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Research article

# A novel modelling framework to prioritize estimation of non-point source pollution parameters for quantifying pollutant origin and discharge in urban catchments

I. Fraga [a], F.J. Charters [b], A.D. O'Sullivan [b], T.A. Cochrane [b, *]

[a] GEAMA (Environmental and Water Engineering Group), E.T.S Caminos, Universidade de A Coruña, Campus Elviña s/n, 15071 A Coruña, Spain
[b] Department of Civil and Natural Resources Engineering, University of Canterbury, Private Bag, 4800, Christchurch, New Zealand

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ABSTRACT

Stormwater runoff in urban catchments contains heavy metals (zinc, copper, lead) and suspended solids (TSS) which can substantially degrade urban waterways. To identify these pollutant sources and quantify their loads the MEDUSA (Modelled Estimates of Discharges for Urban Stormwater Assessments) modelling framework was developed. The model quantifies pollutant build-up and wash-off from individual impervious roof, road and car park surfaces for individual rain events, incorporating differences in pollutant dynamics between surface types and rainfall characteristics. This requires delineating all impervious surfaces and their material types, the drainage network, rainfall characteristics and coefficients for the pollutant dynamics equations. An example application of the model to a small urban catchment demonstrates how the model can be used to identify the magnitude of pollutant loads, their spatial origin and the response of the catchment to changes in specific rainfall characteristics. A sensitivity analysis then identifies the key parameters influencing each pollutant load within the stormwater given the catchment characteristics, which allows development of a targeted calibration process that will enhance the certainty of the model outputs, while minimizing the data collection required for effective calibration. A detailed explanation of the modelling framework and pre-calibration sensitivity analysis is presented.



## 1. Introduction

In New Zealand (and elsewhere), heavy metal contaminants in urban environments are a major ecotoxicity concern (e.g. Zanders, 2005; Pennington and Webster-Brown, 2008). They originate from weathering of roofs (Pennington and Webster-Brown, 2008; Egodawatta et al., 2009), vehicle components such as brake linings (e.g. copper) and tyre fillers (e.g. zinc), as well as oil and petrol additives (Davis et al., 2001). These contaminants accumulate on impermeable surfaces (Egodawatta et al., 2009; Wicke et al., 2012) and are washed off under rainfall-runoff processes as non-point source (NPS) pollution, with the potential to impact downstream aquatic ecosystems (Davis et al., 2001) or overload combined sewer systems. NPS pollution is recognized globally as a key factor responsible for waterways degradation (USEPA, 1984; Shaw, 1994; Gnecco et al., 2005; Ahlman, 2006).

Land-use and impervious surface material type strongly influence the pollutant signatures in urban runoff (Gupta and Saul, 1996; Deletic, 1998; Gnecco et al., 2005), with the first flush wash-off typically containing the greatest pollutant loads (e.g. Novotny and Chesters, 1981; Artina et al., 1999). Therefore, understanding land use characteristics, pollutant sources and hydrological regimes within urban catchments is imperative for efficiently mitigating water quality degradation.

The most commonly employed models for urban systems are deterministic event-based models, developed for catchment-scale studies, such as the USEPA StormWater Management Model (SWMM) (USEPA, 2010), Hydroworks QM Hydrology Model (Wallingford, 2002) and MOUSE/MIKE URBAN (DHI, 2014). An extended overview of stormwater models is reported elsewhere (Zoppou, 2001; Obropta and Kardos, 2007). Although these models perform well in predicting runoff and in routing of stormwater, predictions of surface water quality pollutants are non-specific and

* Corresponding author.
*E-mail addresses:* ignacio.fraga@udc.es (I. Fraga), tom.cochrane@canterbury.ac.nz (T.A. Cochrane).

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therefore limited. The SWMM model, for example, offers the ability to select from a limited number of generic build-up and wash-off equations, but the model does not have inbuilt functionality to program specific heavy metal contaminant equations related to individual impermeable surfaces.

Furthermore, a key feature in most other urban stormwater models is the grouping of areas into different land use categories (residential, industrial etc.). This aggregates variable catchment characteristics in order to simplify the modelling. However, to more accurately quantify pollutant contributions from individual impermeable surfaces, it is necessary to disaggregate impervious surfaces as each surface type has different physical and chemical dynamics. Several studies (e.g. He et al., 2001; Pennington and Webster-Brown, 2008; Wicke et al., 2010) 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 parameters should also be considered in modelling pollutant dynamics from different impervious surface types.

However, as more pollutant variables are considered within a model and the model becomes more site-specific, the number of parameters involved and the degree of freedom of the model increases (Kirchner, 2006). To overcome this problem of over-parameterisation while enhancing model accuracy, a tool such as sensitivity analysis that can selectively identify and rank key influencing variables can be employed. Sensitivity analyses identify the key influences on model outputs and can therefore help prioritize where the model should be most calibrated. A detailed review of sensitivity analysis techniques used in investigating model performance is reported elsewhere (Saltelli et al., 2000a,b; Frey and Patil, 2002; Christiaens and Feyen, 2001; Saltelli et al., 2004).

