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Calibration of the SWMM for a mixed land use and land cover catchment in Yongin, South Korea

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ABSTRACT

Computer-based hydrological model simulates the rainfall-runoff events, which is an important tool for the evaluation of an urban watershed with mixed land use and land cover (LULC). In this research, integration of storm water management model (SWMM), geographic information system (GIS) and statistical analysis such as linear correlation coefficient (R^2), Nash-Sutcliffe efficiency (NSE), percent peak flow error (PFE) and the percent volume error (VE) were used to simulate the quantity and quality of storm water from small mixed LULC catchment (1.451 km^2). Results showed the goodness of fit (NSE ≥ 0.78; R^2 ≥ 0.78) of both modeled hydrographs and pollutographs between observed and calibrated. Therefore, the validity of the SWMM model calibration and the suitability of the calibrated model served as a good prediction tool, and it can be used as baseline data for empirical modeling in future study.

Keywords: Geographic information system; Land use and land cover; Statistical analysis; Stormwater; SWMM

1. Introduction

Urbanization leads to conversion of vegetative areas to impervious covers such as buildings, roads, parking lot, sidewalk and so on [1]. Stormwater runoff in urban area caries various pollutants including biochemical oxygen demand, chemical oxygen demand, heavy metals, nutrients, pathogenic organisms and suspended solids consequently causes of water quality impairment of receiving waters; change in eco-hydrological diversity; and stress in stream hydrology due to increase peak flow at shorter interval [2–5]. Due to negative impacts of urbanization, management of urban stormwater runoff requires monitoring and analysis of constituents entering the system, and subsequent implementation of preventive practices [2]. In an urban runoff, location of sampling site is selected according to specific sources such as highway runoff, industrial, commercial, residential and others, whereas in mixed land use system with new land use and land cover (LULC) development and construction activities, it is difficult to identify the specific pollutant source to be sampled [6]. Also, stormwater monitoring and analyzing are expensive and time consuming. Therefore, stormwater quality and quantity models are needed.

Various computer-based hydrological models have been used to better understand urban stream responses to potential stressors. Stormwater models are readily available for analyses of non-point source pollution, which provides a good alternative to monitoring. Increasing urbanization requires that the effects of urban developments on water resources be assessed in advance, so that preventative maintenance can be practiced. Frequently used models include the Storm Water Management Model (SWMM) [7,8], the Hydrological Simulation Program-Fortran model [9], and the Soil and Water Assessment Tool [10], which can be used to predict hydrological responses to user-designed scenarios at relatively low cost. Among these models, SWMM has been applied in studies of urban area due to its ability to simulate

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the hydraulic dynamics of artificial drainage systems. Also, this model enables appropriate design of drainage systems (e.g., sizing for detention features, evaluating effectiveness of different runoff control strategies), can be used to simulate dynamics of single events or for modeling on a continuous basis, and incorporates precipitation data to simulate surface runoff and pollutant outputs for subcatchment areas which are then conveyed to the watershed outlet by a user-designated drainage system [11].

In this study, therefore, the collected stormwater quality and quantity from June to November 2012 were used: (1) in SWMM, as the rainfall-runoff dynamic model to represent the study site; (2) to calibrate the SWMM as input parameters; (3) in assessing the accuracy of calibrated hydrograph and pollutographs using linear correlation coefficient (R^2), Nash–Sutcliffe efficiency (NSE) (E), percent peak flow error (PFE) and the percent volume error (VE); and (4) to obtain baseline data for stormwater management and empirical water quality modeling.

