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Development of a Catchment Water Quality Model for Continuous Simulations of Pollutants Build-up and Wash-off

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Abstract—Estimation of runoff water quality parameters is required to determine appropriate water quality management options. Various models are used to estimate runoff water quality parameters. However, most models provide event-based estimates of water quality parameters for specific sites. The work presented in this paper describes the development of a model that continuously simulates the accumulation and wash-off of water quality pollutants in a catchment. The model allows estimation of pollutants build-up during dry periods and pollutants wash-off during storm events. The model was developed by integrating two individual models; rainfall-runoff model, and catchment water quality model. The rainfall-runoff model is based on the time-area runoff estimation method. The model allows users to estimate the time of concentration using a range of established methods. The model also allows estimation of the continuing runoff losses using any of the available estimation methods (i.e., constant, linearly varying or exponentially varying). Pollutants build-up in a catchment was represented by one of three pre-defined functions; power, exponential, or saturation. Similarly, pollutants wash-off was represented by one of three different functions; power, rating-curve, or exponential. The developed runoff water quality model was set-up to simulate the build-up and wash-off of total suspended solids (TSS), total phosphorus (TP) and total nitrogen (TN). The application of the model was demonstrated using available runoff and TSS field data from road and roof surfaces in the Gold Coast, Australia. The model provided excellent representation of the field data demonstrating the simplicity yet effectiveness of the proposed model.

Keywords—Catchment, continuous pollutants build-up, pollutants wash-off, runoff, runoff water quality model

I. Introduction

THOUGH human existence is impossible without water, excesses in human activities are responsible for the degradation of the quality of water and water environment. Urban expansion, agricultural activities, fertilizer applications and other human activities alter the natural conditions of the aquatic environment. Stormwater runoff from agricultural and urban areas is a major source of pollution of water bodies [1], [2].

Pollutant loads from catchments vary depending on the characteristics of the catchment surfaces [3]. From the catchment surface the pollutants will transfer to the waterways and water bodies depending on the available pollutants and surface runoff [23], [24]. Surface runoff comes in contact with different types of physical and chemical substances, natural and man made, on catchment surfaces. Some of these substances are pollutants that either dissolve or otherwise transported with runoff and eventually end-up in the waterways and receiving water bodies causing water quality deterioration. However, the severity of impacts depends on the amount of pollutants transferred from the catchment. Hence, estimates of stormwater runoff volume and pollutants loads are required to assess the level of impacts of the pollution on receiving water bodies and to design methods for minimizing the impacts [4]. To understand the cause-effect relationships and assessing the impacts, modelling techniques play an important role. Computer models are the primary tools widely used for the assessment and management of runoff water quality. The major limitation of catchment water quality modeling is the proper identification of the land use of the catchments which controls the pollutants transport with stormwater runoff. In addition, rainfall variability within the same catchment increases the complexity. Traditionally rainfall-runoff models are applied to investigate the water quantities [5]. Outputs of such models are used to investigate wider environmental problems such as water quality parameters [6]. However, a proper understanding of the actual method of pollutants development and transport is often lacking.

This paper describes the development of a simple catchment water quality model, which considers build-up of water quality parameters TSS, TP and TN in a catchment during the dry periods. The model considers pollutants wash-off from the catchment and transport with runoff to the catchment outlet. The model thus improves estimates of pollutants loads entering in waterways and receiving water bodies for any rainfall event. The application of the model was demonstrated using data presented by Egodawatta (2007) including runoff and TSS results for a $3m^2$ catchment in the Gold Coast, Australia.

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II. Model Development

The model presented in this paper is comprised of two integrated models: runoff model; and pollutant model. The runoff model estimates runoff taking into consideration the rainfall losses. It also estimates the volume of surface runoff produced after the storm events. The pollutant model estimates pollutants build-up in the catchment during the dry days and their wash-off to the waterways and receiving water bodies during surface runoff. The runoff and pollutant models were integrated in the model to allow continuous simulation of TSS, TP and TN from a catchment during runoff. The runoff and pollutants models and their integration are discussed in the following sections.

