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ORIGINAL PAPER

Modelling runoff quantity and quality in tropical urban catchments using Storm Water Management Model

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Abstract Due to differences in rainfall regimes and management practices, tropical urban catchments are expected to behave differently from temperate catchments in terms of pollutant sources and their transport mechanism. Storm Water Management Model (SWMM) was applied to simulate runoff quantity (peakflow and runoff depth) and quality (total suspended solids and total phosphorous) in residential, commercial and industrial catchments. For each catchment, the model was calibrated using 8–10 storm events and validated using seven new events. The model performance was evaluated based on the relative error, normalized objective function, Nash–Sutcliffe coefficient and 1:1 plots between the simulated and observed values. The calibration and validation results showed good agreement between simulated and measured data. Application of Storm Water Management Model for predicting runoff quantity has been improved by taking into account catchment's antecedent moisture condition. The impervious depression storages obtained for dry and wet conditions were 0.8 and 0.2 mm, respectively. The locally derived build-up and wash-off parameters were used for modelling runoff quality.

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Introduction

In recent decades, urbanization and industrialization are growing rapidly in many developing countries. Anthropogenic activities in urban areas are the main contributor to water pollution including heavy metals, organic matters, nutrients and bacteria (Phiri et al. 2005; Cetin 2009; Ballo et al. 2009; Mohiuddin et al. 2010; Priadi et al. 2011). Stormwater monitoring programs in urban catchment are crucial for characterizing the quality of stormwater runoff and formulate effective pollution control strategy. There are now enough evidences to relate urban water deterioration to non-point sources pollution (e.g. Taebi and Droste 2004; Nabizadeh et al. 2005; USEPA 2005; Atasoy et al. 2006). Previous studies indicated that there were significant differences in stormwater constituents for different land use categories (Mcleod et al. 2006; Pitt et al. 2004; Al-Jaralla and Al-Fares 2009). Stormwater quality monitoring is often costly, time consuming and laborious. As a result, computer models have become useful tools for simulating the pollutant transport and predicting the stormwater loads. Normally, model calibration and validation are required before a regular application of the model to similar site conditions. The ultimate goals of urban water quality modelling are to characterize urban runoff, provide input to the analysis of receiving water, determine the appropriate size of control structures, perform frequency analysis of quality parameters and finally, provide information for cost benefit evaluation (Huber 1986).

The performance of various stormwater quality models for application in urban areas has been reviewed by many (e.g. Tsihrintzis and Hamid 1997; Zoppou 2001; Elliott and Trowsdale 2007). The most widely used urban water quality model is the Storm Water Management Model (SWMM), developed by the Environmental Protection Agency's (EPA). Application and validation of SWMM have been undertaken at different parts of urban catchments around the world (Warwick and Tadepalli 1991; Abustan 1998; Tsihrintzis and Hamid 1998; Barco et al. 2008; Temprano et al. 2006; Hood et al. 2007; Jang et al. 2007; Nazahiyah et al. 2007; Park et al. 2008; Tan et al. 2008). However, most of these studies were carried out in the temperate areas which have very different storm characteristic from tropical rainfall. In particular, the dry day period in tropical sites is relatively short (Chua et al. 2009), thus may restrict pollutant build up.

Pollutant sources and transport within a catchment are also governed by the land management regime and pollution control practices (Chow et al. 2011). Therefore, the processes that control pollutant transport is site specific and the model input parameters may vary between catchments. Using a broad category of land use, for example urban area, could be misleading as the pollutant build up and transport processes at more specific land use such as commercial, residential and industrial may differ greatly (Liu et al. 2011).

This paper presents results of calibration and validation of SWMM for modelling runoff quantity and quality in three major urban landuse, i.e. residential, commercial and industrial. Stormwater monitoring was carried out in southern Johor, Peninsular Malaysia between June 2008 and March 2010. The study objectives are: (1) to carry out sensitivity analysis on SWMM input parameters for runoff quantity modelling, and (2) to develop model input parameters for runoff quantity and quality modelling using SWMM. We propose a set of model input parameters that are useful for applying SWMM in tropical areas.

Materials and methods

Study area description

The study catchment is located in Skudai, Johor, Peninsular Malaysia (Fig. 1). The average annual rainfall in Skudai is between 2,000 and 2,500 mm. The rainfall is highly localized and dominated by convective type of storms. The monthly rainfall pattern is quite uniform with the highest usually recorded in April and December. Three urban catchments with different land uses were chosen, namely residential, commercial and industrial. Table 1 summarized the characteristics of the selected catchments. The catchment areas for residential and commercial are quite similar (34.2 and 32.8 ha) but the industrial site is much smaller (4.4 ha). The selected commercial and industrial sites are typical of old development scheme with open channel that is separated from sewer system. On the other hand, the residential catchment which was more recently developed has a separate (from sewer line) underground stormwater drain.

