WATERSHED SCALE MODELING OF CRITICAL SOURCE AREAS OF RUNOFF GENERATION AND PHOSPHORUS TRANSPORT[1]

M.S. Srinivasan, Pierre Gérard-Marchant, Tamie L. Veith, William J. Gburek, and Tammo S. Steenhuis[2]

ABSTRACT: A curve number based model, Soil and Water Assessment Tool (SWAT), and a physically based model, Soil Moisture Distribution and Routing (SMDR), were applied in a headwater watershed in Pennsylvania to identify runoff generation areas, as runoff areas have been shown to be critical for phosphorus management. SWAT performed better than SMDR in simulating daily streamflows over the four-year simulation period (Nash-Sutcliffe coefficient: SWAT, 0.62; SMDR, 0.33). Both models varied streamflow simulations seasonally as precipitation and watershed conditions varied. However, levels of agreement between simulated and observed flows were not consistent over seasons. SMDR, a variable source area based model, needs further improvement in model formulations to simulate large peak flows as observed. SWAT simulations matched the majority of observed peak flow events. SMDR overpredicted annual flow volumes, while SWAT underpredicted the same. Neither model routes runoff over the landscape to water bodies, which is critical to surface transport of phosphorus. SMDR representation of the watershed as grids may allow targeted management of phosphorus sources. SWAT representation of fields as hydrologic response units (HRUs) does not allow such targeted management.
(KEY TERMS: watershed modeling; phosphorus transport; precipitation; runoff; SWAT; SMDR; saturation maps.)

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INTRODUCTION AND BACKGROUND

Phosphorus (P) is an essential nutrient for crop growth and productivity. However, P applied in excess to crop needs leads to soil-P build up (Sharpley, 1995). Such accumulation can eventually reduce the capacity of soils to retain P, resulting in accelerated loss of P in runoff (Leinweber *et al.,* 2002). Agriculture has been identified as a major contributor of P to water bodies (USGS, 1999). For example, in Chesapeake Bay, diffused sources account for 60 percent of P entering the bay with agriculture alone accounting for 80 percent of P from these diffused sources (Magnien *et al.,* 2001). Pionke *et al.* (1997) suggested that effective mitigation of P losses from agriculture must focus on defining, targeting, and remediating critical source areas, or CSAs, of P loss. Critical source areas of a nutrient result from the co-location of areas with high levels of that nutrient availability (source areas) with areas with high potential for nutrient movement (transport areas).

At a watershed scale, high-P source areas are easy to identify based on soil test results, historical P application records, and crop productivity records. Focused laboratory scale and plot scale studies have allowed researchers to develop protocols (Sharpley *et al.,* 1999) and relationships (e.g., Barisas *et al.,* 1978; Andraski *et al.,* 1985; Edwards and Daniel, 1993; Pote *et al.,* 1996; Sharpley, 1997; Kleinman and Sharpley, 2003) that define source-P release characteristics to runoff under different soil type, tillage, cover, P management (source type and application method, rate, and timing), and rainfall conditions. Ability to apply controls over P sources has allowed researchers to define P-release characteristics with a great level of certainty.

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While P source areas are locally controlled, P transport areas are controlled by landscape scale and watershed scale hydrologic processes. Since runoff is the major carrier of P to water bodies (Carpenter *et al.,* 1998), areas that generate runoff can be regarded as CSAs of P loss. Runoff generation processes are dynamic over time and space within a watershed, which makes the identification of runoff source areas very difficult. Pilgrim *et al.* (1978) indicated that identification and delineation of runoff source areas at the watershed scale are complicated as there can be distinct variations in hydrological behavior over spatial locations that on the surface appear homogeneous.

Transport processes link source areas to water bodies. To assess or forecast the impact of source on water bodies, a clear understanding of their linkage is vital. However, such "linkage" studies as reported in the literature are scarce (Sharpley and Kleinman, 2003). Many studies have attempted to locate the runoff source areas at hillslope scale (e.g., Dunne and Black, 1970; Anderson and Burt, 1978; Srinivasan *et al.,* 2002). However, watershed scale identification of runoff source areas has been severely limited by lack of standardized (hydrologic) procedures and field instruments. Variable spatial and temporal interactions between surface and subsurface hydrologic processes that lead to runoff generation at landscape scales and watershed scales further complicate such linkage studies.

Storm *et al.* (1988) incorporated a P transport submodel into ANSWERS (Beasley, 1977), a process based model, and validated the submodel using plot scale runoff, sediment, and P transport data. However, the usefulness of this P submodel at watershed scale has not been reported. Simulation models such as the TOPMODEL (Beven and Kirkby, 1979), VSAS2 (Bernier and Hewlett, 1982), and SMorMod (Zollweg, 1994), and indices such as the Topographic Index (Beven and Kirkby, 1979), Soil Moisture Index (O'Laughlin, 1981), and the Phosphorus Index (Sharpley *et al.,* 2003) have applied various strategies to map runoff source areas at landscape or small watershed scale. Many of these strategies were designed for easy delineation of runoff source areas but their validity has not been thoroughly evaluated in the field. For example, the Topographic Index represents surface flow process but does not adequately represent subsurface flow processes. P indices developed to assess the P pollution potential of individual fields apply standard contributing distances, calculated with respect to receiving waters, to account for P transport zones. Gburek *et al.* (2002) presented a generalized methodology to map CSAs at watershed scale, based on drainage density, topography, and rainfall data. However, the approach presented by Gburek *et al.* (2002) is storm specific and does not represent varying watershed conditions over time. The majority of these models, indices, and approaches do not represent the actual runoff generation processes but use proxy watershed parameters such as soil moisture conditions, soil drainage properties, hydraulic conductivity, land cover, drainage density, topography, rainfall return period, and others to identify CSAs. Except for the P index, the models and indices mentioned above are all research oriented tools developed to better understand and represent variable participation of watersheds in runoff generation. However, P management needs practical, user oriented tools and maps that can direct farmers and land managers to identify CSAs of P loss and direct remediation practices to those specific locations within the watershed. The P index offers such an assessment of P source and transport areas at a field scale.

The goal of this study was to evaluate the ability of two watershed scale models, SMDR (Soil and Water Laboratory, 2002) and SWAT (Arnold *et al.,* 1998) to identify CSAs of P loss. This study also assesses the usefulness of these two research based models in generating maps that can be directly used in the field for P management planning and implementation.

SMDR and SWAT provide a fairly complete representation of surface and subsurface processes. SMDR is a physically based model, specifically designed to simulate partial participation of watersheds in runoff generation. SWAT is one of the most widely used water quality models. Both are continuous simulation models operated at daily time steps. Thus, these two models have the capability to continuously track watershed conditions, specifically moisture storage conditions, and select runoff generation variables accordingly. The simulations were conducted in a small headwater watershed, FD-36, in east-central Pennsylvania. The scope of this paper is limited to evaluating the models' ability to identify runoff generation areas, as these runoff areas translate into P transport areas. No P simulations were conducted. In addition to evaluating the models' ability to match the observed stream flows at the watershed outlet, the spatial patterns of runoff generation areas were also compared for selected storms. Needelman *et al.* (2004) indicated the dominance of soil drainage properties on runoff generation in this watershed. Results from the models were compared against the field observations presented by Needelman *et al.* (2004).

STUDY AREA

FD-36 is a 39.5 ha upland watershed within the Valley and Ridge Province of east-central Pennsylvania (Figure 1). This watershed has been a primary

P-transport research watershed of the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) since 1996. Climate in this watershed is temperate and humid, with average annual precipitation and stream flow of 1,030 and 450 mm, respectively (Gburek and Sharpley, 1998). Gburek and Folmar (1999) observed that the surface and subsurface flow systems are predominantly self-contained within this watershed. Figure 2 presents soils and land use data for this watershed. Soils in the watershed are mostly channery silt loam with slopes ranging from 1 to 20 percent. Soils containing fragipan, Albrights and Hustontown soils, cover 23 percent of this watershed. Fragipans are soil layers that severely impede percolation and facilitate lateral flow. Fragipans are located anywhere between 45 and 60 cm from the soil surface. In FD-36, fragipan soils are located next to the stream (see Figure 2a), which can significantly influence surface and subsurface flows to the stream. Needelman (2002) indicated that fragipans might dominate runoff generation in this watershed. FD-36 watershed has a mixed land use – 50 percent soybean (*Glycine max*), wheat (*Triticum aestivum*), or corn (*Zea mays*), 20 percent pasture, and 30 percent woodland (Gburek and Sharpley, 1998).

