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MATHEMATICAL INTERPRETATION OF POLLUTANT WASH-OFF FROM URBAN ROAD SURFACES USING SIMULATED RAINFALL

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ABSTRACT

In the context of stormwater quality modelling, an in-depth understanding of underlying physical processes and the availability of reliable and accurate mathematical equations which can replicate pollutant processes are essential. Stormwater pollutants undergo three primary processes, namely, build-up, wash-off and transport, before accumulating into receiving waters. These processes are expressed mathematically by equations in stormwater quality models. Among the three processes, wash-off is the least investigated. This paper presents the outcomes of an in-depth investigation of pollutant wash-off processes on typical urban road surfaces.

The study results showed that a storm event has the capacity to wash-off only a fraction of pollutants available and this fraction varies primarily with rainfall intensity, kinetic energy of rainfall and characteristics of the pollutants. These outcomes suggest that the exponential equation commonly used for mathematically defining pollutant wash-off would need to be modified in order to incorporate the wash-off capacity of rainfall. Consequently, the introduction of an additional term referred to as the 'capacity factor' C_F is recommended. C_F primarily varies with rainfall intensity. However, for simplicity three rainfall intensity ranges were identified where the variation of C_F can be defined. For rainfall intensities less than 40mm/hr, C_F varies linearly from 0 to 0.5. For rainfall intensities from 40 to around 90mm/hr, C_F is a constant around 0.5. Beyond 90mm/hr C_F varies between 0.5 and 1.

Keywords: pollutant wash-off, urban water quality, rainfall simulation

NOMENCLATURE

C_F	Capacity factor
Fw	Fraction wash-off
I	Rainfall intensity
k	Wash-off coefficient
t	Time
W	Weight of the material mobilised after time t
W_0	Initial weight of the material on the surface

1. INTRODUCTION

Stormwater runoff pollution is one of the most significant environmental issues in urban areas. Pollutant loads originating from urban catchments is significantly higher when compared to rural catchments, leading to adverse impacts on receiving water quality (House et al., 1993; Novotny et al., 1985; Sartor et al., 1974).

In this context, stormwater quality modelling plays an important role in the development of appropriate management strategies. A stormwater quality model is a combination of mathematical procedures which are used to describe the water quality response of a catchment to a particular storm event or a period of time (Akan and Houghtalen, 2003; Zoppou, 2001). A model can be used to estimate concentration of pollutants originating from a catchment and these estimations are used for decision making.

A stormwater quality model incorporates mathematical formulations to replicate three pollutant processes; pollutant build-up, pollutant wash-off and pollutant transport. Different mathematical formulations are available to replicate each pollutant process with varying levels of accuracy and degree of complexity. Most models use suspended solids as their primary indicator pollutant. The general assumption is that the most of the other stormwater pollutants such as nutrients, heavy metals and hydrocarbons are adsorbed to suspended solids (Akan and Houghtalen, 2003; Herngren et al., 2005; Sartor et al., 1974).

Accuracy and reliability of a model is dependent on the precision of the mathematical formulation of pollutant processes. Therefore, the in-depth understanding of the pollutant processes is the key to better modelling approaches. In nature, these processes are complex and are influenced by a range of parameters such as rainfall, runoff, climatic, land-use and surface characteristics (Sartor et al., 1974; Vaze and Chiew, 2002). The complex nature and variability together with a range of parameters create inherent difficulties in the development of accurate and reliable mathematical replication of pollutant processes.

This paper presents the outcomes of a pollutant wash-off study using simulated rainfall on typical urban road surfaces in Gold Coast, Queensland State, Australia. The use of simulated rainfall provides greater flexibility and control of the fundamental rainfall parameters such as intensity and duration and thereby helps to eliminate some of the variables which inherently increases the complexity of stormwater quality research. It can also overcome the constraints of variability and random nature associated with natural rainfall events. Consequently, the use of simulated rainfall enables the generation of a large volume of data in a relatively short period of time (Herngren, 2005).

2. MATERIALS AND METHODS

2.1 Study Area

Three urban road surfaces were selected from the Gold Coast region, Queensland State, Australia. Gold Coast has a sub-tropical climate with wet summers and dry winters. All three sites were located in typical urban residential areas. Characteristics of the three sites are given in Table 1. The surroundings of all three sites was grassed and well maintained with no construction or demolition activities in the vicinity. Therefore, it can be assumed that the pollutants on the road surfaces would primarily originate from traffic, from atmospheric sources or emissions. A street sweeper operates every six weeks within the region. The sweeper is more involved in cleaning the gutter area rather than the road surface where the research was focused on. Therefore, it can be assumed that the influence of street sweeping on the amount of initially available pollutants is minimal.