2. Material and methods

2.1. Study area description

The selected study catchment was located within Geum-Hak stream, Yongin City, Gyeonggi Province, South Korea (Fig. 1(a)). The surface area and average slope are 1.451 km² and 20.98%, respectively. This catchment was categorized as mixed catchment because it covers the agriculture (3.63%), bare land (32.69%), forest (36.74%), grassland (10.93%) and ground (16.01%). According to the hydrological characteristics in the SWMM handbook [8], the study site was divided into six subcatchments, and their LULC distribution is listed in Table 1. Subcatchments either have combination of natural/pipe drainage system or with separate sewage drainage system. Water draining from the subcatchment with natural drainage is collected in channel at the upstream end of the urban area. This channel discharges into a pipe that conveys the water further to sewer area then to the final outfall. The outfall drains into Geum-Hak stream, which eventually flows into Paldang reservoir, the major source of drinking water for the Seoul Metropolitan area and nearby provinces. The selected catchment was based on site-specific and hydrological characteristics to investigate the impacts of LULC development on stormwater runoff quality [12].

2.2. Stormwater runoff sample and monitoring

Six storm events from June 2012 to November 2012 were monitored, and a total of 125 grab samples (n = 11 – 20) were collected. To ensure that there will be enough runoff flow and allow build-up of pollutants during dry days, sampling collection was initiated when there is at least 3 d of antecedent dry days (ADD) and the weather forecasted to produce

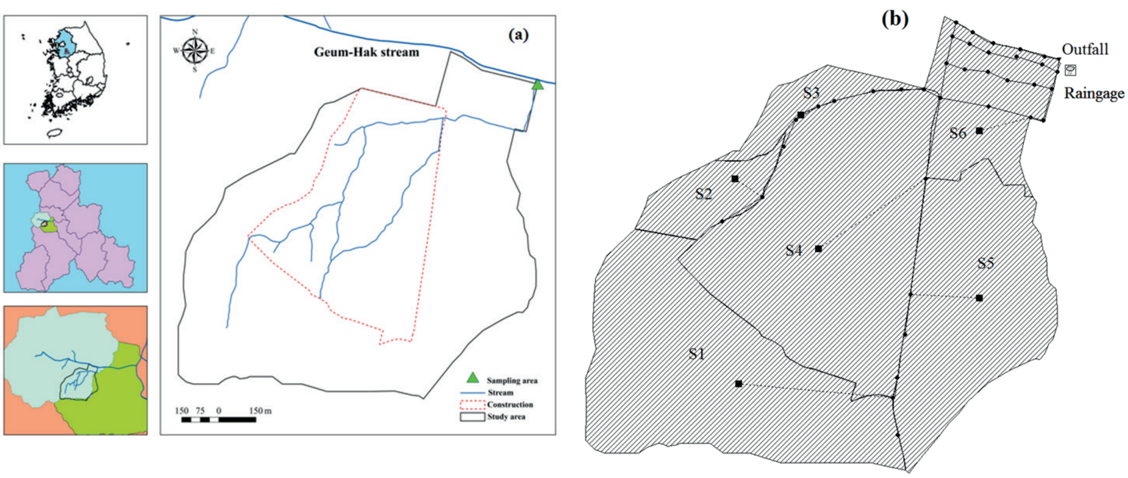

Fig. 1. Study area: (a) location and; (b) discretized catchment distribution.

Table 1
General characteristics of six subcatchment areas

Subcatchments ID	Average slope (%)	Area (m²)	Imperviousness (%)	Percentage LULC				
				Agriculture	Bare land	Forest	Grassland	Urban
S1	20	436,733.12	1.62	0.45	1.96	80.08	15.89	1.62
S2	18	75,154.88	6.01	6.52	0.07	57.50	29.90	6.01
S3	15	48,111.86	12.36	5.35	56.44	19.39	6.46	12.36
S4	13	458,107.70	5.31	0.00	85.80	7.57	1.31	5.31
S5	16	322,698.49	20.86	0.41	19.97	36.81	21.96	20.86
S6	8	110,693.95	100	–	–	–	–	100.00

at least 4 mm of total rainfall and 6 h total rainfall duration. The sampling duration for each event was from the beginning of the runoff until water samples became visually clear (≤30 NTU). Initial sample has 0–30 min time interval; peak sample has 120–240 min or 300–360 min interval and final sample has more than 360 min interval [13]. Flow was measured through automated flow meter with an accuracy of ±5%; the rainfall was measured by a tipping bucket rain gauge installed 100 m away from the catchment outfall in increments of 0.2 mm; and the storm rainfall-runoff samples were collected at the outfall. Other metrological information for each rainfall event was obtained from the Korean Meteorological Administration (http://web.kma.go.kr/eng/index.jsp).

