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Acronyms and Abbreviations

EMC	Event Mean Concentration
BUWO	Build-up and wash-off
NIE	Negative Inverse Exponential

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Executive Summary

In this report we present the development of an improved sediment wash-off model for urban impervious surfaces. This work consists of the following three major parts. Firstly, notable previous studies on sediment wash-off models for urban road surfaces were reviewed and the room for improvement was explored. Based on the findings it was decided to investigate the effect of rainfall intensity, surface slope and initial load on sediment wash-off in a systematic and integrated way. Secondly, 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. Finally, the most widely used exponential wash-off model was improved using the experimental results to take into account the effect of rainfall intensity, surface slope and initial load. This model has been hosted in a web platform for anyone to access and use it. This report also discusses the current limitations and potential extensions of the new wash-off model.

CONTENTS[1]

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[1] *Part of this report is taken from the manuscript titled "Improving the understanding of the underlying physical process of sediment wash-off from urban road surfaces" submitted to Journal of Hydrology (manuscript number: HYDROL25273)*

1. Introduction[2]

1.1 Background

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 rainfall and/or rainfall runoff. These impervious urban surfaces mainly include streets, highways, roofs, and parking areas. The most common pollutant transported by rainfall run-off is sediment which can play a major role in water quality issues of inland surface water bodies in urban areas. Sediments can also contribute to urban floods by depositing in sewers and storm drains and other urban drainage structures that carry water away from roads, impermeable surfaces and building roofs. Further wash-off is often a boundary condition for piped drainage systems. Hence the importance of accurate modelling of sediment wash-off is vital in water quality based decision making. Modelling sediment wash-off is not a straightforward exercise as it often involves using empirically calibrated relationships containing physical parameters that are highly variable in nature such as rainfall, surface and particle characteristics. There are mainly two processes involved in simulating sediment wash-off from an impervious surface; Build-up and Wash-off. Build-up is a process in which sediment accumulates in dry periods. Wash-off is the process where accumulated dry deposition is removed from impervious surfaces by rainfall and/or runoff and incorporated in the flow (Francey et al. 2011). Modelling of pollutant wash-off ranging from simple EMC (Event Mean Concentration, Kayhanian et al. 2007; Charbeneau and Barrett 1998) to sophisticated BUWO (Build-up Wash-off models). An EMC model assumes a single flow weighted concentration can be used across an entire storm event (Charbeneau and Barrett 1998) whereas BUWO models captures dynamics in wash-off load within an event. 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. Hence among the two processes involved in sediment transport from urban surfaces, wash-off process gets most of the attention from the researchers as wash-off load is what urban quality and flood modellers are interested in. The following section reviews some of the widely used wash-off models.

[2] Most part of this chapter is taken from *the manuscript titled "Improving the understanding of the underlying physical process of sediment wash-off from urban road surfaces" submitted to Journal of Hydrology (manuscript number: HYDROL25273)*

1.2 Review of existing wash-off models

1.2.1 Modelling of wash-off process

Wash-off loads can generally be estimated by using variables such as total runoff volume, total event rainfall, runoff rate, and rainfall intensity or a combination of these variables. But out of these variables aggregate measures such as total runoff volume, and total event rainfall will not be able to predict the intra event load dynamics and will not be suited to study the effect of temporal variability of rainfall on sediment loads.

Hence runoff rate and rainfall intensity are preferred by the urban modellers to predict sediment wash-off in urban areas. Although both of these approaches have been used in literature, recently more emphasize has been given to rainfall intensity in predicting sediment wash-off (Egodawatta et al. 2007; Chiew and Vaze 2004; Shaw et al. 2010) mainly due to its ability to explain the spatial variability in the observed sediment load. Another practical advantage of using rainfall data is that it provides a practical means of predicting sediment loads as it is one of the most readily available data (Francey et al. 2011)

1.2.2 Exponential model and associated improvements

One of the earliest studies on sediment wash-off was 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

$$w_t = w_0\left(1 - e^{-kit}\right) \tag{1}$$

where w_t is transported sediment load (g/m^2) after time *t* (hr), w_0 is initial load of the sediment on the surface (g/m^2); *i* is the average rainfall intensity until time *t* (mm/hr); and *k* is wash-off coefficient (mm^{-1}). This equation has widely been used in several models with or without modifications. These modifications were 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/or runoff characteristics (Ammon 1979; Nakamura 1984; Sonnen 1980) and, particle size (Ammon 1979; Sonnen 1980). Apart from refinement in the estimation of *k,* there are also some other modifications suggested by a few studies. 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 Dickinson 1992). Another major modification suggested by Egodawatta et al. (2007) is the multiplication of a capacity factor which 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, the introduction of a capacity factor by Egodawatta et al. (2007), although 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 and channel 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 the subsequent studies or in practical applications.