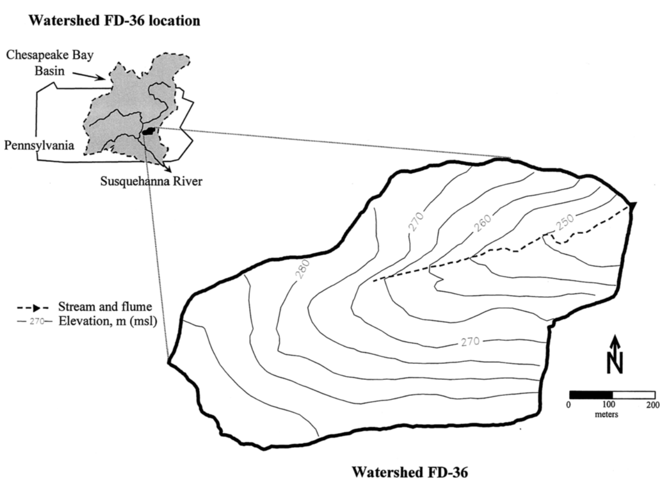

Figure 1. FD-36 Watershed Location Map.

DESCRIPTION OF THE MODELS: SMDR AND SWAT

SMDR is a physically based, fully distributed, non-calibrated model, designed to simulate variable participation of small watersheds in runoff generation processes. SMDR represents watersheds as grids of square cells of equal size. In this study, a cell size of 5 by 5 m was used. Each cell can be segmented, vertically, into five structural layers to represent soil heterogeneities. Water moves both upwards and downwards within the soil profile and laterally downslope from these layers. Percolation is simulated from the bottom soil layer. Percolated water is added to a lumped subsurface reservoir that feeds the base flow at user defined rates. A crop development submodel simulates evaporation from soil layers. Cells saturate from bottom to top. Water in excess of cell storage, percolation, and lateral flow is routed directly to the watershed outlet as saturation excess runoff within the same simulation interval. Soil properties (storage, conductivity, structure, texture) are derived from the MUIR (Map Unit Interpretation Record) database developed and maintained by the USDA (USDA-NRCS, 2004). Apart from flows, SMDR can output spatial maps of saturation excess runoff source areas and surface and subsurface moisture status at user defined intervals.

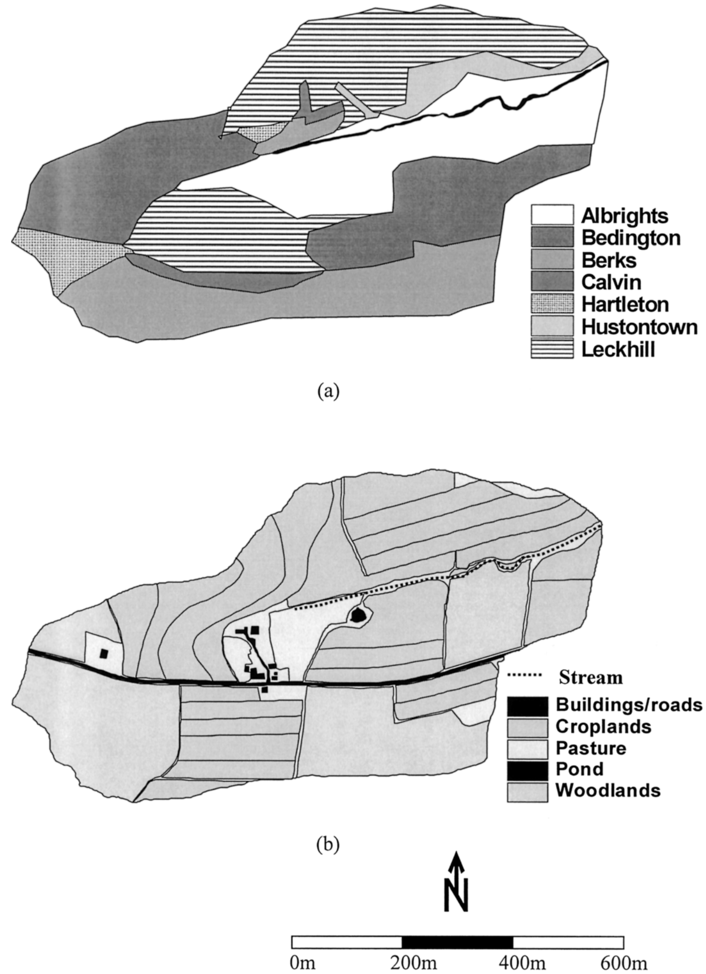

Figure 2. FD-36 Watershed Spatial Data: (a) Soils; (b) Land Use.

SWAT is a watershed scale model extensively used in a variety of watersheds across the country (Arnold *et al.,* 1998). SWAT simulates both surface and subsurface hydrologic processes and allows calibration. SWAT represents watersheds as "hydrologic response units," or HRUs, and subbasins. HRUs represent unique combinations of soils, management, and land uses. Subbasins are defined by surface topography so that the entire area within a subbasin flows to a subbasin outlet. A subbasin may include one or more HRUs and streams. SWAT does not allow interaction between HRUs, and runoff generated from HRUs is directly routed to the stream. Infiltrated water is stored in the soil, after allowing for deep percolation, plant uptake, and evapotranspiration. SWAT outputs both daily outflow from each HRU to the stream and daily streamflow at the subbasin and watershed outlets. In this study, the entire FD-36 watershed was represented as one subbasin.

SWAT uses the Curve Number (CN) to partition rainfall into runoff and infiltration. Runoff simulated using CN does not represent physically based runoff generation processes such as saturation excess or infiltration excess. However, SWAT alters CNs between Moisture Conditions I and III, and thus, attempts to link watershed moisture conditions to the runoff generation processes. Because of its simplicity, the CN technique has been widely used in a variety of research based models and engineering design tools to derive runoff from rainfall. The study presented here serves to evaluate the ability of a CN based model to predict runoff source areas.

SWAT was calibrated in a component wise manner to align the seasonal and annual water balance of the watershed with the observed balance while matching, as closely as possible, the simulated and observed daily streamflow patterns at the outlet. Data from the entire study period were used for calibration. Apart from visual comparison of daily hydrographs, Nash-Sutcliffe (N-S) coefficient and D_v values (discussed in the next section) were used to guide the calibration. Calibration adjustments were made to the curve number, the available water capacity of the soil, and various base flow recession, ground water recharge, evapotranspiration, and snow melt factors.

STATISTICAL ANALYSES

Observed and simulated time series streamflow data were compared using the Nash-Sutcliffe method (N-S coefficient) (Nash and Sutcliffe, 1970) and deviation in runoff volume (D_v) method described by Martinec and Rango (1989). The N-S method evaluates a model performance based on how well the daily simulated values match the daily observed values. A positive N-S coefficient indicates positive correlation between observed and simulated values, while a negative N-S coefficient indicates a negative correlation. D_v represents the cumulative effects of differences in observed and simulated data over a length of time. D_v is not sensitive to the differences in daily observed and simulated values. Apart from these two statistical tests, the ratio of streamflow to precipitation (S-P ratio) was also calculated to evaluate the performance. S-P ratios define precipitation to streamflow conversion and can be calculated for an event or for a period of time. When individual storm events were analyzed, absolute differences in observed and simulated storm flow volumes were compared.

