Relationships between rainfall intensity, duration and suspended particle washoff from an urban road surface

Ian M. Brodie and Prasanna Egodawatta

ABSTRACT

A basic understanding of the relationships between rainfall intensity, duration of rainfall and the amount of suspended particles in stormwater runoff generated from road surfaces has been gained mainly from past washoff experiments using rainfall simulators. Simulated rainfall was generally applied at constant intensities, whereas rainfall temporal patterns during actual storms are typically highly variable. This paper discusses a rationale for the application of the constant-intensity washoff concepts to actual storm event runoff. The rationale is tested using suspended particle load data collected at a road site located in Toowoomba, Australia. Agreement between the washoff concepts and measured data is most consistent for intermediate-duration storms (duration <5 h and >1 h). Particle loads resulting from these storm events increase linearly with average rainfall intensity. Above a threshold intensity, there is evidence to suggest a constant or plateau particle load is reached. The inclusion of a peak discharge factor (maximum 6 min rainfall intensity) enhances the ability to predict particle loads.

Key words | buildup-washoff, particle washoff, road runoff, stormwater, suspended solids

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NOMENCLATURE

A	load adjustment factor
A_C	catchment area (ha)
ADWP	antecedent dry weather period
C	runoff coefficient
D	storm event rainfall duration (h)
D_{95}	limiting load time for 95% washoff (h)
EMC	event mean concentration
I_C	constant rainfall intensity (mm h^{-1})
I_{P1}, I_{P2}	average rainfall intensities (mm h^{-1}) that define conditions for washoff of L_P
I_S	average storm event rainfall intensity (mm h^{-1})
I_{tc}	rainfall intensity (mm h^{-1}) corresponding to the time of concentration of the catchment
I_x	maximum storm rainfall intensity (mm h^{-1}) for a time period of x minutes
k	washoff coefficient (L mm^{-1})
L(t)	cumulative mass load (mg m^{-2}) of suspended particles washed off after time t
L_0	available particle load (mg m^{-2}) washed from the surface
L_P	plateau available particle load (mg m^{-2})
L_S	storm event load (mg m^{-2})
L_{T0}	pre-storm particle load (mg m^{-2}) on the surface
L_{133}	available particle load (mg m^{-2}) for 133 mm h^{-1} constant rainfall intensity
NCP	non-coarse particle
Q_P	peak discharge (L s^{-1})
SE	standard error
SSC	suspended sediment concentration
TSS	total suspended solids

INTRODUCTION

Suspended solids and other pollutants washed from roads during storms are a major cause of water quality degradation.

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Suspended solids is a significant pollutant in its own right and also acts as a mobile substrate to other stormwater pollutants such as heavy metals, nutrients and hydrocarbons. Predicting the mass loading or concentration of suspended solids in road runoff is thus an important part of planning effective control strategies. A range of urban stormwater models such as Storm Water Management Model (SWMM) (Huber & Dickensen 1988), Source Loading and Management Model (SLAMM) (Pitt 1998) and MOdel for Urban SEwers (MOUSE) (DHI 2002) are available for this purpose.

Predictive modelling of suspended solids in road runoff requires an understanding of washoff responses to rainfall and this has been mainly gained from studies using rainfall simulators, notably the early work of Sartor & Boyd (1972). Simulator studies generally involve the collection and analysis of runoff samples from small-scale road plots under constant rates of artificial rainfall application. Rainfall intensity and duration are considered to be important hydrological factors in particle washoff based on the outcomes of Sartor & Boyd (1972) and subsequent rainfall simulator studies (Pitt 1987; Vaze & Chiew 2003; Egodawatta *et al*. 2007).

Although fundamental insights have been obtained by the use of rainfall simulator studies, a key question is: how applicable are findings obtained under controlled conditions to actual storm events which invariably do not have constant rainfall intensities? This question is addressed here by first developing a rationale to describe how particle washoff relationships developed for constant simulated rainfalls could be applied to temporally variable storms. This rationale is then tested using road runoff data collected at a site in Toowoomba, Australia.

A key aspect of the analysis is to establish whether the particle washoff concepts established by simulator studies are apparent across the full range of monitored actual storms. For the washoff concepts to be transferable, an ‘equivalent’ rainfall intensity metric for actual storms is required to substitute for the constant simulated rainfall intensity. Suspended solid loads measured from the Toowoomba road are grouped according to storm duration and plotted against various measures of rainfall intensity. Regression relationships are provided to describe the level of agreement with the measured loads and the expected simulator-based washoff responses. Improvements to the degree of fit are explored by incorporating additional rainfall characteristics within the regression.

