PREDICTING SEDIMENT AND HEAVY METAL LOADS IN STORMWATER RUNOFF FROM INDIVIDUAL SURFACES

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ABSTRACT

Impermeable urban surfaces such as roads, carparks and roofs contribute contaminants through stormwater runoff to urban waterways. Instream water quality monitoring in Christchurch has confirmed elevated sediment and heavy metals. To assist with planning of stormwater improvements to address water quality issues, an event-based contaminant load model has been developed that predicts the contributions from individual surfaces of TSS, copper and zinc based on rainfall characteristics such as rainfall intensity, antecedent dry period, storm duration, and rainfall pH. This model allows the user to spatially identify where high contaminant loads are likely to be generated. It also identifies patterns in the relative contaminant contributions from different surface types, which is helpful for guiding optimal management solutions. The model was calibrated to Christchurch's low intensity rainfall climate by sampling contaminant loads from key impermeable surfaces and then applied to the Okeover catchment in western Christchurch as an initial case study. Results showed that road surfaces contribute the highest TSS loads (61% of catchment TSS load), followed by carparks (38%). Copper contributions are more evenly distributed between roofs, roads and carparks (27%, 45% and 28% respectively), although a small area of copper roof surfaces contributes a substantial proportion of the catchment's overall copper load (8% of catchment copper load from 0.3% of total impervious area), primarily in dissolved form. Galvanized roofs are key contributors of zinc (81% of catchment zinc load), also primarily in dissolved form. The model was run for a full year of rain events to identify the typical event loads from individual surfaces and how these loads were spatially distributed within the catchment. The model framework accounts for the unique combination of different surfaces within a catchment, local rain event characteristics, and can support stormwater management decision-making to an individual surface or property level.

KEYWORDS

Stormwater quality modelling, urban catchments, MEDUSA, TSS, metals

PRESENTER PROFILE

Frances Charters (BE Hons, Natural Resources Engineering) is a PhD student researching sediment and heavy metal characteristics in untreated urban runoff. Her thesis is on the development of this stormwater contaminant load model. She previously worked in consultancy in 3 Waters management and design.

1 INTRODUCTION

Sediment and heavy metals in urban stormwater runoff are significant sources of pollution in urban waterways and estuaries (Hvitved-Jacobsen et al., 2010). In Christchurch, ongoing instream monitoring in the Avon and Heathcote River systems has identified elevated levels of these contaminants, particularly during wet weather flows (Margetts, 2014; Stevenson, 2010). These contaminants adversely affect the health of aquatic communities in these waterways and improved management of stormwater is needed to reduce these impacts.

However, the selection and planning of stormwater management needs to take into account the influence of the contaminant build-up and subsequent wash-off processes from contributing impermeable surfaces. These processes differ between individual surfaces, as surface material type, condition, age, orientation, and other factors influence the rate of contaminant generation during rainfall. TSS is contributed to urban surfaces via atmospheric deposition of particles (dry and wet deposition), breakdown and degradation of surface materials and direct deposition from vehicular sources (e.g. tyre and brake pad wear, dust wash off from vehicle bodies) (Zanders, 2005). Copper (Cu) is contributed from brake pads (it is used as a heat dissipater), industrial uses of Cu (released into the airshed and settled with atmospherically deposited particles) and direct dissolution of Cu materials (Davis et al., 2001; Wicke et al., 2012). Zinc (Zn) is contributed from tyres (it is used as a vulcanizing agent in tyre rubber), industrial uses of Zn and direct dissolution of Zn materials, such as galvanised roof cladding.

Factors affecting the availability and wash-off of specific contaminants (e.g. TSS, Cu, Zn) can be readily identified for individual surfaces. It is therefore appropriate to model pollution in urban runoff on an individual surface scale, accounting for different surface materials.

In addition to contaminant load, the ratio of dissolved to particulate metals provides important guidance for the selection of appropriate treatment technologies, as the treatment processes for removing particulate metals differ significantly than those appropriate for dissolved metals. Dissolved heavy metals are also more biologically available for uptake by aquatic organisms, and therefore it is important to understand heavy metal partitioning in stormwater runoff in anticipation of potential adverse effects on the receiving waterway. Dissolved metals may adsorb to sediment once in stream and be transported slowly through the river system over time. In particular, the Estuary of the Heathcote and Avon Rivers/Ihutai is a vulnerable downstream environment, with filter feeders that bioaccumulate heavy metals associated with sediment (Marsden et al., 2014).

Accordingly, an event-based contaminant load model, Modelled Estimates of Discharges for Urban Stormwater Assessments (MEDUSA), was developed and calibrated for a mixed residential and institutional land use catchment in Christchurch. The model aims to support stormwater management decision-making and planning by identifying where contaminant hotspots occur within a catchment, at an individual surface scale, for individual storm events. The data collected to calibrate the model was the first intensive untreated runoff monitoring effort undertaken in the city and contributes significant knowledge of contaminant concentrations and metals partitioning, the main processes driving contaminant generation for different surface types and how untreated runoff quality responds to rainfall characteristics.

2 METHODOLOGY

2.1 OVERVIEW OF MEDUSA FRAMEWORK

MEDUSA predicts the amount of TSS, Cu and Zn contributed by an individual surface during a rain event, based on the surface area, its material type and its relationship to rainfall characteristics: rainfall pH, average intensity, duration and length of antecedent dry period (Fraga et al., 2016). MEDUSA predicts the TSS event load from each contributing road, carpark and roof surface using a first-order decay relationship, as defined in Egodawatta et al. (2009). Total metal loads from roof surfaces are also predicted using a first-order decay relationship (Sartor et al., 1974), however total metal loads from road and carpark areas are assumed to be proportional to the TSS load. More detail about the model framework can be found in Charters et al. (2014).

