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Application of Build-up and Wash-off Models for an East-Australian Catchment

Iqbal Hossain, Monzur Alam Imteaz and Mohammed Iqbal Hossain

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Abstract—Estimation of stormwater pollutants is a pre-requisite for the protection and improvement of the aquatic environment and for appropriate management options. The usual practice for the stormwater quality prediction is performed through water quality modeling. However, the accuracy of the prediction by the models depends on the proper estimation of model parameters. This paper presents the estimation of model parameters for a catchment water quality model developed for the continuous simulation of stormwater pollutants from a catchment to the catchment outlet. The model is capable of simulating the accumulation and transportation of the stormwater pollutants; suspended solids (SS), total nitrogen (TN) and total phosphorus (TP) from a particular catchment. Rainfall and water quality data were collected for the Hotham Creek Catchment (HTCC), Gold Coast, Australia. Runoff calculations from the developed model were compared with the calculated discharges from the widely used hydrological models, WBNM and DRAINS. Based on the measured water quality data, model water quality parameters were calibrated for the above-mentioned catchment. The calibrated parameters are expected to be helpful for the best management practices (BMPs) of the region. Sensitivity analyses of the estimated parameters were performed to assess the impacts of the model parameters on overall model estimations of runoff water quality.

Keywords—Calibration, Model Parameters, Suspended Solids, Total Nitrogen, Total Phosphorus.

I. INTRODUCTION

IT is widely recognized that watershed management is essential for the protection and improvement of the downstream environment from pollutions. However, efficient management of waterways and receiving water bodies heavily relies on the accurate estimation of the pollutants transferred from the catchment for the design of effective impact mitigation devices and management strategies. Inaccurate measurement of non-point pollutant loads can lead to the design of undersize and ineffective or oversized measures with excessive capital cost and maintenance requirements. The general strategies and programs for watershed management always depend on the modelling results of watershed responses, which involve both flow and pollutants processes [1].

During the last decade abundant hydrologic and water quality models have been developed for the prediction of the transported stormwater pollutants from a particular watershed area. However, the major problem in the application of any stormwater quality model is the selection of appropriate model parameters [2]. Hence, estimation of appropriate sets of parameter values of stormwater quality models is essential to simulate the catchment responses accurately. Tsihrintzis and Hamid (1998) noted that parameter estimation is the most critical step in the practical application of any water quality model [3]. Different researchers have used different procedures for the estimation of model parameters. For example, Deletic and Maksimovic (1998) [4] and Kim et al. (2006) [5] used indirect methods for the estimation of these parameters. The parameters can be determined from the samples collected from each land-use [6]. However, the values of the parameters determined in this manner might only reflect the pollutant loads at a few sample points rather than all over the entire catchment. Other alternative approach for the estimation of these parameters is using the runoff quality data collected at the watershed outlet [7] by the calibration procedure, which reflects the combined effects of the whole catchment. However, Leinster and Walden (1999) discouraged the general application of water quality model parameters from overseas countries [8]. Chen and Adams (2006) and Baffaut and Delleur (1990) found that the model parameters vary not only catchment to catchment, but also differ among different rainfall events [9], [10]. Therefore, Pucket (1995) noted a watershed management plan needs to be developed on an individual watershed basis [11]. Hence, calibration of water quality model with local data is essential for the analysis, improvement and/or update of the existing BMPs for a particular catchment. Calibration procedure attempts not only identifying the best set of parameters, but also help to assess and reduce the uncertainty in parameter values [12].

This paper demonstrates the calibration of a catchment water quality model to obtain a set of parameters for which the predicted pollutant concentrations are close to the measured concentrations. Two major pollutants were analysed for the calibration of the model: TN and TP. These pollutants were chosen for the calibration of the model because of the data availability. Nonetheless, these parameters are generally used as indicators of water quality in receiving water bodies [13]. For the evaluation of the hydrologic outputs of the model, the peak discharges were compared with the calculated discharges from the WBNM and DRAINS models, which are widely used in Australia. Water quality data (TN and TP) was collected from several locations within the HTCC on the Gold Coast, Australia. The calibration of the model was demonstrated using the collected water quality data from the Gold Coast, Australia. The calibrated parameters are expected to be useful for the future use of the model to develop BMPs for pollution

I. Hossain and M. Imteaz are with the Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, Hawthorn, VIC, 3122, Australia).