THEORY BASED ON SIMULATED RAINFALL STUDIES

Previous investigations using simulated rainfall (Sartor & Boyd 1972; Pitt 1987; Egodawatta *et al*. 2007) demonstrated that particle loads washed from road surfaces during a test event under constant rainfall intensity can be described by the exponential relationship:

$$L(t) = L_0(1 - e^{-kI_c t}) \tag{1}$$

where L(t) is cumulative mass load of suspended particles washed off after time t during the test, L_0 is ‘initial’ or ‘available’ mass load washed from the surface, k is washoff coefficient and I_C is constant rainfall intensity. Various units of measurement have been adopted in past studies. In this paper, the following units are used: mg m^{-2} for loads, mm^{-1} for k and mm h^{-1} for rainfall intensity.

The washoff coefficient k is a key parameter dictating the temporal rate of particle washoff during a storm. Early work adopted a near-arbitrary k value of 0.18, on the assumption that 90% of particles are removed by the first ‘half an inch’ of runoff (Metcalf & Eddy Inc. *et al*. 1971). Sartor & Boyd (1972) found that k was independent of rainfall intensity and particle size, but varied slightly according to street texture and condition. However, as noted by Millar (1999), the value of k has been shown to vary depending on rainfall intensity and catchment area (Sonnen 1980) and catchment slope (Nakamura 1984).

The ‘available’ load L_0 is a critical but very misunderstood parameter in the particle washoff equation. It was recognized by the early work of Sartor & Boyd (1972) that L_0 can be defined as the particle load (of a particular size) which ‘could ever be washed from the street surface by rain of intensity ‘r’ even as time approaches infinity’. As described, L_0 is typically not the total amount of particles present on the surface prior to commencement of rainfall but is dictated by rainfall characteristics, specifically those that govern the capacity to detach and transport particles.

This physical interpretation of L_0 is supported by other rainfall simulator studies (Pitt 1987; Vaze & Chiew 2003) that found washoff loads usually represent only a relatively small proportion (in the 3–25% range) of the total pre-storm particle load present on road surfaces. Repeated flushing of an urban street using a rainfall simulator by Malmquist (1978) reached a similar conclusion. Alley & Smith (1981) also stated that the pre-storm measurement of surface particles by sweeping, vacuuming or flushing may not be directly related to the actual amount available for transport by storm runoff. As a result, L_0 can be considered to be predominately a function of rainfall intensity I_C. Although an interrelationship was not quantified, both Sartor & Boyd (1972) and Pitt (1987) recognized that higher intensities of applied rainfall produced greater ‘available’ loads.

Egodawatta *et al*. (2007) related L_0 to I_C by introducing an adjustment factor (capacity factor C_F in their paper) to adjust washoff loads predicted using Equation (1) to measurements conducted at three street sites in the Gold Coast region, Australia. Their tests included rainfall intensities up to 133 mm h^{-1}, corresponding to relatively infrequent events. The adjustment factor varies in accordance to three distinct ranges of rainfall intensity as described by Equation (2):

$$L_0 = A \cdot L_{T0} = A \cdot L_{133} \tag{2}$$

For $I_C < 40$ mm h^{-1}, A varies linearly from 0 to 0.5; for $40 < I_C < 90$ mm h^{-1}, $A = 0.5$ and $90 < I_C < 133$ mm h^{-1}, A varies linearly from 0.5 to 1, L_{133} is the available washoff load for 133 mm h^{-1} constant rainfall intensity. Equation (2) is a reinterpretation of Egodawatta *et al*. (2007) who related A to the pre-test particle mass on the street surface as collected by vacuum cleaning (L_{T0}), but demonstrated that this load was fully washed from the surface at the relatively high 133 mm h^{-1} rainfall intensity.

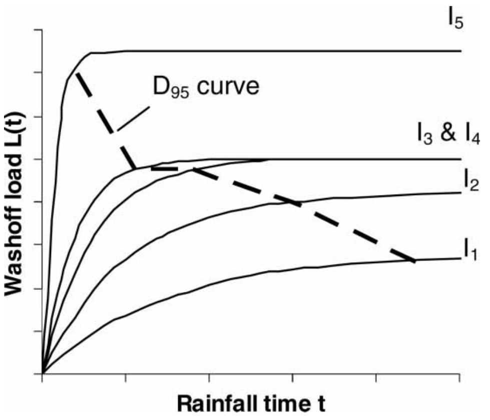

Figure 1 | Generalized curves relating washoff load L(t) with rainfall time t for events of increasing constant rainfall intensity where $I_1 < I_2 < I_3 < I_4 < I_5$, based on Egodawatta *et al*. (2007). The dashed D_{95} curve represents the time at which 95% of the available load (or 0.95 L_0) is attained.