A. *Runoff Model*

The runoff model was developed based on the time-area method for continuous simulation of surface runoff from a catchment. The time-area method was selected as it is the most efficient method of overland flow routing [7], [8]. The method utilizes the convolution of rainfall excess hyetograph into time-area histogram and calculates the runoff from different sub-areas within a catchment in set time increments. The model allows users to calculate the time of concentration (t_c) using a range of established methods. As catchment sub-division is essential for the proper estimation of runoff, the model allows the users to select their own sub-area from a file calculated from the catchment isochrones or the model divides the catchment into sub-catchments using standard methods. Users can choose different established loss models for the calculation of rainfall losses.
Rainfall loss is that part of storm precipitation that does not appear as the immediate runoff [9]. Runoff losses during rainfall events can be characterised by the initial loss rate and continuing loss rate. The initial loss at the early part of storm events can be considered to be a constant. Rahmat et al. (2002) considered the continuing loss to be a constant. In reality however, continuing loss is higher at the beginning of the rainfall event and gradually declines with time as rainfall continues [11]. After meeting losses, excess rainfall causes surface runoff.
The model is able to calculate the quantity of runoff from impervious and pervious areas separately for any duration of rainfall. In calculating the rainfall losses, the model is capable of considering the continuing loss as either constant, linearly decreasing or exponentially decreasing.

1) Exponential Decreasing:

$$CL = A + Be^{-t} \tag{1}$$

2) Linear Decreasing:

$$CL = C - Log(t) \tag{2}$$

3) Constant:

$$CL = Const. \tag{3}$$

The structure of the model is shown in Figure 1. The model input values are: rainfall; average evaporation; and catchment characteristics. The output of the model is the quantity of runoff.

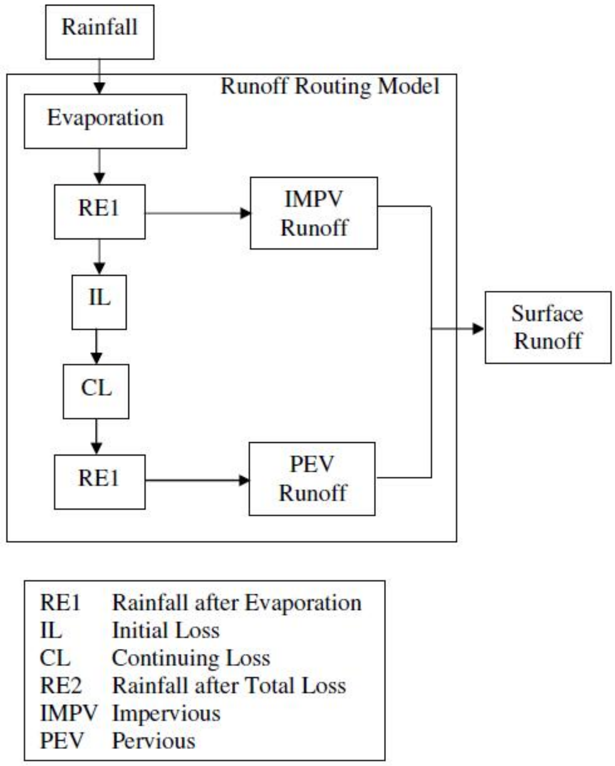

Fig. 1. Structure of the Runoff Model adopted in the model

B. *Pollutant Model*

Stormwater pollutant models are viewed as two stage processes: build-up and wash-off model [4]. Keeping in mind the stages, a pollutant model has been developed and integrated with the runoff model. The model will first estimate the pollutants build-up from a catchment during the antecedent dry days (the days without rain) and then the transport of the pollutants to the waterways and receiving water bodies during surface runoff. Both the pollutants build-up and wash-off can be described through different types of models. Users have the options to select any of the three predefined models for each of the cases. Also the model will allow the users to use different build-up and wash-off coefficients for pervious and impervious surfaces of the catchment. Finally, the model estimates pollutant loads at the catchment outlet.

