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EVALUATION OF A WATERSHED MODEL FOR ESTIMATING DAILY FLOW USING LIMITED FLOW MEASUREMENTS[1]

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ABSTRACT: The Soil and Water Assessment Tool (SWAT) model was evaluated for estimation of continuous daily flow based on limited flow measurements in the Upper Oyster Creek (UOC) watershed. SWAT was calibrated against limited measured flow data and then validated. The Nash-Sutcliffe model Efficiency (*NSE*) and mean relative error values of daily flow estimations were 0.66 and 15% for calibration, and 0.56 and 4% for validation, respectively. Also, further evaluation of the model's estimation of flow at multiple locations was conducted with parametric paired *t*-test and nonparametric sign test at a 95% confidence level. Among the five main stem stations, four stations were statistically shown to have good agreement between predicted and measured flows. SWAT underestimated the flow of the fifth main stem station possibly because of the existence of complex flood control measures near to the station. SWAT estimated the daily flow at one tributary station well, but with relatively large errors for the other two tributaries. The spatial pattern of predicted flows matched the measured ones well. Overall, it was concluded from the graphical comparisons and statistical analyses of the model results that SWAT was capable of reproducing continuous daily flows based on limited flow data as is the case in the UOC watershed.

(KEY TERMS: Soil and Water Assessment Tool; daily flow estimation; model evaluation; Upper Oyster Creek watershed; Texas.)

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INTRODUCTION

In many watersheds, continuous daily flow data may be readily obtained from United States Geological Survey (USGS) gauging stations. However, where only discontinuous or instantaneous daily flow measurements are available and continuous daily flow data are needed, can a watershed model be used to estimate daily flows? In other words, can a model be calibrated to provide continuous and accurate daily flows based on limited flow measurements? For example, total maximum daily loads (TMDLs) are being developed for all impaired surface waters throughout the United States (U.S.) (Cleland, 2002), many of which do not have extensive flow records. For these water bodies with limited flow data, continuous daily streamflow estimates are especially important in TMDL development. One specific application is the load duration curve approach, which has found

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relatively broad acceptance among the regulatory community and has been utilized in many states (USEPA, 2001, 2007; Cleland, 2002; Sullivan, 2002; NDEQ, 2005; Center for TMDL and Watershed Studies, 2006; TDEC, 2006).

The Soil and Water Assessment Tool (SWAT) is widely applied in watershed studies (e.g., Santhi *et al.*, 2002; Saleh and Du, 2004; Du *et al.*, 2006; Gassman *et al.*, 2007). The SWAT model is a physically based, continuous-time mathematical model (Arnold *et al.*, 1998) that was designed to predict daily streamflow and soil and nutrient losses in a watershed theoretically. The modelers and developers summarized the development and application of SWAT by investigating the past published literature and reported that SWAT has been shown to accurately predict flow based on monthly and yearly comparisons with measured data (Gassman *et al.*, 2007). In addition, SWAT has also been evaluated directly in its ability to predict daily streamflow. The study by Jayakrishnan *et al.* (2005) demonstrated the usefulness of radar rainfall data in distributed hydrologic studies and the potential of SWAT for application in daily flow, flood analysis, and prediction. Cao *et al.* (2006) concluded in their study that the predicted daily streamflow matched the observed values, with a Nash-Sutcliffe coefficient of 0.78 during calibration and 0.72 during validation, but with Nash-Sutcliffe coefficient values for subcatchments ranged from 0.31 to 0.67 during calibration and 0.36 to 0.52 during validation. SWAT has not, however, been evaluated in its ability to produce reasonable daily flow estimates in situations where limited measured data are available for calibration. Thus, the objective of the present study is to evaluate the ability of SWAT to reproduce continuous daily streamflows in the case of the Upper Oyster Creek (UOC) watershed based on a limited number of flow measurements. The evaluation was supported by standard statistical analysis. In addition, the authors intend to provide scientific evidence that using SWAT to estimate daily flow holds great promise.

