Modelling Stormwater Contaminant Loads in Older Urban Catchments: Developing Targeted Management Options to Improve Water Quality

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ABSTRACT
An event-based contaminant load model was developed to identify spatial patterns of stormwater total suspended solids (TSS) and heavy metal loads and assess potential reductions in contaminants loads by implementing various stormwater management options. The GIS-Excel based model estimates contaminant loads from an individual storm event based on different contributing impervious surfaces and key climate characteristics (rainfall intensity, duration, pH and antecedent dry days (ADD)). It then calculates the reduction in contaminant loads that could be achieved through source reduction (e.g. green roofs, repainting) as well as from treatment (e.g. raingardens (bioretention basins), wet ponds) applied to different surfaces within the catchment. The model was run for a case study catchment in Christchurch, New Zealand, to identify where 'hotspots' occurred for each contaminant. Model simulations of targeted management options were run, which predicted effective reduction of both TSS and heavy metals could be achieved with a strategy of combined source reduction and downstream treatment.

KEYWORDS
Urban drainage, stormwater quality modelling, stormwater management, sediment, heavy metals, MEDUSA

INTRODUCTION
The ecotoxic effects of stormwater contaminants such as sediment and heavy metals on local waterways is of concern in older urban catchments, where there is typically little stormwater management or mitigation in existing stormwater infrastructure. Contaminant load models are a key tool to assessing both unmitigated loads and the load reductions that can be achieved with stormwater management. However, well-developed international stormwater software for modelling complex urban waterway systems, such as the United States Environmental Protection Agency's stormwater management model (SWMM), requires multiple data sets for deriving reasonable conclusions, and the monitoring required to build these data sets can be expensive. Smaller-scale catchment models can assist in planning and design of stormwater improvements at a more local scale.

A modelling framework, Modelled Estimates of Discharges for Urban Stormwater Assessments (MEDUSA), was developed to estimate contaminant loads generated from various impervious surface types within a catchment during a single rain event (Fraga *et al.*, submitted). This paper outlines improvements to the model to allow simulation of multiple rain events and the implementation of various stormwater management scenarios to assess the reduction in contaminant loads. This approach differs from other models that typically estimate net annual loads in that it can discern differences as a function of varying climate characteristics. The model also disaggregates each contributing surface (i.e. roofs, roads and carparks), in contrast to the aggregation approach in other models that estimate percentage of each land-use cover in the catchment.

This paper also presents how the model framework can be used to develop a targeted stormwater management plan as it predicts:

1. The magnitude of the contaminant loads at each discharge point into the waterway
2. The primary sources of each contaminant at each discharge point (i.e. whether from roof, road or carpark surfaces)
3. The spatial distribution of hotspots for each contaminant within the catchment
4. The sensitivity of the catchment to variations in rainfall event characteristics

This information can be used by design engineers to estimate the expected influent quality range for the design of stormwater treatment systems. Furthermore, the model allows the user to assess the benefits that could be achieved by implementing targeted management options to reduce the contaminant load from individual surfaces. A case study application of the model is presented for an older established urban catchment in Christchurch, New Zealand, as there is significant opportunity to retrofit improved stormwater management as part of the re-build following the 2010 and 2011 earthquakes which severely damaged the city's infrastructure.

METHODS

Overview of Model Framework

The MEDUSA model comprises a combined GIS and numerical calculation framework to estimate contaminant loads in stormwater runoff for total suspended solids (TSS), total copper, total zinc and total lead (Figure 1). These critical contaminants were prioritized because in-stream water quality monitoring of the local receiving Christchurch waterways highlights that TSS and heavy metals are often elevated (e.g. O'Sullivan and Taffs, 2007). Runoff sampling results from these studies do not show elevation of nutrients, so these parameters have not been included in the model at this stage. Several studies (e.g. He *et al.*, 2001; Liu *et al.*, 2013) have shown that TSS and heavy metals have dynamic relationships with the climate characteristics of rainfall pH, rainfall event duration, ADD and rainfall intensity. Therefore, these key climate characteristics were integrated into the model equations, as discussed later in this paper.

