STORM EVENT FLOW AND SEDIMENT SIMULATIONS IN AGRICULTURAL WATERSHEDS USING DWSM

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ABSTRACT. *DWSM, the dynamic watershed simulation model, was expanded with a subsurface and a reservoir flow routing schemes. The hydrology and sediment components of the model were applied to three agricultural watersheds in Illinois, Big Ditch (100 km^2), Court Creek (250 km^2), and Upper Sangamon River (2,400 km^2), to simulate spatially and temporally varying surface and subsurface storm water runoff, propagation of flood waves, upland soil and streambed erosion, and sediment transport; to evaluate these simulation capabilities through calibration and validation; and to conduct various watershed investigative analyses. The new schemes were selected from the literature. DWSM was able to simulate the major hydrologic, soil erosion, and sediment transport processes, and generate reasonable water and sediment discharges in the Big Ditch and Court Creek watersheds, considering complexities of the physical processes simulated and sizes of the drainage areas evaluated. Comparisons of predicted and observed sediment discharges during recession portions of the hydrographs were much better in Court Creek watershed than in Big Ditch because of depth−integrated observation samples in the former, which is necessary during recession and low flow periods when pronounced concentration gradients are expected. Some discrepancies in model predictions were found, which may be due to limitations of the model, especially its single−event nature and lack of backwater simulation, limitations and uncertainties of input data, and temporally constant values of input parameters. Addition of the subsurface flow (tile drain and base flow combined) routing scheme improved predictions of the recession and base flow portions of the subwatershed (100 to 290 km^2) hydrographs in the Upper Sangamon River watershed. Significant improvements were noticed in larger subwatersheds. Scaling effect investigations on the Big Ditch watershed showed different overland Manning's roughness coefficients, effective lateral saturated hydraulic conductivities, and flow detachment coefficients for a coarser and a finer representations (subdivisions) of the watershed. These input parameters required recalibration when watershed subdivision sizes were altered. After recalibration, simulated water and sediment discharges were approximately the same for both representations. DWSM provided a robust tool in ranking overland planes and channel segments in the Court Creek watershed based on comprehensive criteria for flooding and sediment production potentials. The rankings were useful to stakeholders in prioritizing critical parts of the watershed and planning restoration and education programs. The model also provided a robust tool for evaluating detention basins in controlling downstream water and sediment discharges, although evaluations on sediment discharges were limited to large basins.*

Keywords. *BMP, DWSM, Modeling, Restoration planning, Scaling effect, Soil erosion, Subsurface flow, Surface runoff, TMDL.*

Flooding, upland soil and streambank erosion, sedimentation, and contamination of water from agricultural chemicals are critical environmental, social, and economical problems in Illinois and other states of the U.S. and throughout the world (Borah et al., 2002a, 2003; Borah and Bera, 2003). Understanding and evaluating the natural processes in a watershed leading to these problems are continuing challenges for scientists and engineers. Mathematical models that simplify and simulate these complex processes are useful analysis tools for understanding the problems and finding solutions through simulations of land−use changes and best management practices (BMPs). Such models help develop Total Maximum Daily Load (TMDL) planning, required by the Clean Water Act, and help evaluate alternative land−use and BMP scenarios, implementation of which can help meet water quality standards and reduce damaging effects of storm water runoff on water bodies and the landscape. Developing reliable watershed simulation models and validating them with observed data is challenging. Many of the agricultural watersheds in the midwestern states of the U.S., including Illinois, are in flat terrain and have extensive tile drainage systems, which causes additional modeling challenges.

Sources and descriptions of many of the watershed models may be found in Singh (1995) and Singh and Frevert (2002a, 2002b). A comprehensive review and comparisons of eleven commonly used watershed−scale hydrologic and nonpoint−source pollution models are given in Borah and Bera (2003). The review found that the Agricultural NonPoint−Source

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pollution model (AGNPS) (Young et al., 1987), the Annualized Agricultural NonPoint Source model (AnnAGNPS) (Bingner and Theurer, 2001), the Dynamic Watershed Simulation Model (DWSM) (Borah et al., 2002b), the Hydrological Simulation Program − Fortran (HSPF) (Bicknell et al., 1993), the European Hydrological System model or MIKE SHE (Refsgaard and Storm, 1995), and the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) are fully developed models having all the three major components: hydrology, sediment, and chemical. AnnAGNPS, HSPF, and SWAT are long−term continuous simulation models useful for analyzing long−term effects of hydrological changes and watershed management practices. AGNPS and DWSM are storm−event simulation models useful for analyzing watershed responses from severe or extreme storm events and evaluating watershed management practices. MIKE SHE, the most physically based model, has both the long−term continuous and storm−event simulation capabilities. Among the long−term continuous simulation models, SWAT is a promising model for agricultural watersheds, and HSPF is promising for mixed agricultural and urban watersheds. AnnAGNPS is similar to SWAT, and MIKE SHE is data and computationally intensive for efficient simulations of large watersheds (Borah and Bera, 2003).

Among the fully developed storm−event models, AGNPS is a simple and lumped model generating overall responses from a storm, including surface water volume, peak flow, and yields or average concentrations of sediment and nutrients. It does not generate time varying flows (hydrographs) and constituent discharges, which are critical in certain analyses. For example, peak flows, peak constituent concentrations, and their timings are crucial information in flood warning and management, watershed assessment, and BMP evaluations. On the other hand, MIKE SHE is too complicated. DWSM provides a balance and compromise between the simple AGNPS and the complicated MIKE SHE storm−event models because of its physically based robust routines (Borah and Bera, 2003). Review of applications of SWAT, HSPF, and DWSM (Borah and Bera, 2004) showed that SWAT and HSPF are not suitable for analyzing severe storm events, whereas DWSM is suitable for any storm.

This study focused on the storm−event simulation model DWSM. It emerged from SEDLAB, the USDA−ARS National Sedimentation Laboratory watershed model (Borah et al., 1980, 1981), and RUNOFF, the runoff and its constituent simulation model (Borah, 1989a, 1989b; Ashraf and Borah, 1992). In this study, two new schemes were added to the model for routing subsurface and reservoir flows. It currently simulates spatially (distributed) and temporally varying surface and subsurface storm water runoff, propagation of flood waves, upland soil and streambed erosion, sediment transport, and agrochemical transport in agricultural, rural, and suburban watersheds from spatially and temporally varying rainfall inputs resulting from rainfall events (Borah and Bera, 2003, 2004; Borah et al., 2002b, 2002c). Eighteen applications of DWSM components and routines were summarized in Borah and Bera (2004). Three of the applications were on Illinois watersheds, which are elaborated here.

In this article, addition of the subsurface and reservoir flow routing schemes to DWSM and applications of DWSM hydrology and sediment components to three Illinois watersheds are presented. The objectives are:

- Add subsurface and reservoir flow routing schemes to DWSM.
- Calibrate and validate the hydrology and sediment components of DWSM on Illinois agricultural watersheds.
- Conduct watershed investigative analyses using the model: (1) influence of subsurface flows on hydrographs, (2) scaling effects from different watershed subdivision sizes, (3) effects of spatially averaged rainfall, (4) prioritize flow (flood) and sediment critical areas, and (5) impacts of water and sediment control scenarios (watershed scale BMPs).

These objectives were chosen based on availability of data and stakeholders' interests in the watersheds. Statistical criteria, i.e., percent errors of runoff volumes (deviation), peak flows, time to peak flows, sediment yields (deviation), peak sediment discharges, and time to peak sediment discharges, from suggestions in Green and Stephenson (1986), Martinec and Rango (1989), and ASCE Task Committee (1993) were used while comparing simulated (predicted) and observed hydrographs and sediment discharge graphs for single−event storms.

Model Description

To apply DWSM, the watershed is divided into one−dimensional overland planes, channel segments, and reservoir units (Borah and Bera, 2000; Borah et al., 2000, 2002b). These divisions take into account the nonuniformities in topographic, soil, and land−use characteristics, which are treated as being uniform with representative characteristics within each of the divisions. An overland plane is represented as a rectangle, width is equal to the adjacent (receiving) channel length, and length is equal to the overland plane area divided by the width. Representative slope, soil, land cover, and roughness are based on physical measurements and observations. A channel segment is represented with a straight channel having the same length as in the field and having a representative cross−sectional shape, slope, and roughness based on physical measurements and observations. A reservoir unit is represented with a stage−storage−discharge relation (table) developed based on topographic data and discharge calculations using outlet measurements and established relationships.

The overland planes are the primary sources of runoff and sediment. Two overland planes contribute surface runoff, subsurface flow, and sediment to one channel segment laterally from each side. The excess rainfall and eroded soil are routed across an overland plane, resulting in variable flow and sediment discharge along its slope length. However, cross−slope flow and sediment discharge are assumed uniform. Thus, flow and sediment routing are only necessary within a unit−width of the plane. Tile drain flows are combined with lateral subsurface flow using an effective lateral saturated hydraulic conductivity concept (discussed in the *Subsurface Flow Routing* subsection). As a result, each channel receives time−varying, but spatially uniform, lateral inflows of water and sediment from the adjacent overland planes.

The network of channel segments carries the receiving water and sediment from the overland planes toward the watershed outlet. Depending on the sediment load and transport capacity of the flow, further erosion of soil materials from the channel bed or sediment deposition may take place. The model simulates erosion and deposition of the channel bed only, not the banks. Therefore, the model is applicable only to fairly stable streambank channels. In addition, the model does not route sediment through a lake, reservoir, or detention pond. Therefore, the sediment component is applicable to large detention ponds, and perhaps most reservoirs and lakes, where sediment is largely trapped and sediment bypass is negligible.

For routing water and sediment through the watershed, a computational sequence is determined starting from the uppermost overland plane and ending in a channel segment or reservoir unit at the watershed outlet. An efficient scheme is used in which the outgoing and time−varying water and sediment discharges from an overland plane, channel segment, or reservoir unit are temporarily stored in a two−dimensional storage matrix until they are used as incoming water and sediment discharges to route through a downstream channel segment or reservoir unit. Once the time−varying water and sediment discharges are no longer needed, they are erased to make the storage spaces available for the water and sediment discharge time series of another overland plane, channel segment, or reservoir unit (Borah et al., 1981).

Hydrologic Simulations

Rainfall is the primary model input. Rainfall records either from single or multiple raingauges may be used. With multiple raingauges, raingauges are assigned to the overland planes using the Thiessen polygon method (Thiessen, 1911). Rainfall excess and infiltration rates on each overland plane are computed from the rainfall records using two alternative procedures: the Natural Resource Conservation Service (NRCS) runoff curve number method (SCS, 1972) as extended and described in Borah (1989a), or a detailed procedure involving computations of interception losses using a procedure by Simons et al. (1975) and infiltration rates using an algorithm developed by Smith and Parlange (1978), as described in Borah et al. (1981, 2002b). The first method computes rainfall excess rates, which are subtracted from rainfall rates (intensities) to compute infiltration rates assuming that other losses, such as evapotranspiration, are negligible during a storm event. The second method computes interception and infiltration rates, which are subtracted from rainfall intensities to compute rainfall excess rates. Losses in depression storage in the second method are indirectly accounted for in interception as initial losses.

The excess rainfall over the overland planes and through the channel segments are routed using the kinematic wave approximations (Lighthill and Whitham, 1955) of the Saint−Venant or shallow water wave equations, as described in Borah (1989a). The routing scheme is based on analytical and approximate shock−fitting solutions (Borah et al., 1980) of the continuity and approximate momentum equations. The scheme is robust because of the closed−form solutions.

Subsurface Flow Routing

In this study, a subsurface flow routing scheme was added to DWSM. A portion of the infiltrated water in an overland plane flows downstream as subsurface flow and ultimately discharges laterally into the contributing channel. This flow can be accelerated due to the presence of tile drains. After a thorough literature review (Borah et al., 2000), the kinematic storage equation of Sloan et al. (1983) used in the SWAT model (Arnold et al., 1998) was selected for subsurface flow simulations. Although the equation was developed for mountainous watersheds, it is also applicable to flatter slopes such as those of the Big Ditch, Upper Sangamon River, and Court Creek watersheds in Illinois (discussed in the Model Applications section). The lateral subsurface flow is expressed as:

$$q_s = K_s \sin\alpha \frac{2S}{L(\theta_s - \theta_d)} \tag{1}$$

where

q_s = subsurface flow per unit overland width ($m^3\ s^{-1}\ m^{-1}$)
K_s = lateral saturated hydraulic conductivity ($m\ s^{-1}$)
α = angle of the impermeable bed (degrees)
S = drainable volume of water stored in the saturated zone of a unit width of overland ($m^3\ m^{-1}$)
L = slope length (m)
θ_s = saturation water content ($m^3\ m^{-3}$)
θ_d = field capacity ($m^3\ m^{-3}$).