Two liters of samples were collected in polyethylene bottles and transported to the laboratory and refrigerated at 4°C until analyzed. Total suspended solids (TSS) concentration was analyzed for each collected water sample following the standard test methods for the examination of water and wastewater [14]. Sampled rain events varied in duration, total rainfall, total rainfall intensity and runoff, which ranged from low flows to high flows.

2.3. SWMM description

The Environmental Protection Agency SWMM was selected as the rainfall-runoff simulation model for this study. This model is a computer program that computes dynamic rainfall-runoff for single- and long-term (continuous or period of record) runoff quantity and quality from developed urban and undeveloped or rural areas [8]. The model requires physiographic characteristics of the catchment (e.g., the area and slope), physical characteristics of the drainage (e.g., diameter, length, slope and material) and the hydrological/hydraulic parameters such as the width of the subcatchments (e.g., overland flow width), among others. To generate these variables, spatial analysis using geographic information system (GIS) software, ArcGIS 10.1 (Redlands, CA, USA), was utilized (Fig. 2). Values for other catchment characteristics such as catchment surface roughness described by the Manning coefficient, surface depression storage depths and the infiltration rates for pervious areas were based from the ranges given by reference [7]. Subcatchment width was calculated based on the method described by reference [15]. Discretized catchment and the input parameters were entered in SWMM to produce the initial model area (Fig. 1(b)).

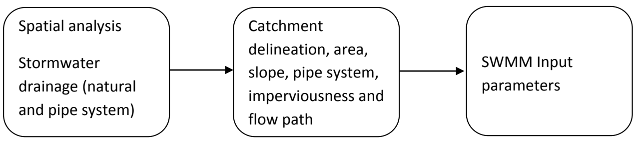

Fig. 2. SWMM input parameters procurement process.

2.4. SWMM calibration

SWMM was coupled with MATLAB to perform auto-calibration model using reference [16] complex method. Water quantity and quality calibration performed separately. First, the SWMM simulate the dependent variables for each storm events and transfer the simulation result to MATLAB, which compare the observed and the simulated data. Then, MATLAB will update the independent variables (model parameters) and return the updated input to SWMM. This process repeated until the maximum iteration was reached.

The flow calibrations taken into consideration in this study were: surface roughness of the impervious (N-Imperv) and pervious (N-Perv) catchment surfaces, and the depths of surface depressions on impervious (Dstore-Imperv) and pervious (Dstore-Perv) areas (Table 2). Following the calibration of modeled flows, water quality subroutines in the SWMM model were also calibrated, assuming the characteristics of the catchment being constant for all storms (land use, physical properties, pollutant inputs in rainwater, and buildup and wash-off rates) [8].

Runoff volume and peak flow rate (Q_p) was chosen as dependent variables while percentage change in subcatchment width, infiltration rate and evaporation rate were the independent variables for water quantity calibration. The percentage change in subcatchment width was computed by calculating the allowable maximum percentage change in each subcatchment with and selecting the minimum value. This method was selected so that it will not exceed the other subcatchment's allowable with change and every change in value of any parameters applies to all the subcatchments because the calibration applied in the whole area as one.

Horton method was used as infiltration model in SWMM for the forest subcatchment. Generally, coniferous

Table 2
General SWMM parameters used in the model

Parameter	$N\text{-}_{\text{IMP}}$	$N\text{-}_{\text{PER}}$	$d\text{-}_{\text{storeIMP}}$	$d\text{-}_{\text{storePER}}$	N	P_1 (kg ha^{-1})	P_2 (1 day^{-1})	P_3	P_4
Value	0.3	0.35	3	3.8	0.011	150	0.36	0.31	9