Model description

SWMM is a comprehensive hydrological and water quality simulation model used for single or continuous events of runoff in urban areas (Rossman 2005). SWMM comprises four computational blocks, namely RUNOFF, STORAGE/TREATMENT, TRANSPORT and EXTRAN. Hydrograph and pollutograph are generated by the RUNOFF block. The basic input parameters required to simulate hydrograph are rainfall hyetograph and the subcatchments physical characteristics. In this analysis, the kinematic wave routing method with 5-min time steps was used for calculating runoff transport. The infiltration loss on pervious area was estimated by Horton equation because of the availability of soil data.

Pollutograph is generated by RUNOFF block based on the volume of storm runoff and catchment antecedent conditions (i.e. dry weather days, street sweeping data and land use). The stormwater pollutant loading is predicted based on the mechanism of build-up and wash-off processes. For a given constituent, build-up can be computed either as a fraction of dust and dirt accumulation, or areal accumulation. The areal accumulation described by mass loading/curb length/dry day (kg/km/day) was used in this study. We used the exponential build-up equation to simulate surface accumulation of constituent and the exponential wash-off equation for simulating the wash-off process.

Model parameterization

SWMM requires three major information for runoff quantity modelling: (1) physical catchment characteristics, (2) rainfall, and (3) infiltration. The physical catchment data are total catchment area (A), percentage of impervious area (%Imp), catchment width (W), average slope (So), surface depression storage and surface roughness. Most of this information was derived from drainage network plans. Field survey was also carried out to confirm the surface and subsurface drainage patterns in order to accurately discretize the subcatchment areas. The area-weighted percent imperviousness was determined by summing the amount of impervious area of each subcatchment and dividing this sum by the total catchment area.

Fig. 1 Location of the study area

Table 1 Characteristics of the study catchments

Characteristics	Commercial	Residential	Industrial
Area (ha)	34.21	32.77	4.38
No. of shops/houses/ factories	597	473	25
Sewer type	Separated	Separated	Separated
Impervious area (%) (%Imp)	95	85	93
Channel slope	1:233	1:530	1:100
Average daily traffic (cars/day)	33,286	7,811	3,148

The subcatchment slope was assumed equal with the flow path slope and was estimated as the elevation difference divided by the flow path length on map. Impervious depression storage (D_{imp}) was estimated from the intercept of regression line between total rainfall against total runoff volume as described by Zaman and Ball (1994). It is related to the subcatchment wetness which according to Abustan (1998) can be categorized into dry, rather dry and wet depending on the antecedent 24 h rainfall. The corresponding 24 h rainfalls are 0–2.5 mm for dry category, 2.5–5.0 mm for rather dry and >5.0 mm for wet. Within SWMM, the potential for runoff to commence immediately after rainfall is considered by allowing a percentage of the impervious area to have a zero depression storage. The default value of zero depression storage used is 25 %. The surface roughness values were adopted from the SWMM User's manual (Huber and Dickinson 1988). Manning roughness coefficients of 0.011 for smooth asphalt that made up impervious surfaces and 0.03 for fallow soil on pervious surfaces were applied in all catchments. Rainfall data were recorded automatically at 5 min interval at the study catchments.

The infiltration parameters required in the model are maximum infiltration rate (f_0), ultimate infiltration rate (f_c), and decay constant (k). Because it was not feasible to obtain this detailed information through field samples, the infiltration parameters derived by Nazahiyah et al. (2007) based on the soil types were used. Build-up and wash-off parameters that are needed for modelling runoff quality were determined in the field. Dust and dirt accumulation on road surfaces was extracted using an industrial vacuum cleaner. The build-up limit (B_{lim}) and build up exponent (B_{exp}) were estimated from exponential relationships between loading of dust and dirt against duration (day) (Sartor and Boyd 1972). The wash off coefficient (W_C) and wash off exponent (W_{exp}) were then derived from exponential equation between the cumulative wash-off coefficients against cumulative runoff rate as described by Nix (1994).

