

INNOVATIVE PROPOSITION AND PREDICTION OF URBAN WET WEATHER WASHOFF USING SIMULATED RAINFALL

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Abstract:

Washoff is an important process that describes the transportation of pollutants into water ways during the wet weather event. Washoff is a multifarious phenomenon that encapsulated other varied processes ranging from the pollutants deposition during the dry weather period (buildup), to the higher load transport at the beginning of the storm (first flush). Most of the washoff studies were localised to non-tropical regions, where the laxity to wait for dry weather period exist. However, in the tropical regions, the assurance for prolonged dry weather period is near absent, due to frequency of rainfall. This research experimented two new approaches to washoff sampling suitable for tropical regions, alongside with the traditional washoff sampling method. To obtain highly accurate data, the rainfall parameters were confined to selection by employing a very efficient rainfall simulator to gain the washoff data. The washoff of Total suspended solids (TSS) as an indicator of pollution under different simulated rainfalls was established. The result indicated higher mobilisation of the TSS in the first five minutes of rain, and disposes to a steady mobilisation rate after 40 minutes of simulated rain. The washoff percentages for the three road surfaces suggests that the rain intensity plays a more prominent role in washoff prior to the occurrence of first flush, while intense rain mobilises higher amount of TSS within shorter duration of rain. The first flush effect was quantified based on the common definitions of pollutants load-volume relationships of 20/80, 30/80, and 20/40. In all the road surfaces, at least 40% of the pollutants loads were transported in the first 20% of the runoff volumes.

Keywords: First flush; rain duration; rain intensity; simulated rain; TSS; washoff.

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INTRODUCTION

Washoff is a wet-weather process describing the dislodgement, and transportation of accumulated sediments and pollutants after the buildup process. Washoff encapsulates varied complex phenomena and processes, ranging from deposition, wind transport to the street cleaning. The understanding of the washoff process is critically important when describing the variability of pollution load in urban sealed up surfaces (Hvitved-Jacobsen 2011; Butcher 2003). The direct measurement of washoff is not common (Butcher 2003), often researchers use empirical relations to predict the washoff load for a particular rain event through repetitive experiments (Hvitved-Jacobsen 2011). The use of rainfall simulator (RS) offers an opportunity to understand the intricate nature of the washoff process within complex dynamics of natural events (Brodie & Egodawatta 2011). Therefore, the objective of this study is to investigate the washoff process by employing the use of RS to confine natural rainfall parameters to selection.

Until recently, washoff has not been defined in a concrete terms. Svensson (1987) was among the first researchers to conceptualised washoff process. Svensson (1987) theorised that, the governing principle of particle detachment is proportional to the kinetic energy of raindrops thrashing the sealed surface in an urban environment, and that the amount of sediment transport is directly related to the generated runoff and the bottom shear stress of the flow. Svensson concluded that the sediment transportation rate could be hindered by the detachment rate and the particles size distribution.

Total suspended solids (TSS) have been identified as a pollution indicator in washoff (Egodawatta *et al.* 2007). However, there were many factors that govern the dislodgement and transportation of pollutants in the washoff process, ranging from the surface texture, armouring, and the spatial distribution of the pollutants in the environment. In addition, factors such as re-suspension, the nature of buildup, land uses, nature of traffic, and geoclimatic conditions were also identified as influencers of washoff process (Burian *et al.* 2001).

First flush is the most common manifestation used in the assessment of washoff process and its variability between different governing processes (Bertrand-Krajewski *et al.* 1998; Chow *et al.* 2011; Deletic 1998; Mahbub *et al.* 2012). First flush signifies higher pollutants transport at early stage of the runoff than at the subsequent runoff volumes. There is no universal definition of first flush. The first flush quantification criteria were meant to give the first flush a conceptual estimation based on the amount of pollutant washoff within some fractions of the runoff or time. The variations of these criteria make comparison of first flush results difficult. Saget *et al.* (1996) reported that the contention of the first flush phenomenon is related to the definition of the first flush process. The followings are

the three most published definitions to the assessment of first flush (Saget *et al.* 1996; Bertrand-Krajewski *et al.* 1998; Sansalone & Cristina 2004).