In addition to the calibration of parameter *k*, another important input to this equation is the initial load w_0. Sartor and Boyd (1972) provided an exponential equation to calculate the build-up load, which is essentially the initial sediment load in wash-off prediction, where they modelled 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 recently (Charbeneau and Barrett 1998; Shaw et al. 2010; He et al. 2010). 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. Although this modeling approach to predict build-up proposed by Sartor and Boyd (1972) was criticised in the above studies, 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.

1.2.3 Other wash-off models

In addition to the well-known exponential wash off model described in section 1.2.2, there are some other models which have been proposed and used in a few studies (e.g. Duncan 1995, Francey et al. 2011; Shaw et al. 2010; Zhao et al. 2015), but none of them have been applied and tested as extensively as the model proposed by Sartor and Boyd (1972). Among these, the regression model proposed by Duncan (1995), which uses a simple regression approach as presented in Equation 2, is the most widely used model.

$$Event\ Load = \sum_{i=1}^{n} aI^b \tag{2}$$

Where *I* = rainfall intensity as recorded in each of the n time steps (mm/hr); and *a* and *b* = calibration coefficients depending on the surface and sediment characteristics; *n* =

number of time steps over the period of interest. *I* is calculated by assuming that total rainfall depth, recorded in one time step, occurred just within that very time step. Therefore, *I* strongly depends on the resolution of rainfall records. The above model was formulated based on a regression modelling approach and the cumulative nature of this model represents the on-going input of energy produced by raindrop impact. The applicability of this model or a very similar approach (eg: Σ runoff rate models, square of the rainfall intensity) has only been tested in a very few studies (Chiew and Vaze 2004; Brodie 2007; Francey et al. 2011). Inadequate representation of the initial load of sediment in this approach is another major drawback of this model given the lack of evidence to show it is justifiable.

1.2.4 Summary of findings and the room for improvement

- Among the models used to predict the wash-off load, the exponential model originally proposed by Sartor and Boyd (1972) together with its modified versions are the most widely used and tested models.
- Most of the refinements applied to Eq.1 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 interaction of other parameters. Thus, highlighting the lack of an integrated approach in these studies which is necessary to investigate the combined effect of dominant parameters associated with rainfall characteristics, surface characteristics and sediment characteristics.
- In addition to rainfall intensity and the calibration parameter *k*, another important input to this equation is the initial load w_0. Although the use of a build-up equation to derive w_0 has been criticised in a few studies, 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.

1.3 Aim and objectives

1.3.1 Aim

In this study we aim to present a new model which is an improved version of the exponential model proposed by Sartor and Boyd (1972) by incorporating the effect of three parameters which we discussed above; rainfall intensity, surface slope and initial load.

1.3.2 Objectives

1. Carry out a series of laboratory experiments to explore the effect of rainfall intensity (*i*), surface slope and initial load (w_0) on wash-off process in an integrated and systematic way.
2. Use the experimental results derived from step 1 to improve the model presented in Eq. (1).

3. Host the improved model derived from step 2 in a website where anybody can access and use it.

2. Model improvement[3]

2.1 Experimental set-up

Experiments were conducted in a full scale laboratory setup, described in Fig. 1, comprising of a rainfall simulator (used in, for example, 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. The surface was tested for texture and impermeability before the experiments. Surface texture was measured using sand patch tests (Highway Department UK 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 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.

Table 1: Summary of experimental conditions and sampling frequency

Slope (%)	**Initial load (g/m^2)**	**Intensity (mm/hr)**				
		33	**47**	**75**	**110**	**155**
2%	200	9 samples at 5, 10, 17, 25, 31, 38, 45, 52,		11 samples at 2, 5, 8, 13, 19, 25, 31, 38, 45, 52, 60 minutes		
4%	50,100,200					

[3] Most part of this chapter is taken from *the manuscript titled "Improving the understanding of the underlying physical process of sediment wash-off from urban road surfaces" submitted to Journal of Hydrology (manuscript number: HYDROL25273)*

