Process Representation in Watershed-scale Hydrologic Models: an Evaluation in an Experimental Watershed

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Abstract

Hydrologic response varies within a watershed as a function of topography, soil, and land cover. Spatial and temporal data from experimental watersheds may provide information on where, when, how, and why the response varies. This study examined the hydrologic response of an agricultural watershed, FD-36, in the Appalachian Valley and Ridge physiographic region. FD-36 is characterized by shallow, fragipan soils in near-stream areas and deep, well-drained soils in upland areas. Three computer simulation models – Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS-2000), Soil and Water Assessment Tool (AVSWAT2000), and Soil Moisture Distribution and Routing (SMDR) – were used to simulate the surface hydrologic processes in FD-36. The three models vary in their temporal and spatial process representations. AVSWAT2000 and SMDR are daily time-step models while ANSWERS-2000 runs at a one-minute time step. Spatially, ANSWERS-2000 and SMDR divide the watershed into grid cells; AVSWAT2000 uses hydrologic response units (HRUs). Of the three models, temporal output from AVSWAT2000 matched measured stream flow most closely ($r^2 = 0.67$). ANSWERS-2000 and AVSWAT2000 both reacted to variations in land cover and soils, whereas SMDR did not. ANSWERS-2000 and AVSWAT2000 indicated the majority of high runoff depths from croplands on near-stream, fragipan soils. Overall, AVSWAT2000 was determined the most favorable for depicting hydrological processes in FD-36, although spatial representation of runoff processes in this model may need further refinement.

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Introduction

Variations in spatial and temporal efficiencies of watershed-scale rainfall-to-runoff conversion have led to stream flow generation concepts such as variable-source-area (Hewlett 1961) and partial-source-area (Dunne and Black 1970). Often, less than 10% of a watershed directly participates in storm flow generation (Freeze 1974). Even in these hydrologically active areas, rainfall-to-runoff conversion rates vary with the types of runoff generation processes: infiltration excess or saturation excess. Spatial and temporal variations in the hydrologic behavior of a watershed directly impact nutrient transport from land to water. Engman (1974) argued that management of nonpoint source pollution at the watershed scale could be confined to controlling losses from hydrologically active areas.

The cited studies motivate a need for accurately modeling spatial as well as temporal hydrologic responses within a watershed before modeling pollutant losses within that watershed. Simulation models have been very useful in studying spatial and temporal hydrological processes at watershed scales (e.g., Beven and Kirkby 1979). The objective of this study was to determine the impact of model representation of spatial and temporal processes on the characterization of runoff generation for a case watershed.

Watershed Description

The study watershed, FD-36, is a 39.5-ha headwater subwatershed of the USGS-gauged Mahantango watershed in east-central Pennsylvania. FD-36 is a study watershed of the Pasture Systems and Watershed Management Research Unit, USDA-ARS. Hydrology and nutrient transport studies have been conducted in

FD-36 since 1996. Previous field work has provided 5-m grid detail on topography and soil classification. Multi-year data were also available on the dynamics of weather, land management, and stream flow. Climate is typically temperate and humid. This watershed has a mixed land use: 50% soybean/wheat/corn, 30% forest, 19% pasture, 1% urban (Figure 1).

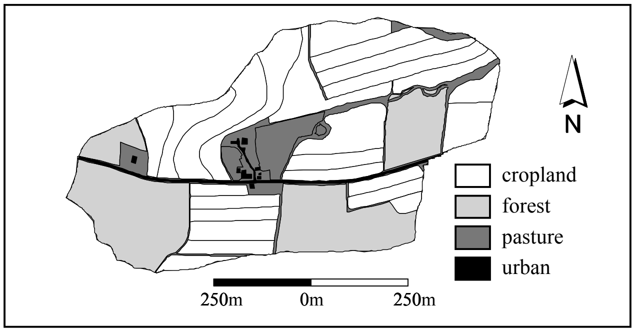


Figure 1. Land use within FD-36.

FD-36 is characterized by shallow, fragipan soils in near-stream areas and deep, well-drained soils in the uplands (Figure 2). Fragipan soil layers impede percolation, facilitating lateral flow. Field studies by Zollweg (1996) and Srinivasan et al. (2002) in an adjacent, non-fragipan watershed established that near-stream areas are hydrologically active during storm events. A landscape-scale study in FD-36 demonstrated the dominance of fragipan soils in runoff generation (Needelman 2002). FD-36, with fragipan soils in near-stream areas, appears to be a good candidate for model comparisons of hydrologically active areas.