- 20/40 FF – 40% of the pollutant load transported in first 20% of runoff volume.
- 20/80 FF – 80% of the pollutant load transported in the first 20% of the runoff volume.
- 30/80 FF – 80% of the pollutant load transported in the first 30% of the runoff volume.

For instance, Saget *et al.* (1996) found only single rainfall event in 197 events to have exhibited suspended solid first flush in storm water sewer based on the 80/30 definition, leading the study to conclude that the first flush is a rare phenomenon. In a similar study by Deletic (1998) to access the first flush phenomenon in urban drainage system, concluded that the regression curve are not dependable technique in defining first flush. However, in another study by Bertrand-Krajewski *et al.* (1998) involving 197 natural rainfall events, the study found 50% of the rainfall events to have transported 80% of the total pollutant's loads in the first 74% or more of the storm volume. In another study, Lau *et al.* (2009) considered the characteristics of road runoff from three different highways in Los Angeles California, and found that the dissolved and the total exhibits similar first flush in washoff, with 20% of the runoff volume washing 30 – 35 % of the total mass. **Table 1** summarises the three most widely employed methods.

Method 1 is usually expressed in graphical form by plotting normalized cumulative pollutant load (P_L) and normalized cumulative runoff volume (R_V) on the dependent axis against normalized time on the independent axis. By definition, first flush occurs when the plot of P_L lies above the R_V . This indicates a higher proportionate load delivery than corresponding runoff volume. In method 2, time was eliminated as a variable

Table 1. Summary of first flush methodologies

Method	Definition	Reference
Method 1: P_L and R_V vs. T_C	FF occurrence if $P_L > R_V$, strong FF effect when large divergence occur	Sansalone & Cristina (2004)
Method 2: P_L vs. R_V	Upward divergence from bisector line signify FF, more divergence indicate strength of the FF	Saget <i>et al.</i> (1996)
Method 3: Power Function b Coefficient; P_L vs. R_V in power form $P_L = (R_V)^n$	$b = 1$ uniform loading, $b < 1$ FF effect, $b > 1$ dilution effect	Deletic (1998)

P_L - Normalized cumulative pollutant load; R_V - Normalized cumulative runoff volume; T_C - Normalized Cumulative Time.

in the assessment of the first flush. The bisector line lies at 45° with the axes at a slope of 1:1. In other words, the bisector line is a plot of P_L versus P_L . Based on this method, a first flush occurs when P_L lies above the bisector line, and how far it lies indicates the strength of the first flush. Method 3 is the mathematical representation of method 2 by obtaining the coefficient using power equation. for $b=1$ represent the bisector line in method 2, for b coefficient values < 1.0 indicates the occurrence of first flush, since the bisector line will lay below the P_L curve, and a P_L curve below the bisector line indicates absence of mass flow first flush, but dilution in concentration flow (Sansalone & Cristina 2004).

MATERIAL AND METHOD

The study was carried out in Skudai, Johor on two institutional parking spaces and one industrial road. The study area was characterised as humid tropic with short duration high intensity rainfall (Chow *et al* 2012; Yakubu *et al.* 2014a). The maximum ADD ever recorded in the last 34 years was just about 30 days Deni *et al.* (2008). The study area is highly urbanised with over 80% of surface been impervious (Chow *et al.* 2011, Chow *et al.* 2013). **Figure 1** showed the location map of the study area.