RESULTS AND DISCUSSION

Characterization of the Study Period Based on Observed Data

Model simulations were conducted on daily time steps from January 1997 to November 2000. For data analyses, the simulation period was classified into four seasons – winter (January, February, March of the present year and December of the previous year), spring (April and May), summer (June, July, and August), and fall (September, October, and November). Figure 3 illustrates the precipitation and air temperature conditions in the watershed, and Table 1 presents average values of seasonal and annual conditions during the simulation period. Based on average annual precipitation data presented in Table 1, 1997 was classified as below normal (844 mm of rainfall), 1998 as above normal (1,093 mm), and 1999 and 2000 as normal years (948 and 962 mm, respectively). However, streamflows recorded at the watershed outlet did not appear to follow the same annual precipitation trends. During the study period, 281, 557, 255, and 430 mm of streamflows were recorded during 1997, 1998, 1999, and 2000, respectively. Thus, based on streamflows measured at the watershed outlet, 1998 and 2000 were above normal years and 1997 and 1999 were below normal years.

The S-P ratios presented in Table 2 indicate a larger conversion of precipitation to stream flow in 1998 (0.51), an above normal year based on precipitation, than any other year. However, 1999, which received more precipitation than 1997, recorded less streamflow and a lower S-P ratio than 1997. This may imply that the available storage for soil moisture was greater in 1999 than in 1997, allowing for increased

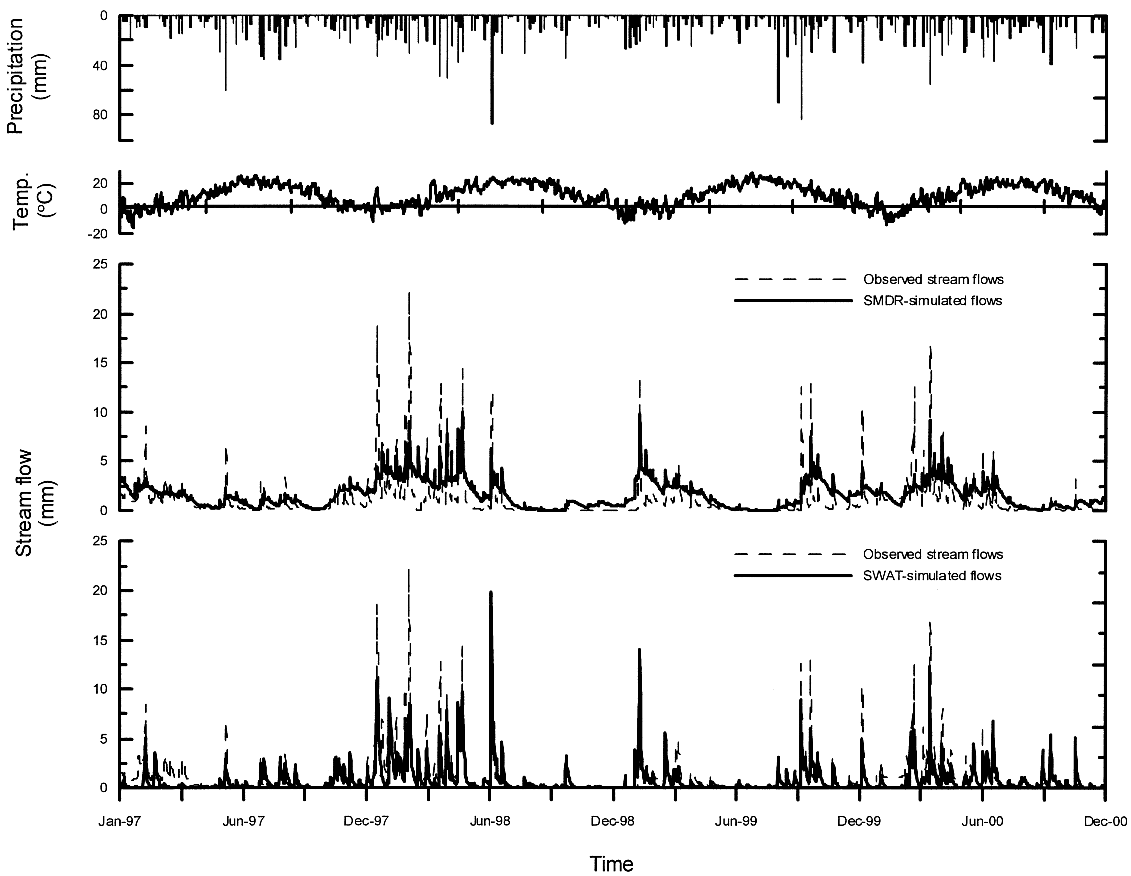

Figure 3. Observed Precipitation and Air Temperature and Observed and Simulated Streamflow Hydrographs for the FD-36 Watershed From January 1997 Through November 2000.

infiltration in 1999. Comparison of S-P ratios presented in Table 2 for various seasons between 1997 and 1999 indicated that streamflow conversions were greatly different in winter and summer between those two years. Summer streamflows were very low in 1999 (see Figure 3). Plant uptake and evapotranspiration significantly reduced the S-P ratios during this season, though it received the most precipitation during the year. Though average summer temperatures were not significantly different between years (< 2˚C), 1999 recorded just 3 mm of streamflow, as opposed to a four-year summer average flow of 41.6 mm (Table 1).

During the winter season, precipitation recorded in FD-36 watershed included both snowfall and rainfall. On average, air temperatures remained below freezing conditions for 45 days of the year. Fifty-one millimeters of precipitation occurred during these periods, accounting for 19 percent of total winter precipitation. During the winter seasons of the simulation period, the average air temperature during below freezing periods was -3.6˚C. It can be assumed that the soil did not freeze at this temperature and infiltration continued to occur. During the winter seasons of 1997 and 1999, 170 and 288 mm, respectively, of precipitation was received, and 132 and 122 mm, respectively, of streamflows were recorded, which suggests active recharge of subsurface reservoirs in 1999. Despite this active recharge during winter 1999, the S-P ratios for spring and summer of 1999 were the smallest for those respective seasons for the entire simulation period (see Table 2).

TABLE 1. Seasonal and Annual Average Values of Observed Air Temperature, Precipitation, and Streamflow Data and Streamflow to Precipitation Ratio in the FD-36 Watershed During the Simulation Period of January 1997 to November 2000.

	Temperature (˚C)	Precipitation (mm)	Streamflow (mm)	S-P Ratio
Winter	1.1	269.0	212.4	0.79
Spring	12.7	174.0	85.6	0.49
Summer	20.7	301.0	41.6	0.14
Fall	11.1	218.0	41.7	0.19
Annual	10.4	963.0	381.3	0.40

TABLE 2. Streamflow to Precipitation Ratio Calculated Based on Observed and Simulated Data for the FD-36 Watershed.

	Streamflow/Precipitation 1997			Streamflow/Precipitation 1998			Streamflow/Precipitation 1999			Streamflow/Precipitation 2000		
	SMDR	**SWAT**	**Observed**	**SMDR**	**SWAT**	**Observed**	**SMDR**	**SWAT**	**Observed**	**SMDR**	**SWAT**	**Observed**
Winter	1.10	0.25	0.86	1.12	0.66	0.91	0.87	0.39	0.41	0.99	0.47	0.99
Spring	0.50	0.09	0.35	0.70	0.41	0.59	0.77	0.11	0.31	0.80	0.29	0.50
Summer	0.21	0.15	0.15	0.37	0.33	0.19	0.07	0.11	0.01	0.37	0.25	0.17
Fall	0.42	0.29	0.23	0.24	0.17	0.03	0.63	0.31	0.30	0.29	0.32	0.10
Annual	0.47	0.20	0.33	0.69	0.44	0.51	0.59	0.26	0.27	0.61	0.33	0.45

Analyses of seasonal precipitation and streamflow trends provide some insight into the "variations" exhibited by the watershed in converting precipitation to streamflow. Precipitation data from individual seasons suggested that seasonal precipitation trends might not necessarily reflect annual trends. For example, summer precipitation data from 1997 indicated that precipitation levels were above normal for that season (384 mm), while 1997, on the whole, was classified as a below normal precipitation year. Similarly, during the fall of 1998, precipitation levels were below normal (149 mm), though 1998 received precipitation in excess of annual average values. Observed streamflows reflected these seasonal precipitation trends. Although the annual S-P ratio for 1998 (Table 2) indicated that 48 percent of the precipitation received was converted to streamflow, only 3 percent of the precipitation became streamflow during the fall of that year. Overall, 1998 was an above normal year, although the precipitation levels were below normal during the spring and summer seasons and above normal during the winter and fall seasons of that year.

