Water Resour Manage
DOI 10.1007/s11269-010-9670-4

Development and Integration of Sub-hourly Rainfall–Runoff Modeling Capability Within a Watershed Model

Jaehak Jeong · Narayanan Kannan · Jeff Arnold · Roger Glick · Leila Gosselink · Raghavan Srinivasan

Received: 1 February 2010 / Accepted: 6 May 2010

Abstract Increasing urbanization changes runoff patterns to be flashy and instantaneous with decreased base flow. A model with the ability to simulate sub-daily rainfall–runoff processes and continuous simulation capability is required to realistically capture the long-term flow and water quality trends in watersheds that are experiencing urbanization. Soil and Water Assessment Tool (SWAT) has been widely used in hydrologic and nonpoint sources modeling. However, its subdaily modeling capability is limited to hourly flow simulation. This paper presents the development and testing of a sub-hourly rainfall–runoff model in SWAT. SWAT algorithms for infiltration, surface runoff, flow routing, impoundments, and lagging of surface runoff have been modified to allow flow simulations with a sub-hourly

J. Jeong (✉) · N. Kannan
Texas AgriLife Research, 720 East Blackland Rd, Temple, TX 76502, USA
e-mail: jjeong@brc.tamus.edu

N. Kannan
e-mail: nkannan@brc.tamus.edu

J. Arnold
Grassland, Soil, and Water Research Laboratory, USDA-ARS,
808 East Blackland Rd, Temple, TX 76502, USA
e-mail: jeff.arnold@ars.usda.gov

R. Glick · L. Gosselink
Watershed Protection and Development Review Department, City of Austin,
PO Box 1088, Austin, TX 78767, USA

R. Glick
e-mail: roger.glick@ci.austin.tx.us

L. Gosselink
e-mail: leila.gosselink@ci.austin.tx.us

R. Srinivasan
Spatial Sciences Laboratory, Texas A&M University, College Station, TX 77845, USA
e-mail: r-srinivasan@tamu.edu

Published online: 08 June 2010

time interval as small as one minute. Evapotranspiration, soil water contents, base flow, and lateral flow are estimated on a daily basis and distributed equally for each time step. The sub-hourly routines were tested on a 1.9 km^2 watershed (70% undeveloped) near Lost Creek in Austin Texas USA. Sensitivity analysis shows that channel flow parameters are more sensitive in sub-hourly simulations ($\Delta t = 15$ min) while base flow parameters are more important in daily simulations ($\Delta t = 1$ day). A case study shows that the sub-hourly SWAT model reasonably reproduces stream flow hydrograph under multiple storm events. Calibrated stream flow for 1 year period with 15 min simulation ($R^2 = 0.93$) shows better performance compared to daily simulation for the same period ($R^2 = 0.72$). A statistical analysis shows that the improvement in the model performance with sub-hourly time interval is mostly due to the improvement in predicting high flows. The sub-hourly version of SWAT is a promising tool for hydrology and non-point source pollution assessment studies, although more development on water quality modeling is still needed.

Keywords SWAT · Rainfall–runoff modeling · Watershed modeling · Subdaily simulation · Sub-hourly simulation

1 Introduction

Hydrological processes in watersheds may be defined as a continuous circulation of water on the earth through the processes of rainfall, surface runoff, base flow, stream flow, and evapotranspiration. The natural circulation is however altered as watersheds experience urbanization. Permeable surfaces are overlain with impervious cover such as buildings, roads, and pavements that disconnect the surface processes from sub-surface processes during the urbanization process. Urban impervious cover makes stormwater runoff instantaneous and flashy by increasing surface runoff and reducing infiltration. The amount of base flow decreases as less water infiltrates to the soil profile. Hantush and Kalin (2006) found 31% reduction in the base flow as 60% of a forested watershed was converted to commercial and low density residential areas. In the same context, Corbett et al. (1997) suggests a linear relationship between percent impervious surface and runoff volumes. The increased surface runoff tends to make hydrographs flashy with higher peaks and shorter durations. In the aspect of long term analyses, the impact of urbanization may be more significant during individual storm events than in the mean annual runoff (Chang 2007). However, its long term impact can also be significant depending on human practices (Burns et al. 2005). Therefore, the capability of simulating individual storms is important for watershed models to adequately capture hydrologic processes between short intervals, while continuous simulation capability is also necessary for investigating long term impacts of urbanization in urbanizing watersheds.

Instantaneous hydrologic responses in small watersheds or urbanizing areas often convey multiple flow events in a day when combined with flash storms. Therefore, simulation time interval should be as short as possible to properly capture these short duration storms. There are only a few watershed-scale simulation models that have both long-term continuous and event-based simulation capabilities. The US Environmental Protection Agency (EPA)'s Storm Water Management Model (SWMM) is a dynamic rainfall–runoff model used for single event or continuous simulation in urban areas (Rossman 2004). SWMM has been used worldwide including the United States for storm water and combined sewer simulation of urban watersheds. The wide use and popularity makes it a strong choice for field scale system drainage modeling. However, for large watersheds the input and output processes can be tedious and time consuming. In addition, stability problem in the numerical modeling algorithms is a known issue. Some of these drawbacks discourage the use of SWMM especially in modeling large watersheds in which urban areas are only a sub-unit of the watershed. Kim and Lee (2009) suggests integrating SWMM with SWAT to mitigate these drawbacks in simulating large scale watersheds. Source Loading and Management Model (SLAMM) (Pitt and Voorhees 1995) is another urban watershed management tool capable of continuous and event-based simulation. Special emphasis has been placed for small storm hydrology and particulate wash-off. SLAMM has strength in simulating various urban land uses with conventional or innovative types of storm water BMPs to determine how effectively they mitigate flash runoff and remove pollutants associated with urban stormwater. SLAMM is strongly based on actual field observations, with minimal dependence on theoretical processes. However, there is a limitation on number of land uses (six) and the source areas within each land use the model can handle. As well, the model cannot simulate snowmelt, base flow and in-stream processes. Hydrological Simulation Program—Fortran (HSPF; Bicknell et al. 1995) is a part of US EPA's Better Assessment Science Integrating point & Nonpoint Sources (BASINS) modeling system for the analysis of Total Maximum Daily Loads (TMDL). HSPF runs at any time step from 1 minute to 1 day and, therefore, can simulate individual storm events. However, HSPF may not be adequate for simulating intense single-event storms because of its conceptualization of overland areas as detention storage and flow routing using storage-based equations (Borah and Bera 2003; Xiong and Melching 2005). CASCade 2 Dimensional (CASC2D), a hydrologic model to calculate surface runoff on a cascade of planes in 2-Dimension (Julien and Saghafian 1991) and MIKE SHE (Refsgaard and Storm 1995) are both physically-based models for which numerical approximation techniques solve multi-dimensional simplified (or full) Saint-Venant equations. As is inherent in the numerical solutions, these models require relatively intense computation compared to the models with analytical solutions when simulating long periods or large watersheds. Quality hydrological model (QUALHYMO; http://beta.waterbalance.ca/) is a continuous simulation model capable of modeling runoff and pollutants for urban as well as rural watersheds. It is widely used as a management tool by agencies in Alberta and Ontario provinces in Canada. However, the model is not validated adequately in other parts of the world. Lack of significant improvement of the model over the past few years since its development could be a concern for its use.

Soil and Water Assessment Tool (SWAT) is a continuous simulation model that has proven to be an effective tool for assessing the impact of management on water supplies and nonpoint source pollution in rural watersheds and large river basins (Arnold et al. 1998; Neitsch et al. 2005a; Gassman et al. 2007). Examples include TMDL analyses (Borah et al. 2006; Benham et al. 2006; Radcliffe et al. 2009), applications within the US Department of Agriculture's Conservation Effects Assessment Project (van Liew et al. 2007; Harmel et al. 2008; Richardson et al. 2008; Mausbach and Dedrick 2004), nonpoint source pollution analyses (Borah and Bera 2003; Santhi et al. 2001). Recently, Bracmort et al. (2006) used SWAT to study long term impact of structural Best Management Practices (BMPs) on sediment and phosphorus loads. While SWAT is a widely used tool in watershed modeling, SWAT 2005 version has limited capability to simulate hydrological processes at subdaily time scales: weather and infiltration processes are assessed at any sub-hourly time interval; channel routing is simulated at hourly time interval and all other processes at daily interval. However, these subdaily routines in SWAT have not been fully validated up to date and also require a fundamental restructuring in the model's framework to further expand subdaily simulation capabilities such as sediment and nutrients simulated at a sub-hourly time interval as small as 1 minute.