Due to the frequent rainfall nature of the study area which seldom allows for accumulation of pollutants, three different washoff approaches were implemented on the three chosen locations (two parking lots and one road) for washoff investigation. Buildup samples were collected on these sealed surfaces during dry days as reported by Yakubu *et al.* (2014b), and preserved in a desiccator until required for the washoff experiment. R1*

is an industrial road with moderate mean road texture depth (MTD), R1 is a chosen replacement road for R1*. The replacement of R1* with R1 became necessary because of logistics, and safety issues. R2 and R3 were institutional parking spaces with smooth road texture depth. MTD is a measure that quantifies the roughness of the surface in terms of the average depth of its texture expressed in mm. The MTD is express as Eq. (1) according to ASTM (2006).

$$MTD = \frac{4V}{\pi D^2} \tag{1}$$

V is the volume of sample in measuring cylinder (mm^3)
 D is the mean diameter of the patch (mm)

The R1 road was chosen inside University Teknologi Malaysia (UTM) and was made as an allogamous (adopted from the word allogamy which means cross fertilisation in the field of biological reproduction describing the fertilisation of an ovum from one individual with the spermatozoa of another) of industrial road (R1*) where a known quantity of buildup was earlier collected during dry days corresponding to 5 ADD. The important criterion for roads in terms of their environmental significance is their MTD and Average daily traffic (ADT) (McGhee & Flintsch 2003). Therefore, the UTM road was chosen as a replacement for industrial road based on the similarity of their MTD calculated from Eq. (1) the MTD result presented in Table 2 shows that the similarity between the chosen and the replaced road was 97%, this was considered satisfactory. The MTD was measured using the sand patch method according to ASTM (2006) standard test method for measuring pavement macro texture depth. The R1 was made allogamous by scratching the surface repeatedly along the length and the breadth of the plot until the entire surface’s sediments were removed. A known quantity of industrial road dust collected from the same plot size (3 m^2) was then spread and assumed that the only available pollutants were from the spread sediments. A 60 minutes rainfall was simulated and the runoff collected after every 5 minutes within first 20 minutes of rain and every 10 minutes thereafter.

The R2 is a student parking space inside UTM and was made autogamous (from the word autogamy which



Fig. 1 Location of Skudai in Johor, Peninsular Malaysia

Table 2. Mean texture depth of the road surfaces according to ASTM (2006) standard test method

Measured Diameter	R1*	R1	R2	R3
D1 (mm)	325	280	370	440
D2 (mm)	325	310	390	560
D3 (mm)	315	360	420	510
Ave. D (mm)	322	317	393	503
MTD (mm)	1.60	1.65	1.07	0.65

* Industrial road

means self-fertilisation in the field of biological reproduction describing the fertilisation of an ovum from the same individual) by removing the available dust and sediments using highly efficient vacuum cleaner SYSTEMA® model BF 585-3. The preference of this vacuum cleaner and its description has been reported elsewhere (Yakubu & Yusop, 2015). After vacuuming, it was assumed that the surface was prepared as it was before vacuuming. A known amount of preserved 5 ADD road dust collected from the same location during dry weather was applied, and assumed the surface was brought back to its state before buildup sampling. A 30 minutes rainfall was simulated and the runoff collected in the first 2 minutes, subsequent 3 minute and then every 5 minutes thereafter.

R3 is an isolated parking in the University's newly completed sport complex. Unlike R1 and R2, the road surface of R3 was allowed in its condition after 2ADD, and a 30 minute rain with the same incremental protocol as implemented in R2 was simulated with the assumption that the pollutant buildup was similar through the year. Table 3 shows the rainfall intensities simulated at each road.

Brief description of the rainfall simulator

A highly efficient rainfall simulator suited for urban studies was developed based on the recommended criteria of Yakubu & Yusop. (2017), and was used to simulate different rainfall intensities for the washoff study. The rainfall simulator was developed to closely simulate rain as closely as possible with the natural rainfall dynamics of the study area as defined by Yakubu *et al.* (2014a, 2014c). The RS consisted of two Veejet 80100 pressure spray nozzle spaced 1.0 m apart on suspended boom raised 2.5 m from 1.6 x 1.8 m plot. The combination of flow meter and the speed of the nozzle boom regulate the intensity of the RS. The RS is shown in Fig. 2 with its various interrelated components. The RS has achieved 86% rain uniformity, ± 0.13 mm of the natural rainfall's median drop diameter, over 80% terminal velocity, and up to 87% of kinetic energy.