Sensitivity analysis, calibration and validation

Runoff quantity

Sensitivity analysis is necessary to examine the influence of input parameters as listed in Table 3 on the model outputs (runoff depth, peak flow). In this analysis, %Imp and W were varied within ±10 % ranges. Other input parameters were tested within the ranges suggested in the literature: 0.01–0.03 for impervious Manning roughness (Wanielista 1997), 0.02–0.45 for pervious Manning roughness (Huber and Dickinson 1988), 0.3–2.3 mm for impervious depression storage (Huber and Dickinson 1988), and 2.5–5.1 mm for pervious depression storage (Huber and Dickinson 1988). For the infiltration parameters, Bedient and Huber (2002) suggested test ranges for f_0, f_c, and k of 50–200 mm/h, 0.5–12 mm/h and 0.000389–0.00389 L/s, respectively. The sensitivity analysis was carried out by varying the value of a particular input parameter while holding the other parameters constant during the simulation. The sensitivities of peak flow rate and runoff depth to the input parameters are represented by the sensitivity coefficient (Sr).

$$\mathrm{Sr} = \left(\frac{x}{y}\right)\left(\frac{y2 - y1}{x2 - x1}\right), \tag{1}$$

where x is the input parameter and y is the predicted output. $x1$, $x2$ correspond to ±10 % ranges of the initial default value and $y1$, $y2$ are the corresponding output values (James and Burges 1982). The greater the Sr, the more sensitive a model output parameter is to that particular input parameter.

Runoff quality

Four input parameters were used for calibrating the runoff quality in SWMM, i.e. B_{lim}, B_{exp}, W_{C} and W_{exp}. During model calibration, each parameter was adjusted within a certain range until good agreements between the observed and predicted values were obtained with respect to total pollutant load, peak concentration and the event mean concentration (EMC). The average calibrated parameter values were then used for validating the model.

Goodness-of-fit test

Once important input parameters have been identified in the sensitivity analysis, SWMM was calibrated and validated for runoff quantity simulation. The simulated runoff was then used for modelling the quality. The number of event needed to adequately calibrate the model varies with the modelling objective, but in most cases, six events for each calibration and validation should be sufficient (CHI 1998). In this study, the number of events used for runoff quantity and quality calibration and validation are shown in Tables 5 and 6. The reliability of calibration and validation results was evaluated using the following goodness-of-fit tests:

1. Relative error (RE) and absolute relative error (ARE)

$$\mathrm{RE}\,(\%) = \frac{(O - P)}{O} \times 100 \tag{2}$$

$$\mathrm{ARE}\ (\%) = \left[\frac{|(O - P)|}{O}\right] \times 100, \tag{3}$$

where O is the measured value and P is the predicted output. For quantity assessment criteria, a model calibration can be considered good if the average RE is within ±10 % and the average ARE is less than 15 % (Baffaut and Delleur 1989; Sriananthakumar and Codner 1992). For quality assessment criteria, Baffaut and Delleur (1990) suggested that a good calibration must have an average ARE less than 20 % while Sivakumar et al. (1995) suggested less stringent criteria; good when the average ARE is less than 30 % and satisfactory when the average ARE is less than 60 %.

2. Root mean square error (RMSE) and normalized objective function (NOF) are expressed as follows:

$$\mathrm{RMSE} = \sqrt{\left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}\right]} \tag{4}$$

$$\mathrm{NOF} = \frac{\mathrm{RMSE}}{\bar{O}}, \tag{5}$$

where P_i is the predicted values, O_i is the observed values for the n observations, and $\bar{O}$ is the mean of observed values. The ideal value for NOF is 0 but values between 0.0 and 1.0 are acceptable when site-specific data are available for calibration (Kornecki et al. 1999).

3. Nash–Sutcliffe coefficient (NSC) is calculated as follow (Nash and Sutcliffe 1970).

$$\mathrm{NSC} = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}, \tag{6}$$

where P_i is the predicted values, O_i is the observed values for the n observations, and $\bar{O}$ is the mean of observed values. The optimal statistical value occurs when the NSC is close to 1.

4. Regression method

$$P_i = \gamma O_i \tag{7}$$

Linear regression line (Eq. 7) is fitted between the predicted and observed values where its slope γ is compared to the 1:1 slope (perfect match). Generally, the best calibration requires that both slope γ and coefficient of determination, r^2 be as close to 1.0 as possible.

Results and discussion

Sensitivity analysis results

Input parameters that have significant influence (Sr > 0.01) on runoff depth and peakflow are listed in Table 2. The most influential parameter is %Imp with Sr values ranging from 0.836 to 0.966 on runoff depth and 0.564–0.722 on peakflow. Catchment width has strong influence on peakflow but relatively weak on runoff depth. Negative Sr values indicate that the output parameters (runoff depth and peakflow) decrease with increasing input parameters as observed for D_{imp} and N_{imp}. Tan et al. (2008) in Singapore also found strong influence of %Imp, W and N_{imp} on peak flow and runoff depth. However, D_{imp} was less important in the Singapore's study because the site was not intensively developed. The fraction impervious, that were estimated from the slopes of linear regressions between Runoff (Y) and rainfall (X) (Eq. 8a–c) were 0.85, 0.95 and 0.93 for the residential, commercial and industrial catchments, respectively. These %Imp values were fixed throughout the model calibration process as suggested by Liong et al. (1991). Meanwhile W, D_{imp} and N_{imp} were adjusted in order to get the best agreement between the observed and simulated runoff. Values of N_{per}, D_p, f_0, f_c, and k of 0.03, 2.5 mm, 150 mm/h, 15 mm/h, and 0.00115 s^{-1}, respectively, were adopted from Nazahiyah et al. (2007) for a nearby site.