The City of Austin, Texas has experienced urbanization in the last several decades and more development is expected in the upcoming years. The preservation of water resources in the Edward aquifer and the Colorado River with the growing population is the main concern for the city. SWAT has been used for simulating hydrologic processes in Austin watersheds, but increasing urbanization has created challenges for accurately simulating flow. Thus, a sub-hourly simulation capability is needed to improve flow simulation relative to daily time intervals in areas with rapid flow response. Especially, the rainfall–runoff processes such as flooding and bank erosion in their creeks and rivers in response to short and intense rainfall events in urban areas or at the fringe of urban areas are of great concern. If sub-hourly simulation capability is added, the SWAT model will be suitable for simulating hydrological processes in watersheds with various land uses in Austin areas. Debele et al. (2009)'s recent work on the Enhanced Soil and Water Assessment Tool (ESWAT) convinces our theory. They found ESWAT performed better in hourly simulations as they added hourly evapotranspiration and overland flow routines to the model.

The ultimate goal of this study is to develop sub-hourly algorithms for flow, erosion and stormwater BMPs modules within a continuous and distributed modeling framework. This paper focuses on a development of sub-hourly surface runoff and stream flow modeling components. SWAT routines for weather, infiltration, overland flow, impoundments, and channel flow have been modified to accommodate the sub-hourly simulation capability. Impact of simulation time scale to flow prediction is investigated using 15 min, 1 h, and 1 day interval. Performance of the Green and Ampt model and the SCS Curve Number method is compared to access improvement in the model output. The development of sub-hourly erosion and BMPs modules is beyond the scope of the paper and left as future work.

2 Methods

This section describes the methods used for sub-hourly rainfall–runoff modeling including model equations, source code changes, and the strategy for modifying the model structure that is necessary for the development of sub-hourly modeling capability in SWAT.

2.1 Estimation of Infiltration and Excess Rainfall

SWAT provides two methods for estimating surface runoff: the SCS curve number (CN) method (SCS 1972) and the Green and Ampt Mein Larson (GAML) excess rainfall method (Mein and Larson 1973). The CN method is an empirical model that is based on more than 20 years of studies involving rainfall–runoff relationships from small rural watersheds with various land use and soil types across the USA. The Green and Ampt equation is a physically based model that allows continuous simulation of infiltration process assuming the soil profile is homogeneous and antecedent moisture is uniformly distributed in the profile. The GAML equation uses a direct relationship between infiltration and rainfall rate based on physical parameters allowing continuous surface runoff simulation. While the CN method is widely used, its usage in continuous simulation is controversial because it estimates direct runoff using empirical relationships between the total rainfall and watershed properties (Garen and Moore 2005); therefore, the CN method may be abused if used in sub-daily runoff simulation. A study conducted by King et al. (1999) suggests that the CN method under-simulates surface runoff while the GAML method has no pattern associated with storm events implying less bias to the model prediction with the GAML method. After simulating the response of the Green and Ampt equation for 47 storms collected at seven locations, King (2000) recommends that an operational time interval of 10 min yields the best results for the Green and Ampt equation. Therefore, the GAML method is considered to be suitable for sub-hourly surface runoff simulation in SWAT. The GAML infiltration rate is expressed as

$$f(t) = K_e\left(1 + \frac{\Psi\,\Delta\theta}{F(t)}\right) \tag{1}$$

where $f(t)$ is the infiltration rate at time t (millimeters per hour), K_e is the effective hydraulic conductivity in which the impact of land cover is incorporated (Nearing et al. 1996), Ψ is the wetting front matric potential (millimeters), $\Delta\theta$ is the change in moisture content, and $F(t)$ is the cumulative infiltration (millimeters). The SWAT routine for the GAML infiltration is modified to accommodate the comprehensive reconstruction of SWAT structure for sub-hourly hydrologic processes.

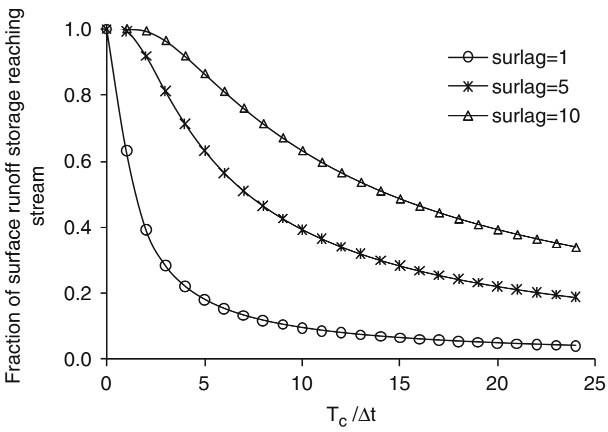
2.2 Surface Runoff Lag

Once the total amount of excess rainfall is determined by the GAML equation, a fraction that lags in the HRU is estimated by a lag equation. The existing lag equation in SWAT (Neitsch et al. 2005a, equation 2:1.4.1, pp: 112) is developed for daily simulation and is not sufficient for subdaily runoff modeling. This equation relates the surface runoff lag with *surlag* coefficient and time of concentration but not with operational time interval because daily interval is implicitly assumed. As time interval narrows down to a fraction of an hour one would expect less portion of excess rainfall to reach the main channel. Therefore, a new lag equation that relates lag amount with the time interval as well as *surlag* coefficient and time of concentration is developed for the sub-hourly model. A first order equation that estimates the surface runoff lag during the time interval is defined by

$$Q_{surf,i} = \left(Q'_{surf,i} + Q_{stor,i-1}\right)\left(1 - \exp\left[\frac{-surlag}{t_c/\Delta t}\right]\right) \tag{2}$$

where $Q_{\mathrm{surf,i}}$ is the amount of surface runoff discharged to the main channel at the end of time step i, $Q'_{\mathrm{surf,i}}$ is the amount of surface runoff generated in the subbasin, $Q_{\mathrm{stor,i-1}}$ is the surface runoff stored (or lagged) from the previous time step, *surlag* is the surface runoff lag coefficient, Δt is time interval, and t_c is the time of concentration for the subbasin. *surlag* is a user input parameter. As shown in Fig. 1,

Fig. 1 Influence of *surlag*, t_c, and Δt on fraction of surface runoff released to the main channel



Eq. 2 gives reasonable amount of surface runoff lag with respect to the operational time interval as well as a great flexibility in calibrating the output. For example, for $t_c = 60$ min and $\Delta t = 15$ min $Q_{\mathrm{surf,i}}$ ranges 0.2 to 0.95 as *surlag* varies $1 \sim 10$.

2.3 Unit Hydrograph

Surface runoff generated at each time step is routed using a dimensionless unit hydrograph (UH) method in which a hydrologic response to a pulse input (i.e. excess rainfall at a time step) is distributed in a triangular shape (retained from SWAT 2005) or newly developed gamma distribution function based on the hydrologic property of the watershed. The triangular UH is defined by

$$q_{uh} = t/t_p \;\text{ if }\; t \leq t_p \tag{3a}$$

$$q_{uh} = \frac{t_b - t}{t_b - t_p} \;\text{ if }\; t > t_p \tag{3b}$$

where q_{uh} is unit flow rate at time t, t_p is time to peak flow since the direct runoff started, and t_b is time of recession. The unit flow rate is then normalized by the total amount of unit flow under the triangle. The duration of a UH in response to a pulse input of excess rainfall is related to hydrologic characteristics of the watershed, represented by t_c.

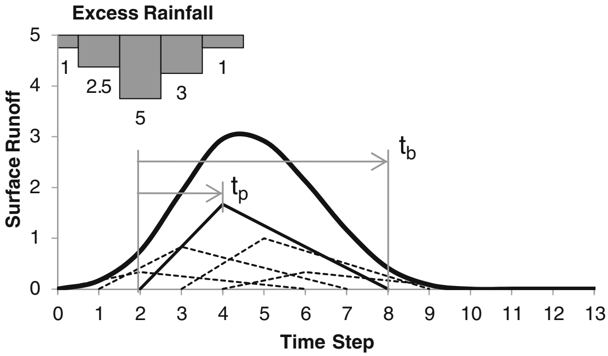
$$t_b = 0.5 + 0.6t_c + tb\_adj \tag{4}$$

In this equation, *tb_adj* is a user input factor for adjusting subdaily unit hydrograph. Then, the time to peak flow is estimated based on the SCS dimensionless unit hydrograph (SCS 1972) method in which 37.5% of the total volume is assigned to the rising side.

$$t_p = 0.375\, t_b \tag{5}$$

For example, the UH triangle in bold lines in Fig. 2 shows the unit hydrograph during time steps 2 to 8, multiplied by the excess rainfall that occurred at time step 2. Similarly, unit hydrographs that are associated with the excess rainfalls during the

Fig. 2 Surface runoff hydrograph generated by superimposing dimensionless triangular unit hydrographs



time steps from 0 to 4 are plotted separately, and then all UHs are superimposed at each computation node to generate the runoff hydrograph shown on the top of the figure in a smooth curve. Because the computational nodes are regularly spaced in time, t_p and t_b take the nearest integer values. The gamma distribution UH method adapted from Aron and White (1982) defines unit flow as follows:

$$q_{uh} = \left(\frac{t}{t_p}\right)^{\alpha} \cdot \exp\left(\left(1 - \left(\frac{t}{t_p}\right)\right)^{\alpha}\right) \tag{6}$$

where α is a dimensionless shape factor which is larger than zero.