Broad statements can be made in relation to particle washoff based on the cited rainfall simulator studies. In regard to this, a generalized set of particle washoff curves for a series of hypothetical events of increasing rainfall intensity is presented in Figure 1. For discussion purposes, the findings of Egodawatta *et al*. (2007) were used to prepare the washoff curves. During each event, the applied rainfall intensity is constant. From the form of the washoff curves, it is evident that for a given constant rainfall intensity, the washoff load asymptotically approaches an upper limit (equal to the available load L_0 in Equation (1)). Generally the available load increases with rainfall intensity, but in some conditions ($40 < I_C < 90$ mm h^{-1}) this may not be the case and the upper limit is relatively constant, as illustrated by the I_3 and I_4 washoff curves in Figure 1.

It is also clear from Figure 1 that the duration of rainfall application required for the available washoff load to be reached varies depending on the rainfall intensity. This elapsed period of time is termed the ‘limiting load time’ in this paper. Due to the asymptotic nature of the washoff curves, the limiting load time can be approximated by the time to achieve 95% washoff (D_{95}). A $L(t)/L_0$ ratio of 0.95 was substituted into Equation (1) in order to derive the equation for D_{95} (Equation (3)). A generalized form of the D_{95} curve is overlaid onto Figure 1. As seen in Figure 1, higher rainfall intensity leads to shorter limiting load times (and higher available washoff loads). The time also depends on the magnitude of the washoff coefficient k and decreases as k increases.

$$D_{95} = -\ln 0.05 / k\, I_C \tag{3}$$

where D_{95} is limiting load time (h)

The D_{95} curve provides a basis to determine the particle mass washed from a street surface for an event of constant rainfall intensity. Providing the rainfall duration exceeds D_{95} then, by definition, the event load is simply approximately equal to the available washoff load as expressed by Equation (4). If these rainfall duration conditions are met, then the storm event load L_S is expected to follow the

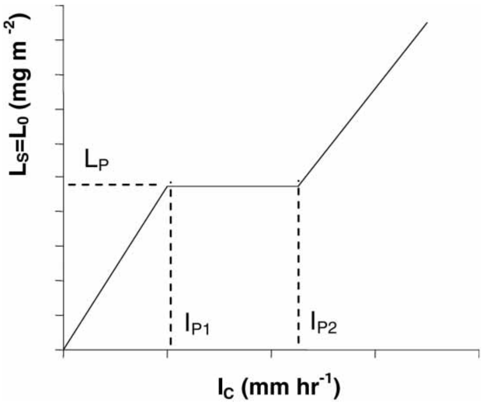

Figure 2 | Generalized relationship based on Equation (2) between storm event load L_S and constant rainfall intensity I_C. This relationship is based on Egodawatta *et al*. (2007) and applies if the duration of rainfall D exceeds D_{95}. The 'plateau' washoff load L_P coincides with rainfall intensity ranging from I_{P1} to I_{P2}.

generalized relationship illustrated by Figure 2 (which is based on Equation (2)).

For

$$D > D_{95}, L_S \approx L_0 \tag{4}$$

where D is the storm duration and L_S is the storm event load (mg m^{-2}). L_0 is a function of constant rainfall intensity I_C (e.g. of the form given by Equation (2)).

A characteristic feature of the relationship between storm event load L_S and constant rainfall intensity I_C (Figure 2) is that, under certain conditions, the available washoff load is constant. In this paper, this load is termed the 'plateau' load L_P and occurs within the rainfall intensity range from I_{P1} to I_{P2}. Based on tests conducted by Egodawatta *et al.* (2007), $I_{P1} = 40$ mm h^{-1}, $I_{P2} = 90$ mm h^{-1} and the plateau load L_P varied for each of the three street sites and ranged from 1550 to 5400 mg m^{-2} (calculated from data provided). L_P is used as a point of reference in this paper to define particle washoff behaviour from road surfaces.

MATERIALS AND METHODS

Rationale for the application of washoff relationships to actual storm conditions

The generalized relationships (Figures 1 and 2, as well as Equations (1) to (4)) encapsulate the particle washoff responses established from the cited rainfall simulator investigations. Compared to simulations, which are generally set at a constant intensity, the intensity of actual storm rainfall exhibits significant temporal variability. An approach is required to enable a comparison between the non-uniform rainfall pattern of storms and the constant conditions under which the characteristic washoff curves were derived. The approach taken in this paper involves the following logic.

1. If the storm duration is sufficiently long (i.e. $D > D_{95}$), a time period of rainfall has occurred such that an available washoff load is reached.
2. It is assumed that there is a rainfall intensity metric that provides an 'equivalent' washoff response to I_C (described by Equation (2)) conceptualized from the simulator studies. In this study, rainfall intensity averaged over a fixed time period and over the storm duration are trialled.
3. By definition, under the above conditions, the event load in response to the storm matches the available washoff load L_0 and can be determined by Equation (4).
4. If the storm duration is relatively short (i.e. $D < D_{95}$), the time period of rainfall is not sufficient to attain conditions that yield an available washoff load limit and the resulting event load is of a lesser magnitude.

