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Storm Event and Continuous Modeling of an Illinois Watershed to Evaluate Surface Water Supplies

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Abstract. *Based on recent reviews of leading watershed-scale hydrologic and nonpoint-source pollution models, the long-term continuous model SWAT was selected to enhance with storm event simulation algorithms from a storm event model. It will be used as a source-water protection and assessment tool for small public water supply systems. This enhanced SWAT will simulate hydrology, soil erosion, and transport of sediment and agrochemicals during storm events with short time intervals (minutes or hours) to capture rapid changes, especially during severe events causing most of the environmental damages, in addition to long-term simulations with longer time intervals (days, months, and years) while studying long-term impacts. The 8,400 km^2 Little Wabash River watershed in Illinois was selected for this study because of its favorable small drinking water supplies and watershed attributes. Using multi-year period (1995-2002) of observed precipitation, stream flow, and concentrations of sediment and water quality data, the continuous model is being calibrated and validated. Established statistical indicators (coefficient of determination and Nash-Sutcliffe coefficient) are used to measure and improve model predictions. Using storm event rainfall and flow data at smaller (15 minute) time intervals, the storm event hydrologic model is also being calibrated and validated. The calibrated and validated model will be used for both long-term and storm event water quantity and quality evaluations throughout the watershed, including at intakes of small public water supply systems under existing and alternative land use and management practices. Flow calibration results at an upstream station reveal that the storm event hydrology model with less parameter predicts more accurate flows, especially peak flows, than the continuous daily model.*

Keywords. Continuous model, hydrology, storm event model, SWAT, water supply.

Introduction

Water quantity and quality at surface water supply intakes are of serious concern nationwide. Land degradation is widespread and many of the nation's surface waters are categorized as impaired (303d lists) by nonpoint pollution. In the Mississippi River watershed, nonpoint-source pollution from agriculture is the most widespread source of impairment. Agriculture in Illinois has been identified as a particularly severe offender (Doering et al., 1999). Many Midwestern U.S. streams and rivers draining agricultural watersheds have elevated concentrations of nitrate-nitrogen (NO_3-N) which also drain into the Gulf of Mexico (Goolsby et al., 1999). In Illinois, some drinking water supplies suffer from high concentrations of sediment as well as concentrations of NO_3-N and other agriculturally-related chemicals that exceed health standards (e.g., Keefer et al., 1996; Mitchell et al., 2000; Borah et al., 2003). And the sediment problem is so severe as to also seriously reduce the water supply capacities of Illinois' lakes and reservoirs (e.g, Fitzpatrick et al., 1985, 1987).

Various studies have focused on characterization and assessments of public water supplies, e.g., Warner (2000), Eimers et al. (2000), and Delaware Division of Water Resources (2002), numerous others on characterization of water quantities and qualities in watersheds through field monitoring at specific locations (stations), as reviewed in Borah et al. (2003). Many modeling studies are mostly involved with calibration and validation of models on monitored watersheds with a few evaluating management strategies, as reviewed in Borah and Bera (2004). However, there exists no research on evaluation of water quantity and quality at surface water supply intakes and development of comprehensive watershed modeling tools to do so.

No leading watershed model is capable of simulating all of the hydrologic, upland soil and stream bank erosion, sediment transport, and fate and transport of nutrients and pesticides processes that are necessary to comprehensively assess the water quality and quantity problems and help make best management decisions to minimize them (Borah and Bera, 2003, 2004). However, it was found that the USDA's watershed-scale long-term continuous simulation model SWAT, the Soil and Water Assessment Tool (Arnold et al., 1998; Neitsch et al., 2002) – which is also part of USEPA's BASINS, Better Assessment Science Integrating Point and Nonpoint Sources (Luzio et al., 2002) – is the most promising watershed model for enhancement into the desired comprehensive model (Borah and Bera, 2003, 2004). Other studies (Van Liew et al., 2003; Saleh and Du, 2004) support these findings. SWAT is an operational or conceptual model used for predicting and assessing long-term impacts of management of water, sediment, and agricultural chemical yields in large watersheds or river basins. It simulates hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management.

