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

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 164mg/L. Similar variability's were also observed for measured copper and lead on both concrete and asphalt boards. This variation is attributed to factors such as the number and type of vehicles parking over boards. The application of this experimental data to parameterize our initial model resulted in predictions that seemed realistic and comparable to measured TSS and copper concentration stormwater samples.

Key Words: urban catchment model, Christchurch, heavy metals, stormwater runoff

1. INTRODUCTION

Urban waterways are an important part of Christchurch's aesthetic beauty 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 ending up in urban waterways in Christchurch and around New Zealand are zinc, copper, and lead (Zanders, 2005; Suren and Elliot, 2004; Adams et al, 2007). The main source of these contaminants are dust from vehicle tyres and brake linings which accumulate on paved surfaces and are washed off during rainfall events into waterways (Moores and Pattinson, 2008; Zanders, 2005). Sampling of 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 ANZECC guidelines for the protection of aquatic species in waterways (Adams, et al., 2007; Hutchinson and Funnell, 2008).

Although direct sampling of stormwater runoff is an ideal way to quantify total contaminant contribution from a specific area during a given storm event, it is an expensive and time consuming task. Data from sampling is therefore very limited and generally insufficient to construct robust models for predicting stormwater contamination. Furthermore, direct sampling of runoff masks the potential spatial variability of contaminant sources. Given the 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 contaminants, determine the extent of spatial variability of contaminant build-up within urban catchments, 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 build-up and wash-off functions for modelling purposes.

2. METHODOLOGY

Our experimental system consisted of capturing contaminants on thin boards which are placed on various types of impermeable surfaces in an urban catchment (roads, sidewalks, or carparks). The rimmed plywood boards (75 cm x 75 cm, total height: 3 cm) are filled with materials such as asphalt or concrete to replicate the ability of these surfaces to retain and release contaminants over time. For our initial experiments, 8 boards, 4 filled with concrete and 4 filled with a smooth asphalt type (3 mm congregate) were exposed for 9 days (16.6.2009-25.06.2009) on a University carpark at various locations (see Fig. 1).

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

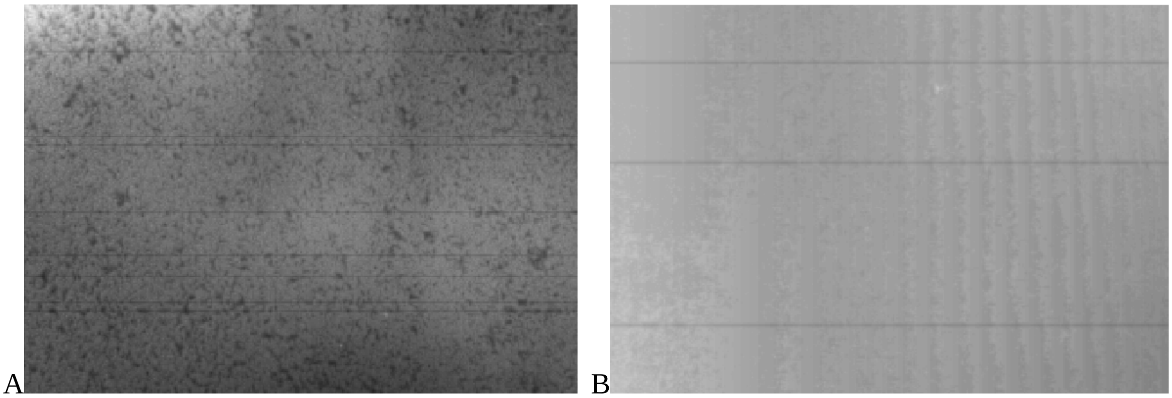


Fig. 2: Images of boards derived from a surface laser scanner. A: asphalt surface; B: concrete surface. Heights are represented in gray levels with darker tones for lower elevations.

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 all boards were collected and placed under a laboratory rainfall simulator (two nozzle Veerjet 80100 Norton type rainfall simulator, Norton and Brown, 1992). The rainfall simulator was run at 22 mm/h rainfall intensity and runoff from the boards was collected. The total wash-off time was 90 minutes with samples taken at 0, 15, 30, 60 and 90 minutes. Samples were measured instantaneously for pH, conductivity and turbidity. Total suspended solids (TSS) were measured within 24 hours according to the APHA method. Measurements of heavy metals were done by an accredited laboratory for samples taken at 0, 15 and 30 minutes.