$$\text{Residential}: \; Y = 0.85X - 1.08 \quad (8a)$$

$$\text{Commercial}: \; Y = 0.95X - 1.32 \quad (8b)$$

$$\text{Industrial}: \; Y = 0.93X - 0.59 \quad (8c)$$

Table 2 Sensitivity results of input parameters on runoff depth and peakflow

Output parameter	Land use	Sensitivity coefficient (Sr)			
		%Imp	W	D_{imp}	N_{imp}
Runoff depth	Residential	0.836	0.156	−0.191	−0.060
	Commercial	0.975	0.026	−0.205	−0.021
	Industrial	0.966	0.033	−0.085	−0.027
Peak flow	Residential	0.564	0.444	−0.177	−0.423
	Commercial	0.583	0.483	−0.261	−0.391
	Industrial	0.722	0.340	−0.099	−0.289

Model calibration results

The intensities of 48 sampled storms are plotted on intensity–duration–frequency curves for Johor Bahru as shown in Fig. 2. More than 80 % of the storms were small or medium sizes with return period less than 3 months. This storm category is crucial because the bulk of pollutant transport in tropical urban catchments is governed by small but more frequent storms (DID 2000). Besides intensity (I), the storms were also characterized in terms of rainfall depth (R_d), rainfall duration (R_{dur}), and antecedent dry day (ADD). Eight storm events were used for calibrating the model in the residential catchment (R_d: 4.8–46.0 mm, R_{dur}: 0.18–1.2 h, I: 9.8–99.5 mm/h, ADD 0.83–6.3 days); ten storms for the commercial catchment (R_d: 2.0–107.4 mm, R_{dur}: 0.33–4.85 h, I: 2.7–53.7 mm/h, ADD: 0.03–16.53 days) and nine storms

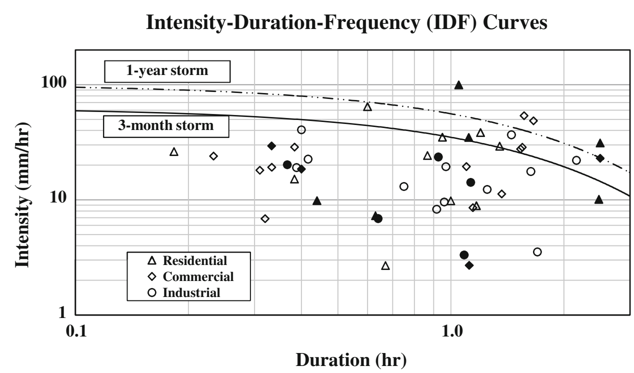

Fig. 2 Over lay of storm intensity on intensity–duration–frequency curves for Johor Bahru. Legend in black is storm event with wet antecedent moisture condition

Table 3 SWMM's calibrated input parameters for simulating runoff quantity

Parameters	Default values		
	Residential	Commercial	Industrial
Percentage of impervious surfaces	85	95	93
Total width of the catchment	732	802	447
Impervious depression storage			
Dry	0.8	1.05	0.6
Wet	0.2	0.75	0.3
Pervious depression storage	2.5	2.5	2.5
Impervious manning's n	0.011	0.012	0.011
Pervious manning's n	0.03	0.03	0.03
Horton's maximum infiltration rate	150	150	150
Horton's minimum infiltration rate	15	15	15
Horton's decay rate	0.00115	0.00115	0.00115

Table 4 The calibrated build-up and wash-off input parameters for simulating runoff quality

Studies	Site	Land use	Parameter	Build up limit (B_{lim})	Build up exponent (B_{exp})	Wash off coefficient (W_C)	Wash off exponent (W_{exp})
This study	Malaysia	Residential	TSS	3.0	0.8	0.2	1.4
			TP	0.3	0.05	0.41	1.46
	Malaysia	Commercial	TSS	15	0.8	1.4	0.9
			TP	0.5	0.1	0.4	1
		Industrial	TSS	13	0.7	3.0	0.6
			TP	0.3	0.16	0.8	1.08
Temprano et al. (2006)	Spain	Residential	TSS	46	0.3	46	1
Barco et al. (2004)	Italia	Residential	TSS	18[a]	0.3	0.13	1.2
Hood et al. (2007)	Estonia	Urban	TSS	25	1	4.9	1.57
			TP	0.25	0.0025	500	2.35
Aubourg (1994)	Australia	Residential	TSS	13	0.35	na	na

na data not available

[a] In unit of kg/ha

Table 5 Goodness-of-fit test results for assessing the reliability of calibration results