The model was initially assigned coefficient values (for describing the relationship of contaminant load to each rainfall characteristic) from published international literature. However, these relationships have been observed to vary with climate. In particular, Christchurch has low intensity rainfall: 95% of events >6 hr duration have an intensity <5 mm.hr^{-1}. In comparison, Auckland's rainfall intensity is >8 mm.hr^{-1} for equivalent events, and both Hamilton and Wellington are >6 mm.hr^{-1}; however, Dunedin is also <5 mm.hr^{-1} (NIWA, 2011). Local stormwater data was therefore required to calibrate the model to Christchurch conditions by updating the coefficient values.

2.2 CASE STUDY CATCHMENT

The model was calibrated and applied to the Okeover Catchment in Western Christchurch as an initial case study (Figure 1). The Okeover catchment comprises 61 ha of mixed residential and institutional (University of Canterbury campus) land use.

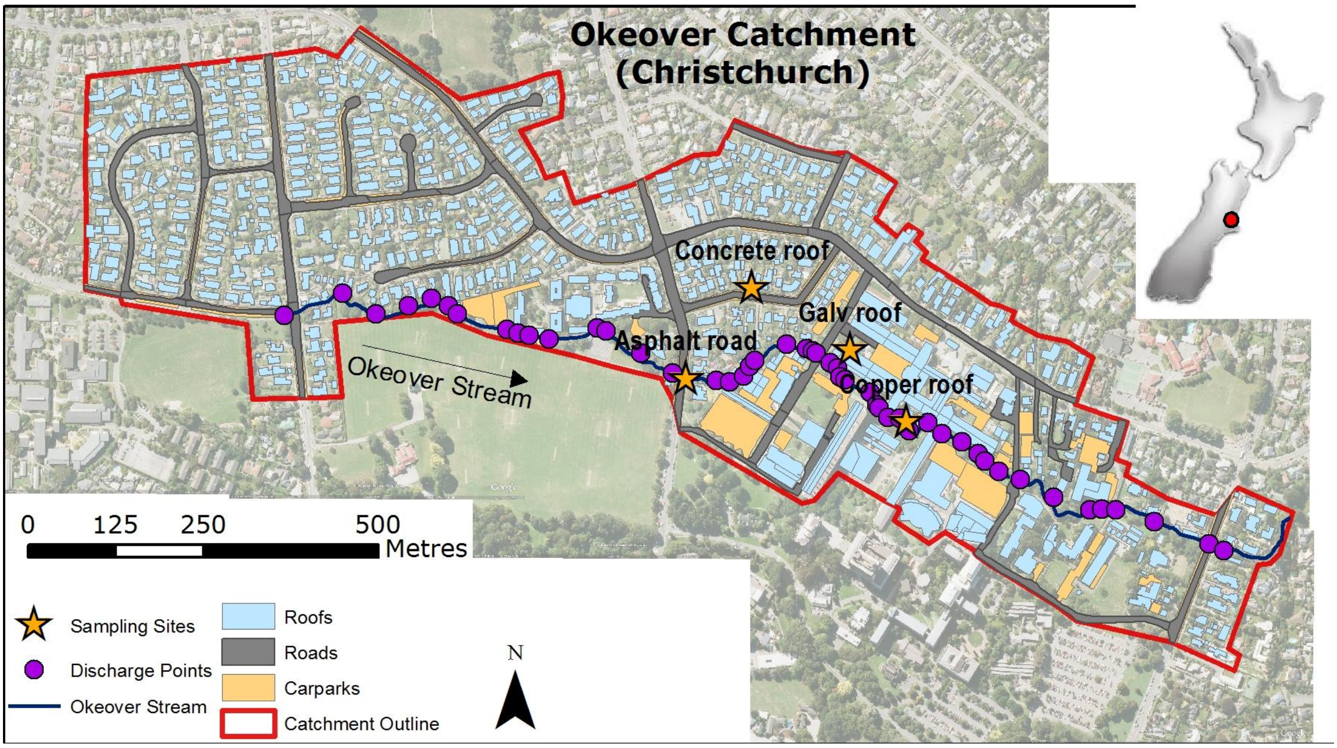

Figure 1: Key features and contributing impermeable surfaces of the Okeover catchment

2.3 CALIBRATION DATA COLLECTION AND ANALYSIS

2.3.1 SAMPLING SITES

Untreated runoff from four different impermeable surface types were sampled: a concrete tile roof (common residential roofing type), an unpainted galvanized roof (common residential and institutional roofing type in the catchment), a copper roof (used on some University roofs) and an asphalt road (Ilam Road, with 12,000 annual average daily traffic (AADT) units). All four surfaces (within 320 m of each other) were sampled, and therefore the surfaces were assumed to have been exposed to the same dry weather contaminant build-up and rainfall characteristics. Any differences in runoff quality between the surfaces was attributed to differences in surface material, condition and wash-off processes.

2.3.2 SAMPLE COLLECTION AND LAB ANALYSIS

A combination of grab sampling and automatic samplers were used to collect initial (defined as the first 2L of runoff, following Wicke et al. (2014)) and steady state samples over 24 rainfall events between December 2013 and March 2015.

Samples were analysed for TSS (APHA method 2540 D), and total and dissolved copper and zinc (APHA method 3125B, followed by Inductively-Coupled Plasma Mass Spectrophotometry (ICP-MS) analysis) at the Environmental Lab in the Department of Civil and Natural Resources Engineering, University of Canterbury. The total and dissolved metal concentrations were used to assess metals partitioning (i.e. total metal = particulate + dissolved).

