rainfall simulator at a rain intensity of 22 mm/h.

Table 1: Comparison of first flush runoff concentrations: boards (concrete and asphalt) and catchment (carpark – measurements from 2007 and 2008 as in Wicke et al. 2009).

	Runoff concentrations in mg/L			
	ANZECC 90%	concrete boards	asphalt boards	carpark sampling
TSS	n/a	63 – 164	15 – 66	19 – 120
Copper (total)	0.0018	0.020 – 0.041	0.015 – 0.066	0.012 – 0.046
Lead (total)	0.0056	0.004 – 0.015	0.003 – 0.008	0.001 – 0.006

3.2 Modelling

Wash-off concentrations measured from board experiments (Fig. 4) were used to determine the parameters for the wash-off function (equation 1). Results for the wash-off coefficient C_1 and initial contaminant build-up (determining the starting point of the modelled curve) for the asphalt and concrete surfaces are listed in Table 2. An appropriate pair of C_1 and C_2 values could be determined in the future by measuring wash-off at different rainfall intensities (resulting in a different q in equation 1), which would set the necessary constraint for solving this mathematical problem.

Table 2: Contaminant build-up mass (per board) and values for wash-off coefficients C_1 for $C_2=1$.

		Asphalt		Concrete	
		buildup [mg]	C_1	buildup [mg]	C_1
TSS	upper	189	0.196	584	0.154
	mean	105	0.190	374	0.154
	lower	49	0.231	169	0.207
Cu	upper	0.229	0.159	0.143	0.158
	mean	0.130	0.140	0.119	0.139
	lower	0.093	0.089	0.113	0.098
Pb	upper	0.029	0.159	0.044	0.190
	mean	0.017	0.165	0.037	0.142
	lower	0.012	0.158	0.023	0.100

The derived upper, mean, and lower wash-off load function curves are shown in Fig. 5 for TSS. Similar functions were obtained for copper and lead. Build-up values for the wash-off function are only a reflection of the total amount of contaminants measured during the wash-off. Asphalt has a substantially lower (approximately a third) value of calculated contaminant build-up than concrete, which means that Asphalt likely retains more contaminants if it is assumed that both concrete and asphalt boards were exposed to a similar range of dust or particles. These data concur with the measurements from the experimental and monitoring studies given in Table 1.