1) Pollutant Build-up Model: Between rainstorms, rain-washable pollutants build-up in catchments [12]. Pollutants accumulation on catchment surfaces is a function of the number of preceding dry weather days [13], [4]. The maximum accumulation of pollutants depends on climatic and other site-specific factors [14]. In this study, the pollutants build-up in catchments was represented by any of the three defined functions described in the following sections.
(a) Power Function: Build-up of a pollutant in a catchment increases with the increase in number of antecedent dry days until a maximum limit is reached [13], [15], [16], as represented in Equation 4:

$$B = Min(C_1, C_2 t^{C_3}) \tag{4}$$

where, B is pollutant build-up (mass per unit area), C_1 is the maximum build-up possible (mass per unit area), C_2 is the build-up rate constant, t is the number of antecedent dry days and C_3 is the time exponent.
(b) Exponential Function: Pollutant build-up on the catchment surface can be expressed as exponential accumulation and approaches maximum limit asymptotically [13]. This function, shown in Equation 5, was also supported by Grottker (1987).

$$B = C_1(1 - e^{-kt}) \tag{5}$$

where, B is pollutant build-up (mass per unit area), C_1 is the maximum build-up possible (mass per unit area), k is the build-up rate constant $(1/day)$ and t is the number of antecedent dry days.
(c) Saturation Function: Accumulation of pollutants on catchment surfaces starts at a linear rate and continuously decline until a saturation value is reached [13]. The saturation function is presented in Equation 6:

$$B = \frac{C_t}{p+t} \tag{6}$$

where, B is pollutant build-up (mass per unit area), C_1 is the maximum build-up possible (mass per unit area), p is the half saturation constant, i.e. days to reach half of the maximum build-up, t is the number of antecedent dry days.

2) Pollutant Wash-off Model: Pollutant wash-off is significantly influenced by the available pollutants on the catchment surfaces [16]. In this study, pollutants wash-off was represented by any of the three defined functions described in the following sections.
(a) Power Function: Pollutants wash-off load from a catchment is proportional to the product of runoff raised to some power and available pollutants [13], as in Equation 7:

$$W = E_1 q^{E_2} B \tag{7}$$

where, W is pollutant wash-off (kg/km^2), E_1 is the wash-off co-efficient, E_2 is the wash-off exponent, q is the runoff rate per unit area (mm/hr) and B is the pollutant build-up (kg/km^2).
(b) Rating Curve Function: In the rating curve function (Equation 8), the amount of transported pollutants from a catchment can be expressed as proportional to surface runoff raised to some power [13].

$$W = E_3 Q^{E_4} \tag{8}$$

where, W is pollutant wash-off (kg/km^2 per second), E_4 is the wash-off exponent, E_3 is the wash-off co-efficient, Q is the runoff rate (l/s).
(c) Exponential Function: Pollutant wash-off from impervious surface can be estimated as exponential function [18], [16], as in Equation 9.

$$W = (1 - e^{-E_5 I t}) \tag{9}$$

where, W is pollutant wash-off at time $t(kg/km2)$, E_5 is the wash-off exponent, I is the rainfall intensity, B is the initial weight of the pollutant on the catchment surface.

III. Model Application Results and Discussion

A. Model Sensitivity

As a first step to demonstrate the usefulness and capability of continuous simulation of runoff and pollutants wash-off, the model was used to simulate runoff and TSS loads from a hypothetical catchment using assumed values for the different model parameters. The purpose of the simulations was to assess whether the model predictions were capable of generating logical trends that are consistent with expected runoff and pollutant wash-off behaviour.
In the first simulation, the two rainfall events were assumed to be 29 hours apart and to have similar intensities, as shown in Figure 2. The chosen catchment had an area of $25km^2$ and estimated runoff slope of $1m/km$. The rainfall loss parameters were assumed to be in accordance with Australian Rainfall Runoff [19], with initial loss of $15mm$. The continuing loss was assumed to follow an exponentially decreasing loss model. The coefficients of the continuing loss model were assumed to be $A = 1.5$ and $B = 3.0$, within the recommended Australian Rainfall Runoff IEAust values. For the calculation of the pollutant accumulation on the catchment surface power function build-up equation was used. The coefficients of the power function equation for impervious surface are: $C_1 = 6000kg/km^2$, $C_2 = 2600kg/km^2$, $C_3 = 0.16$ and for pervious surface are: $C_1 = 3000kg/km^2$, $C_2 = 800kg/km^2$, $C_3 = 0.16$. For the calculation of transported pollutants exponential pollutant wash-off function was used. The parameters used for the function are: $E_1 = 0.1$, $E_2 = 0.15$ for the impervious surface area and $E_1 = 0.07$, $E_2 = 0.05$ for pervious surface area.