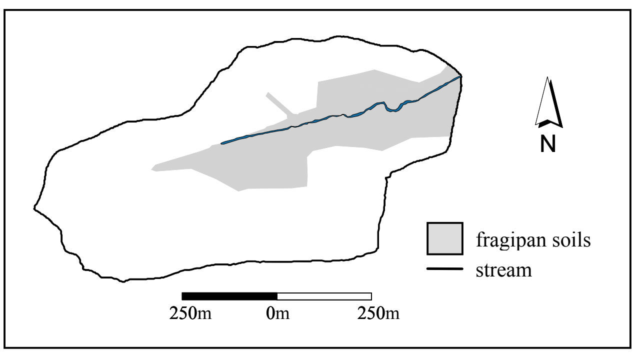


Figure 2. Extent and location of fragipan soils in FD-36.

Simulation Models

Three continuous, watershed-scale, simulation models were selected: ANSWERS-2000 (Bouraoui and Dillaha 1996), AVSWAT2000 (Arnold et al. 1998), and SMDR (Soil and Water Laboratory 2002). All three models are designed for use in ungaged, agricultural watersheds. ANSWERS-2000 and SMDR are physically-based and not suited to calibration. AVSWAT2000 can be calibrated when data are available, as was the case in this study. Additionally, each model represents spatial and temporal processes differently (Table 1).

ANSWERS-2000 and SMDR use more detailed spatial resolution than does AVSWAT2000 (Table 1). Also, ANSWERS-2000 employs a much smaller time step for both precipitation and model processing than do the other two models. These increases in temporal and spatial resolution have the potential to improve depictions of hydrologic response.

ANSWERS-2000 calculates runoff using both infiltration and saturation excess mechanisms (Table 1). AVSWAT2000 uses the Curve Number approach to calculate runoff based on soil moisture and land cover. SMDR calculates surface runoff as saturation excess.

The rigor of surface flow routing within the watershed declines from ANSWERS-2000 to AVSWAT2000 to SMDR (Table 1). However, both AVSWAT2000 and SMDR route subsurface flow laterally, while ANSWERS-2000 contains only a limited groundwater recharge component and no stream base flow component. Absence of a subsurface flow component may be a disadvantage in FD-36 where lateral flow across fragipan soils is thought to be a key factor.

Results and Discussion

The models were run for a four-year period, 1997-2000. During this period the average annual precipitation was 1021 mm, resulting in an average measured runoff depth of 393 mm. For the purpose of discussion, 1999 was considered typical of the four-year simulation period. In 1999, 1021 mm of rainfall and 297 mm of stream flow were recorded.

Temporal output

Figure 3 shows observed and simulated stream flow hydrographs during 1999. Of the three models considered, AVSWAT2000 stream flow values agreed most strongly with the observed flows ($r^2 = 0.67$, Nash-Sutcliffe = 0.66). In ANSWERS-2000, the effect of a storm event on stream flow does not last beyond the storm day. Steep falling limbs of ANSWERS-2000 hydrographs are indicative of quick conversion,

Table 1. Comparison of spatial and temporal processes within simulation models.

		ANSWERS-2000	AVSWAT2000	SMDR (ver. 2002)
1.	Watershed representation	5-m grid	Hydrologic response units (HRUs): unique combinations of soils and land use	5-m grid
2.	Simulation interval	60 seconds	Daily	Daily
3.	Precipitation interval	Breakpoint	Daily	Daily
4.	Rainfall-runoff conversion	Green-Ampt infiltration equation	Curve Number (adjusted for soil moisture)	Infiltration capacity from soils data
5.	Surface flow routing	Cell to cell	HRU to stream	Cell to watershed outlet

routing, and cell outflow of surface runoff during storm events. Considering only storm events and adjusting for concurrent measured base flow, ANSWERS-2000 matched weakly with observed values (r^2 = 0.27, Nash-Sutcliffe = -1.26). SMDR-simulated stream flows also correlated weakly with observed values (r^2 = 0.33, Nash-Sutcliffe = 0.03). Absence of an infiltration excess runoff component in SMDR was noticeable during large storm events. While SMDR did not match observed peak flows during storm events, it produced larger than observed flows on days following storm events. This resulted in a mismatch of base flows and base flow recession curves as compared to measured data. Observed and SMDR-simulated storm flow volumes were comparable but flow timings were not.