Sites	Parameter	Hydrograph		Loading		Peak conc.		EMC	
		Runoff depth	Peak flow	TSS	TP	TSS	TP	TSS	TP
Residential	*n*	8	8	6	6	6	6	6	6
	RE	−9.47	−3.17	8.64	−8.61	−2.80	−11.07	10.87	0.99
	ARE	9.47	5.60	20.87	12.46	9.66	21.06	13.47	10.44
	NOF	0.099	0.061	0.379	0.070	0.071	0.167	0.244	0.045
	NSC	0.968	0.992	0.847	0.990	0.991	0.840	0.753	0.898
	γ	1.075	0.988	0.745	0.981	1.085	0.774	0.737	0.979
	r^2	0.989	0.992	0.958	0.99	0.986	0.858	0.768	0.285
Commercial	*n*	10	10	9	9	9	9	9	9
	RE	1.5	−7.33	−10.72	1.87	3.02	3.69	−2.59	8.96
	ARE	3.6	10.61	13.96	13.00	15.66	10.22	10.88	15.98
	NOF	0.062	0.087	0.063	0.139	0.086	0.177	0.018	0.181
	NSC	0.996	0.989	0.951	0.973	0.899	0.924	0.992	0.929
	γ	0.967	0.989	1.111	0.954	0.927	0.937	0.996	0.865
	r^2	0.998	0.989	0.978	0.977	0.914	0.931	0.999	0.982
Industrial	*n*	9	9	7	6	7	6	7	6
	RE	−3.3	−1.46	7.84	13.31	−4.67	−13.82	9.70	13.70
	ARE	8.0	10.01	14.21	23.09	8.16	15.44	14.90	20.51
	NOF	0.092	0.177	0.284	0.130	0.075	0.037	0.124	0.029
	NSC	0.988	0.924	0.741	0.714	0.994	0.952	0.800	0.979
	γ	0.993	0.930	0.803	0.829	1.037	1.120	0.844	1.099
	r^2	0.987	0.916	0.796	0.761	0.997	0.991	0.818	0.961

for the industrial catchment (R_d: 6.0–53.2 mm, R_{dur}: 0.39–1.7 h, I: 3.5–36.7 mm/h, ADD: 0.02–13.02 days).

During calibration, the simulated runoff depth, peak flow, loadings of TSS and TP, peak concentrations of TSS and TP, and EMCs of TSS and TP show good relationships with the measured values in all catchments. The resulted input parameter values for calibrating runoff quantity are presented in Table 3, and Table 4 for the quality. The goodness-of-fit results are summarized in Table 5. Judging from the low NOF values of less than 1.0, the model is