2.2 Rainfall Simulation

A specially designed rainfall simulator as shown in Figure 1 was used to generate the artificial rainfall events. The rainfall simulator consists of three Veejet 80100 nozzles connected to a nozzle boom and stands at 2.5m above the ground level. The nozzle boom swings in either direction with controlled speed and delay. Water is supplied to the nozzle boom by pumping from an externally located tank. De-mineralised water spiked to replicate typical rainfall quality in the region was used for the simulation. The simulator was designed to re-produce natural rainfall events as closely as possible. Important characteristics of natural rainfall as noted in literature are rainfall intensity, drop size distribution and kinetic energy (Best, 1950; Hudson, 1963; Rosewell, 1986). The speed and delay of the nozzle boom was calibrated in order to make sure it simulates the selected rainfall intensities. It was verified that the drop size distribution and kinetic energy of each event is closely replicated. Details on the design and operation of rainfall simulator can be found in Herngren, (2005).

2.3 Experimental Design and Sample Collection

Simulation intensities and durations

Water quality research is primarily focused on long term pollutant yield from catchments. Pollutant yield could be influenced by each and every significant storm event within a given period of time rather than a small number of uncommon events with high average recurrence interval (ARI). In this context, investigation of pollutant wash-off for a wide range of storm events is important. A study was conducted to identify the range and variation of rainfall intensities within the region. This was done by statistically analysing maximum 5 min. rainfall intensities obtained from every significant storm event during a 5 year period (1999 to 2003). In order to encompass the applicable range of intensities, the six rainfall intensities as shown in Table 2 were simulated. The rainfall durations were selected based on results published by Herngren, (2005). He observed that there was no significant wash-off of pollutants beyond a threshold value of rainfall duration.

Field Investigations

Study sites on the selected roads were identified so that they are straight sections about 50 m long with uniform slope. Seven plot surfaces equidistant from the road edge and centre line and of area 3 m^2 (2 m x 1.5 m) were demarcated at each site. The relative fraction of different pollutants was assumed to be uniform throughout the length and width of the road as the traffic volume is relatively low and the pollutant re-distribution would be limited. The total amount of pollutant build-up on the road surfaces was determined by collecting samples using a vacuum cleaner from the most downstream plot at each study site. The amounts collected were 32.6 g, 9.3 g and 10.6 g from Gumbeel Ct., Lauder Ct. and Piccadilly Pl. sites respectively. The respective samples belonged to 77, 27 and 36 antecedent dry days of build-up. The particle size distributions of the collected samples are shown in Figure 2. The validity of using a vacuum cleaner for collecting pollutant samples has been confirmed in previous research (Herngren, 2005; Vaze et al., 2000). A calibration study found that the efficiency of the vacuum system for collecting and retaining particulates was within satisfactory range. The minimum efficiency recorded was 92% for 1 to 10 µm particle size range. The overall efficiency was 97%. The rainfall intensities were simulated over each study plot starting from the second most downstream plot and moving upstream for the next rainfall intensity. The runoff samples were collected using a catch tray and the vacuum system and stored in drums as described by Herngren (2005).

2.4 Laboratory Analysis

As suspended solids was adopted as the indicator pollutant, the primary emphasis was to determine parameters such as total suspended solids (TSS) and particle size distribution. Testing for TSS was undertaken according to Test Method No. 2540D (APHA, 1999). Particle size distribution was determined using a Malvern Mastersizer S particle size analyser. The analyser used was a reverse Fourier lens of 300 mm diameter and was able to analyse particles in the range of 0.05-900µm. In this range, the manufacturer has specified a reading accuracy of ±2% of the volume median diameter (Malvern Instrument Ltd. 1997).

3. RESULTS AND DISCUSSION

Suitable analytical parameters were selected after an initial trial analysis using all possible parameters. It was noted that wash-off is influenced by rainfall intensity, rainfall duration and runoff volume. These three parameters highly correlate with each other and therefore the degree of influence they exert individually cannot be clearly discerned (Chiew and McMahon, 1999; Chui, 1997; Mackay, 1999). Initial analysis revealed that very little information can be gained by relating wash-off to runoff volume. Therefore, rainfall intensity and duration was selected as the primary variables for the analysis. Figure 3 shows the variation of 'fraction wash-off' of pollutants for the three study sites. Fraction wash-off (F_W) is defined as the weight ratio of cumulative washed-off pollutants to the initially available pollutants (build-up). Definition of F_W enables to eliminate the influence of initially available pollutants on the wash-off process and thus the results from different sites can be compared.

From the information in Figure 3, two main conclusions can be derived. Firstly, the highest F_W is in the range of 0.8 and 0.9 and belongs to the 133 mm/hr intensity rainfall simulated for around 20 min duration. Reference to storm events in the study region, this is in the range of a 10 year ARI event. This would mean that the most common storm events are not capable of removing all of the build-up pollutants on road surfaces. Secondly, though the initial pollutant availability in the three different sites was significantly different, wash-off patterns are similar. The initial pollutant availability at Gumbeel Ct. site was 32.6 g and it was 9.3 g and 10.6 g at Lauder Ct.

and Piccadilly Pl. sites respectively. This suggests that the influence of initial pollutant availability on pollutant wash-off processes is not significant.