M. Hossain is with Gold Coast City Council, Qld, 9729, Australia.

control in this region.

II. Materials and Methods

A. Study Area

The catchment studied for this work was the Hotham Creek Catchment (HTCC), located on the Gold Coast of eastern Australia. The catchment area considered for this study is 302.35 ha and is predominantly pervious. The impervious percentage for the sub-catchments were determined from the aerial photograph, which reveals that only 2.61% percent of the total catchment area has impervious surfaces. The upper portion of the catchment is dominated by farming, which includes dairy and beef cattle, bananas and various other crops. As watershed delineation is important in hydrological modelling, the area was divided into eight sub-catchments. A detailed map of the catchment showing the location of the sub-catchment areas is shown in Figure 1. Table I shows detailed sub-catchments information for the HTCC.

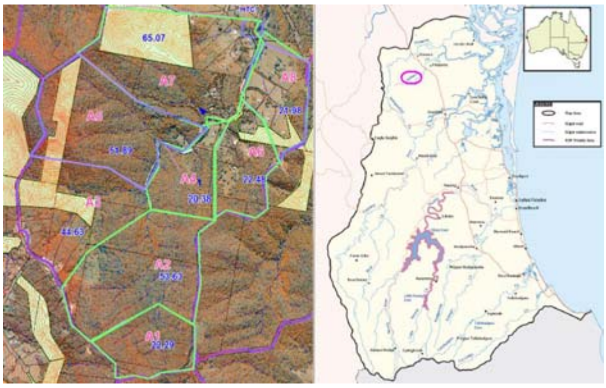


Fig. 1 Location of Hotham Creek Catchment

TABLE I
DETAILED SUB-CATCHMENTS INFORMATION FOR THE HTCC

Sub-catchments	Parameters	
	Area (ha)	Imperviousness (%)
A_1	22.29	0.00
A_2	56.63	0.00
A_3	44.63	0.00
A_4	20.38	0.00
A_5	51.89	0.00
A_6	22.48	5.00
A_7	65.05	7.00
A_8	21.98	10.00

B. Data Collection

For the assessment of any watershed response in hydrologic and water quality systems, precipitation data is the key information. Hourly precipitation data was collected from the Bureau of Meteorology (BoM) for the rainfall station 'Gold Coast Seaway' (station no. 40764) for the calibration period. As the aim of the research was to estimate the amount of pollutants transferred during the storm events, the rainfall data period was chosen to align with the water quality measurement. Water quality sampling and measurement was conducted by the Gold Coast City Council (GCCC), Australia. Data from the HTCC was used for the calibration of the model. GCCC has been monitoring water quality parameters at different locations within the catchment. For the present calibration, the upper most sub-catchments were selected to obtain unaltered pollutants transported only from the catchment, i.e. to avoid the alterations of runoff water quality through processes within the creek.

C. Hydrologic Model

The hydrologic model was developed by considering the initial loss-continuing loss $(IL - CL)$ model and time-area routing method. The usual practice of CL consideration is constant [14]. However, Ilahee and Imteaz (2009) found that for many east Australian catchments the CL is higher at the beginning of the rainfall event and gradually decreases with time as the rainfall continues [15]. To account for variable CL, the developed model has three different options (exponential decreasing, logarithmic decreasing and constant). Detailed description of the CL models is given by Hossain et al. (2010) [16]. The time-area method was applied to represent the partial area contribution of the catchment. The model input values are: rainfall; daily average evaporation; IL; CL parameters; and catchment characteristics. The output of the model is the quantity of surface runoff at the catchment outlet.

D. Pollutant Model

For the simulation of pollutants, the model provides three methods for pollutant accumulation and three methods for pollutant transportation. However, this study is limited to one pollutant build-up (exponential function) and two wash-off (power and rating curve functions) models. The calculations of the pollutant build-up and wash-off processes are very similar to the widely used Storm Water Management Model (SWMM) model described by Rossman (2004) [17].