2.4 Channel, Impoundment Routing

In SWAT, stream flow is routed through the channel network using the variable storage routing method (Williams 1969) or the Muskingum routing method (Overton 1966). Both the variable storage routing method and the Muskingum routing method are variations of the kinematic wave (KW) model which predicts short duration storms better than the nonlinear reservoir model that is often used in hydrologic modeling (Xiong and Melching 2005). Impounded water bodies are assessed in four different types: ponds, wetlands, depressions/potholes, and reservoirs. Ponds, wetlands, and depressions/potholes are located within a subbasin off the main channel while reservoirs are located on the main channel. The routines for channel routing and impoundment routing were modified such that these routines run at sub-hourly time intervals as small as 1 minute to accommodate the capability of sub-hourly simulation.

2.5 Processes in Sub-hourly Simulation

The schematic of the sub-hourly model structure is presented in Fig. 3. The GAML procedure simulates excess rainfall from each HRU in a subbasin at every time interval. The amount of water that lags at the end of time step is estimated by Eq. 2, and the lag amount is added to the excess rainfall that occurs in the next time step. HRU output values are aggregated at subbasin scale for flow routing. Estimated values at the end of day are retained in temporary arrays for continuous simulation over midnight. There are 3 layers of iteration loops for temporal marching ($\Delta t \rightarrow$day$\rightarrow$year) of solution processes and one iteration loop for spatial discretiza-

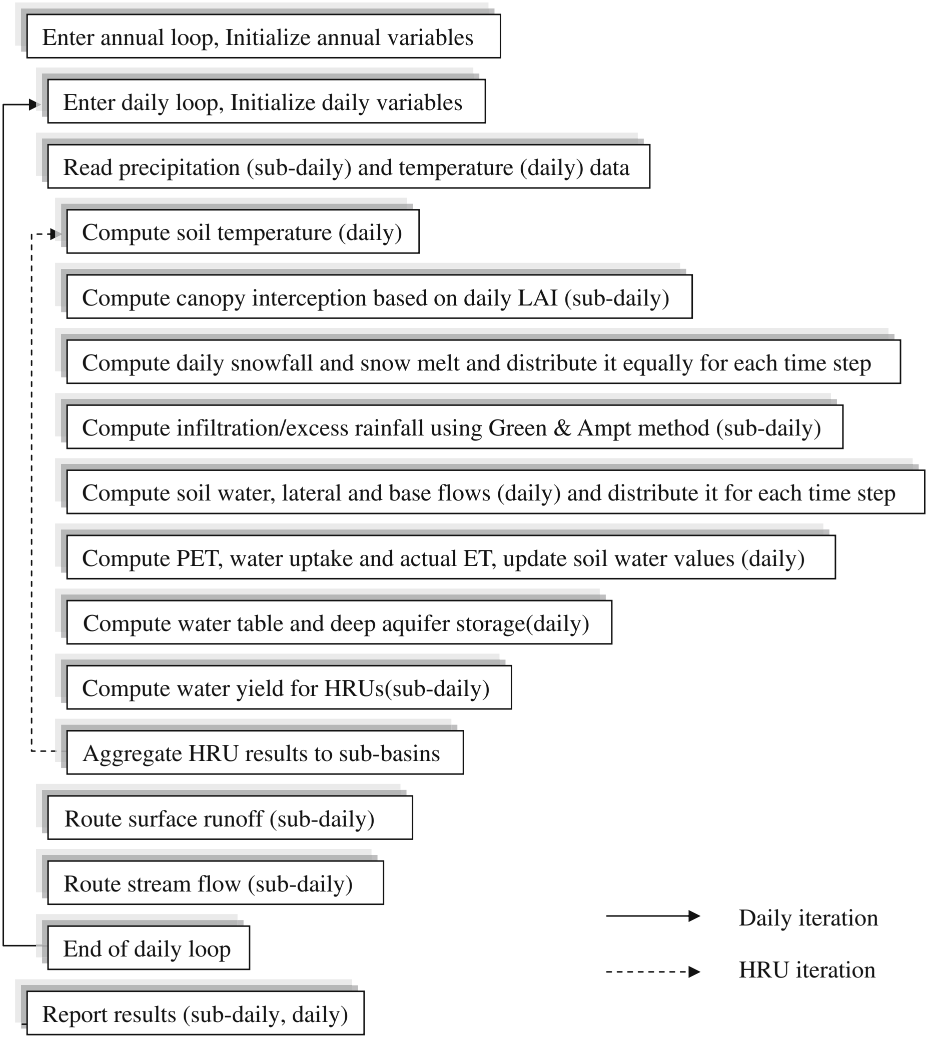


Fig. 3 Schematic flow chart showing the stream of processes in the sub-hourly simulation model

tion covering all HRUs. For upland processes, HRU results are aggregated for processing at larger spatial scales (HRUs→Subbasins→Watershed). Surface runoff, channel flow, and impoundment storage including ponds and reservoirs are routed at a subdaily time interval, but base flow and evapotranspiration are calculated on a daily basis and distributed for each time step.

3 Case Study

A small, mostly pristine watershed in Austin, TX was selected for testing the sub-hourly model (Fig. 4). The study area, Lost Creek Golf course Area (LGA) water-

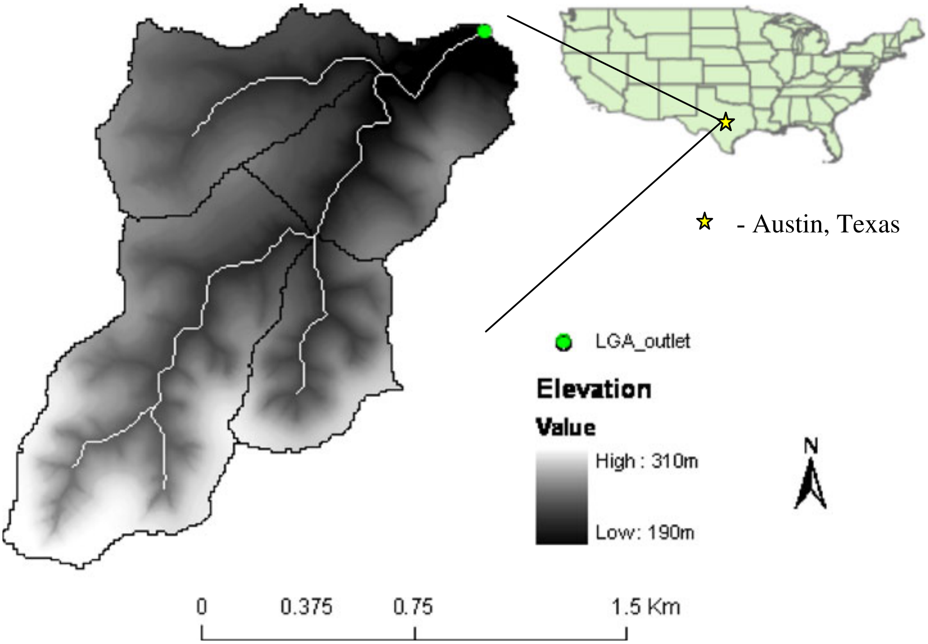


Fig. 4 LGA watershed in Austin, Texas

shed (1.94 km^2), is mostly undeveloped with no significant discharge or recharge of groundwater to deep aquifer (City of Austin 2006). The GAML infiltration method with Hargreaves evapotranspiration (ET) estimation method (Hargreaves et al. 1985) is used for the sub-daily model runs. For the daily runs, CN method with Hargreaves ET is used. The modeling time step always corresponds to the resolution of precipitation data (e.g., 15 min precipitation data is used in 15 min model runs). However, daily maximum and minimum temperature data is used for all the model runs irrespective of time step. Channel routing is carried out using the Muskingum method for all the model runs. Given the goals of the current project, applicability of the sub-hourly SWAT model, and short deadlines, the sub-daily soil water or evapotranspiration (ET) calculations are not attempted in the present study.

3.1 Description of the Watershed and Input Data

A Digital Elevation Model (DEM) with 0.3 meter (1 foot) resolution was prepared by City of Austin for watershed delineation. Soil data was obtained from Natural Resources Conservation Service (NRCS) Soil SURvey GeOgraphic (SSURGO) database. A land cover map of the study area for the year 2003 was prepared by City of Austin through aerial survey. Rainfall data of 1 minute interval recorded at a weather station near the watershed outlet was collected, and then aggregated to 15 minute interval. The watershed was divided into 4 subbasins and 36 HRUs based on the delineated stream network, land use, soil and slope combinations. The dominant soils are fine textured (proportion of clay + silt > 65%) shallow soils underlain by karstic rocks. Most of the soils are classified as hydrologic soil group C and D. The dominant land use is undeveloped (70%), which includes small residential structures and roads. Golf course/pasture (18%) and residential (12%) are other dominant land uses in the watershed. The main channel in the LGA watershed is highly ephemeral, having no stream flow for more than 70%–80% of time during the test period.