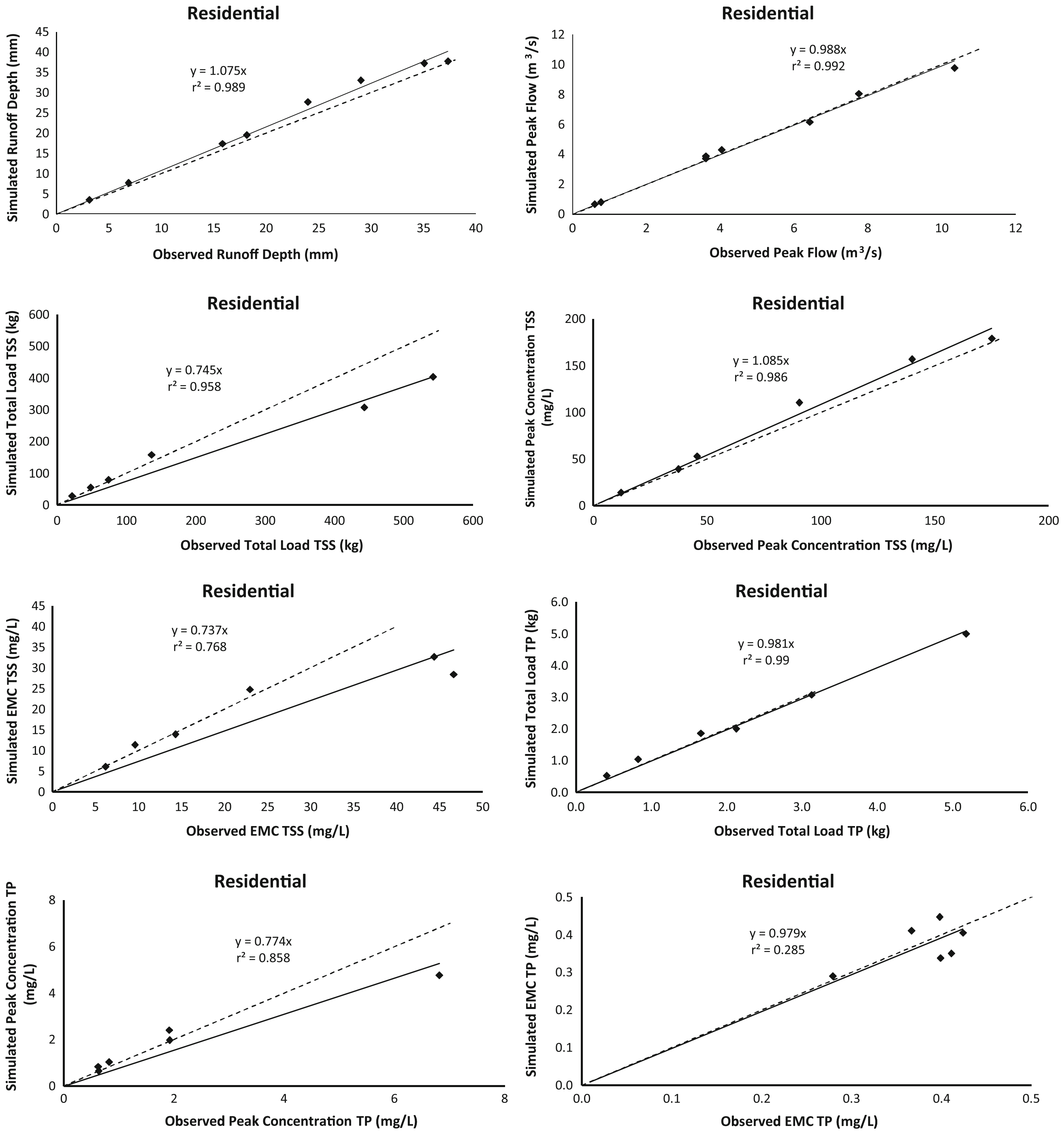

Fig. 3 Simulated against measured values of selected runoff quantity and quality from SWMM calibration

considered well calibrated for estimating the runoff depth and peak flow. The NSC values around 1.0 for each catchment are also acceptable. The goodness of fit was also assessed by plotting the simulated versus observed values of runoff depth and peak flow as shown in Fig. 3. The slope coefficients, γ, for runoff depth and peak flow are also close to 1.0.

The sound calibration results could be attributed to a larger number of storm events used in this study compared to others (e.g. Tsihrintzis and Hamid 1998; Barco et al. 2004; Temprano et al. 2006; Nazahiyah et al. 2007). The quantity calibration was also improved by taking into account the catchment's antecedent moisture condition and the impervious depression storage value. Huber and