1) Pollutant Build-up Model: Pollutant build-up from the catchment surface was estimated by the exponential build-up model described in Equation 1:

$$B_{t_d}(p,s) = min\begin{cases} A(s)F(s)C_1(p,s), \\ A(s)F(s)C_1(p,s)\{(1-e^{kt_d}) + B_0(p,s)\} \end{cases} \tag{1}$$

Where, B_{t_d} is the accumulation of pollutant 'p' (kg) to the land surface 's' during the 'antecedent dry days'; $A(s)$ is the area of the sub-catchment 's' (km^2); $F(s)$ is the impervious or pervious fraction of the land surface; $C_1(p,s)$ is the maximum amount of pollutant (kg/km^2) that can be accumulated on the land surface 's'; t_d is the number of 'antecedent dry days'; 'k' is the accumulation rate coefficient $(1/day)$; $B_0(p,s)$ is the amount of pollutant remaining on the land surface after the previous storm (kg); 's' refer to the pervious or impervious surface.

2) Pollutant Wash-off Model: Pollutant wash-off from the land surface during the storm event can be calculated by either the power function or the rating curve function as described in Equations 2 and 3 respectively.

$$W_t(p,s) = \frac{E_1(p,s) \times (q_t(s))^{E_2(p,s)} \times B_{t_d}(p,s)}{1000 V_t(s)} \quad (2)$$

$$W_t(p,s) = \frac{E_3(p,s) \times (Q_t(s))^{E_4(p,s)}}{1000 V_t(s)} \quad (3)$$

Where, $W_t(p,s)$ is the wash-off rate for the pollutant 'p' (mg/l) from land surface 's' within time 't'; $E_1(p,s)$ is the pollutant wash-off coefficient; $q_t(s)$ is the runoff rate (mm/hr) per unit area; $E_2(p,s)$ is the pollutant wash-off exponent $(dimensionless)$; $V_t(s)$ is the volume of surface runoff (m^3) within time 't'; $E_3(p,s)$ is the coefficient for the wash-off parameter; $E_4(p,s)$ is the exponent or power of the wash-off parameter $(dimensionless)$; $Q_t(s)$ is the runoff rate (m^3/s) from the land surface 's'.

III. RESULTS AND DISCUSSIONS

A. Calibration and Parameters Estimations

Prediction of stormwater pollutants by the models depend on the proper selection of model parameters. However, it is difficult to determine the model parameters accurately. On the other hand, the accuracy of the modelling results largely depends on the accuracy of its parameters. Also, there is a possibility of identifying numerous sets of alternative parameters. However, appropriate values of build-up rate and exponent; wash-off coefficients and exponents are required before using the models.

The usual practice for the models parameters estimation is performed by the calibration procedure. In this study calibration of the model was intended to determine the appropriate parameter values for both the runoff and pollutant models. The major parameter values of the runoff, build-up and wash-off models were constantly adjusted until the deviation or standard error between the simulated and observed values were reduced to a satisfactory level. Two major pollutant components (TN and TP) were selected for the calibration. These parameters were selected due to the availability of water quality data, although the developed model can be used to simulate for other water quality parameters as well. The runoff and water quality components of the model were calibrated separately.

As the outputs of the runoff model are essential for the pollutant model, the runoff model was calibrated before the pollutant model. No runoff measurement was conducted during the sampling period. For this reason, the developed model was calibrated with the results of the widely used Australian models WBNM and DRAINS. For these models, IL and CL values were adopted by reviewing the available literatures for similar geographical conditions. Percent impervious values were determined from the aerial photograph. Four storm events ranging from low to high intensity were selected for the calibration of the runoff model. The summary of the computed peak discharges and their comparison with calculated discharges from other models are shown in Table II.