3.2 Sensitivity Analysis

A sensitivity analysis was conducted to investigate the impact of model operational time step in the subdaily SWAT applications. The sensitivity of stream flow to SWAT was indexed for various time intervals and those highly ranked parameters were selected for the model calibration. Due to the importance of the relative influences between parameters, a global method—the Latin hypercube sampling method incorporated with one-factor-at-a-time analysis technique (LH-OAT)—was used in the study. LH-OAT is a highly efficient global method based on the Monte Carlo simulation but uses a stratified technique that reduces computational time (van Griensven et al. 2006). It subdivides each parameter into N intervals and assumes the parameter is uniformly distributed within each interval. Random values of the parameters are generated such that the parameter is sampled only once for each interval. The total number of model runs is $N \times (K + 1)$, where N is the number of intervals and K is the number of parameters. Based on the literature review (Muleta and Nicklow 2005; Neitsch et al. 2005a, b; Kannan et al. 2007; Di Luzio and Arnold 2004; Immerzeel and Droogers 2008; Santhi et al. 2001), 15 mostly used parameters in calibrating hydrologic processes were selected (Table 1) for the sensitivity test. The 15 parameters ($K = 15$) were divided into 10 intervals ($N = 10$) of equal probability. Therefore, a total of 160 model runs was made for the LHS-OAT sensitivity analysis. This compares well with the number of model runs that a local method requires in which every possible combination of parameters is simulated ($N^K = 1.0\text{E} + 15$).

In the OAT analysis method, the derivatives of the model output are calculated for each parameter (x_i) as a small perturbation (Δx_i) is added while other parameters are fixed. The change in the model output is entirely attributed to Δx_i. A sensitivity index, defined as a normalized change in the model output divided by a normalized change in the input parameter, is useful to facilitate a direct comparison of parameters (Wang et al. 2005).

$$S_{ij} = \frac{\dfrac{|M(x_1, \ldots, x_i + \Delta x_i, \ldots, x_K) - M(x_1, \ldots, x_i, \ldots, x_K)|}{M(x_1, \ldots, x_i + \Delta x_i, \ldots, x_K) + M(x_1, \ldots, x_i, \ldots, x_K)}}{|\Delta x_i|/x_i} \tag{7}$$

where S_{ij} is the relative partial effect of parameter x_i around the LH point j, K is the number of parameters, and M is the model output. In this study, M represents time series result of stream flow at every time step at the watershed outlet. The partial sensitivity index values for x_i are averaged to get the final sensitivity index (S_i).

A public domain FORTRAN code developed by van Griensven and Meixner (2003) was adapted for the analysis. Multiple analyses were conducted for flow in 2004 with 2-year warm-up period using subdaily (15 min and 1 h interval) and daily intervals. In SWAT, many physically-based parameters vary at the HRU level and thus a significant number of parameters need to be assessed for the sensitivity analysis while each parameter has little influence on the model output. Therefore,

Table 1 SWAT parameters used in the sensitivity analysis

Parameter	Definition	File name	Range of values	
			Min.	Max.
ALPHA_BF	Base flow recession constant (days)	.gw	0.001	1
SURLAG	Surface runoff lag coefficient (days)	.bsn	0.001	15
AWC	Available water capacity	.sol	−25%[a]	+25%[a]
CH_K 1,2	Effective hydraulic conductivity of channel (mm/h)	.rte, .sub	0.025	150
CH_N 1,2	Manning's n value for the main and tributary channels	.rte, .sub	0.01	0.07
CN2	SCS runoff curve number for moisture condition II	.mgt	−4.0[b]	+4.0[b]
EPCO	Plant uptake compensation factor	.hru	0.001	1
ESCO	Soil evaporation compensation factor	.hru	0.001	1
GW_DELAY	Delay time for aquifer recharge (days)	.gw	0.001	100
GW_REVAP	Groundwater revap coefficient	.gw	0.02	0.2
GWQMN	Threshold water level in shallow aquifer for base flow (mm)	.gw	0.01	100
Ksat	Saturated hydraulic conductivity (mm/h)	.sol	−50%[a]	+50%[a]
MUSK_CO1	Weighting factor for influence of normal flow on storage time constant value	.bsn	0.01	10
MUSK_CO2	Weighting factor for influence of low flow on storage time constant	.bsn	0.01	10
OVR_N	Manning's n value for overland flow	.hru	0.05	0.8

[a]Value varies with land use; changes by multiplying a ratio within the range
[b]Value varies with land use; changes by adding/subtracting a value within the range

these parameters were assessed in a clustered way by adding or multiplying relative changes to the default values (e.g. −4 ∼ +4 for CN2 or −25% ∼ +25% for AWC).

3.3 Calibration of Stream Flow

A simple semi-automated procedure was developed for calibrating the subdaily SWAT model. Parameters for calibration were selected based on a sensitivity analysis. As there were many sensitive parameters included for calibration, it was decided to do the calibration in an efficient way, covering the whole parameterization process in a few steps. In this procedure, parameter values vary one at a time in an iterative loop covering all different possible combinations of parameters.

The calibration procedure is coupled with a statistical tool that evaluates model performance statistics. The model performance is evaluated at the end of iteration based on statistical measures and the breakdown of water balance components. The statistical criteria include Nash and Sutcliffe efficiency (NSE), coefficient of determination (R^2), percent bias (PBIAS), and root mean square error standard deviation ratio (RSR; Abulohom et al. 2001; Moriasi et al. 2007). NSE provides a normalized indicator of the model performance in relation to a benchmark. NSE = 1 is the optimal value. Values should be larger than 0.0 to indicate "minimally acceptable" performance and a value equal to or less than 0.0 indicates that the mean observed flow is a better predictor than the model value. Generally, a daily NSE of 0.65 or higher is considered good but the criteria may be lower for subdaily results and higher for monthly or annual outputs since performance improves as time interval increases. PBIAS measures the average tendency of the simulated component to be larger or smaller than their observed counterparts. With the optimal value of 0.0, positive values indicate model underestimation bias and negative values indicate model overestimation bias. As a general rule, a PBIAS of 10% or less is considered very good, 15% or less is good, and 25% or less is satisfactory (van Liew et al. 2007). RSR normalizes root mean standard error (RMSE) using the standard deviation of observation, incorporating the benefits of error index statistics with a normalization factor. RSR varies from 0 to a large positive value. RSR = 0 is the optimal value indicating a perfect model performance. Lower values of RSR indicate lower RMSE which means better model performance. A RSR value of 0.5 or less is considered very good, and 0.55 or less is good and 0.6 or less is considered satisfactory. R^2 describes the proportion of the variance in the residuals (the difference between observed flow and predicted flow) ranging from 0 to 1. A high value indicates less error with $R^2 = 1$ meaning the perfect match.

3.4 Strategy for Calibration-Validation

Subdaily simulation models are often calibrated for individual storm events rather than for a long continuous period (Zhang and Cundy 1989; Feng and Molz 1997; Tisdale and Yu 1999; Di Luzio and Arnold 2004; Jain and Singh 2005). However, the new sub-hourly SWAT model is developed for long term continuous simulations and thus, the model is expected to yield good results not only for individual storm events but also for long term periods. Therefore, a one year period was selected for the model calibration, and another one year was used for model validation. In some of the previous studies, it is found that better results can be obtained if a model is calibrated with wet condition data than dry condition data (Kannan et al. 2007; van Liew and Garbrecht 2003). In Austin, TX where the LGA watershed is located, year 2004 is the wettest year in the simulation period; thus, the model was calibrated to the stream flow data in 2004 with two years of warm-up period (2002–2003). Because the LGA watershed has experienced urbanization since 2005, an earlier period (year 2002) was selected for validation to make sure that the results are not affected by the changes in land use.

An automated base flow separation technique (Arnold et al. 1995) was used to separate base flow from stream flow using 5 years of data (2002–2006). Estimates of base flow are important to understand low flow characteristics of the streams and to investigate water pollution assessment. For example, the sub-hourly model was able to adequately reproduce stream flow with different percent contributions of surface runoff varying from less than 2% (i.e. 98% base flow) to more than 50%. Since multiple percent surface runoff profiles guaranteed good fittings of model output to the stream flow observation, the uncertainty in the model output could easily overwhelm the model reliability when used in water quality modeling because some of instream water quality is highly dependent on surface runoff. The base flow filter estimated the contribution of base flow to the stream flow as 40% for LGA. In calibration and validation, however, the percentage of surface runoff was assumed slightly smaller than 60% because of the following reasons. The geomorphic characteristics of LGA is represented by thin soil layers (20 to 40 cm) above fractured base rock and steep slopes (average slope = 6.2%) which promotes high lateral flow. SWAT output confirms this theory with significant lateral flow contributing 30% to the stream flow (see Table 3). We concluded that a considerable amount of lateral flow filtered as surface runoff by the base flow filter. Therefore, the average ratio was adjusted to around 55% surface runoff and 45% base flow during the calibration period.