3.1 Mathematical Replication of Pollutant Wash-off

Pollutant wash-off from an impervious surface is commonly replicated as an exponential equation in the form of:

$$W = W_0(1 - e^{-kIt}) \tag{1}$$

(Sartor et al., 1974)

Different derivations of this equation have been used in various stormwater quality models, such as, US EPA's Stormwater Management Model (SWMM) and US Army Corps's STORM model (Huber and Dickinson, 1988; USACE, 1977).

In this study the original exponential equation (Equation 1) proposed by Sartor et al. (1974) was tested in order to replicate observed wash-off patterns. The equation was re-written in order to incorporate Fw:

$$Fw = \frac{W}{W_0} = (1 - e^{-kIt}) \tag{2}$$

However, the equation did not replicate the observed wash-off pattern satisfactorily. It is evident from Figure 4 that the fraction wash-off approaches a finite value <1 which varies with the rainfall intensity. This phenomenon was visually observed during the rainfall simulation where the latter part of most of the less intense rainfall events produces relatively cleaner runoff. This suggests that a rainfall event has the capacity to mobilise only a fraction of solids on the road surface and once it reaches that capacity, relatively clean runoff results even though a significant fraction of pollutants is still available. The equation proposed by Sartor et al. (1974) is based on the assumption that every storm event has the capacity to remove all the available pollutants from that surface if it were to continue for an adequate duration. The findings from the current study confirmed the need to modify the wash-off equation.

The exponential pollutant wash-off equation (Equation 2) was modified by introducing the 'capacity factor' (C_F) and can be written as:

$$Fw = \frac{W}{W_0} = C_F(1 - e^{-kIt}) \tag{3}$$

C_F will have a value ranging from 0 to 1 depending on the rainfall intensity. However, other factors such as road surface condition, characteristics of the available pollutants and slope of the road may also have an influence on C_F and are discussed below.

3.2 Estimation of Wash-off Parameters

To use the modified wash-off equation (Equation 3), the parameters k and C_F must be estimated. The wash-off coefficient k is an empirical parameter with units (mm^{-1}) and no direct physical meaning. Water quality models such as SWMM use a constant value for k. However, there is evidence to claim that k is site specific (Millar, 1999). The value of k may vary with the pollutant type, rainfall intensity, catchment area and catchment slope (Alley 1981; Alley and Smith, 1981; Millar, 1999). However, the use of a constant value for k will reduce the complexity of the wash-off equation. It has been noted by Huber and Dickinson (1988) that a constant value is used for the SWMM model and it performs relatively well in the estimation process. In the study, the best possible values for C_F and k were determined using the theory of least squares. Figure 4 illustrates the replication equation developed and Table 3 shows the C_F and k values determined for the different sites.

The validity of Equation 3 was evaluated by analysing the mean and coefficient of variation (CV). Mean was calculated by averaging the ratio between predicted value to observed value for each data point. CV was calculated by dividing the standard deviation from the expected return which is one. The mean and CV for each site is given in Table 4.

According to Table 4, all three values for the mean are close to one and therefore, it can be argued that the overall performance of the prediction equation is quite good. However, the CV values indicate that there are significant errors in estimating each data point. The performance of the wash-off equation for Gumbeel Ct. data is poor whereas the performance of the equation for Lauder Ct. and Piccadilly Pl. are satisfactory. The variation between observed data and predicted data would be due to reasons such as the build-up data being non-representative for the site and errors in the calculation of the equation parameters. Gumbeel Ct. site had significantly high amount of pollutants. As such there can be a greater possibility of selecting a non-representative sample.

Considering the above, the most appropriate values for the C_F and k would be the values obtained for Lauder Ct. and Piccadilly Pl. road sites. The constant k value of 8.0×10^{-4} is proposed for use in the prediction equation and C_F values could be averaged. However, care should be taken when using these values particularly when the initial pollutant availability is comparatively high.

3.3 Understanding the Wash-off Process

Apart from mathematically replicating, understanding the mechanism of pollutant wash-off is also important. Figure 5 shows the variation of C_F with rainfall intensity. The graph consists primarily of three parts. For an intensity less than around 40 mm/hr, C_F increases linearly to almost 0.5. It is hypothesised that this is due to the change in kinetic energy for different rainfall events. According to Rosewell (1986), the kinetic energy of sub-tropical storm events increase from 0 to around 25 $J/m^2/mm$ for intensities from 0 to about 40 mm/hr and beyond that, it is relatively constant at about 25 $J/m^2/mm$. It is hypothesised that C_F varies linearly with kinetic energy within this range.

