MODELLING STORMWATER MANAGEMENT OPTIONS IN ESTABLISHED URBAN AREAS

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ABSTRACT

The majority of Christchurch's stormwater has historically been discharged untreated directly into urban surface waterways. These receiving waterways have become adversely affected by the contaminants carried in the stormwater, particularly sediment and heavy metals. An event-based contaminant load model was developed to identify the distribution and magnitude of contaminant loads entering the waterway, as well as to assess the reduction in TSS and heavy metal loads that can be achieved by 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 rainfall characteristics (rainfall intensity, duration, pH and antecedent dry days). It then calculates contaminant reduction loads that could be achieved through source reduction (e.g. green roofs, repainting) as well as from treatment (e.g. raingardens, wet ponds) applied to different surfaces within the catchment. This model differs from other annual load models as it is event-based and accounts for storm characteristics in its calculation of contaminant loads. Christchurch is a valuable case setting due the unique opportunity for retrofitting improved stormwater management in the post-earthquake rebuild. It is anticipated that this modelling approach could later be adapted for use in other urban settings outside of Christchurch.

KEYWORDS

Stormwater quality modelling, urban catchments, contaminant loads, MEDUSA

PRESENTER PROFILE

Frances Charters (BE Hons) is a PhD student in the Department of Civil and Natural Resources Engineering at the University of Canterbury. Her thesis is on the development of this stormwater contaminant load model.

1 INTRODUCTION

In Christchurch, there is 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. 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. However, smaller-scale catchment models can assist in planning and design of stormwater improvements at a more local scale. There is a role for these models in identifying the location of key contaminant sources within a catchment, as well as a need to simulate the impact of stormwater improvement options as part of the management planning process.

A modelling framework, Modelled Estimates of Discharges for Urban Stormwater Assessments (MEDUSA), has been developed that estimates contaminant loads generated from various impervious surface types within a catchment during a single rain event (Fraga et al., 2014). Furthermore, the model has since been advanced with the ability to estimate the reduction in contaminant loads that can be achieved with implementation of various stormwater management scenarios. The framework differs from other models that typically estimate net annual loads in that it can discern differences as a function of varying rainfall characteristics. This information can be used to estimate the expected influent quality range for the design of stormwater treatment systems. 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 outlines the framework for the model, including the implementation of management scenarios, and its application to the Okeover Stream catchment, a tributary of the Avon River in Christchurch. A simulation and analysis of applying various management scenarios to the Okeover catchment is also presented.

2 MODELLING METHODS

2.1 OVERVIEW

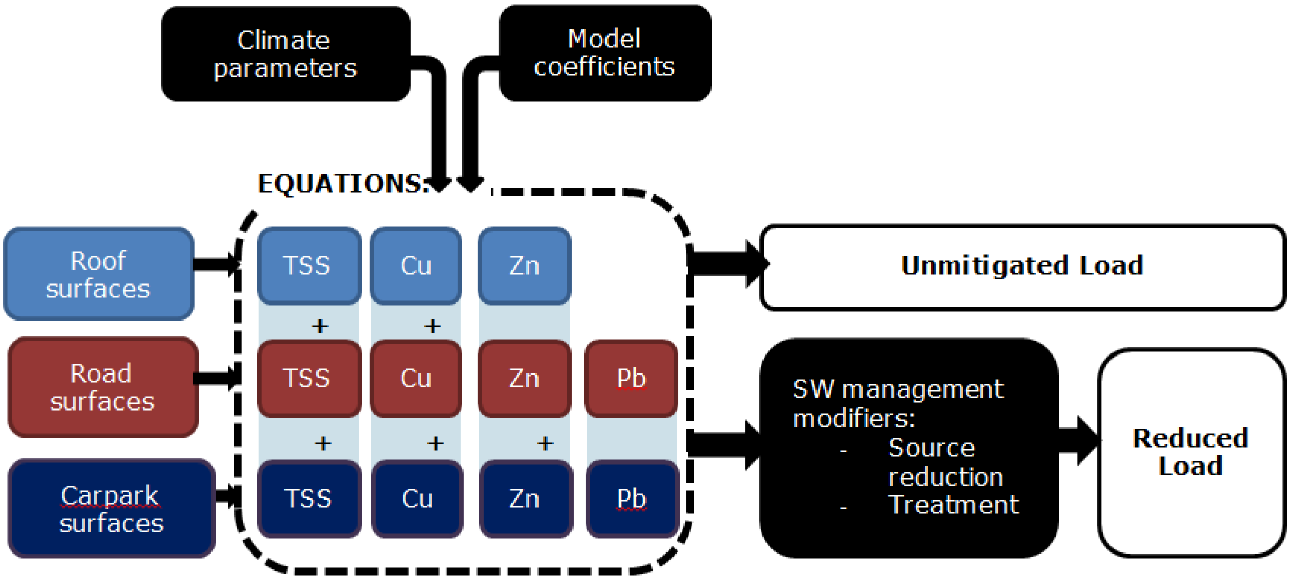
The MEDUSA model uses a combined GIS and numerical calculation platform to estimate contaminant loads in stormwater runoff for total suspended solids (TSS), total copper, total zinc and total lead. These critical contaminants were prioritised because in-stream water quality monitoring of the local receiving Christchurch waterways highlights that TSS and heavy metals are often elevated (e.g. Stevenson (2010), O'Sullivan et al. (2012)), and initial results from runoff sampling as part of this research also confirm this. The initial runoff sampling results do not show elevation of nutrients, so these parameters have not been included in the model at this stage. Several studies (e.g. Wicke et al. (2010), Pennington and Webster-Brown (2008), He et al. (2001)) have shown that TSS and heavy metals have dynamic relationships with the climate characteristics of rainfall pH, rainfall event duration, the number of antecedent dry days and rainfall intensity. Therefore, these key climate characteristics were integrated into the model.