The rationale for adapting the simulator-based washoff curves to actual storms is tested based on whole-of-event particle loads for various storms, rather than the washoff response during individual storms. This is because the measured data involved event mean concentrations (EMC) only. A major objective of the data analysis is to establish the form of the relationship between the 'equivalent' rainfall intensity and event particle loads and to determine if it is consistent with that conceptualized from previous rainfall simulator studies.

Measured road runoff data

Runoff samples were collected from a 75 m long section of bitumen road pavement located at Toowoomba, Australia. A flow splitter device described by Brodie (2005) was used to obtain flow-weighted composite samples in response to 32 storms during the period December 2004 to January 2006. No discrete samples were taken to quantify within-storm responses to rainfall, as the main purpose of the

Table 1 | Rainfall statistics for monitored storm events at Toowoomba road site

Statistic	Depth (mm)	Duration (hrs)	Average intensity (mm h^{-1})	Max. 6-min intensity (mm h^{-1})
Maximum	64.3	21.3	40.0	72.1
Minimum	2.5	0.2	1.0	3.8
Median	13.8	2.4	3.6	23.3
Mean	16.6	5.0	6.4	24.4
Coefficient of variation	0.79	1.07	1.15	0.67

monitoring was to collect time-integrated event data. Rainfall was recorded by a 0.25 mm tipping bucket pluviometer installed near the sampling site. Event rainfalls varied from 2.5 mm to 64.25 mm at average intensities ranging from 1 mm h^{-1} to 40 mm h^{-1}. Event rainfall statistics are provided in Table 1. The road drainage area occupies 450 m^2 and the average daily traffic count was 3500 vehicles per day. A full description of the monitoring program is provided by Brodie & Porter (2006).

Runoff samples were analyzed using a modified suspended sediment concentration (SSC) method (ASTM 2002) to determine the EMC of particles less than 500 μm in size. An additional screening step was used to obtain <500 μm particles, referred to as non-coarse particles (NCP) to distinguish from SSC and the more commonly used total suspended solids (TSS).

RESULTS AND DISCUSSION

Equivalent rainfall intensity

It is assumed that there is an 'equivalent' rainfall intensity for actual storms that substitutes for the constant rainfall intensity I_C utilized in the simulator-based washoff relationships. Two basic forms of rainfall intensity were investigated: the maximum intensity averaged over a fixed time period during the storm and the event average rainfall intensity (total rainfall depth/storm duration).

Rainfall intensity based on a fixed time period was firstly explored. Guidance on the selection of an appropriate time period was obtained from past rainfall simulator studies of street surfaces. The Sartor & Boyd (1972) tests were conducted at two intensities (5.1 mm h^{-1} and 20.3 mm h^{-1}) on three surfaces (two asphalt and one concrete). Samples collected at 15 minute intervals during each 2 h 15 min duration test showed that most of the particle washoff load occurred within the initial one hour period, or less. On this basis, two time periods (30 and 60 min) were trialled to derive equivalent rainfall intensities. Figure 3 shows NCP load plotted against the maximum 30 min intensity (I_{30}). The plot generated for the maximum 60 min intensity (not presented) is similar to Figure 3.

It is clear from Figure 1 that the magnitude of D_{95} is variable and the selection of a fixed time period may not lead to consistent results across all monitored storms. The measured road NCP load plotted against the average rainfall intensity I_S for each storm event is provided as Figure 4. In this case, the time period used is the duration D of the storm event defined as the total period when rainfall exceeded a nominal 0.25 mm h^{-1}. The durations of the monitored storms ranged from 0.2 h to 21.3 h.

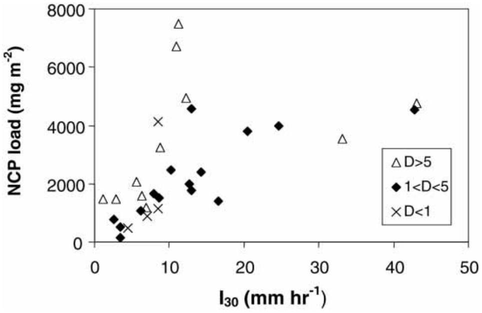

Figure 3 | Plot of road NCP loads against storm maximum 30 min rainfall intensity I_{30}, grouped by rainfall duration D.

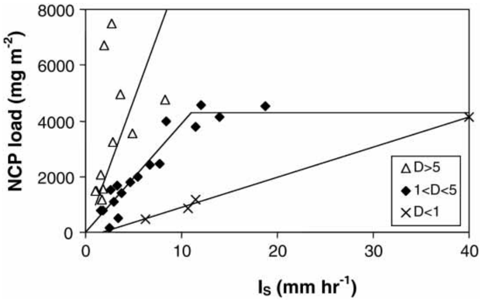

Figure 4 | Plot of road NCP loads against storm event average rainfall intensity I_S, grouped by rainfall duration D. Regressions for NCP loads for each storm class are also shown.