The simulated rain of R2, and R3 road surfaces were operated at a higher intensity than R1 but were evaluated at half the duration (30 minutes). The choice of sampling equipment was based on the recommendation for a tropical region suggested by the authors of this study (Yakubu & Yusop 2014; Yakubu & Yusop 2015). The wet vacuum sucker was utilised for the washoff sampling; each of the collected runoff was measured and converted to rain depth after each incremental rain duration. The TSS sampling was carried out according to EPA (2012), and the concentrations measured according to the EPA (1993) using a weighing scale accurate to 0.001g. The filter papers were dried at 105°C prior and after sample filtration.

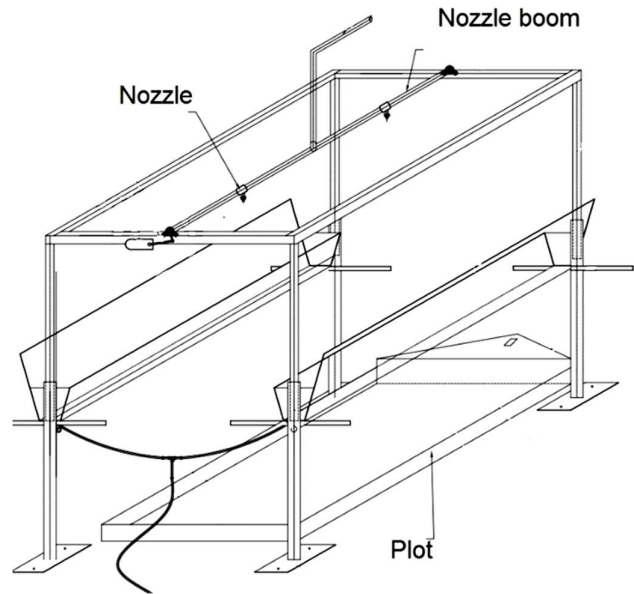


Fig. 2 Rainfall simulator

Table 3. Simulated rain intensities on each road surfaces

Location	Rain intensity (mm h ⁻¹)	Remarks
R1	145	Constant intensity
R2	180	Constant intensity
R3	145-180	Varies: 145 mm h ⁻¹ at first 2 min; 180 mm h ⁻¹ thereafter

RESULT AND DISCUSSIONS

Fig. 3 presents the percent sediment remaining on the surfaces as a fraction of the initial TSS load for different rain intensities. The 145mm h⁻¹ rain intensity mobilises 22% of the TSS in the R1 within the first five minutes of rain; while the percent mobilisation in the other road surfaces considered in this research were 34 and 26% for R2 and R3 at 180 mm h⁻¹ and 145-180 mm h⁻¹ respectively. These values for R2 and R3 were cumulative of two minutes and the subsequent three minutes of rain. At the first two minutes, the percentage washoff for R2 and R3 road surfaces were 22 and 16% respectively. The R3 road surface received the same rain intensity as R1 in the first two minutes of simulated rain, and the same rainfall intensity as R2 at the succeeding three minutes.

Figure 3 shows that the percentage washoff after the first five minutes of simulated rain were consistently similar irrespective of the rain intensity, with R3 having higher value of washoff percentages at 15 and 20 minutes. At 10 minutes, the 145mm h⁻¹ at R1 was able

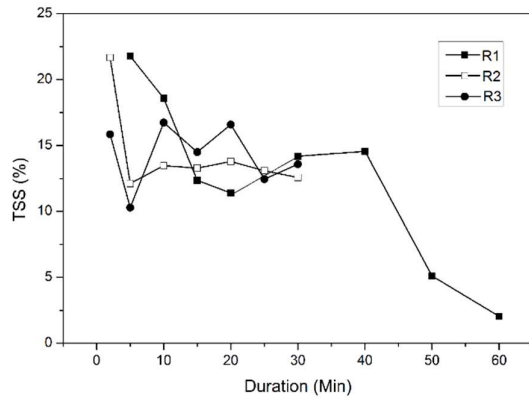


Fig. 3 Percentage TSS washoff with duration of storm.