$N\text{-}_{\text{IMP}}$	Manning's n for overland flow over the impervious portion of the subcatchment
$N\text{-}_{\text{PER}}$	Manning's n for overland flow over the pervious portion of the subcatchment
$d\text{-}_{\text{storeIMP}}$	Depth of depression storage on the impervious portion of the subcatchment
$d\text{-}_{\text{storePER}}$	Depth of depression storage on the pervious portion of the subcatchment
N	Manning's roughness coefficient of the conduit
P_1 (kg ha^{-1})	The maximum potential buildup (mass per unit of area)
P_2	Buildup rate constant
P_3	Wash-off coefficient
P_4	Wash-off exponent

forest was found in the study area, which characterizes to be fine sandy loam [17]. According to reference [7], this soil type has maximum infiltration rate, minimum infiltration rate and decay constant of (3–5) × 2 in hr^{-1}, 0.43 in hr^{-1} and 2–7 h^{-1}, respectively. While reference [18] proposed 6–10 in hr^{-1}, 0.3–0.45 in hr^{-1} and 4.14 hr^{-1} as values for maximum infiltration rate, minimum infiltration rate and decay constant, respectively. However, reference [19] suggested ranges of 1–5 in hr^{-1}, 0.01–4.7 in hr^{-1} and 2–7 hr^{-1} for maximum infiltration rate, minimum infiltration rate and decay constant, respectively. In this study, 8 in hr^{-1}, 0.43 in hr^{-1} and 4.14 hr^{-1} were used for maximum infiltration rate, minimum infiltration rate and decay constant, respectively.

The variation of the TSS in the study area is described by the hydrograph $Q(t)$ and the pollutographs $C(t)$, where Q is the flow rate and C the pollutant concentration. To calibrate the water quantity, TSS discharge load and TSS mass flow rate were the dependent variables while maximum buildup, rate of constant of buildup and wash-off coefficient were the independent variables. The amount of buildup (as a function of the number of antecedent dry-weather days) and wash-off was computed using exponential function. Reference [20] suggested values between 0.22 and 0.382 per day for the buildup rate constant for exponential functions of pollutant buildup. TSS event mean concentration (EMC) value of 1.5 mg L^{-1} was used for pollutant concentrations coming from deciduous and coniferous forest runoff [21]. The EMC (mg L^{-1}) can be defined as the total mass pollutant load yielded from a site during a storm event divided by the total runoff water volume discharged during the storm [12].

2.5. Goodness of fit criteria

The goodness of fit of the modeled hydrographs and pollutographs was evaluated based on the criteria used in reference [5]. The criteria were the linear correlation coefficient R^2 (Eq. (1)); the NSE (Eq. (2)); the percent PFE (Eq. (3)) and the percent VE (Eq. (4)). NSE [22] is a criterion most widely used for calibration and evaluation of hydrological models with observed data. NSE is dimensionless and being scaled from (–) infinity to 1.0:

$$R^2 = \frac{\sum_{i=1}^{n}\left(Q_{0,i} - \bar{Q}_o\right)(Q_{m,i} - \bar{Q}_m)}{\sqrt{\sum_{i=1}^{n}(Q_{0,i} - \bar{Q}_o)^2 (Q_{m,i} - \bar{Q}_m)^2}} \quad (1)$$

$$E = 1 - \frac{\sum_{i=1}^{n}(Q_{0,i} - Q_{m,i})^2}{\sum_{i=1}^{n}(Q_{0,i} - \bar{Q}_o)^2} \quad (2)$$

$$\text{PFE} = \frac{Q_{0,p} - Q_{m,p}}{Q_{0,p}} \times 100 \quad (3)$$

$$\text{VE} = \frac{V_0 - V_{m,p}}{V_{0,p}} \times 100 \quad (4)$$

where $Q_{0,i}$ and $Q_{m,i}$ [l s^{-1}] are the observed and modeled discharge values, respectively; Q_0 and Q_m [l s^{-1}] are the observed and modeled mean discharge values, respectively; $Q_{0,p}$ and $Q_{m,p}$ [l s^{-1}] are the observed and modeled peak discharge values, respectively; V_0 and V_m [mm] are the observed and modeled total discharge volume, respectively; and n is the number of observations [5].