Contaminant loads are calculated for each impervious surface type (roofs, roads and car parks) and then summed for each stormwater discharge point (Figure 1), to give the predicted unmitigated load for each rain event. Load reductions ('management modifiers', Figure 1) are then applied to individual surfaces for user-selected management options to calculate the reduced load. Stormwater management scenarios considered in the model include both reduction at source (e.g. permeable paving, green roofs and repainting) and stormwater treatment infrastructure scenarios such as on-site options (e.g. raingardens and infiltration swales) and offsite options (e.g. wetlands and dry basins). The reduced load can be compared against the unmitigated discharged load to help optimize stormwater management options to meet regulatory criteria or water quality targets.

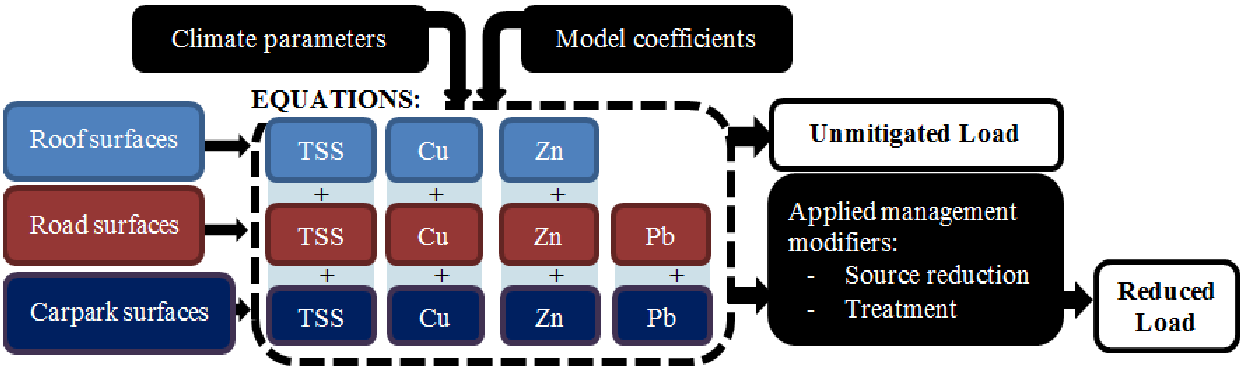

Figure 1. Schematic of MEDUSA model process with an additional component for estimating contaminant load reductions from treatment systems

Representation of Total Suspended Solids Loads in MEDUSA

Contaminant loads in stormwater are typically replicated in stormwater quality models as the outcome of two processes: build-up of the contaminant and then wash-off (e.g. SWMM 5 model by USEPA, Egodawatta *et al.*, 2009). Egodawatta *et al.* (2009) concluded that contaminant wash-off can be represented as an exponential decay function (as identified in Sartor *et al.*, 1974), modified with a wash-off capacity factor. This modification factor was derived from field experiments which demonstrated that only a fraction of the total available contaminants on a surface are mobilised during a rainfall event as a function of rainfall intensity. Equation 1 outlines the resultant function used in MEDUSA to calculate TSS load contributed from a surface during a rain event.

$$w_t = w_0.Area.C_f.(1 - e^{-kIt}) \qquad (1)$$

where w_t is the total load in grams, w_0 is the initial available amount of contaminant (g), C_f is the capacity factor (which varies with rainfall intensity), k is the wash-off coefficient relating the rate of wash-off for a particular surface type (i.e. k is dependent on various factors such as surface roughness and slope), I is rainfall intensity (mm/hr) and t is the event duration (hrs). Field investigations by Egodawatta *et al.* (2009) showed that the initial available amount of contaminant (w_0) can be described as a power relationship to ADD, while the capacity factor, C_f, has a step-wise linear relationship to rainfall intensity.

Representation of Heavy Metals Loads in MEDUSA

For roof surfaces, heavy metal concentrations can be described as a first order decay function, with the highest concentration occurring during first flush conditions before reducing to steady-state conditions (e.g. Wicke *et al.*, 2010), as described in Equation 2.

$$[X]_{Surface} = \begin{matrix} [X]_0.e^{-kIt} & for\ t < t_e \\ [X]_{est} & for\ t \geq t_e \end{matrix} \qquad (2)$$

where $[X]_{Surface}$ is the concentration of metal X from any contributing roof surface in g/m^3, $[X]_0$ is the first flush concentration of metal X (g/m^3), $[X]_{est}$ is the steady state concentration of metal X (g/m^3), k is the wash-off coefficient relating the rate of wash-off to a particular surface type, I is rainfall intensity (mm/hr), t is the event duration (hrs) and t_e is the time to reach steady state conditions (hrs). Equation 2 was therefore incorporated into the MEDUSA model to represent heavy metal behaviour within the catchment.