Equation 1 is used here with a modification to the K_s term to represent the lateral subsurface and tile−drain contributions from the overland planes to the channel flow, including base flow. In the presence of a tile drainage system, the overall hydraulic conductivity increases, and as a result the subsurface flow contribution to the channels (q_s) also increases. Therefore, a tile drainage system in the model is represented through modifying the saturated hydraulic conductivity (K_s) to a combined hydraulic conductivity called the effective lateral saturated hydraulic conductivity (ELSHC). The ELSHC depends on the drainable porosity of the soil and the tile drainage system and may be different from field to field and overland to overland. In the model, the ELSHC is assumed time independent and its value for each overland plane is estimated through calibration and validation using monitored flow data.

Conservation of subsurface water mass is maintained by continuously updating the water volume (S) through solving the following spatially uniform and temporally varying continuity equation:

$$fL - q_s = \frac{dS}{dt} \tag{2}$$

where

f = rate of infiltration ($m\ s^{-1}$)
t = time (s).

Reservoir Flow Routing

A reservoir flow routing scheme was also added to DWSM using the storage−indication or modified Puls method (U.S. Bureau of Reclamation, 1949). The method assumes a level water surface within the reservoir, invariable storage−discharge relation, and steady−state flow during small time intervals. The method is based on the spatially uniform and temporally varying continuity equation, similar to equation 2. Initially, depth of water or water surface elevation in the reservoir and outflow from the reservoir are known. The inflow hydrograph is known or estimated. The outflows, and thus the outflow hydrograph, are computed by repeatedly using the closed−form solution of the continuity equation and the stage−storage−discharge relation for the reservoir, as described in Hjelmfelt and Cassidy (1975).

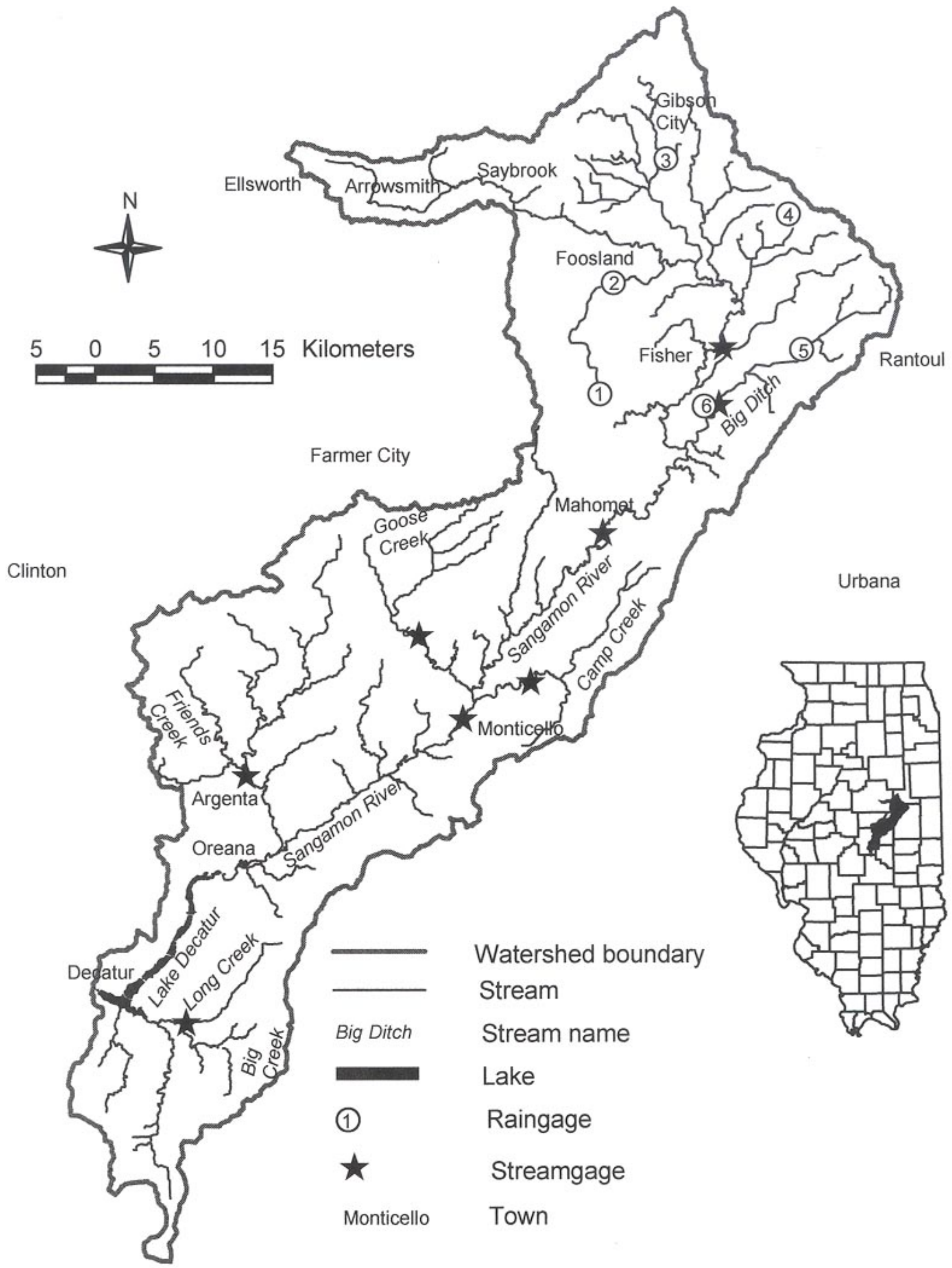

Figure 1. Upper Sangamon River watershed in Illinois draining into Lake Decatur.

Erosion and Sediment Simulations

The eroded soil or sediment is divided into a number of particle size classes (groups). In an agricultural watershed having extensive soil aggregates, the sediment is divided into five size groups: sand, silt, clay, small aggregate, and large aggregate (Foster et al., 1985). Erosion, deposition, and transport of each size group are simulated individually, and total responses in the forms of sediment concentration, sediment discharge, and bed elevation change are obtained through integration of the responses from all the size groups. The model maintains a loose soil depth on each overland plane and channel bed to keep track of loose soil accumulated from bed materials detached by raindrop impact and/or from deposited sediment. Sediment entrainment takes place from this loose soil layer as long as the sediment transport capacity of the flow is higher than the sediment load, or all the materials from the layer are entrained and become part of the sediment load. If the transport capacity continues to exceed the load, the flow erodes additional soil from the parent bed material and the potential erosion is the difference between the two. Actual erosion is computed simply by multiplying the potential erosion by a flow detachment coefficient (FDC), which is a distributed calibration parameter.

If the sediment transport capacity is lower than the sediment load, the flow is in a deposition mode and the potential rate of deposition is equal to the difference of the two. The actual rate of deposition is computed by taking into account particle fall velocities. From the actual erosion and

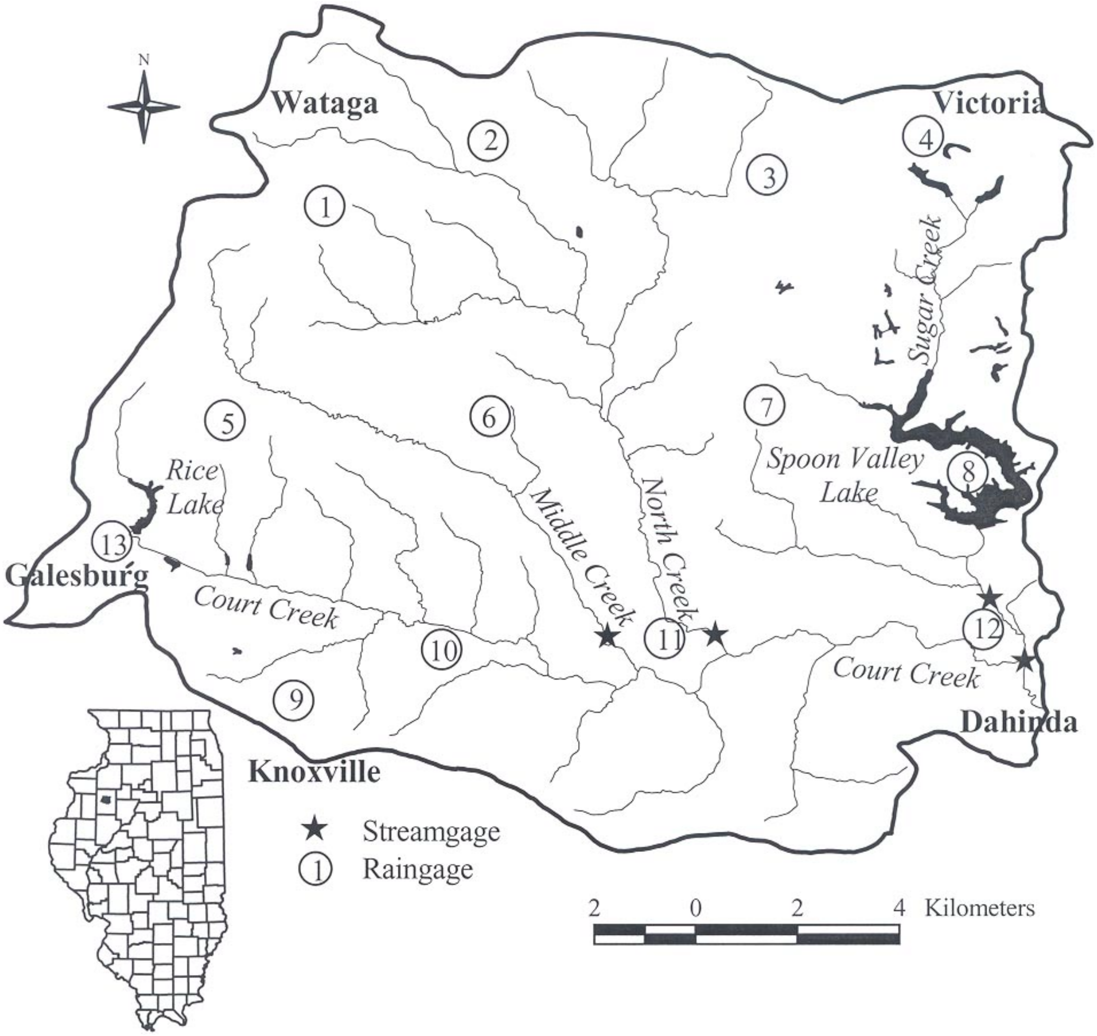

Figure 2. Court Creek watershed in Knox County, Illinois (after Roseboom et al., 1982a).

deposition, change in bed elevation during a computational time interval is computed. All these processes are interrelated and must satisfy locally the conservation principle of sediment mass expressed by the sediment continuity equation. With some approximations, the continuity equation is solved by the method of characteristics, and the solution is used to keep track of erosion, deposition, sediment discharge, and bed elevation change along the unit−width of an overland plane or a channel segment. All these procedures are described in Borah (1989b).

MODEL APPLICATIONS

The modified DWSM was applied to three watersheds in Illinois to test model performance through calibration and validation and conduct investigative analyses of the watersheds. The watersheds are the Upper Sangamon River (2,400 km^2), the Big Ditch (100 km^2), and the Court Creek (250 km^2) watersheds. The Big Ditch is a tributary subwatershed of the Upper Sangamon River watershed, both located in east central Illinois (fig. 1). This predominantly agricultural (87% corn and soybean rotation) watershed drains into Lake Decatur, the water supply reservoir for the city of Decatur. Lake Decatur has been experiencing water quality problems, with nitrate−nitrogen concentration exceeding the 10 mg/L drinking water standard of the U.S. and Illinois Environmental Protection Agencies (USEPA and IEPA) from time to time. The lake has also sedimentation problem, slowly reducing its water supply capacity. The watershed lies in the Till Plains section of the Central Lowland physiographic province. Bed slope of the main stem of the Upper Sangamon River varies from 0.00017 to 0.00084 m/m with an average of 0.00049 m/m. Slopes in the major tributaries vary mostly from 0.00053 to 0.00088 m/m, rarely up to 0.00538 m/m. The soils are mostly silt loams and silty clay loams, poorly drained, and are very fertile with high organic content and high water−holding capacity. The watershed has extensive tile drainage, a typical east central Illinois farming practice. During intense rainfall events, the fields are drained through surface runoff over grassed waterways and subsurface tile drains. Borah et al. (2003) monitored the Big Ditch at its streamgauge (fig. 1) for flow, suspended sediment, and agricultural chemicals (nitrate, phosphate, atrazine, and metolachlor) during 1998 and 1999 spring rainfall events. Breakpoint rainfall was recorded in raingauge number 6 (fig. 1) during both years and in raingauge number 5 only in 1999. These rainfall, flow, and sediment data were used here to calibrate and validate the hydrology and sediment components of DWSM.