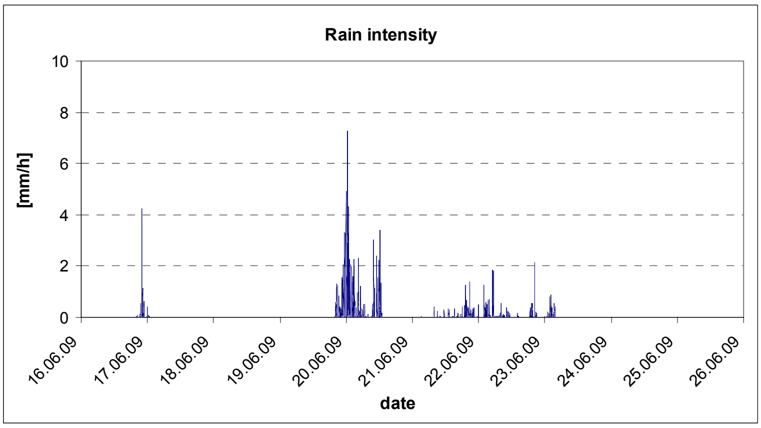


Fig 3: Rain intensity during time of exposure of the boards

2.1 Modelling

Modelling of contaminant runoff from the carpark was done 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 the wash-off functions for TSS, copper, and lead for the two different surfaces (concrete and asphalt). 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.

$$W = C_1 \cdot q^{C_2} \cdot B \tag{1}$$

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 using EXCEL solver.

The wash-off functions developed from our experiments were then used to simulate runoff concentrations of TSS and total copper 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/m^2, C_2 (half saturation constant)=7.8 days; Copper: C_1= 0.0076 mg/m^2, 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 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 held back in pores and cavities (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 ANZECC guidelines for heavy metal concentrations (black lines in Fig. 4), the data consistently shows that copper concentrations are of greater concern than lead. Copper exceeds the ANZECC guidelines throughout the entire sampling period of both asphalt and concrete surfaces.

Contaminant concentrations from board experiments were also compared to carpark runoff concentrations 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 carpark sampling.