Experimental studies of roof surfaces (He *et al.*, 2001; Wicke *et al.*, in press) have identified relationships between total copper and total zinc at first flush and steady state conditions with the climate parameters of rain intensity, ADD and rainfall pH. These mathematical relationships are used in the MEDUSA model to define X_0 and X_{est}. For example, steady state zinc concentrations have been found to have a linear relationship to pH, while steady state copper concentrations have a power relationship to rainfall pH. Lead was not included in the model for roof surfaces as the contribution of lead from roofs was found by Wicke *et al.* (in press) to be significantly less than that of copper and zinc, and so it has been assumed to be insignificant. For road and carpark surfaces, copper and lead loads are assumed to be directly proportional to the TSS load generated from that surface, as confirmed by Wicke *et al.* (2010) in a local study of carpark runoff quality.

Case Study

Following the 2010 and 2011 major earthquakes in Canterbury, New Zealand, there is ongoing extensive repair and rebuilding of stormwater infrastructure throughout the city of Christchurch (including residential, industrial and the Central Business District (CBD) areas). This presents significant opportunity for improving stormwater management in the established urban areas, through changes to both stormwater infrastructure and stormwater management policies. However, there is a need to better understand the effectiveness of the different management options, specifically in the Christchurch context, as a tool to assist in selection of retrofit options.

The enhanced MEDUSA model was applied to the Okeover Stream, a 61-ha urban stream catchment within Christchurch city. The Okeover Stream is a first-order tributary of the Avon River, which is one of two major rivers flowing through Christchurch. The land-use of the upper catchment is primarily residential while the lower catchment passes through the University of Canterbury campus. The runoff in the catchment is collected from roofs, roads and carpark surfaces and conveyed to the Okeover Stream, primarily via underground pipes. These pipes then discharge into the Okeover at 48 separate discharge points along the stream. The model was run for the range of rainfall event characteristics that could be expected for the Okeover catchment based on local meteorological and monitoring data (Table 1).

Table 1. Range of values for each rainfall event characteristics used in model simulation

Rainfall Event Characteristic	Minimum Value	Maximum Value	*Baseline Event Value*
Rainfall Intensity (mm/hr)	0.5	10	*5.5*
Rainfall pH	4	8.5	*2.5*
Event Duration (hours)	0.5	20	*4*
ADD (days)	1	14	*6*

RESULTS AND DISCUSSION

Contributing Surfaces for Single Event

Since build-up is modelled for each individual surface, MEDUSA enables the user to assess which discharge points are contaminant 'hotspots' as well as which types of surfaces are contributing the most load at these discharge points. This can be used to target the type of treatment or source reduction technique on an individual surface or subcatchment scale to achieve an optimum combination of management for the overall catchment. Figure 2 shows contaminant loads at each discharge point, for each major surface type, for the baseline event described in Table 1.

Figure 2 shows that the 'hotspots' for TSS are the subcatchments contributing to discharge points 1, 12, 15 and 23. Copper 'hotspots' occur at discharge points 20 and 32 (due to the presence of copper roofs in those subcatchments). Zinc 'hotspots' occur at discharge points 1, 12 and 15. Therefore, the subcatchments that should be prioritized for most effective load reduction within this catchment are 1, 12, 15 for TSS and zinc, 23 for TSS, and 20 and 32 for copper.

Different surface types within the catchment influence the amount of contaminant generated (and conveyed to each discharge point). Figure 2 shows the primary contributor of TSS throughout the catchment is from roof surfaces which is likely a direct reflection of their relative (71%) dominating impervious area compared to roads in this case study. In contrast, the majority of the total zinc and copper loads originate from road and carpark surfaces (Figure 2). The only exception is when copper roofs drain runoff to the discharge point, as copper roofing material has a high propensity to contribute copper to stormwater through dissolution of the roofing material (e.g. Karlen *et al.*, 2002; Wicke *et al.*, in press). This indicates that effective TSS and copper load reductions could be achieved by implementing management options in this catchment that target roof surface runoff; however, this strategy would be expected to achieve little reduction in zinc loads.