For rainfall intensities ranging from 40 mm/hr to around 90 mm/hr, C_F has a relatively constant value of 0.5. This indicates that the rainfall intensities in this range have the capability to mobilise only around 50% of the pollutants available. The D_{50} for the initially available pollutants is in the range of 100 to 150 μm and the D_{50} of the wash-off samples for the 40, 65 and 86 mm/hr rainfall intensities is in the range of 50 to 100 μm. This suggests that most of the smaller particle sizes are subjected to wash-off during these events and the rainfall intensities are not capable of creating adequate turbulence to mobilise larger particles. However, the upper limit of the constant C_F (90 mm/hr) could change with the texture depth of the road and particle size distribution of the pollutants available. Rainfall events with intensity more than 90 mm/hr have a greater capability to mobilise solid pollutants. It is hypothesised that this is due to the relatively high degree of turbulence in the overland flow. The pollutant export study done in the same urban catchment by Egodawatta et al. (2006) confirmed the higher mobilisation capacity of high intensity rainfall events which results in relatively higher pollutant concentrations and larger average size of the wash-off particles.

4. CONCLUSIONS

The outcomes from this research suggest that a rainfall event has a specific capacity to mobilise pollutants and invariably remove only a fraction of the available pollutants. This confirms the need to modify the commonly adopted pollutant wash-off equation for better replication of pollutant removal. It is recommended that the typical exponential equation is modified by introducing an empirical term, referred to as the capacity factor, C_F. C_F represents the rainfall event's capacity to mobilise pollutants from paved surfaces. Kinetic energy of the rainfall events and the turbulence created in overland flow are the decisive factors influencing C_F. High intensity rainfall events can mobilise relatively coarser particles due to the creation of high turbulence in overland flow.

C_F primarily varies with rainfall intensity. However, for simplicity three rainfall intensity ranges were identified where variation of C_F can be defined. For the rainfall intensities less that 40 mm/hr, C_F varies linearly from 0 to 0.5. For rainfall intensities from 40 to around 90 mm/hr, C_F is a constant around 0.5. Beyond 90 mm/hr C_F varies between 0.5 and 1.

5. REFERENCES

Akan, A.O. and Houghtalen, R.J. (2003). Urban Hydrology, Hydraulics and Stormwater Quality - Engineering Applications and Computer Modelling. New Jersey: John Willey and sons.

Alley , W.M. (1981). Estimation of Impervious-Area Wash-off Parameters. Water Resource Research, **17**(4), 1161-1166.

Alley , W. M. and Smith, P. E. (1981). Estimation of Accumulation Parameters for Urban Runoff Quality Modelling. Water Resources Research, **17**(6), 1657-1664.

APHA. (1999). Standard Methods for the Examination of Water and Waste Water. Washington, D.C: American Public Health Association.

Best, A.C. (1950). The Size Distribution of Raindrops. Quarterly Journal of the Royal Meteorological Society, **76**(327), 16-36.

Egodawatta, P., Goonetilleke, A., Thomas, E. and Ayoko, G.A. (2006). Understanding the interrelationship between stormwater quality and rainfall and runoff factors in residential catchments. Proceedings of the Seventh International Conference on Urban Drainage Modelling and the Fourth International Conference on Water Sensitive Urban Design (Eds. Deletic, A and Tim Fletcher, T.) Melbourne, Australia, pp 43-50.

Herngren, L. (2005). Build-up and Wash-off Process Kinetics of PAHs and Heavy Metals on Paved Surfaces Using Simulated Rainfall. PhD Thesis, Queensland University of Technology, Brisbane, Australia.

Herngren, L., Goonetilleke, A. and Ayoko, G.A. (2005). Understanding Heavy Metal and Suspended Solids Relationships in Urban Stormwater Using Simulated Rainfall. Journal of Environmental Management, **76**, 149-158.

House, M.A., Ellis, J.B., Herricks, E.E., Hvitved-Jacobsen, T., Seager, J., Lijklema, L., Aalderink, H. and Clifforde, I. T. (1993). Urban Drainage Impact on Receiving Water Quality. Water Science and Technology, **27**(12), 117-158.

Huber, W.C. and Dickinson, R.E. (1988). Stormwater management model (SWMM), version 4, User's manual (No. EPA/600/3-88/001a). Athens, GA: US Environmental Protection Agency.

Hudson, N.W. (1963). Raindrop Size Distribution in High Intensity Storms. Agricultural Research, **1**, 6-11.

Millar, R.G. (1999). Analytical determination of pollutant wash-off parameters. Journal of Environmental Engineering, **125**(10), 989-992.

Novotny, V., Sung, H.M., Bannerman, R. and Baum, K. (1985). Estimating Nonpoint Pollution from Small Urban Watersheds. Journal Water Pollution Control Federation, **57**, 744-748.