The plotted data in Figures 3 and 4 are divided into three storm categories, corresponding to short duration events of less than 1 h (labelled $D < 1$), longer events exceeding 5 h (labelled $D > 5$) and intermediate duration events (labelled $1 < D < 5$). As found by previous analysis of a partial set of the NCP data (Brodie 2007), these storm categories led to distinct clustering of the plotted data into separable groups. The clusters are most evident in the NCP plot against average rainfall intensity I_S given in Figure 4.

Using I_S as a measure of equivalent intensity appears to be more appropriate than an intensity based on a fixed time period, as demonstrated by the greater amount of scatter in Figure 3. Average rainfall intensity is based on a rainfall duration that varies from event to event and, due to this variance, appears to provide a better representation of the required equivalent rainfall intensity compared to using a single fixed duration.

The relevance of the particle washoff concepts to each of the three storm groups monitored at Toowoomba is discussed in the following sections.

Particle washoff for intermediate storms

Compared to the other storm groups, a regression line shown on Figure 4 for NCP loads generated from intermediate $1 < D < 5$ storms most closely resembles the generalized linear relationship indicated by Figure 2, and appears to cover at least part of the range associated with a 'plateau' washoff load L_P. Graphically, the NCP loads for $1 < D < 5$ storms support the assumption that the rainfall durations are sufficiently long to produce washoff of an available load.

The regression line relating storm event NCP load L_S ($= L_0$) to average rainfall intensity is provided in Equation (5) ($n = 18$, $R^2 = 0.922$, $SE = 410\ \mathrm{mg\ m^{-2}}$). For reasons outlined later in this paper, the $D < 1$ data point coinciding with the relatively high rainfall intensity of $40\ \mathrm{mm\ h^{-1}}$ is also included. The plateau washoff load L_P is used as a point of reference in Equation (5), in preference to other load measures such as the pre-storm particle load on the road surface L_{T0}.

$$L_S = L_0 = A\,L_P \tag{5}$$

where $A = 0.091\,I_S$ for $I_S < 11\ \mathrm{mm\ h^{-1}}$, $A = 1$ for $I_S > 11\ \mathrm{mm\ h^{-1}}$ and $L_P = 4300\ \mathrm{mg\ m^{-2}}$. This relationship is applicable for $1 < D < 5$ class of storm events and $I_S \leq 40\ \mathrm{mm\ h^{-1}}$.

The generation of the plateau washoff load L_P corresponds to $11\ \mathrm{mm\ h^{-1}}$ (i.e. $I_{P1} = 11\ \mathrm{mm\ h^{-1}}$). An upper rainfall intensity limit for L_P is not evident in the NCP load data, as the intensities of the monitored storms are moderate compared to the expected I_{P2} magnitude of $90\ \mathrm{mm\ h^{-1}}$. The I_{P1} of $11\ \mathrm{mm\ h^{-1}}$ is significantly less than the $40\ \mathrm{mm\ h^{-1}}$ determined by Egodawatta *et al.* (2007), and exceeds the average rainfall intensity of $7\ \mathrm{mm\ h^{-1}}$ at which rainfall will cause 'cleansing' of a road surface based on measured data at Sydney, Australia (Ball 2000). Interestingly, the I_{P1} of $11\ \mathrm{mm\ h^{-1}}$ is more consistent with the $12.7\ \mathrm{mm\ h^{-1}}$ contained within the often-used default assumption that '90% of pollutants will be washed off in one hour for a 0.5 in/hr ($12.7\ \mathrm{mm\ h^{-1}}$) runoff rate' (Jewell & Adrian 1978).

Particle washoff for short storms

As shown in Figure 4, the NCP loads associated with the small number of observed short duration storms ($D < 1$) are generally less in magnitude than the available washoff loads defined by the $1 < D < 5$ regression line (Equation (5)). This is consistent with the rationale given earlier in this paper, providing it can be demonstrated that D is less than D_{95} for these individual storms. Under conditions of incomplete washoff of the available load Equation (4) is not applicable, but an estimate of the storm event load L_S can be made based on the underlying exponential washoff equation (Equation (1)). This provides an opportunity to derive estimates of the washoff coefficient k as for $D < D_{95}$:

$$L_S = L_0(1 - e^{-kI_S D}) \tag{6}$$

where L_0 is available NCP washoff load based on Equation (5). This relationship is applicable for $I_S \leq 40\ \mathrm{mm\ h^{-1}}$, corresponding to the measured range of storms under analysis.