MATERIALS AND METHODS

Site Description

The 276 km^2 UOC watershed is located within the Brazos River basin, immediately southwest of Houston in northern Fort Bend County (Figure 1). The watershed consists of a main stem stream, four major tributaries, and a diversion canal. UOC has been

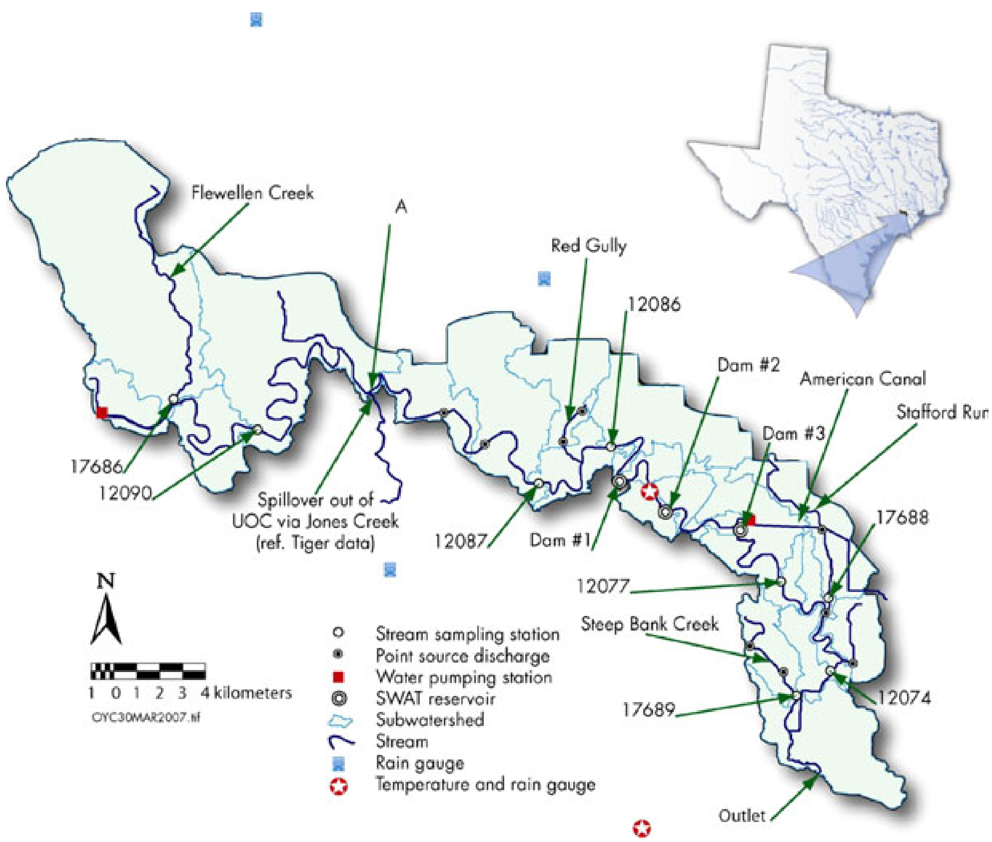

FIGURE 1. Location of Monitoring Stations on Upper Oyster Creek (segment 1245).

highly modified and three dams were built on the main stem channel. Portions of the creek serve as a part of a water conveyance system for the Gulf Coast Water Authority (Figure 1). The creek flows through the city of Sugar Land where it is impounded to create several interconnected shallow lakes.

Data Preparation for SWAT Application

We used the SWAT2003 version with the AVSWATX (ArcView Soil and Water Assessment Tool eXtender) interface (Di Luzio *et al.*, 2004) which employs the Soil Survey Geographic (SSURGO) Database, a spatially refined soils database.

Measured streamflow, rainfall, weather, point source withdrawals and additions along with spatial topographic, soils, and land use data were utilized to apply SWAT2003. All other required input data were generated using default model values.

Flow in the UOC streams was determined from velocity measurements and corresponding cross sectional channel surveys. Under wadeable stream conditions, velocity was measured with either a SonTek Flow Tracker™ Acoustic Doppler Velocimeter (SonTek/YSI Inc., San Diego, California) or a Global Water Flow Probe™ (Global Water Instrumentation Inc., Gold River, California) calibrated to a Teledyne-Gurley™ model 622F Type AA current meter (Gurley Precision Instruments, Troy, New York) in the Tarleton State University Department of Hydrology fluids laboratory. Under non-wadeable stream conditions, the AA current meter was used at stations with accessible bridge crossings along with a Rickly™ Hydrological sounding reel and crane (Rickly Hydrological Co., Columbus, Ohio). The discontinuous daily flow measurements covered low and high flow conditions of the model evaluation period from October 2002 to September 2004. The measured daily flow data were used for model calibration and validation.

The 30-m digital elevation models (DEM) for Fort Bend County, Texas were downloaded from webGIS (2005) and GeoCommunity (2005). The same DEM scenes were reprojected based on their metadata files to reach a united format. The multiple DEMs were assembled using the ArcView Mosaic command. The tears, holes, or sinks in the merged DEM map were fixed using the Neighborhood Statistics of Analysis at a threshold value of three cells. Based on the DEM layer, all other GIS data of the UOC watershed within the Fort Bend County, including soil and land use/land cover layers, were projected in NAD 1927 UTM zone 15.