The model has several empirically-derived coefficients to express the relationships between each contaminant and individual climate parameters. It adopts specific build-up and wash-off equations for each contaminant and, coupled with climatic variables, estimates each net contaminant load (Egodawatta et al. (2009), Wicke et al. (2012)) for each runoff event. The model can calculate the resultant contaminant load from multiple rain events, allowing seasonal and annual loads to be assessed.

All modelled contaminant loads originating from each impervious surface type (roofs, roads and car parks) are summed for each stormwater discharge point (Figure 1). In addition to the model's inclusion of climatic variables in its calculation of contaminant load, another feature of the model is to apply load reductions for user-selected management options (i.e. 'SW management modifiers' referred to in Figure 1), where the options may be applied singly or in combination. The reduced load can be compared against the unmitigated discharged load to help optimise stormwater management decisions to meet regulatory criteria or direct future policy for stormwater management.

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 off-site options (e.g. wetlands and dry basins). The model allows the user to select different management options, applied in series, to each individual surface by applying load reduction modifiers to the unmitigated load using the estimated performance range of each management option.

Figure 1: Schematic of MEDUSA model process



For the initial run of the model, the model coefficients have been derived from literature, using data from Christchurch wherever possible to help apply it to the initial study catchment. Field work to collect and analyse stormwater within the Okeover catchment in western Christchurch (see Section 3) is currently underway, which will allow the model to be calibrated and validated for local conditions. Other future work on the model includes incorporation of particle size distribution relationships, flow routing, sediment transport and instream mixing. At this stage, the model acts as an initial screening tool for estimating the benefits of management scenarios, and considers the generation of contaminant loads through to each discharge point entering the waterway.

2.2 TOTAL SUSPENDED SOLIDS

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. USEPA's SWMM, 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 (i.e. the highest concentration occurring during first flush conditions before reducing to steady-state conditions). The wash-off capacity 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. Therefore, the exponential function for contaminant load contributed from a surface during a rain event becomes:

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

where w_t is the total load in g, 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; k differs between roof and road surfaces

(Egodawatta and Goonetilleke (2008), Egodawatta et al. (2009)), I is rainfall intensity (mm/hr) and t is the duration of the rain event (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 the number of antecedent dry days, while the capacity factor, C_f, has a step-wise linear relationship to rainfall intensity.

2.3 HEAVY METALS

For roof surfaces, heavy metals 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), Pennington and Webster-Brown (2008)) as described in Equation (2).

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

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 for a particular surface type, I is rainfall intensity (mm/hr), t is the duration of the rain event (hrs) and t_e is the time to reach steady state conditions (hrs).

Experimental studies of roof surfaces (He et al. (2001), Wicke et al., (2014)) have identified relationships between total copper and total zinc at first flush and steady state conditions with the climate parameters of rain intensity, number of antecedent dry days 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. 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 Christchurch study of carpark runoff quality.

Lead was not included in the model for roof surfaces as the contribution of lead from roofs was found by Wicke et al. (2014) to be significantly less than that of copper and zinc, and so it has been assumed to be insignificant in this version of the model. However, the mobilization of lead from road and carpark surfaces is included in the model, in which it is assumed that the lead load is directly proportional to the TSS load generated from that surface (as it is for copper and zinc).