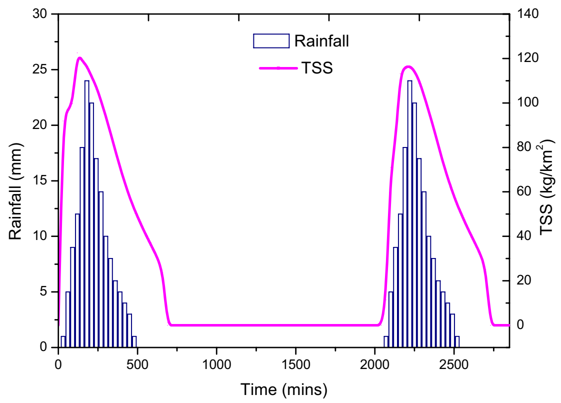

Fig. 2. Simulation of Rainfall and TSS Wash-off for two isolated Rainfall Events

The data in Figure 2 shows the runoff and TSS simulation results. The simulation results followed show that the TSS wash-off for the second event was lower than the TSS wash-off for the first event and that there was no TSS wash-off between the two rainfall events during the period when there was no surface runoff. Although the same rainfall intensities were used for both rainfall events, the TSS wash-off for the first rainfall event was higher than that for the second rainfall event. This is because following TSS washout during the first event, the intermediate dry period was not long enough to build-up significant additional TSS to produce higher wash-off during the second rainfall event. Similar wash-off patterns were observed for the simulations of TP and TN.

The performance of the model in simulating a significant continuous rainfall event was also tested. For a continuous rainfall event, the rainfall loss declines with time and surface runoff lasts for extended period of time. However, pollutants wash-off is limited by the amount of available pollutants, which are mostly removed during the first-flush. The data in

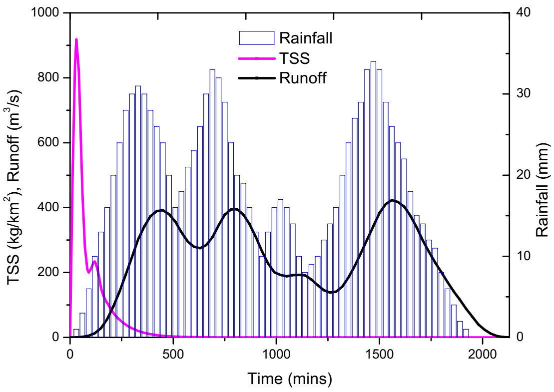

Fig. 3. Simulation of Rainfall, Surface runoff and TSS Wash-off for a continuous Rainfall Event

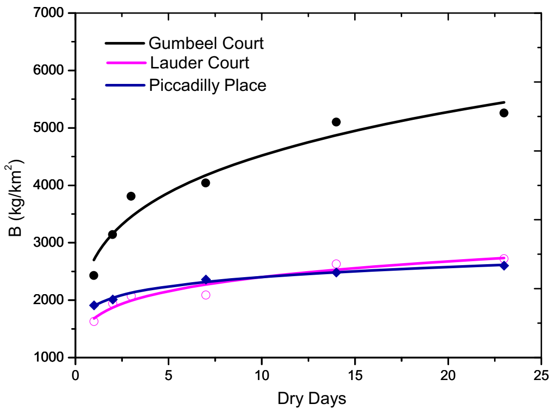

Fig. 4. Relationship between Build-up and Dry days (Road Surfaces)

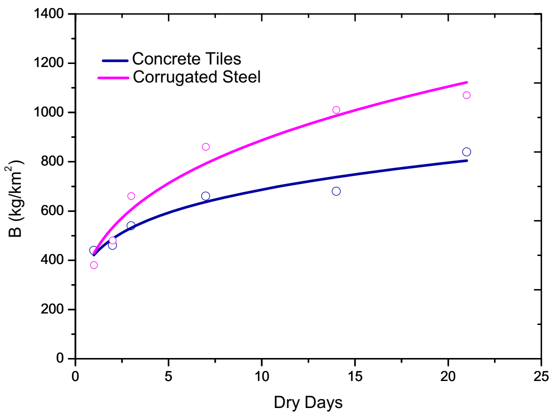

Fig. 5. Relationship between Build-up and Dry days (Roof Surfaces)