3. Results and discussion

3.1. Storm monitoring summary

Table 3 summarizes the hydrological characteristics of six storm events that were monitored between June 2012 and November 2012. The antecedent dry days (ADD) varied from 3 to 31 d; rainfall duration varied from 480 to 980 min; rainfall depth varied from 7.5 to 65.7 mm; and average rainfall intensities varied from 1.1 to 5.7 mm h^{-1}. Also, shown are the total runoff volume and peak flow rate, which were used in the quantity calibration of the model. Runoff coefficient, which is equal to the ratio of runoff to rainfall volume through the entire event [23], was also given. The fifth storm

Table 3
Hydrological description of stormwater sampled

Event (2012)	Antecedent dry day (days)	Rainfall duration (min)	Rainfall depth (mm)	Average rainfall intensity (mm h^{-1})	Runoff volume (m^3)	Peak flow rate ($m^3 hr^{-1}$)	Runoff coefficient
29 Jun	31	980	63.7	3.8	30,697.04	3,510.0	0.814
18 Jul	3	880	33.5	2.6	21,604.56	7,501.6	0.797
12 Aug	23	690	28.5	2.4	24,502.20	10,021.00	0.805
4 Sep	3.8	775	65.7	5.7	32,321.76	12,340.00	0.878
22 Oct	11	495	30.5	5.7	9,583.32	3,145.60	0.606
16 Nov	3	480	7.5	1.1	2,125.62	450.00	0.621

Table 4
Summary of water quantity parameter calibration

Evaporation rate (mm day^{-1})		Infiltration (curve number)		% change in subcatchment width	
Constraints	Calibrated	Constraints	Calibrated	Constraints	Calibrated
1.32–35	35	56–67	58.35	1.25–1.61	1.61

event had small runoff coefficient which may caused by the small amount of rainfall on that particular monitoring date. Generally, the runoff coefficient from commercial is ranged from 0.5 to 0.95 [24].

3.2. Water quantity and quality calibration

Table 4 summarizes the independent variables used for quantity calibration in this study: evaporation rate (35 mm), infiltration curve number (58.35) and percentage change in the subcatchment width (161%). The evaporation rate used in this study reflects the anticipated losses infiltration through damage or cracks in impervious covers such as roads and sidewalks. Exact delineation of the subcatchment's pervious areas due to massive groundwork activities during monitoring period maybe was another factor for the runoff loss. In addition, the stormwater runoff from pervious surfaces is more difficult to predict than the runoff from impervious surfaces. This is because it depends on the soil and vegetation type, drainage system, storm intensity and duration as well as on antecedent conditions [25]. In addition, during monitoring, leaks in the pipe/sewer systems were observed, therefore introducing losses in the runoff.

For water quality calibration, maximum buildup of 150.0 kg/ha, buildup rate constant of 0.36 and was-off coefficient of 0.31 were used as the independent variables (Table 2). Table 5 shows the summary of calibrated water quality parameters per event. The average values were used as the single representation of the calibrated values per event.

Table 5
Summary of water quantity parameter (per event) calibration

Event	Maximum buildup possible (kg ha^{-1})		Buildup rate constant (day^{-1})		Wash-off coefficient	
	Constraint	Calibrated	Constraint	Calibrated	Constraint	Calibrated
29 Jun	30–160	126.03	0.271–0.485	0.59	0.1–0.25	0.35
18 Jul		120.81		0.37		0.42
12 Aug		258.07		0.58		0.21
4 Sep		77.46		0.19		0.22
22 Oct		240.07		0.19		0.38
16 Nov		77.54		0.21		0.29
Average		150		0.36		0.31