2.3.3 COMPARISON OF MODEL PREDICTED AND OBSERVED CONTAMINANT LOADS

Event (per area) loads were derived for each sampled surface as a function of the measured concentrations and the rainfall depth accumulated in each period between time-series samples. These loads are hereafter referred to as observed loads.

The Nash-Sutcliffe model efficiency (NSE) was used to assess the predictive power of the model and goodness of fit. The NSE was developed for assessing hydrological models (Nash and Sutcliffe, 1970), but has also been employed for modelling sediment and nutrient loadings (Moriasi et al., 2007). It describes the predictive accuracy of the model in comparison to the observed loads. An efficiency, E, of 1 indicates a perfect fit between the modelled and observed loads, an efficiency of $0<E<1$ indicates the model is a better predictor than the observed mean, $E= 0$ indicates the model is only as accurate as the observed mean, while $E<0$ indicates the observed mean is a better predictor than the model. Modelled and observed loads were log-transformed before the NSE was applied to reduce the influence of any peak events as they increase the sensitivity of NSE to systematic over- or under-prediction (Krause et al., 2005).

2.4 MODELLING SCENARIOS

MEDUSA was first run using the sampled event characteristics (25 events) to assess model performance. It was then run for a full year of rain events from the year 2012 (88 events; Table 1), as researchers at the University of Canterbury had measured rainfall pH for several rain events in 2012. Therefore a relatively complete set of characterised rainfall events was available, with minimal assumptions required for rainfall pH. While there will be variation from year to year, 2012 had relatively normal annual rainfall for Christchurch (Christchurch Botanic Gardens weather station recorded 631 mm annual rainfall for 2012 (NIWA, 2013b); Christchurch's mean annual rainfall is 647 mm (NIWA, 2013a)) and it provides an indication of the expected variation of rain events across a year. Average event loads were derived from the average of all 88 events of 2012.

Table 1: Rainfall event characteristics for the year 2012

Rainfall parameter	Median value (range)
Number of rain events	88
Rainfall pH	6.01 (5.19 – 7.15)
Average intensity (mm/hr)	0.53 (0.12 – 4.00)
Antecedent dry days (days)	3.0 (0.2 – 19.0)
Event duration (hours)	5.0 (1.0 – 41.0)

3 UNTREATED RUNOFF QUALITY RESULTS

3.1 COMPARATIVE QUALITY BETWEEN SURFACES

As expected, the road runoff consistently produced the highest TSS concentrations under initial and steady state conditions. While atmospheric deposition is shared across the four sampled surfaces, only roads have the additional (and substantial) contribution of vehicular-derived sediment. However, surprisingly high initial TSS was seen from the copper roof. This is thought to result from the wash-off of copper patination byproduct as a result of oxidation and degradation of the copper roofing material during dry weather (Charters et al., 2016).

The copper roof produced copper concentrations that were two orders-of-magnitude higher than any of the other surfaces, even the road, with its additional vehicular-derived sources of copper. Likewise the galvanized roof had the highest zinc concentrations, although the average zinc concentration from the galvanized roof was only a factor of 4 higher than the road runoff.

Table 2: Contaminant concentrations in untreated runoff samples (modified from Charters et al. (2016))

Surface	TSS (mg/L)		Total copper(ug/L)		Total zinc(ug/L)	
	n	Mean (range)	n	Mean (range)	n	Mean (range)
Concrete tile roof	65	5.1 (0.1-30.8)	54	9.0 (2.2-27.8)	54	17.4 (5.4-44.5)
Copper roof	45	46 (0.2-453)	43	1,691 (423-7,861)	43	42 (5.0-292)
Galvanised roof	58	5.0 (0.1-22)	49	6.0 (2.5-13)	49	491 (75-2,369)
Asphalt road	38	81 (6.6-327)	27	29 (7.0-84)	27	124 (20-429)

3.2 HEAVY METALS PARTITIONING

Zinc was primarily in dissolved form for the three roof surfaces, although zinc concentrations for copper and concrete roof surfaces were not particularly high. Nearly all the zinc generated by the galvanized roof was in dissolved form. Zinc from road runoff was more evenly distributed between dissolved and particulate form, although a higher proportion of zinc was in dissolved form than copper was in road runoff.

The majority of copper was found to be in particulate form for road, galvanized roof and concrete roof runoff, however the opposite was seen for copper roof runoff (Figure 2). This is consistent with dissolution processes being the dominant source of copper from this surface type. More of the copper from the copper roof is in particulate form than zinc is from the galvanised roof, where both surfaces are contributing metals primarily through direct dissolution. The higher proportion of particulate copper is likely due to the copper in the patination byproduct that is washed off in the initial stages of a rain event.