8%	50,100,200	60 minutes
16%	50,100,200	

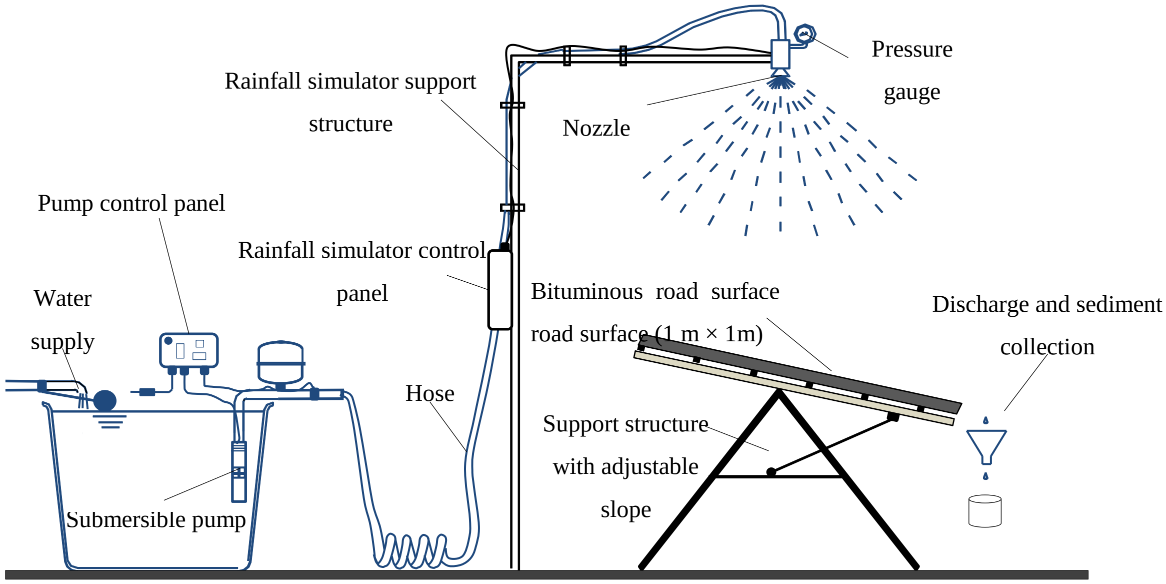

Figure 1: Sketch of the experimental setup

The rainfall simulator (refer Fig. 1) has a pressurised hydraulic system comprised of: (i) a steady downward oriented full-cone nozzle (1/4-HH-14W 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 & 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 high purity 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 33-155 mm/hr, four slopes ranging from 2-16 % and three initial load ranging from 50-200 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 an hour, refer Table 1) rainfall intensity in UK is 92 mm/hr (MetOffice UK 2017). Further the Department of Transport in UK suggests a maximum gradient of 10 % for most of the roads other than in exceptional circumstances (Manual for Streets, 2009). Finally, the average of `ultimate` 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 a few 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 2 % slope the wash-off load was found to be less than 2 % of initial load even for the highest intensity of 155 mm/hr; hence only simulations with 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 samples were then weighed using a high precision (accuracy of 0.1 g) laboratory measuring scale.

2.1.1 Quality control

The bituminous road surface was sub divided into 16 equal squares to be able to distribute the sediment uniformly over the surface. At the beginning, a few trial simulations were repeated with the same conditions (rainfall intensity, surface slope and initial load) to check if the experimental setup gives consistent results. Comparing results from these repeated simulations showed that the difference was only within ±2%. At the end of both the trial and the actual simulations the remaining sand from the surface was collected by washing off the surface to carry out mass balance check. In all cases the mass loss was found to be less than 2 % ensuring that there is no any significant loss of sand during the simulations.

2.2 Experimental results

To compare the results from different initial weights on a common scale, we used a wash-off fraction (ref Eq. 3) a normalised measure which is defined as the fraction of w_t , the weight of transported pollutant after time t, and w_0, the initial weight of the pollutant on the surface. Figure 2 shows the fraction wash-off plotted against the duration for all the simulations summarised in Table 1.

$$F_w = \frac{w_t}{w_0} \tag{3}$$

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 its effect only when the rainfall intensity is higher than 110 mm/hr. In these cases there is an increasing pattern 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.

Looking at the effect of intensity and slope, for a given intensity, the F_w increases with increasing slope regardless of initial load. Similarly, for a given slope, the wash-off fraction increases with increasing slope 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/hr. The highest F_w after an hour is ~0.9 for the extreme case where intensity, slope and initial load are 155 mm/hr, 16% and 200 g/m^2 respectively

Another important observation from the Fig.2, 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 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 simulation, it would have reached this value if the simulations 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 characterises these curves; wash-off rate and maximum fraction both of which increases with increasing slope and increasing intensity.