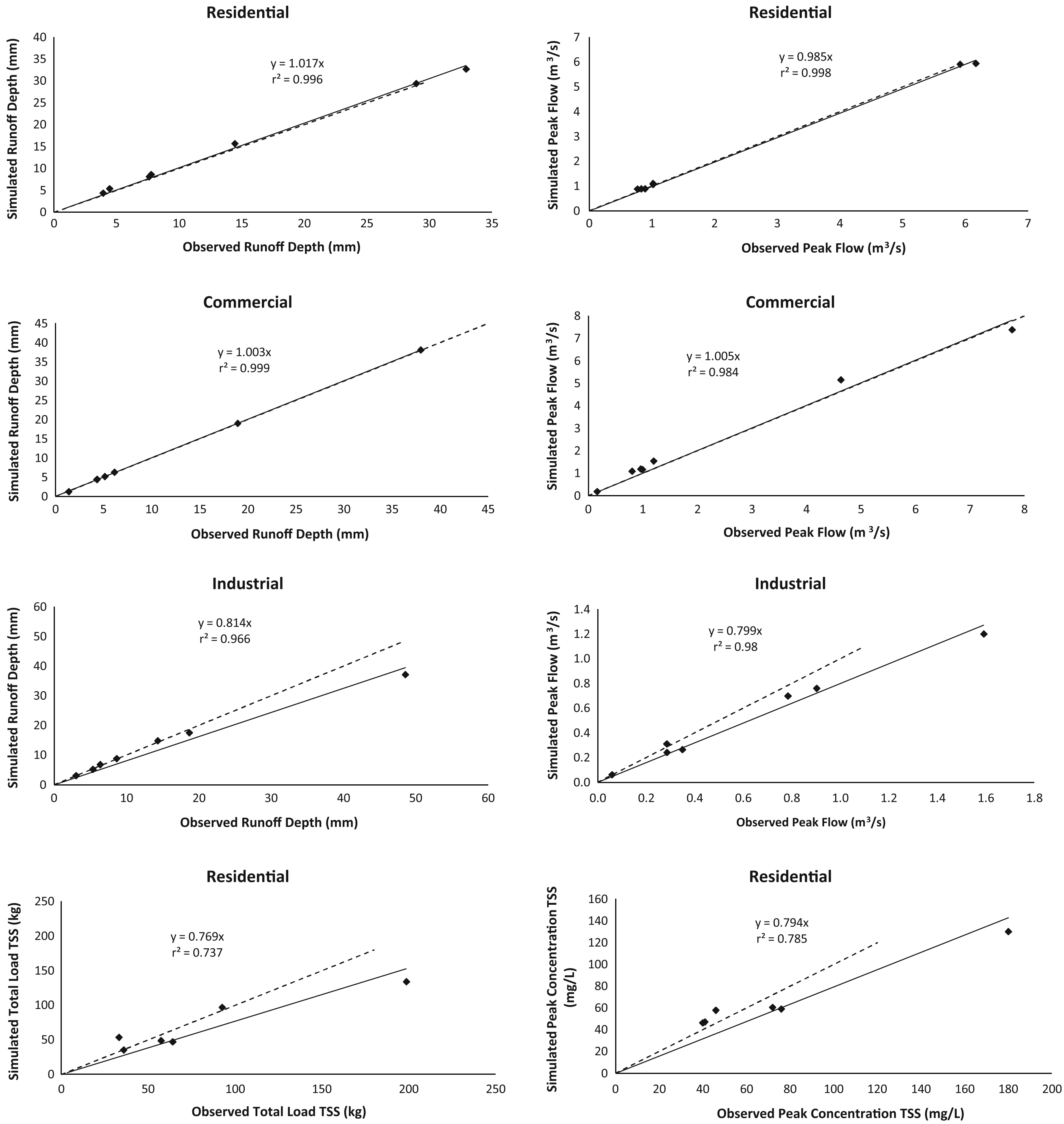

Fig. 4 Simulated against measured values of selected runoff quantity and quality from SWMM validation

Dickinson (1988) suggested impervious depression storage between 0.3 and 2.3 mm for typical urban catchment. In this study, the calibrated values of impervious depression storage in all catchment were from 0.2 to 1.05 (see Table 3). In Sydney, Australia, Abustan (1998) obtained impervious depression storages for residential catchment of 0.8 and 0.2 mm during dry and wet conditions, respectively. These are comparable with values obtained here: 1.0 mm for dry conditions and 0.2 mm for wet condition.

Except for the residential catchment, the loadings and EMCs of TSS were well calibrated with r^2 values above 0.8 and γ greater than 0.75 (Fig. 3; Table 5). The weak correlation for the EMC of TP may suggest that it is not

Table 6 Goodness of fit criteria used for validation of SWMM

Sites	Parameter	Hydrograph		Loading		Peak conc.		EMC	
		Runoff depth	Peak flow	TSS	TP	TSS	TP	TSS	TP
Residential	n	7	7	6	6	6	6	6	6
	RE	−8.28	−3.85	1.45	−6.33	1.47	−4.26	3.00	2.24
	ARE	8.47	5.26	23.53	22.93	20.52	24.37	22.10	20.10
	NOF	0.051	0.045	0.359	0.267	0.302	0.327	0.217	0.353
	NSC	0.996	0.998	0.747	0.782	0.809	0.909	0.855	0.919
	γ	1.017	0.985	0.769	1.137	0.794	0.809	0.914	1.104
	r^2	0.996	0.998	0.737	0.913	0.785	0.957	0.859	0.926
Commercial	n	7	7	7	7	7	7	7	7
	RE	−0.69	−17.54	−14.00	−14.12	12.53	11.41	−3.36	−3.35
	ARE	2.60	18.97	28.11	23.73	22.72	14.35	19.70	15.46
	NOF	0.01	0.134	0.203	0.195	0.15	0.224	0.101	0.264
	NSC	0.99	0.986	0.900	0.910	0.719	0.661	0.915	0.801
	γ	1.003	1.005	0.903	1.038	0.815	0.870	0.986	1.172
	r^2	0.999	0.984	0.918	0.909	0.710	0.784	0.952	0.956
Industrial	n	7	7	6	6	6	6	6	6
	RE	2.78	11.74	0.52	4.70	2.60	10.36	−9.80	0.56
	ARE	6.75	14.66	15.26	21.90	9.60	19.87	13.10	23.16
	NOF	0.292	0.272	0.241	0.258	0.086	0.203	0.128	0.347
	NSC	0.910	0.885	0.969	0.868	0.958	0.813	0.648	0.570
	γ	0.814	0.799	0.872	0.871	0.993	0.959	1.065	0.932
	r^2	0.966	0.980	0.965	0.894	0.982	0.826	0.249	0.558