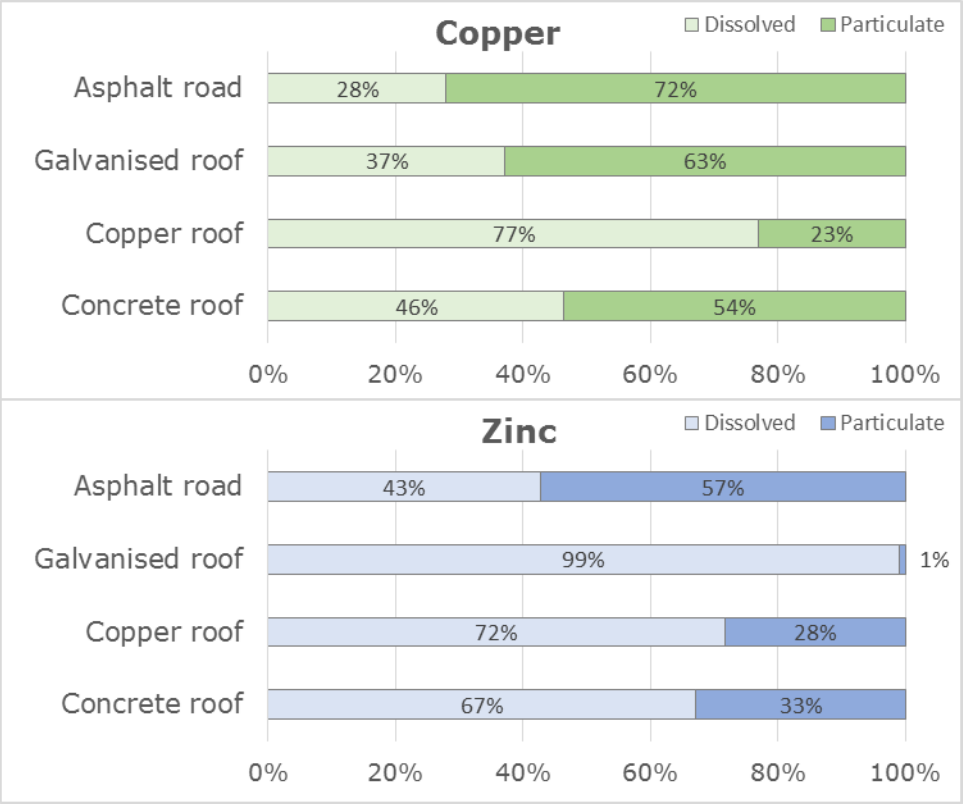

Figure 2: Average dissolved to particulate copper and zinc partitioning

4 MODELLING RESULTS

4.1 MODEL CALIBRATION

Reasonable fits were found for the calibrated TSS, total copper and total zinc models, for all surface types (*Figure 3*). It is capable of predicting across a wide range of contaminant loads. The Okeover-calibrated MEDUSA model is most effective at predicting contaminant loads from road runoff (NSEs of 0.69–0.74), out of the four surface types (Table 3). Effective modelling of road runoff loads is particularly important, as road runoff produces the largest TSS loads and second largest copper and zinc loads (after roofs made of these materials).

Of the three contaminants, MEDUSA is generally better at predicting copper and zinc than TSS. However, it has a tendency to overestimate total copper and zinc loads from galvanized roof runoff, and a tendency to underestimate total copper loads from copper roof runoff (*Figure 3*).

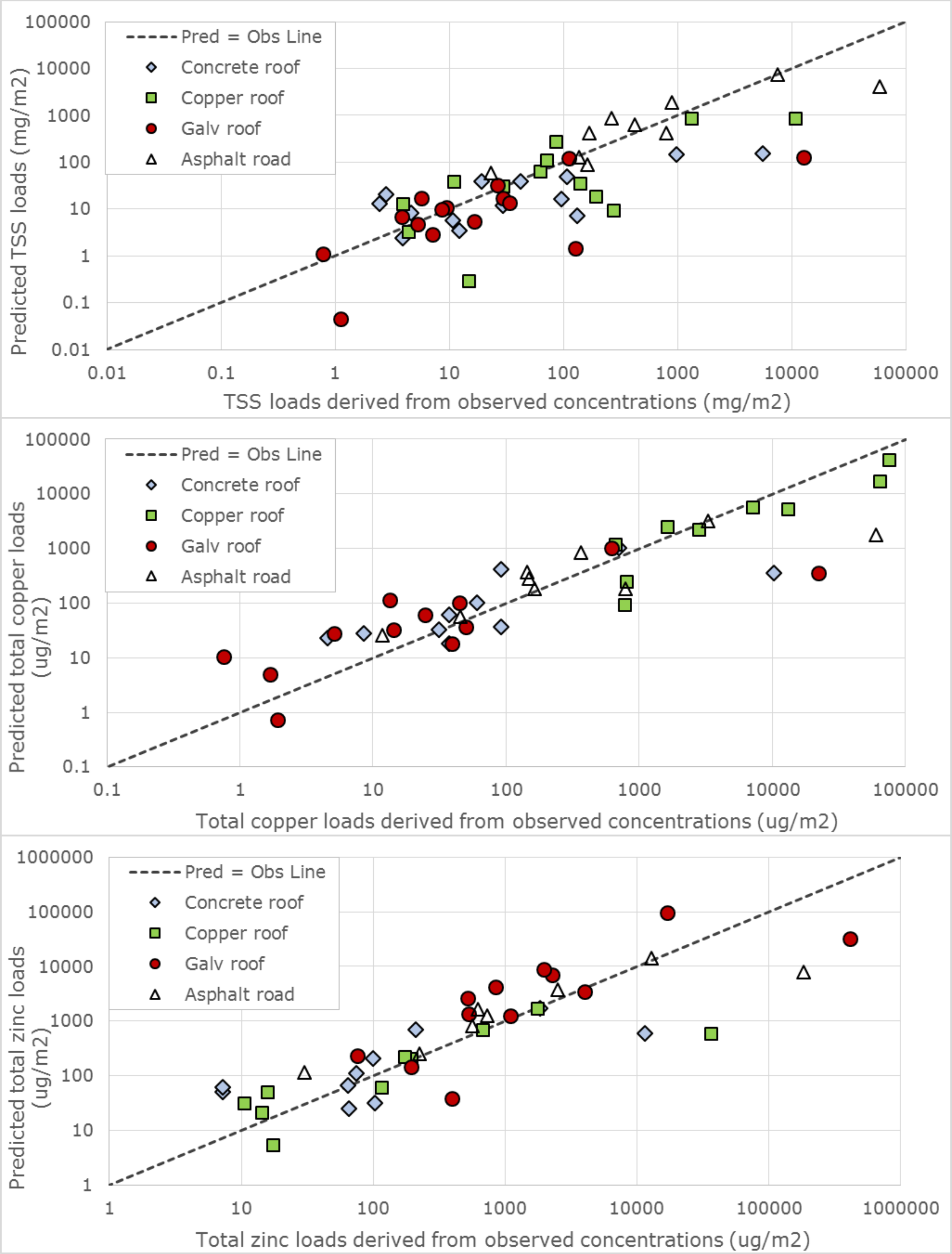

Figure 3: Modelled predicted per area loads compared with observed per area loads