Precipitation and temperature data were collected from five rain gauges and two weather stations located within and around the watershed (Figure 1). The five precipitation stations are Sugar Land, Clodine, Richmond, Thompsons 3 WSW, and Katy in Fort Bend County. The weather data were downloaded from the National Climatic Data Center website (NCDC, 2005). Precipitation data from January to July 2003 at the Sugar Land weather station were not available, so precipitation data were estimated with data from an automated weather observing station located at Hull Airport in Sugar Land (NWS, 2005).

The Fort Bend soil data map, which was downloaded from the SSURGO Database of the Natural Resources Conservation Service at the National Cartography and Geospatial Center website (NCGC, 2005), provided detailed soils data. The most common soil types are Brazoria clay, Lake Charles clay, Katy fine sandy loam, Norwood silt loam, and Katy-Waller complex, which collectively comprise about 65% of the watershed's area (Table 1).

The necessary digital land use/land cover data were compiled by Baylor University using satellite imagery from the period of 1996-1997 (Baylor University, 1997). The main land use categories in the watershed are pasture, range, forest, and urban, among which pasture land cover is dominant and accounts for about 56% of total area (Table 2). The urban area occupied about 25% of land cover within the UOC watershed at the time of the satellite imaging.

Municipal wastewater treatment plants (WWTPs) and the Gulf Coast Water Authority pumping of water into and out of the watershed were represented in the model as point sources. There are two Gulf Coast Water Authority operated pumping stations in the UOC watershed. One is the Shannon Pump Station, which is located on the west side of the watershed (Figure 1) and pumps water from the Brazos River into the

TABLE 1. Soil in the Upper Oyster Creek Watershed.

Soil Type and Soil ID. No.	Area (%)
Brazoria clay (TX157Ma)	17.8
Lake Charles clay (TX157La)	16.4
Katy fine sandy loam (TX157Ka)	11.6
Norwood silt loam (TX157Nc)	10.6
Katy-Waller complex (TX157Kc)	8.9
Others	each < 5

TABLE 2. Land Use in Upper Oyster Creek Watershed (1996-1997; Baylor University, 1997).

Land Use	Area (%)
Forest	7.2
Pasture	56.1
Range land	9.5
Residential	10.7
Urban (mixed)	13.3
Water	3.2

system. The other is the Second Lift Station on the east side, through which water is pumped into a canal and carried out of the watershed.

The monthly self-reporting discharges from nine municipal WWTPs (Figure 1) were obtained for the modeling period. The average daily discharge for each month from January through December was calculated for each WWTP using the self-reporting data.

Modification of the SWAT Model

Because SWAT2003 does not have the function to remove daily water out of a reservoir and out of the watershed system, a modification of SWAT2003 was conducted. A new subroutine was created so that a daily amount of water is read and subtracted from the reservoir storage. The subtracted water is removed from the watershed system. This feature was necessary to accommodate the removal of water from UOC at the Second Lift Station.

Creation of Input Data Using AVSWATX

The UOC watershed has relatively flat topography and three small dams located on Oyster Creek. The flat topography made it difficult to proceed with a completely automated process to divide the watershed into the computational sub-basins. To facilitate demarcation of the subwatershed boundaries in this low-relief landscape, information and maps provided by the Fort Bend County Drainage District were utilized to reflect modifications to the natural drainage patterns and UOC watershed boundaries as a result of drainage improvements (David Jalowy and other Fort Bend Drainage District Staff, March 2, 2005, personal communications). A GIS mask was used to prevent the subwatershed boundaries from extending out of the UOC watershed or into the adjacent Brazos River drainage. Broken streams resulting from the low-relief as represented in the DEM were manually connected. The subwatersheds were delineated by superimposing the fixed stream onto the DEM and using the mask. The boundaries on the northeast part of the delineated watershed were modified based on the digitized drawing of the drainage area, which was spatially registered into ArcView using Smartimage image manipulation software for ArcView.

The locations of monitoring stations from water sampling surveys were primarily used to determine the number of sub-basins, resulting in 24 sub-basins for the watershed (Figure 1). The three dams were treated as three reservoirs (Figure 1) as they were constructed along the main channel. The multiple hydrologic response units (HRUs) feature within SWAT was selected at a threshold level of 1% for land use and 10% for soil, which produced a total of 332 HRUs.

Calibration of SWAT2003 for Streamflow

Model Calibration Methodology. SWAT was calibrated to the periodic streamflow measurements of year 2004 and then validated to those of years 2003-2002 from eight stations (Figure 1). Note that the time periods of the calibration and validation can be exchanged in the studied case because both time periods involved wet-dry season flow data.