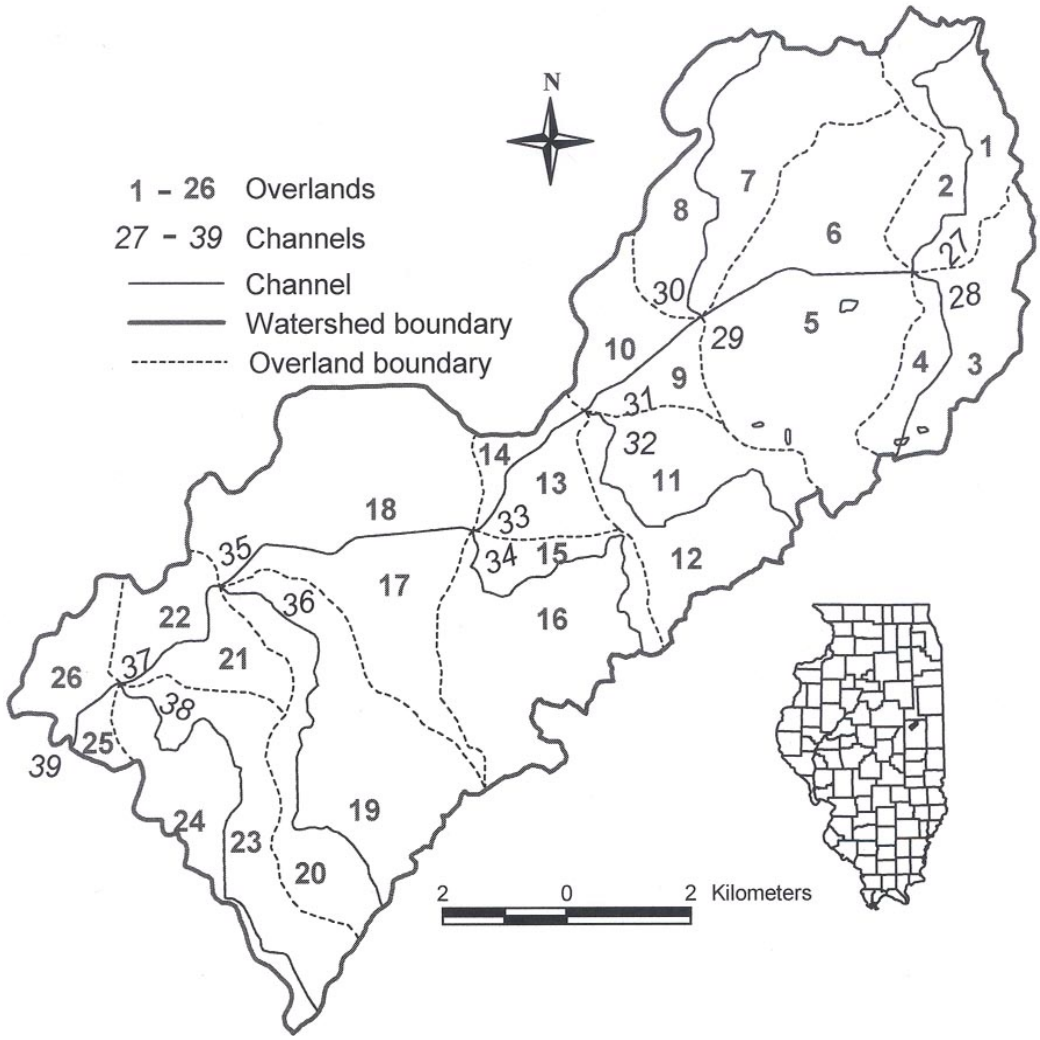

Figure 3. Big Ditch watershed in Illinois divided into 26 overland planes and 13 channel segments.

The Court Creek watershed is located in Knox County, western Illinois (fig. 2). It discharges into the Spoon River, a western tributary of the Illinois River, at Dahinda. There are two major lakes in the watershed: Spoon Valley Lake (207 ha) on Sugar Creek, and Rice Lake (12 ha) on upper Court Creek. Roseboom et al. (1982a, 1982b, 1986, 1990) collected hydrologic, land use, and water quality data on the Court Creek watershed during 1980 to 1988. Land use in the watershed is predominantly agriculture with row crop fields occurring on 49% of the watershed. More than 70% of the row crop acreage is corn. Pasture, wooded pasture, and strip mine pasture occupy 29% of the watershed. The remaining land uses are residential housings, animal feed lots, and land fills. Thirty−nine percent of the land in the watershed has slopes greater than 15%, mostly in pasture, wooded pasture, strip−mine pasture, and woods. More than 50% of the watershed has slopes less than 6%, used mostly for row crop agriculture and residential housing. Extensive monitoring stations were established to monitor rainfall, flow, and water quality parameters. Data from this monitoring study were also used in this study to calibrate and validate DWSM hydrology and sediment components. The Court Creek watershed was selected as one of the pilot watersheds in Illinois to investigate and study watershed problems and their solutions through BMPs and is part of the Illinois Conservation Reserve Enhancement Program (ICREP, 2002).

DWSM hydrology and sediment components were calibrated and validated on the Big Ditch and Court Creek watersheds. Influence of subsurface flows on hydrographs was investigated on the Upper Sangamon River watershed using calibrated parameters from an earlier study (Borah et al., 2002a). Scaling effects resulting from larger and smaller subdivision representations of the watershed were investigated on the Big Ditch watershed. Effects of spatially averaged rainfall, prioritizing flow (flood) and sediment critical areas for planning restoration under ICREP (2002), and evaluating water and sediment control scenarios (watershed−scale BMPs) were investigated on the Court Creek watershed. These specific investigations on the specific watersheds were conducted because of suitability of the available data and stakeholders' interests.

Calibration and Validation

Big Ditch Watershed

For calibration and validation of DWSM hydrology and sediment components, the Big Ditch watershed was divided into 26 overland planes and 13 channel segments (fig. 3). Sizes of overland planes ranged approximately from 1 to

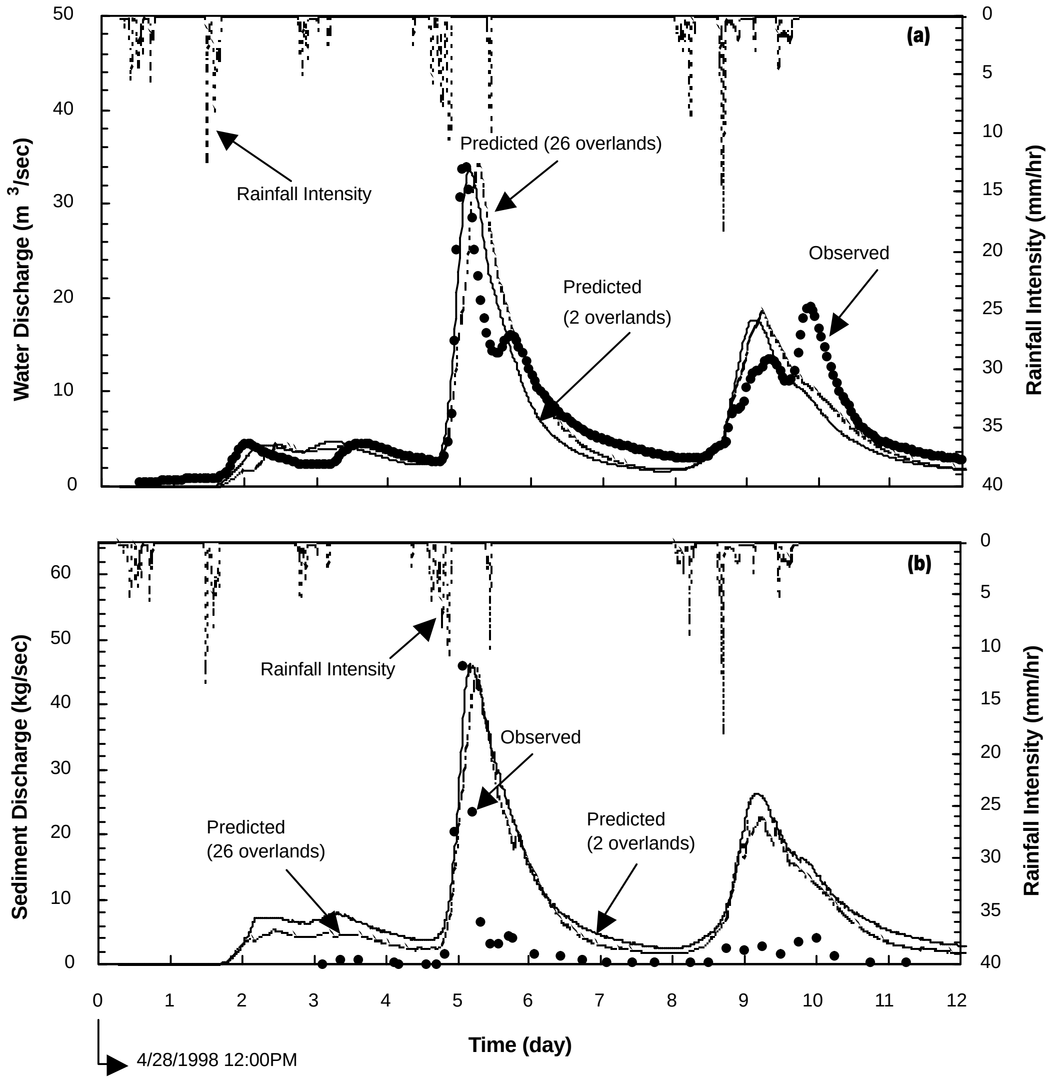

Figure 4. Water and sediment discharges from the Big Ditch watershed divided into coarse (2 overland) and fine (26 overland) subdivisions resulting from the May 1998 storms: Model calibration.

9 km^2, and channel segment lengths ranged from 1 to 8 km. The major tributary catchments were divided into two overland planes and one channel segment. Areas of the overland planes, lengths of the channel segments, and their representative (average) slopes were measured and/or estimated from U.S. Geological Survey (USGS) 7.5−minute series (topographic) quadrangle maps, available from the USGS (Reston, Va.) and the State Geological Survey (Champaign, Ill.). Channel cross−sectional measurements were used to develop wetted perimeter versus flow cross−sectional area relations (Borah, 1989a) for the channels.

Rainfall, flow, and sediment data from storms during May 1998 (Borah et al., 2003) were used to calibrate the model, and corresponding June 1998 data (Borah et al., 2003) were used to validate it. As shown in Borah et al. (2002b), DWSM generated almost identical flows from both alternative procedures of rainfall excess computations (i.e., the runoff curve number method and the interception−infiltration routine). Results from the interception−infiltration routine are presented and discussed here. During calibration, sensitive model input parameters, i.e., vertical and effective lateral saturated hydraulic conductivities (ELSHC), overland and channel Manning's roughness coefficients, and flow detachment coefficient (FDC), were varied, starting with literature values, until the best visual comparison of the simulated and observed graphs were found. The validation runs were made with the same parameters used in the calibration runs. Figure 4 shows the calibration and figure 5 shows the validation results, where simulated and observed water and sediment discharges are compared. Results from another subdivision of the watershed (coarser with two overland planes and one channel segment) are superimposed in these figures for scaling investigations (discussed in the *Scaling Effects* subsection). Statistical comparisons were made for the intense storms in each of the periods (calibration and validation), and the results are shown in table 1. The intense storm in May 1998 began on May 2 at 8:17 p.m. and lasted for 26.64 h with a total rainfall of 34.3 mm that produced the flow hydrograph in figure 4a from day 4.6 to day 8.0 with a peak flow of 34 m^3/s. The intense storm in June 1998 began on June 16 at 1:00 a.m. and lasted for 7.68 h with a total rainfall of 33.0 mm that produced the flow hydrograph in figure 5a from day 7.6 to day 9.2 with a peak flow of 66 m^3/s.