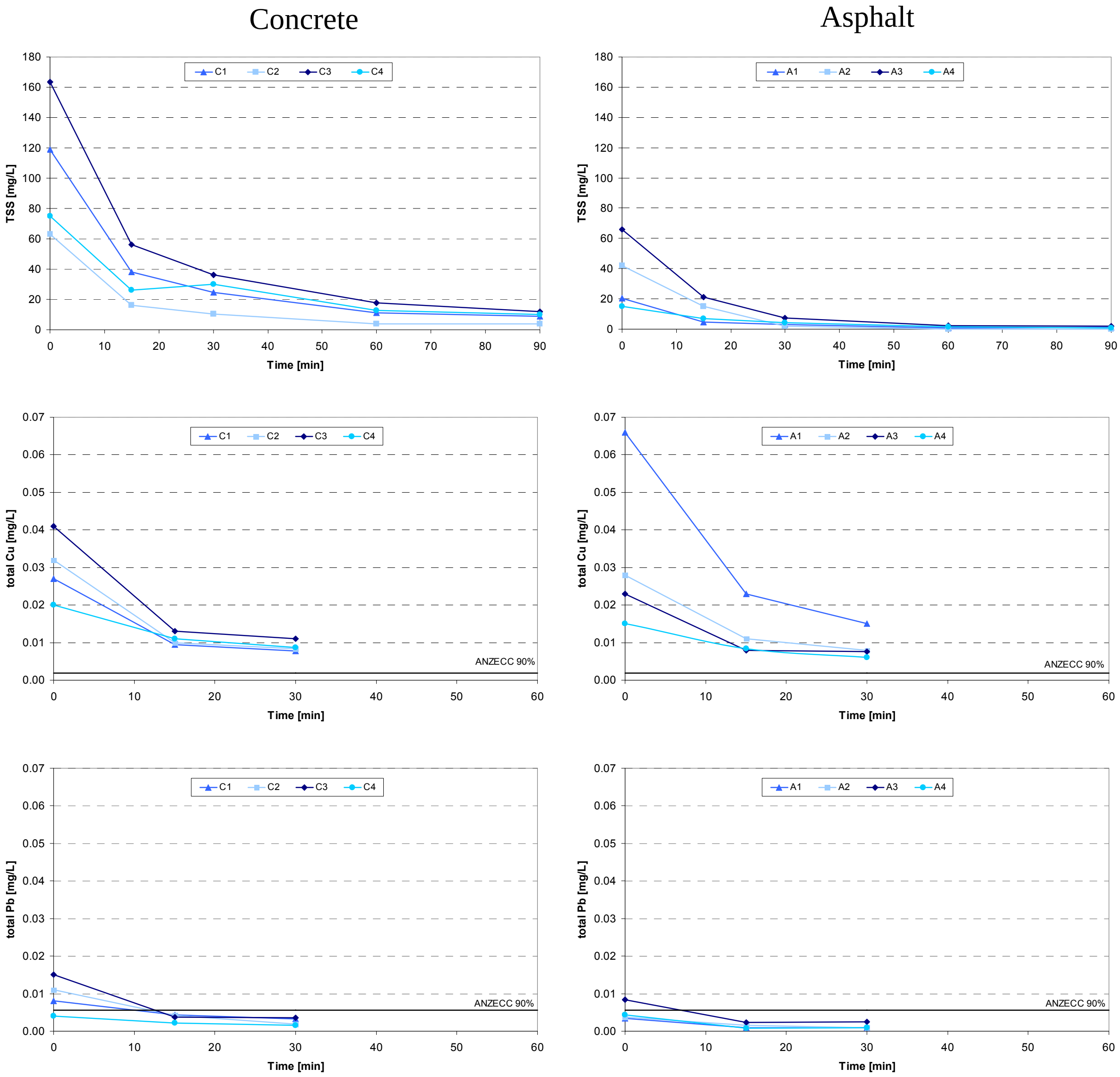


Fig. 4: Measured concentrations of TSS, copper and lead for runoff from concrete and asphalt boards using a rainfall simulator at an rain intensity of 22 mm/h.

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

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).

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). As mentioned earlier this was done by applying EXCEL solver 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 (minimum of the sum of the squared differences between experimental and modelled values). EXCEL solver varies the specified parameters to find a solution for this condition. However, since several mathematical solutions are possible for C_1 and C_2 resulting in the same wash-off curve for our experimental conditions, 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. 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.

The derived upper, mean, and lower wash-off load function curves are shown in Fig. 4 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 significantly lower value of calculated build-up than concrete, which means that Asphalt retains more contaminants if we assume that both concrete and asphalt boards were exposed to a similar range of dust or particles.

