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Particle size distribution variance in untreated urban runoff and its implication on treatment selection

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ABSTRACT

Understanding the particle size distribution (PSD) of sediment in urban runoff assists in the selection of appropriate treatment systems for sediment removal as systems vary in their ability to remove sediment across different particle size fractions. Variation in PSD in runoff from individual urban surfaces both during and across multiple rain events is not well understood and it may lead to performance uncertainty in treatment systems. Runoff PSDs in international literature were compiled to provide a comparative summary of PSDs from different urban surfaces. To further assess both intra-event and inter-event PSD variation, untreated runoff was collected from road, concrete roof, copper roof, and galvanized roof surfaces within an urban catchment exposed to the same rainfall conditions and analysed for PSD and total suspended solids (TSS). Road runoff had the highest TSS concentrations, while copper roofs had high initial TSS that reduced to very low levels under steady state conditions. Despite variation in TSS concentrations, the median particle diameter of the TSS was comparable across the surfaces. Intra-event variation was generally not significant, but substantial inter-event variation was observed, particularly for coarser road and concrete roof surfaces. PSD variation for each surface contributed to a wide range in predicted treatment performance and suggests that short-retention treatment devices carry a high performance risk of not being able to achieve adequate TSS removal across all rain events.

1. Introduction

Sediment in untreated runoff from direct discharge stormwater systems is a key contributor to urban waterway pollution, as sediment is considered to be a dominant stressor in urban aquatic ecosystems (Marshall et al., 2010). Excess suspended sediment in waterways can affect aquatic ecosystem health through depositional effects such as clogging of the waterway bed (leading to refugia loss and reduction in the exchange capacity between benthic and water column zones), reduced food quality and smothering of biota, as well as through suspended effects such as respiratory damage, light attenuation and transport of other pollutants such as heavy metals (Clapcott et al., 2011; Ryan, 1991). Along with individual particle shape, size and composition (i.e. organic or mineral), the overall particle size distribution (PSD) dictates many of the sediment properties and efficiency of treatment processes.

Urban runoff sediment is heterogeneous in composition as it is derived from several sources. These include direct (local) sources such as vehicle tyre and brake wear, surface material degradation and soil erosion (Egodawatta et al., 2009; Wicke et al., 2012; Zanders, 2005), and indirect (global) sources such as atmospheric deposition (Murphy et al., 2014). However, studies of the diversity in particle size composition for untreated runoff are limited and the majority of PSD profiling of runoff to date has focused on road runoff (both highway and urban streets) (Kim and Sansalone, 2008; Sansalone et al., 1998; Sartor and Boyd, 1972; Shaheen, 1975), with less information on other types of urban runoff. A study by Selbig et al. (2013) shows large differences in PSDs amongst and between various land uses and urban source areas, and confirms that assuming a single PSD profile for a land-use type or whole catchment is not likely to be very representative of runoff at any particular location within the catchment.

A limited number of studies examined variations in PSDs from a single site during individual rain events (intra-event variation) or

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across multiple rain events (inter-event variation). A study by Furumai et al. (2002) of the wash-off behaviour of different particle size fractions in highway runoff observed a stepwise relationship in TSS wash-off under varying natural runoff conditions attributed to different wash-off behaviour of finer versus coarser particles. Muthukaruppan et al. (2003) analysed particle size composition of road surface runoff and concluded that underlying catchment geology impacted the PSD, while minimal inter-event variation was observed in each catchment. Further studies by Brodie and Dunn (2009), Selbig and Bannerman (2012) and Selbig (2013) compared PSDs from various urban surfaces across multiple events using flow-weighted composite samples (i.e. inter-event variation analysis only).

Sediment treatment processes include physical filtration, sedimentation (settling) and enhanced sedimentation via chemical coagulation/flocculation (Clark and Pitt, 2012). However, the design and performance of these treatment systems are sensitive to many factors, particularly the concentration and particle size composition of the sediment in the untreated runoff, as the capability of the treatment unit varies across particle size fractions. For example, PSD characterization is considered an important aspect of wet pond design, as particle settling velocity influences the pond size (Greb and Bannerman, 1997). A review of published literature and technical manuals showed that while many documented overall TSS removal efficiencies, treatment performance was not typically quantified in terms of percent removal for individual particle size fractions. Ferreira and Stenstrom (2013) reported on the theoretical and experimentally-measured TSS removal by a hydrodynamic separator and a dry detention basin, and the Toronto Region and Conservation Authority (2002) reported on experimentally-measured TSS removal achieved in a 151,000 m^3 pond and wetland system treating runoff from a 600 ha residential catchment.