The major shortcoming of SWAT is that it is mainly a daily time step model and was not initially formulated to simulate storm events (Arnold et al., 1998). As summarized from many investigations documented in the literature (Borah and Bera, 2004), the SWAT long-term continuous model is reliable for yearly and monthly (average) predictions, except for the months having severe hydrologic conditions (storms). Daily predictions are generally less reliable, especially for the days having intense storms. A storm event simulation option was added to the model with sub-daily time steps (King et al., 1999) using the Green and Ampt (1911) infiltration equation. This option has not been widely used and one of the reasons could be its requirement of intensive soil test data for parameterization (King et al., 1999).

Resolution of precipitation data input is becoming another concern in watershed modeling. Precipitation is a major driving force of watershed processes and is often highly variable on spatial and temporal scales. Current watershed models, including the SWAT, are unable to capture accurately the distributions because of limited resolution of precipitation data inputs from discrete, and usually sparse, raingages. On the other hand, recent availability of the NOAA multi-sensor (radar plus gauge) hourly 4-km precipitation analysis and progress in mesoscale regional climate model (RCM) simulations (Liang et al., 2004) brings an unprecedented opportunity to substantially enhance the temporal and spatial resolutions of watershed model precipitation input.

Principal enhancements needed for the development of an enhanced, comprehensive SWAT are: better and additional routines to simulate storm events and stream bank erosion as well as to incorporate high resolution precipitation data such as the recently available NOAA near real-time multi-sensor data and mesoscale RCM simulations (Liang et al., 2004). These enhancements are needed to accurately simulate intense storm events, which are critical in generating and transporting disproportionately large amounts of sediment and chemicals.

The objectives of this study are to enhance the long-term continuous model SWAT with better storm event simulation algorithms, apply the enhanced SWAT to a major watershed in Illinois having small public water supply systems using surface waters, use it to assess water quantities and qualities at the surface water supply intakes, and evaluate various management scenarios. The work presented in this paper includes application of the SWAT to the 8,400-km^2 Little Wabash River watershed in southeastern Illinois having seven small and three large public water supply systems using surface waters and investigation of its enhancement with storm event hydrologic simulations (Borah et al., 2002, 2004). Calibrated flow results at an upstream station from both the continuous SWAT and storm event model are presented and discussed. Further SWAT enhancement investigations and use of the model to assess and evaluate various management scenarios to maintain and/or enhance water quantities and qualities at the surface water supply intakes are in progress.

Little Wabash River Watershed

The 8,400-km^2 Little Wabash River Watershed (Figure 1), located in the southeastern Illinois, consists of 2 USGS 8-digit watersheds: watersheds of the main-stem Little Wabash River (HUC No. 05120114) and the Skillet Fork River (HUC No. 05120115). For Illinois, the Little Wabash River watershed has a relatively high density of public intrastate surface water supplies. There are seven small (population < 10,000) Altamont, Clay City, Fairfield, Flora, Neoga, Olney, and Wayne City and three large public surface water supply systems: Effingham (18,065), Mattoon (19,787), and the Rend Lake Intercity Water Systems (110,778), serving communities in the watershed. All but the last system are located within the watershed drawing its waters.

The Little Wabash River is a principal tributary of the Wabash River; the latter is the largest source of NO_3-N to the Ohio River (Goolsby et al., 1999). Virtually every major stream and river mile of the Little Wabash River watershed has impairment from sediment, nutrient enrichment, and other agricultural chemicals (IEPA, 2004). All of the water supply sources have detectable levels of atrazine, a commonly used herbicide, but few exceed the maximum allowable concentration of 1 part per billion (USGS and IEPA, 2003).

The developmental history of the Little Wabash River watershed shows that watershed growth was retarded by the low level of water resources development (State Water Survey Staff, 1948; Barker et al., 1967; U.S. Army Corps of Engineers, 1979) – resulting in a very rural and sparsely populated agricultural watershed, the least developed major watershed in Illinois (IDNR, 2001). The uniquely favorable combination of natural and human setting conspire to make the Little Wabash River a watershed favorable for developing the enhanced SWAT model and for researching non-point water quality and quantity issues that are of strong regional, state, national, and international interests.