Figure 3 show the simulation of catchment runoff and TSS for a long continuous rainfall event. Model simulation revealed the obvious first-flush phenomenon with significant TSS wash-off at the early stage of the storm. As the rainfall continued, pollutant wash-off decreased with time to negligible values. The data in Figure 3 also indicate that at one stage of the decreasing trend, there was a sudden increase in wash-off generating a localised TSS peak, which can be attributed to the difference in the time of arrival of TSS from the different impervious and pervious areas of the catchment. With runoff from impervious surfaces starting earlier than from pervious surfaces, the contribution of pervious surfaces to TSS wash-off starts upon arrival of runoff from the pervious surfaces.
The above model simulations demonstrated that the model was capable of generating logical runoff and TSS wash-off trends that are consistent with expected behaviour. However, the usefulness of the model requires further testing using real data.

B. Parameter Estimation

Parameters estimation is a critical step in model implementation [20]. Depending upon the physical characteristics of the catchment, the model input parameters can vary significantly. Obviously, it is difficult to measure accurate build-up and wash-off rates in catchments due to various reasons, among which for example is the access limitation within any catchment. However, appropriate values of build-up coefficients (C_1, C_2, C_3, k and p) in Equations 4 to 6 and wash-off coefficients (E_1, E_2, E_3, E_4, and E_5) in Equations 7 to 9 are required before using the models. Deletic and Maksimovic (1998) and Kim et al. (2006) proposed indirect methods for estimating these parameters.

In this study, the build-up and wash-off parameters were estimated based on the experimental data presented by Egodawatta (2007). Egodawatta (2007) assessed pollutants wash-off from road and roof surfaces in the Gold Coast, Australia, for low and high population density residential areas using simulated rainfall. The maximum pollutants loads collected from the experimental sites varied in the range of 3000 to 6000 kg/km^2. The maximum pollutants loads are representatives of coefficient C_1 in Equations 4 to 6.

The data in Figures 4 and 5 show the relationship between build-up amounts with antecedent dry days for three different catchments and two different surfaces (road and roof). To derive general relationships, the best-fit curves were drawn for each of the catchments. The derived best-fit curves had coefficients of determination (R^2) more than 0.90, indicating good fits for the available data. From the plotted best-fit equations, the values of the build-up coefficients C_2 and C_3 were estimated. From the Figure 4, it is clear that the high population density catchment (Gumbeel Court) had the highest pollutant build-up load compared with the lower populated catchments, Lauder Court and Piccadilly Place for the road surfaces. For roof surfaces (Figure 5), the initial build-ups were same for both the roads. However, with the continuing dry days, the pollutants build-up on corrugated steel was higher than the build-up on the concrete surface. This might be due

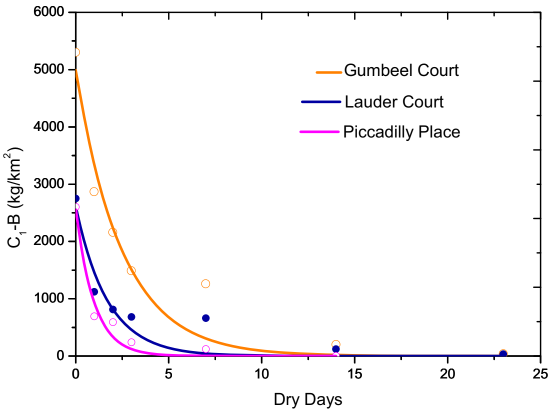

Fig. 6. Exponential Function Build-up Parameters Estimation (Road Surfaces)

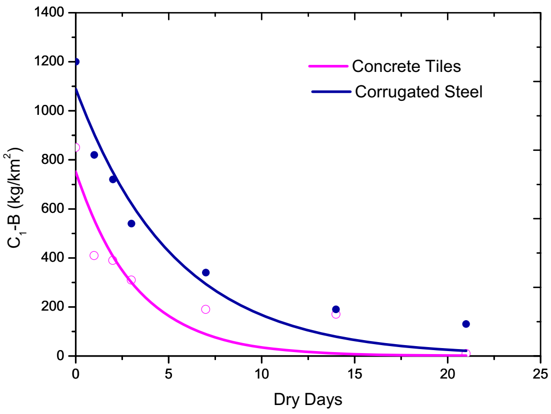

Fig. 7. Exponential Function Build-up Parameters Estimation (Roof Surfaces)

to the roughness of the roof materials.