2.4 LOAD REDUCTIONS FROM MANAGEMENT OPTIONS

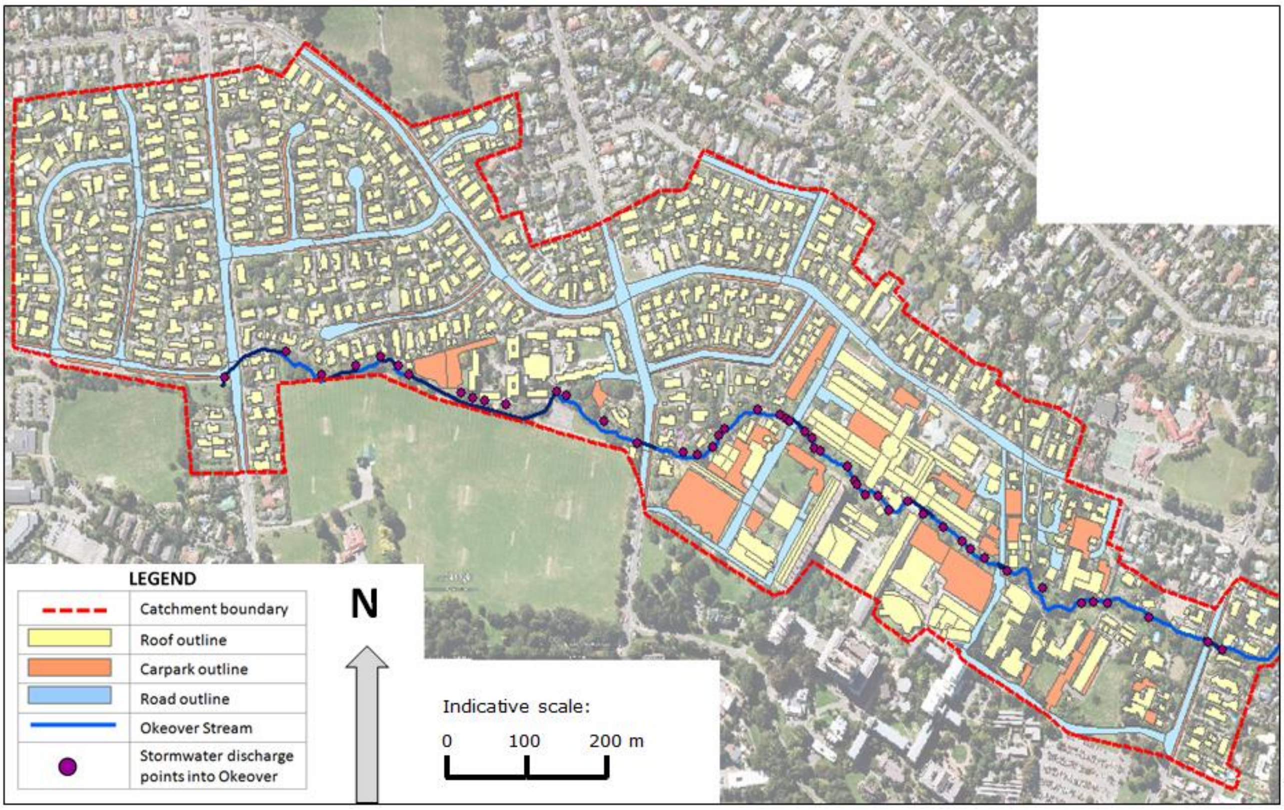
A benefit of the model is that it allows for stormwater management options to be applied to each individual surface. This enables the user to target ‘hotspots’ within a catchment (e.g. copper roof) and also to assess the net reduction in contaminant load across the whole catchment from different management options implemented in subcatchments (e.g. one cluster of roofs conveying stormwater to an infiltration basin, another section of road conveying runoff to rain gardens and another cluster of roofs undergoing maintenance such as painting). The management options can be applied singly, or in a treatment train, presently of up to three options, with a percentage removal applied for each management option derived from performance data in the relevant literature. The model assumes that there is no bypassing of flows.

3 CASE STUDY CATCHMENT: OKEOVER STREAM, CHRISTCHURCH

Following the 2010 and 2011 earthquakes in Canterbury, 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). Historically, the stormwater system developed in established (older) urban areas of Christchurch collects and conveys untreated stormwater via underground pipes directly to the nearest waterway. The need to repair and redevelop urban infrastructure in Christchurch 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 both the contaminant loads contributed from different surface types and the effectiveness of the different management options, specifically in the Christchurch context, as a tool to assist in selection of retrofit options.