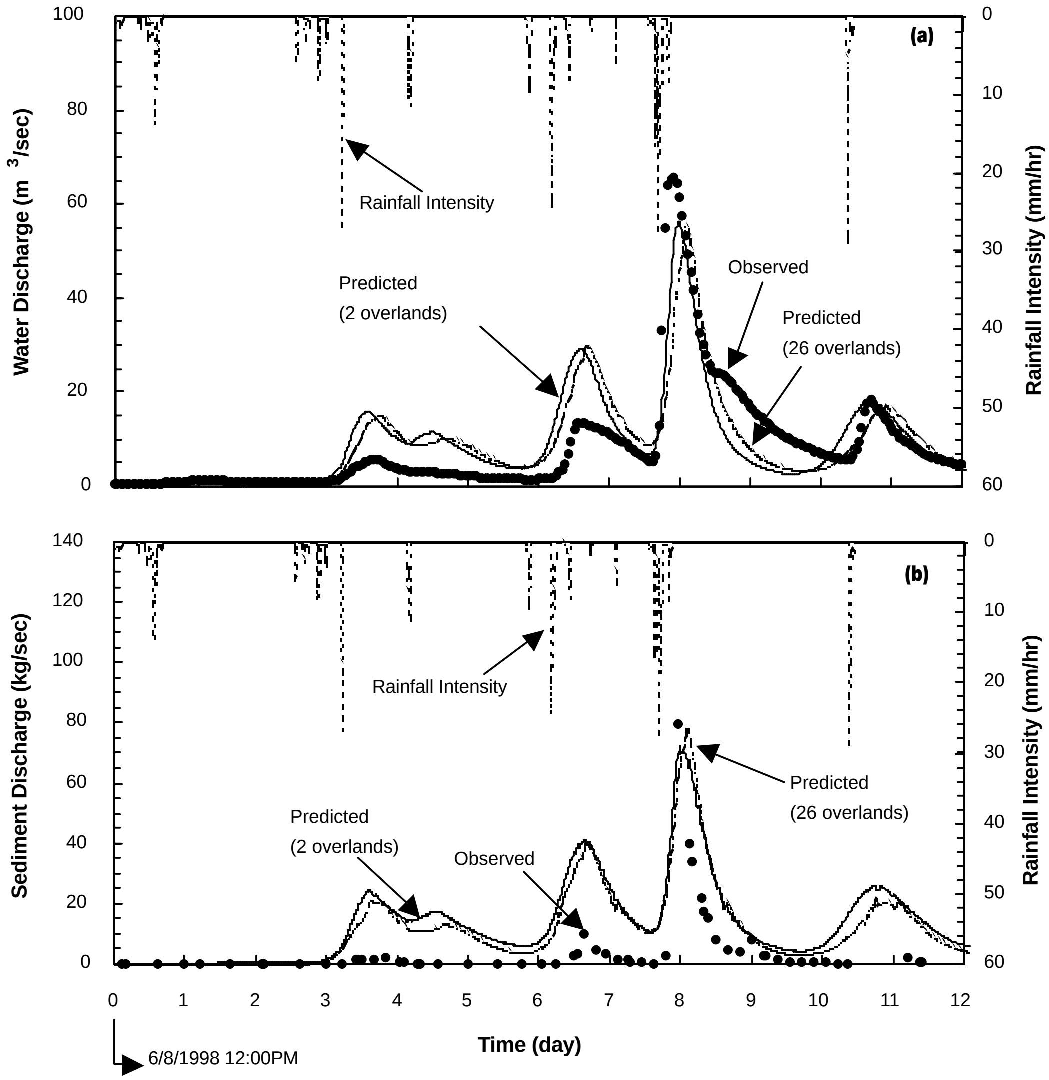

Figure 5. Water and sediment discharges from the Big Ditch watershed divided into coarse (2 overland) and fine (26 overland) subdivisions resulting from the June 1998 storms: Model validation.

In the calibration run (fig. 4, May 1998 storms), the model performed reasonably well in predicting the observed water discharges. Predictions for the intense storm (day 4.6 to 8.0 in fig. 4a) are reasonable with −2% error in runoff volume (table 1) and almost perfect matches of the peak flows. In the validation runs (June 1998 storms, fig. 5a), the model showed −15% error in predicting peak flow, good matches for time to peak flow (3% error), and −30% error in predicting runoff volume for the intense storm (day 7.6 to 9.2, fig. 5a and table 1). The model overpredicted water discharges during some less intense storms (fig. 5a). These storms are mostly June 1998 storms that produced the first two peaks in figure 5a, the

Table 1. Comparisons of observed and predicted water and sediment parameters during two intense storms in the Big Ditch watershed.

		Coarse Subdivision (2 overlands)			Fine Subdivision (26 overlands)		
Storm Event	Parameter	Predicted	Observed	% Error	Predicted	Observed	% Error
May 3 (1:55) to 6 (12:00) 1998 (Day 4.6 to 8.0 in fig. 4): Model calibration	Runoff volume (ha−m)	268	293	−9	288	293	−2
	Peak flow (m^3/s)	34	34	0	34	34	0
	Time to peak flow (days)	5.1	5.1	0	5.2	5.1	2
	Sediment yield (t)	3940	2679	47	3480	2679	30
	Peak sediment discharge (kg/s)	46	46	0	45	46	−2
	Time to peak sediment (days)	5.2	5.1	2	5.2	5.1	2
June 16 (2:00) to 18 (17:00) 1998 (Day 7.6 to 9.2 in fig. 5): Model validation	Runoff volume (ha−m)	335	515	−35	360	515	−30
	Peak flow (m^3/s)	56	66	−15	56	66	−15
	Time to peak flow (days)	8.0	7.9	1	8.1	7.9	3
	Sediment yield (t)	5188	5073	2	4580	5073	−10
	Peak sediment discharge (kg/s)	72	79	−9	78	79	−1
	Time to peak sediment (days)	8.0	8.0	0	8.1	8.0	1

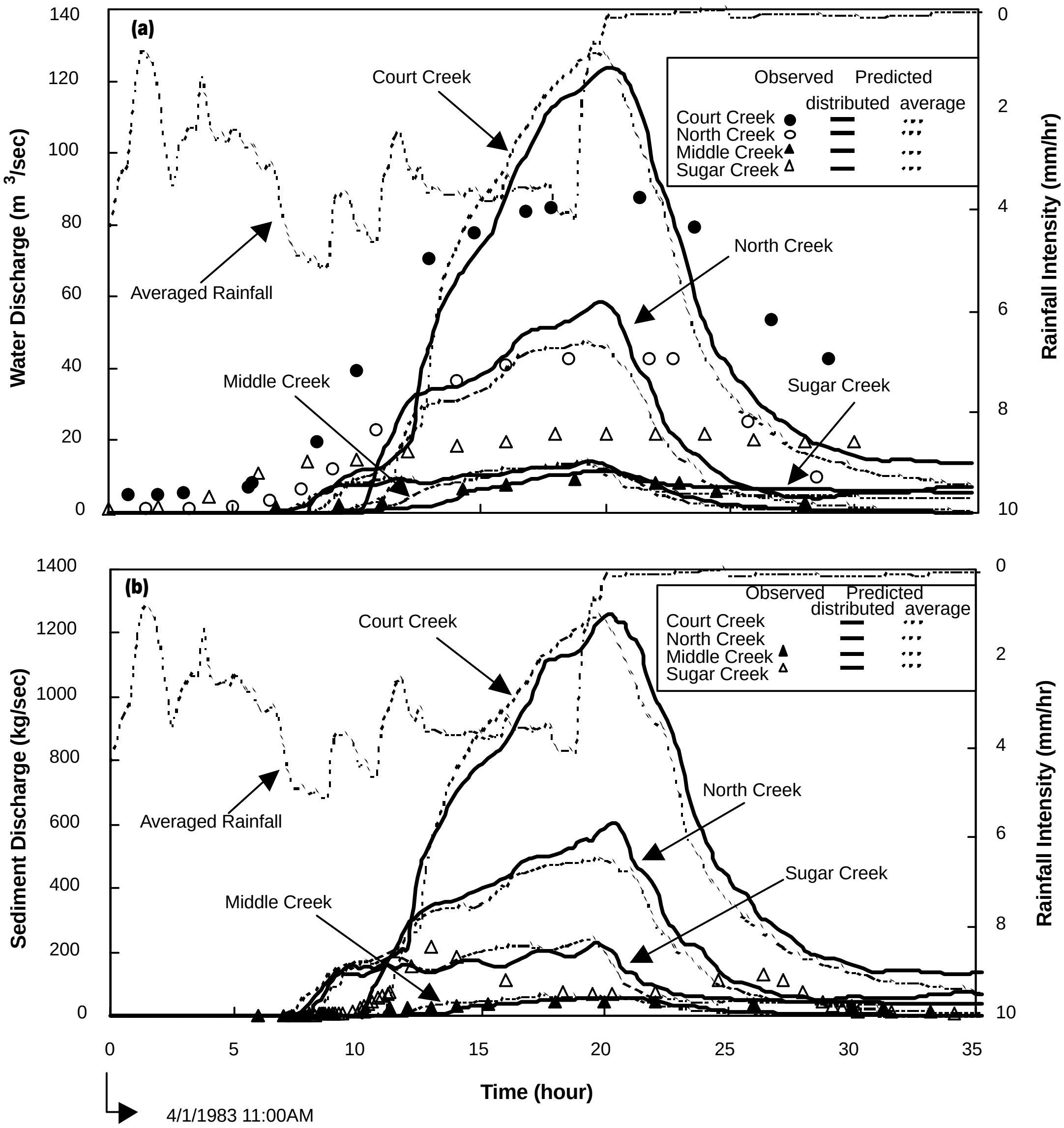

Figure 6. Observed and predicted water and sediment discharges in the Court Creek watershed resulting from spatially distributed and average rainfall of April 1, 1983, storm: Model calibration.

first peak (5.5 m^3/s) resulting from 20.8 mm rainfall lasting 16.56 h and the second peak (13.3 m^3/s) resulting from 27.4 mm rainfall lasting 15.36 h. There may be several reasons for these discrepancies. First, due to its single−event nature, the model is unable to account for the losses of runoff water and soil moisture through evapotranspiration between storms. Second, there were possible measurement errors and/or inadequacies, including only one raingauge (number 6 in fig. 1) active in 1998, and thus rainfall data from that station at the watershed outlet may not be representative, especially for the upstream overland planes. Third, the constant values of the input parameters may not be representative for all the storms simulated, due to the changes in antecedent moisture and ground cover (plant growth).

Sediment results are similar for both the runs (fig. 4b: calibration, and fig. 5b: validation). Predicted peak and time to peak of sediment discharges for the intense storms of May and June matched very well with the observed data, resulting from −2% to 2% errors (table 1). However, sediment yields during the May storm showed some discrepancies (30% error). Sediment yield predictions during the June storm, which was a more intense storm (higher rainfall intensity and peak flow) than the May storm, were much improved (−10% error). As shown in figures 4b and 5b, the model predicted rising and peak sediment discharges reasonably well during intense storms and overpredicted sediment discharges during falling or recession hydrographs of intense storms and during less intense storms. The less intense storms in May are shown in figure 4 during day 1.5 to 4.5, producing the first and second peak flows of 4.6 m^3/s, and a third during day 8 to 9.8 with a peak flow of 19 m^3/s. Sometimes, the overprediction of sediment discharges during less intense storms is due to overprediction of runoff, but most of the time it is due to other factors. As discussed in Borah et al. (2003) while presenting the monitored data, the observed sediment discharges during low flows and recession portions of hydrographs may be an underestimation of the actual values. The sediment concentrations measured in water samples taken near the water surface using an automated sampler may be much lower than the depth−averaged concentrations. Pronounced sediment

Table 2. Comparisons of observed and predicted water and sediment parameters in the Court Creek watershed using distributed (and average) rainfall input.

Storm Event	Station	Parameter	Predicted	Observed	% Error
April 1, 1983: Model calibration (fig. 6)	Middle Creek	Runoff volume (ha−m)	36 (44)	53	−32 (−17)
		Peak flow (m^3/s)	12 (14)	9[a]	33 (56)
		Time to peak flow (h)	20 (19)	19	5 (0)
		Sediment yield (t)	1857 (2240)	3073	−40 (−27)
		Peak sediment discharge (kg/s)	58 (47)	46[a]	26 (2)
		Time to peak sediment (h)	20 (18)	20	0 (−10)
	North Creek	Runoff volume (ha−m)	212 (166)	263	−19 (−37)
		Peak flow (m^3/s)	59 (47)	43[a]	37 (9)
		Time to peak flow (h)	20 (19)	22	−9 (−14)
	Sugar Creek	Runoff volume (ha−m)	81 (74)	173	−53 (−57)
		Peak flow (m^3/s)	14 (14)	22[a]	−36 (−36)
		Time to peak flow (h)	19 (19)	20	−5 (−5)
		Sediment yield (t)	10264 (10861)	6343	62 (−71)
		Peak sediment discharge (kg/s)	227 (242)	213[a]	7 (14)
		Time to peak sediment (h)	20 (19)	13	54 (46)
	Court Creek	Runoff volume (ha−m)	485 (469)	622	−22 (−25)
		Peak flow (m^3/s)	124 (128)	88[a]	41 (45)
		Time to peak flow (h)	20 (20)	21	−5 (−5)
December 24, 1982: Model validation (fig. 7)	North Creek	Runoff volume (ha−m)	47	53	−11
		Peak flow (m^3/s)	31	23[a]	35
		Time to peak flow (h)	30	31	−3
		Sediment yield (t)	4355	4011	9
		Peak sediment discharge (kg/s)	284	259[a]	10
		Time to peak sediment (h)	30	31	−3
	Sugar Creek	Runoff volume (ha−m)	31	20	55
		Peak flow (m^3/s)	32	33[a]	−3
		Time to peak flow (h)	29	31	−6
	Court Creek	Runoff volume (ha−m)	147	188	−22
		Peak flow (m^3/s)	80	63[a]	27
		Time to peak flow (h)	29	32	−9

[a] Highest observed, may not be the peak.

concentration gradients, higher near the bed and lower or zero (clear water) near the surface depending on the sediment size distribution, are expected during low flows and flows in the falling or recession limb of a hydrograph. Therefore, the comparisons might have improved if depth−width−integrated samples had been taken during flood recession and low flow periods, as in the Court Creek watershed (discussed in the *Court Creek Watershed* subsection).