Figures 6 and 7 show the relationships and parameter estimations of the exponential function for road surfaces and roof surfaces respectively. The exponents in Figures 6 and 7 provide the build-up rate constants. Figures 8 and 9 show the relationships and parameters estimations of the saturation function for road surfaces and roof surfaces respectively. The slope of the lines in Figures 8 and 9 passing through the origin represents the different values of the half saturation constant, p. The estimated values of the road surface and roof surface build-up parameters are shown in Tables I and II respectively.

The values of the wash-off parameters were also estimated from the experimental study done by Egodawatta (2007) on the road surfaces and similar materials of the roof surfaces within the same catchments. Based on the data the ratio between wash-off and remaining build-up (W/B) and q have been calculated for different rainfall intensities and durations. Figure 10 shows the graph of W/B vs. q for the road surfaces

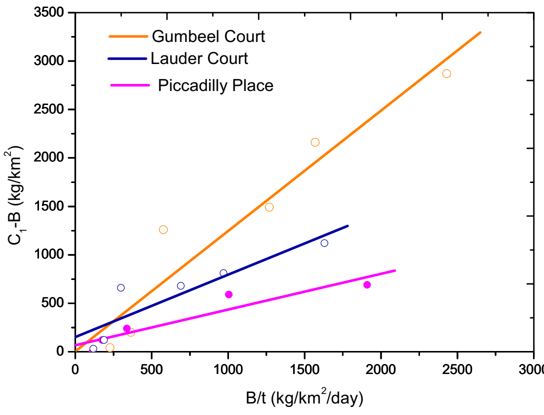

Fig. 8. Saturation Function Build-up Parameters Estimation (Road Surfaces)

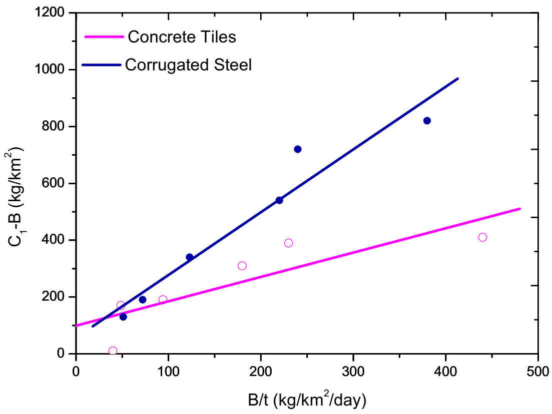

Fig. 9. Saturation Function Build-up Parameters Estimation (Roof Surfaces)

TABLE I
ESTIMATED VALUES OF BUILD-UP PARAMETERS FOR ROAD SURFACES

Catchment Name	C_1 kg/km^2	C_2 kg/km^2	C_3	k $1/days$	p
Gumbeel Court	5300	2623.8	0.238	0.222	1.244
Lauder Court	2750	1678.5	0.155	0.210	0.784
Piccadilly Place	2600	1900.7	0.102	0.382	0.418

TABLE II
ESTIMATED VALUES OF BUILD-UP PARAMETERS FOR ROOF SURFACES

Catchment Name	C_1 kg/km^2	C_2 kg/km^2	C_3	k $1/days$	p
Concrete Tiles	850	424.22	0.208	0.188	1.208
Corrugated Steel	1200	401.33	0.349	0.122	0.434

of Piccadilly place catchment for different durations. Figure 11 shows the graph for the roof surface of concrete tiles. Co-

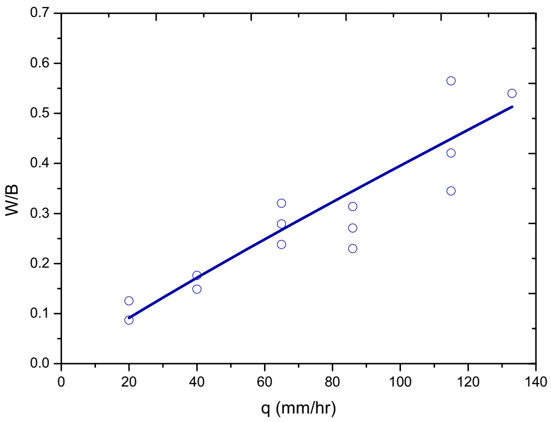

Fig. 10. Power Function Wash-off Parameters Estimation (Piccadilly Place Road Surface)