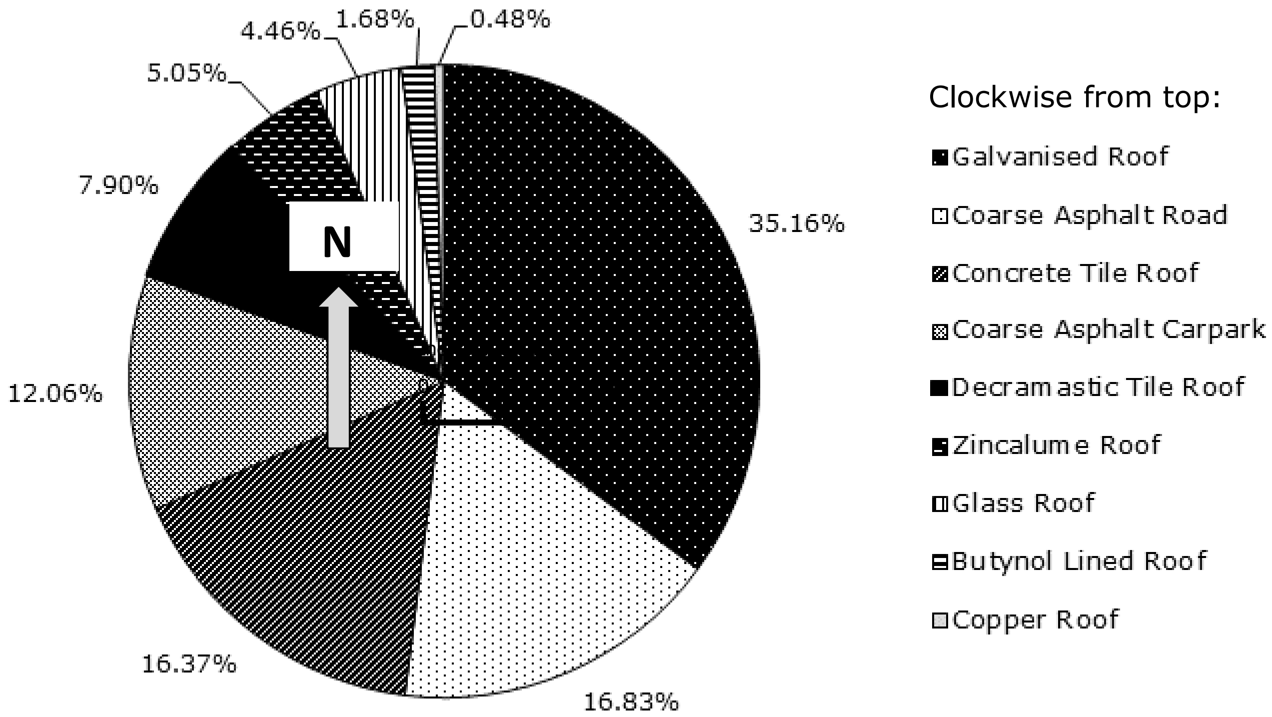
The Okeover Stream catchment, a 61-ha catchment within an established urban area of Christchurch city, was selected as the first model case study. The Okeover Stream is a first-order tributary of the Avon River. The upper (ephemeral) catchment receives stormwater from an established residential area, while the lower (perennial) part of the catchment flows through the University of Canterbury grounds (Figure 2). The model delineates contributing surfaces to stormwater, including roofs, roads (with a range of traffic intensities), and carparks (with some on-street parking and some large university campus carparks), as summarised in Figure 3. This accounts for approximately 25 ha of the catchment area. Overland flow and smaller hardstand areas on private property are not included at this stage. Stormwater is conveyed by underground pipes to discharge at 48 points along the Okeover Stream.

Figure 2: Map of Okeover Stream Catchment, western Christchurch, showing impervious surfaces that contribute stormwater to the Okeover Stream



Research at the University of Canterbury has built a database of water quality information about the Okeover since 2006, and therefore it is also a particularly useful catchment as a case study for model implementation of an established urban catchment. The key sources of annual contaminant loads to the Okeover Stream have been identified as copper from air-conditioning discharges (O'Sullivan et al., 2012), zinc and copper from roads and roof runoff, lead from roads and atmospheric deposition (O'Sullivan et al. (2012), O'Sullivan and Taffs (2007)).

Figure 3: Summary of Okeover Catchment Modelled Contributing Surface Areas by Surface Material Type



4 MODEL RESULTS

The model was run for the Okeover catchment for five different rain events that occurred during a monthly period from 2 January to 4 February 2013, as an initial assessment of multiple events. Climate parameter values for each event are outlined in Table 2.