From model outputs, combined sediment yield from channel segments 27 and 28 (fig. 3) going into channel segment 29 during the May 1998 storms (fig. 4b) was 1167 metric tons (t), whereas yield going out of channel segment 29 was 320 t. The difference of 847 t of sediment was deposited in this 3.6 km stream reach with an average slope of 0.041% during that period. Similarly, combined sediment yield from channel segments 33 and 34 going into channel segment 35 was 3053 t, whereas yield going out of channel segment 35 was 1103 t. The difference (1950 t of sediment) was deposited in this 4.5 km stream reach with an average slope of 0.034% during that period. These predictions agree with physical conditions of these flat stream reaches, where periodic dredging is done to remove deposited sediments and keep these reaches flowing for drainage purposes.

Overall, the model performances in simulating peak and time to peak water and sediment discharges during the intense storms were very good. Simulations for the less intense storms were not always good. Intense storms are the most critical storms for moving large amounts of sediment and agricultural chemicals across a watershed (David et al., 1997; Borah et al., 2003). Therefore, as a storm−event model, DWSM provides a useful tool in predicting water and sediment discharges from agricultural and rural watersheds during intense rainfall events.

Court Creek Watershed

The Court Creek watershed (fig. 2) was divided into 78 overland planes, 39 channel segments, and 2 reservoir units (Borah and Bera, 2000). The basic input data were prepared based on USGS 7.5−minute series (topographic) quadrangle maps and data available in Roseboom et al. (1982a, 1986), National Dam Safety Program Inspection Reports (Department of the Army, 1978, 1979), Chow (1959), and the *National Engineering Handbook* (SCS, 1972). Roseboom et al. (1986) recorded three storms, which occurred on December 2 and 24, 1982, and April 1, 1983. Continuous rainfall records (charts) for all three storms at 13 stations (fig. 2) and water and sediment discharge records at four gauging stations near the outlets of Middle Creek, North Creek, Sugar Creek, and Court Creek (fig. 2) were obtained from Roseboom (1999, personal communications). Based on adequacy of the available data, the April 1, 1983, storm was chosen for calibration, and the December 24, 1982, storm was chosen for validation.

The intense rainfall for the April 1, 1983, storm began at 11:00 a.m. on that day and continued till 7:00 a.m. the next day (April 2, 1983). Including light rain (drizzle), the storm

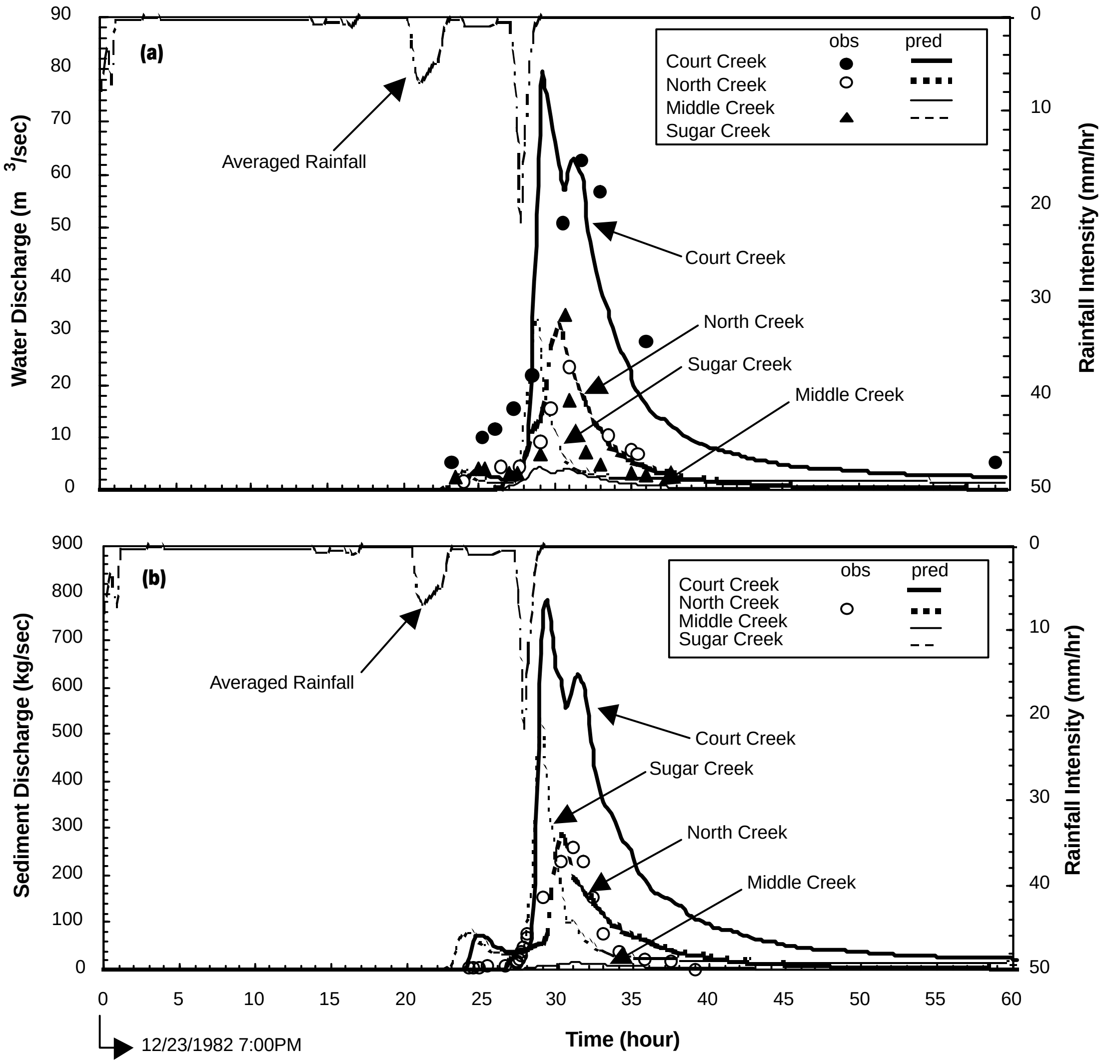

Figure 7. Observed and predicted water and sediment discharges in the Court Creek watershed resulting from the December 24, 1982, storm (distributed rainfall): Model validation.

was almost 24 h long. Breakpoint rainfall records from 12 stations (records from station 1 were erroneous) were assigned to overland planes according to the areas of influence given by Roseboom et al. (1982a), which was based on the Thiessen polygon method (Thiessen, 1911). With a computational time step of 15 min, the hydrologic and sediment components of DWSM were run for this rainfall event. The runoff curve number procedure was used to compute rainfall excess. The curve numbers and Manning's roughness coefficients were adjusted to improve comparisons of the predicted and observed hydrographs. The resulting curve numbers ranged from 73 to 85, and Manning's roughness coefficient was 0.04 for all overland planes and 0.032 for all channels. The flow detachment coefficients (FDC) for overland planes and channels were adjusted to best match predicted sediment discharges (graphs) with observed discharges. FDC values ranged from 0.004 to 0.020. The effective lateral saturated hydraulic conductivity (ELSHC) for all overland planes was calibrated as 0.025 mm/h. Therefore, the calibration process simply involved adjustments of the curve numbers, Manning's roughness coefficients, FDC, and ELSHC.

The comparisons of predicted and observed water and sediment discharges are shown in figure 6 (solid lines for predicted and discrete points for observed) in separate graphs for water and sediment, along with the average rainfall intensity graph. Table 2 shows the statistical parameters of these comparisons. The model was run again with the average rainfall intensities of the storm, keeping other variables and data the same, and those results are also shown in figure 6 (dashed lines) and the statistical comparisons with observed data are presented in table 2 (within parentheses). These results are discussed in the *Effects of Spatially Averaged Rainfall* subsection.

Flow comparisons were made for all four stations. Visual flow comparisons (fig. 6a) look better for stations with smaller drainage areas. For example, Middle Creek has a drainage area of 26 km^2 and shows better predictions than North Creek, which has a drainage area of 78 km^2. Predictions for North Creek are better than predicted outflows at the watershed outlet on Court Creek, draining 250 km^2. Sugar Creek discharges are affected by Spoon Valley Lake, which is reflected on both the predicted and observed hydrographs. Runoff volume at this station shows the highest discrepancy (−53% error, table 2). The remaining stations show runoff volume errors of −19% to −32%, all underpredicted. Because the measurements were made at

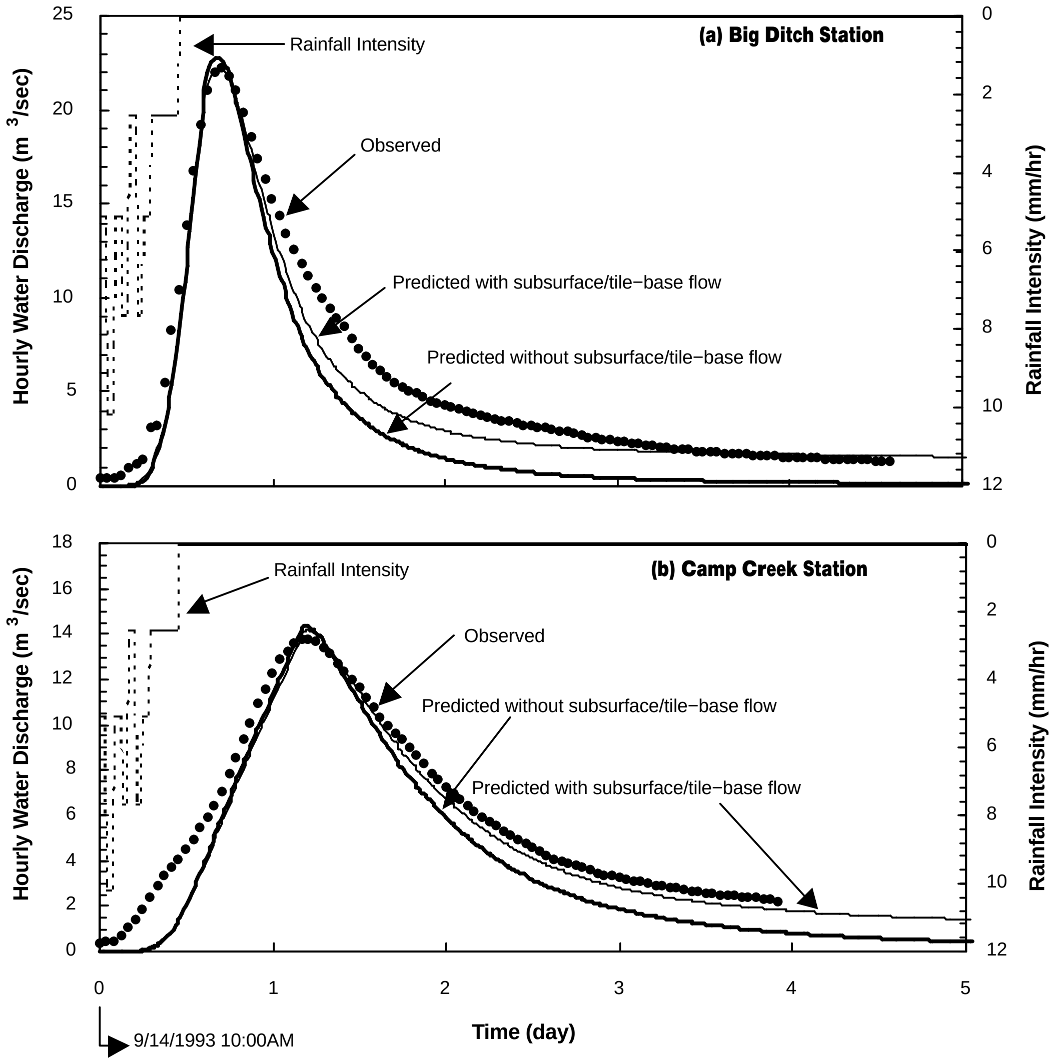

Figure 8. Observed and predicted (with and without subsurface/tile−base flow) hydrographs at (a) Big Ditch and (b) Camp Creek stations resulting from the September 14, 1993, storm.

discrete times, the peak flow may not have been measured. However, the highest observed flows were compared with the predicted peak flows in table 2. Peak flows were all overpredicted (errors of 33% to 41%), with Court Creek at the watershed outlet being the highest. The challenge in calibration was to balance between the runoff volume and peak flow comparisons. Time to peak flow errors ranged from −9% (ahead) to 5% (behind).