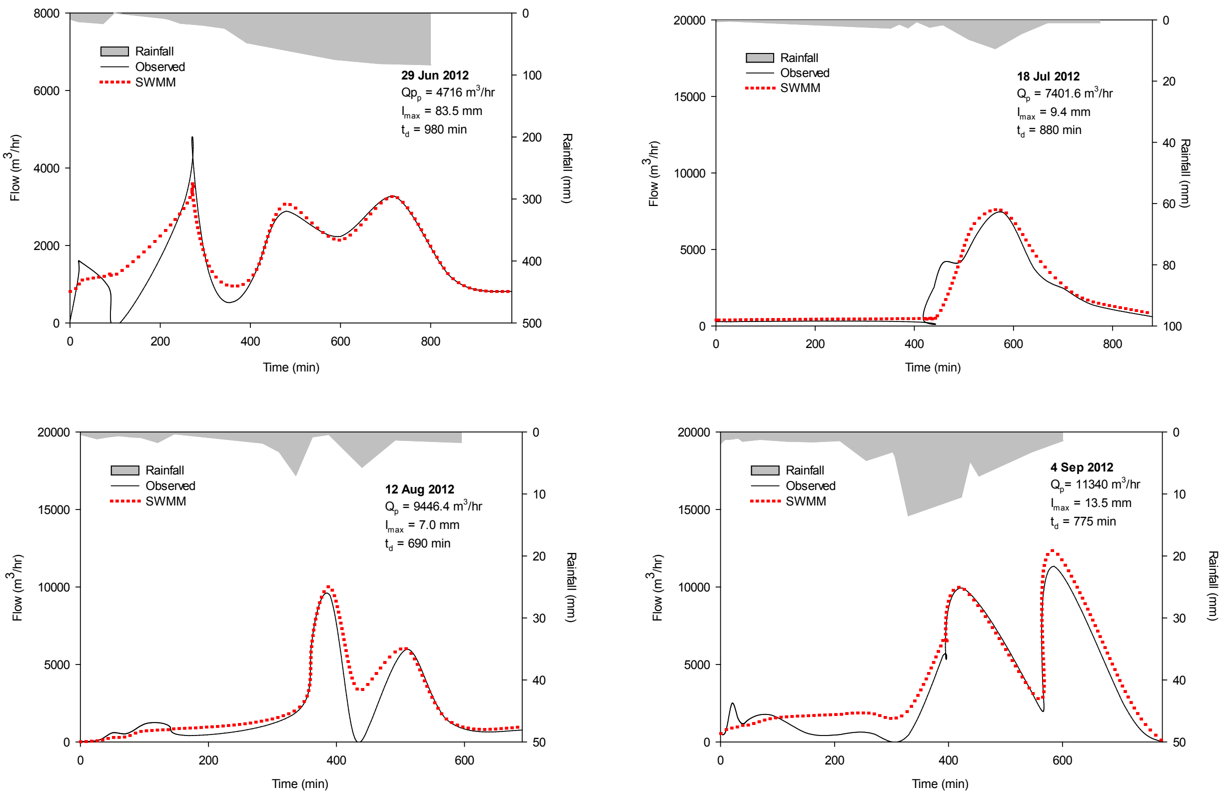

Fig. 3. Observed (solid line) and modeled (hatched line) storm event hydrographs for mixed LULC catchment.

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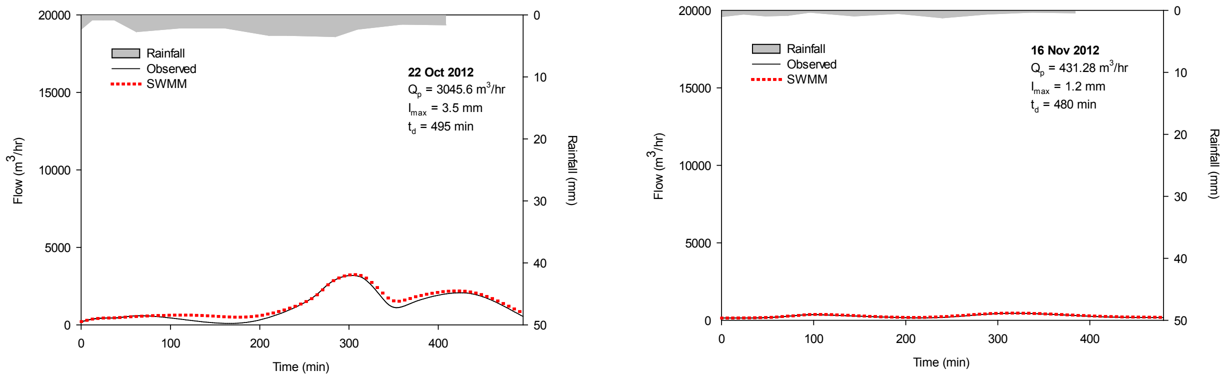