The rainfall pH for these events are within the range for "normal" rain, as rainwater is slightly acidic due to the presence of carbonic acids. The rainfall intensities are all low, which is typical for Christchurch rain events. Of particular note, the 10 January event had a very low intensity for a short duration. In contrast, the 4 February event had the longest duration, longest antecedent dry period and highest pH of the five events. The 2 January and 17 January events have comparable intensity and duration, but differ in rainfall pH.

Table 2: Summary of Rainfall Event Characteristics used in the Initial Model Simulation

	Date of Event				
Parameter	**2-Jan-13 (Event 1)**	**10-Jan-13 (Event 2)**	**15-Jan-13 (Event 3)**	**17-Jan-13 (Event 4)**	**4-Feb-13 (Event 5)**
Rainfall pH [1]	5.29	5.50	5.50	4.74	6.13
No. of antecedent dry days (days) [2]	2	7	5	2	17
Average rainfall intensity (mm/hr) [2]	0.87	0.55	1.24	0.91	0.98
Duration (hrs) [2]	10	2	12	10	20

[1] Rainfall pH measured for each rainfall event
[2] Rainfall characteristics derived from NIWA Climate Station data for the Kyle St Weather Station, approximately 2.5 km SE of the case study catchment

Figure 4 provides an example of the modelled results for the 4 February 2013 rain event for TSS and Total Copper. Clearly, different surface types within the catchment influenced the amount of contaminant generated (and conveyed to each discharge point). Roof surfaces (Roof) are consistently the highest contributor of TSS throughout the catchment (Figure 4), which is likely a direct reflection of their relative contributing area of 71% compared to roads (Road) of 4.5 % (Figure 3).

However, roads and carparks (CP) are the most *frequent* sources of total zinc and total copper entering the waterway within the drainage network (Figure 4). Nonetheless, the *magnitude* of total copper load is significantly higher from roofs at three discharge points within this catchment (Figure 4), which corresponded to areas with copper roofs. This highlights the practical opportunity to reduce copper loads received by urban waterways through selection and maintenance of roof surfaces. These model results can therefore assist in identifying subcatchments of most concern for stormwater management improvements.

Figure 5 shows the estimated total contaminant load generated in each of the five rain events. It shows how the contaminant loads vary as a function of the different rainfall event characteristics. For example, the 10 January event (Event 2) was light intensity for a short duration only and therefore all contaminant loads were minimal. The 2 January and 17 January events (Events 1 and 4, respectively) are of similar intensity and duration but Event 4 has a lower rainfall pH. Correspondingly, we see an increase in copper load for that event compared to the Event 1 results, which reflects the effect of the power relationship of metals such as copper to pH (see Section 2.3) that has been incorporated into the model. The results allow the user to assess the range and distribution of total contaminant loads across several events, as part of defining the expected influent quality range for stormwater treatment systems. Calibration and validation of the model, which is currently underway, will be used to compare the predicted loads from the model against actual values to confirm the appropriateness of the modelled relationships.

Figure 4: Estimated TSS, total zinc and total copper loads for the 4 February 2013 event, showing relative contributions from each surface type at each of the Okeover's 48 discharge points