Variations in the influent PSDs both during and over multiple rain events present an additional uncertainty that can influence the overall performance of the treatment system. Studies to date on PSD intra-event variability consider only single site road runoff, and inter-event variability studies considered only event mean PSDs. Particle size composition and its variability across multiple surface types for the same rainfall conditions need to be examined to enable robust runoff quality modelling and targeted treatment system selection.

This paper reviews multiple studies of urban runoff PSDs to provide a comparative context for future studies. It then reports on the findings of a field study that aims to identify variations and their causes in untreated runoff PSDs for different urban surface types within close geographical proximity. First flush PSD was compared to steady state flow PSD during individual rain events (intra-event variation) and across multiple rain events (inter-event variation). The paper also discusses implications of the results for expected treatment performance of different systems.

2. Methodology

2.1. Review and compilation of published PSD data

PSD data from studies of untreated urban runoff was compiled for all available urban surface types reported in literature. PSDs derived from street sediment (i.e. vacuum samples direct from a dry street surface) were included for general comparison, although it is recognized that particle aggregation may occur in such sediments and therefore not provide a necessarily representative PSD for sediment entrained in runoff (Slattery and Burt, 1997).

2.2. Sample collection and analysis

Runoff samples were collected from 15 rainfall events from four impermeable surfaces within a mixed residential/institutional catchment (the Okeover Stream catchment) in western Christchurch, New Zealand (Fig. 1). The surfaces included a concrete tile roof (a common residential roofing material), a copper roof (used as an architectural material), a galvanized roof (a common industrial, commercial and residential roofing material) and a coarse asphalt road (most common road surface in the city; with an annual average daily traffic count of 11,000 (Christchurch City Council, 2012)) (Table 1). The four sites were in close proximity of each other (within 320 m) such that they were considered to have been exposed to the same climate characteristics, including antecedent dry period and rainfall conditions for each sampled event.

A combination of grab sampling and automatic sampling (ISCO 6712C Compact Portable Automatic Sampler) was used to capture untreated runoff during first flush (FF; defined as the first 2 L of runoff), transitional and steady state (SS) conditions. Samples were taken back to the lab and stored in a refrigerator (at 4 °C) prior to analysis.

PSD analysis was completed within 6 h of collection (following Li et al. (2005)). A Horiba LA-950 Laser Particle Size Analyzer was used to analyse the PSD for each sample (volume basis, range of 0.01–3000 μm). A refraction index value of 1.56 (i.e. $1.17 \times RI_{water}) + 0.0001i$ was selected for all PSD analysis in this study, following a recommendation in Andrews et al. (2010) for mixed composition environmental samples. The samples were analysed as non-dispersed samples as this is considered to represent how sediment would aggregate and be transported under natural runoff conditions (Slattery and Burt, 1997). Christchurch has a nearby source of wind-blown dispersive soils (loess) which may contribute to atmospherically-deposited TSS in Christchurch's airshed. To enable comparison of this source material to mixed composition runoff, a sample of loess material taken from a hill site facing the city (8.1 km SE of the study area) was also analysed for PSD using the same analyser settings.

For each sample, the total suspended solids (TSS) concentration was also measured within 24 h of collection. TSS analysis was conducted via vacuum filtration with 1.2 μm filter paper, then oven-dried at 105 °C for 1 h, as per APHA method 2540 D (APHA, 2005).

2.3. Weather data collection

Average and 5-min peak rainfall intensity, event duration and length of the antecedent dry period were recorded for each event using a University weather station adjacent to the copper roof site. This data was compared against meteorological records from the National Institute of Water and Atmosphere's (NIWA) Weather Station, 2.2 km from the sampling sites, and found to be similar and therefore representative of rainfall conditions for the wider Christchurch. The NIWA station data was used when the University weather station data was not available for maintenance reasons. Rainfall pH was measured for each event from a wet deposition sampler adjacent to the copper roof site.

2.4. Rainfall characteristics

Samples were obtained from 15 rainfall events between March to June 2014 (i.e. autumn to early winter) and October 2014 to March 2015 (i.e. spring to mid-summer). Due to the different runoff characteristics of each surface type and sampling logistics, not all surfaces could be sampled for every event, however there were six sampling events where all four surfaces were sampled concurrently. Rainfall pH ranged between 5.1 and 6.4, which is relatively