Fig. 3. (*Continued*) Observed (solid line) and modeled (hatched line) storm event hydrographs for mixed LULC catchment.

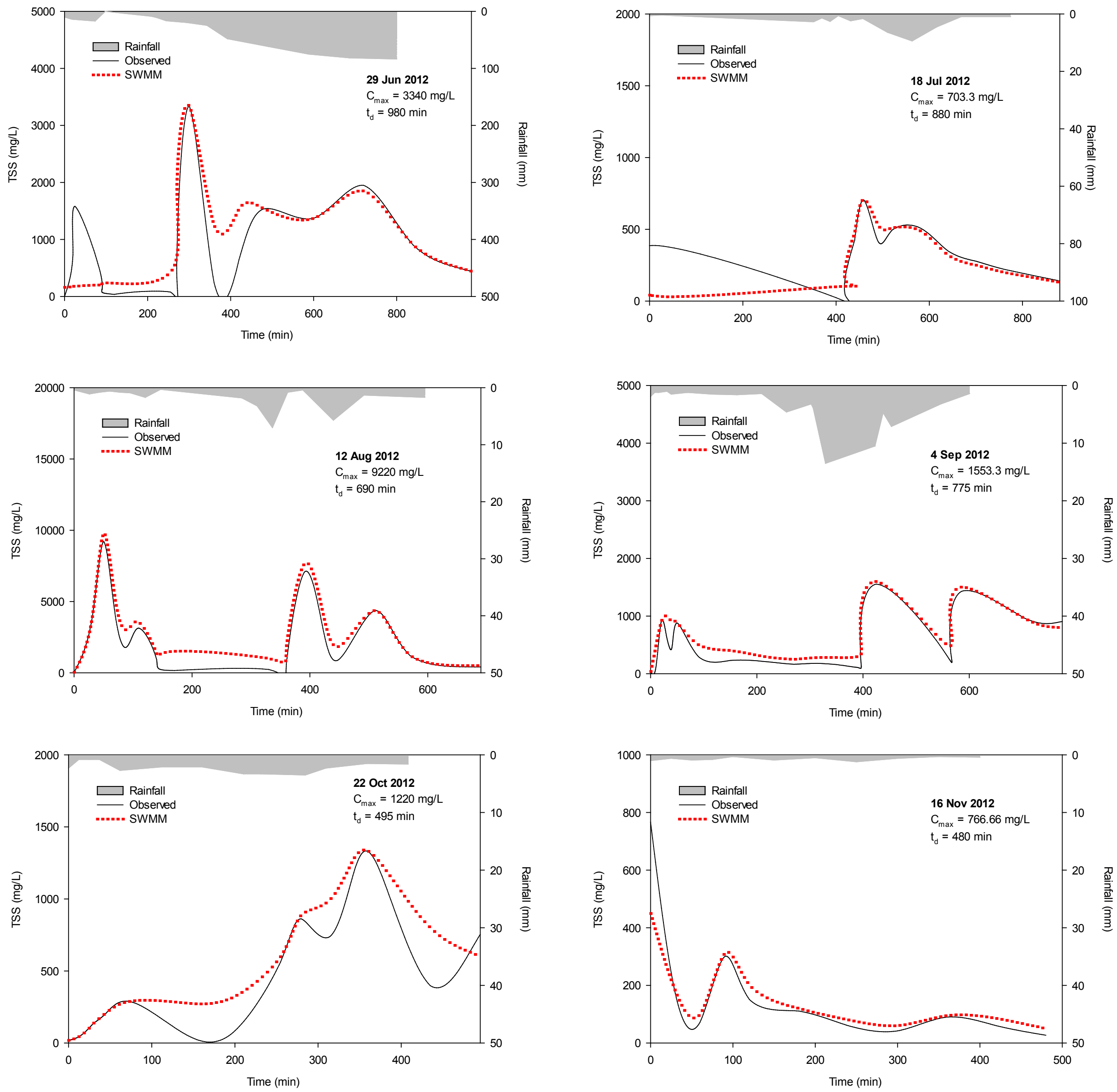

Fig. 4. Observed (solid line) and modeled (hatched line) storm event for TSS for mixed LULC catchment.

Table 6
Performance statistics for individual calibration events. The model was evaluated for Nash–Sutcliffe efficiency (NSE); linear correlation (R^2); percent peak flow error (PFE); and percent volume error (VE) for hydrographs (first row) and pollutographs (second row)

Parameter	29 Jun	18 Jul	12 Aug	4 Sep	22 Oct	16 Nov
NSE	0.78	0.90	0.88	0.80	0.95	0.82
	0.94	0.87	0.80	0.78	0.87	0.84
R^2	0.67	0.87	0.83	0.73	0.91	0.78
	0.91	0.80	0.78	0.65	0.81	0.83
PFE (%)	11.3	5.8	–3.1	13.3	–9.3	15.7
	10.4	6.3	–2.3	14.2	–8.1	14.1
VE (%)	7.3	3.2	2.1	10.4	5.2	12.2
	6.8	2.6	2.9	9.5	4.8	11.5

3.3. Model performance

The goodness of fit of the modeled hydrographs and pollutographs (TSS) was described by the linear regression correlation coefficient R^2 which for quantity simulations was, on average, greater than 0.80, and for quality simulations; it was greater than 0.79, on average. With R^2 larger than 0.73 for five out of six events, the best fit was noted for event of October 22, 2012, and the worst fit for June 29, 2012. The data in Figs. 3 and 4 indicate that the agreement between the observed and modeled hydrographs and pollutographs was fairly good. Furthermore, hydrographs and pollutographs have good fit of between observed and calibrated data. Because both have NSC of range 0.78–0.95, reflecting a satisfactory predicting power for runoff volume. NSC is one of the ways to assess the predictive power of hydrological models. The closer the NSC is to one, the more accurate the model is. The percent PFE was ranged