to washed away 19% of the TSS, while for the same rain duration at R2 and R3, 180 mm h⁻¹ and 150 mm h⁻¹ intensities were able to washed away 13 and 17% correspondingly. This corresponds to 40, 47 and 43% as a cumulative percentages for R1, R2 and R3 respectively (Fig. 4). The washed TSS as percentages after 30 minutes of simulated rain was 14% for R1 and R3, while it was 13% for the R2. For R1, as the duration of the simulation was prolonged, the washoff process continues, until the percentage washoff approaches zero. The percentage washoff has drastically reduced to 5% and 2% after 50 and 60 minutes of simulation respectively. **Figure 3** further suggests that the rain intensity plays more important role prior to the occurrence of first flush. Thus, higher rain intensity mobilises higher amount of TSS within shorter duration of rain. Consequently, rain depth took precedence as the most important factor after the occurrence of the first flush and continues to play a more central role in the total washoff event. This result indicated that a significant pollutants mass were not washed away in tropical regions, like Malaysia, which experiences short duration high intensity rainfall, but could generate higher pollutants loads within shorter duration of rain.

This study noticed three phases of washoff, the first flush region, the constant rate, and the steady phase. Based on our data, the first five minutes indicates the first flush phase, the first 30 minutes indicates a constant rate, and the region after 40 minutes indicates a steady phase, where there was no significant washoff difference between the successive sample times after the 40 minutes.

The R1 shows a promising exponential relationship of TSS with duration of rainfall than R2 and R3. As presented in **Fig. 4**, R2 and R3 showed the surge of the TSS early enough at five minutes equivalent to gradient value of 16 and 13 respectively, and were represented by the first and second points on the figures. However, this surge was near absent in R1 with a recorded gradient value of only 4.6. Nonetheless, the TSS mobilisation

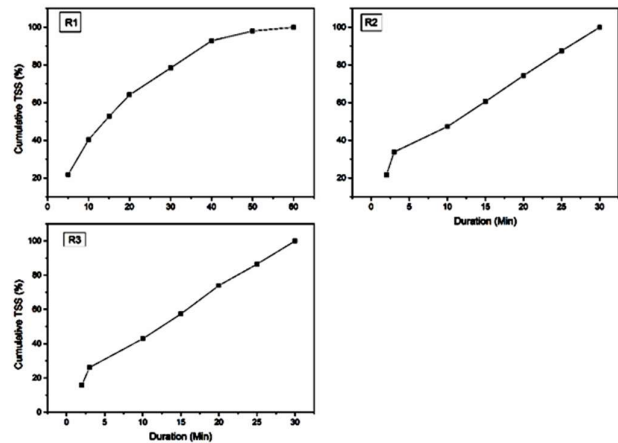


Fig. 4 Relationship between TSS washoff and duration of storm for R1, R2, and R3.

after the occurrence of the first flush increases in a nearly constant rate, and it disposes to a steady mobilisation rate after 40 minutes of rain in the R1 road surface as shown in **Fig. 4**. While, the TSS washoff has shown an almost linear trend in R2 and R3 road surfaces.

Fig. 4 further indicates that despite been operated at higher rainfall intensities, the rain duration of R2 and R3 were not operated long enough to have reached the steady state. This bring to fore the implication of rain duration on the mobilisation of pollution in urban environment. The mobilisation and transport of TSS in R1 shows an almost uniform washoff rate. This almost uniform trend could be due to the time incremental programme of five minutes, or the steep slope of the catchment. Thus, most of the TSS must have been washoff in a much shorter time within the first time the first sample was taken.

The urban storm water manual for Malaysia, developed by the department of irrigation and drainage, DID (2006) identified 30 minutes rain duration as capable of washing away 90% of pollutants in urban environment. The DID (2006) therefore identified 30 minutes rain duration as the most important in wet weather pollutants' washoff process. In this study, the short duration rainfalls were found to washoff higher percentages of the pollutants compared with the longer duration that was operated at a lower intensity. The total washoff of pollutants in the R1, R2, and R3 road surfaces were 78%, 87%, and 86% respectively. These percentages almost collaborates with the stipulation of the DID (2006). However, there is need to further classify the particular rain intensity that was capable of washing off pollutants that would corresponds to the 90% identified by the DID (2006).