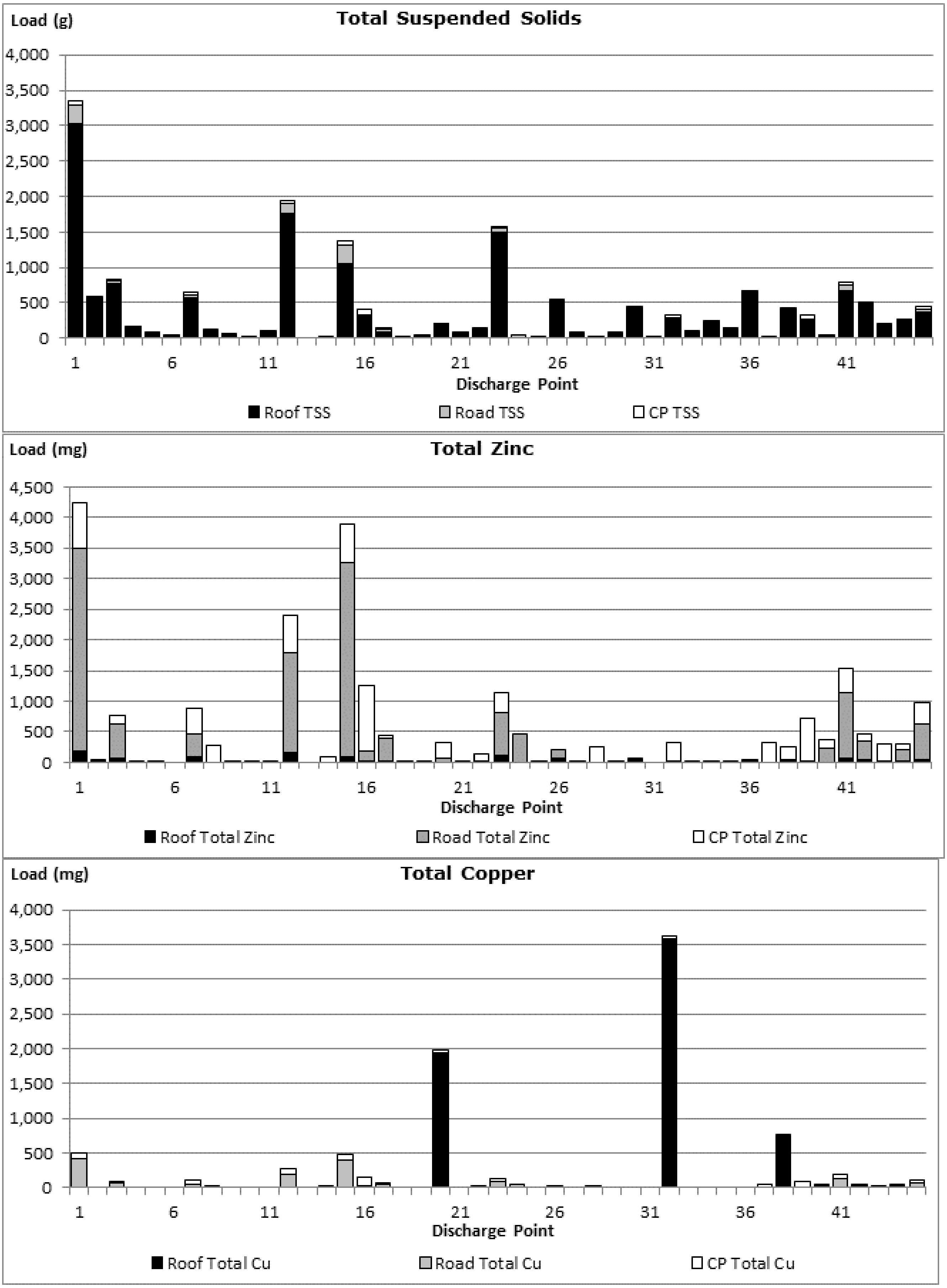
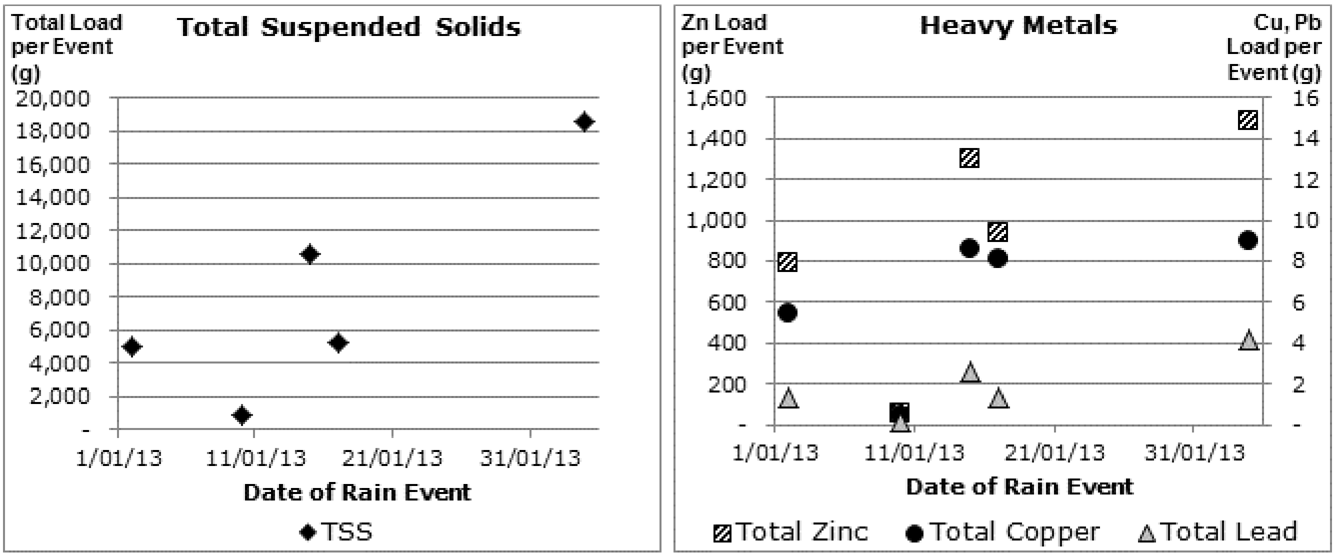