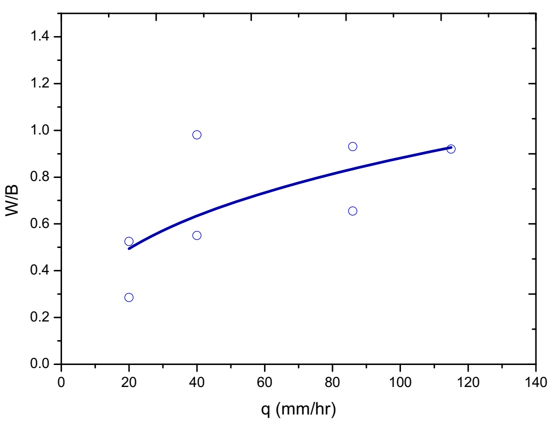

Fig. 11. Power Function Wash-off Parameters Estimation (Concrete Tile Roof Surface)

efficient and exponent of the best-fit curves provide the values of wash-off co-efficient, E_1 and exponent, E_2 respectively. Similar relationships were observed for other catchments and roof surfaces as well.

Figure 12 shows the graph of W vs. Q, for the estimation of wash-off parameters for 'rating curve function' for road surface (Gumbeel Court). Figure 13 shows the graph of W vs. Q, for the estimation of wash-off parameters for rating curve function for roof surface (corrugated steel). Similar to the power function parameters estimations, the co-efficient and exponent of the best-fit equations provided the wash-off coefficients E_3 and E_4 for the rating curve function. The derived co-efficient values are outlined in Tables III and IV.

In estimating the parameters of the exponential wash-off function graphs between $(B - W)$ vs. (It) have been plotted. Figures 14 and 15 show the graph for Lauder Court catchment for road surfaces and concrete tiles roof surface respectively.

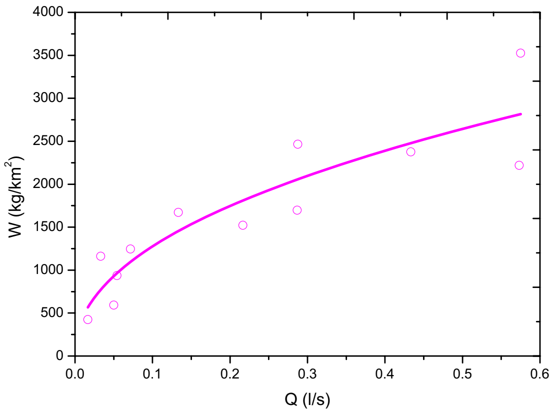

Fig. 12. Rating Curve Wash-off Parameters Estimation (Gumbeel Court Road Surface)

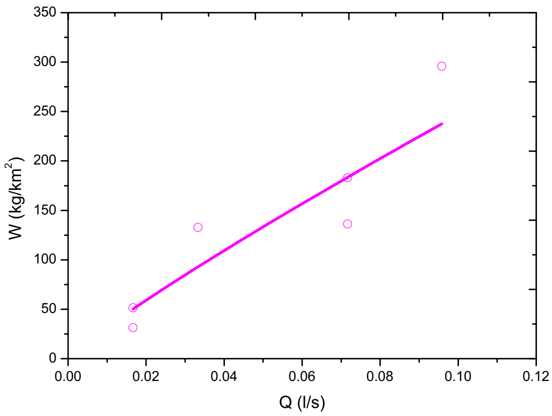

Fig. 13. Rating Curve Wash-off Parameters Estimation (Corrugated Steel Roof Surface)

TABLE III
ESTIMATED VALUES OF WASH-OFF PARAMETERS FOR ROAD SURFACES

Catchment Name	E_1	E_2	E_3 kg/km^2	E_4	E_5
Gumbeel Court	0.0029–0.0135	0.608–0.986	3414.4–5260.4	0.472–0.580	0.011
Lauder Court	0.0015–0.0059	0.945–1.270	1649.0–2927.8	0.344–0.744	0.028
Piccadilly Place	0.0062–0.011	0.753–0.914	1864.6–2992.1	0.413–0.564	0.026