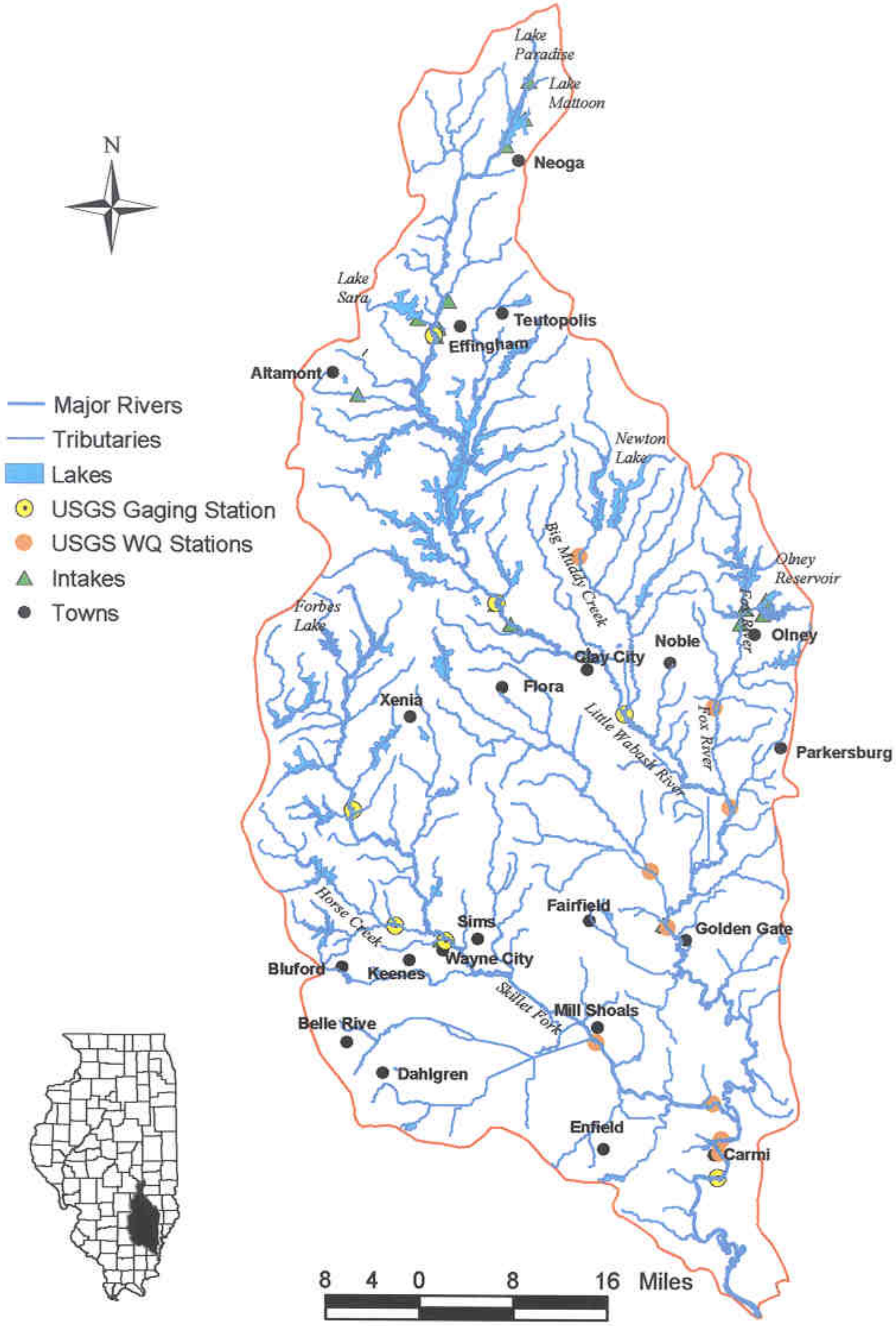

Figure 1. Little Wabash River Watershed in Illinois (1 mile = 1.609 km).

Daily rainfall data are available at thirteen National Weather Service (NWS) stations in and around the watershed: Effingham, Carmi, Fairfield, Flora, Iuka, Louisville, Mattoon, Olney, Wayne City, Clay City, Newton, Salem, and Mt. Vernon. Fifteen-minute interval rainfall data are available at three of these stations: Effingham, Flora, and Carmi. Out of seven USGS continuous-discharge measuring gauging stations, four are currently active: Effingham, Clay City, Wayne City, and Carmi (Figure 1). The seven USGS discharge measurement stations were also used to measure water quality parameters. In addition to these, there are nine IEPA ambient water quality monitoring stations (AWQMN) in the watershed where water quality parameters have been monitored and analyzed periodically (e.g., Hite et al., 1993; Shasteen et al., 2002; 2003). The IEPA (2003), in cooperation with the IDNR, conducted an intensive survey of the Little Wabash and Lower Wabash River basins collecting water quality data.