Also, the effect of one season on the following season was evident from precipitation to streamflow conversions. A dry season preceding a normal or wet season resulted in low S-P ratios during the succeeding season. For example, above normal precipitations were recorded during summer 1997 and winter 1999 (384 and 288 mm, respectively). However, a dry spring season (91 mm of rainfall) preceding the summer 1997 and a dry fall season (149 mm) preceding winter 1999 resulted in low S-P ratios during summer 1997 and winter 1999. On the other hand, the winter 2000 that followed a wet fall season (323 mm) recorded the largest S-P ratio among all seasons. Thus, to capture rainfall to streamflow conversion dynamics, it is necessary to continuously track watershed conditions and alter watershed parameters within the models to match observed watershed response. Large time scales such as annual may be useful in describing average watershed response, but they may not sufficiently capture the dynamics of runoff generation processes and watershed conditions leading to runoff generation. Analyses of seasonal data indicated that streamflow generation dynamics were greatly impacted by precipitation received during individual seasons and moisture transferred from preceding seasons. Thus, seasonal prediction of watershed behavior is critical to understanding runoff generation dynamics and, hence, P transport.

Evaluation of Models' Performance Based on Temporal and Spatial Responses

Temporal results are presented at four levels – daily, seasonal, annual, and the entire simulation period. Daily flow simulations are useful in identifying runoff events that have large propensity to transport nutrients to water bodies. Seasonal flow trends and watershed conditions are given an additional focus later in this paper, as agricultural management activities are planned based on seasonal conditions.

Daily observed and simulated stream flow data are shown in Figure 3. Over the entire simulation period, based on daily observed and simulated stream flow data, N-S coefficients were 0.33 for SMDR and 0.62 for SWAT. Thus, SWAT daily simulations of stream flow matched better with the observed than did the SMDR simulations (compare SWAT, SMDR, and observed hydrographs shown in Figure 3). D_v values for the entire simulation period indicated that SMDR overpredicted total observed flows by 50 percent, while SWAT underpredicted the same by 20 percent. However, these results varied widely across seasons and years (see Table 3).

An examination of seasonal N-S coefficients for SMDR and SWAT models (Table 3) indicates that daily observed and simulated flows did not show similar levels of agreement over different seasons. This can also be taken as an indicator of model response to

TABLE 3. Results From Seasonal and Annual Statistical Analyses of Simulated Streamflow Data for the FD-36 Watershed.

	N-S*Coeff. 1997		N-S*Coeff. 1998		N-S*Coeff. 1999		N-S*Coeff. 2000		Dv** 1997		D_v** 1998		D_v** 1999		D_v** 2000	
	SMDR	SWAT	SMDR	SWAT	SMDR	SWAT	SMDR	SWAT	SMDR	SWAT	SMDR	SWAT	SMDR	SWAT	SMDR	SWAT
Winter	0.17	-0.40	0.39	0.54	0.01	0.59	0.39	0.62	-27	71	-24	26	-114	4	0	52
Spring	0.74	0.32	0.53	0.77	-0.77	0.55	0.12	0.51	-43	73	-18	30	-150	65	-59	42
Summer	0.32	0.56	0.36	0.69	0.94	0.76	0.27	0.82	-29	2	-48	-71	-80	-750	-55	-47
Fall	0.48	0.88	0.80	0.76	-0.07	0.77	0.58	-0.07	-86	-29	-648	-419	-109	-2	-200	-228
Annual	0.34	0.26	0.44	0.63	0.06	0.69	0.36	0.58	-40	40	-34	14	-120	1	-37	26

*Nash-Sutcliffe Coefficient = 1-{Σ(Observed Flow - Simulated Flow)^2 / Σ(Observed Flow - Observed Average Flow)^2}

**Dv = Σ(Observed Flows - Simulated Flows) / Σ(Observed Flows); expressed in percent.

varying input (precipitation) and receiving (watershed) conditions. While SMDR daily simulations in the fall of 1998 indicated a large N-S coefficient (0.80), the winter and spring seasons (1999) that followed indicated poor daily simulations (N-S coefficient: 0.01 and -0.77, respectively). Again, the model showed an improved performance in summer 1999 (0.94), before declining again during the 1999 fall season (-0.07). Thus, over five consecutive seasons, fall 1998 to fall 1999, the model simulations displayed mixed levels of agreement with the observed. For SMDR simulations, N-S coefficients during the spring and fall of 1997, all four seasons of 1998, summer of 1999, and winter and fall of 2000 were greater than the N-S coefficient of the entire simulation period (0.33). Thus, the model formulations can not be regarded inaccurate for any particular season, but the model could not adequately capture the seasonal dynamics of the watershed processes. Seasonal N-S coefficients for SWAT daily simulations indicated that SWAT matched the observed values better than the SMDR model matched the observed. For the same period between fall 1998 and fall 1999, when the SMDR simulations showed rising and falling levels of agreements with the daily observed data, SWAT simulations displayed consistently good matches with the observed.

Both models assume precipitation occurring during below freezing temperatures as snow fall and accumulate the snow on the watershed until the temperature rises above freezing. Streamflow to precipitation ratios greater than one during two of the winter seasons (SMDR simulations, 1997 and 1998; see Table 2) inferred that streamflows produced were greater than precipitation received, causing a drain on the watershed storage. On the other hand, SWAT consistently underpredicted winter stream flows, implying excessive watershed storage during winter seasons. While SMDR snow routines are still under development (Soil and Water Laboratory, 2002), many studies have indicated that SWAT snow simulation routines need improvement (e.g., Peterson and Hamlett, 1998). Fontaine *et al.* (2002) presented recommendations to improve the snow simulation routines of the SWAT. However, the version of SWAT model used in this study did not include any of those recommended snow simulation routines. When simulations from winter season were excluded from statistical analyses, the performance of the models improved – N-S coefficients increased to 0.39 for SMDR and 0.71 for SWAT. The difference between the total observed and SWAT simulated stream flow volumes over the entire simulation period was less than 1 percent when winter simulations excluded. However, the D_v value for SMDR indicated that the model overpredicted the flows by 70 percent without winter simulations. From

Tables 2 (S-P values) and 3 (D_v values), it can be seen that SMDR consistently overpredicted stream flows during all seasons, and thus, excluding winter simulations from analyses did not significantly improve the model performance.

SWAT continued to underpredict streamflows during the spring seasons (Table 2), while SMDR continued to overpredict the same. Underprediction of flows during the winter periods implied that SWAT recharged the subsurface storage in excess of observed. However, underprediction of observed streamflows in spring indicated that either the excess storage from winter was not impacting the spring flows adequately by allowing the model to choose large CNs to represent wet conditions, or the SWAT simulated drainage of subsurface storage was quicker than observed.

Although many of the large precipitation events were recorded during summer and early-fall seasons, the majority of peak flow events were recorded during late fall, winter, and early spring periods (see Figure 3). Pionke *et al.* (1997) indicated the dominance of five to seven large storm events on P transport from this watershed, with many of them occurring during the spring periods. Hence, for P transport simulations, it is important that these two models predict the large spring storm flows accurately. Summer and early fall periods were characterized by dry watershed conditions, which could have resulted in small streamflows during these seasons. SWAT simulations indicated that the model overpredicted the observed storm flow during fall seasons (see negative D_v values for the fall seasons in Table 3). This may be an indication that either model formulations do not adequately represent this season or the calibration parameters need to be appropriately adjusted.

Temporal Simulation Results for Selected Precipitation Events

Three precipitation events, one each from spring, summer, and fall during the simulation period, were selected to examine the temporal and spatial dynamics of runoff source areas. These three selected events allow a comparison and evaluation of the models' performance over different seasons. Observed and simulated hydrographs for extended periods before, during, and after these three storm events are depicted in Figures 4a, 5a, and 6a. Observed and simulated streamflows before the selected events are indicative of actual and simulated watershed conditions, respectively, while post-storm flows infer how quickly the simulated watershed conditions match the observed conditions (base flow recession). Spatial extents of runoff generation areas, as simulated by the models, along with the depths of runoff generated during the spring (32 mm of rainfall on April 8, 2000), summer (60 mm of rainfall on June 4, 1997), and fall events (39 mm of rainfall on September 12, 2000) are shown in Figures 4b, 5b, and 6b, respectively.