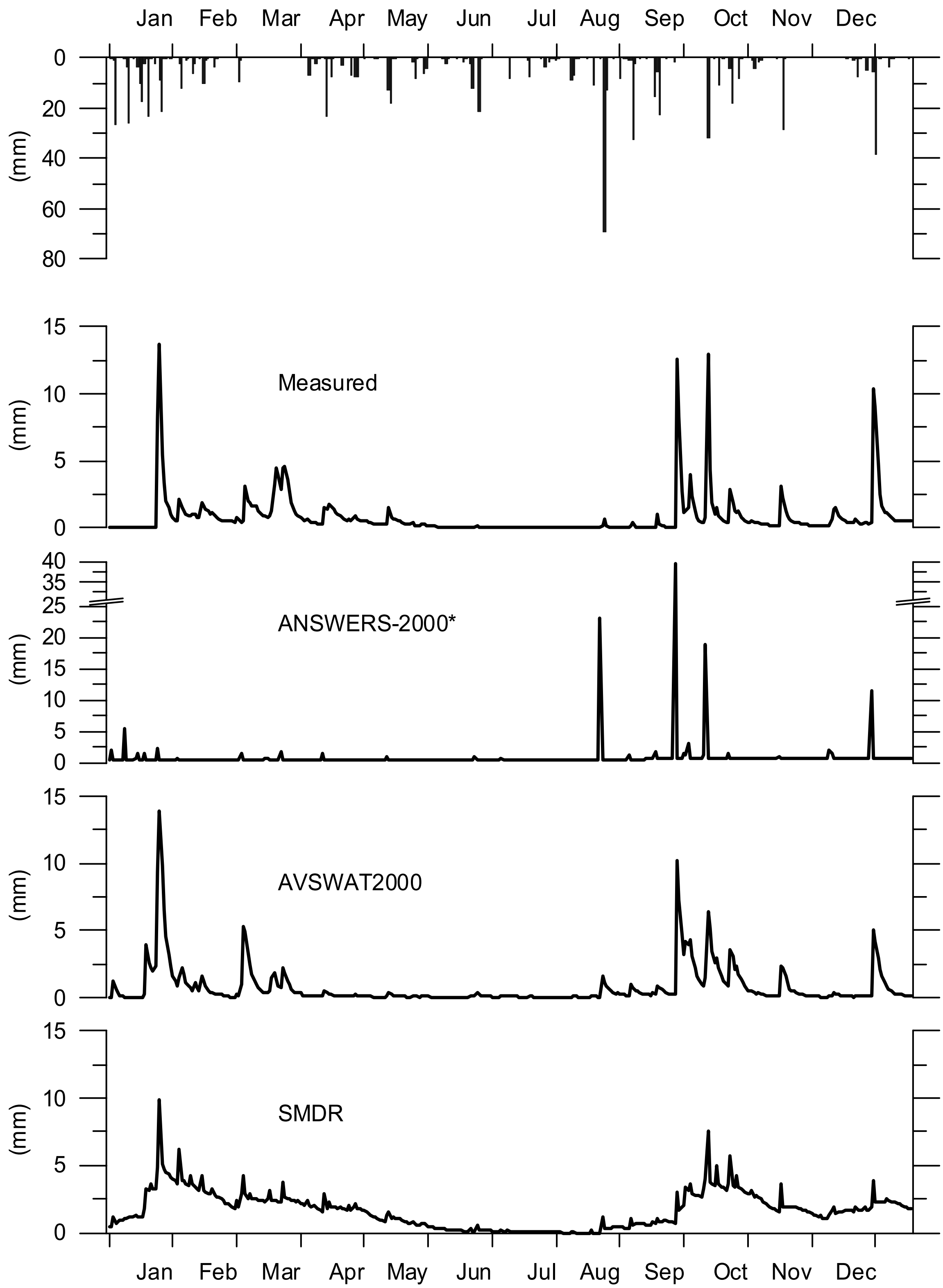
Below-freezing temperatures and significant snowfall were observed during the early part of 1999. AVSWAT2000 best matched the observed stream flow responses during this period. ANSWERS-2000 treats all forms of precipitation as rain. Immediate conversion of snowfall to stream flow and absence of snow pack in ANSWERS-2000 affected soil moisture conditions and storm flow simulations during winter months and the warm period immediately following. The slow hydrograph recession of SMDR-simulated stream flow during winter supports conclusions by Srinivasan et al. (2003) that snowmelt routines in SMDR need further refinement.