Rosewell, C.J. (1986). Rainfall Kinetic Energy in Eastern Australia. Journal of Applied Meteorology, **25**(11), 1695-1701.

Sartor, J.D., Boyd, G.B. and Agardy, F.J. (1974). Water pollution aspects of street surface contaminants (No. EPA-R2-72/081). Washington, DC, USA: US Environmental Protection Agency.

USACE, U. S. A. C. E. (1977). Storage, treatment, overflow, runoff model (STORM): user's manual (No. Rep. NTIS AD-A955-817): Hydrologic engineers centre, Davis, Calif.

Vaze, J. and Chiew, F.H.S. (2002). Experimental Study on Pollutant Accumulation on an Urban Road Surface. Urban Water, **4**, 379-389.

Vaze, J., Chiew, F.H.S., Suryadi, L. and Khanal, K. (2000). Pollutant accumulation on an urban road surface. Melbourne: University of Melbourne, Australia.

Zoppou, C. (2001). Review of urban storm water models. Environmental Modelling & Software, **16**(3), 195-231.

Table 1 – Characteristics of road sites

Site	Living standard/land-form	Slope of the road (%)	Texture depth of the surface (mm)
Lauder Ct.	Medium-socio-economic single detached housing	10	0.66
Gumbeel Ct.	Medium-socio-economic duplex housing	7.2	0.92
Piccadilly Pl.	High-socio-economic single detached housing	10.8	0.83

Table 2 – Simulation durations and intensities

Intensity (mm/hr)	Durations (min)			
	1	2	3	4
20	10	20	30	40
40	10	15	25	35
65	10	15	20	30
86	10	15	20	25
115	5	10	15	20
133	5	10	15	20

Table 3 - Estimated values for C_F and k

Site	Wash-off Coefficient k	Capacity Factor C_F					
		20mm/hr	40mm/hr	65mm/hr	86mm/hr	115mm/hr	133mm/hr
Gumbeel Ct.	5.6×10^{-4}	0.20	0.48	0.50	0.50	0.73	1.00
Lauder Ct.	8.0×10^{-4}	-	0.48	0.54	0.54	0.80	0.89
Piccadilly Pl.	8.0×10^{-4}	0.30	0.45	0.49	0.49	0.66	0.94

Table 4 – Validity of the pollutant wash-off equation

Parameter	Gumbeel Ct.	Lauder Ct.	Piccadilly Pl.
Mean	1.12	0.98	0.98
CV	27%	7%	12%