TABLE II
COMPARISON OF PEAK DISCHARGES WITH WIDELY USED AUSTRALIAN RUNOFF MODELS

Events	Dates	Peak Discharges (m^3/s)			
		Simulated	WBNM	DRAINS	Rational Method
1	15/01/2004	32.96	35.29	30.80	27.34
2	30/08/2005	0.06	0.057	0.06	1.79
3	13/02/2007	104.37	110.77	104.00	83.16
4	08/07/2008	8.77	9.53	6.74	8.98

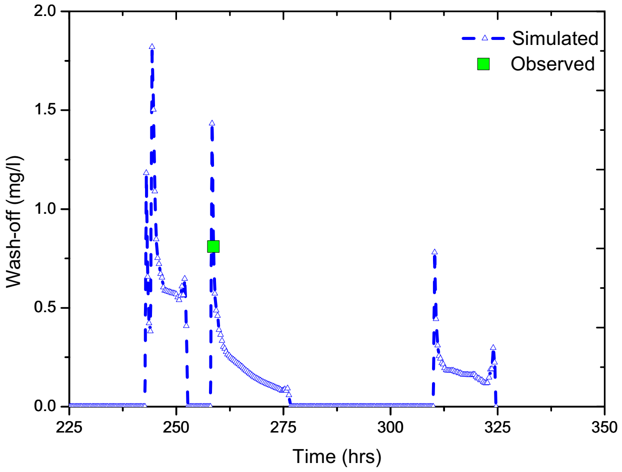
From the Table II, it is clear that the rational method gives a higher peak for the low intensity rainfall. On the other hand for higher intensity rainfall, this method underestimates the peak flow. This is due to the effects of the partial area contribution considered in other methods. Due to partial area contribution, in reality during low intensity rains, whole catchment does not contribute at the formation of peak runoff, which was considered in other models. However, the rational method is unable to consider this partial area impact, leading to estimation of higher values. During high intensity rainfalls, partial area impact is not dominant. In general, simulated peak discharges of the model are very close to the peak discharges simulated by the other widely used Australian models, indicating the suitability of the developed model for runoff simulation. However, observed runoff data is needed to achieve more accurate calibration.

TABLE III
SUMMARY OF ESTIMATED VALUES OF THE BUILD-UP AND WASH-OFF PARAMETERS

Parameters	TN		TP	
	IMPV	PEV	IMPV	PEV
C_1(p,s)	300	400	150	200
k(p,s)	0.23	0.23	0.15	0.15
E_1(p,s)	0.0013 - 0.0017	0.0024 - 0.0032	0.00012 - 0.0005	0.00070 - 0.00021
E_2(p,s)	0.75 - 0.80	0.75 - 0.80	0.75 - 0.90	0.75 - 0.90
E_3(p,s)	0.0004	0.00065 - 0.00070	0.00002 - 0.00004	0.000035 - 0.000070
E_4(p,s)	0.90	0.90	0.78 - 0.88	0.78 - 0.88

Calibration of the pollutant components of the model required the estimation of the build-up and wash-off parameters. Calibration for both of the sub-models (build-up and wash-off) was done simultaneously until the total predicted loadings matched with the measured ones. However, water quality at the beginning of the rainfall event will be dominated by the build-up parameters. After analysing the rainfall data, corresponding 'antecedent dry days' was determined. For the continuous simulation, the intermediate dry days were calculated by the model automatically. It was assumed by the model that, if 'antecedent dry days' was less than one, there would be no pollutant build-up during this time period. The summary of the estimated build-up and wash-off parameters for the catchment is shown in Table III. The values of the parameters have been estimated for impervious and pervious surfaces separately. However, the catchment is predominantly (97.39%) pervious. So the parameters of the pervious surface can be considered as the dominating parameters for the catchment.