D_v values for winter 2000 (Table 3) indicated SMDR simulated volumes exactly matched the observed storm flow volumes. Hence, the watershed conditions as represented by SMDR should closely match the observed conditions. However, prior to the spring event on April 8, 2000, SMDR simulated streamflows were three times greater than the observed. SWAT simulated streamflows were 50 percent less than the observed values. Thus, SMDR indicated a wetter watershed conditions than observed, whereas SWAT indicated a drier watershed condition.

During the spring event, 32 mm of rainfall was recorded on April 8. This rainfall event occurred toward the end of that day, and hence, the observed peak was recorded on April 9. Input data to SMDR and SWAT indicated the precipitation event occurred on April 8 and they produced the peak flows on the same day. (It should be noted here that such discrepancies in rainfall timings, and hence peak flow timings, between the observed and simulated conditions can negatively influence the N-S coefficients but not the D_v values.) SMDR simulated peak flow (7.5 mm) better matched the observed (8.1 mm) than did the SWAT simulated peak flow (4.4 mm). The observed peak flow depth recorded an eight-fold increase over the base flow depth recorded the day preceding the event. However, SMDR simulated peak flow was twice as that of the preceding day's base flow, and SWAT simulated peak flow was 12 times that of the previous day's base flow. Wet watershed conditions allowed SMDR simulated storm flows to more closely match the observed flow as compared to SWAT. However, SWAT predicted flow increases from base flow to storm flow more closely matched the observed than did the SMDR.

During the summer event that occurred on June 4, 1997 (Figure 5a), neither SWAT simulated nor SMDR simulated peak flows increased as much as the observed. Prior to the storm event on June 4, both observed and simulated streamflows indicated dry watershed conditions. Base flows on June 3 were 0.2 mm (observed), 0.6 mm (SMDR), and 0.1 mm (SWAT). Peak flows recorded on June 4 were 6.7 mm (observed), 2.3 mm (SMDR), and 2.9 mm (SWAT). Observed and SWAT simulated flows recorded an increase of approximately 30 times from base flow to peak flow, while SMDR simulated only a four-fold increase. Since the SWAT simulated base flow was less than half of the observed, the model underpredicted the observed peak. Also, during this storm,

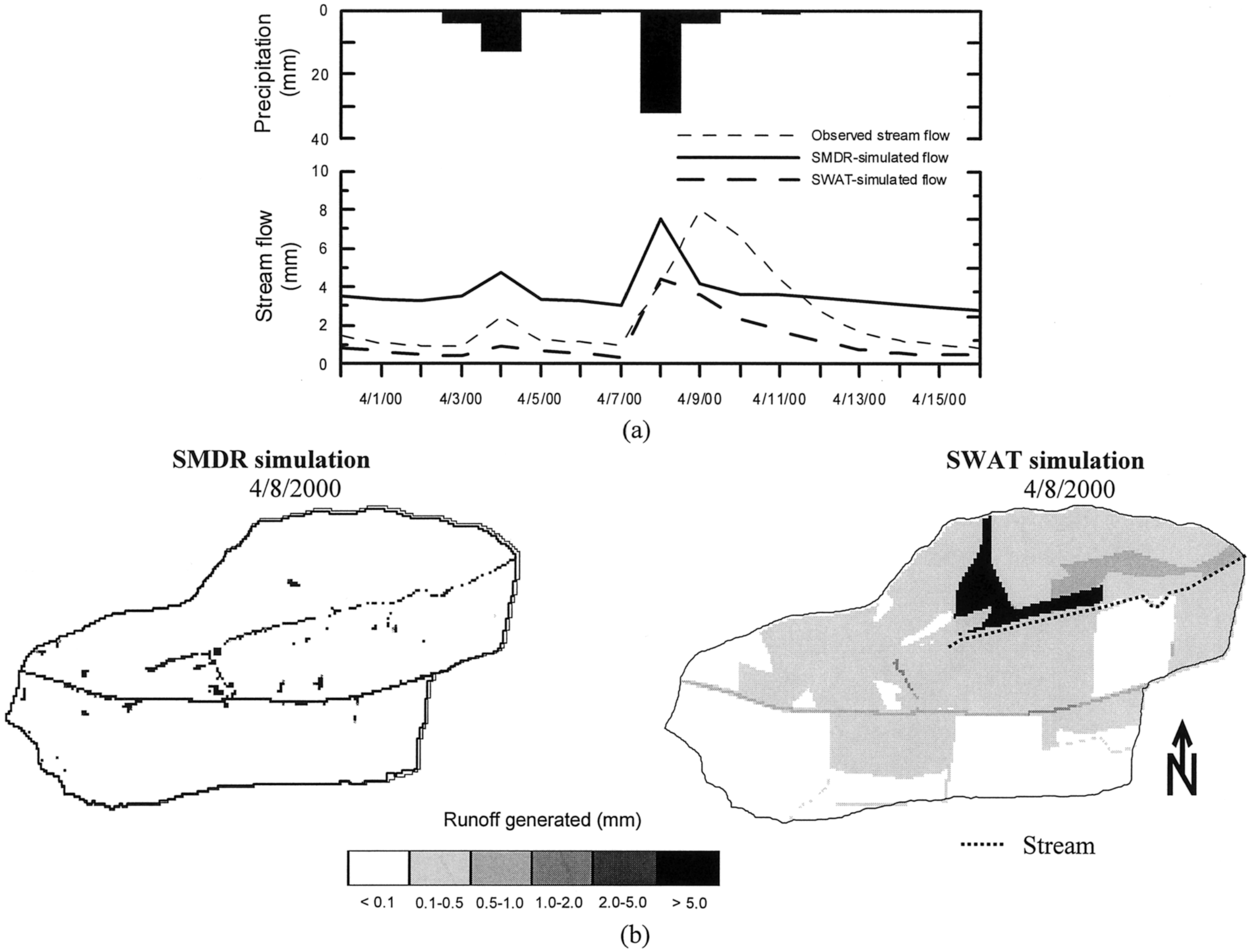

Figure 4. Temporal and Spatial Data for a Precipitation Event That Occurred on April 8, 2000, in the FD-36 Watershed: (a) Observed and Simulated Streamflow Hydrographs; (b) SMDR Simulated and SWAT Simulated Runoff Source Areas.

36.5 mm of rainfall was received in less than 130 minutes after the storm began. This high intensity storm could have resulted in significant infiltration excess runoff, which SMDR does not simulate. SWAT does not explicitly represent infiltration excess and saturation excess runoff processes. Both models use total precipitation depths on a daily basis, instead of rainfall intensity data.

During the fall event that recorded 39 mm of rainfall on September 12, 2000 (Figure 6a), the observed peak flow was 1.3 mm, while SMDR simulated and SWAT simulated peak flows were 0.9 and 5.2 mm, respectively. Similar to the spring event, because of the timing of the precipitation event, the observed peak flow was recorded the following day. Prestorm base flows simulated by SWAT were comparable to that of observed. However, the peak flow generated by SWAT was four times greater than the observed. SWAT simulated recession curve indicated larger base flows on days following the storm event, which resulted in larger than observed storm flows for this event (see Figure 6a). Larger than observed S-P ratios (Table 2) and negative D_v values (Table 3) over all fall seasons for SWAT indicated that this model underpredicted the available watershed storage during fall periods. D_v values for SWAT simulation during the summer periods shown in Table 3 indicated that except for the summer of 1997, SWAT generally overpredicted the flows during summers. Thus, underprediction of total storm flows during winter and spring and overprediction during summer and fall allowed the SWAT simulated total streamflow volumes to better match with the observed on an annual basis. However, N-S coefficients for SWAT model during the fall seasons were greater than the N-S coefficients calculated for the SWAT model for the entire