Sediment discharges were compared for Middle Creek and Sugar Creek (only available data), with Middle Creek showing good visual comparisons and Sugar Creek some discrepancies (fig. 6b). Sediment yield comparisons showed −40% errors for Middle Creek and 62% errors for Sugar Creek. Time to peak sediment discharge showed a perfect match for Middle Creek and 54% error for Sugar Creek.

There may be many reasons for some of the above discrepancies. Model performance depends on accuracy of the input data derived based on measurements of physical characteristics of the watershed, and monitoring of the hydrological and meteorological conditions of the simulated storms. The data used in this modeling study were collected and measured two decades ago using older techniques for different objectives, not necessarily for modeling. For example, runoff measurements were made at discrete time intervals. Due to lack of sufficient data, many of the model inputs were approximated. An example is wetted perimeter versus cross−sectional area relationships from a few stream cross−sectional measurements. Another example is lack of dam operation records of the two lakes, especially Spoon Valley Lake, which has a major impact on the discharges through the Sugar Creek and Court Creek gauging stations (fig. 2).

Model shortcomings may also contribute to some of the discrepancies. Major shortcomings of this and many other hydrologic models are the assumption of initial dry conditions in the stream channels with no base flows and inability to simulate backwater effects. Backwater from Spoon River, where Court Creek empties, may have an impact on the outflows measured at the Court Creek streamgauge near Dahinda (fig. 2). This could be the primary reason for the overprediction of peak flow at the mouth of Court Creek (fig. 6a; table 2).

In spite of the discrepancies, the model was able to generate results comparable to observations, considering the complexities of the physical processes being simulated, the sizes

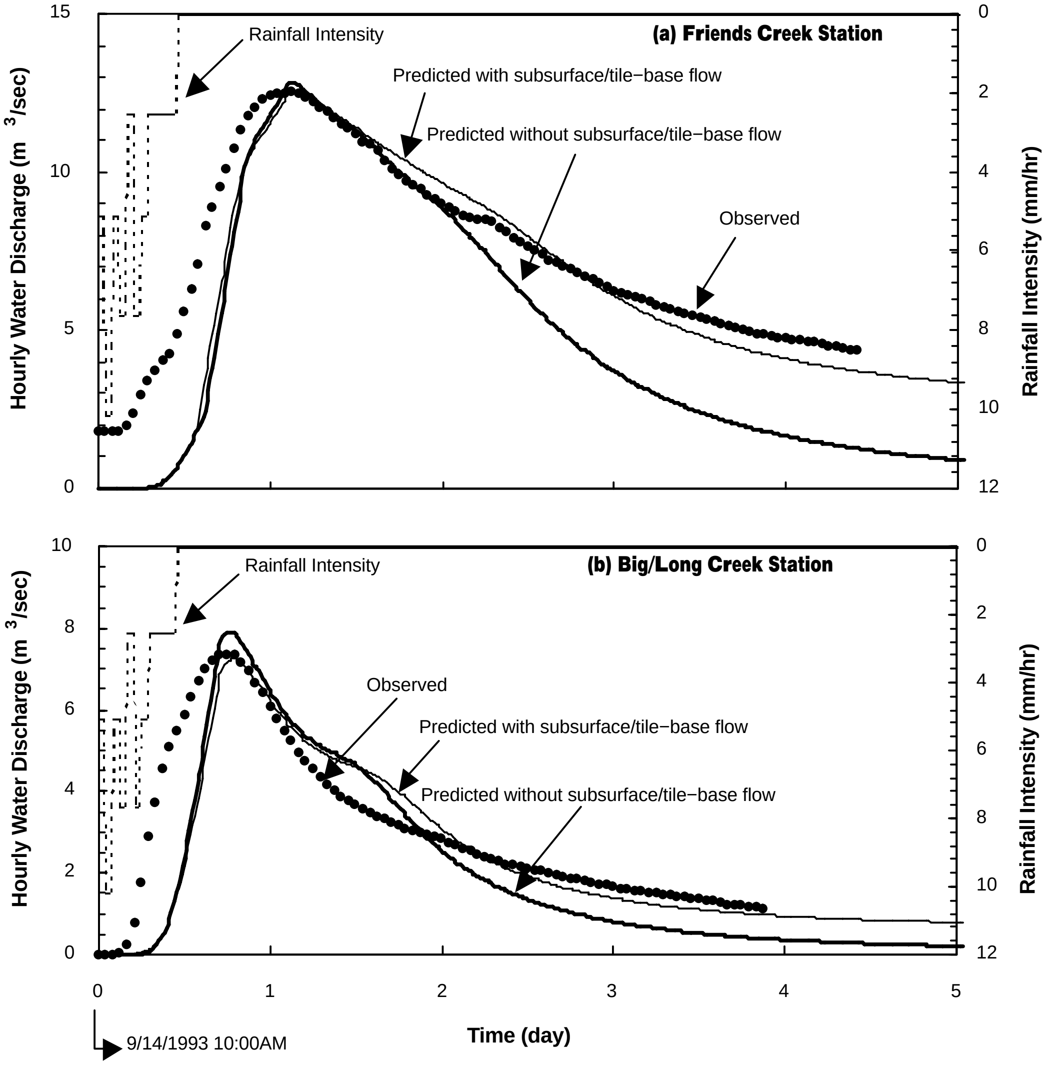

Figure 9. Observed and predicted (with and without subsurface/tile−base flow) hydrographs at (a) Friends Creek and (b) Big/Long Creek stations resulting from the September 14, 1993, storm.

of the drainage areas, the limitations of the available data for preparation of the model inputs, and the uncertainties of the observed data used in the comparisons. The model simulated the major hydrologic, soil erosion, and sediment transport processes and predicted the hydrographs and sediment discharge graphs close enough for preliminary planning of watershed restoration. More stream cross−sectional measure−ments, continuous flow measurements at more upstream sections of the streams, and dam operation records of Spoon Valley and Rice Lakes would improve calibration of the model, model input parameters, and the predictions.

The December 24, 1982, storm was used to validate the model. All the input data and model parameters were kept identical to the calibrated (April 1, 1983) values except the rainfall intensities, which were replaced with intensities of the December 24 storm. Rainfall data at all the 13 stations (fig. 2) were available for this storm, and all were used in the simulations. Although this storm was considered a 29 h storm beginning at 7:00 p.m. on December 23, 1982 (fig. 7) and ending at 0:00 a.m. on December 25, the intense portion of the storm was only during the last 9 h, beginning at 3:00 p.m. on December 24 (20 h later). Figure 7 shows the hyetograph of average rainfall intensities and the predicted and observed hydrographs and sediment discharge graphs (plotted separately) resulting from distributed rainfall intensities of the 13 stations.

Figure 7 shows the predicted hydrographs and sediment discharge graphs from Middle, North, Sugar, and Court Creeks. Observed flows were available from North, Sugar, and Court Creeks, and observed sediment discharges were available only for North Creek, which are also plotted in figures 7a and 7b, respectively, to compare with the predictions. Table 2 shows the statistical parameters of these comparisons, computed for the observed period (23 to 40 h in fig. 7). As may be seen visually in figure 7a, the predicted hydrograph from North Creek matched almost perfectly the discrete observed flows. However, North Creek runoff volume, peak flow, and time to peak flow show −11%, 35%, and −3% errors (table 2), respectively, which may be due to missing observation at the peak. Some discrepancies may be noticed also on the comparison of the predicted hydrograph at the Court Creek station (near the watershed outlet) with the observed flows (fig. 7a; table 2). Sugar Creek predictions look good except for advancements of the hydrograph, including the peak (fig. 7a). Lack of backwater simulations in the model and absence of Spoon Valley Dam operation

Table 3. Comparisons of observed and predicted flow parameters in the Upper Sangamon River watershed resulting from the September 14, 1993 storm.

Station	Parameter	Without Subsurface Simulation			With Subsurface Simulation		
		Predicted	Observed	% Error	Predicted	Observed	% Error
Big Ditch (fig. 8a)	Runoff volume (ha−m)	139	213	−35	178	213	−16
	Peak flow (m^3/s)	23	22	5	22	22	0
	Time to peak flow (days)	0.7	0.7	0	0.7	0.7	0
Camp Creek (fig. 8b)	Runoff volume (ha−m)	161	203	−21	179	203	−12
	Peak flow (m^3/s)	14	14	0	14	14	0
	Time to peak flow (days)	1.2	1.2	0	1.2	1.2	0
Friends Creek (fig. 9a)	Runoff volume (ha−m)	199	265	−25	239	265	−10
	Peak flow (m^3/s)	13	13	0	13	13	0
	Time to peak flow (days)	1.1	1.1	0	1.1	1.1	0
Big/Long Creek (fig. 9b)	Runoff volume (ha−m)	19	24	−21	21	24	−13
	Peak flow (m^3/s)	8	7	14	7	7	0
	Time to peak flow (days)	0.8	0.8	0	0.8	0.8	0

records may be the primary reasons for these discrepancies. The observed and predicted sediment discharges at the North Creek outlet matched reasonably well (fig. 7b), with yield, peak discharge, and time to peak deviating 9%, 10%, and −3%, respectively (table 2). It must be noted that sediment predictions in North Creek (fig. 7b) and in Middle Creek (fig. 6b) during the recession portions of the hydrographs are much better than in Big Ditch (figs. 4b and 5b) because of the depth−integrated suspended sediment samples taken in the Court Creek watershed (Roseboom et al., 1982a).

Based on these comparisons, it can be concluded that the model performed reasonably well for this validation storm using the calibrated parameters and was capable of generating reasonable water and sediment discharges throughout the watershed. Therefore, the model provides a robust tool for preliminary investigations of the watershed and for understanding some of the dominant hydrologic processes and their dynamic interactions within the watershed. The model can be used for preliminary planning of restorations through prioritizing critical areas and evaluating alternative land uses and BMPs.

Watershed Investigative Analyses

Influence of Subsurface Flows on Hydrographs

DWSM hydrology with the new subsurface flow component was applied to the entire 2,400 km^2 Upper Sangamon River watershed (fig. 1) to investigate influence of subsurface flows on hydrographs. Basic input data and parameters were taken from an earlier modeling study (Borah et al., 2002a). The watershed was subdivided into 40 overland planes, 20 channel segments, and one reservoir unit. Lake Decatur storages for different stages were calculated based on lake cross−sectional surveys (Fitzpatrick et al., 1987). Water discharges for the respective stages were calculated using weir formula with a weir coefficient of 3.6 (Chow, 1959). From these calculations, the stage−storage−discharge relationship (table) of the lake was developed.

The rainfall event of September 14, 1993, was used in Borah et al. (2002a) to validate the AGNPS model. The same storm was used in this study to investigate influence of subsurface flows on hydrographs by comparing hydrographs predicted by the model with and without the subsurface flow routine. Observed hourly flows at four tributary stations (Big Ditch, Camp Creek, Friends Creek, and Big/Long Creek, shown in fig. 1) were obtained from Demissie et al. (1996) and compared with the simulated hydrographs. Rainfall data were obtained from National Weather Service (NWS) records at stations in Urbana, Farmer City, Decatur, and Sullivan (fig. 1, Sullivan is farther south and not shown here). Rainfall for this storm was approximately uniform across all observed stations, and thus throughout the watershed, with an average depth of 53 mm. Breakpoint hourly records at the NWS stations were available, based on which average breakpoint rainfall depths for the watershed were calculated and input into the model.