In the calibration of streamflow, the two key adjustment parameters were *esco* (a soil evaporation compensation coefficient) and *cn2* (condition II runoff curve number). The main groundwater parameters describing water movement, such as *gwqmn* (threshold depth of water in the shallow aquifer required for return flow to occur), *gw_revap* (the coefficient of ground water moving to an adjacent unsaturated zone), and *alpha_bf* (base-flow alpha factor) were adjusted when predicted base flow or total water balance deviated from measured values. The other calibrated parameter used in this study was *surlag* (surface runoff lag time), which influences flow peak calibration. The ranges of adjusted parameters suggested for use in SWAT2003 and the calibrated values of the adjusted parameters used for flow calibration for UOC are listed in Table 3.

TABLE 3. Calibrated Values of Adjusted SWAT2003 Input Parameters.

Parameter	Description	Suggested Range	Calibrated Value
esco	Soil evaporation compensation factor	0.2 to 1.0	0.92
*cn*2	Initial SCS runoff curve number for moisture condition II	30 to 100	49 to 92
gwqmn	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	-	50
gw_revap	Coefficient of groundwater moving to an adjacent unsaturated zone	0.02 to 0.2	0.05 to 0.2
alpha_bf	Base-flow alpha factor (days)	0.0 to 1.0	0.148 to 0.748
surlag	Surface runoff lag coefficient	1 to 12	4

Note: SWAT, Soil and Water Assessment Tool.

Evaluation of Model Performance. Several indicators were used in this study to evaluate the performance of SWAT in predicting daily flows. These include: (1) graphical comparisons, (2) parametric and nonparametric tests of means or medians, and (3) traditionally applied goodness-of-fit indicators.

After initial graphical comparisons were made, the Nash-Sutcliffe model efficiency (*NSE*) (Nash and Sutcliffe, 1970) was employed for evaluation of model performance during the calibration and validation phases. *NSE* was calculated as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2}, \qquad (1)$$

where P_i are predicted values, O_i are measured values, $\bar{O}$ is an average measured value, and n is the number of predicted/measured values. *NSE* ranges from $-\infty$ to 1. A value of $NSE = 1.0$ indicates that the pattern of model estimation perfectly matches the measured data. The farther away from 1 the *NSE* value becomes, the larger the error in the predicted pattern when compared with the measurements. Based on the past studies of environmental model applications (Moriasi *et al.*, 2007), an *NSE* value of greater than 0.50 and mean relative error (*MRE*) value of less than 25% are considered numeric ratings for satisfactory model performance in this study. Based on the overly sensitive nature of *NSE* to extreme values (Legates and McCabe, 1999) and our experience that this indicator should be used with caution when the number of data points is small, *NSE* was applied to the model calibration and validation data across all stations and not for individual stations.

Because there were multiple flow and water quality monitoring sites in UOC (as in many TMDL studies), SWAT estimation of flow at each site needed to be assessed. Either a parametric (paired *t*-test) or a nonparametric (sign test) statistic was applied to evaluate the difference between the means or medians of measured *vs*. predicted flows depending upon normality of the distribution of the streamflow at each of the eight monitored stations. An *a priori* $\alpha = 0.05$ probability level was used to test for statistical significance of paired *t*-test or sign test. A normality test of the distribution of flow data were performed using the Shapiro-Wilk test. If the distributions were normal, the paired *t*-test was applied, otherwise the sign test was applied. The results of statistical computations were obtained by applying the Univariate procedure in SAS Institute (1999).

The traditionally applied model goodness-of-fit indicator, the *MRE* was applied to all evaluation procedures. *MRE*, defined as relative error or % bias between predicted and measured values, was computed as

$$MRE = \frac{\sum_{i=1}^{n} (P_i - O_i)}{\sum_{i=1}^{n} O_i}, \qquad (2)$$

where *MRE* is the mean relative error, O_i are measured values, P_i are predicted values, and n is the number of predicted/measured values. A value of $MRE = 0$ indicates that the predicted total amount of flow equals the measured value.

RESULTS AND DISCUSSION

Both tributary and main stem daily flows simulated by SWAT were compared with measured flows in the UOC watershed with graphical and statistical techniques, as recommended by Legates and McCabe (1999) and Moriasi *et al.* (2007).