This study presents a novel framework for modelling pollutant origin and discharge in an urban catchment. It comprises a GIS-based pollutant source and discharge model (MEDUSA – Modelled Estimates of Discharges for Urban Stormwater Assessments) coupled with a two-step sensitivity analysis process that prioritises the parameters for any future model calibration. The focus of the paper is not on model calibration (which can be conducted in many subsequent studies), but rather on the unique framework within which MEDUSA operates to enable other model users to adopt in their studies. A test application to the Okeover stream catchment in Christchurch, New Zealand is used as an example to demonstrate capabilities and limitations of the modelling framework. This catchment was chosen as the researchers have an extensive dataset of water quality data from which the modelling framework could be tested.

## 2. Framework description

The MEDUSA modelling framework consists of three integrated processes as shown in Fig. 1. Firstly, a GIS-based pollutant model computes TSS, copper, zinc and lead build-up and wash-off for all individual impervious surfaces in the defined catchment based on meteorological data, geometrical data, and pollutant equations. The calculation of computed loads per rain event from individual impervious surfaces depends on the accurate estimation of pollutant parameters, defined through empirical coefficients of the contaminant equations used in the model. The second process consists of a sensitivity analysis to identify the key equation coefficients influencing pollutant loads for the defined catchment. Sensitivity ranges for the different contaminant equation coefficients are derived by running the model repeatedly for different input parameters. The third process consists of calibrating the model for the most sensitive coefficients, allowing prioritisation of data collection to calibrate the model.

### 2.1. Pollutant source model

The pollutant model calculates the amount of TSS, copper, zinc and lead discharging (untreated) to the receiving waterway. Each impervious surface is initially delineated in GIS and assigned its surface material type. Typical impervious materials within urban catchments and their associated pollutants are detailed in Table 1, but these can be expanded to include other materials and pollutants to suit any catchment under investigation. Every surface is linked to a corresponding discharge point through drainage network data. The model currently assumes that there is no interaction of flows between individual source areas. Rainfall characteristics, which include rainfall intensity, duration, pH and antecedent dry days, are assigned to each impervious surface. Both uniform and spatially variable rainfall patterns can be defined for the catchment. Multiple rain events can also be simulated consecutively to obtain the amount of pollutant mobilized through a specified period such as providing a seasonal or annual load. For each impervious surface type and rainfall inputs, pollutant loads washed-off are derived using user-defined equations. For the test application to the Okeover stream catchment, empirical coefficient values were adopted from Wicke et al. (2011) for road and car park surfaces and from He et al. (2001) and Pennington and Webster-Brown (2008) for roof surfaces.

#### 2.1.1. Roof pollutants equations

Roofs are sources of solids (TSS) and can also be sources of copper and zinc depending on the roofing material (Table 1). The total TSS washed-off by a single rain event was computed in the model for each roof surface using the equation defined in Egodawatta et al. (2009):

$$w_{TSS,Roof} = w_o \cdot A \cdot C_{i,F} \cdot \left(1 - e^{-Riwo \cdot I \cdot t}\right) \tag{1}$$

where $w_{TSS,\ Roof}$ is total solids mass mobilized in a rain event (g), $w_o$ is available mass of solids on the roof at the beginning of the rain event (g m$^{-2}$), $A$ is roof area (m$^2$), $c_{i,F}$ is a dimensionless capacity factor and $R_iwo$ is a wash-off coefficient (mm$^{-1}$) for roof type $i$ (detailed in Table 1), $I$ is the rainfall intensity (mm h$^{-1}$) and $t$ is the rainfall duration (h).

The initial amount of available pollutant on a roof, $w_o$, primarily depends on antecedent dry days. The following power law equation relating antecedent dry days to TSS build-up was used (Egodawatta et al., 2009):

$$w_o = RiBa \cdot t_D^{RiBb} \tag{2}$$

where $RiBa$ and $RiBb$ are empirical coefficients for the roof type $i$ defined in Table 1, and $t_D$ is the number of antecedent dry days.

The metal loads yielded from roofs are assumed to be generated from corrosion processes only and therefore only metallic roofs are considered in the model to generate metallic pollutant wash-off loads. Copper roofs are the only sources of copper, while Zincalume™ and galvanized roofs are sources of zinc. To compute the amount of metal yielded during a rain event, it is assumed that the metal concentration in the runoff diminishes during the first flush until a steady state is reached. Thereafter the concentration remains constant during the rest of the event. He et al. (2001), Pennington and Webster-Brown (2008) and Wicke et al. (2010) all found from experiments that the concentrations of copper and zinc varied according to the following first order exponential decay equation, which is used in MEDUSA: