Journal of Hydrology 557 (2018) 426–433

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Improving understanding of the underlying physical process of sediment wash-off from urban road surfaces

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A R T I C L E I N F O

Article history:
Received 20 June 2017
Received in revised form 30 October 2017
Accepted 23 November 2017
Available online 26 November 2017
This manuscript was handled by L. Charlet, Editor-in-Chief, with the assistance of Joanna Crowe Curran, Associate Editor

Keywords:
Sediment wash-off
Sediment build-up
Exponential model
Capacity factor
Surface slope
Water quality
Rainfall simulator

A B S T R A C T

Among the urban aquatic pollutants, the most common is sediment which also acts as a transport medium for many contaminants. Hence there is an increasing interest in being able to better predict the sediment wash–off from urban surfaces. The exponential wash-off model is the most widely used method to predict the sediment wash-off. Although a number of studies proposed various modifications to the original exponential wash-off equation, these studies mostly looked into one parameter in isolation thereby ignoring the interactions between the parameters corresponding to rainfall, catchment and sediment characteristics. Hence in this study we aim (a) to investigate the effect of rainfall intensity, surface slope and initial load on wash-off load in an integrated and systematic way and (b) to subsequently improve the exponential wash-off equation focusing on the effect of the aforementioned three parameters. A series of laboratory experiments were carried out in a full-scale setup, comprising of a rainfall simulator, a 1 m^2 bituminous road surface, and a continuous wash-off measuring system. Five rainfall intensities ranging from 33 to 155 mm/h, four slopes ranging from 2 to 16% and three initial loads ranging from 50 to 200 g/m^2 were selected based on values obtained from the literature. Fine sediment with a size range of 300–600 μm was used for all of the tests. Each test was carried out for one hour with at least 9 wash-off samples per test collected. Mass balance checks were carried out for all the tests as a quality control measure to make sure that there is no significant loss of sand during the tests. Results show that the washed off sediment load at any given time is proportional to initial load for a given combination of rainfall intensity and surface slope. This indicates the importance of dedicated modelling of build-up so as to subsequently predict wash-off load. It was also observed that the maximum fraction that is washed off from the surface increases with both rainfall intensity and the surface slope. This observation leads to the second part of the study where the existing wash-off model is modified by introducing a capacity factor which defines this maximum fraction. This capacity factor is derived as a function of wash-off coefficient, making use of the correlation between the maximum fraction and the wash-off rate. Values of the modified wash-off coefficient are presented for all combinations of rainfall intensities and surface slopes, which can be transferred to other urban catchments with similar conditions.

1. Introduction

Pollutant wash-off is the process by which non-point source pollutants including sediment, nutrients, bacteria, oil, metals and chemicals are removed from urban surfaces by the action of rainfall and runoff. Among the transported pollutants, the most common is sediment which plays a major role in water quality issues of inland water bodies in urban areas (Guy, 1970; Collins and Ridgeway, 1980; Chiew and Vaze, 2004). Sediment also contributes to urban floods by filling up drainage systems and reducing the hydraulic capacity of these systems that are designed to rapidly carry water away from roads and properties (Ivan, 2001). Hence, accurate modelling of sediment wash-off is important for water-quality-based decision-making. But modelling sediment wash-off is not a straightforward exercise as it often involves empirically calibrated equations containing parameters with a highly variable nature against rainfall, catchment surface and particle characteristics. There are two main processes involved in the transport of sediment from an impervious surface: Build-up and Wash-off (Sartor and Boyd 1972). Build-up is a process in which sediment

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https://doi.org/10.1016/j.jhydrol.2017.11.047
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accumulates during dry weather. Wash-off is the process where accumulated sediment deposition is removed from impervious surfaces by rainfall and runoff and then incorporated in the run-off flow over the surface. Modelling of pollutant wash-off ranges from simple EMC (Event Mean Concentration) (Kayhanian et al., 2007; Charbeneau and Barrett, 1998) to more sophisticated BUWO (Build-up Wash-off models).

One of the earliest studies on sediment wash-off was carried out by Sartor and Boyd (1972). They derived separate build-up and wash-off functions based on an experimental study of runoff pollution in eight US cities. The original exponential wash-off equation proposed by Sartor and Boyd (1972) is given below

$$w_t = w_o(1 - e^{-kit}) \tag{1}$$

where w_t is transported sediment load after time t, w_o is initial load of the sediment on the surface; i is rainfall intensity; and k is the wash-off coefficient. This equation is widely used in several models with or without modifications. These modifications are mainly focused on k. It has been shown that k needs to be calibrated for each catchment as it depends on many parameters corresponding to surface characteristics (Nakamura, 1984; Sonnen, 1980), rainfall and runoff characteristics (Ammon, 1979; Nakamura, 1984; Sonnen, 1980) and particle size (Ammon, 1979; Sonnen, 1980). Apart from refinement in the estimation of k, some studies also suggest other forms of modifications. For instance, a power term to i was suggested to be able to predict the increase in concentration that corresponds to an increase in rainfall rate during an event (Huber and Robert, 1992). Another major modification suggested by Egodawatta et al. (2007) is the inclusion of a multiplicative capacity factor on the right side of the Eq. (1) varies with rainfall intensity for a better modelling of sediment removal. However, most of the above-mentioned refinements are very site specific and not easily transposed or generalised. Also most of these studies paid attention to one single parameter in isolation, thereby ignoring the effect and interactions of other parameters. For instance, although the introduction of a capacity factor by Egodawatta et al. (2007), is shown to be a meaningful modification, has only been investigated against rainfall intensity. An integrated approach which is lacking in these studies is necessary to investigate the combined effect of dominant parameters associated with rainfall characteristics, surface characteristics and sediment characteristics. Another interesting observation is the lack of attention given to the surface slope in the above studies. Two processes that drive sediment mobilisation are impact energy from rainfall drops (Coleman, 1993) and shear stress from overland flow (Akan, 1987; Deletic et al., 1997) both of which are sensitive to surface slope especially the latter. With the exception of Nakamura (1984) none of the above studies paid attention to the effect of slope. Nakamura (1984) results show that k increases with surface slope, but this study was based only on two randomly selected slopes and was not extensive enough to be used in subsequent studies or in practical applications.

In addition to the calibration of parameter k, another important input to the exponential wash-off equation is the initial load w_o. Sartor and Boyd (1972) provided an exponential equation to calculate the build-up load, which is essentially the initial sediment load in the wash-off prediction. They modelled sediment build-up against antecedent dry days. Although this approach of modelling build-up mainly using antecedent dry days has been used in some models (Bertrand-Krajewski et al., 1993), it has also been criticised, especially in recent studies (Charbeneau and Barrett, 1998; Shaw et al., 2010; He et al., 2010). Among these studies, Shaw et al. (2010) provided an overview of a number of studies which indicated that the mass of washed-off particulate matter during a storm event is relatively insensitive to the time between storm events. This was confirmed by He et al. (2010) who studied the quality of storm-water runoff from a semi-arid, urban residential catchment in Calgary, Alberta. They could not find any relationship between the event mean values of total suspended solids and the antecedent dry weather period. Despite these criticisms, the effect of build-up on wash-off has not been explored in depth in any of the above studies. Hence the question of whether there is a need to model build-up remains unanswered.

Considering the above gaps and room for improvements in sediment wash-off modelling, we designed and carried out a series of laboratory experiments to:

- Study the effect of three dominant parameters corresponding to rainfall, surface and sediment characteristics in an integrated and systematic way. These parameters are, rainfall intensity (i), surface slope and initial load (w_o) respectively., and
- Improve Eq. (1) using the experimental results focusing on the effect of the above three parameters.

2. Methodology

2.1. Experimental setup

Experiments were conducted in a full-scale laboratory setup, described in Fig. 1, comprising of a rainfall simulator (Carvalho et al., 2014; de Lima et al., 2013; Isidoro and Lima, 2013; Montenegro et al., 2013), a 1 m^2 bituminous road surface and a continuous wash-off measuring system. Steady artificially simulated rainfall was employed in order to eliminate the dependency on naturally occurring rainfall. This approach provides better control over influential variables such as rainfall intensity and duration. Consequently, the use of simulated rainfall enables the generation of a large volume of data in a relatively short period of time (Herngren et al., 2005).

A typical urban road surface of 1 m^2 was prepared for the experiments by using bituminous asphalt concrete (Fig. 2). The surface was tested for texture and impermeability before the experiments. Surface texture was measured using sand patch tests (Highway Department, 1989) on 16 equally divided grids. The mean texture depth index is 0.4 mm with a standard deviation of 0.03 mm. This surface texture is an average representation of wide ranges of impervious urban surfaces where the mean texture depth index varies from ~0 (tiled pavements) to ~1.0 mm (road surfaces). Mass balance of surface runoff was carried out to check the impermeability and the results show that the surface is completely impermeable. This surface was fixed on a metal support structure with adjustable slope as shown in Fig. 1.

The rainfall simulator (Fig. 1) has a pressurised hydraulic system comprised of: (i) a steady downward oriented full-cone nozzle (1/4-HH-14 W FullJet from Spraying Systems Co., USA), with 3.58 mm orifice diameter, positioned 2.2 m above the geometric centre of the surface; (ii) a hydraulic system attached just in front of the nozzle to eliminate pressure fluctuations (more details in Isidoro and Lima, 2013); and (iii) a submerged pump (76.2 mm SQ from Grundfos Holding A/S, Denmark), installed in a constant head reservoir supplied with tap water. This system allows a steady operating pressure at the nozzle to produce rainfall with consistent intensity, with a spray angle of 120° (wide angle). The pressure at the nozzle is adjusted to change the rainfall intensity. D_{10} and D_{90} of the sand used in the experiment are 300 μm and 600 μm respectively. It is a washed, dried and accurately graded sand, free from organics, clay, silt or metallic inclusions and has a sub-angular to semi-rounded shape.

The effect of three parameters: rainfall intensity, surface slope and initial sediment load on sediment wash-off were tested. Five intensities ranging from 33 to 155 mm/h, four slopes ranging from

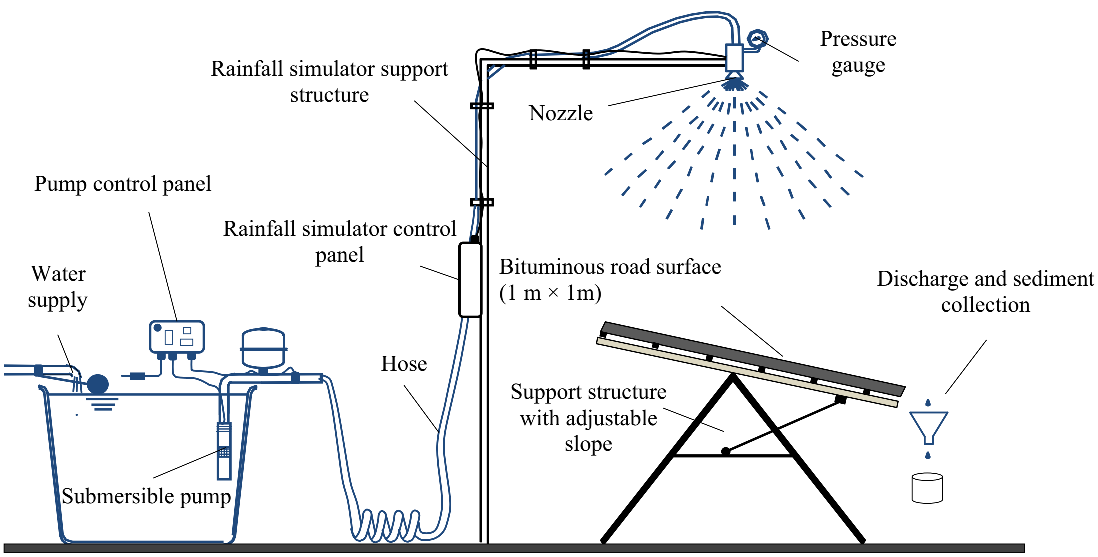

Fig. 1. Sketch of the experimental setup.

Fig. 2. Photographs of (a) Experimental set up during data collection (b) Bituminous road surface with grids and (c) Nozzle with pressure gauge during the experiment.

2 to 16% and three initial loads ranging from 50 to 200 g/m^2 were selected. These upper limits cover the extreme values derived from literature. For example, the highest ever recorded one hour (note that all simulations were carried out for one hour, Table 1) rainfall intensity in UK is 92 mm/h (MetOffice UK, 2017). Further, the UK Department of Transport suggests a maximum gradient of 10% for most types of the road other than in exceptional circumstances (Manual for Streets, 2009). Finally, the average of 'ultimate' sediment loads found in 8 selected urban sites located in Lambeth, UK is 172 g/m^2 (Butler and Clark, 1995). The lower limits were selected using trial simulations to be able to produce a measurable amount of wash-off. Sampling times are adjusted based on the corresponding intensities and at least nine samples were collected for each simulation, see Table 1. Note that for the 2% slope the wash-off load was found to be less than 2% of the initial load even for the highest intensity of 155 mm/h; hence only simulations with an initial load of 200 g/m^2 were carried out for this slope. All wash-off samples were collected using numbered foil containers and then these foil containers were dried using standard laboratory moisture extraction ovens until they are completely dry. All dried sam-

Table 1
Summary of experimental conditions and sampling frequency.

Slope (%)	Initial load (g/m^2)	Sampling times (min)
2%	200	5, 10, 17, 25, 31, 38, 45, 52, 60 [for intensities 33 mm/h and 47 mm/h] 2, 5, 8, 13, 19, 25, 31, 38, 45, 52, 60 [for intensities 75 mm/h, 110 mm/h and 155 mm/h]
4%	50,100,200	
8%	50,100,200	
16%	50,100,200	

ples were then weighed using a high precision (accuracy of 0.1 g) laboratory measuring scale.

2.2. Quality control

The bituminous road surface was subdivided into 16 equal grid squares (Fig. 2b) to aid distribution of the sediment uniformly over the surface. Initially, trial tests were repeated with the same conditions (rainfall intensity, surface slope and initial load) to confirm that the experimental setup gave consistent results. Comparing results from these repeated tests showed that the difference was within ±2%. At the end of both the trial and the actual tests, the remaining sand from the surface was collected by washing off the surface to carry out a mass balance check. In all cases, the mass loss was found to be less than 2% of the original sediment load ensuring that there is no significant loss of sand during the tests.

3. Results and discussion

3.1. Experimental results

To compare the results from different initial loads on a common scale, we used a normalised measure, the wash-off fraction (F_w) which is a ratio between transported sediment load after time t (w_t) and initial load of the sediment (w_o) (Eq. (2)). Fig. 3 shows the wash-off fraction plotted against the duration for all of the tests summarised in Table 1.

$$F_w = \frac{w_t}{w_o} \tag{2}$$

The most interesting observation is the effect of initial load on F_w. Initial load does not affect F_w until the slope gets steeper (8% and 16%). Even in the case of 8% slope, initial load has an effect only when the rainfall intensity is higher than 110 mm/h. In these cases there is an increasing pattern of values of F_w with increasing initial load. These combinations of high rainfall intensity and steep slope where the initial load has an impact on F_w are very rare in reality (MetOffice UK, 2017; Manual for Streets, 2009). It implies that the effect of initial load on F_w is negligible for most general combinations of rainfall intensity and surface slope. This essentially means the actual mass of sediment washed off at any given time (w_t) is proportional to initial load for a given rainfall intensity and surface slope. Hence the prediction of build-up is perhaps the most preferred way to subsequently predict wash-off compared to the methods presented in recent studies (e.g. Shaw et al., 2010). But on the other hand, as Shaw et al. (2010) correctly pointed out, it is a challenging task to model the build-up process due to unpredicted occurrences of activities like construction work or the input of vegetative debris from wind storms. Despite these challenges the strong correlation observed between build-up load and wash-off load indicates the importance of modelling the

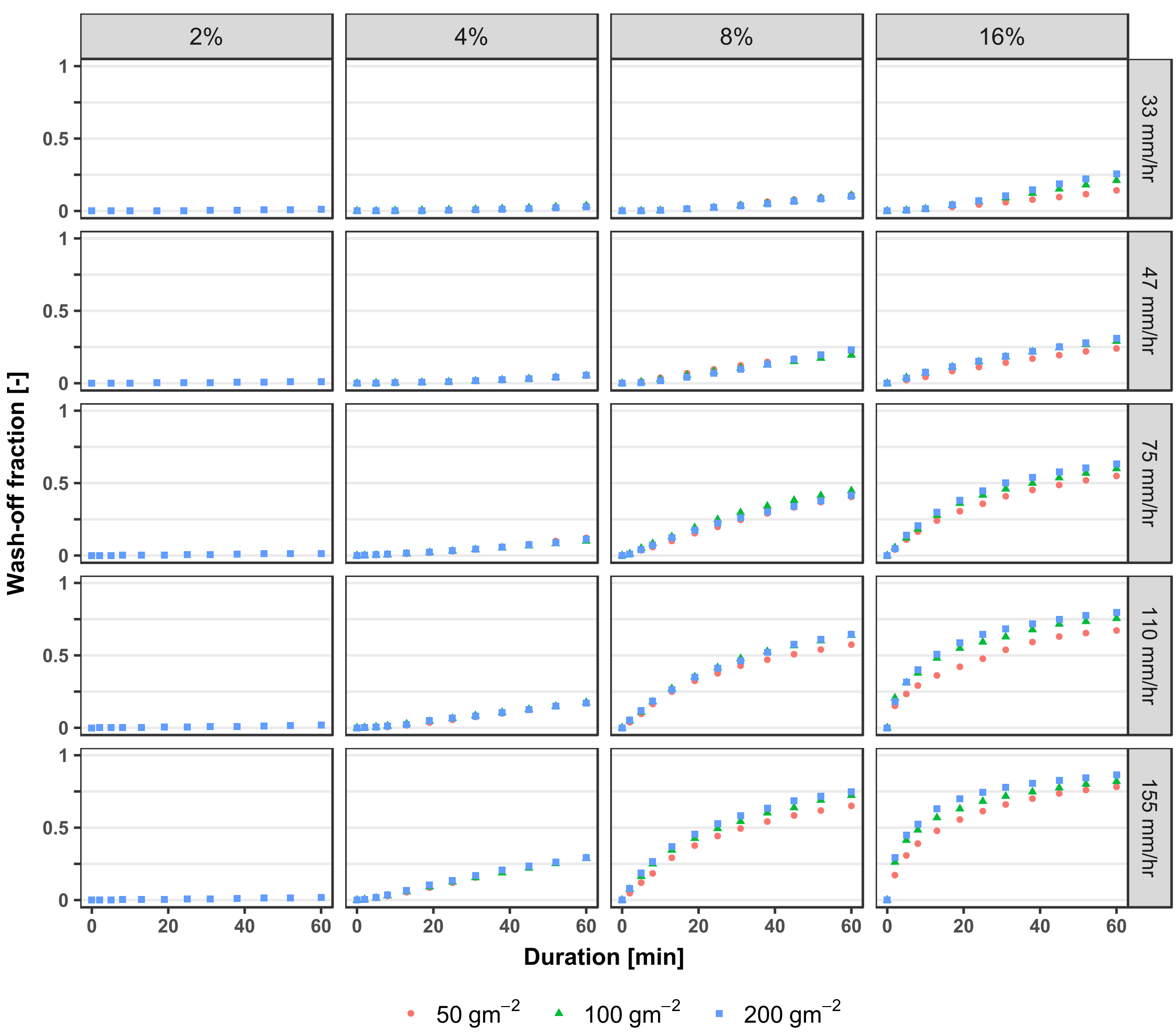

Fig. 3. Wash-off fraction for all combinations of rainfall intensity, surface slope, and initial load.

build-up process. This observation does not necessarily invalidate the criticisms on the build-up model of Sartor and Boyd (1972) by Charbeneau and Barrett (1998), Shaw et al. (2010) and He et al. (2010) as their criticism is mainly on the use of antecedent dry days as the main parameter controlling the build-up process. Rather this finding calls for more attention to be paid on modelling of build-up process taking more parameters (Wijesiri et al., 2015; Morgan et al., 2017) into consideration in addition to antecedent dry days.

Looking at the effect of intensity and slope, for a given intensity, F_w increases with increasing slope regardless of initial load. Similarly, for a given slope, F_w increases with increasing intensity regardless of the initial load. At 2% slope, the wash-off load is negligible for all the rainfall intensities with a maximum F_w of 0.018 at the highest rainfall intensity of 155 mm/h. The highest F_w after one hour is ~0.9 for the extreme case where intensity, slope and initial load are 155 mm/h, 16% and 200 g/m^2 respectively.

Another important observation from Fig. 3, especially at steeper slopes (8% and 16%), is that only a certain fraction of the available sediment is mobilised during a simulated rain event before the curve becomes almost flat and this maximum fraction increases with rainfall intensity and surface slope. This behaviour suggests a rainfall event for a given surface slope has the capacity to mobilise only a fraction of sediment from the road surface and once it reaches that capacity, as observed during the experiments, wash-off becomes almost zero even though a significant fraction of the original sediment is still available on the surface. Although at milder slopes (2% and 4%) the wash-off fraction has not reached its maximum value within the duration of the test, it would have reached this value if the tests were long enough. This trend was also observed in a similar study by Egodawatta et al. (2007) in which they analysed this maximum fraction against rainfall intensity. Hence there are two parameters which characterise these curves; wash-off rate and maximum fraction both of which increase with increasing slope and increasing intensity. The negative inverse exponential pattern (NIE) of these curves can mainly be attributed to the first flush effect. The concept of first flush is that the initial period of storm flow carries most of the pollutant including sediments from the urban surface (Helsel et al., 1979; Sansalone and Steven, 1997; Bertrand-Krajewski et al., 1998). The most common value of k – 4.6 in^{-1} (0.18 mm^{-1}) in Eq. (1) is basically derived from the concept that the first one-half inch of total run-off in one hour would wash-off 0.9 fraction of the initial load (Huber and Robert, 1992).

But such generalisation is not valid for all the conditions as can be seen in Fig. 3 where the strength of first flush changes with rainfall intensity and surface slope. We believe, in addition to rainfall intensity and surface slope, surface texture and sediment size also play a major role in deciding the strength of the first flush. Fig. 3 shows the effect of first flush is negligible during smaller intensities and milder slopes. This can mainly be attributed to the surface texture depth and/or sediment size used in the experiments. If it is a smoother surface typically associated with roofs, the effect of the first flush will possibly be magnified (Farreny et al., 2011). Also with a smaller sediment size, one would expect a more pronounced first flush and a higher wash-off fraction. For instance, Egodawatta and Goonetilleke (2008) in their study found that the most of the sediment that is washed off initially is the finer sand (<200 μm). But it can be noted that the range of sediment sizes used in Egodawatta and Goonetilleke (2008) is much wider (0–1000 μm) compared to the sediment size used in this study which also explains the higher wash-off fractions they observed in a similar experimental setup. Although we would expect an increase in wash-off fraction with smaller sediment size there is also a possibility for smaller sediment to get trapped in the pores of the surface due to the surface roughness and so significantly reduce their mobility. But on the other hand, if the sediment size is bigger than the surface texture depth, it might be too large for the rainfall impact to mobilise the particles and for the runoff process to transport it, especially on mild surface slopes. When the surface is rougher similar to the one used in this study the interaction between sediment size and texture depth becomes complicated and it needs to be explored in depth.

3.2. Model improvement

We attempt to modify Eq. (1) based on the experimental data discussed in Section 3.1. From Fig. 3 and the corresponding discussion, it is clear that the effect of the initial load on the wash-off fraction is negligible for most cases. Hence the effect of initial load has not been considered in this section and a modification in Eq. (1). is proposed based only on experimental results from a constant initial load of 200 g/m^2.

As discussed in the previous section, only a certain fraction of the available sediment is mobilised during a simulated rain event before the curve becomes almost flat and this fraction increases with rainfall intensity and surface slope. To replicate this behaviour in the modelling of wash-off, Egodawatta et al. (2007) introduced a new parameter called the capacity factor (C_F), ranging from 0 to 1, into Eq. (1) as shown in Eq. (3).

$$\frac{W_t}{W_o} = C_F(1 - e^{-kit}) \tag{3}$$

But due to the limitations of their study, they concluded that C_F primarily varies with rainfall intensity, disregarding the effect of other parameters such as slope. But from Fig. 3 it is clear that this fraction of sediment which a rainfall event has the capacity to wash-off also strongly depends on the surface slope in addition to rainfall intensity. This implies C_F needs to be adjusted according to the surface slope too. Hence C_F which is the maximum fraction available and k which defines the wash-off rate both need to be calibrated for all combinations of rainfall intensities and surface slopes. From Fig. 3 it can also be noted that the higher the maximum fraction, the faster the F_w reaches the maximum fraction meaning these two parameters are dependent. Fig. 4 is a simplified version of the experimental results to illustrate this concept where the maximum wash-off fractions are indicated by F_{w1}, F_{w2}, and F_{w3} and the time taken to reach these fractions are indicated by t_1, t_2 and t_3 respectively. This figure shows that $F_{w1} < F_{w2} < F_{w3}$ and consequently $t_1 > t_2 > t_3$. Applying this concept into Eq. (3) suggests that C_F and k are dependent. Therefore it was decided to make C_F a function of k as shown in Eq. (4) instead of introducing a new C_F altogether as in Egodawatta et al. (2007). This way it does not only give some physical meaning to this empirical equation, but also avoids the compensation of two independent parameters in order to over fit the experimental results. Such compensation between two independent parameters could lead to identifiability problems (Sorooshian and Gupta, 1983).

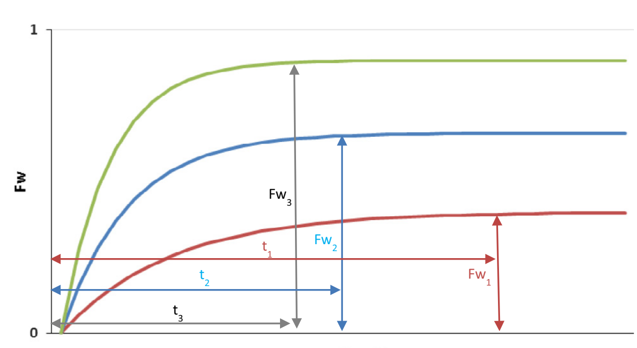

Fig. 4. Variation of maximum wash-off fraction and corresponding duration.

$$\frac{w_t}{w_o} = f(k)(1 - e^{-kit}) \tag{4}$$

Having introduced a new C_F in the form of $f(k)$, the next step is to estimate this $f(k)$ and subsequently estimate the k values for each combination of slope and intensity. The following steps explain the procedure to estimate $f(k)$ and k values.

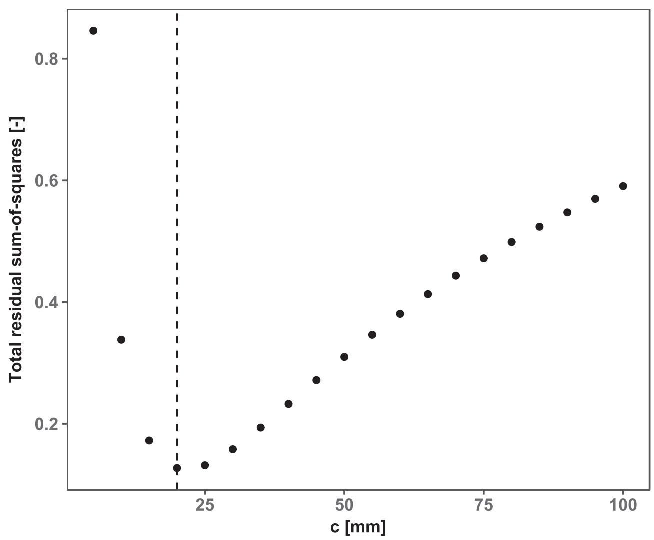

Fig. 5. Total sum of residual-sum-of-squares plotted against c values ranging from 0 to 100, the dashed line shows the c value at which the total residual sum-of-squares is minimum.

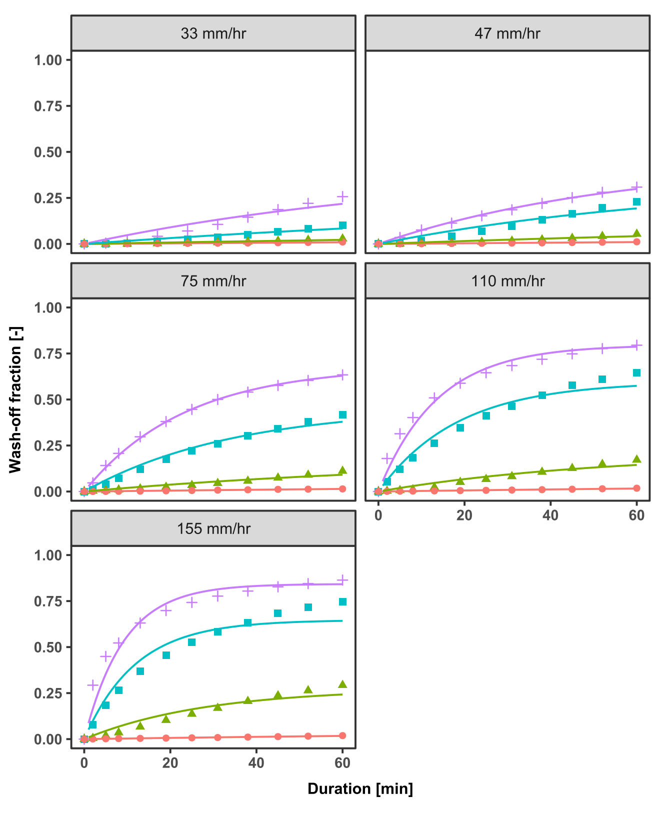

Fig. 6. Measured wash-off fraction (points) and corresponding fitted curves (lines) derived from Eq. (5) (for $c = 20$ and k' values as shown in Fig. 7.) for all combinations of rainfall intensity and surface slopes where initial load is 200 g/m^2.

1. The first step is to find $f(k)$ which best fits the experimental results. To keep the new equation as simple as possible, $f(k)$ is assumed as a factor of k which leads to the following equation:

$$\frac{w_t}{w_o} = ck'(1 - e^{-k'it}) \tag{5}$$

where c is a constant with a unit of mm as unit of k' is mm^{-1}. Note that k is changed to k' since the new values for k' will be different from conventional k values.

2. The next step is to estimate the value of c (constant) and k' (varies with slope and intensity) which gives the smallest residual sum-of-squares between the fitted models and experimental results. Hence for a given value of c, the residual sum-of-squares are calculated for 20 fitted curves derived from 20 k' values each corresponding to a combination of a slope and an intensity. The objective function is to minimise the sum of all residual sum-of-squares derived from these 20 curves for different c values. There are two constraints. The first constraint is that c and k' cannot have negative values and the second constraint is that the product of c and k' cannot exceed the maximum possible fraction which is 1.

Fig. 5 shows the sum of residual sum-of-squares plotted against the range of c. It can be seen that the sum of residual sum-of-squares is at its minimum when c is 20. The corresponding fitted curves with different k' are shown in Fig. 6 for all the combinations

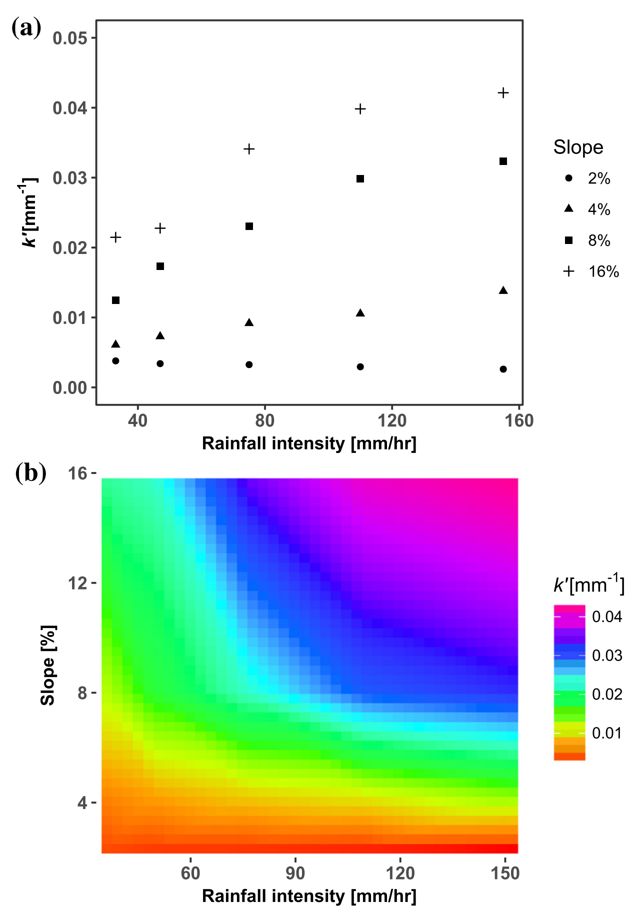

Fig. 7. (a) Derived k' values for all the combinations of rainfall intensity and surface slope and (b) raster image of interpolated k' values over the domain.

of intensity and slope where the initial load is 200 g/m^2. The sum of the residual sum-of-squares for all these fitted curves is only 0.13 which shows the model fits well with the experimental results.

The k' values derived from the fitted models corresponding to a c value of 20 are plotted against intensity for each slope in Fig. 7(a). Fig. 7(b) shows the surface plot that is obtained by linearly interpolating k' values over the domain. From both plots, it can be noted that the rate of change in k' values against slope increases with increasing rainfall intensities. At 2% slope, the change of k' against rainfall intensity is negligible due to the negligible difference in the wash-off fraction against rainfall intensity at this slope. At 8% and 16% slopes the rate of change in k' values after 110 mm/h shows a drop. This is a reflection of the similar drop in the increase in the wash-off fraction as can be seen in Fig. 6. The k' values range from 2.6×10^{-3} to 4.2×10^{-2} which gives a range of 0.05–0.84 for C_F (=20 k'). The highest C_F of 0.84 corresponds to the extreme case where intensity and slopes are 155 mm/h and 16% respectively.

When transferring these c and k' values to other catchments other parameters has to be taken into account especially the sediment size and surface texture. Both the capacity factor ($c \times k'$) and wash-off rate (represented by k') would most likely to increase with decreasing sediment size and/or decreasing surface texture depth. Nevertheless, the improved model structure as shown in Eq. (5) is expected to perform well for any sediment size and surface texture as the underlying physical processes will be the same as those on which the equation was developed.

4. Conclusions

In this study, we investigated the effect of rainfall intensity, surface slope and initial load on sediment wash-off using an artificial rainfall generator and a typical urban road surface of 1 m^2. There has not been a previous experimental study which explored the effect of all the above three dominant parameters on wash-off in an integrated and systematic way.

The experimental results show that:

- The effect of initial load on wash-off fraction at any given time is negligible for most general combinations of rainfall intensity and surface slope. This essentially means that the washed off load at any given time is proportional to initial load for a given combination of a rainfall intensity and a surface slope. Hence, a dedicated modelling approach to predict build-up to help subsequently predict wash-off, despite the challenges mentioned in Shaw et al. (2010) should not be overlooked.
- The negative-inverse-exponential (NIE) trend due to the effect of first flush is clearly observed at combinations of catchment slopes steeper than 8% and rainfall intensities higher than 75 mm/h. For combinations of milder slope and lower rainfall intensity, the effect of first flush becomes negligible. Note that these threshold values could be different for a different sediment size and/or a different surface roughness.
- A rainfall event has the capacity to mobilise only a fraction of sediment from the road surface and once it reaches that capacity, as observed during the experiments, wash-off becomes almost zero even though a significant fraction of sediment is still available on the surface. The maximum fraction that can be washed off from the surface increases with both rainfall intensity and the surface slope.

This final observation above led us to the second part of the study where the existing wash-off model is modified by introducing a capacity factor which defines the maximum fraction. This capacity factor is derived as a function of wash-off coefficient making use of the correlation between maximum fraction and the wash-off rate. This new and improved equation is expected to perform better compared to the original equation as it models the underlying physical process better. Values for the wash-off coefficient are derived for combinations of rainfall intensity and slope which can be transferred to other urban catchments with similar conditions. In the future, in addition to the initial load, rainfall intensity and surface slope, it is important to examine the effect of surface texture and sediment size on the wash-off process. This way a complete matrix of values for capacity factor and wash-off coefficient can be derived which can be transferred to any urban catchments.

Acknowledgements

This research was carried out as part of the Marie Curie ITN – Quantifying Uncertainty in Integrated Catchment Studies project (QUICS). This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under Grant Agreement no. 607000.

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