a) Power Function Wash-off



b) Rating Curve Wash-off

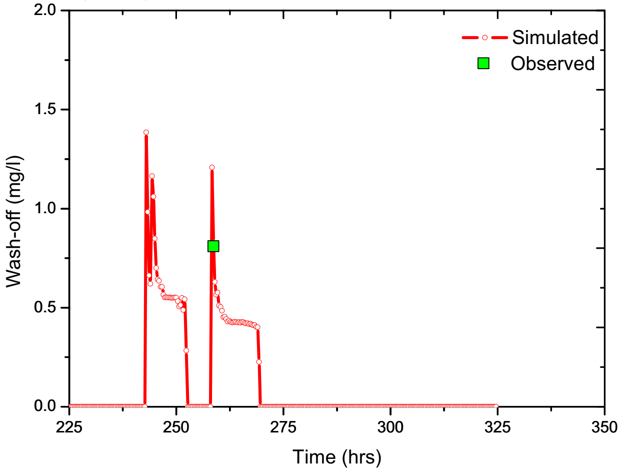
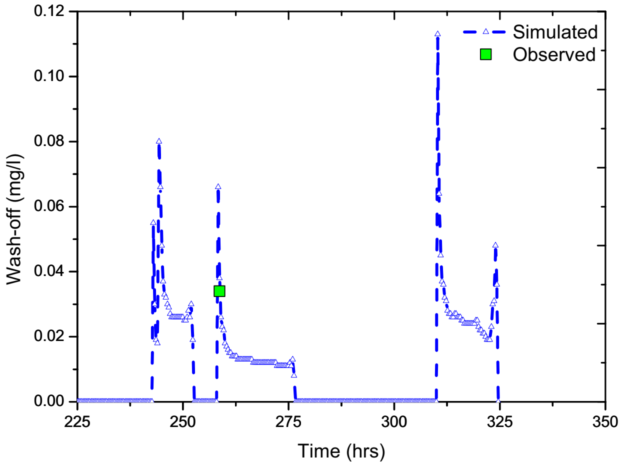


Fig. 2 Simulation of TN (Exponential Build-up Model)

Simulation of the plotted results for TN wash-off with the calibrated parameters for the catchment is shown in Figure 2 for two different wash-off models with one build-up model. From the Figure 2(a), it is clear that there is higher TN wash-off during the initial period of the storm for the power function model compared with the rating curve model shown in Figure 2(b). However, the pollutant build-up was same in both cases. This indicates that the capability of the rating curve wash-off model to simulate first-flush phenomena for TN is lower compared to the power function. However, Deletic and Maksimovic (1998) found that first-flush occur only in a limited number of storm events [4]. It is also observed from the figures that there is no wash-off at the end of the storm for the rating curve wash-off. This is due to the fact that most of the pollutants were already washed away during the middle of the storm and the available pollutant to be washed-off was vanished before the end of the storm.

a) Power Function Wash-off



b) Rating Curve Wash-off

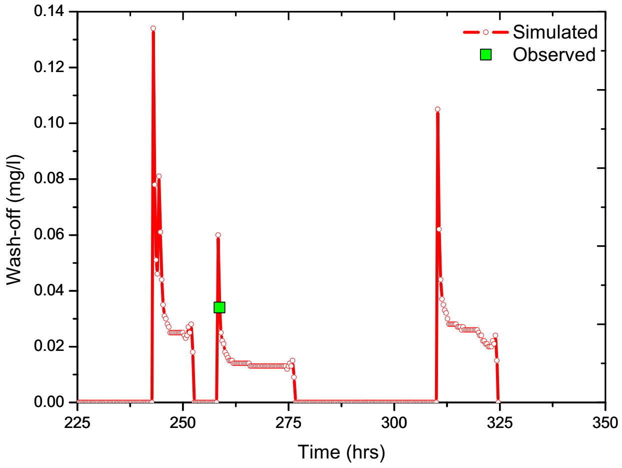
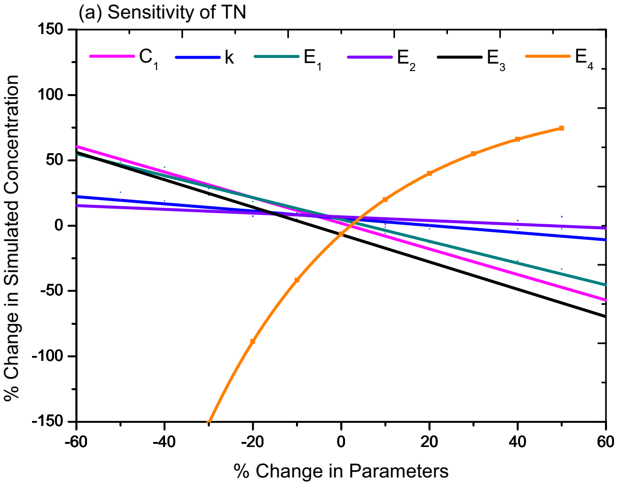


Fig. 3 Simulation of TP

The simulation of TP with exponential build-up model for two (power function and rating curve) wash-off models are shown in Figure 3. Although the shapes of the pollutographs are same for both the wash-off models, initial TP wash-off for the power function wash-off is less compared with the rating curve wash-off, indicating that the capability of the power function wash-off model to simulate first-flush of TP is less than the rating curve wash-off. Also, there is a higher pollutant wash-off for power function wash-off at the end of the storm shown in Figure 3(a). As for this case, there was no significant first-flush of pollutants; there were more available pollutants to be washed off during the later part of the storm. As for the case of the rating curve wash-off model, as less pollutants were available towards the end of storm period, the TP wash-off was less shown in Figure 3(b).