from –9.3% to 15.7% for hydrographs and –8.1% to 14.2% for pollutographs, and VE was ranged from 2.1% to 12.2% for hydrograph and 2.6% to 11.5% for pollutographs. Table 6 shows the performance statistics for individual events. Such results confirm the validity of the SWMM model calibration and the suitability of the calibrated model to serve as a good prediction tool.

4. Conclusions

A mixed LULC catchment was monitored for six storm events and was calibrated the hydrograph and the pollutograph using SWMM. The methodology adopted in this study, to generate criteria of evaluation to be used for future application for specific geographical location, is an effective way of extrapolating input parameters for other water quality parameters (e.g., fecal indicator bacteria) and land uses in future research. The calibrated model shows a goodness of fit in simulating hydrograph with NSE (0.78–0.95) and R^2 (0.67–0.91) and PFE (–9.3 to 15.7); and pollutograph with NSE (0.78–0.94), R^2 (0.65–0.91) and PFE (–0.81 to 14.2). Therefore, the SWMM performed well in this study in predicting water quantity and quality parameters with correlations between the observed and simulated hydrographs characterized. One of the major impediments statistical approaches in studying the relationships between the hydrological characteristics and pollutant transport is caused by the scarcity of flow quality data. Additional research concerning these impediments and application of probabilistic approach in this study area is in progress. Furthermore, the calibration, addressing only the identified parameters and hence drastically reducing the number of calibration parameters, produced good results throughout the calibrated statistical measures.

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