Table 3: Nash-Sutcliffe Efficiencies of model fit for the Okeover-calibrated MEDUSA model

Surface type	TSS	Total copper	Total zinc
Concrete tile roof	0.41	0.55	0.53
Copper roof	0.25	0.46	0.65
Galvanised roof	0.26	0.58	0.54
Asphalt road	0.74	0.69	0.73

4.2 RELATIVE CONTRIBUTION OF CONTAMINANTS

Average event loads for the whole catchment were modelled (for all year 2012 rain events) and the contribution from each surface type was compared to its relative surface area (Figure 4). While roof surfaces make up the majority of the modelled impermeable surfaces, they contribute very little TSS, a disproportionally low amount of copper but the vast majority of zinc. Conversely, road and carpark surfaces are nearly the sole contributors of sediment and a disproportionally high amount of copper. However, further assessment of the subcategories of roof runoff clearly show that the copper roofs at the University (within the modelled catchment) are contributing very high copper loads for their small cumulative surface area. These results yield important implications for modelling other catchments with copper roofs or cladding (as typical in architectural designs).

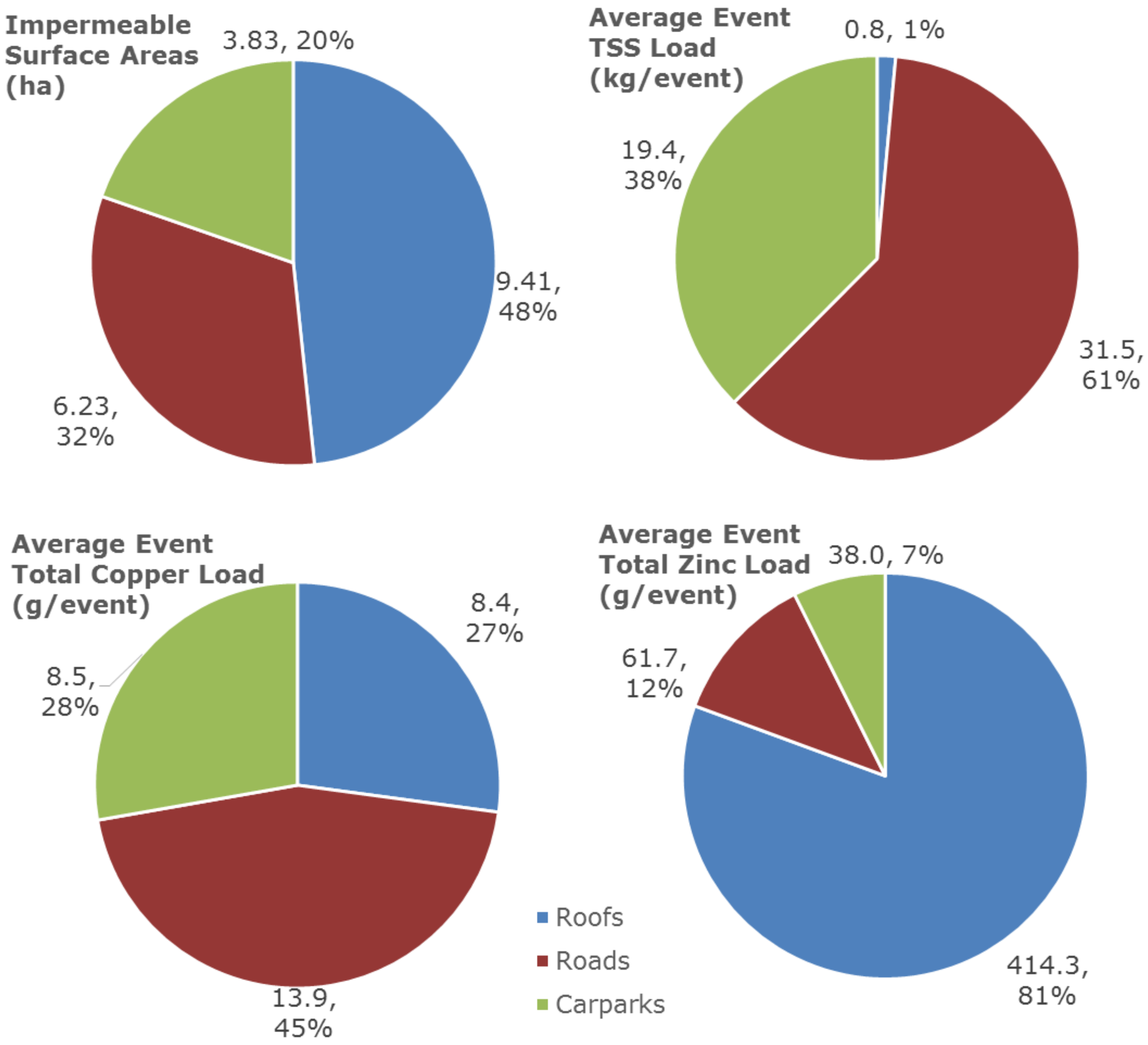

Figure 4: Average event loads by main surface types, compared to their relative surface area

4.3 SPATIAL DISTRIBUTION OF LOADS

Average event loads were calculated for each surface based on the 88 modelled events from 2012, and mapped to show the spatial distribution of contaminant loads (Figure 4 to Figure 6). Results clearly show that roads throughout the catchment are contributing the highest sediment loads, along with the two largest carparks in the University (that drain to the Okeover): the Science and Geology carparks (Figure 5).