The procedure to derive the k values involves first estimating the available washoff load L_0 from Equation (5), using the average rainfall intensity I_S for the storm event. As the storm duration D is also known, the k value can be estimated by iterating Equation (6) so the predicted load matches the measured load. A check was then made to determine if the storm duration D is less than D_{95} as determined from Equation (3).

Although the number of $D < 1$ class storms is limited, the variation in k values shows some indicative trends. For the cluster of three storms corresponding to rainfall intensities less than 12 mm h^{-1} (as plotted in Figure 4), the calculated k values ranges from 0.039 to 0.085 (mean 0.06). Storm duration D is less than D_{95} for all of these events, consistent with the underlying assumption of incomplete washoff. Their washoff coefficients are an order of magnitude less than the k value ($k = 0.40$) associated with the single, higher intensity storm ($I_S = 40$ mm h^{-1}). Although this storm is very short ($D = 0.2$ h), the duration of rainfall matches the limiting load time ($D_{95} = 0.19$ h, calculated from Equation (3)) suggesting that complete washoff of the available load is achieved by this event. Furthermore, the plotting position of this event on Figure 4 coincides with the 'plateau' washoff load L_P. This result points to this particular storm event being also closely allied with the $1 < D < 5$ class of storms and was included in the Equation (5) regression.

The large range in k values across the four monitored storms (0.039–0.40) is comparable with analysis by Alley (1981) of suspended solids data collected from a 5.95 ha urban catchment in Florida, USA. By using an optimization technique, k values for eight storms varied from 0.036 to 0.43. Individual storm durations were not reported. Pitt (1987) derived a similar range (0.078–0.38) of k values based on rainfall simulator testing of various road surfaces located in Toronto, Canada. All tests were conducted over a 2 hour period, with rainfall application ranging from 5 to 25 mm.

Although not definitive due to the limited data, a linear relationship provided as Equation (7) is apparent ($n = 4$, $R^2 = 0.995$, SE = 100 mg m^{-2}) for the $D < 1$ storm class:

$$L_S = 108\, I_S - 190 \tag{7}$$

This relationship is applicable for $D < 1$ class of storm events and $I_S \leq 40$ mm h^{-1}, corresponding to the measured range of storms under analysis.

Rainfall depth for the $D < 1$ storm class ranges from 2.5 to 8 mm. Other studies have identified a linear response of particle load to various hydrological parameters in the specific case of relatively minor rainfall events. Berretta *et al.* (2007) found that TSS loads generated from two urban sites in Genoa, Italy were in linear proportion to the cumulative runoff volume for low-intensity storms less than 5 mm rainfall. This class of storms were referred to as 'flow-limited low runoff volume' events, as used previously by Sansalone *et al.* (1998) in their study of highway runoff at Cincinnati, Ohio who also observed a linear response. A linear response is also consistent with Alley (1981) who demonstrated that, for a given k value, the curvature of the load characteristic curves decreases as the total storm runoff decreases towards minor rainfalls of a few millimetres. This tendency is also evident in the shape of the generalized washoff curves shown in Figure 1.

Particle washoff for long storms

For longer duration storms ($D > 5$), the NCP loads are higher than the available loads. They are defined by the $1 < D < 5$ data in Figure 4, and thus an 'additional' particle source is associated with these rainfall events. Possible mechanisms for this within-storm particle contribution is attributed to vehicle traffic and include enhanced particle mobilization due to the pumping action of tyres in contact with wet road surfaces, dislodgment of particles from vehicles by water spray and wet-deposition of exhaust particles (Gupta *et al.* 1981). Past road runoff studies have also identified that traffic-induced particle loads can be significant during prolonged wet weather, more so with heavy traffic conditions during the event (Asplund *et al.* 1982; Sansalone *et al.* 1998; Kim 2002).

Many of the $D > 5$ storms have successive bursts of rainfall separated by periods of low rainfall, and a typical example is shown in the hyetograph given in Figure 5. It is expected that in such a multi-burst storm, washoff occurs due to the initial rainfall burst but particles are progressively replenished by traffic during the subsequent period of low to no rainfall. The second rainfall burst washes off some of the replenished store of particles on the wet road surface. A cycle of particle removal and replenishment provides an explanation for the 'additional' particle source for the $D > 5$ storms.