Influence of Climate Characteristics on Catchment Contaminant Load

Contaminant load profiles expected in response to varying rainfall characteristics are unique to the catchment being modelled, because each catchment has a unique combination of impervious surface types. Figure 3 presents the changes in contaminant load generated for the range of rainfall characteristics values shown in Table 1. Results show that for the case study catchment (i.e. a residential-institutional catchment), a change in the number of antecedent dry days will substantially influence the TSS and total zinc loads but have less impact on the copper and lead loads. However, a change in rainfall pH will have no impact on TSS load but will impact on copper and zinc loads, which show a power and linear decrease respectively. It would be expected that a catchment with a different dominant land-use would have a different response to the same changes in rainfall event characteristics due to different contributing surfaces (i.e. roof, road and carpark) and the different relationships between contaminant generation and climate conditions (e.g. Wicke *et al.*, 2010; He *et al.*, 2001).

Modelling contaminant loads across the expected range of rainfall characteristic values is also valuable for defining the expected influent contaminant loads, and hence an appropriate design strategy for downstream treatment systems.

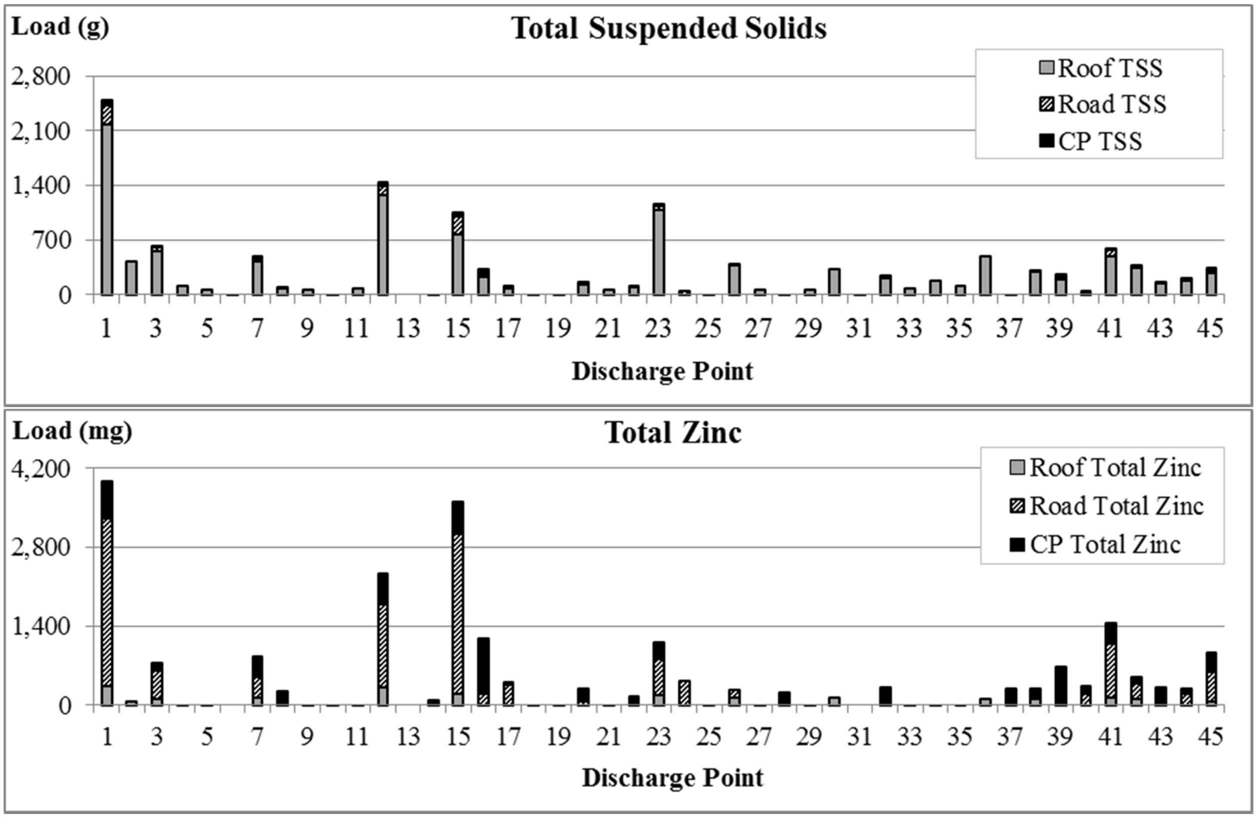

Figure 2. TSS and total zinc load at each discharge point along the Okeover stream for the baseline event (see Table 1) originating from roof, road, and car park (CP) surfaces.