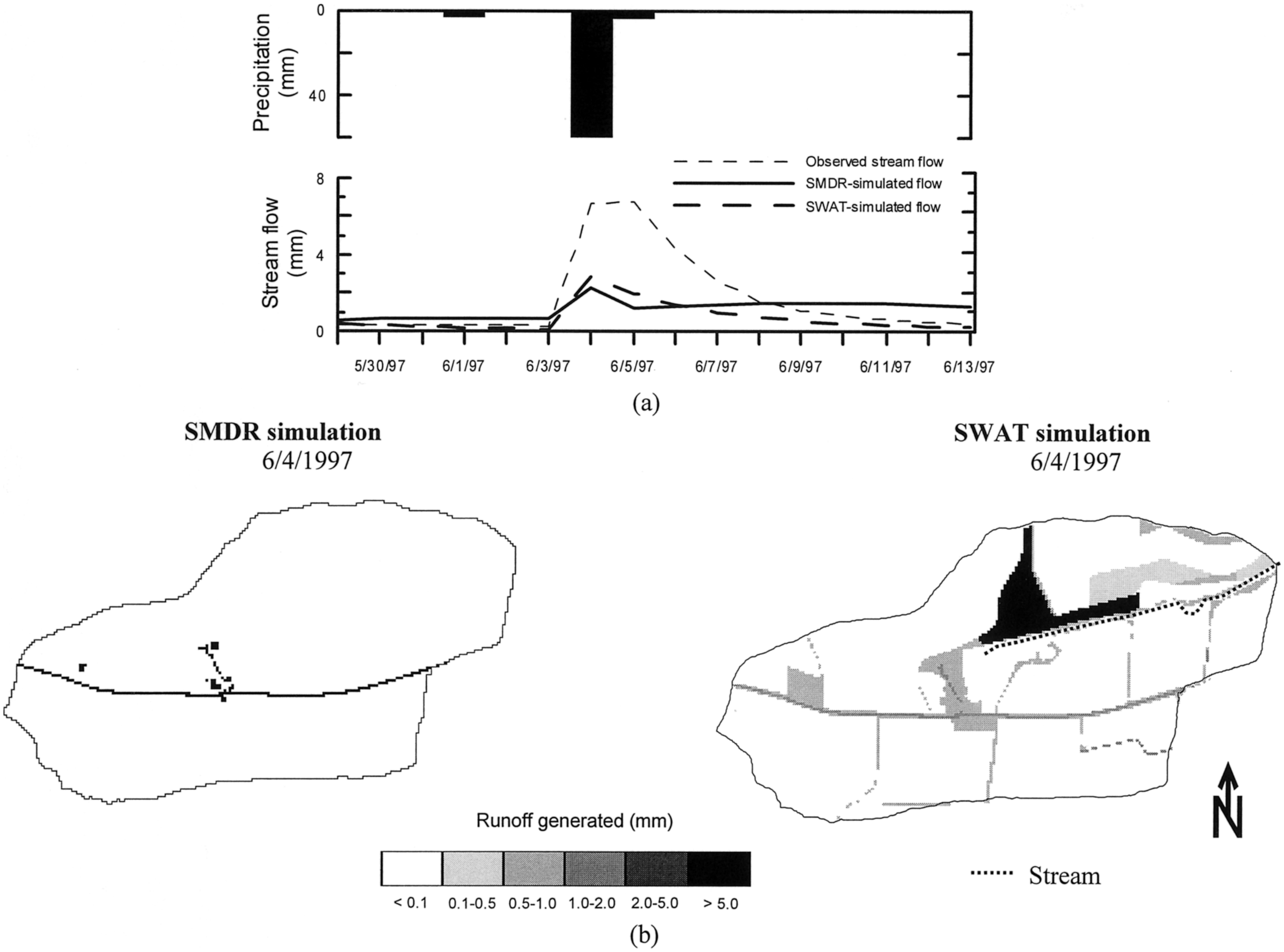

Figure 5. Temporal and Spatial Data for a Precipitation Event that Occurred on June 4, 1997, in the FD-36 Watershed: (a) Observed and Simulated Streamflow Hydrographs; (b) SMDR Simulated and SWAT Simulated Runoff Source Areas.

simulation period, which indicated that the model formulations may not be necessarily incorrect during the fall seasons.

Spatial Simulation Results for the Selected Precipitation Events

Figures 4b, 5b, and 6b present spatial maps of runoff source areas from SMDR and SWAT simulations for the above discussed three precipitation events. The current version of the SMDR model does not explicitly represent streams. Hence no streams are shown in SMDR spatial maps. Spatial maps from selected storms indicated that SWAT produced storm flows from a larger area within the watershed than did SMDR. This could have resulted in quick increases from base flow to storm flow in SWAT than SMDR. The extent of runoff generation areas directly influences the P transport to the water bodies. However, overall flow data indicated that SMDR overpredicted the total observed flows than did SWAT. Movement of moisture towards the stream on successive days (Figure 7) and slow recession of base flow curves (Figure 4a, 5a, and 6a) simulated by SMDR indicate that this model's responses are not as quick as the observed. However, subsequent days of subsurface drainage in the SMDR model led to excessive drainage of watershed storage. Consistent overprediction of observed seasonal storm flows by SMDR (see Tables 2 and 3, large S-P values and negative Dv values, respectively) indicates that this model allows less than observed

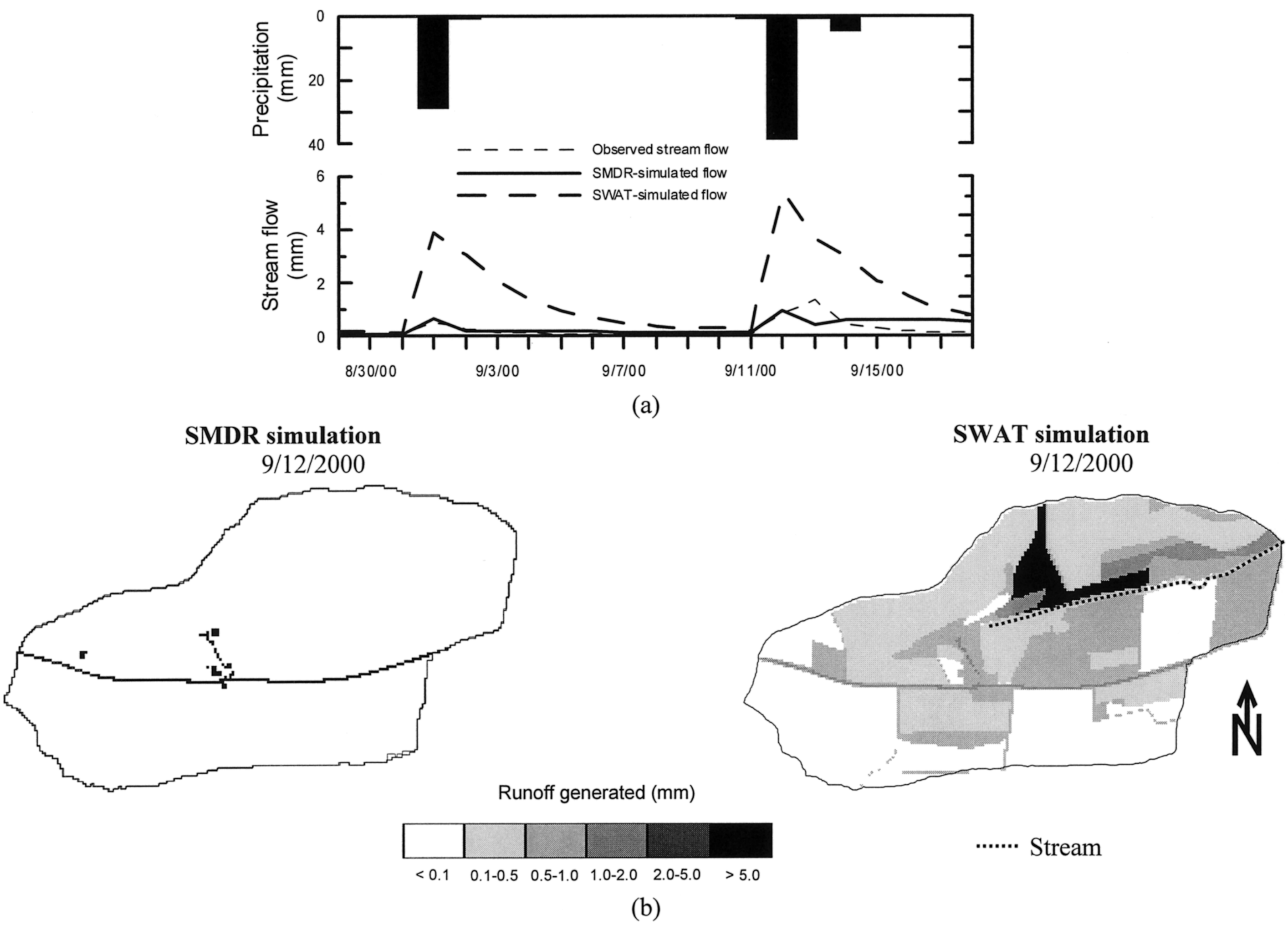

Figure 6. Temporal and Spatial Data for a Precipitation Event That Occurred on September 12, 2000, in the FD-36 Watershed: (a) Observed and Simulated Streamflow Hydrographs; (b) SMDR Simulated and SWAT Simulated Runoff Source Areas.