Stream flow was calibrated at the watershed outlet through a combination of manual and automatic procedures. During the initial manual calibration, the range of parameter values are narrowed down based on the statistical measures and water balance. Then the semi-automatic calibration finds a set of parameters that gives the best efficiency values (NSE and R^2) and water balance. By repeating the manual and semi-automatic procedures, a set of parameters that yields the best efficiency values as well as realistic breakdown in water balance components can be found in relatively shorter time than a full manual calibration. The integration of automatic and manual calibration can substantially increase the calibration efficiency compared to a fully automatic procedure depending on modeler's experience and expertise (White 2009).

4 Results

4.1 Parameter Sensitivity

The result of the sensitivity analysis is summarized in Table 2. The sensitivity of SWAT parameters was significantly influenced by the model operational time step. The parameters related to channel routing (*CH_N*, *CH_K*, *MSK_CO1, and MSK_CO2*) became very sensitive as time scale narrows down. On the other hand, the significance of groundwater flow parameters (*GWREVAP*,*GWQMN*, *ALPHA_BF*, *and GWDELAY*) was relatively higher with the daily time interval. Plant available water capacity parameter (*AWC*) was highly influential in all tests and no meaningful correlation was found between *AWC* and model operational time

Table 2 Sensitivity of SWAT parameters for different operational time intervals ($\Delta t = 15$ min, 1 h, and 1 day)

Rank	$\Delta t = 15$ min		$\Delta t = 1$ h		$\Delta t = 1$ day	
	Parameter	S_i	Parameter	S_i	Parameter	S_i
1	CH_N	116.7	ALPHA_BF	25.7	AWC	21.2
2	AWC	43.4	AWC	24.5	GWREVAP	10.7
3	SURLAG	19.5	GWQMN	9.5	GWQMN	7.8
4	MSK_CO2	9.2	ESCO	8.6	ESCO	7.4
5	KSAT	8.8	GWDELAY	7.0	ALPHA_BF	6.5
6	OVR_N	8.1	CN2	4.7	GWDELAY	5.8
7	ALPHA_BF	6.8	GWREVAP	3.4	CN2	4.5
8	ESCO	6.6	KSAT	2.4	SURLAG	3.4
9	CH_K	5.7	SURLAG	1.1	KSAT	1.8
10	CN2	4.9	CH_N	0.7	EPCO	0.5
11	GWDELAY	4.8	MSK_CO2	0.4	OVR_N	0.2
12	MSK_CO1	2.9	CH_K	0.4	MSK_CO2	0.1
13	GWQMN	1.2	EPCO	0.3	CH_N	0.1
14	GWREVAP	0.9	OVR_N	0.2	MSK_CO1	0.1
15	EPCO	0.6	MSK_CO1	0.1	CH_K	0.0

interval. Meanwhile, *KSAT, ESCO, CN2*, and *SURLAG* were marginally ranked for sensitivity in all tests.

4.2 Water Balance

Shown in Table 3 is the predicted water balance in the upland processes scaled to the percent annual rainfall. There was more rainfall during the calibration period (1,186 mm/year) than in the validation period (870 mm/year); therefore, it was reasonable that the predicted surface runoff was estimated higher in the calibration period than in the validation period and vice versa for the evapotranspiration. According to the Texas Irrigation Center (2004), solar radiation recorded during the validation period was 34% higher than calibration period. The relatively higher amount of evapotranspiration in the validation period may be explained by the high amount of solar radiation during this period.

4.3 Analysis of Model Performance

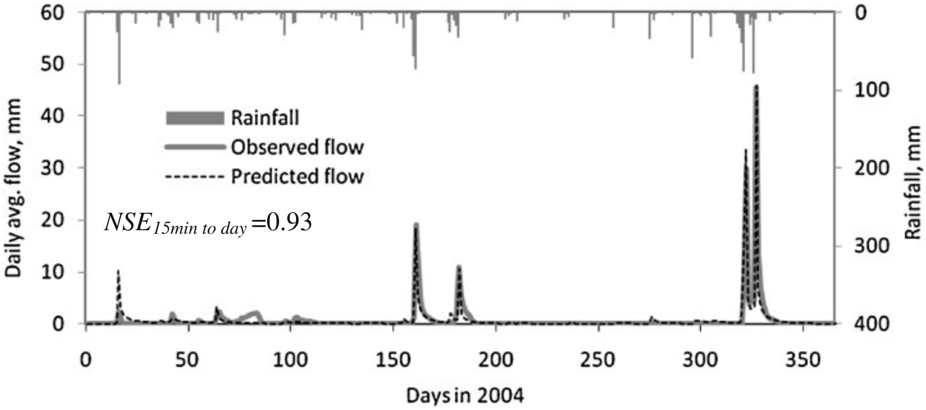
Stream flow hydrographs are presented in Figs. 5, 6 and 7 showing both model predictions and field observations for 15 min, hourly and daily time step, respectively. Since one of the objectives of the study was to investigate the advantage of the new sub-hourly simulation model over existing daily model, sub-hourly results were aggregated to daily averages to directly compare the outputs from sub-hourly model to those from daily simulation model. Figure 5a shows the performance of sub-hourly model during the calibration period, where predicted 15 min stream flow was aggregated to daily values. Due to the large number of data points in 15 min output, the sub-hourly hydrograph with 15 min interval was plotted for only 1 month period during the calibration period (Fig. 5b). Figure 5c shows the predicted and observed stream flow during the validation period. In Fig. 5c, 15 min output is plotted in terms of daily averages same as Fig. 5a. Similarly, 1 h and 1 day results are presented in Figs. 6 and 7 respectively.

4.3.1 Model Results at Various Time Steps

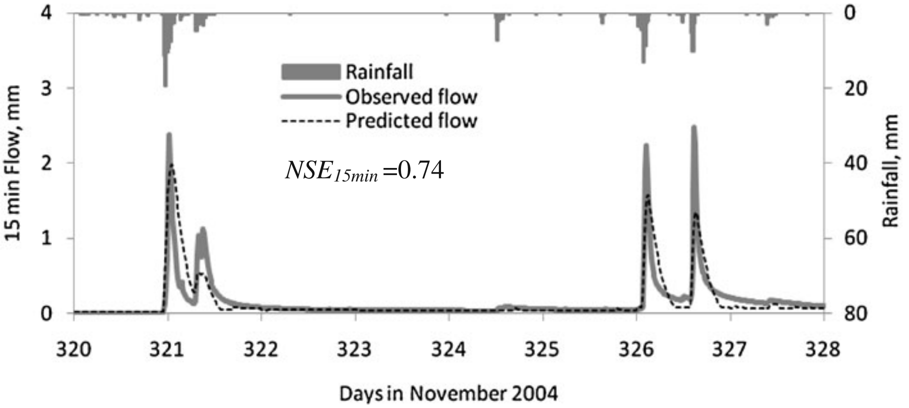
Model output with sub-daily operational time steps (Figs. 5 and 6) was better in predicting peak flows than the daily output (Fig. 7). NSE values increased appreciably when sub-daily results were aggregated to daily averages (e.g., 15 min calibration: $NSE_{15\ min} = 0.74$ to $NSE_{15\ min\ to\ 1\ day} = 0.93$, 1 h calibration: $NSE_{1\ h} =$

Table 3 Predicted water balance components

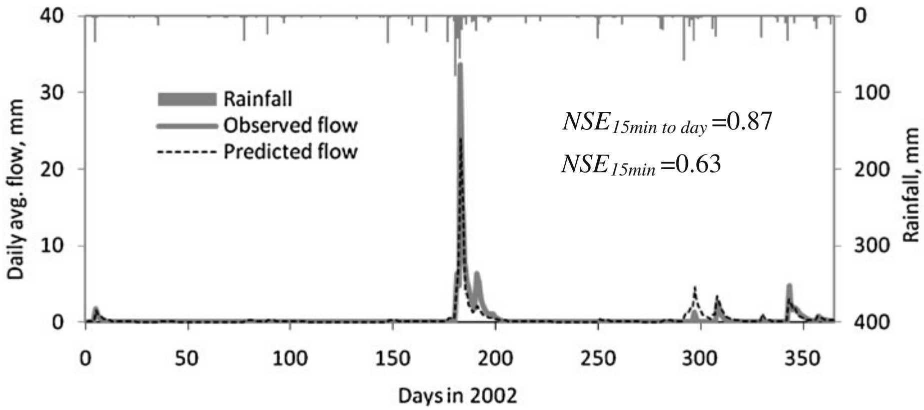
Time interval	Period	Water balance components in terms of percent annual rainfall				
		Surface runoff	Lateral flow	Groundwater flow	Total water yield	Evapotranspiration
15 min	Calibration	12.1	8.8	2.0	22.9	59.0
	Validation	4.0	8.6	6.0	18.4	70.0
1 h	Calibration	12.5	5.8	5.2	23.5	59.0
	Validation	3.7	6.0	9.3	18.9	68.8
1 day	Calibration	12.2	6.3	5.1	23.5	46.7
	Validation	6.1	6.8	2.8	15.6	54.9



(a) Daily stream flow aggregated from 15min output (calibration)