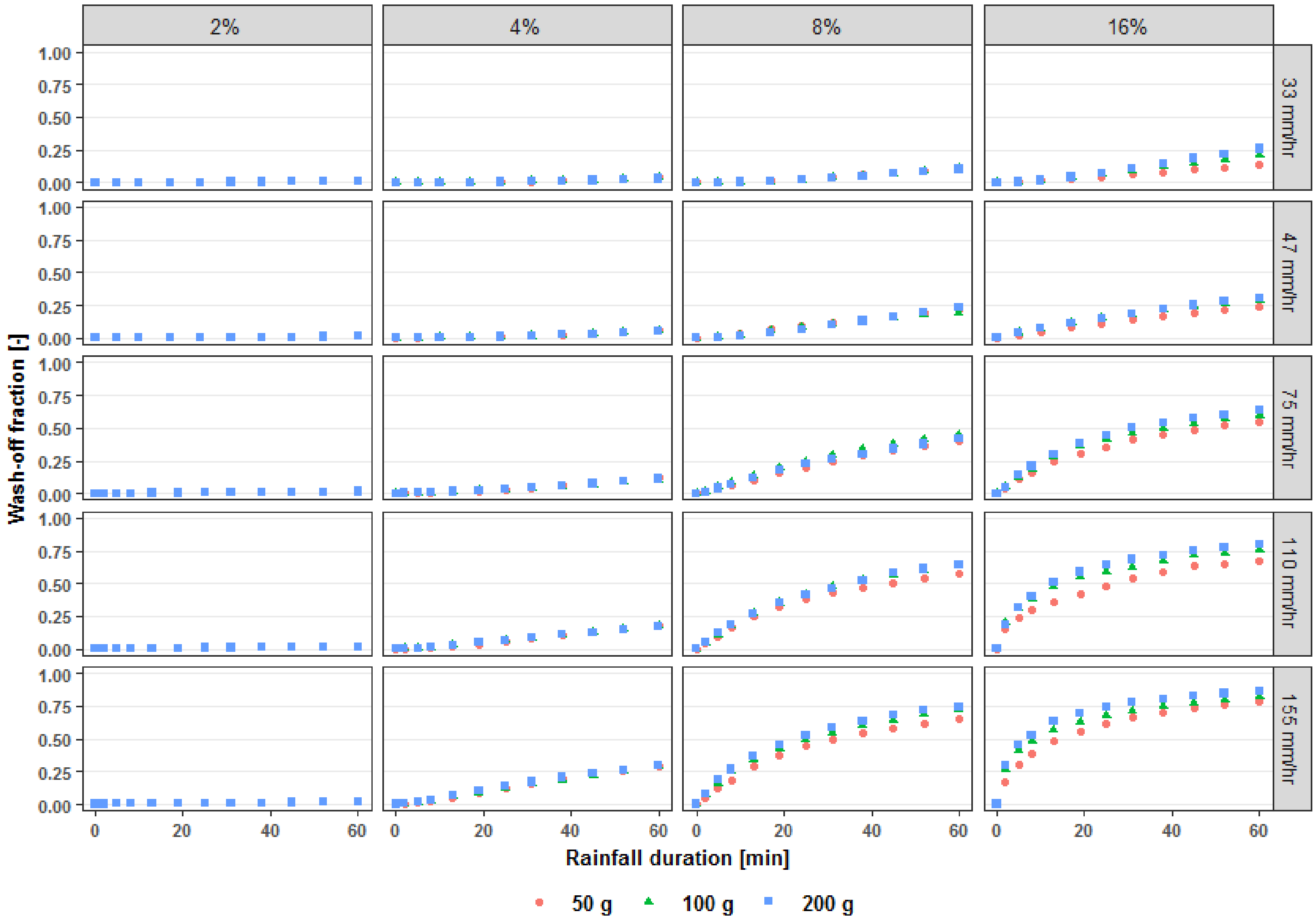

Figure 2: Wash-off fraction for all combinations of rainfall intensity, surface slope, and initial load

2.3 Mathematical interpretation and model refinement

We attempt to modify Eq.1 based on experimental data discussed in Section 2.2. From Fig. 2 and corresponding discussion, it is clear that the effect of initial load on wash-off fraction is negligible for most general 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 section 2.2, 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.4.

$$\frac{w}{w_0} = C_F\left(1 - e^{-kit}\right) \tag{4}$$

But due to the limitation in their study, they concluded that C_F primarily varies with rainfall intensity only disregarding the effect of other parameters such as slope. But from Fig. 2 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 based surface slope too. Hence C_F which is the maximum fraction available and k which defines the wash-off rate both needs to be calibrated for all combinations of rainfall intensities and surface slopes. From Fig. 2 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. Figure 3 is a simplified version of the experimental results to illustrate this concept where the maximum wash-off fractions are indicated by F_{w_1}, F_{w_2} and F_{w_3}, and the time taken to reach these fractions are indicated by t_1,t_2 and t_3, respectively. This figure shows that $F_{w_1} < F_{w_2} < F_{w_3}$ and consequently $t_1 < t_2 < t_3$. Applying this concept in to Eq.4 suggests that C_F and k are dependent. Therefore, we decided to make C_F a function of k as shown in Eq. 5 instead of introducing a new C_F altogether like 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 purely statistical based compensation between two parameters could result in unintelligible correlation between the parameters and intensity or slope.