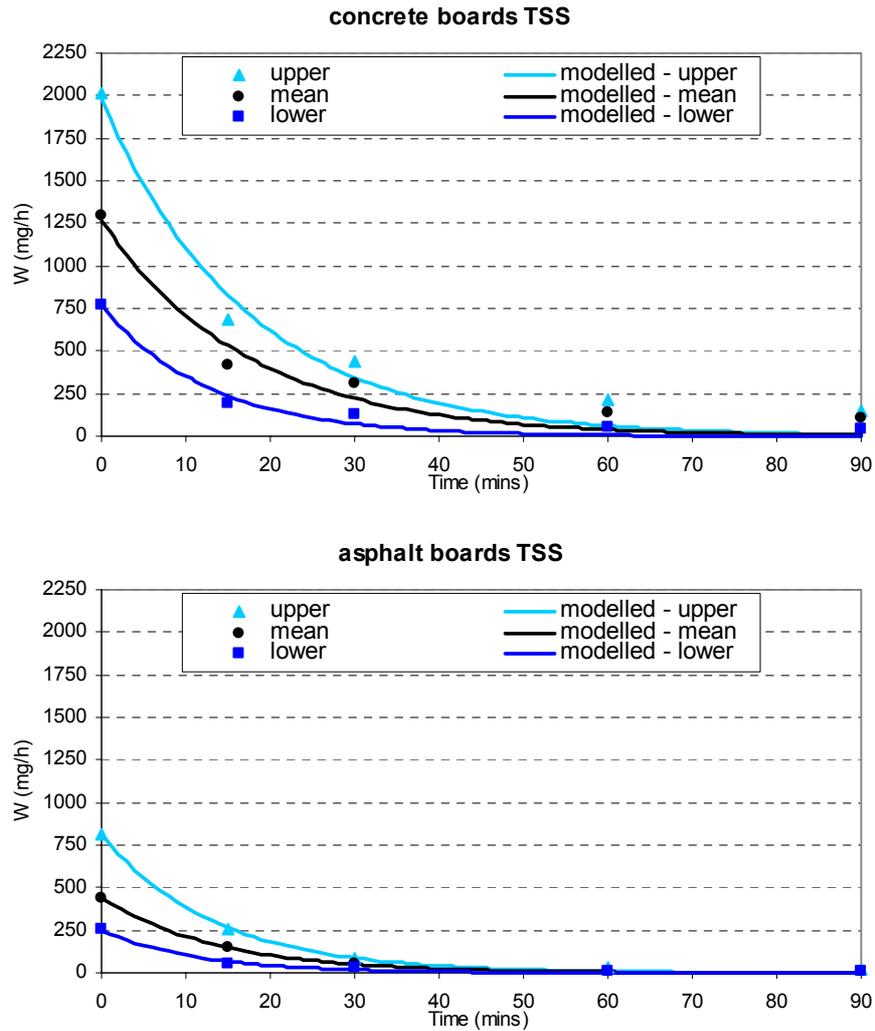
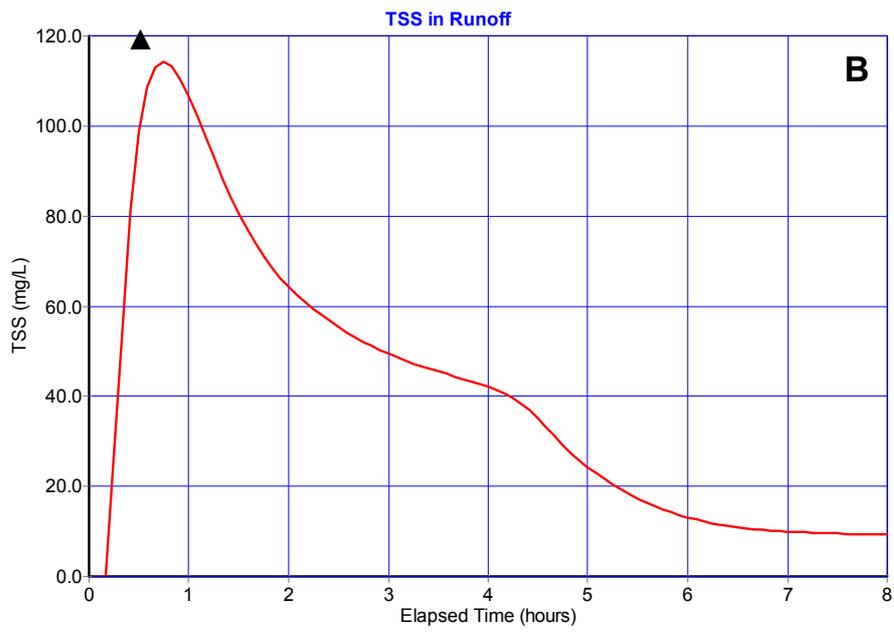
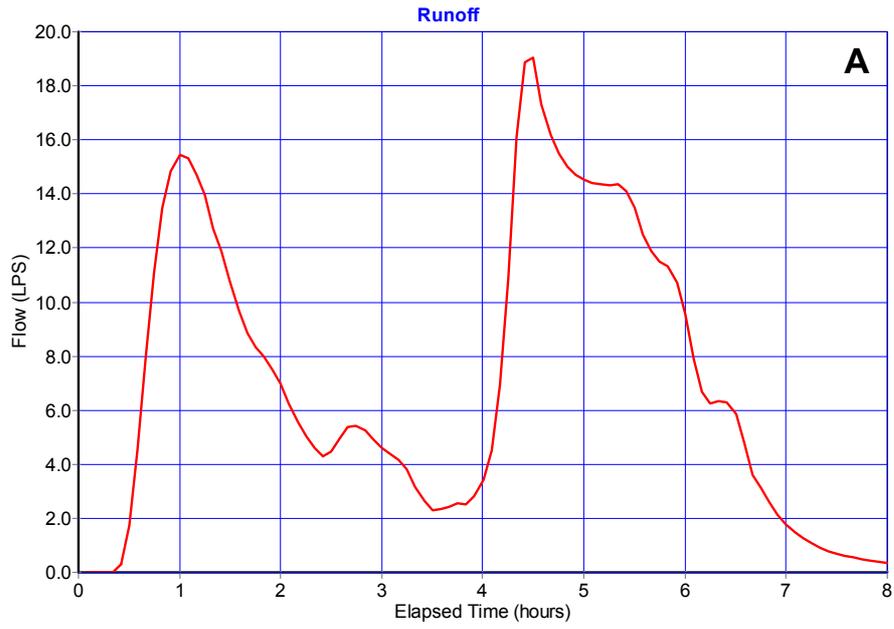