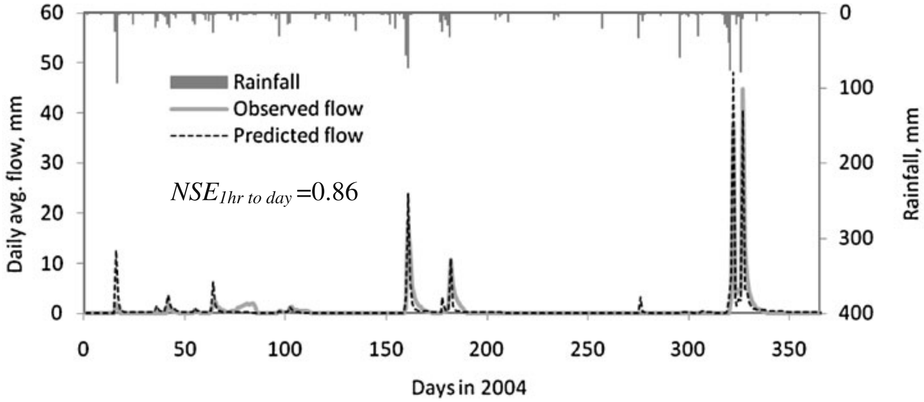


(b) 15min stream flow (calibration). NSE_{15min} is estimated for the entire year

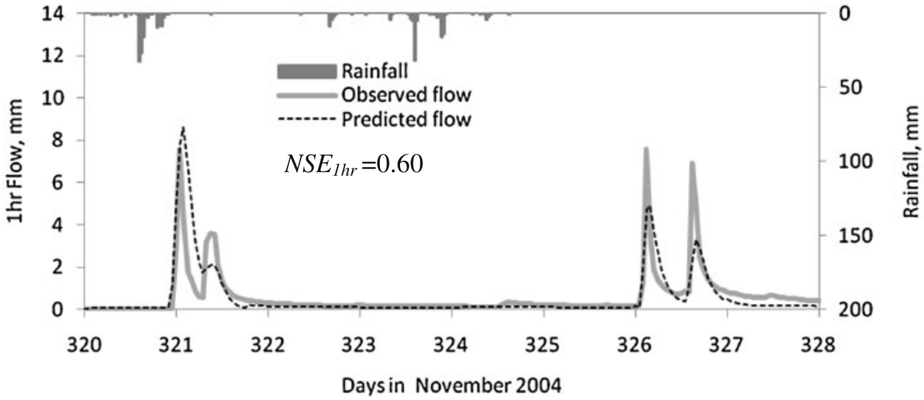


(c) Daily stream flow aggregated from 15 min output (validation)

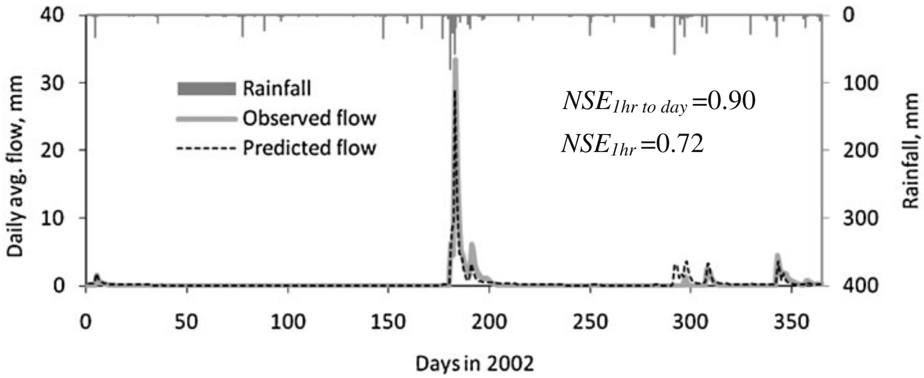
Fig. 5 Stream flow hydrographs for $\Delta t = 15$ min



(a) Daily stream flow aggregated from 1hr output (calibration)

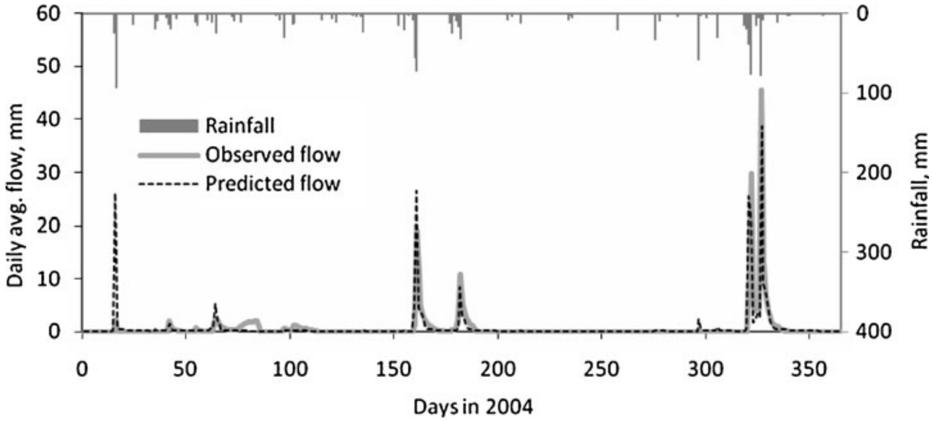


(b) 1hr stream flow (calibration). NSE_{1hr} is estimated for the entire year

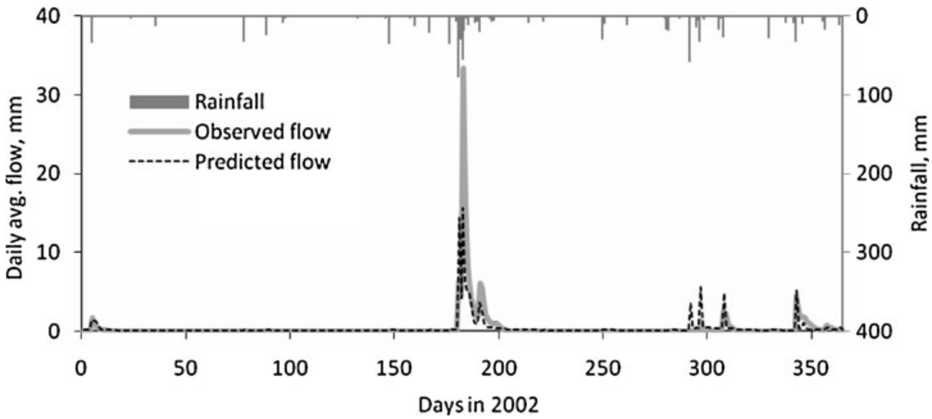


(c) Daily stream flow aggregated from 1hr output (validation)

Fig. 6 Stream flow hydrographs for $\Delta t = 1$ h



(a) Daily stream flow in the calibration period (estimated daily), NSE_{1day}=0.72



(b) Daily stream flow in the validation period (estimated daily), NSE_{1day}=0.65

Fig. 7 Calibration and validation results for $\Delta t = 1$ day

0.6 to $NSE_{1\text{ h to 1 day}} = 0.86$) as summarized in Table 4. When compared with daily output, the aggregated sub-daily results were far better (e.g., $NSE_{15\text{ min}->1\text{ day}} = 0.93$ and $NSE_{1\text{ day}} = 0.72$ in the calibration period). In both calibration and validation periods, the predicted stream flow with sub-daily operational time step is more reliable than daily simulation results. High resolution precipitation data (15 min and 1 h for the respective sub-daily model runs) and subsequent calculation of rainfall intensity, infiltration/surface-runoff and routing of overland flow at sub-daily time steps could be attributed to the better performance of sub-daily model results over daily results.

The steep slopes and short flow lengths (time of concentration [t_c] < 2 hours) of LGA's landscape may result in flashy and spiky hydrographs as observed in Figs. 5, 6 and 7. In addition, the stream flow of LGA has more than 50% of contribution from surface runoff (53% surface runoff and 47% base flow). Therefore, daily operational time step may be too sparse to adequately capture multiple sub-daily storm events.

Table 4 Performance evaluation of different time intervals

Simulation interval	Rain data resolution	Runoff generation method	Period	NSE		R^2	PBIAS (%)	RSR
				Δt	1 day			
15 min	15 min	Green and Ampt method	Calibration	0.74	0.93	0.76	−3.84	0.51
			Validation	0.63	0.87	0.64	−12.47	0.61
1 h	1 h	Green and Ampt method	Calibration	0.60	0.86	0.67	−6.88	0.64
			Validation	0.72	0.90	0.73	−15.58	0.53
1 day	1 day	Curve Number method	Calibration	0.72		0.74	−6.25	0.53
			Validation	0.65		0.70	6.15	0.59

In all model runs, better performance was observed in the calibration period than in the validation period.