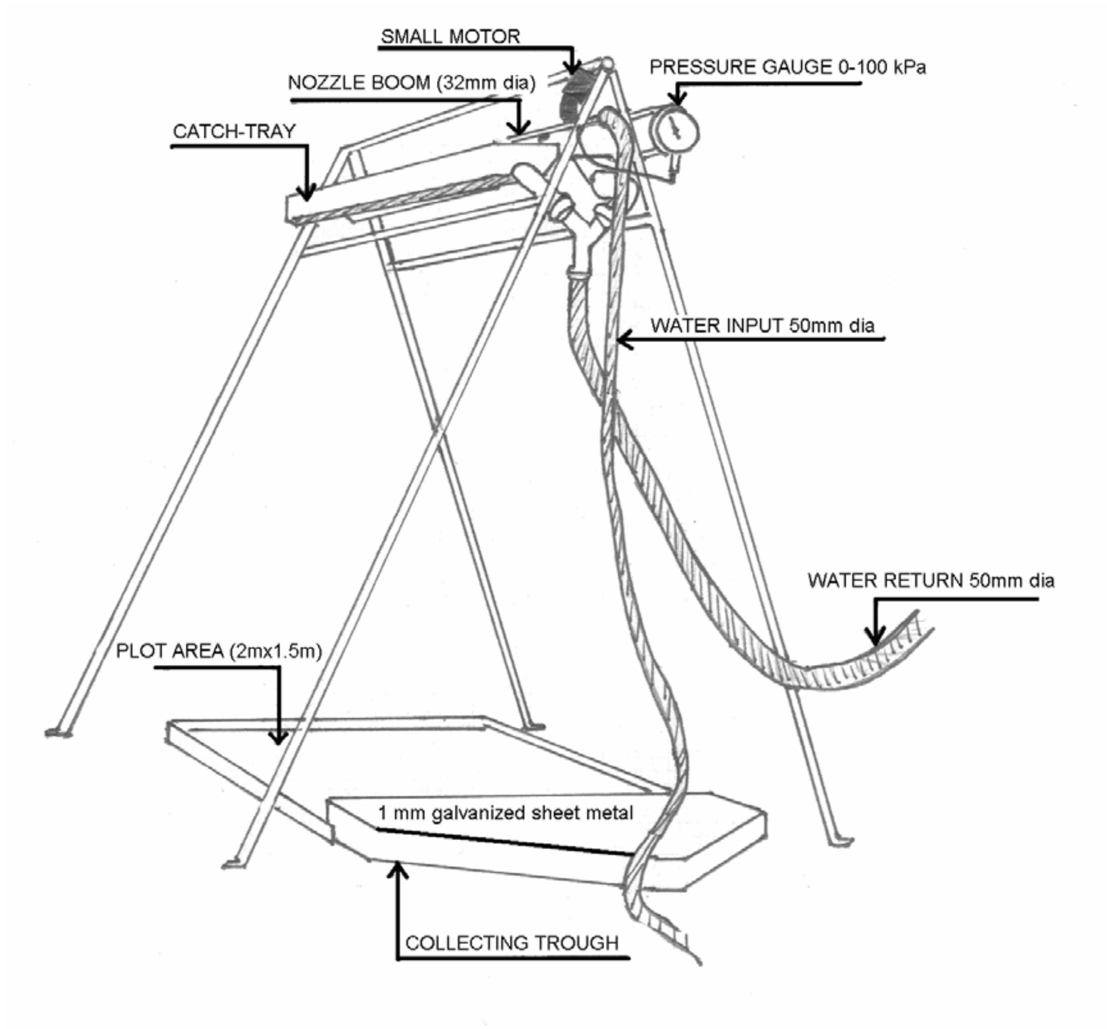

Figure 1 – Sketch of rainfall simulator

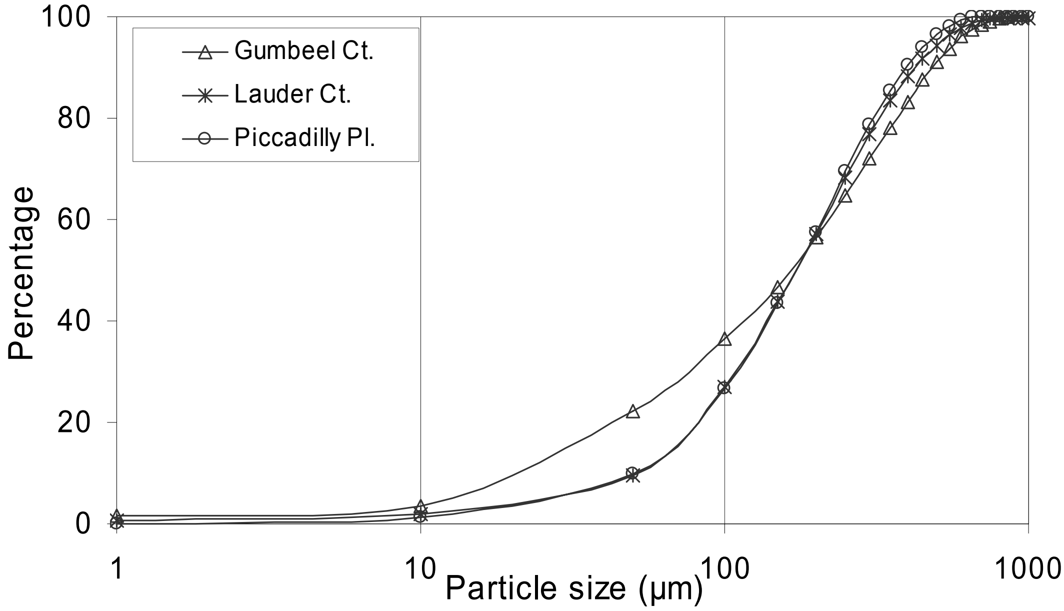

Figure 2 –Particle size distribution of build-up samples and sample used for vacuum cleaner calibration