SWAT Application to Little Wabash River Watershed

The SWAT was applied to the Little Wabash River watershed. Geographic Information System (GIS) data on topography, soil, and land use for the two USGS 8-digit watersheds in the Little Wabash River watershed were retrieved from the USEPA's BASINS database at http://www.epa.gov/OST/BASINS/. These data are used to define watershed and sub-watershed boundaries, compute their dimensions and representative slopes, and estimate various model parameters. The watershed was divided into 88 sub-watersheds. The model groups these sub-watersheds based on climate, hydrologic response units (HRU), ponds, ground waters, and main channels. HRUs are lumped land areas within the subbasin which are comprised of unique land cover, soil, and management combinations with uniform parameter values. Parameter values were started with the suggested default values given by the model based on literature data and adjusted during model calibration to best match the simulated values with the observed data. Daily precipitation and air temperature data at the thirteen precipitation gages were obtained from the Midwest Climate Center. Based on availability of data, a five-year period (1995-1999) was chosen to calibrate the model and a three-year period (2000-2002) was chosen to validate it. Observed stream flow records are available at four gaging stations: the Little Wabash River near Effingham (drainage area 620 km^2), below Clay City (2,930 km^2), at Carmi (8,000 km^2) near the watershed's outflow, and at Wayne City (1,200 km^2) on the Skillet Fork (Figure 1).

While calibrating the model for runoff and stream flow simulations, adjustments were made to the calibration parameters for the sub-watersheds contributing to a gaging station, including SCS runoff curve number (CN2), soil evaporation compensation factor (ESCO), plant uptake compensation factor (EPCO), threshold water level in shallow aquifer for base flow (GWQMN), threshold water level in shallow aquifer for re-evaporation and/or deep percolation (REVAPMN), groundwater re-evaporation coefficient (GW_REVAP), groundwater delay (GW_DELAY), baseflow recession constant (ALPHA_BF), and deep aquifer percolation fraction (RCHRG_DP). Once calibrated, parameters for upstream sub-watersheds were kept the same while adjusting those on further downstream sub-watersheds based on downstream flows.

Figure 2 shows monthly (average) simulated and observed stream flows on the Little Wabash River near Effingham for both the calibration and validation periods (1995-2002). Calibration during the first five years (1995-1999) resulted in the highest combined (cumulative) coefficient of determination (COD or r^2) of 0.61 and Nash-Sutcliffe coefficient (NSC, Nash and Sutcliffe, 1970) of 0.53 (Figure 3b) showing satisfactory model performances (Van Liew et al., 2003). For the entire calibration and validation period (1995-2002), the COD and NSC improved slightly to 0.64 and 0.56, respectively. As shown in Figure 3a, the model performed very well for certain years, e.g., 2002 with COD and NSC of 0.91 and 0.81, respectively, and poorly for a few years, e.g, 2001 with COD and NSC of 0.10 and -0.08, respectively.

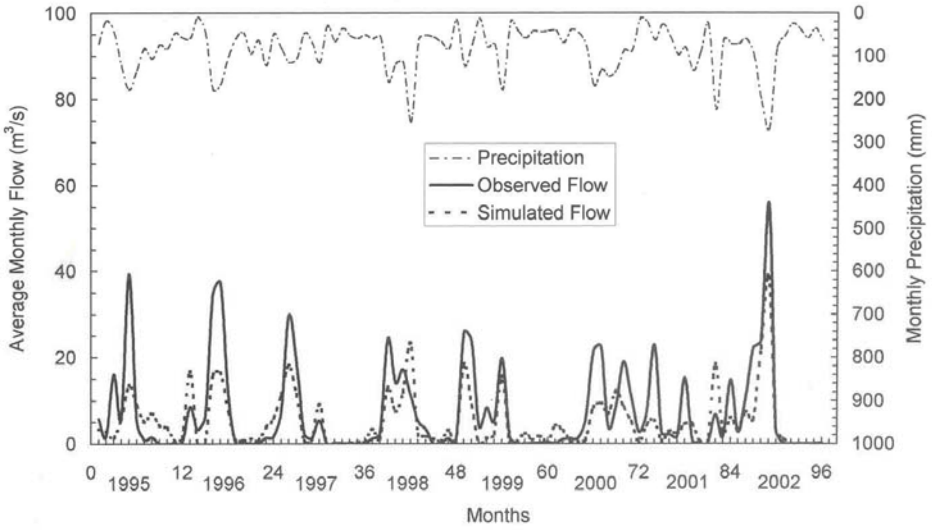

Figure 2. Monthly flows and precipitation on the Little Wabash River near Effingham.