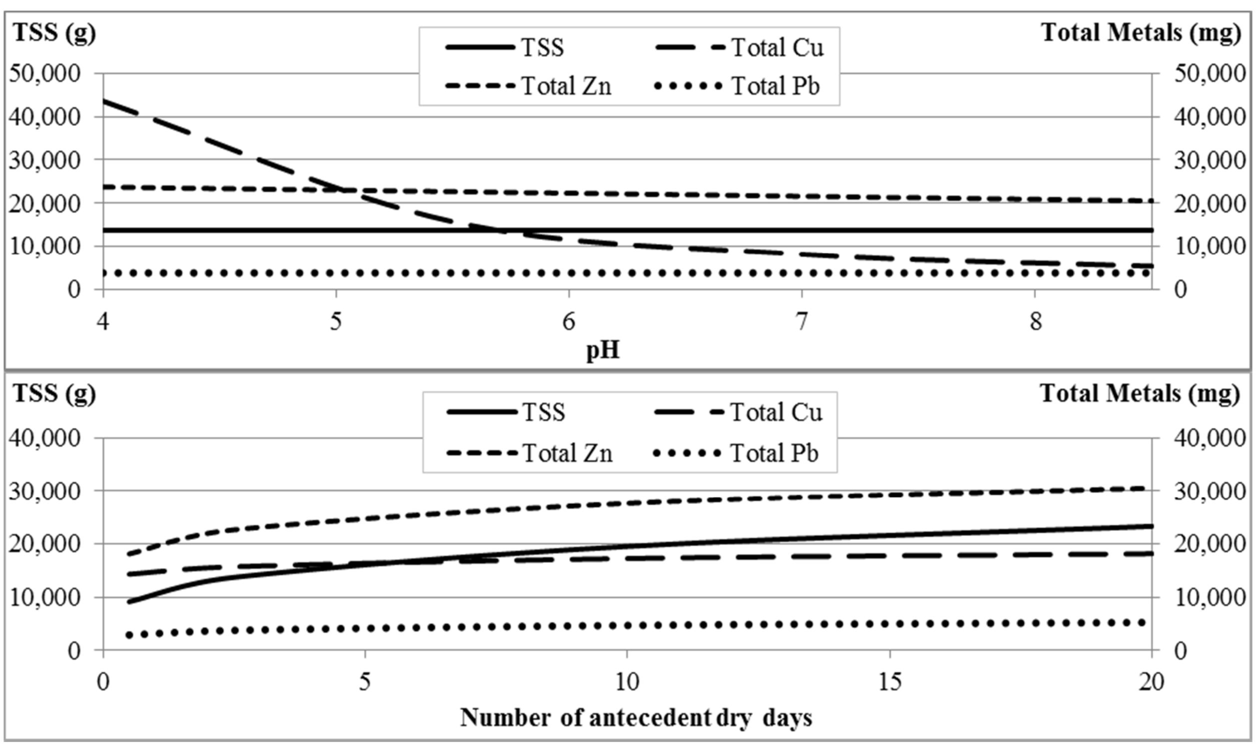

Figure 3. Contaminant load response to changes in selected rainfall characteristics

Implementation of Targeted Management Scenarios

The model simulations presented in this paper highlighted the following key features of the stormwater contaminant loads generated for the case study catchment:

- The primary contributor of TSS is roofs, with the highest TSS load at discharge points 1, 12, 15 and 23 (which cumulatively contribute ~45% of the total TSS load);
- The primary contributor of total copper is from two copper roofs, at discharge points 20 and 32 (up to 95% of the total copper load);
- The primary contributor of total zinc is roads followed by carparks, with the highest loads at discharge points 1, 12, 15, 23 and 26 (~41% of the total zinc load); and
- The primary contributor of total lead is also roads followed by carparks, with the highest loads at discharge points 1, 12 and 15 (~46% of the total lead load).

Therefore, the targeted management scenarios outlined in Table 2 were modelled to quantify the expected load reduction that could be achieved in the catchment.