$$\frac{w}{w_0} = f(k)\left(1 - e^{-kit}\right) \tag{5}$$

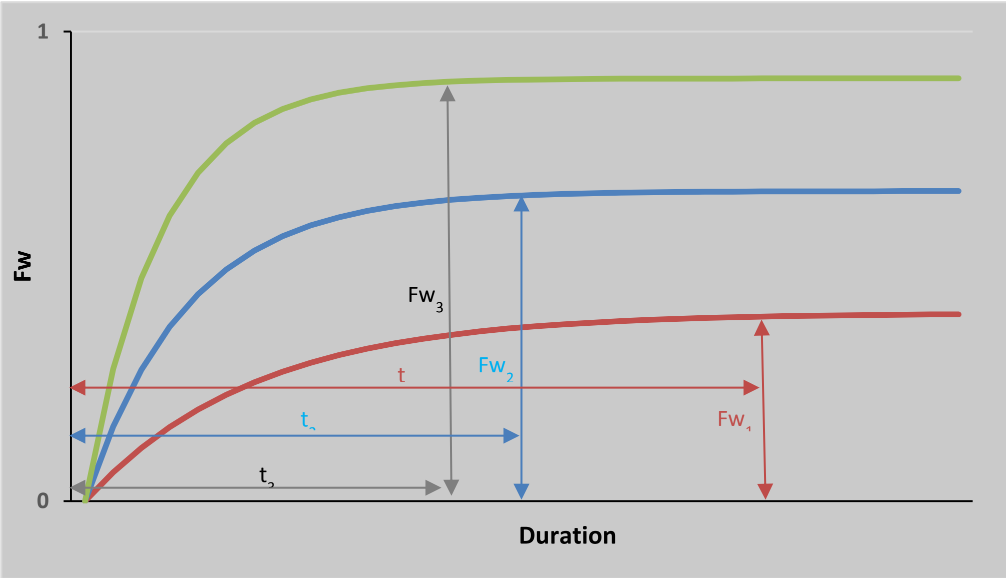

Figure 3: Variation of maximum wash-off fraction and corresponding duration

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 explains the procedure to estimate *f(k)* and *k* values.

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:

$$\frac{w}{w_0} = ck'\left(1 - e^{-k'it}\right) \tag{6}$$

   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 *c* (constant) and *k'* (varies with slope and intensity) which gives the smallest residual sum-of-squares between fitted models and experimental results. Hence for a given value of *c,* residual sum-of-squares are calculated for 20 fitted curves derived from 20 *k'* values each corresponds 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. First constraint is that *c* and *k'* cannot be negative values and the second constraint is that the product of *c* and *k'* cannot exceed the maximum possible fraction which is 1.

Figure 4 shows the sum of residual sum-of-squares plotted against 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. 5 for all the combinations of intensity and slopes where initial load is 200 g/m^2. Sum of residual sum-of-squares for all these fitted curve is only 0.13 which shows the model fits well with the experimental results.

The *k'* values derived from the fitted models corresponding to *c* value of 20 are plotted against intensity for each slope in Fig. 6 (Top). Figure 6 (Bottom) shows the raster image derived by 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/hr shows a drop reflecting the similar drop on increase in wash-off fraction as can be seen in Fig. 5. The *k'* values ranges from 2.6×10^{-3} to 4.2×10^{-2} which gives a range 0.05 to 0.84 for the C_F (=20 *k'*). The highest C_F 0.84 corresponds to the extreme case where intensity and slopes are 155 mm/hr and 16% respectively.