Total copper mapping showed that the two copper roof surfaces, despite their small area, contributed event loads substantially higher than any other individual surface in the catchment. Of the remaining surface types, the large Science carpark is highlighted as a significant contributor of copper, along with the linear road surfaces.

Zinc loads have a distinctly different spatial pattern than sediment and copper as the rate of zinc generation is so much higher from any zinc-based roof material.

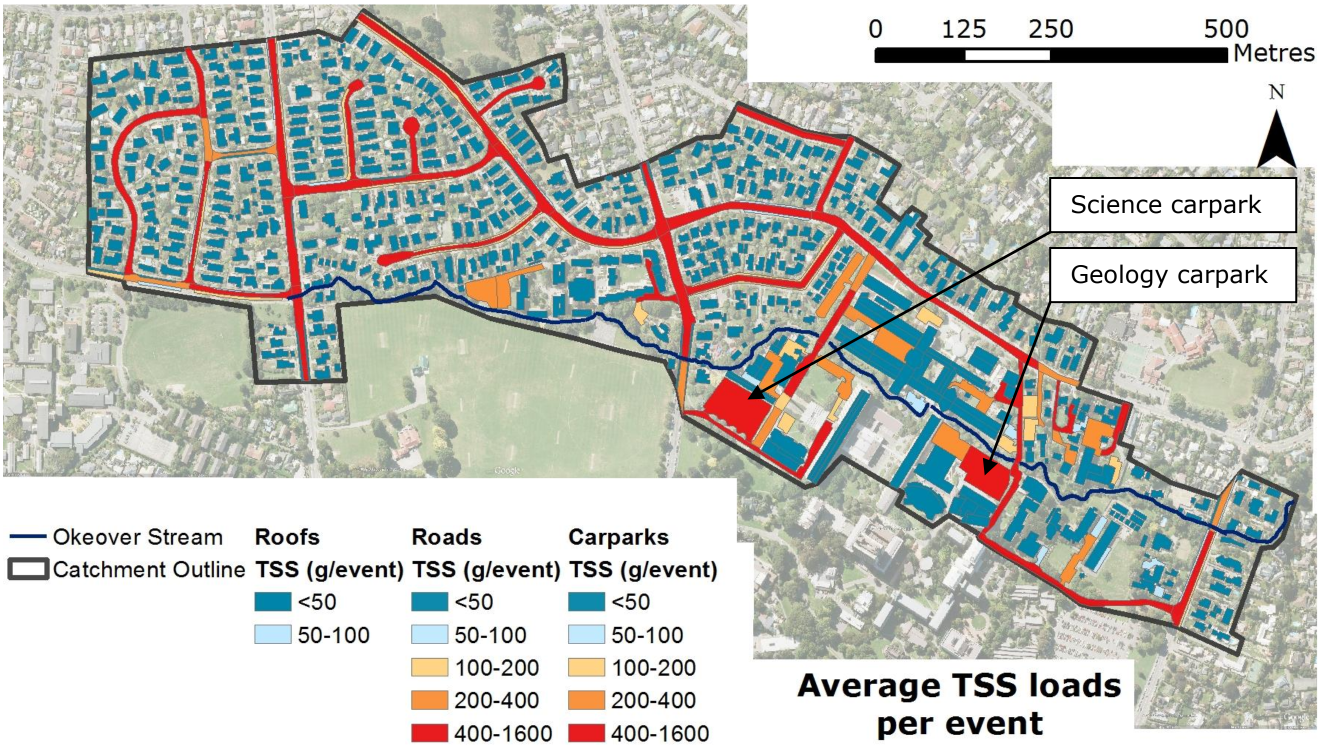

Figure 5: Average TSS event loads from individual surfaces in the Okeover catchment