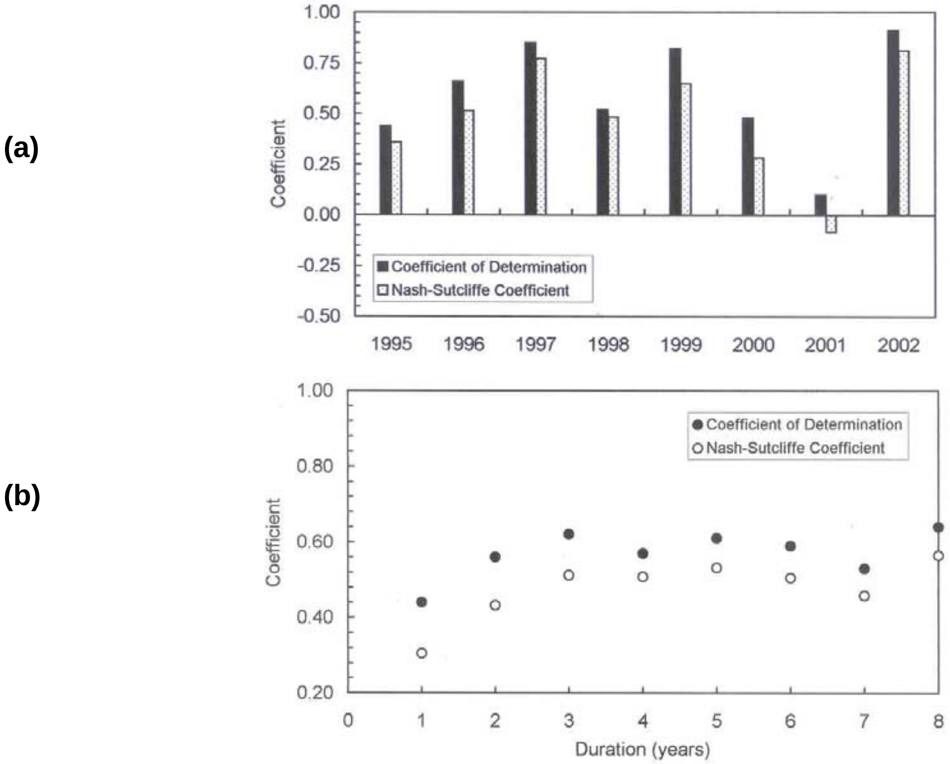

Figure 3. Comparative parameters for simulated and observed flows in figure 2 for: (a) Individual years and (b) Cumulative years (duration).

Although the overall statistics on comparisons of the simulated and observed flows were reasonable (Figure 3), the model substantially under predicted most of the monthly peak flows (Figure 2). Among many other reasons, the discrepancies may be due to spatial variations of rainfall and not enough raingages to accurately capture the variations.

Storm Event Hydrologic Model for SWAT Enhancement

Storm events are critical in generating and carrying much, if not most, of yearly sediment and chemical loads. In recent reviews of eleven leading watershed-scale hydrologic and nonpoint-source pollution models having long-term continuous and/or storm event simulation capabilities (Borah and Bera, 2003, 2004), it was shown that the storm event modeling procedures described by Borah et al. (2002, 2004) are robust and effective for analyzing impacts of storm events, including severe actual or design single-event storms, on watershed management practices. The model simulates spatially and temporally varying (distributed: small time steps) surface and subsurface storm water runoff, propagation of flood waves, upland soil and streambed erosion, sediment transport, and agrochemical transport in agricultural and suburban watersheds from spatially and temporally varying rainfall inputs resulting from rainfall events. The work presented here involves only the hydrologic procedures (model) and their applications to the Little Wabash River watershed.