Table 2. Summary of modelled management scenarios

Scenario	Brief description
0 – Status Quo	No stormwater management is implemented.
1 – Targeted TSS Reduction	Subcatchment 1, 12, 15 and 23 roofs have downpipes disconnected so runoff infiltrates to ground.
2 – Targeted Cu Reduction	Resurfacing of copper roofs (there are only 2) with new galvanised steel material.
3 – Targeted Zn and Pb Reduction	Subcatchments 1, 12, 15, 23 and 26 roads and carparks are resurfaced with permeable paving so rainwater infiltrates to ground.
4 – Mixed Targeted Management	Subcatchments 1, 12, 15, 23 and 26: all roofs have downpipes disconnected, all roads and carparks are resurfaced with permeable paving. Subcatchments 41 – 45 have stormwater treated in a wet pond system. All remaining road runoff is treated via raingardens.

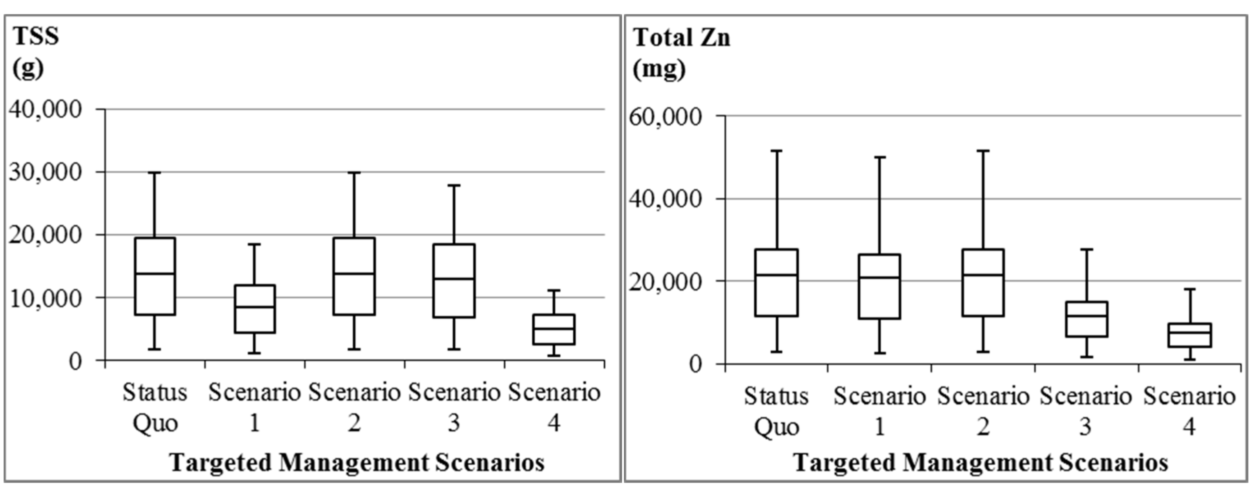

Figure 4. Distribution of TSS and total zinc loads for range of rainfall events (Table 1), with various management scenarios implemented (Table 2)

By targeting the primary contributors of TSS, approximately half the TSS load could be reduced from entering the receiving waterway for Scenario 1 (Figure 4). Likewise, Scenario 3 is predicted to be effective at reducing the total zinc load. However, little TSS reduction is achieved in scenarios that are focussed on reducing contaminants other than TSS (i.e. Scenario 2 for copper and Scenario 3 for zinc). A combined source reduction and treatment scenario (Scenario 4) provides effective reduction of both TSS and total zinc, however the requirements of implementing this option (e.g. policies and treatment infrastructure) must then be assessed against other drivers, such as cost and land availability for treatment infrastructure.

CONCLUSIONS AND RECOMMENDATIONS

MEDUSA provides a flexible framework for determining contaminant discharges that could be applied to other catchments where impervious surface type and rainfall characteristics can be modified. It has the benefit of being less input data intensive compared to more complex software, yet integrates local climatic conditions into the contaminant load calculations. The management option load reductions can be amended to reflect local performance of the different options where such information is available. An event-based model such as MEDUSA enables peak contaminant loadings to be quantified, which informs the loading criteria to be used in the design of stormwater management infrastructure. Future research is focused on calibrating and validating the model with local field data, and defining the relationship between total and dissolved metals to allow modelling of dissolved metal loads.

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