With a computational time step of 15 min, the DWSM hydrology with and without the subsurface flow routine was run for the above rainfall event. The runoff curve number method was chosen to compute rainfall excess because of the available curve number values (Borah et al., 2002a). Due to the addition of subsurface flow simulations in the overland planes, it was necessary to reduce the runoff curve number values by 1% to 3%. The resultant curve numbers ranged between 68 and 78. Figures 8 and 9 show comparisons of the predicted hydrographs with and without subsurface flow and observed hydrographs from four subwatersheds (Big Ditch, Camp Creek, Friends Creek, and Big/Long Creek) ranging from 100 to 290 km^2. As can be seen in these figures, addition of the subsurface (tile drain and base flow combined) routine improved predictions of the recession and base flow portions of the hydrographs. Significant improvement can be seen in larger subwatersheds, for example, the 290 km^2 Friends Creek subwatershed (fig. 9a) with percent error of runoff volume reduced from −25% to −10% (underprediction). Values of the statistical criteria from these comparisons are given in table 3 and were calculated for periods for which observed data were available. In Big Ditch, Camp Creek, and Big/Long Creek (figs. 8a, 8b, and 9b, respectively), percent error of runoff volumes changed from −35%, −21%, and −21% to −16%, −12%, and −13%, respectively (table 3). Peak flows matched very well with the observations. Subsurface simulations improved peak flow predictions even further, with percent errors reducing from a range of 0% to 14% to all 0% (table 3). Times to peak flows matched perfectly in both cases, with percent errors 0% for all (table 3).

Scaling Effects

Watershed scaling issues have been addressed in the literature for a long time (Gupta et al., 1986; Zhang, 2002); however, the issues are far from over. In this study, effects from different watershed subdivision sizes on model input parameters and model outputs (water and sediment dis−

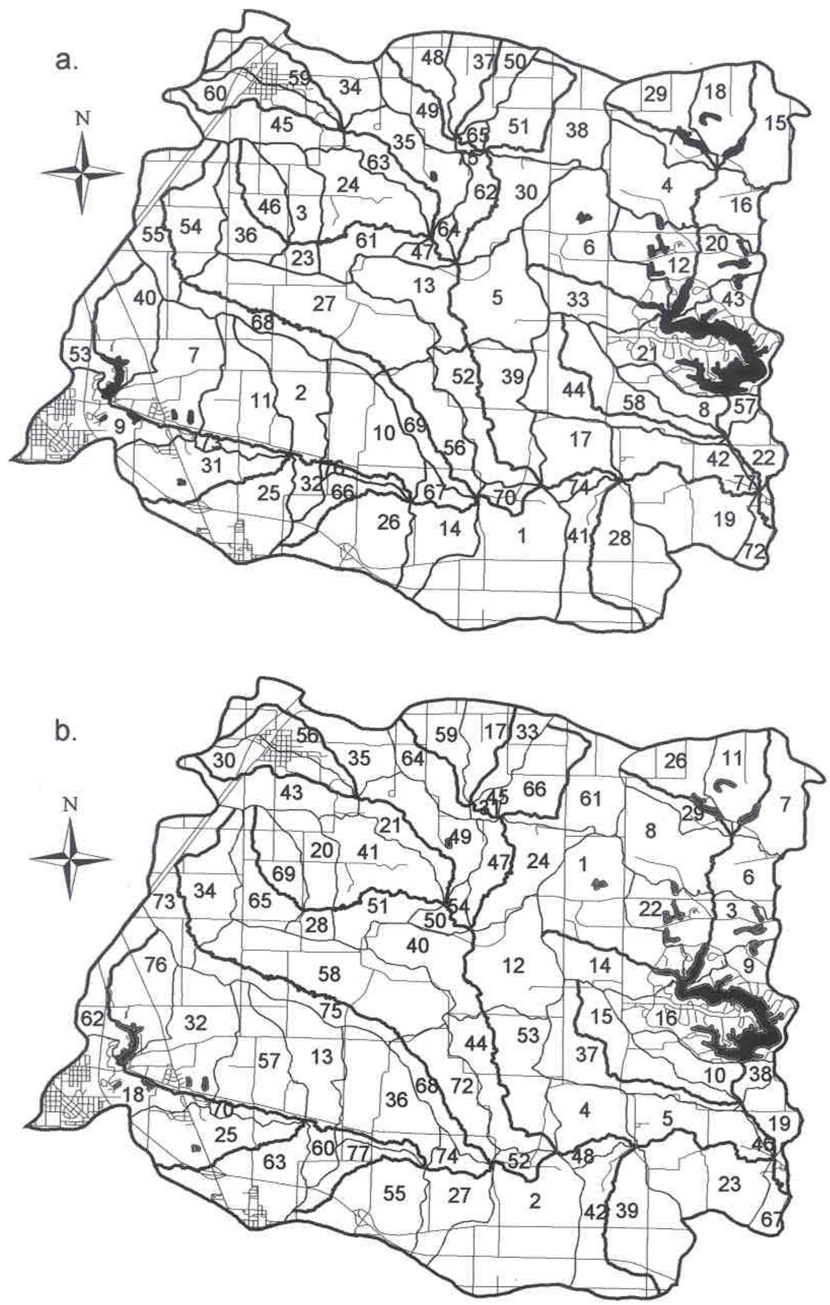

Figure 10. Ranking of Court Creek watershed overland planes generating highest to the lowest (a) unit−width peak flows and (b) unit−width sediment yields predicted from the April 1, 1983, storm (average rainfall).

charges), one form of scaling effect in watershed modeling, is investigated. The Big Ditch watershed (figs. 1 and 3) was represented with another set of overland planes and channel segments, this time much coarser: two overland planes and one channel segment. The main stem of Big Ditch beginning at the upstream boundary of the watershed and ending at the streamgauge was represented with one channel segment. Lands on both sides of the main stem Big Ditch were represented with two overland planes, one on each side of the channel. All the tributaries (channels) were considered part of the overland planes.

DWSM hydrology and sediment components were run for this coarse representation of the Big Ditch watershed, simulating the May 1998 (fig. 4) and June 1998 (fig. 5) storms. The input parameters were the same as for the fine representation (fig. 3: 26 overland planes and 13 channel segments) of the watershed, except for the overland Manning's roughness coefficient, effective lateral saturated hydraulic conductivity (ELSHC), and flow detachment coefficient (FDC). These input parameters were recalibrated for the coarse representation because their values differ with different representations of the watershed, as discussed here. For simplicity in the analysis, these input parameters were kept uniform throughout the watershed. The overland roughness for the coarse division (0.14) was almost one third of the roughness for the fine division (0.40). However, the channel roughness in both divisions remained the same at 0.08. The difference in overland roughness was because the

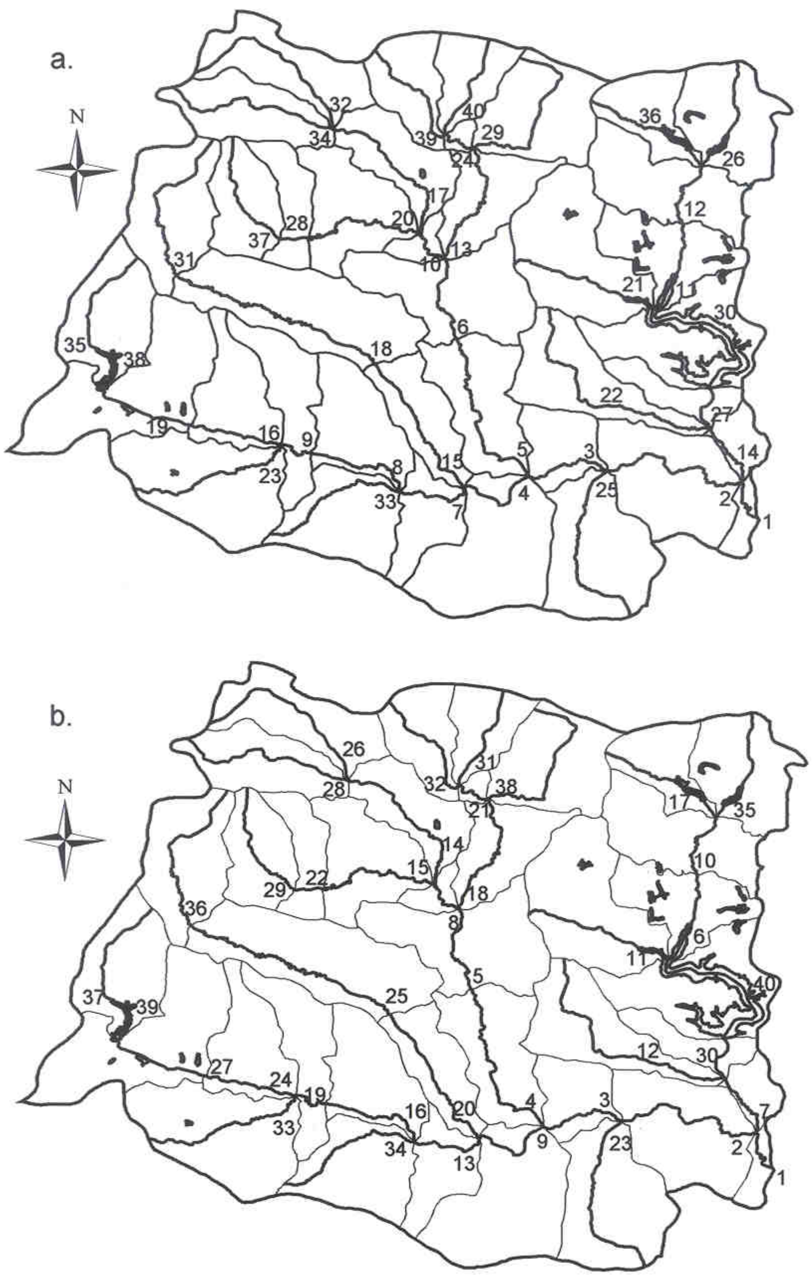

Figure 11. Ranking of Court Creek watershed channel segments generating highest to the lowest (a) peak flows and (b) sediment yields predicted from the April 1, 1983, storm (average rainfall).

coarse overland planes incorporated all the tributary channels represented as individual channel segments in the fine division (fig. 3). Channels are generally smoother, with lower roughness coefficients than overland surfaces.

In a similar manner, the ELSHC for the coarse overland planes (1.14 mm/h) was five times the value for the fine overland planes (0.23 mm/h) due to the presence of the tributary channels as part of the coarse overland planes. This may also be interpreted as making up for the channels not considered as channels in the coarse overland planes. Overland planes contribute both surface and subsurface flows into the channel segments. For the coarse division, the subsurface flows travel long distances before discharging into the channels; therefore, the ELSHC is higher to compensate for the unaccounted channels.

The FDC for the coarse division (0.0092) was two thirds of its value for the fine division (0.0140). Due to longer slope lengths in the coarse division generating higher overland flows toward downstream, the model simulated excessive sediment discharges. Therefore, to keep the sediment discharges close to the real values, the FDC needed to be reduced. The input parameter values should be considered more realistic for the fine division.

The finer subdivisions of the Big Ditch watershed did not add substantial accuracy to the water and sediment discharges (figs. 4 and 5; table 1), except for some minor improvements in the recession hydrographs. Therefore, unless detailed flow and sediment data are available within the fine segments for accurate calibration of the model, or need arises to differentiate finer areas for evaluations of BMPs, coarse divisions with less data preparation efforts may be sufficient for reasonable model predictions. However, more analyses are needed with watersheds having different shapes and characteristics.

Effects of Spatially Averaged Rainfall

Better model predictions are expected with spatially distributed rainfall data because rainfall generally varies spatially across a watershed. For example, rainfall depths during the April 1, 1983, storm on the Court Creek watershed (fig. 2) varied from 58 mm at station 13, located at the southwestern corner of the watershed, to 97 mm at station 3, located toward the northeast (fig. 2) with an average depth of 70 mm throughout. It would be interesting to know the effect of using such spatially distributed rainfall records in the model as opposed to average values of the breakpoint rainfall recorded at those stations. Most models use spatially averaged rainfall data. In this study, spatially averaged rainfalls were also used in prioritizing flow (flooding) and sediment critical overland planes and channel segments and in evaluating water and sediment control scenarios. Spatially averaged rainfalls were used to avoid biases in responses from different parts of the watershed due to non−uniform rainfall. Therefore, investigating the differences was of interest.

A test run was made for the April 1, 1983, storm with rainfall intensities averaged from rainfall recorded at the 12 raingauge stations. The resultant hydrographs and sediment discharge graphs at the four streamgauge stations were compared with the graphs previously predicted using the distributed records, and the comparisons are shown in figure 6 along with the discrete observed data. The dashed lines in figure 6 are simulation results using average rainfall. Statistical parameters of their comparisons with the observed data are shown in table 2 (within parentheses). As may be seen in figure 6 and table 2, the predicted hydrographs and sediment graphs with spatially distributed and average rainfall intensities were similar, with some mixed differences that could be considered minor. These differences are not pronounced because of fairly uniform rainfall over a major portion of the watershed. Except for the three northern stations, the remaining nine stations' rainfall depths were 58 to 73 mm; five of them were less than 64 mm. With variable rainfall patterns associated with localized thunderstorms, the results from spatially distributed and averaged rainfall would be much different. More analysis is needed with widely varying distributed rainfall data.