A regression function ($n = 11$, $R^2 = 0.27$, SE = 2160 mg m^{-2}) fitted to the $D > 5$ storm data is given as Equation (8). The low coefficient of determination suggests that contributing

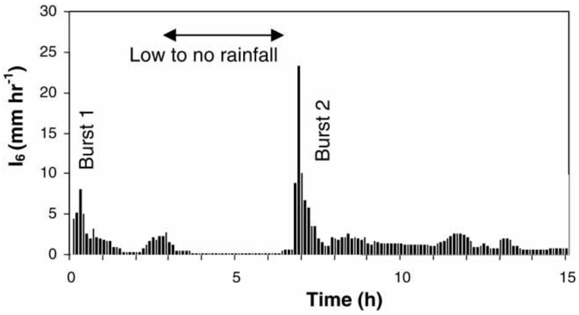

Figure 5 | Hyetograph of 15 June 2005 storm showing two rainfall bursts with intervening period of low to no rainfall.

factors other than average rainfall intensity (such as traffic variables) are important for the $D > 5$ storm class:

$$L_S = 943\, I_S. \tag{8}$$

This relationship is applicable for $D > 5$ class of storm events and $I_S \leq 10\ \mathrm{mm\,h^{-1}}$, corresponding to the measured range of storms under analysis.

Inclusion of a peak discharge factor for intermediate storms

Data for the intermediate ($1 < D < 5$ h) storms provides the best explanatory fit to the particle washoff rationale previously described in this paper. The inclusion of hydrological factors other than average rainfall intensity may further enhance the ability to predict particle loads generated during these storms, as discussed herein.

Rainfall intensity is a variable in the exponential washoff relationship (Equation (1)) and is closely associated to the kinetic energy of raindrops (Van Dijk *et al.* 2002; Brodie & Rosewell 2007) leading to the detachment of particles from surfaces. However, a companion process is the transport of particles to and along the street drain (usually in the form of a roadside gutter or kerb) by overland flow. Mobilization of suspended particles from the street surface to a point of discharge has thus been conceptualized as a two-step process; particle detachment and washoff by rainfall from the surface followed by a transport phase by overland flow (Price & Mance 1978; Deletic *et al.* 1997).

Overland flow processes have been accounted for in predictive models based on parameters such as flow depth (Sriananthakumar & Codner 1995), shear stress (Akan 1987) and runoff rate (Pope *et al.* 1978; Ichikawa 1981). Given this recognition in previous studies, the benefit of including a factor in addition to I_S to specifically represent peak overland flow conditions was considered for the $1 < D < 5$ class of storms.

Peak overland flow in small urban areas can be estimated by the well-known Rational Method based on Equation (9) which links peak discharge to the rainfall intensity corresponding with the time of concentration of the catchment I_{tc}. As the time of concentration of the Toowoomba road site is approximately 6 min, the maximum 6 min rainfall intensity (Max I_6) provides a measure of peak overland discharge:

$$Q_P = 0.00278\, C\, I_{tc}\, A_C \tag{9}$$

where Q_P is peak discharge (L s^{-1}), C is runoff coefficient, I_{tc} is rainfall intensity corresponding to the time of concentration of the catchment and A_C is catchment area (ha).

In the case of the Toowoomba data, NCP loads are moderately correlated ($n = 18$, $R^2 = 0.824$, $SE = 580\ \mathrm{mg\,m^{-2}}$) to Max I_6 for the $1 < D < 5$ class of storms as shown in Figure 6. The regression relationship is provided as Equation (10):

$$L_S = 109\, \mathrm{Max}\, I_6 - 690. \tag{10}$$

This relationship is applicable for $1 < D < 5$ class of storm events and Max $I_6 < 50\ \mathrm{mm\,h^{-1}}$, corresponding to the measured range of storms under analysis.

NCP loads plotted against I_S Max I_6 are presented in Figure 7. For the $1 < D < 5$ class of storms, there appears

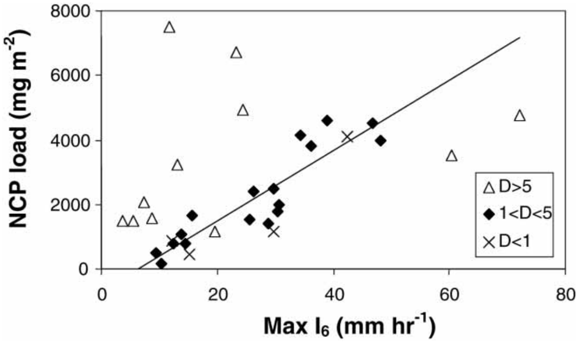

Figure 6 | Plot of road NCP loads against maximum 6 min rainfall intensity (Max I_6), grouped by rainfall duration D. Regression for NCP loads for $1 < D < 5$ storms is also shown.