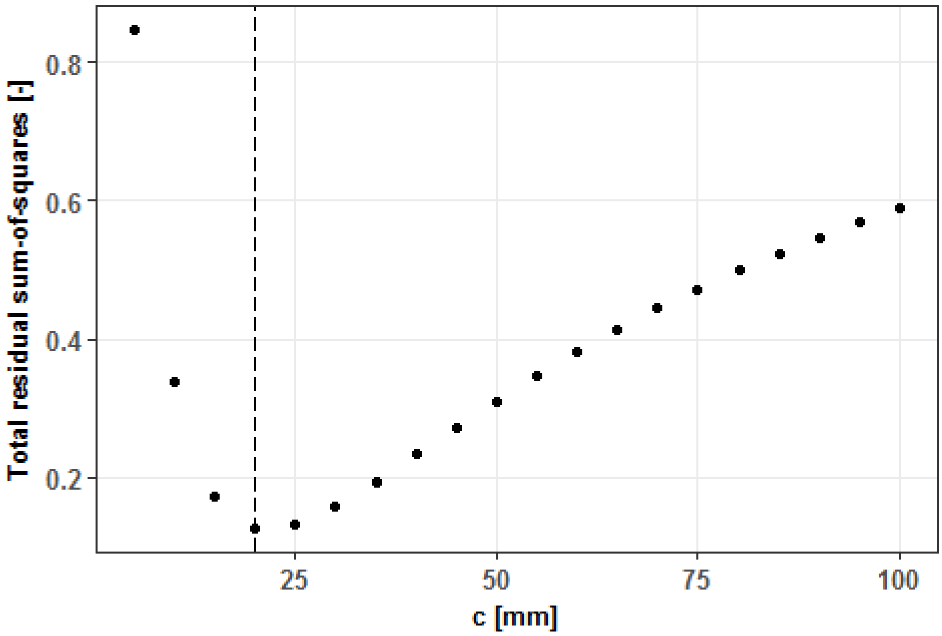

Figure 4: Total sum of residual-sum-of-squares plotted against c *values ranging from 0 to 100, the dashed line shows the* c *value at which the total residual sum-of-squares is minimum*