Prioritizing Flooding and Sediment Critical Overland Planes and Channel Segments

While planning restoration measures, such as in ICREP (2002), with limited resources, it becomes necessary to prioritize critical areas. As part of ICREP (2002), DWSM was used to rank flooding and sediment critical overland planes and channel segments in the Court Creek watershed (fig. 2) and help prioritizing those for restoration planning. DWSM hydrology and sediment components were run again for the Court Creek watershed using the calibrated and validated input parameters, and spatially averaged rainfall intensities for the April 1, 1983, storm. As discussed in Borah et al. (2001), the April 1, 1983, storm, a historical 1−year, 24 h storm (Huff and Angel, 1989), provided more practically useful results than similar design storm based on SCS (1972, 1986) rainfall distribution.

Two criteria were used to rank the overland planes: first, "unit−width peak flow" identifying runoff production potentials, and second, "unit−width sediment yield" identifying soil erosion and sediment production potentials. Similar criteria were used to rank the channel segments: first, "peak flow" identifying flooding potentials, and second, "sediment yield" identifying upstream net sediment production potentials. The unit−width peak flow for overland planes and peak flow for channel segments dynamically account for time of concentration. Similarly, the unit−width sediment yield for overland planes and sediment yield for channel segments dynamically account for sediment delivery, which is the fraction (net) of sediment volume exiting the catchment from the total volume of sediment produced from soil erosion within the catchment. Thus, the model eliminates determination of these key factors from empirical relations. These criteria are comprehensive and more effective in evaluating the environmental conditions than other commonly used criteria. For example, a commonly used criterion for runoff potential is runoff volume in terms of water depth (mm), which is a uniform depth of water over the catchment with no regard to its travel speed. For sediment, a commonly used criterion is soil loss per unit area (t/ha) with no regard to its delivery to the receiving water body.

Figure 10 shows rankings of the overland planes based on unit−width peak flow and unit−width sediment yield from the highest to the lowest values. Figure 11 shows rankings of the channel segments based on peak flow and sediment yield from the highest to the lowest values. The first ranking (fig. 10a) indicates overland planes with relative potentials of producing severe runoff flows in terms of magnitude and velocity as expressed in unit−width peak flow. Similarly, the second ranking (fig. 10b) indicates overland planes with relative potentials to erode soil and deliver sediment to the contributing channel in terms of unit−width sediment yield. These rankings have been useful to the Illinois Department of Natural Resources (ICREP, 2002), University of Illinois Extension (2002) in Knox County, Illinois, and the Court Creek Pilot Watershed Planning Committee, a citizen−based group, in prioritizing critical areas within the watershed for planning restoration projects, educating local farmers and citizens about flooding and soil erosion problems in the watershed, and alleviating those problems through implementation of various BMPs.

Similarly, stream segments were ranked based on peak flow (fig. 11a) and sediment yield (fig. 11b). As expected, peak flow is highest at the watershed outlet on Court Creek (ranking 1; fig. 11a), followed by the three upstream segments of Court Creek (ranking 2 to 4) and the last segment of North Creek (ranking 5). The Court Creek segment ranking 4 drains 96 km^2 and North Creek ranking 5 drains 78 km^2. These peak flow rankings are expected due to their decreasing drainage areas. However, the sediment yield rankings were not the same (fig. 11b); the last segment of North Creek ranked 4, and the next North Creek segment ranked 5. The Court Creek segment upstream of its confluence with North Creek dropped down to 9 (fig. 11b) from 4 with peak flows (fig. 11a). These rankings agreed with physical observations and monitoring data of Roseboom et al. (1982a, 1982b, 1986) that North Creek produces the highest sediment yield among the tributaries and upper Court Creek. Steep wooded pasturelands along North Creek are believed to be responsible for such high sediment yields.

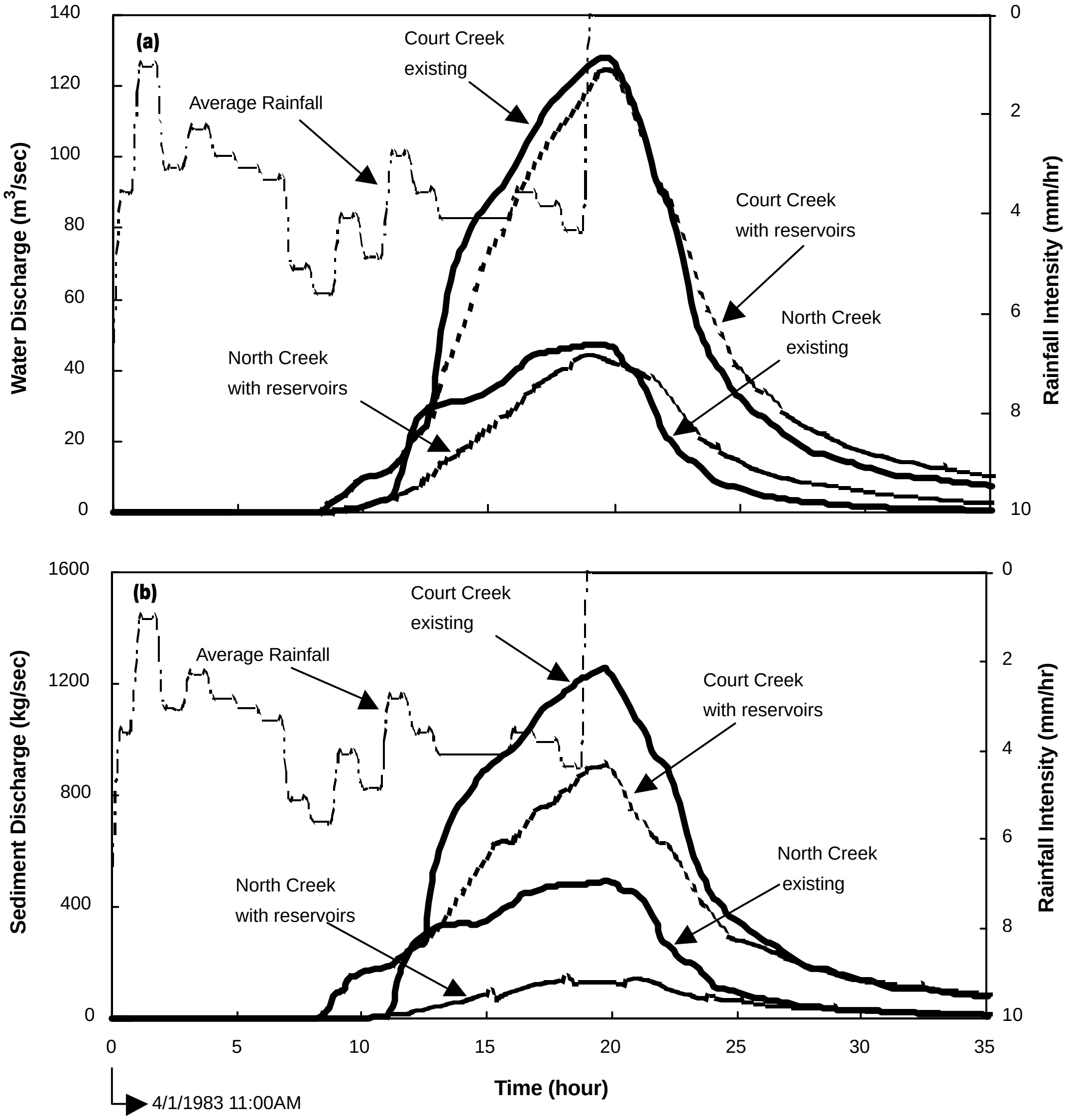

Figure 12. Predicted water and sediment discharges at the North and Court Creek outlets resulting from the April 1, 1983, storm (average rainfall) and assuming two Rice Lake size reservoirs at the two branches of North Creek.

These rankings may be useful to indicate severity of flooding and sediment delivery at any stream section throughout the watershed and prioritize those for restoration. The overland and channel rankings may be used simultaneously to prioritize stream sections and isolate severe overland planes above those stream sections for implementations of effective BMPs and other restoration measures.

Evaluating Water and Sediment Control Scenarios

DWSM provides a robust tool to evaluate water and sediment control scenarios. Using the calibrated and validated Court Creek watershed model, alternative watershed management scenarios in this watershed were analyzed. Results from one of those scenarios are presented here. Assuming two Rice Lake size reservoirs installed at the two major branches of North Creek (fig. 2), the model was run again for the April 1, 1983, storm using spatially uniform average rainfall intensities. Impacts of these two reservoirs on the water and sediment discharges at the North and Court Creek outlets are shown in figure 12. As shown in this figure, impacts on water discharges are minimal: 7% and 3% peak flow reductions, respectively, at the North and Court Creek outlets (fig. 12a). As expected, hydrographs at both locations are delayed, more in North Creek than in Court Creek. Dramatic impact on sediment discharges is shown: 70% and 26% reductions of sediment yields, respectively, at the North and Court Creek outlets (fig. 12b).

The above example shows that the model is capable of predicting impacts of lakes, reservoirs, wetlands, and detention ponds on downstream water and sediment discharges. However, it should be noted that the model assumes that all incoming sediment is trapped inside the lake, reservoir, wetland, or detention pond and downstream release is negligible. Therefore, the sediment component of the model is strictly applicable only to large lakes, reservoirs, wetlands, and detention ponds.

CONCLUSIONS

DWSM, the Dynamic Watershed Simulation Model, was expanded with a subsurface and a reservoir flow routing schemes. The hydrology and sediment components of the model were used to simulate spatially and temporally varying surface and subsurface storm water runoff, propagation of flood waves, upland soil and streambed erosion, and sediment transport in three agricultural watersheds in Illinois: Big Ditch, Court Creek, and Upper Sangamon River. Model performances were evaluated through calibration and validation, and watershed investigative analyses were conducted based on suitability of available data and stakeholders' interests.

The overall model performance in predicting water and sediment discharges in the 100 km^2 Big Ditch watershed was good, especially during intense storms, which are the most critical storms in moving large amounts of sediment and agricultural chemicals through a watershed. However, comparisons of sediment discharges during hydrograph recession and low flow periods showed substantial discrepancies, which may be due to possible underestimation of observed sediment concentrations from only point measurements near the water surface during times when pronounced concentration gradients were expected.

In spite of some discrepancies, the model was able to simulate the major hydrologic, soil erosion, and sediment transport processes and generate reasonable results in the 250 km^2 Court Creek watershed, considering the complexities of the physical processes simulated and the sizes of the drainage areas evaluated. Sediment predictions during recession portions of the hydrographs were much better than in the Big Ditch watershed because of depth−integrated observation samples, which are necessary during recession and low flow periods when pronounced concentration gradients are expected. Discrepancies in model predictions may be due to limitations of the model, especially its single−event nature and lack of backwater simulation, limitations and uncertainties of the input data, and temporally constant parameter values.

Addition of the subsurface flow (tile drain and base flow combined) routing scheme to DWSM improved predictions of the recession and base flow portions of the subwatershed (100 to 290 km^2) hydrographs in the Upper Sangamon River watershed. Significant improvements were noticed in larger subwatersheds. Addition of the reservoir flow routing scheme enabled the model to simulate lake, reservoir, and detention pond flows and evaluate their effectiveness (watershed−scale BMPs) in minimizing downstream flood and sediment flux.

Scaling effect investigations on the Big Ditch watershed showed different overland Manning's roughness coefficients, effective lateral saturated hydraulic conductivities, and flow detachment coefficients for a coarser and a finer representations (subdivisions) of the watershed. These input parameters required recalibration when watershed subdivision sizes were altered because their values differ with different sizes of the subdivisions. After recalibration, simulated water and sediment discharges were approximately the same for both the representations.

The hydrographs and sediment discharge graphs in the Court Creek watershed, simulated using spatially distributed and average rainfall intensities of the April 1, 1983, storm, differed very little because of fairly uniform rainfall over the watershed. However, variable rainfall patterns associated with localized thunderstorms would result in much different water and sediment discharges from spatially distributed and averaged rainfall inputs, which require further investigation using widely varying distributed rainfall data.

DWSM provided a robust tool for ranking overland planes and channel segments in the Court Creek watershed based on unit−width peak flows and unit−width sediment yields for overland planes and peak flows and sediment yields for channel segments, a set of comprehensive criteria for flooding and sediment production potentials. The rankings were useful to the Illinois Conservation Reserve Enhancement Program, the Court Creek Pilot Watershed Planning Committee, and University of Illinois Extension in prioritizing critical parts of the watershed and planning restoration and education programs. The model also provided a robust tool for evaluating detention basins in controlling downstream water and sediment discharges, although evaluations on sediment discharges were limited to large detention ponds, lakes, and reservoirs.

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