Quantification of the first flush

In this study, method 2 for quantifying first flush as outlined in Table 1 was used to assess the first flush in the washoff. This method will make it easier to assess the first flush based on the percentage of runoff volume. **Fig.**

5 is the plots of the normalized TSS load vs the normalized runoff volume. From the figure each location exhibits the effect of the first flush, but with varying degrees and at different runoff volume percentages. The significant effect was highest at the point where there was highest divergence between the normalized curves and the 45° bisector line.

The normalized plot of R1 in Fig. 5 stresses the uniformity of R1 washoff and further indicated that the strength of the first flush in R1 was strongest at the first 33% of the runoff volume. Thus, 80% of the TSS load was washoff in first 33% of runoff volume (33/80); the corresponding values of the TSS load washed in the first 33% of the rainfall volumes for R2 and R3 were 67 and 61% respectively. However, the first flush in R2 and R3 were strongest at first 14 and 15% of the runoff volumes. In this regard, the rain intensity in R2 washed 55% of the TSS load in just 15% of the runoff volume (15/55); while, the rain intensity in R3 transported 50% of the TSS in 14% of the runoff volume (14/50%). The corresponding percentages of TSS washoff for these volumes in R1 were 48% and 45% respectively. These values indicated the occurrence of the first flush based on the differences in the rain intensities simulated at each road surface and other differing parameters based on the condition of the locations, like road texture, implemented experimental protocols, slope etc.

This research explored the occurrence of first flush based on the common definitions of pollutants load volume relationships of 20/80, 30/80, and 20/40. None of the road surfaces was found to transport 80% of the pollutant load in the first 20% or 30% of the runoff volume. Specifically, 80% of the TSS was transported in the first 33% of the runoff volume for R1, 59% for R2 and 63% for R3. However, in all locations, at least 40% of the pollutants loads were transported in the first 20% of the runoff volumes (R1= 13/40, R2=12/40, and R3=8/40).

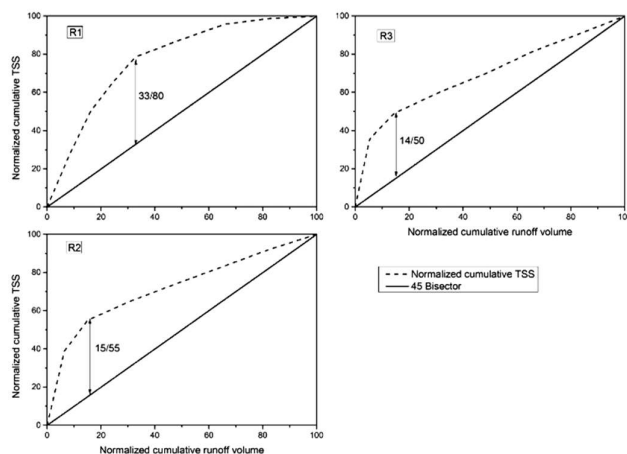


Fig. 5 Plots of the normalized TSS load vs the normalized runoff volume.

CONCLUSION

This study examined the washoff in a typical urban road landscape in tropical region and its associated phenomenon of first flush. The implication of pollutants washoff during wet weather process was accessed using shorter and longer duration rainfalls. The shorter duration higher intensity rainfall were found to transport higher amount of pollutants both at the initial and on the entire runoff, and has displayed a pronounced first flush effect. The longer duration has shown an almost uniform washoff rate, thereby showing little first flush effect. The finding of this study collaborates with stipulations of DID. Neither of the road surfaces transported 20% or 30%. But, there is need to further classify the washoff based on different rain intensities for the purpose of identifying the range of intensities that could be capable of washing off 90% of the pollutants.

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