4.3.2 High Flow vs. Low Flow

Predicted stream flow hydrographs at sub-daily time intervals successfully captured both the timing and magnitude of peaks. Recession flows were also well simulated for high to medium storm events (Figs. 5 and 6), but the performance was marginal for small events (or low flows) as indicated by PBIAS values especially for the 1 h result (−15.58%). The daily simulation result (Fig. 7) generally overestimated small to medium flows and underestimated high flows, which is similar to the findings in some of the previous studies (Eckhardt and Arnold 2001; Muleta and Nicklow 2005; Borah et al. 2007). This is further evident in the flow duration curves (FDCs) plotted with 15 min, 1 h, and 1 day outputs aggregated to daily time step showing the regimes for high flows (<10% exceedance) and medium to low flows (>10% exceedance) in Fig. 8. The FDCs in Fig. 8a show that sub-daily results are superior to daily results when high flows are of concern. As expected, none of the simulated results reasonably fits the observation on low flows (see Fig. 8b) while sub-daily SWAT model performs very well on high flows. Since low flows are contributed mostly by base flow and there was no improvement made in the model for base flow, not much improvement is expected in the simulated sub-daily results for the regime of low flows. The clear discrepancy may be in part exaggerated by the semi-log scale used in the plotting because extreme values are generally exaggerated in semi-log plots. If plotted in normal exceedance curve, the big gaps in the medium to low flows would not be noticeable. The main reason for the model's poor performance in low flows might be attributed to the daily calculation of base flow and the equal distribution of the daily estimates to each time step. Difficulty in simulating subsurface hydrology due to high heterogeneity in the soil profile is also an important factor.

4.3.3 Calibration vs. Validation

The statistical measures obtained from calibration and validation periods are given in Table 4. For all calibration schemes PBIAS values are less than zero meaning slight model bias toward overestimation, but all values remain within 10% in magnitude indicating "very good" ratings (Moriasi et al. 2007). In the validation period, PBIAS values for sub-daily model runs are worse than daily result. The PBIAS rank for 15 min validation (−12.47%) is "good" while the rank for 1 h validation (−15.58%) is "satisfactory". The other statistical measures (NSE, R^2, and RSR) indicate that the model performance is very good in all cases. However, when compared to each

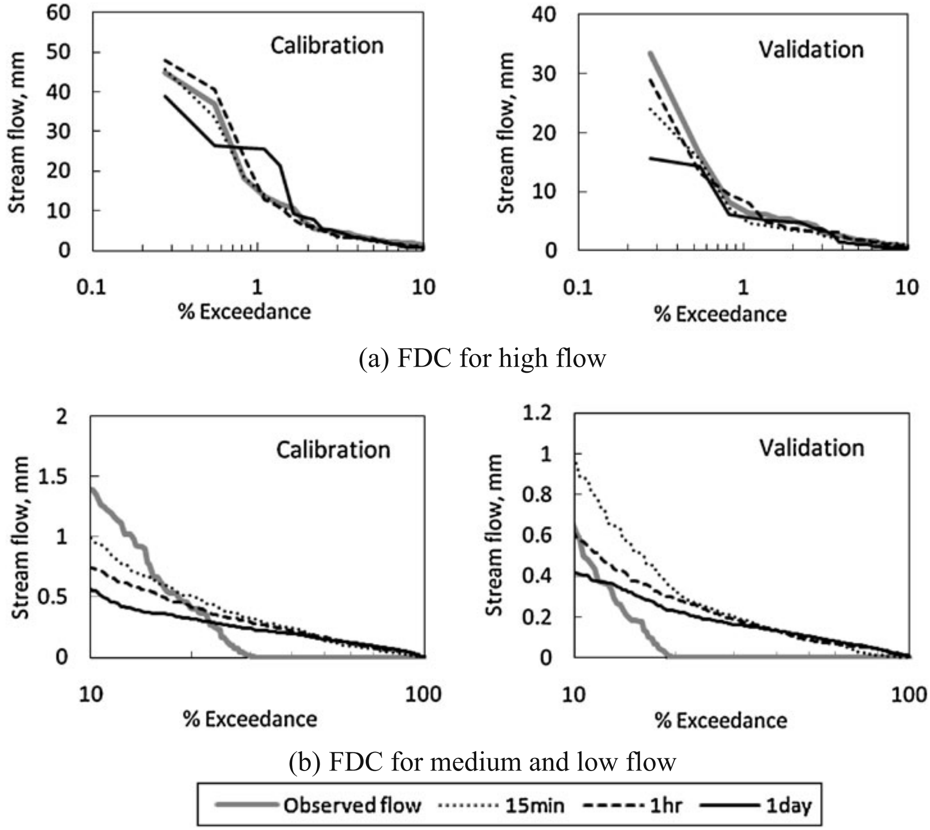


Fig. 8 Flow duration curves for LGA watershed showing the impact of temporal resolution (15 min, 1 h, 1 day) on the stream flow in different flow regimes

other, the model performance is better in calibration period than in validation period. A possible explanation for this behavior is that when data from wet conditions are used for calibration, and the model is validated for dry conditions the model needs to function just inside the range of model calibration. The data used for calibration is from the wettest year in the simulation period. Therefore, better results are expected for LGA in calibration than validation.

4.3.4 GAML Method vs. CN Method

The CN method with daily precipitation was used for the daily model runs and GAML with sub-daily/sub-hourly precipitation for the sub-daily runs. In the previous sections it was established that the sub-daily model results outperform the daily results. In other words, GAML performed better than the CN method for the LGA watershed. This could be attributed to better resolution of precipitation data (sub-daily intervals) used in the Green and Ampt method and subsequent physically based calculation of infiltration, and surface runoff and channel routing at sub-daily time steps. However, the results presented in this study differ from some of the previous studies (King et al. 1999; Kannan et al. 2007) outlining no better results from Green and Ampt method. Quality of precipitation data and size of watershed might be the possible reasons for the difference in results.

5 Summary and Recommendations

Sub-hourly flow simulation capability was added to the SWAT 2005 model. The new sub-hourly model components in SWAT allow simulation of runoff/infiltration, overland flow routing, reservoir/pond/wetland routing, and channel routing at any sub-daily time scale, while base flow is simulated at daily interval then distributed equally to each time step. The difference in the computational time scale between surface runoff and base flow may be a drawback of the model; however, a case study on a 1.94 km^2 watershed shows significant improvement in the model output especially in the prediction of high flows compared to the daily SWAT model. The improvement in high flow predictions can benefit water quality modeling especially in the area of nonpoint sources pollution modeling as nonpoint sources are known to be a dominant environmental stressor in high flows. With the enhanced fine resolution in operation time step, the sub-hourly SWAT model is expected to successfully address hydrologic issues in urban watersheds.

Simulating sub-daily hydrological processes requires different strategy for modelers. Using SWAT, we found that the model operational time step greatly affects the model parameters' sensitivity to the model output (see Table 2). A sensitivity analysis outlined in this study showed that the SWAT parameters related to channel routing become more influential as time interval decreases down to 15 min and groundwater flow parameters get more influential as time interval increases.

A combination of automatic and manual calibrations used in this study made the calibration process very efficient. A strategy for auto-calibration was made during manual calibrations by narrowing down the range of parameters while maintaining the water balance between surface runoff and base flow in realistic ranges. Due to the complexity in hydrological processes and the formation of SWAT model, there was no unique combination of parameters that gave the best fitting to the observations whilst maintaining adequate water balance. A combination of parameters that yielded the most realistic proportion of base flow to the stream flow as well as good fitting against stream flow observations was selected after calibration of stream flow. A good knowledge on the watershed properties such as the ratio of surface runoff and base flow to the stream flow was necessary for the model calibration. Otherwise, subsequent water quality modeling can be very difficult because in-stream water quality is often very sensitive to the surface runoff.

High flows are better estimated with the sub-hourly model than the existing version of daily SWAT and therefore the developed sub-hourly model is expected to perform better in the non-point source pollution assessment studies. However, not much improvement is obtained in the low flow prediction because low flows are dominated by base flow and the model still uses soil water and ET estimation routines at daily time step. When tested for quality of flow results from CN and GAML method, our study pointed out better results from Green and Ampt method mainly due to the high quality of precipitation data and physically based nature of infiltration/surface runoff estimation procedure.

A reasonable time interval should be selected for a sub-daily simulation based on the scale and characteristics of the watershed. Surface runoff needs be estimated at least once before it reaches the channel. Stream flow also needs to be calculated at least once before it reaches the end of channel segment. Therefore, it is recommended that the simulation time interval not to exceed the smaller of overland flow travel time and stream flow travel time. However, this does not necessarily mean that the finer the time interval always improves model performance. In the future, more capabilities will be added to sub-hourly SWAT for simulating stormwater BMPs in urban watersheds and further validation will be performed on highly impermeable urban watersheds.

6 Limitations

The enhanced SWAT model for sub-hourly flow simulation is intended for simulating short duration storms. Due to the lack of urban modules such as storm sewer network or storm water BMPs including Low Impact Development, this model may not be applicable to address hydrologic processes in intensely urbanized areas.

Acknowledgements We wish to acknowledge Watershed Protection and Development Review, City of Austin, Texas for providing funding and all the data for this study. We also thank our 3 anonymous reviewers for their constructive comments toward the improvement of the manuscript.