storage in the watershed. Smaller than observed watershed storage can negatively impact other processes such as evaporation, recharge, and soil storage, and hence runoff generation processes. Even though increasing the watershed storage in SMDR can reduce the seasonal overprediction of streamflows, it can also further reduce peak flow discharges. Peak flow discharges are critical for P transport.

An investigation into the process of runoff simulation is useful in understanding the spatial data from these two models. SMDR is primarily a storage based model. Cell storage can be controlled either by increasing the grid size or by increasing the soil depth. However, as cell storage increases, the propensity of that cell to produce runoff decreases. Upon saturation, cells, irrespective of their location within the watershed, contribute runoff to the watershed outlet. As subsurface water moves from higher to lower elevations of the watershed, a subsurface wetting front is observed within the watershed. Figure 7 presents a snapshot of this wetting front immediately after the spring event depicted in Figure 4. In the FD-36 watershed, when the subsurface flow enters fragipan soils from nonfragipan soils, reduced available storage in the fragipan soils results in saturation zones at the interface. This interface clearly marks the upper end of fragipan soils in Figure 7. Subsurface flow at this interface in excess of storage is transferred to the watershed outlet within the same time step in SMDR model. As the subsurface water movement continues beyond the interface into the fragipan soils, the saturation zones dissipate (see simulated soil saturation data on April 13, 2000, in Figure 7). In reality, moisture in excess of soil storage results in surface saturation zones. Over a period of time, these surface saturation zones lose moisture by runoff,

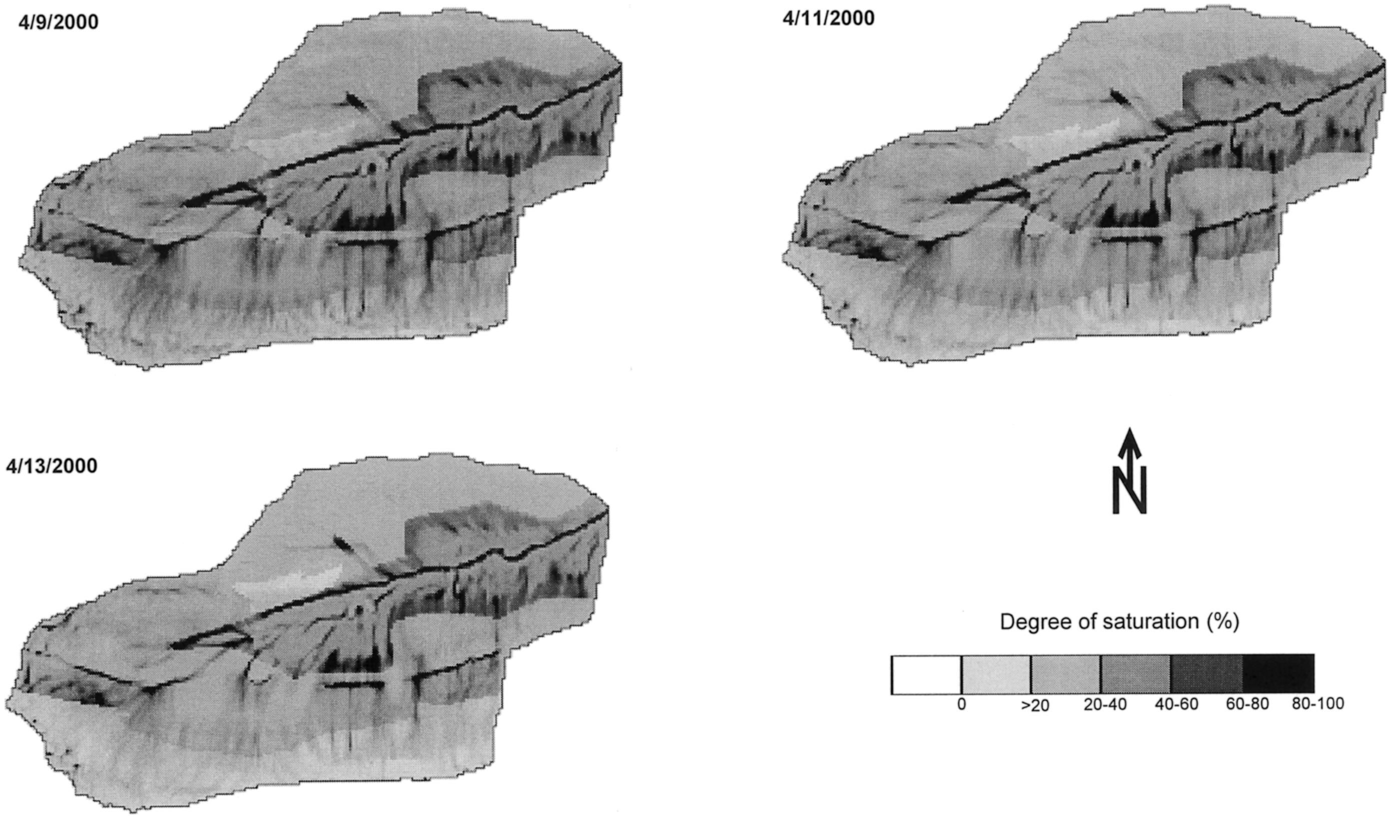

Figure 7. Subsurface Moisture Movement and the Dynamics of Soil Saturation Within the FD-36 Watershed, as Simulated by the SMDR Model Immediately Following a Storm Event That Occurred on April 8, 2000 (event shown in Figure 4).

infiltration, and/or evaporation. Unless these saturation zones are hydraulically connected to water bodies, the moisture from these zones does not reach the water bodies. Field observations in this watershed have indicated the occurrence of such saturation zones at the interface. Thus, these interfaces have high potential to generate runoff during and immediately following rainfall events, but in the absence defined flow paths, the generated runoff may not reach the stream.

SMDR peak discharges can be improved by using smaller cell sizes, allowing more cells to generate runoff. However, this can lead to overprediction of flow volumes. Using smaller cell sizes in the near-stream areas and areas that have shown potential to generate quick runoff and larger cell sizes in the rest of the watershed could be an alternative to generate quick flows in SMDR. However, SMDR in its present form does not support variable cell sizes within the watershed.

SWAT alters the CN to represent watershed (moisture) conditions and generate runoff. Hence, watershed storage plays a critical part in CN selection. D_v values for SWAT (Table 3) indicated that SWAT consistently underpredicted winter and spring stream flows, and overpredicted fall flows. This can be directly related to the selection of CN. As indicated earlier, during winter and spring seasons SWAT appears to be draining the subsurface quickly to the deeper systems, thereby simulating dry soil conditions. These dry soil conditions could result in small CNs and small runoff events. On the other hand, large runoff volumes during fall seasons are indicative of large CNs and slow drainage rates during this period.