Figure 5: Estimated contaminant load generated per event over period from 2 January to 4 February 2013



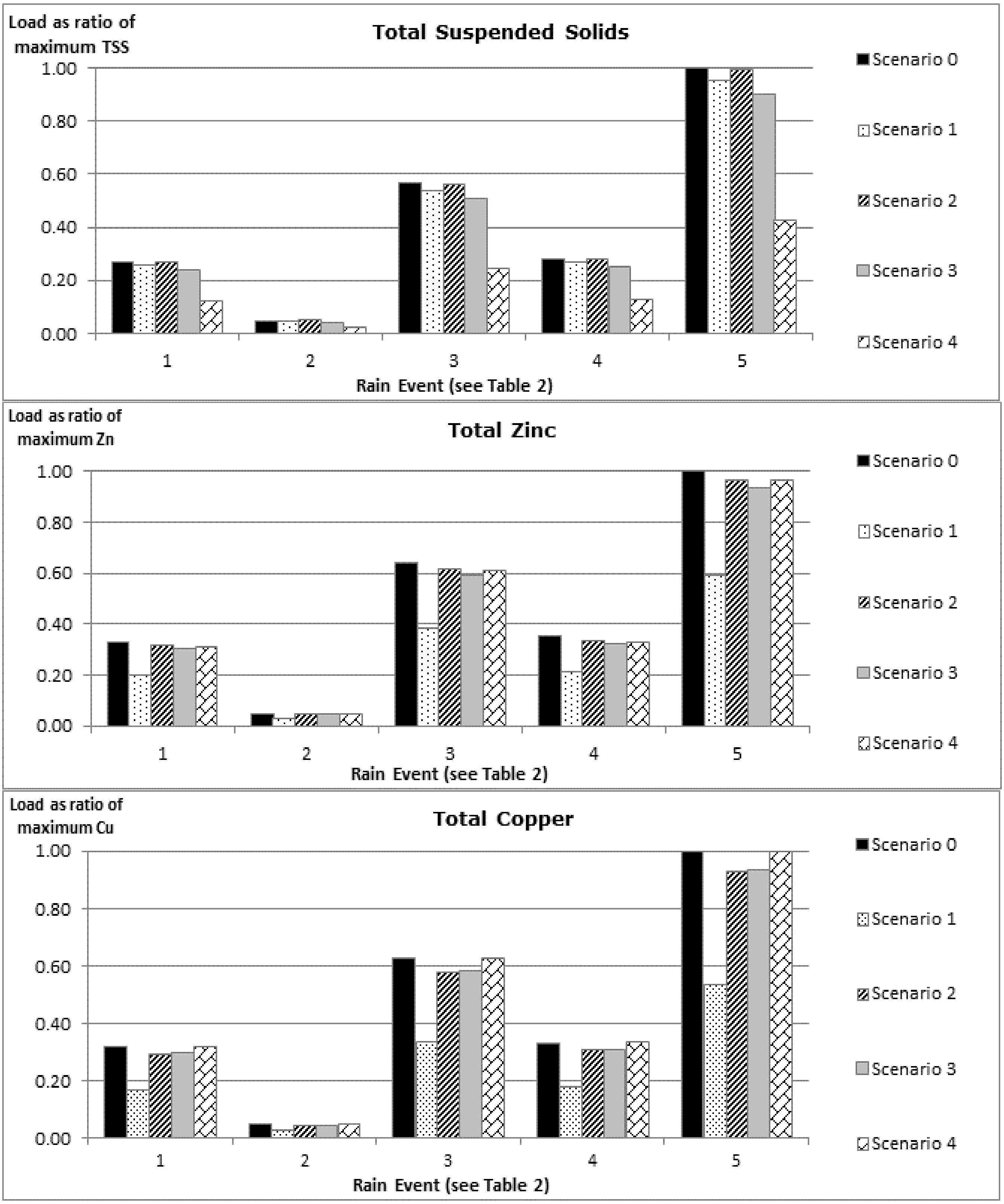
Various management scenarios (Table 3) were applied to the model after contaminant loads were estimated. This allows the user to compare the reduction in contaminant load that could be achieved by each management scenario in comparison to the current unmitigated load. The selected scenarios aim to demonstrate the effects of a wide range of source reduction and treatment options, however, the specific constraints of each catchment need to be taken into account when selecting appropriate management options. For the purposes of this example, such constraints (e.g. the suitability of the ground to infiltrate runoff) have not been considered within the model at this time. Likewise, the common configuration of having roof runoff piped to the road kerb means there is opportunity for both roof and road runoff to be treated in Scenario 1, however, only road runoff is considered in this model simulation.