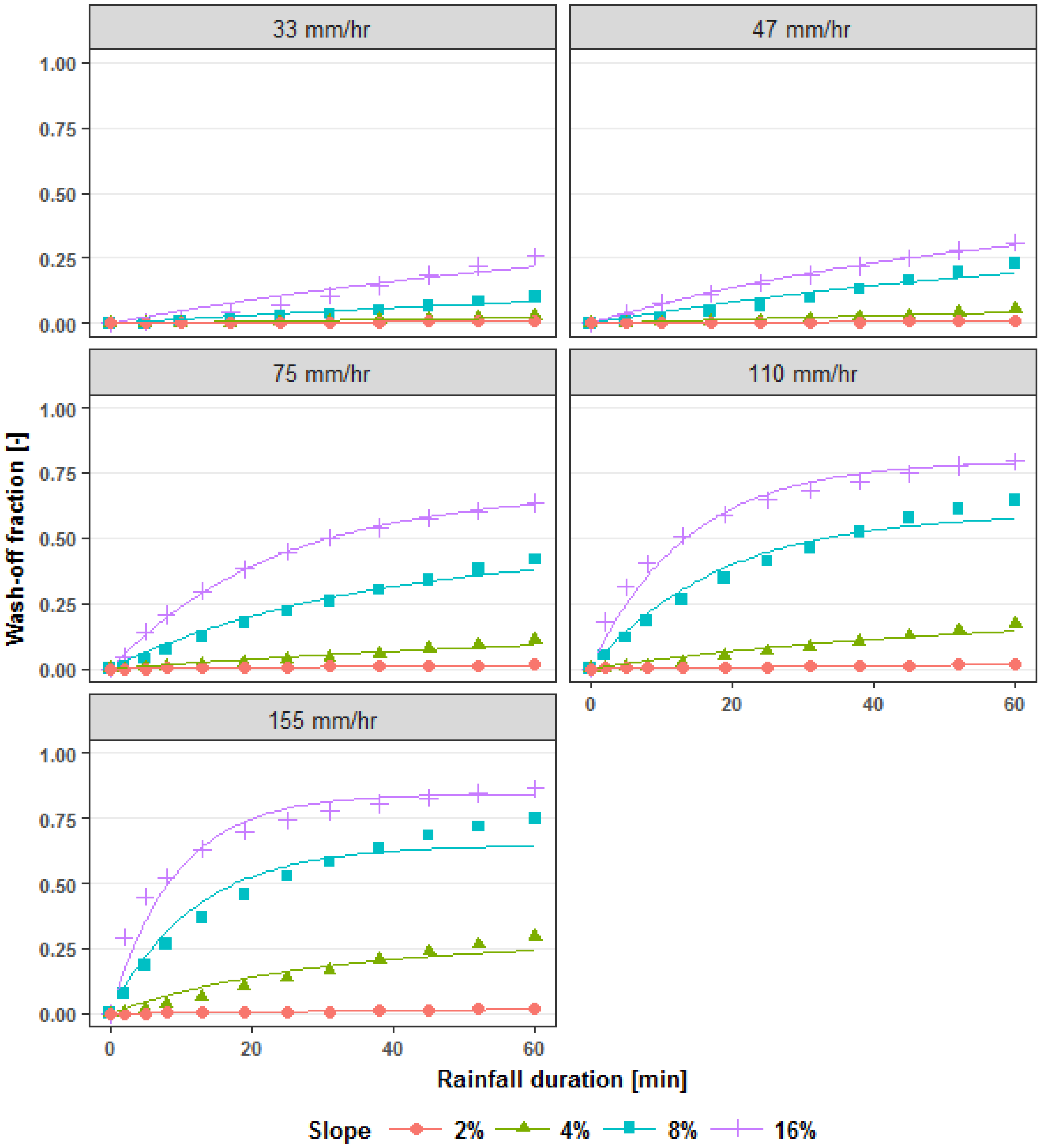

Figure 5: Measured wash-off fraction and corresponding fitted curves derived from Eq. 6 (for c *= 20 and* k' *values as shown in Fig 6.) for all combinations of rainfall intensity and surface slopes where initial load is 200 g/m*^{2}

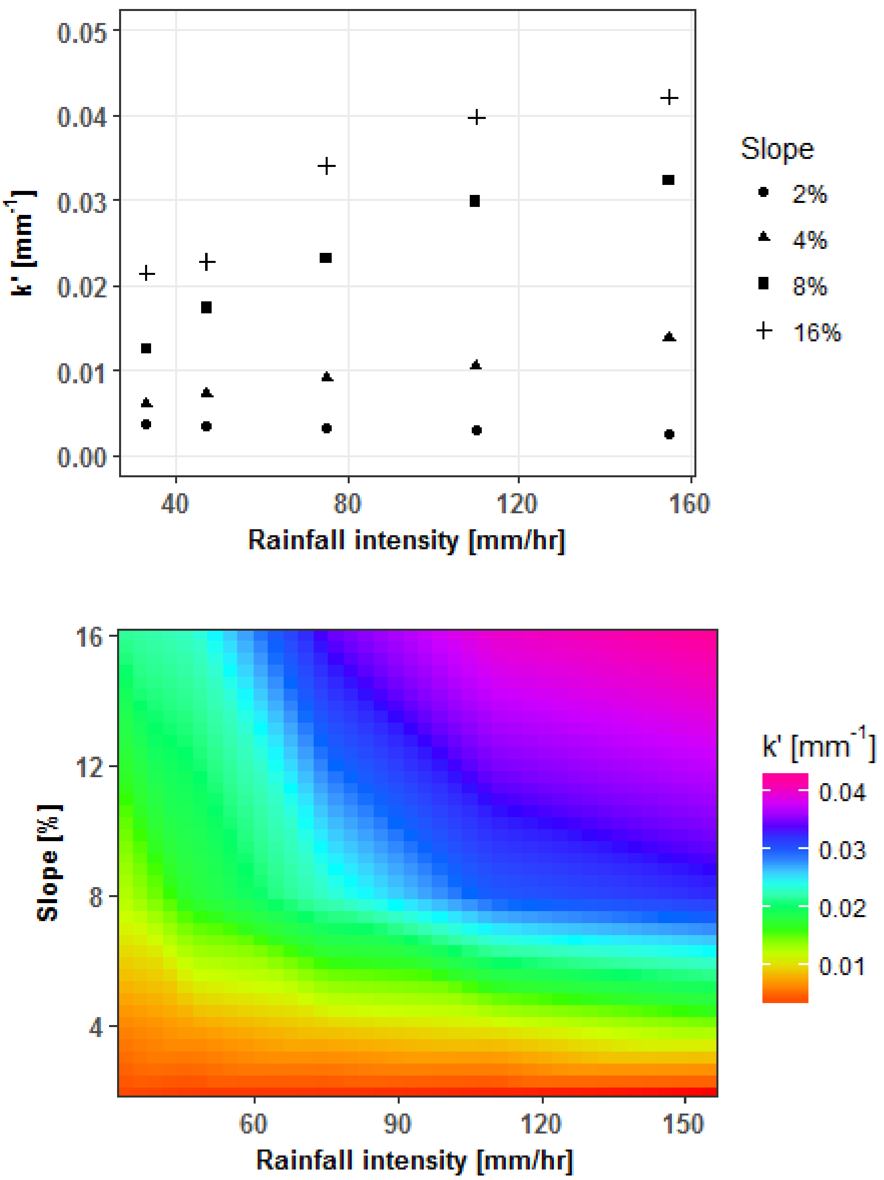

Figure 6: (Top) Derived k' *values for all the combinations of rainfall intensity and surface slope and (Bottom) raster image of interpolated k' values over the domain*

3. Model presentation

The revised model as presented in Eq. 6 (with a *c* value of 20) has been implemented in R and it can accessible at https://mmuthu.shinyapps.io/washoffmodelling-app/. This website is developed using Shiny. Shiny is a web application framework for R. More information on Shiny can be found at https://shiny.rstudio.com/.