Model Calibration and Validation

The graphical comparison (Figure 2a) of SWAT-predicted flows to measured ones for the calibration phase depicted that most of flow estimates were close to measurements though some overestimations or underestimations were observed. It is also apparent that the model reasonably predicted the trends of high and low flows. The *NSE* and *MRE* values of daily flow estimations of the calibration phase were 0.66 and 15%, respectively, indicating that the model was relatively well calibrated for daily flow. A similar result was achieved in the validation phase (Figure 2b). Reasonable agreement was attained between the predicted and measured high and low flows, but overestimations or underestimation did occur on some days. The *NSE* of 0.56 and the *MRE* of 4% indicated that SWAT could rather reliably predict continuous daily flow for the UOC watershed even if the model was calibrated against sparse measured flow data. The good agreement between flow predictions and measurements is also reflected in their standard deviation (SD) values (Table 4).

Model Simulation of Flows at Three Tributary Stations

The graphics of the flow simulations in three tributary stations are Figures 3a-c and the statistical results are provided in Table 5.

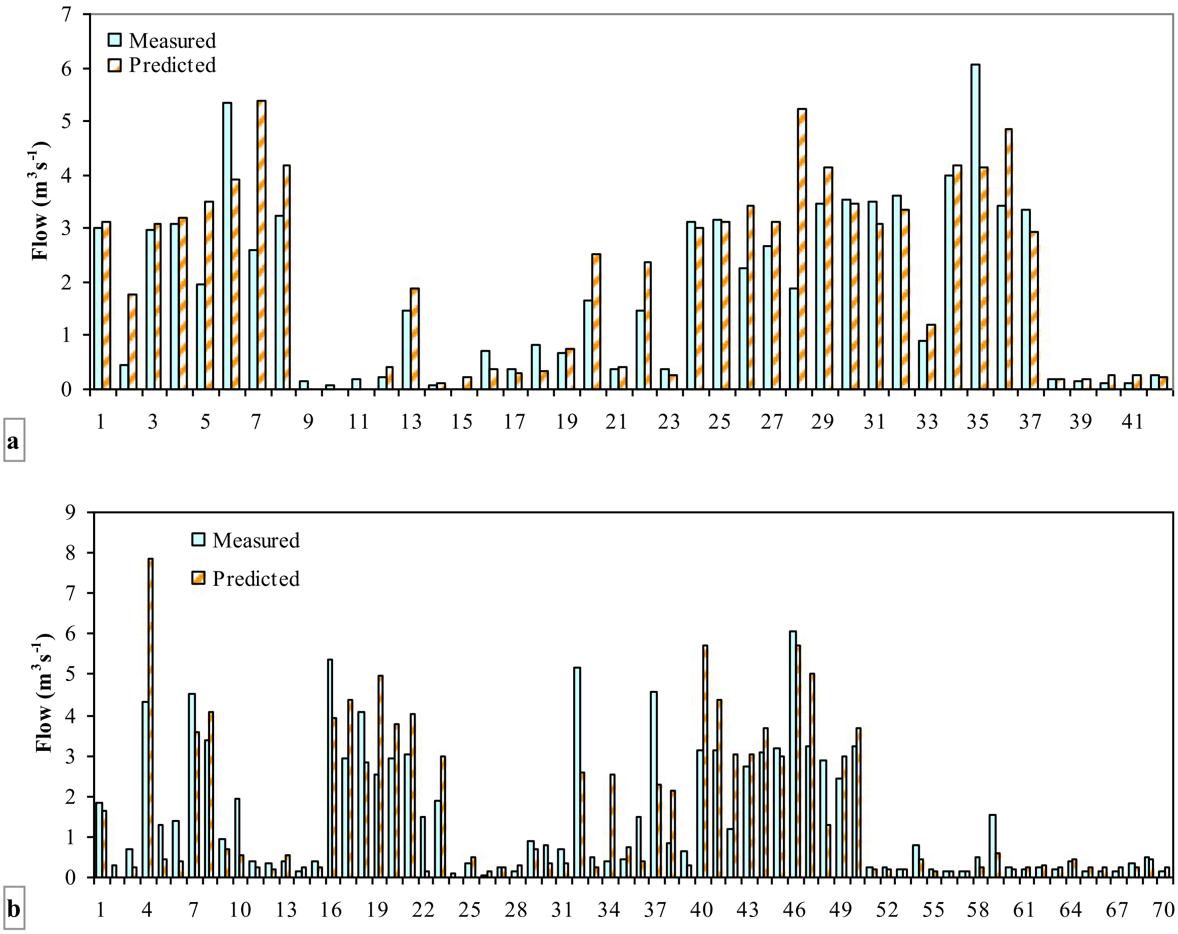

FIGURE 2. Measured *vs*. Predicted Daily Flows for Calibration (year 2004) (a) and Validation (2002-2003) (b).