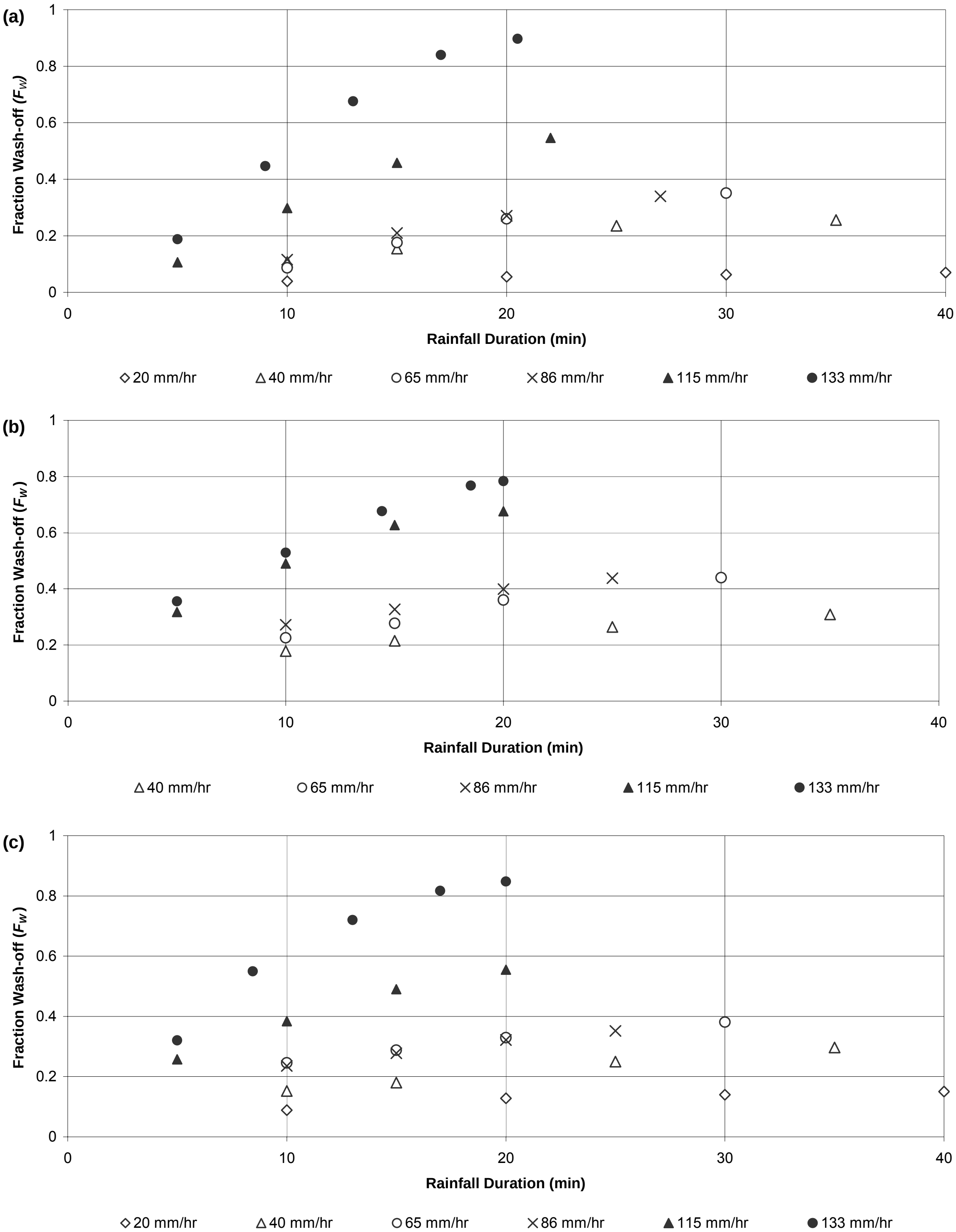

Figure 3 – Variation of fraction wash-off with rainfall intensity and duration: (a) Gumbeel Ct. site, (b) Lauder Ct. site and (c) Piccadilly Pl. site