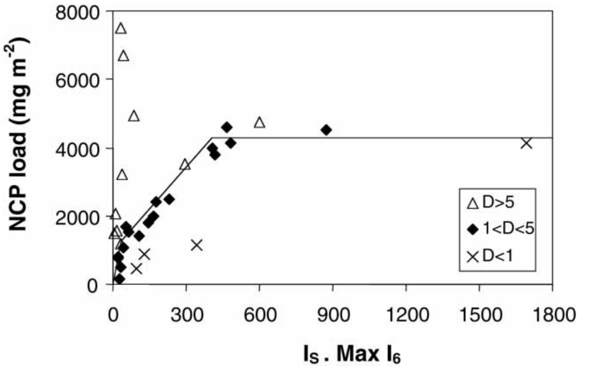

Figure 7 | Plot of road NCP loads against product of average rainfall intensity and maximum 6 min rainfall intensity (I_S Max I_6), grouped by rainfall duration D. Regression for NCP loads for $1 < D < 5$ storms is also shown.

to be an 'initial' amount of NCP load that is washed from the road surface at comparatively low values of I_S Max I_6. As a result, a compound linear relationship was fitted to the data as given by Equation (11). The 'initial' load, representing approximately 30% of the plateau load L_P, is associated with an $I_S \cdot$ Max I_6 value that is less than 10% of the corresponding value required for plateau load washoff:

$$L_S = A\,L_P \qquad (11)$$

where A varies linearly from 0 to 0.29 for I_S Max $I_6 < 40$, A varies from 0.29 to 1 for $40 < I_S$ Max $I_6 < 450$ and $A = 1$ for I_S Max $I_6 > 450$ and $L_P = 4300$ mg m^{-2}. This relationship is applicable for $1 < D < 5$ class of storm events and I_S Max $I_6 < 1700$ mm^2 h^{-2}.

The relationship for $1 < D < 5$ storms (Equation (11)) suggests the presence of two particle types: an 'initial' particle load that is readily washed off and transported and particles that are not as easily mobilized. This partitioning of particles according to energy requirements for washoff and transport is analogous to the 'free' and 'fixed' particles described by Vaze and Chiew (2002) on the basis of the increasing energy required for their physical removal from a street surface in dry weather. Murakami *et al.* (2004) also considered that road particles can be classified into highly and less mobile fractions. Their distinction between particles was not based on physical properties including size, as both types were classed as fine (<45 μm).

The correlation statistics for Equation (11) ($n = 18$, $R^2 = 0.970$, SE = 250 mg m^{-2}) indicate that using I_S Max I_6 provides a more accurate predictor of NCP load for $1 < D < 5$ storms than the use of I_S alone. Standard error of NCP estimates is reduced from 410 mg m^{-2} to 250 mg m^{-2} (or 6% of the plateau load L_P).

CONCLUSIONS

Knowledge of particle washoff from roads gained by rainfall simulator tests under constant intensity is transferable to the more variable conditions of actual storms. Based on the non-coarse particle (NCP < 500 μm) loads measured at the Toowoomba road site, we make the following conclusions.

1. A key concept is the available load L_0 which is the particle mass washed from the road surface in response to a sustained time period of rainfall. Available load varies with the intensity of rainfall, but a minimum duration of rainfall is also required to generate full washoff of the available load. This limiting load time D_{95} is also dependent on rainfall intensity (and washoff coefficient k). Due to this interdependency between rainfall intensity, limiting load time and available load, the average rainfall intensity of a storm event I_S appears to be more suitable than a fixed-duration intensity in the determination of available loads.
2. Available load increases linearly with average rainfall intensity I_S until a plateau load L_P is reached for rainfalls above threshold intensity I_{P1}. For road runoff measured at the Toowoomba site, the conditions that lead to complete washoff of the available load are associated with intermediate duration events ($1 < D < 5$).
3. For short storms ($D < 1$), the duration of rainfall may be less than the required limiting load time D_{95} resulting in incomplete washoff of the available load. However, as D_{95} reduces with increased rainfall intensity, some short storms of sufficient intensity may produce complete washoff conditions.
4. For longer duration storms ($D > 5$), measured NCP loads exceed the available load indicating an additional particle contribution is associated with these events. This within-storm contribution is attributed to vehicle traffic, with particle accumulation occurring in periods of low to no rainfall and subsequently washed off by later rainfall bursts. More research is required to fully quantify traffic-induced particle effects during $D > 5$ storms.

5. The inclusion of a peak discharge factor (Max I_6) enhances the ability to predict NCP loads for intermediate $1 < D < 5$ storms. This is consistent with the dual processes that govern particle washoff, which are the detachment of particles from the surface by rainfall kinetic energy (represented by I_S) and particle transport by overland flow (represented by Max I_6). The NCP load response to the rainfall index I_S Max I_6 suggests that particles in road runoff can be grouped either as an initial load that is easily washed off or as a less mobile particle mass that has a higher rainfall energy and flow transport requirement for washoff.

The analysis described in this paper provides evidence that particle washoff responses established by constant-intensity rainfall simulator studies are transferable to small road catchments under actual storms. Average storm event rainfall intensity appears to be an appropriate substitute for the constant simulated rainfall intensity. More work is required to test the generality of this outcome to other suspended solids measures (TSS and SSC), different urban surfaces and at larger catchment scales.

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