sufficient to model TP in the residential catchment by considering only the catchment physical characteristics and hydrological variable. Other factor such as pattern of detergent consumption might be necessary to improve the calibration results. For all catchments, the NSC values range from 0.71 to 0.99.

Model validation results

The input parameters that were derived in the calibration process were used to validate the model. The purpose of model validation is to confirm whether the input parameters are able to mimic new events. Seven storm events were used in each catchment for the model validation (total 21 for three catchments). The storm characteristics for the residential catchment were R_d: 5.8–39.4 mm, R_{dur}: 0.38–2.5 h, I: 7.3–31.2 mm/h, ADD: 0.08–8.53 days; commercial catchment: R_d: 2.2–42.4 mm, R_{dur}: 0.23–1.53 h, I: 6.9–27.7 mm/h, ADD: 0.93–4.99 days; and the industrial catchment: R_d: 4.4–47.6 mm, R_{dur}: 0.39–2.16 h, I: 6.9–40.5 mm/h, ADD: 0.2–2.02 days. As shown in Fig. 4, regression analysis between the simulated and observed values was again used to check the SWMM validation performance. The slopes coefficients, γ, of runoff depth and peak flow were all close to 1.0 (Table 6). However, the peak flow at the industrial catchment was slightly under-predicted ($\gamma = 0.799$). The RE and ARE values are also acceptable and within the recommended +10 and 15 % limits, respectively (Sriananthakumar and Codner 1992), except for peakflow in the commercial and industrial catchments (Table 6). Earlier, Nazahiyah et al. (2007) at a nearby site found higher ARE values for runoff depth validation at residential and commercial catchments of 23 and 8.9 %, respectively.

The validation results for quality parameters were also good. With exceptions to loading and peak concentration of TSS in the residential catchment, the other predicted results closely matched the observed values (Table 6). The NOF values are low, ranging from 0.01 to 0.359 (mean = 0.209, median = 0.221), whereas the NSC are high, from 0.57 to 0.99 (mean = 0.85, median = 0.89). While RE values are generally acceptable (within +10 %), the ARE values slightly exceeded the 15 % limit.

The success of runoff quality simulation is also influent by the reliability of build-up and wash-off parameter estimates. The calibrated B_{lim}, B_{exp}, W_C and W_{exp} values for residential, commercial and industrial catchments are shown in Table 4. The B_{lim} for residential catchment is relatively small compared to findings by Aubourg (1994), Temprano et al. (2006) and Hood et al. (2007). This supports the hypothesis that the frequent storm occurrence in tropical urban catchment limits the build-up of dust and dirt. Meanwhile, the W_C and W_{exp} for the residential catchment are comparable with the results given by Barco et al. (2004). The B_{lim} values for the commercial and industrial catchments are lower than those obtained by Hood et al. (2007) at an urban area in Estonia.

Conclusion

The EPA SWMM version 5.0 was successfully applied for modelling quantity and loading of TSS and TP in urban catchments. The monitored storm events were of small and medium sizes which occur more frequently than the larger storms. The SWMM input parameters derived from this study is crucial and can add on the very scarce data for tropical urban catchment. The following conclusions can be made:

1. Runoff depth and peak flow are sensitive to changes in the input parameters of %Imp, W, D_{imp} and N_{imp}. This suggests that a slight change in any of these input parameters will significantly change the simulated runoff depth and peakflow.
2. Application of SWMM for predicting storm runoff quantity was improved by taking into account the catchment's antecedent moisture condition and the impervious depression storage value. For tropical residential catchment, the impervious depression storages for dry and wet conditions are 0.8 and 0.2 mm, respectively.
3. Local estimates of build-up and wash-off parameters that were determined based on dirt and dust accumulation at the study were able to improve the SWMM performance for modelling runoff quality, in particular concentrations and loadings of TSS and TP
4. The B_{lim} for residential catchment is relatively small compared to those reported in the temperate area. This supports the hypothesis that the frequent storm occurrence in tropical urban catchment limits the build-up of dust and dirt.

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