TABLE 4. Statistics of the Calibration/Validation of the UOC SWAT Model (flow in m^3 s^{-1}).

	Flow Data	Mean	SD	*MRE* (%)	*NSE*
Calibration	Measured	1.84	1.62		
	Predicted	2.11	1.73	15	0.66
Validation	Measured	1.50	1.56		
	Predicted	1.56	1.84	4	0.56

Notes: *MRE*, mean relative error; *NSE*, Nash-Sutcliffe model efficiency; SD, standard deviation; SWAT, Soil and Water Assessment Tool; UOC, Upper Oyster Creek.

Tributary Station 17686 on the downstream end of Flewellen Creek is located toward the upstream end or western edge of the system. The graphic result (Figure 3a) illustrates that most predicted flows were close to measured flows. The average flows of measured and predicted were 0.46 and 0.42 m^3/s, respectively, which are not significantly different based on the paired *t*-test with a $p = 0.632$ (Table 5). The *MRE* value of −0.10 indicates an overall 10% underestimation. Based on these indicators, SWAT was considered to provide good estimates of flow for Station 17686.

Tributary Station 17688 is located near the downstream end of another major tributary to the Oyster Creek system, Stafford Run. Figure 3b shows that most of the flow estimations were well matched to the measurements, though substantial deviations occurred for the two largest flows. As the data were not normally distributed according to the Shapiro-Wilk test ($\alpha = 0.05$), the sign test was applied and indicated that median predicted flow was significantly different from the measured flow (Table 5). The model underestimated flow by 46% according to the *MRE*. These results indicate unsatisfactory model performance at this site.

Tributary Station 17689 is located on Steep Bank Creek in the southeast portion of the watershed. Figure 3c illustrates that most flow estimations were good. The paired *t*-test (Table 5) indicated that predicted mean streamflow was significantly different from measured values. However, the *MRE* value of 23% (<25%) indicated relatively small overestimation of streamflow.

In these comparisons, it is important to note that flows were relatively small (<13% of the highest