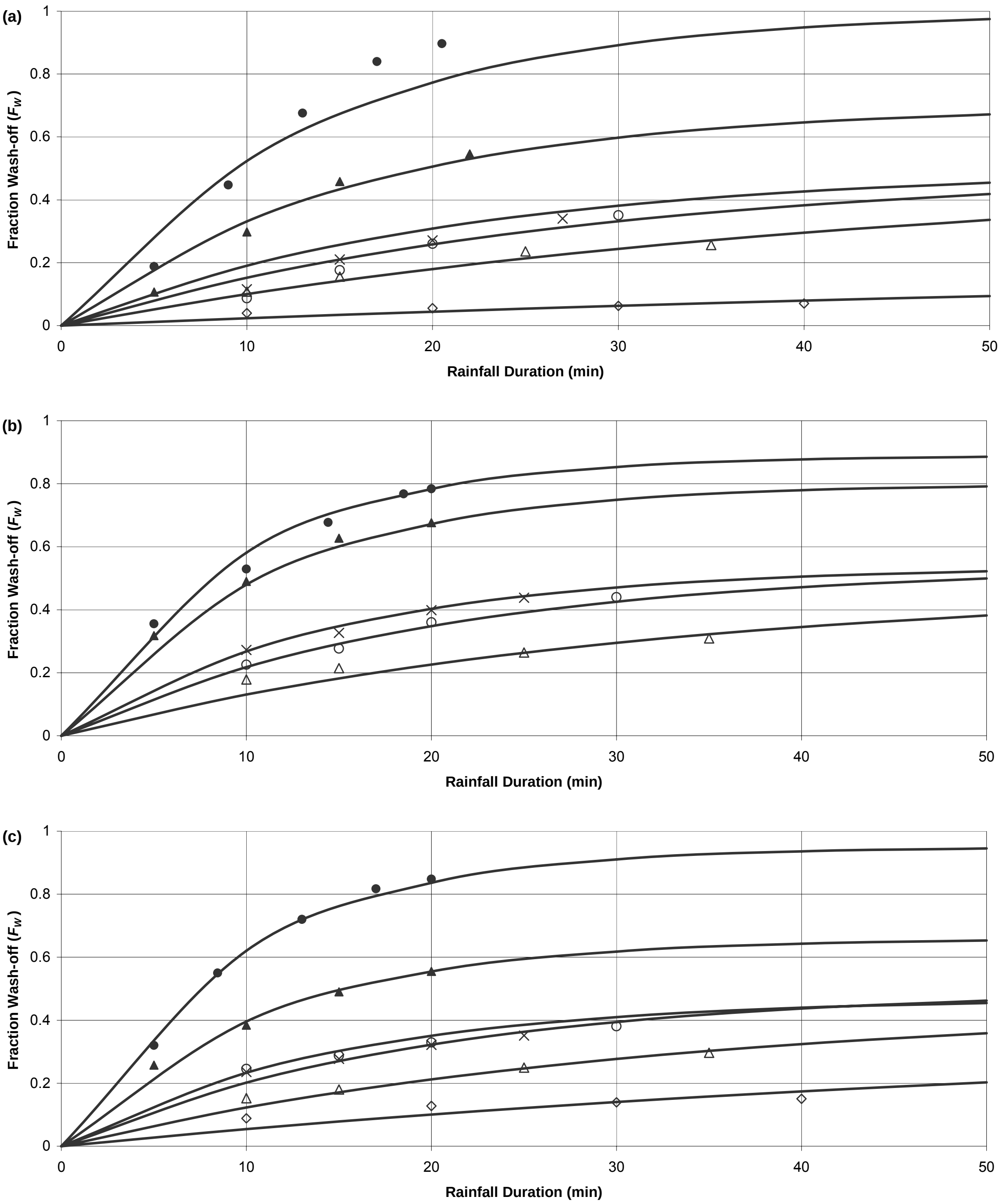

Figure 4 – Performance of the replication equation for pollutant wash-off for: (a) Gumbeel Ct. site, (b) Lauder Ct. site and (c) Piccadilly Pl. site

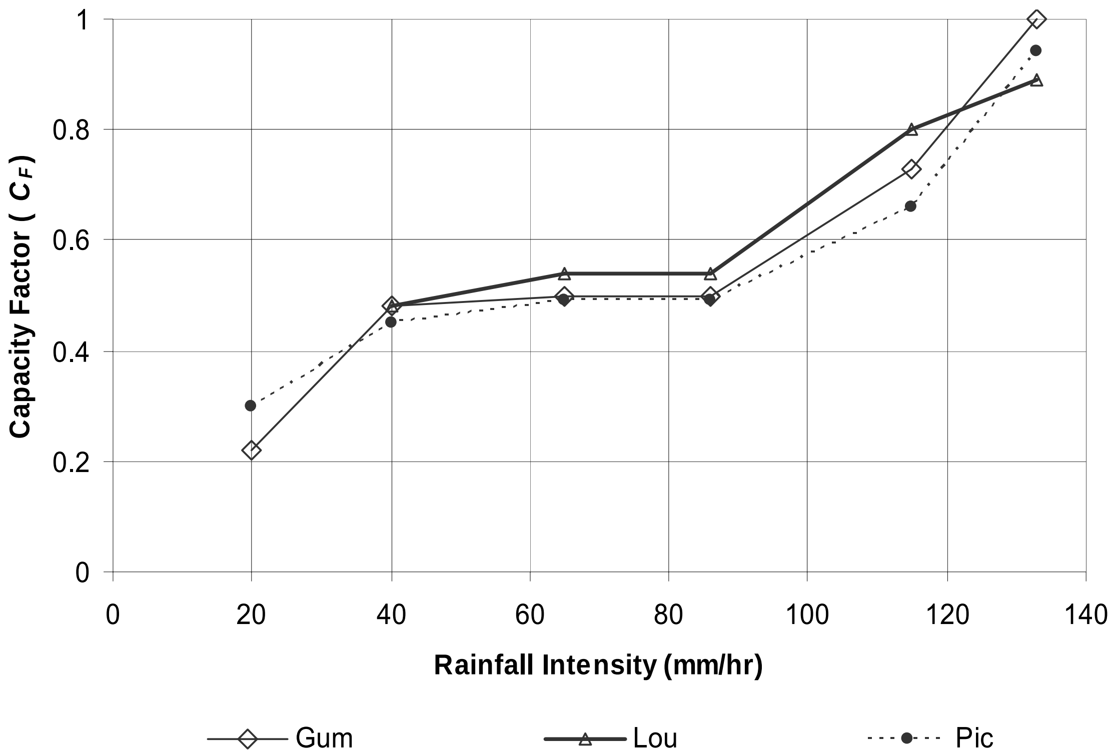

Figure 5 – Variation of C_F with rainfall intensity