In this storm event model (Borah et al., 2002, 2004), rates of infiltration and rainfall excess are calculated using one of the two alternative procedures: an extension of the SCS (1972) runoff curve number method (Borah, 1989) or a detailed procedure considering interception (Simons et al., 1975) and infiltration (Smith and Parlange, 1978) losses, as described in Borah et al. (2002). In this study, the SCS runoff curve number extension is used. The excess rainfall is routed over overland planes and through channel segments using analytical and approximate shock fitting solutions (Borah et al., 1980; Borah, 1989) of the kinematic wave equations (Lighthill and Whitham, 1955). Combined subsurface flow ─ including interflow, tile drain flow, and base flow ─ is computed using a modification to the Sloan et al. (1983) kinematic storage equation and using the spatially uniform and temporally varying continuity equation (Borah et al., 2004). Water through a reservoir unit is routed using the storage indication or modified Puls method (U.S. Bureau of Reclamation 1949), as described in Hjelmfelt and Cassidy (1975).

Storm Event Hydrologic Modeling of Little Wabash River Watershed

Each of the 88 sub-watersheds were further subdivided into two overland planes and one channel segment ─ totaling 176 overland planes and 88 channel segments in the watershed. Areas, lengths, widths, and representative slopes of the overland planes, and channel segments were computed using the same BASINS GIS data as used in SWAT. Channel widths and depths given by these GIS data were used to develop relationships of wetted perimeters versus cross sectional areas. Fifteen-minute precipitation data from three gages – Effingham, Carmi, and Flora (Figure 1) – were taken from the NWS. Fifteen-minute flow data at the four stream gaging stations were obtained from the USGS. A major storm occurred in the middle of May 1995 was used to verify the model. The key model parameters: SCS runoff curve number, lateral saturated hydraulic conductivity, and Manning's roughness coefficients for overland planes and channel segments were taken from the SWAT calibrated values. Figure 4 shows comparisons of observed and simulated hydrographs along with daily rainfall and 15-minute intensity data from May 1 to June 5, 1995. In addition to the major storm event during days 15-20, as shown in Figure 4, there were smaller events before and after, which were also simulated. Figure 4 shows comparisons of observed daily flows with SWAT daily flow simulations on the Little Wabash River near Effingham in addition to the comparisons of observed 15-minute flows with 15-minute storm event flow simulations. Table 1 gives the simulated and observed peak flows, time to peak flows, runoff volumes, and percent differences (errors) of the respective observed and simulated values.