Figure 5: Modelled curves and measured values for wash-off loads (W) of TSS from two different surfaces (concrete and asphalt)

The derived wash-off coefficients (C_1) were then used in the SWMM model to simulate concentrations for TSS and copper in runoff from the 1.5 ha carpark for a storm event in August 2008 following 5 antecedent dry days. Rainfall data logged by a rain gauge (attached to a building at the carpark) was used as input parameters for the runoff calculations. The runoff curve generated by SWMM for this event is shown in Figure 6a. Figure 6b and Figure 6c show TSS and copper concentrations, respectively, in the runoff as simulated by SWMM. These curves clearly show distinct first flush concentrations that are also readily observed in monitored catchment studies. The increase in flow in the second half of the storm event (after 4 hours – see Figure 6a) does not result in a similar increase in contaminant concentrations. This situation clearly illustrates the depletion of accumulated contaminants over time as formulated by the wash-off load (W) function. Measured first flush samples from the car park (composite samples of the first 30 minutes) were 120 mg/L for TSS and 0.036 mg/L for copper, showing close proximity to modelled values.



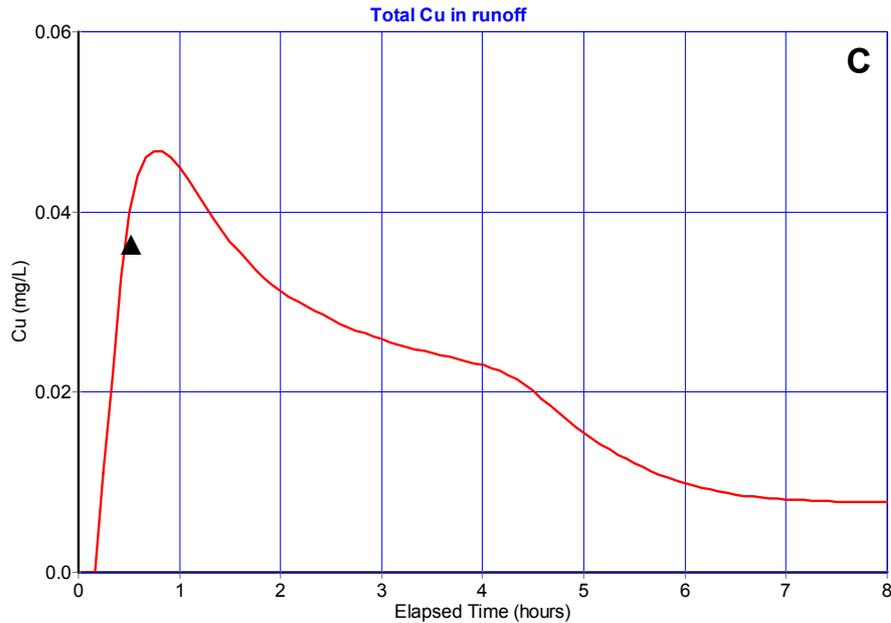


Figure 6: Flow (A) and TSS (B) and copper (C) concentrations in runoff from a carpark as generated by SWMM. Experimental values for first flush concentrations are indicated by ▲.

4. CONCLUSIONS

The unique experimental method for capturing contaminants on different surfaces by using thin constructed boards proved to be successful. Results from the experiments clearly show that there is a high level of spatial variability in contaminant accumulation within urban catchments, even within a relatively small area such as a 1.5 ha carpark. This variability is attributed to the frequency of car traffic and the different types of vehicles parking over experimental boards. The experiments also showed that there is a significant difference in contaminant accumulation behaviour for different surfaces. Asphalt seems to retain deposited particles more efficiently than concrete, resulting in lower runoff concentrations. Wash-off contaminant concentration data from the board experiments were used to estimate modelling parameters to derive wash-off functions. The resulting parameters were successfully applied with the SWMM model. Resulting modelled contaminant curves seemed likely and were comparable to measured first flush samples of monitored storm events.