Table 3: Summary of example management scenarios used in model simulation

No.	Management Scenario	Brief Description
0	Current situation (status quo)	Estimate of the current, unmitigated load generated within the catchment. It forms the baseline for comparing the relative mitigation that can be achieved by the other management scenarios.
1	Rain gardens for road runoff	All road runoff in the (sub)catchment is treated via rain gardens
2	Porous paving for carparks	All carparks in (sub)catchment are resurfaced with porous pavement so runoff infiltrates directly to ground.
3	Combined roof maintenance and wet pond for neighbourhood	97 residential roofs in a neighbourhood at the western end of the catchment, plus their associated road network and carpark surfaces, (i.e. all surfaces contributing to Discharge Point 1) have the stormwater runoff treated via a wet pond. Additionally, all old roofs in the neighbourhood are repainted.
4	Roof runoff onsite disposal to ground	All residential roof surfaces in the (sub)catchment have their runoff disposed to ground onsite via soakage.

An example model result is shown in Figure 6 illustrating the comparative reductions in TSS and total zinc loads from management scenarios described in Table 3. Note that all loads are shown as a ratio of the maximum load calculated across all the scenarios.

Figure 6: Comparative TSS, total zinc and total copper loads per rain event over the period from 2 January to 4 February 2013 (example stormwater management scenarios; Table 3)



The examples shown in Figure 6 demonstrate how the management scenarios differ in their ability to reduce TSS, total zinc or total copper loads; for example, the implementation of rain gardens to treat road runoff (i.e. Scenario 1) across all events is expected to achieve a significant reduction in total zinc and total copper but only produce a minimal reduction in TSS. This is a reflection of the particular characteristics of the case study catchment, where roofs provide approximately 71% (Figure 3) of the contributing impervious surface area and therefore, the overall majority of TSS (so any TSS reduction reflects little contributing road area). However, the large total zinc and copper load reductions with Scenario 1 are attributed to the road surfaces that contribute a higher proportion of these metals to the overall total zinc and total copper loads within the study case catchment (see Figure 4). As discussed previously, there is opportunity to use raingardens to treat both road and roof runoff which would provide greater reduction in overall TSS load.

Scenarios 2 and 3 provide little reduction in load, demonstrating how the model can be used to identify poorly targeted options or ones that address too small an area to provide significant benefits. Scenario 2 focusses solely on reducing runoff from carparks, which form 12% of the total contributing surface area. However, as can be seen in Figure 4, the majority of the contaminant load can be attributed to non-carpark surfaces and Scenario 2 results confirm there is little benefit from this poorly targeted management option. Scenario 3 targets all surfaces within the subcatchment contributing stormwater to Discharge Point 1, which has one of the higher contaminant loads of all the discharge points. While the subcatchment itself receives the benefit of both reduction of contaminant generation (through improved roof condition) and downstream treatment of runoff, overall the benefits are not very significant on a catchment scale. Multiple other subcatchments would need to be included in the stormwater improvements for an appreciable reduction to be seen in the contaminant load entering the Okeover Stream.

In comparison, disposal of residential roof runoff to ground (via soakage) (Scenario 4) shows that this option is effective at reducing TSS (to less than half the unmitigated load). However, it has less impact on reducing total zinc or total copper, again because the majority of these metal loads originate from roads, carparks and non-residential roof surfaces.

5 CONCLUSIONS

The MEDUSA model allows contaminant loads to be estimated from individual impervious surfaces within a catchment for each rainfall event. It couples the generation of each key contaminant to the important climate characteristics of rainfall pH, intensity, number of antecedent dry days and duration, which are known to influence the build-up and wash-off of contaminants from impervious surfaces. The model also enables multiple rain events to be modelled together, to assess seasonal and annual loads. This flexibility allows the model to be readily adapted to the user’s needs in terms of time scale, local climate characteristics and catchment features. Stormwater monitoring and subsequent water quality analyses is underway and will be used to help calibrate and validate the MEDUSA model for Christchurch conditions.

Stormwater management options (including source reduction and treatment options) can be applied within the model for individual impervious surface types to estimate the reduction in contaminant runoff load. This model should help provide a guide for practitioners in conceptual planning of stormwater management retrofits for any catchment. (Wicke et al., 2010)

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