Both SWAT and SMDR identified the road that runs east/west along the watershed as one of the primary runoff source areas. In both models, the representative units of the watershed appeared to be very critical in identifying runoff source areas. For example, during all three storms, SWAT identified a large corn field to the north of the stream as a major runoff source area (compare the dark colored area presented in Figures 4b, 5b, and 6b). This field had gentler slope near the ridge (< 4 percent) and steeper slopes near the stream (approximately 25 percent). Because of the large slope, SWAT identified this field to be a major runoff source area. However, SMDR, which represented the watershed as a 5 m grid, identified only a small portion of near stream areas within this corn field as runoff source areas (comparison of SMDR simulations and SWAT simulations presented in Figure 4).

Also, SWAT simulations appeared to be more sensitive to land use than soils. Since CN values, in general, are larger for agricultural land use than forest, agricultural land tends to produce more runoff in SWAT than forest for the same soil types. When fragipan soils were located within woodlands, SWAT did not identify them as runoff source areas. On the other hand, when agricultural land use intersected with fragipan soils, SWAT tended to generate runoff from those soils.

Approach to P Transport Zones Within a Watershed

Watershed scale P transport requires co-location of source and transport areas. Both SMDR and SWAT simulate transport (runoff generation) areas, but they do not simulate landscape scale routing of surface runoff from runoff generation areas to the stream. Thus, the transport areas as simulated by SMDR and SWAT are incomplete without the routing routines. The runoff generation areas depicted in Figures 4b, 5b, and 6b were all assumed to contribute runoff to the stream (in the case of SWAT) or to the watershed outlet (in the case SMDR). In the case of SWAT, surface routing of runoff would allow interaction among HRUs. SMDR allows interaction of cells while routing subsurface flow. For surface routing, SMDR may need to apply sub-daily time steps to allow routing across the watershed.

Field studies in humid regions (Ward, 1984) have shown that near stream areas are more active during storm events, producing the majority of storm flow. Humid regions are characterized by high precipitation to potential evapotranspiration ratios (Visher, 1966). Though SWAT did pick up some of the near stream areas as runoff source areas, it was not consistent. Surface routing in combination with runoff infiltration would allow the runoff from far stream areas to infiltrate into the soil before reaching the stream.

SMDR allows the user to generate daily, monthly, seasonal, and annual runoff and soil saturation maps. Based on input-output-storage dynamics during the simulation period, seasonal maps generated by SMDR are shown in Figure 8. These maps classify the watershed areas based on their propensity to become saturated over the course of a season. These saturated areas have greater potential to generate runoff upon receiving precipitation. Thus, areas that remain saturated for longer periods during a season have greater potential to produce runoff and hence have greater potential to transport P to the streams. By generating such maps on a seasonal basis, management practices within fields can be designed.

Watershed representation is a critical part of such maps. Since SMDR operates on a grid basis, seasonal maps allow management practices to be altered within small portions of a field, instead of implementing the practice over the entire field. In case of SWAT, where the entire field may be represented as one HRU, management practices can not be selectively applied within that field.

CONCLUSIONS

Two simulations models, SMDR and SWAT, were applied within a small headwater watershed in east-central Pennsylvania to identify critical runoff source areas for P transport. The empirically based SWAT model predicted time series streamflow much better than the physically based SMDR model (Nash-Sutcliffe coefficient: 0.62 and 0.33, respectively). Analyses of observed precipitation and streamflow during the simulation period indicated that understanding seasonal variations in watershed behavior is central to understanding runoff generation processes in this watershed.

While both models allowed variations in streamflows, the simulations did not consistently match with the observed data over all seasons. For example, SWAT underpredicted stream flow during the early part of the year (winter and spring) and overpredicted the flows towards the end of the year (summer and fall). SMDR overpredicted the seasonal streamflows throughout the simulation period. SMDR simulations indicated that the model does not allow sufficient storage in the watershed.

Spatial data from these two models indicated their ability to represent runoff generation areas at a watershed scale. However, as neither model allowed runoff routing across the watersheds, runoff from all runoff generation areas was assumed to reach the stream or watershed outlet. Such assumption may not be valid where surface runoff can infiltrate before reaching the streams.

SMDR simulations allow generation of seasonal soil saturation maps. Such maps, when prepared based on multiple years of observed and/or simulated data can be excellent tools for land managers and farmers. Small watershed representative units used in SMDR allow targeted management of P management within large fields.

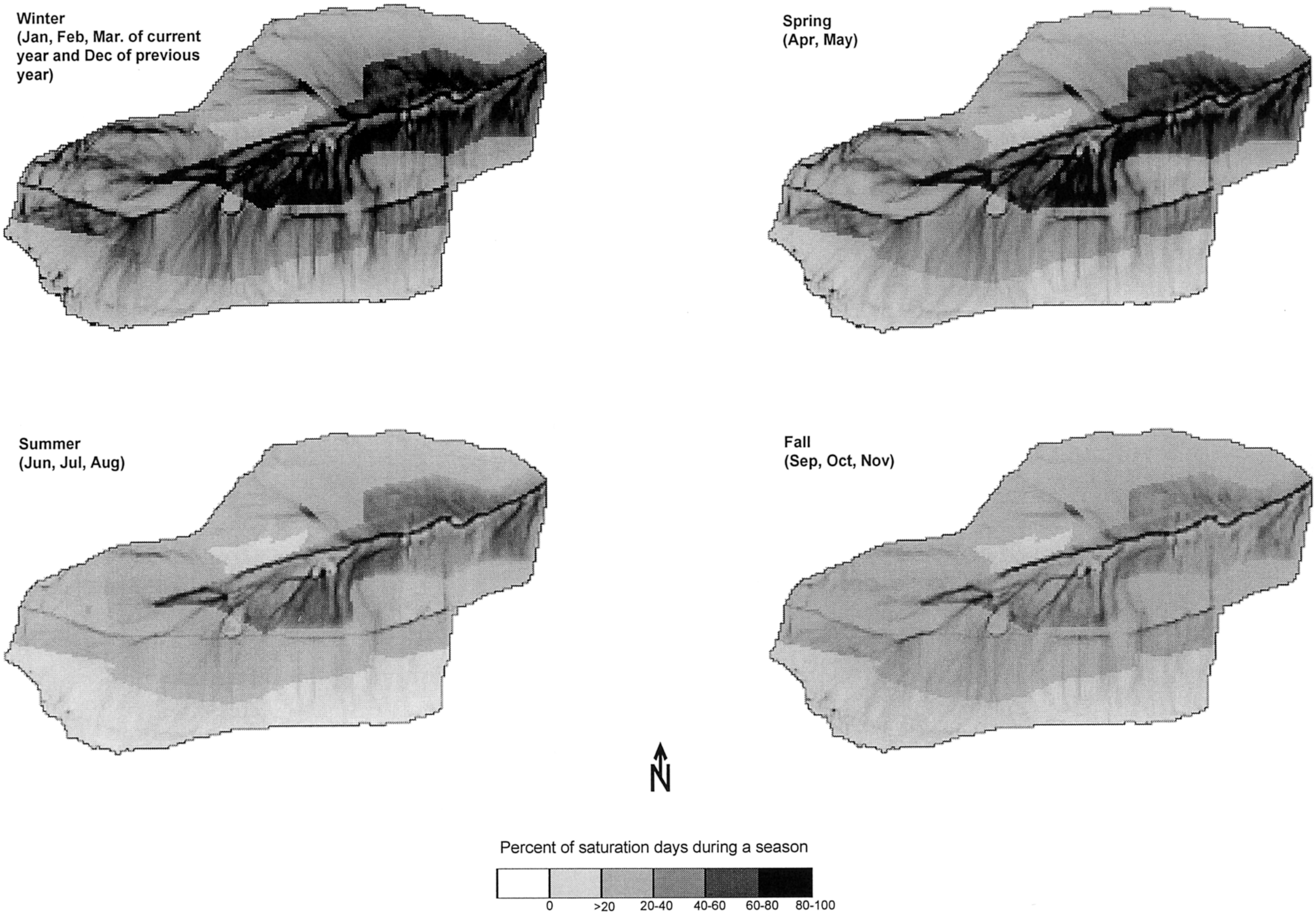

Figure 8. SMDR Prediction of Saturation Areas Over Different Seasons Based on Four-Year Simulation Data in the FD-36 Watershed.

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