The agreement of the simulated results with the measured water quality data for the estimated parameters appears to be reasonable for both the pollutants. Due to the limitation of data, calibration was done only for one observation. More observed data is needed to assess the capability of the model.

B. Sensitivity Analysis


(a) Sensitivity of TN

(b) Sensitivity of TP

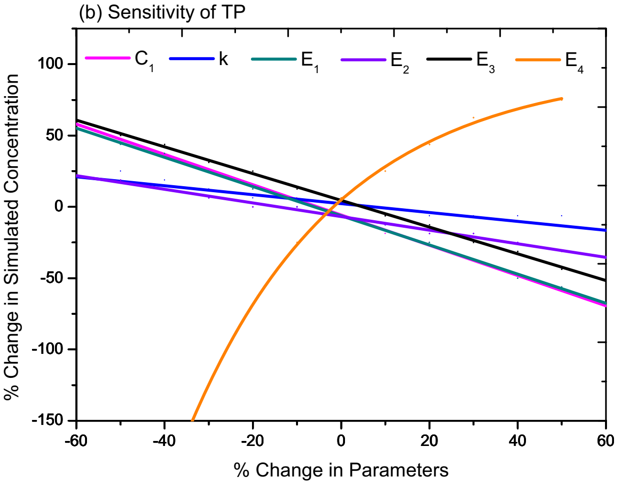


Fig. 4 Parameters Sensitivity for Hotham Creek Catchment

The general purpose of the sensitivity analysis is to assess the impacts of various parameters on final model results. The analysis was performed around the optimal calibrated parameters in order to asses the impacts of selecting inaccurate values for the parameters. Figure 4 shows the sensitivity of the build-up parameters (C_1 and 'k') and the wash-off parameters (E_1, E_2, E_3 and E_4) with the measured values of TN and TP. The sensitivity analysis was performed by changing each parameter while keeping others constant and observing the changes in the model output. From the figure, it is clear that the exponent of the wash-off parameter, E_4 is the most sensitive parameter shown in Figure 4(b). The second most sensitive parameter is the maximum build-up rate (C_1), shown in Figure 4(a). Changes in all other parameters did not produce significant changes in the model results. The least sensitive parameter is the build-up rate coefficient, 'k'. The sensitivity of the parameters for both the TN and TP are very similar as shown in Figure 4.

IV. CONCLUSIONS AND RECOMMENDATIONS

A catchment water quality model was developed and calibrated for the Hotham Creek Catchment located on the Gold Coast, Australia. The runoff component of the model was calibrated using the rainfall data from a nearby rainfall station, 'Gold Coast Seaway'. The runoff estimations of the model were compared with the runoff calculations of two commercial models (WBNM and DRAINS) widely used in Australia. The water quality (pollutant) component of the model is much more complex having many parameters/coefficients to be determined. These parameters can vary a lot depending on geographical locations, land-uses and percent imperviousness of the surface. The pollutant component of the model was calibrated for TN and TP using the observed data collected by the Gold Coast City Council. The study was carried out to test the applicability of the developed model in Gold Coast, Australia and to provide users with a set of parameters that can be used for modelling typical water quality parameters in this area. The results obtained show the considerable predictive capability of the model when the parameters are selected properly.

However, the phenomena for the non-point pollutant build-up and wash-off are influenced by a large number of factors, and their dynamics are still not well known. Estimation of model parameters should be performed through calibration from real measurements for specific areas for several continuous storm events, instead of a single rainfall event. The outcomes of the study suggest that the model is a potential tool which could aid in the development of management strategies for complex watershed areas like HTCC. It should be noted that the estimation of model parameters has been performed with only a limited number of observations. Therefore, care should be taken when using the findings. However, the results are promising and may be used for catchments with similar conditions.