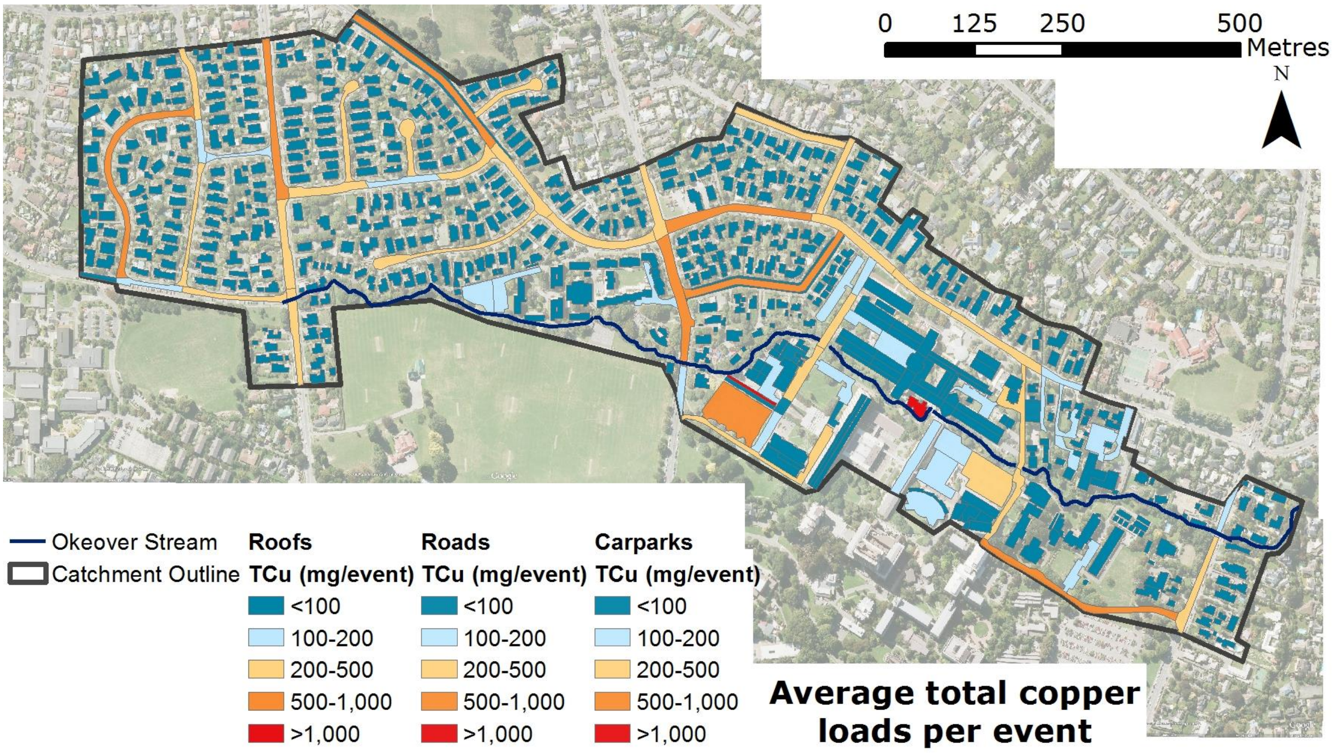

Figure 6: Average total copper event loads from individual surfaces in the Okeover catchment

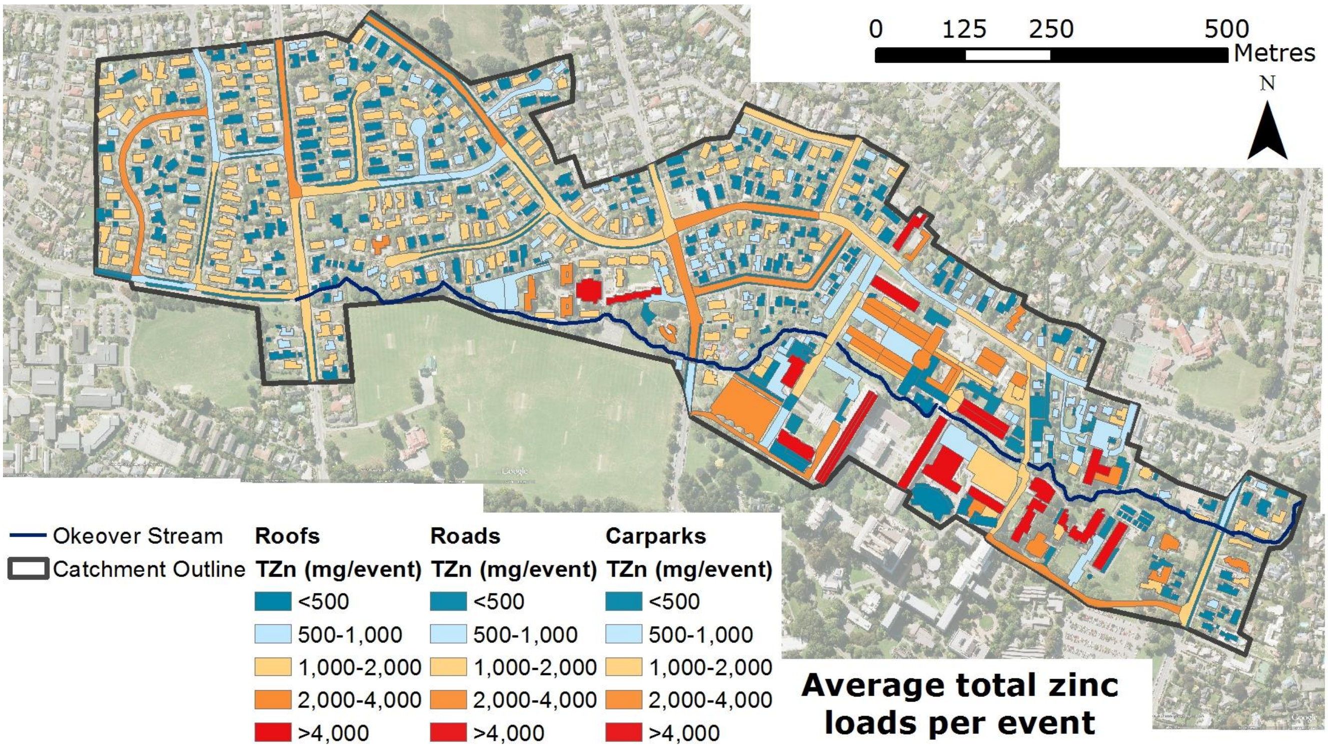

Figure 7: Average total zinc event loads from individual surfaces in the Okeover catchment

5 DISCUSSION

5.1 IMPLICATIONS FOR MANAGEMENT OPTIONS

Road runoff is clearly the key contributing surface type for TSS in the catchment. The contrasting low TSS concentrations from the sampled roof surfaces suggest that the mixing of roof and road runoff in kerb and channels is creating larger volumes of 'diluted' runoff. Interception of road runoff prior to reaching the kerb and channel may therefore be beneficial for reducing the volume of runoff requiring treatment (Charters et al., 2016). Treatment technologies that could achieve this include median strip bioretention swales, tree pits and bioretention basins amongst parking spaces. Independent, international studies have shown that treatment of higher concentrated runoff can achieve higher treatment efficiencies (Lau and Stenstrom, 2001; Strecker et al., 2001).