Future work will include a more accurate determination of wash-off function parameters (especially the C_2 exponent) by performing additional experiments with the boards under different rainfall intensities. Additionally, experiments will be repeated without Zn contamination from the header tank so that modelling coefficients for this metal can be derived. Specific experiments will also be conducted to verify and further develop build-up functions, which are necessary for modelling contaminant loads in urban stormwater.

5. ACKNOWLEDGEMENTS

Funding for analysis costs was provided by Environment Canterbury. The authors thank Peter McGuigan for analysis of TSS and assistance with experimental setup.

6. REFERENCES

[1] Adams, J., Mahar, T., and Broad, S. (2007). "Monitoring stormwater discharge into the Avon River from the Fine Arts Carpark at the University of Canterbury for resource consent renewal. ",

Report submitted in partial fulfilment of the requirements for the BE (Hons) Degree in Natural Resources Engineering, University of Canterbury.

- [2] ANZECC (2000). "Australian and New Zealand Guidelines for Fresh and Marine Water Quality.", Australian and New Zealand Environment and Conservation Council.
- [3] Brown, J. N. and Peake, B. M. (2006). "Sources of heavy metals and polycyclic aromatic hydrocarbons in urban stormwater runoff." *Science of the Total Environment* 359(1-3): 145-155.
- Christchurch City Council, CCC 2003. "Waterways, Wetlands and Drainage Guide-Ko Te Anga Whakaora mo Nga Arawai Repo. *Part B: Design*". McMurtrie, S. & Walter, J. (eds). Christchurch, Christchurch City Council.
- [4] Darboux, F. and Huang, C. (2003). "An instantaneous-profile laser scanner to measure soil surface microtopography." *Soil Science Society of America Journal* 67(1): 92-99.
- [5] Gobel, P., Dierkes, C. and Coldewey, W. C. (2007). "Storm water runoff concentration matrix for urban areas." *Journal of Contaminant Hydrology* 91(1-2): 26-42.
- [6] Hutchinson, J. and Funnell, E. (2008). "Development of an eco-hydrological model for determining contaminant loading and transport in urban catchments", Report submitted in partial fulfilment of the requirements for the BE (Hons) Degree in Natural Resources Engineering, University of Canterbury.
- [7] Moores, J. and Pattinson, P. (2008). "Characterising loads of copper and zinc in road runoff" *Proceedings of 5th South Pacific Stormwater Conference, May 2008, Rotorua, New Zealand.*
- [8] Norton, L.D., Brown, L.C. (1992). "Time-effect on water erosion for ridge tillage". *Transactions of the ASAE* 35 (2), 473–478.
- [9] Suren, A and Elliot, S (2004). "Effects of urbanisation on streams". In Harding, J, Mosley, P, Pearson, C, Sorrell, B, eds. *Freshwaters of New Zealand*. New Zealand Hydrological Society.
- [10] Timperley, M., and Reed, J. (2008). "Modelling the fate of Auckland's stormwater chemicals over the next 100 years.", *Proceedings of 5th South Pacific Stormwater Conference, May 2008, Rotorua, New Zealand.*
- [11] Wicke, D., Cochrane, T., O'Sullivan, A., Hutchinson, J., and Funnell, E. (2009). "Developing a rainfall contaminant relationship model for Christchurch urban catchments", *Proceedings of 6th South Pacific Stormwater Conference, April/May 2009, Auckland, New Zealand.*
- [12] Zanders, J.M. (2005). "Road Sediment: Characterisation and implications for the performance of vegetated strips treating road runoff", *Science of the Total Environment* 339(1-3): 41-47.
- [13] Zollhoefer, J. (2009). "First flush stormwater; time series and event mean concentrations.", *Proceedings of 6th South Pacific Stormwater Conference, April 2009, Auckland, New Zealand.*