Dry weather conditions from April to August resulted in very low stream flows. All three models simulated these low flow conditions. A large storm event (69 mm) ended this dry spell but resulted in less than 1% conversion of rainfall to runoff. Both AVSWAT2000 and SMDR produced low flows similar to the observed for this event; ANSWERS-2000 converted more than 50% of the rainfall to runoff. A similar situation occurred for a September event. These high over-predictions of storm flow by ANSWERS-2000 could be due to poor tracking of soil moisture conditions during dry periods or shortness of simulated storm duration.

Spatial output

Figure 4 presents annual runoff generated by each cell (ANSWERS-2000 and SMDR) or HRU (AVSWAT2000) in FD-36 during 1999. ANSWERS-2000 routes surface runoff from cell to cell. This interaction between cells enables infiltration or accumulation of runoff, depending on downstream conditions. For example, runoff levels remained low over the pasture in the center of the watershed (Figure 4), indicating runoff entering from surrounding cropland infiltrated into the pasture. In contrast, runoff through the forest on the southern side of the watershed accumulated as it followed the flow path north through forest and cropland to the stream. ANSWERS-2000 generally simulated high runoff depths where croplands occur on fragipan soils. However, these areas are also near-stream areas. It is unclear, using the output formats currently available, whether ANSWERS-2000 treated the near-stream areas as hydrologically more active than other areas, as simply transporting upland accumulation, or as some combination. Clarification of this issue is advisable before looking at pollution transport associated with this routing procedure.

AVSWAT2000 routes both surface and subsurface flow directly from HRU to stream, with no interaction between HRUs. Thus, an upland HRU may contribute more flow per unit area to a stream



* Note: ANSWERS-2000 does not simulate base flow. For comparison purposes, base flow has been added here.

Figure 3. Observed and simulated stream flow depths from the FD-36 watershed during 1999.