A sensitivity analysis was performed that showed that the exponent of the wash-off parameter is the most sensitive parameter. The second most sensitive parameter is the maximum build-up rate and the least sensitive parameter is the build-up rate coefficient, 'k'. All other parameters are not significantly sensitive to the final model results. However, there would be

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a wide range of different sets of parameter values, which may produce same model outcomes. This fact suggests that the generic application of a sophisticated build-up wash-off model should be performed cautiously. Further research is needed to derive appropriate values of the build-up and wash-off model parameters for the application with a greater degree of confidence in this region.

REFERENCES

[1] C. L. Chang, S. L. Lo and M. Y. Chen, *Uncertainty in watershed response predictions induced by spatial variability of precipitation*. Environmental Monitoring and Assessment, 127(1-3), pp. 147-153, 2007.

[2] I. E. Ball, R. Jenks and D. Aubourg, *An assessment of the availability of pollutant constituents on road surfaces*. Science of the Total Environment, 209(2-3), pp. 243-254, 1998.

[3] V. A. Tsihrintzis and R. Hamid, *Runoff quality prediction from small urban catchments using SWMM*. Hydrological Processes, 12, pp. 311-329, 1998.

[4] A. B. Deletic and C. T. Maksimovic, *Evaluation of water quality factors in storm runoff from paved areas*. Journal of Environmental Engineering, 124(9), pp. 869-879, 1998.

[5] L. H. Kim, K. D. Zoh, S. M. Jeong, M. Kayhanian and M. K. Stenstrom, *Estimating pollutant mass accumulation on highways during dry periods*. Journal of Environmental Engineering, 132(9), pp. 985-993, 2006.

[6] J. D. Sartor and G. B. Boyd, *SWMM (Stormwater Management Model) Version 5, User Manual*. Water pollutants aspects of street surface contaminants. Report No. EPA-R2-72-081, EPA, Washington D.C., United States, 1972.

[7] W. M. Alley and P. E. Smith, *Estimation of accumulation parameters for urban runoff quality modelling*. Water Resources, 17(6), pp. 1657-1664, 1981.

[8] S. Leinster and W. Walden, *The application of sophisticated stormwater quality estimation techniques in Australian catchments- A Queensland case study*. Water 99: Joint Congress, Brisbane, Australia, pp. 589-595, 1999.

[9] J. Chen and B. J. Adams, *Analytical urban storm water quality models based on pollutant buildup and washoff process*. Journal of Environmental Engineering, 132(10), pp. 1314-1330, 2006.

[10] C. Baffaut and J. W. Delleur, *Calibration of SWMM runoff quality model with expert system*. Journal of Water Resources Planning and Management, 116(2), pp. 247-261, 1990.

[11] L. J. Puckett, *Identifying the major sources of nutrient water pollution*. Environmental Science and Technology, 29(9), pp. 408-414, 1995.

[12] M. B. Beck, *Principles of modelling*. Water Science and Technology, 24(6), pp. 1-8, 1991.

[13] J. Vaze and F. H. S. Chew, *Nutrient loads associated with different sediment sizes in urban stormwater and surface pollutants*. Journal of Environmental Engineering, 130(4), pp. 391-396, 2004.

[14] A. Rahman, P. E. Weinmann, T. M. T. Hoang and E. M. Laurensen, *Monte Carlo simulation of flood frequency curves from rainfall*. Journal of Hydrology, 256(3-4), pp. 196-210, 2002.

[15] M. Ilahee and M. A. Imteaz, *Improved continuing losses estimation using initial loss-continuing loss model for medium size rural catchments*. American Journal of Engineering and Applied Sciences, 2(4), pp. 796-803, 2009.

[16] I. Hossain, M. Imteaz, S. Gato-Trinidad and A. Shanableh, *Development of a catchment water quality model for continuous simulation of pollutants build-up and wash-off*. International Journal of Civil and Environmental Engineering, 2(4), pp. 210-217, 2010.

[17] L. A. Rossman, *SWMM (Stormwater Management Model) Version 5, User Manual*. US EPA (Environmental Protection Agency), Washington D.C., United States, 2004.