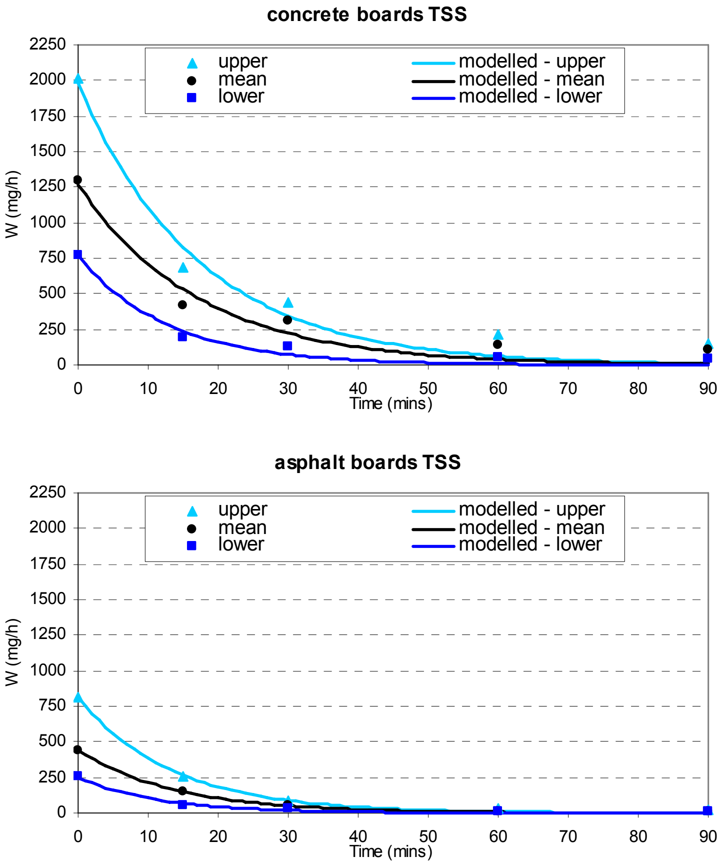


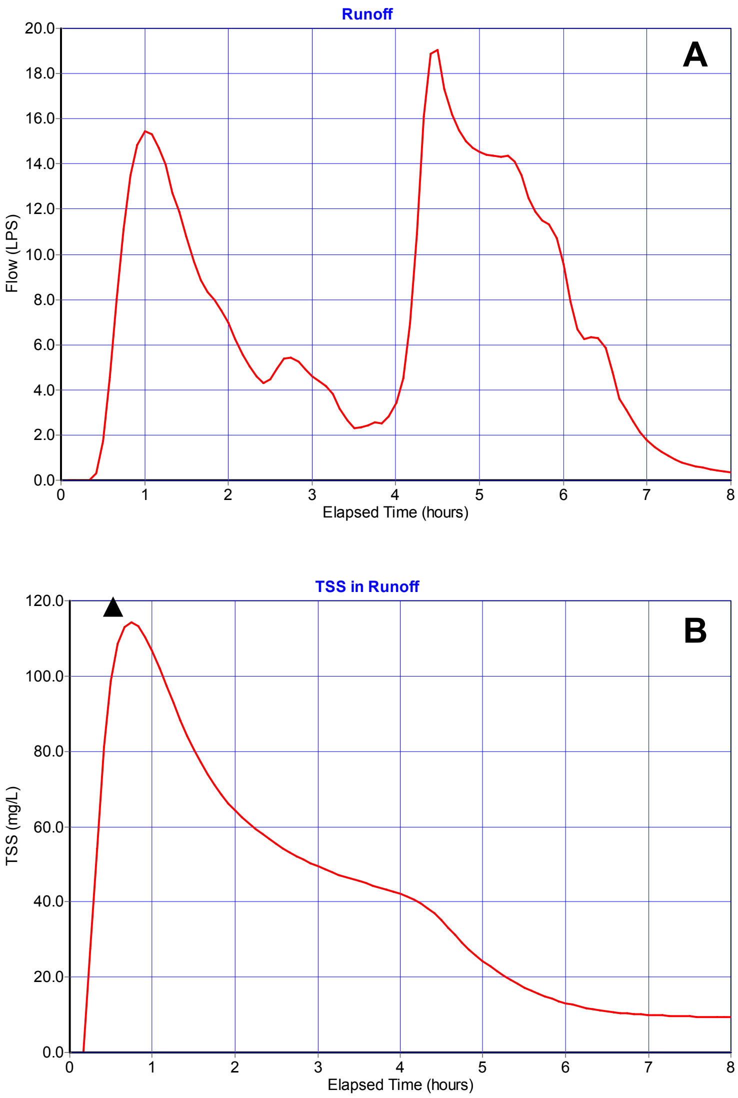
Figure 5: Modelled curves and measured values for wash-off loads (W) of TSS from two different surfaces (concrete and asphalt)

		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

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

The derived wash-off coefficients were then used in SWMM 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. The runoff curve generated by SWMM for this event is shown in Figure 6a. Figure 6b and c show TSS and copper concentrations in the runoff as simulated by SWMM. These curves clearly show high first flush concentrations that are also readily observed in 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 formulate 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.



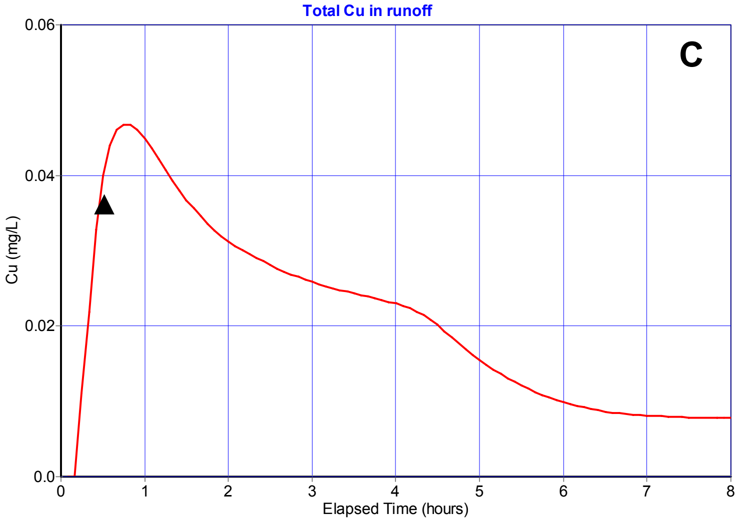


Figure 6: Flow (A) and TSS (B) and copper (C) concentrations in runoff from a carpark as generated by SWMM. Experimental values for first flush concentrations are indicated by ▲.

4. CONCLUSIONS

The unique experimental method for capturing contaminants on different surfaces by using thin boards proved to be successful. Results from the experiments clearly show that there is a high level of spatial variability in contaminant accumulation in urban catchments, even within a relatively small area such as a carpark. This variability is attributed to the amount of car traffic and the 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 boards were used to estimate modelling parameters for wash-off functions. The resulting parameters were successfully applied with the SWMM model. Resulting modelled contaminant curves seemed reasonable and were comparable to measured first flush samples.

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 rain intensities. Specific experiments will also be done to verify and further develop build-up functions which are necessary for modelling contaminant loads in urban stormwater.

5. ACKNOWLEDGEMENTS

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