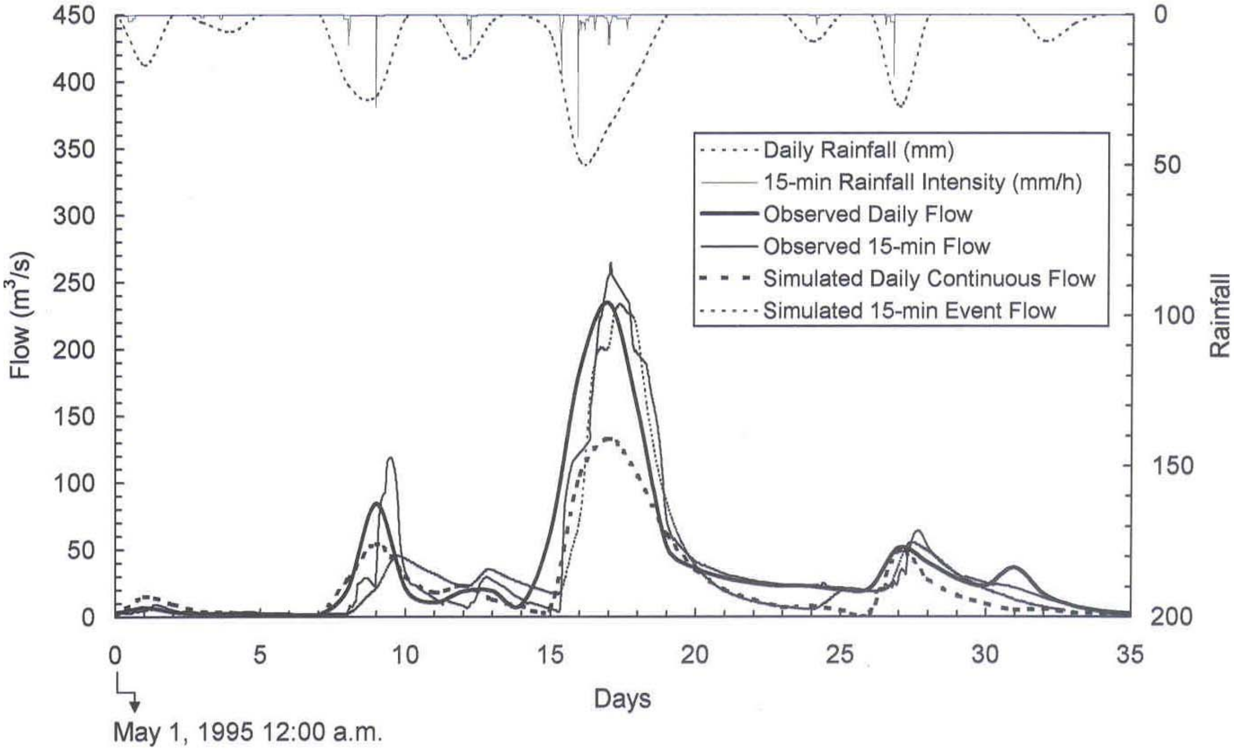

Figure 4. Observed and simulated continuous daily and 15-min event flows on the Little Wabash River near Effingham.

Table 1. Comparisons of observed and simulated continuous daily and 15-minute event peak flows, time to peaks, and runoff volumes on the Little Wabash River near Effingham.

	Continuous Daily Simulation			Event 15-Min Simulation		
Parameter	Simulated	Observed	% Error	Simulated	Observed	% Error
Peak flow (m^3/s)	133	234	43	234	264	11
Time to peak flow (days)	17	17	0	17.38	17.05	2
Runoff volume (ha-m)	7,232	11,142	35	9,376	7,684	22

As shown in Figure 4 and Table 1, the storm event model predicted the peak flow and runoff volume for the simulation period better than the continuous model with daily time steps. The storm event model results are more detailed than the continuous daily results. It shows the precise time of arrival of the peak flow – 15 minute resolution in this case. In this application (Figure 4), the storm event simulations predicted the intense-storm high flows (Days 15-20), much better than the daily continuous simulations. The storm event simulated peak flow 234 m^3/s has a deviation of 11 percent from its observed value (264 m^3/s). The simulated daily peak flow from the continuous model (133 m^3/s) is 43 percent under predicted from the observed daily peak flow of 234 m^3/s, which is actually 50 percent less than the 15-minute observed peak flow of 264 m^3/s, a more realistic peak flow to be concerned with for flood warning, protection, or prevention.

Conclusions

Recent reviews of leading watershed-scale hydrologic and nonpoint-source pollution models found that the SWAT watershed-scale long-term continuous simulation model is the most promising watershed model for enhancement into a comprehensive model to be used as a source-water protection and assessment tool for small public water supply systems using surface waters.

The storm event model described here would enhance SWAT's hydrologic simulations as it showed promise when applied to the Little Wabash River watershed in Illinois. Calibration results at an upstream station (Effingham, 620 km^2) showed that the storm event model predicted the high flows including the peak and runoff volume for a period of 35 days having a major rainfall event and few smaller events better than the existing SWAT continuous model with daily time steps.

Comparisons of observed and SWAT monthly flows for a period of 8 years showed variable results – model performing very well for some years giving coefficient of determination (COD) and Nash-Sutcliffe coefficient (NSC) values up to 0.91 and 0.81, respectively, and performing poorly for a few other years giving COD and NSC as low as 0.10 and -0.08, respectively. Among many other reasons, inadequate spatial distribution of rainfall data could be a major factor of poor performances of SWAT for certain years.

Further adjustment or calibration of model parameters are necessary for better model predictions, which are currently in progress along with further investigations of SWAT enhancements with storm event erosion, sediment transport and water quality simulations and applications of the model to the Little Wabash River watershed for both long-term and storm event water quantity and quality evaluations throughout the watershed, including at intakes of small public water supply systems under existing and alternative land use and management practices.

SWAT enhancement work will involve developing proper procedures for converting SWAT's existing sub-basins and HRUs into overland and channels flow segmentation scheme required by the storm event simulations.

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