References

Abulohom MS, Shah SMS, Ghumman AR (2001) Development of a rainfall–runoff model, its calibration and validation. Water Resour Manag 15:149–163

Arnold JG, Allen PM, Muttiah R, Bernhardt G (1995) Automated base flow separation and recession analysis techniques. Ground Water 33(6):1010–1018

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Large area hydrologic modeling and assessment part I: model development. J Am Water Resour Assoc 34(1):73–89

Aron G, White EL (1982) Fitting a gamma distribution over a synthetic unit hydrograph. J Am Water Resour Assoc 18(1):95–98

Benham BL, Baffaut C, Zeckoski RW et al (2006) Modeling bacteria fate and transport in watersheds to support TMDLs. Trans ASABE 49(4):987–1002

Bicknell BR, Imhoff JC, Kittle JL Jr, Donigian AS Jr, Johanson RC (1995) Hydrological simulation program—FORTRAN. User's Manual for Release 11

Borah DK, Bera M (2003) Watershed-scale hydrologic and nonpoint-source pollution models: review of mathematical bases. Trans ASAE 46(6):1553–1556

Borah DK, Yagow G, Saleh A, Barnes PL, Rosenthal W, Krug EC, Hauck LM (2006) Sediment and nutrient modeling for TMDL development and implementation. Trans ASABE 49(4):967–986

Borah DK, Arnold JG, Bera M, Krug EC, Liang XZ (2007) Storm event and continuous hydrologic modeling for comprehensive and efficient watershed Simulations. J Hydrol Eng 12(6):605–616

Bracmort KS, Arabi M, Frankenberger JR, Engel BA, Arnold JG (2006) Modeling long-term water quality impact of structural BMPs. Trans ASABE 49(2):367–374

Burns D, Vitvar T, McDonnell J, Hassett J, Duncan J, Kendall C (2005) Effects of suburban development on runoff generation in the Croton River basin, New York, USA. J Hydrol 311 (1–4):266–281

Chang HJ (2007) Comparative streamflow characteristics in urbanizing basins in the Portland Metropolitan Area, Oregon, USA. Hydrol Process 21(2):211–222

City of Austin (2006) Stormwater runoff quality and quantity from small watersheds in Austin, TX, City of Austin. Water Quality Report Series, COA-ERM/WQM 2006-1

Corbett CW, Wahl M, Porter DE, Edwards D, Moise C (1997) Nonpoint source runoff modeling—a comparison of a forested watershed and an urban watershed on the South Carolina coast. J Exp Mar Biol Ecol 213(1):133–149

Debele B, Srinivasan R, Parlange JY (2009) Hourly analyses of hydrological and water quality simulations using the ESWAT Model. Water Resour Manag 23:303–324

Di Luzio M, Arnold JG (2004) Formulation of a hybrid calibration approach for a physically based distributed model with NEXRAD data input. J Hydrol 298(1–4):136–154

Eckhardt K, Arnold JG (2001) Automatic calibration of a distributed catchment model. J Hydrol 251(1–2):103–109

Feng K, Molz FJ (1997) A 2-D, diffusion-based, wetland flow model. J Hydrol 196(1–4):230–250

Garen DC, Moore DS (2005) Curve number hydrology in water quality modeling: uses, abuses, and future directions. J Am Water Resour Assoc 41(2):377–388

Gassman P, Reyes M, Green C, Arnold JG (2007) The soil and water assessment tool: historical development, applications, and future research directions. Trans ASABE 50(4):1211–1250

Hantush MM, Kalin L (2006) Impact of urbanization on the hydrology of Pocono creek watershed: a model study. National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio 45268

Hargreaves GL, Hargreaves GH, Riley JP (1985) Agricultural benefits for Senegal River basin. J Irrig Drain Eng 111(2):113–124

Harmel RD, Rossi CG, Dybala T et al (2008) Conservation effects assessment project research in the Leon River and Riesel watersheds. J Soil Water Conserv 63(6):453–460

Immerzeel WW, Droogers P (2008) Calibration of a distributed hydrological model based on satellite evapotranspiration. J Hydrol 349(3–4):411–424

Jain MK, Singh VP (2005) DEM-based modelling of surface runoff using diffusion wave equation. J Hydrol 302(1–4):107–126

Julien PY, Saghafian B (1991) CASC2D user's manual: a two-dimensional watershed rainfall–runoff model. Colorado State University, Center for Geosciences, Hydrologic Modeling Group

Kannan N, White SM, Worrall F, Whelan MJ (2007) Sensitivity analysis and identification of the best evapotranspiration and runoff options for hydrological modelling in SWAT-2000. J Hydrol 332(3–4):456–466

Kim NW, Lee J (2009) Integration of SWAT and SWMM models. In: Proceedings of the 2009 international SWAT conference. Boulder, CO

King KW (2000) Response of Green-Ampt Mein-Larsen simulated runoff volumes to temporally aggregated precipitation. J Am Water Resour Assoc 36(4):791–797

King KW, Arnold JG, Bingner RL (1999) Comparison of Green-Ampt and curve number methods on Goodwin Creek watershed using SWAT. Trans ASABE 42(4):919–925

Mausbach MJ, Dedrick AR (2004) The length we go: measuring environmental benefits of conservation practices. J Soil Water Conserv 59(5):96A–103A

Mein R, Larson C (1973) Modeling infiltration during a steady rain. Water Resour Res 9(2):384–394

Moriasi D, Arnold JG, van Liew M et al (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans ASAE 50(3):885–900

Muleta MK, Nicklow JW (2005) Sensitivity and uncertainty analysis coupled with automatic calibration for a distributed watershed model. J Hydrol 306(1–4):127–145

Nearing MA, Liu BY, Risse LM, Zhang X (1996) Curve numbers and Green–Ampt effective hydraulic conductivities. J Am Water Resour Assoc 32:125–136

Neitsch SL, Arnold JG, Kiniry JR, Williams JR (2005a) Soil and water assessment tool theoretical documentation. Grassland, Soil and Water Research Service, Temple

Neitsch SL, Arnold JG, Kiniry JR, Srinivasan R, Williams JR (2005b) Soil and water assessment tool input/output file documentation. Version 2005, Grassland, soil and water research service, Temple, TX

Overton D (1966) Muskingum flood routing of upland streamflow. J Hydrol 4:185–200.

Pitt R, Voorhees J (1995) Source loading and management model (SLAMM)

Radcliffe DE, Lin Z, Risse LM, Romeis JJ, Jackson CR (2009) Modeling phosphorus in the Lake Allatoona watershed using SWAT: I. Developing phosphorus parameter values. J Environ Qual 38(1):111–120

Refsgaard JC, Storm B (1995) MIKE SHE. Chapter 23 in computer models of watershed hydrology, pp 809–846

Richardson CW, Bucks DA, Sadler EJ (2008) The conservation effects assessment project benchmark watersheds: synthesis of preliminary findings. J Soil Water Conserv 63(6):590–604

Rossman L (2004) Storm water management model User's manual version 5.0. Water Supply and Water Resources Division National Risk Management Research Laboratory Cincinnati
Santhi C, Arnold JG, Williams JR et al (2001) Application of a watershed model to evaluate management effects on point and nonpoint source pollution. Trans ASAE 44(6):1559–1570
SCS (1972) National engineering handbook, section 4, hydrology. US Department of Agriculture, SCS, Washington, DC
Texas Irrigation Center (2004) ET and Weather Data. http://texaset.tamu.edu/. Accessed 12 Dec 2010
Tisdale TS, Yu JMHL (1999) Kinematic wave analysis of sheet flow using topography fitted coordinates. J Hydrol Eng 4(4):367–370
van Griensven A, Meixner T (2003) LH-OAT sensitivity analysis tool. University of Arizona, Department of Hydrology and Water Resources, Tucson. http://www.sahra.arizona.edu/software/index_main.html. Accessed 12 Dec
van Griensven A, Meixner T, Grunwald S et al (2006) A global sensitivity analysis tool for the parameters of multi-variable catchment models. J Hydrol 324(1–4):10–23
van Liew MW, Garbrecht J (2003) Hydrologic simulation of the little Wichita river experimental watershed using SWAT. J Am Water Resour Assoc 39(2):413–426
van Liew M, Veith T, Bosch D, Arnold J (2007) Suitability of SWAT for the conservation effects assessment project: comparison on USDA agricultural research service watersheds. J Hydrol Eng 12:173
Wang X, Youssef MA, Skaggs RW et al (2005) Sensitivity analyses of the nitrogen simulation model, DRAINMOD-N II. Trans ASAE 48(6):2205–2212
White M (2009) Personal conversation. USDA-ARS Grassland, Soil and Water Research Laboratory, Temple, Texas; Email: mike.white@ars.usda.gov
Williams J (1969) Flood routing with variable travel time or variable storage coefficients. Trans ASAE 12(1):100–103
Xiong YY, Melching CS (2005) Comparison of kinematic-wave and nonlinear reservoir routing of urban watershed runoff. J Hydrol Eng 10(1):39–49
Zhang WH, Cundy TW (1989) Modeling of two-dimensional overland-flow. Water Resour Res 25(9):2019–2035