TABLE IV
ESTIMATED VALUES OF WASH-OFF PARAMETERS FOR ROOF SURFACES

Catchment Name	E_1	E_2	E_3 kg/km^2	E_4	E_5
Concrete Tiles	0.051–0.202	0.363–0.603	585–805	0.556–0.797	0.388
Corrugated Steel	0.112–0.213	0.333–0.414	2362–2685	0.993–1.000	0.134

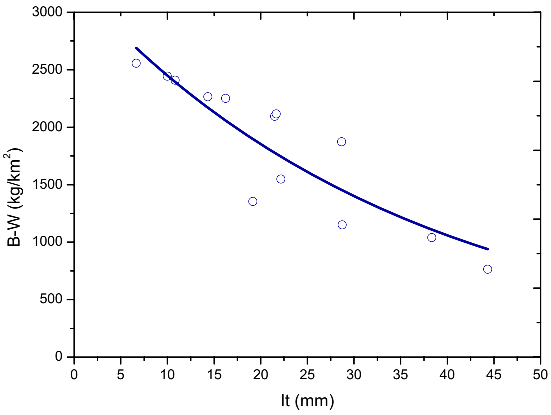

Fig. 14. Exponential Wash-off Parameter Estimation (Lauder Court Road Surface)

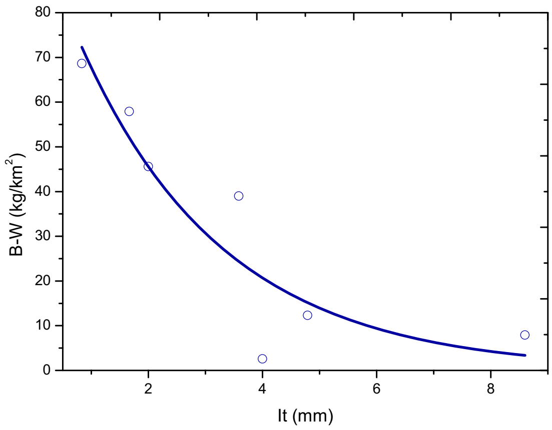

Fig. 15. Exponential Wash-off Parameter Estimation (Concrete Tile Roof Surface)

Road surfaces and roof surfaces in other catchments also follow the similar pattern. The exponent of the graph is the wash-off parameter (E_5) of the exponential function. The estimated values for the road and roof surface wash-off parameters are shown in III and IV respectively.

IV. Conclusion and Recommendation

An integrated water quality model that continuously simulates pollutants build-up and wash-off from a catchment was developed. The model allows estimation of pollutants build-up during dry periods and pollutants wash-off as a result of rainfall events. The model was setup to simulate TSS, TN and TP; however the model can easily be extended to incorporate other water quality parameters.

For calculating runoff, the model allows estimation of the continuing runoff losses using any of the available estimation methods, rather than using a fixed rainfall loss value for the whole duration of rainfall (i.e., constant, linearly varying or exponentially varying). The model thus accounts for the fact that the continuing loss does not remain constant for the whole duration of the event but decreases with time.

For estimating runoff water quality parameters, the model provides various pollutants build-up and pollutants wash-off models. The various build-up and wash-off models are meant to reflect differences in catchment-pollutant-runoff characteristics between different catchments. As such, the user has the option of choosing the best pollutants build-up and wash-up models to represent the problem under consideration.

The sensitivity analysis that involved applying the model using a hypothetical catchment and assumed model parameters demonstrated that the model produced reasonable trends in reflecting the runoff and water quality behaviour in the catchment. The model considers runoff, pollutants build-up and wash-off from pervious and impervious areas and availability of pollutants in the catchment due to successive or extended rainfall events.

The model was used to represent available field measurements collected from street and roof surfaces in residential catchments in the Gold Coast, Australia. The experimental data were used to estimate the parameters of all of the different pollutants build-up and wash-off equations used in the model. The estimated parameters revealed which of the different pollutants build-up and wash-off equations best represented the field data for the particular catchment in Gold Coast, Australia. It should be noted that other user-defined pollutants build-up and wash-off models can be integrated in the model. With further application of the model on various catchments in different regions, a range of values for the different model parameters can be established.

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