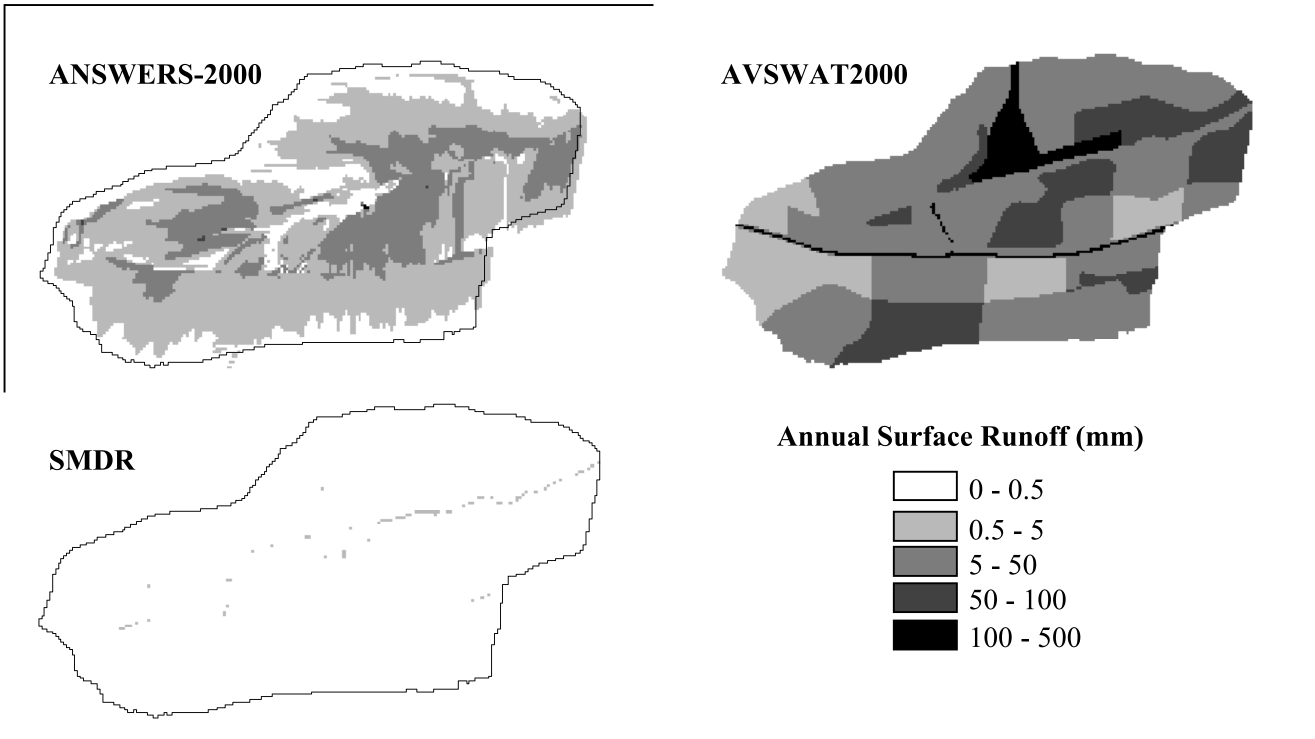


Figure 4. Spatial depictions of hydrological response during 1999: total surface runoff from each spatial unit.

than a near-stream HRU (Figure 4). For example, from within each field AVSWAT2000 generated more surface runoff from some soils than others. Overall, in AVSSWAT2000, cropland produced the most runoff and forest the least, as might be expected. Particularly high runoff depths were seen on roads and on one field remaining in wheat stubble for the latter half of the year.

SMDR is appropriate for small watersheds, such as FD-36, where surface routing periods are less than a day. SMDR produces surface runoff only after a cell becomes saturated. Upon saturation, excess water is moved directly from the cell to the watershed outlet as surface runoff, with no surface interaction among cells. At the subsurface level, SMDR routes water from cell to cell at a rate of one cell per day. By routing subsurface flow from upland to near-stream cells in between storm events, SMDR causes near-stream cells to remain relatively wetter than upland cells. Due to simulating greater soil water storage than actually available in FD-36, SMDR did not produce the volumes of surface runoff that ANSWERS-2000 and AVSWAT2000 did (Figure 4). SMDR did identify near-stream areas as hydrologically more active than upland areas (data not shown). Including infiltration excess mechanisms may improve SMDR's performance.

Conclusions

This study assessed the ability of three models to depict spatial and temporal processes of a small, agricultural watershed with fragipan soils. All three models captured most major temporal variations seen in total surface runoff from the watershed in 1999; AVSWAT2000 achieved the strongest temporal statistical correlation. In contrast, spatial identification of runoff generation areas varied distinctly among the three models. Unlike SMDR, AVSWAT2000 and ANSWERS-2000 recognized differences in land use and soil characteristics within the watershed. This recognition is critical for making proper management recommendations. ANSWERS-2000 and, to a lesser extent, AVSWAT2000 depicted higher runoff depths from the near-stream, fragipan soils than from other areas. Differences were also seen in the ranges of simulated runoff depths. AVSWAT2000 produced as much as 100 mm of runoff per HRU while SMDR surface runoff depths did not exceed 5 mm over a 5-m grid cell. ANSWERS-2000 runoff values ranged between 0 and 100 mm per 5-m grid cell, representing upstream flow accumulation from watershed boundary.

Although AVSWAT2000 uses less detailed process representations than ANSWERS-2000 or SMDR, AVSWAT2000 was chosen out of the three models as most accurately depicting the hydrological processes of the FD-36 watershed. Nevertheless, spatial distribution of runoff generation areas in AVSWAT2000 may need further analysis and refinement.

The success of AVSWAT2000 is likely due to a combination of factors. For example, AVSWAT2000 includes snowmelt and subsurface flow components not present in ANSWERS-2000 and, unlike SMDR, a mechanism for estimating infiltration excess. Also, AVSWAT2000 results may have benefited by the ability to calibrate the model specifically for characteristics of FD-36; unique aspects of this watershed's physical processes may not be adequately represented by the two physically-based models considered.

This study has improved understanding of how models with different temporal and spatial process representations simulate the characteristics of FD-36. By accurately modeling hydrologic response in this type of watershed, future efforts in modeling pollutant source and transport can build on a solid foundation. This work is an important step in developing and evaluating management techniques for water quality protection and improvement in small agricultural watersheds with fragipan soils.

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