Small copper roofs were predicted to produce very high loads of copper, despite their small surface area, and the majority of this is in dissolved form (see Section 3.2). Likewise, galvanised roofs were found to produce high loads of dissolved zinc. As well as contributing to toxicity in the receiving environment, dissolved metals in stormwater runoff can be more difficult to treat as majority of the standard stormwater treatment systems are based on filtration or settling processes that primarily aim to remove sediment. A reduction in metal load is achieved in these systems by proxy as particulate metals are removed along with the sediment. However, dissolved metals may pass through these systems untreated.

Dissolved metals can be effectively treated in stormwater runoff provided a suitable treatment process is selected that facilitates processes of precipitation, sorption, filtration, or plant uptake and binding of the dissolved metals (LeFevre et al., 2014). Examples of systems that employ these processes include bioretention basins (LeFevre et al., 2014), carbonate/hydroxide dosing, wetlands (sulphide precipitation), proprietary organic/humic filters, gravel/rock biofilters and some engineered fabric filters. The performance of these systems varies with external factors such as temperature, runoff pH, and variations in redox conditions from fluctuations between wet and dry periods, and internal system factors such as media life expectancies, clogging and media cell structure (LeFevre et al., 2014).

Large variations have been observed in the particle size distribution (PSD) of the TSS in road runoff (Charters et al., 2015). This means that the sediment-removal efficiency of treatment systems that employ settling and filtration-based processes may vary between events, as the ability of these systems to remove particles varies with particle size.

Source reduction techniques which prevent the generation of the dissolved heavy metals should be a priority in this catchment, particularly as it is the copper roofs and unpainted galvanized roofs that are key contributors of high metal loads. For the roof surfaces this would include replacement of the roof material or painting.

5.2 LIMITATIONS AND APPLICABILITY TO OTHER CATCHMENTS

MEDUSA uses rainfall characteristics as the independent variables in its contaminant load equations. It also varies coefficient values and equations by surface material type. However, there are other factors that influence the build-up and wash-off of contaminants from impermeable surfaces: surface factors such as age, condition and orientation, and environmental factors such as topography and air quality. While MEDUSA is a generalised model framework rather than a catchment-specific model framework, some local data is required to enable catchment-specific calibration of the model to account for surface and environmental influences. The model could be used in areas that are undergoing redevelopment, such as the Christchurch CBD, which is undergoing extensive redevelopment post-earthquakes, to help guide the development of appropriate stormwater management policies. The model can also be applied to established urban catchments (such as the Okeover) where the focus of stormwater management may include identification of contaminant hotspots and retrofitting of on-site treatment. The generalised framework of the model allows it to applied to other urban centres, within New Zealand or overseas, with calibration of the model parameters to local conditions.

MEDUSA predicts the contaminant load in untreated runoff as it runs off an individual surface. The contaminant concentrations and metals partitioning will change as the runoff then mixes with runoff from other surfaces, is conveyed through the stormwater network and mixes instream in the receiving waterway. However, predictions of single-rain-event contaminant loads at the point of runoff from individual surfaces allows property owners and policy developers to identify and target individual surfaces for source reduction or surface-specific treatment.

6 CONCLUSIONS

This case study demonstrates the applicability of the event-based contaminant load model, MEDUSA, to produce an understanding of individual surfaces’ contribution of sediment and heavy metals in stormwater runoff. MEDUSA has been successfully calibrated using untreated runoff quality data to a residential/institutional catchment in Christchurch.

Road and carpark runoff were found to be nearly the sole contributors of TSS load in the Okeover catchment (61% and 38%, respectively). While roof surfaces make nearly half of the impermeable surfaces (48%), they contribute little TSS. However, the galvanized roofs in the catchment contribute over 81% of the zinc load (from 30% of the total impermeable area), and the majority of this is in dissolved form. Mapping of individual surface zinc loads show the highest zinc loads are from the large galvanized roofs and large Science carpark within the University. The majority of copper is contributed by road and carpark runoff (45% and 28%), with the majority of the copper in particulate form. However, with only 0.4% of the total impermeable surface area, two copper roofs in the University are contributing 9% of the total copper load, confirming that copper cladding releases very high amounts of copper on a per-area basis.

Management of road runoff prior to mixing with other runoff may be warranted to control the volume of runoff requiring treatment. Additionally, higher treatment efficiencies have been observed for higher concentrated runoff. As the majority of metal loads are associated with sediment (i.e. are in particulate form), sediment settling and filtration treatment for sediment removal will also remove substantial amounts of metals. However multi-functional treatment systems that can also treat dissolved metals would be beneficial for treating mixed runoff as the majority of metals from roof runoff are in dissolved form, and the dissolved component of metal loads from road and carpark runoff still forms a substantial amount.

As more rebuilding continues in Christchurch, particularly at large institutions like the University and in the Central Business District, there is opportunity to use this new knowledge of local untreated runoff quality to guide policy around surface material selection and management of runoff within individual properties. Further runoff sampling data in different areas of the city would help improve our understanding of how geographic and topographic influences (e.g. the Port Hills, the sea) affect the runoff quality through contributions of atmospherically-deposited contaminants or altered weathering rates of surfaces.

The MEDUSA model can also be applied to other urban centres across NZ; however, calibration of wash-off and build-up parameters for local conditions is recommended.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Ignacio Fraga (Universidade de A Coruña, Spain) for his collaborative work in the initial development of the model framework. Funding support has been provided by the Christchurch City Council, the Waterways Centre for Freshwater Management and a University of Canterbury Doctoral Scholarship.

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