3.1 User interface

A screen shot of the user interface is given in Fig. 7. This simple user interface has 4 sections; Model description, Model input, Help and Model Results.

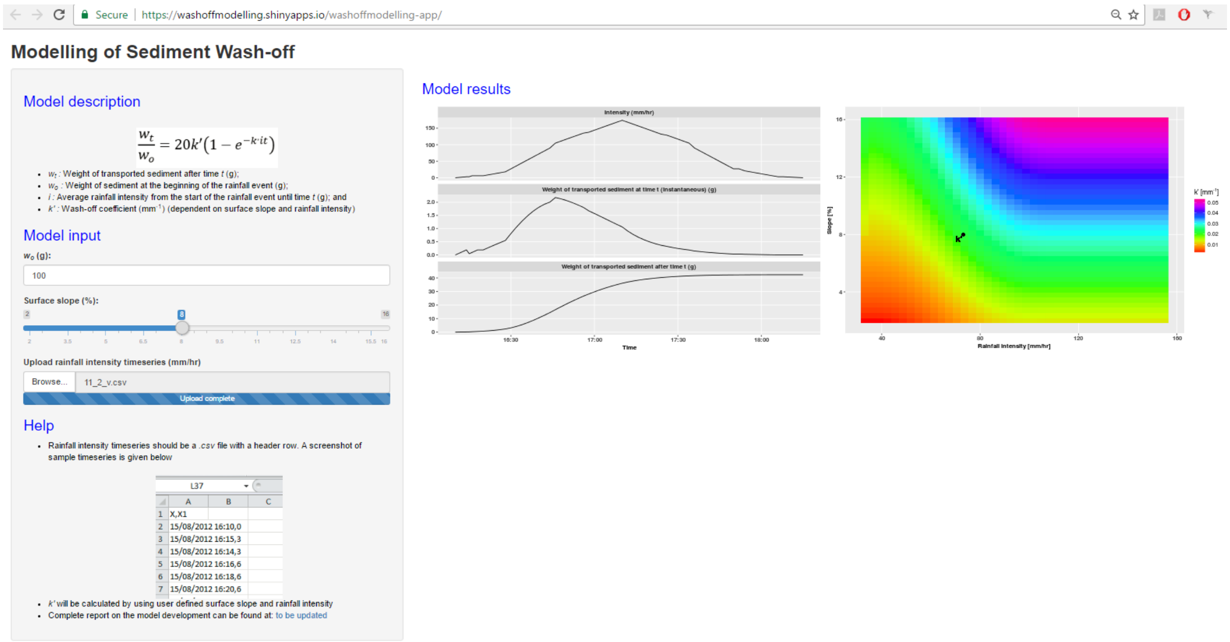

Figure 7: Screen shot of the user interface of wash-off Modelling application accessible at https://mmuthu.shinyapps.io/washoffmodelling-app/.

4. Current limitations and potential improvements

Like most of the models derived from experimental results, this model also comes with limitations mainly due to the experimental conditions under which this model was developed. It should be noted *c* and *k´* values of the Eq.6 were derived for an urban surface with texture depth of 0.4 mm and sediment size range of 300–600 µm. Hence care should be given when these values are transferred to other urban surfaces. For a smaller sand size and smoother surface, the *k´* values are expected to be higher than the values used in this model. Also consider that this model was developed using the simulations where rainfall intensity was kept constant. Hence this model's applicability for a varying rainfall intensity still needs to be tested under real world conditions. But it is expected to perform well since the basic form of this model is a widely used and tested exponential model.

The possible extensions of this model in the future are listed below

- **Inclusion of the effect of other parameters**
  In addition to the initial weight, rainfall intensity and surface slope, it would be interesting to look at the effect of surface texture, rainfall kinetic energy and

sediment size on wash-off process. This way a complete matrix of *c* and *k´* values can be derived which can be transferred to any urban catchments.

- **Black box approach to transparent approach**
  Instead of using a black box approach to derive *k'* values i.e. using a look-up image for *k',* it would be better if surface slope and rainfall intensity can be explicitly included in the model. This way the model will be more transparent. This possibility is being currently explored.

- **Uncertainty estimation**
  Since all the models come with certain degree of uncertainty, inclusion of estimation of model uncertainty and propagation of input uncertainty can be very useful. This possibility is being currently studied.

Acknowledgements

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