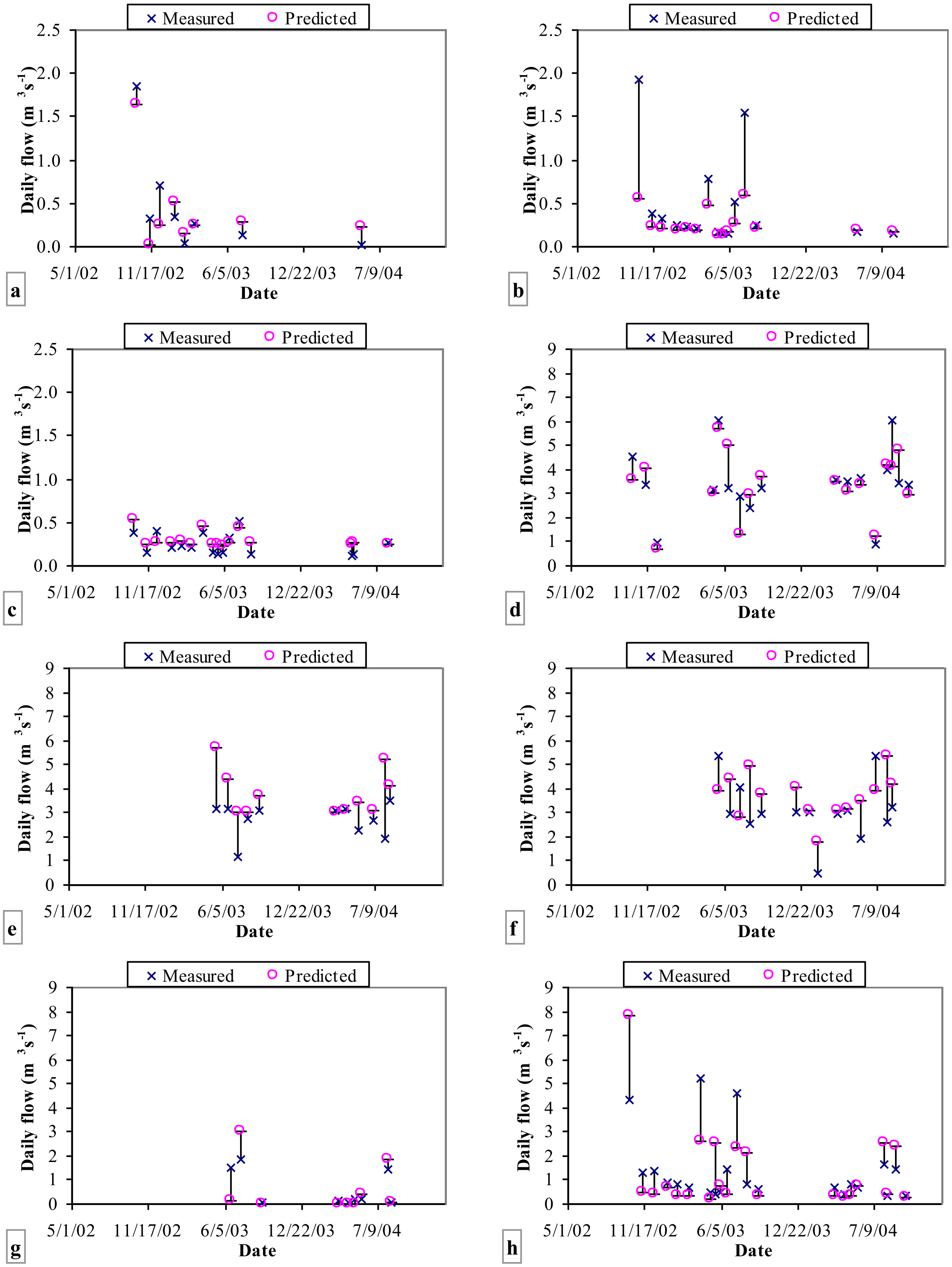

FIGURE 3. Measured *vs*. Predicted Daily Flows at Eight Stations [17686 (a), 17688 (b), 17689 (c), 12090 (d), 12087 (e), 12086 (f), 12077 (g), and 12074 (h)].

mean flow of the main stream). We found that the model generally simulated large flows better than small flows on a relative basis, but the absolute magnitude of differences in large events can adversely impact flow estimation results. When streamflow magnitude in a watershed ranges from very small to

TABLE 5. Comparison of Measured *vs*. Predicted Daily Flows (m^3/s) at the Tributary and Main Stem Stations.

Station	Flow Data	Mean (m^3/s)	SD (m^3/s)	*p*-Value Normality Test	*p*-Value Paired *t*-Test	*p*-Value Sign Test	*MRE*	*RMSE*
17686	Measured	0.46	0.26					
	Predicted	0.42	0.12	0.229	0.632	-	−0.10	0.24
17688	Measured	0.48	0.39					
	Predicted	0.26	0.14	<0.0001	-	0.035	−0.46	0.45
17689	Measured	0.24	0.12					
	Predicted	0.30	0.07	0.0624	0.020	-	0.23	0.1
12090	Measured	3.43	1.42					
	Predicted	3.37	1.42	0.744	0.804	-	−0.02	0.91
12087	Measured	2.72	0.73					
	Predicted	3.81	0.75	0.215	0.009	-	0.40	1.61
12086	Measured	3.11	1.16					
	Predicted	3.71	0.96	0.395	0.114	-	0.19	1.52
12077	Measured	0.63	0.50					
	Predicted	0.62	0.69	0.181	0.982	-	−0.01	0.61
12074	Measured	1.36	1.32					
	Predicted	1.31	0.95	<0.0001	-	0.286	−0.04	1.28

Note: *MRE*, mean relative error; RMSE, root mean squared error; SD, standard deviation.

very large and SWAT is calibrated to fit the overall streamflow, the model produces greater errors in stream segments with smaller flows. This could be one reason for the failure of the simulation of the small tributary flows.

Model Simulation of Flows at Five Main Stem Stations

Main stem Station 12090 is the most upstream monitoring site close to the watershed headwater (Figure 1). Figure 3d illustrates that predicted flows corresponded well with measured values for both high and low flows. The predicted and measured mean flows were not significantly different (Table 5). The *MRE* value (−2%) was low relative to the measured mean, which also indicated good flow estimations for this site.

Station 12087 is located in the middle of the UOC watershed and upstream of the three dams (Figure 1). Figure 3e illustrates substantial overestimations for numbers of flows. The reasons for the overestimation of the flows could be improper representation of the relatively complex hydrologic flood control measures. When water levels were sufficiently high to cause potential flooding downstream, a portion of water was diverted out of the watershed at an upstream location (Point A of Figure 1). This flood control process was only roughly represented by the model. These overestimations resulted in significant differences in measured and predicted means (Table 5). SWAT overestimated flow 40% according to the *MRE*. Overall, the results indicate unsatisfactory model performance at Station 12087.

Station 12086 is located on Oyster Creek downstream of Station 12087 and upstream of Dam #1. The *MRE* was 19%, which indicated rather small errors of average flow estimation. As indicated in Figure 3f, predicted streamflows were at times higher than measured flows, but most were within measurement uncertainty boundaries. Similar to Station 12087, the overestimation was most prominent during the August 2004 storms. Average predicted flow was not significantly different from the measured average due to the low *p*-value (Table 5). Thus, overall model performance was satisfactory for this station.

Station 12077 is located below Dam #3 (Figure 1). The Second Lift Station pumps from the pool of Dam #3, and the pumping at this location removes large amounts of water from Oyster Creek resulting in a sharp plunge of streamflows at Station 12077. The comparisons of predicted and measured flows in Figure 3g illustrate adequate results for low flows but overestimations and underestimations on large flows. The paired *t*-test indicated that the average flow (0.62 m^3/s) predicted by the model was similar to the measured one (0.63 m^3/s) at Station 12077, and the *MRE* value was only −1% (Table 5). Therefore, model performance was satisfactory at 12077.

Station 12074 is located in the eastern portion of watershed on Flat Bank Creek, which is close to the watershed outlet and the downstream continuation of Oyster Creek. Similar to the flow simulation at Station 12077, the average predicted flow on this site was not statistically different from the measured data (sign test, $p = 0.286$) at a small *MRE* value of −0.04 (Table 5). Figure 3h demonstrates that SWAT accurately predicted low flow but either overpredicted or underpredicted large flows. These

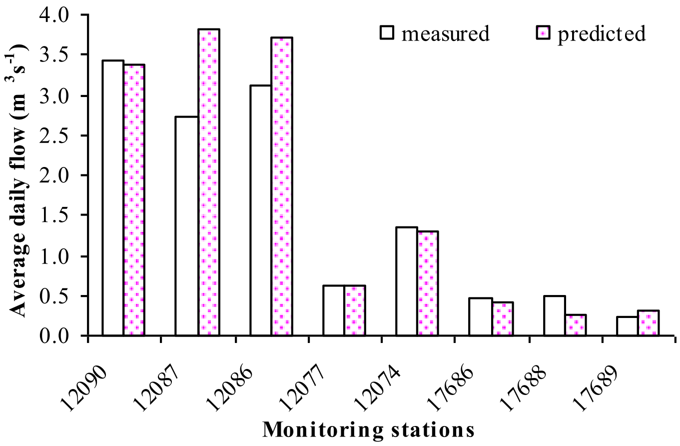

FIGURE 4. Spatial Pattern Comparison of the Measured *vs*. Predicted Flows of the Period 2002-2004 in UOC.

results indicate satisfactory model performance at this site.

Spatial Pattern of Daily Flow Estimations

As shown on Figure 1, the eight monitored stations used in model calibration are distributed across most of the watershed area. This distribution of stations provides means to further verify the accuracy of the flow simulation in terms of the characteristics of the spatial distribution of flows. The average daily streamflow data of the years 2002-2004 at each of all the eight stations were calculated to evaluate overall performance of the flow simulation by SWAT. Figure 4 demonstrated that the spatial pattern of the predicted flows reasonably matched that of the measured flows, including substantial decline of both measured and predicted average flows in downstream after Station 12086 and to Station 12077 due to water pumping out of the watershed system from Dam #3, and the sudden increase when it came to Stations 12074 because of inflows from the tributary Stafford Run and two WWTPs.

CONCLUSIONS

The SWAT2003 hydrologic model of the UOC watershed was calibrated and validated against a limited number of flow measurements of the years 2002-2004. The *NSE* and *MRE* values of daily flow estimations are 0.66 and 15% for calibration, and 0.56 and 4% for validation, respectively. These results indicate that the SWAT estimations of daily flow had a reasonable agreement to the measured data. Further, parametric paired *t*-test and nonparametric sign tests at a 95% confidence level were employed to evaluate model estimation of flow at each of all eight monitoring stations. Among the five main stem stations, four stations were statistically tested with a good agreement between predicted and measured flows. SWAT underestimated the flow of the 5th main stem station possibly because of the existence of complex flood control measures upstream of the station. SWAT estimated the daily flow at one tributary station very well, but with relatively large errors for the other two tributaries. As a result of the evaluation by graphical techniques and statistical tests, SWAT was properly responsive to hydrologic forcing (e.g., rainfall, WWTP discharges, and Gulf Coast Water Authority pumping rates) and capable of providing reasonable simulated daily streamflow data, though some events were poorly represented. Similarly, the spatial pattern of predicted flows matched the measured ones, which indicated that SWAT adequately represented watershed processes and anthropogenic withdrawals and inputs.

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