

# PRECIPITATION-RUNOFF MODELING TO COMPARE HYDROLOGIC PROCESSES GOVERNING SOLUTE TRANSPORT IN AN AGRICULTURAL WATERSHED IN MARYLAND

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**ABSTRACT:** As part of the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program, two quasi-distributed hydrologic models, the Soil and Water Assessment Tool (SWAT) and the Water, Energy, and Biogeochemical Model (WEBMOD), were used to identify dominant hydrologic processes in an agricultural watershed in Maryland. Results of simulations using default parameter sets indicated each model over-predicted streamflow peaks: WEBMOD produced an excess of peak volume, and SWAT simulated maximum streamflow values in excess of observed streamflow peaks, and both models overestimated baseflow. Although the underlying environmental processes were represented differently in each model, both models were capable of simulating the hydrologic response of the watershed. Model calibration required that 16 WEBMOD parameters and 18 SWAT parameters be adjusted. Simulations of the validation period yielded Nash-Sutcliffe efficiency values that exceeded 0.5. The validity of the specific hydrologic processes simulated by the models will be evaluated by analyzing the fate and transport of agricultural chemicals.

## INTRODUCTION

Accounting for the spatial variability of runoff generation has been a focus of precipitation-runoff watershed models since their inclusion in contemporary hydrology. Most probably, as Moore et al. (1991) indicated, this is a result of the need to understand the solute transport mechanics above and below the land surface in a variety of landscapes. In an effort to understand the sources, transport, and fate of agricultural chemicals in agricultural watersheds, a precipitation-runoff model was developed and applied as part of the Agricultural Chemical Team (ACT) topical study, which was undertaken as part of the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program (Capel et al., 2004). The ACT study examined a watershed in each of the following States: California, Indiana, Maryland, Nebraska, and Washington. Using a precipitation-runoff model to identify hydrologic processes affecting chemical transport in watersheds of different environmental settings required a spatially distributed, process-based approach able to represent a variety of hydrologic pathways. In addition, the hydrologic model needed to be coupled with a chemical transport model. The Water, Energy, and Biogeochemical Model (WEBMOD) was specifically designed to meet these criteria (Webb et al., 2005, this proceedings).

WEBMOD uses the Topmodel algorithm (Beven and Kirkby, 1979) for simulating Durnian (saturation-excess) overland flow. An assumption in this algorithm is that the likelihood of a point to generate Durnian overland flow increases with higher values of the topographic wetness index (TWI), which is defined as:  $\ln(\alpha/\tan \beta)$ , where  $\alpha$  is the upslope area contributing

to a given point and  $\beta$  is the slope angle of the land surface. WEBMOD simulates a unique hydrologic response for each different TWI value. Using the cumulative response of each TWI value within a watershed, WEBMOD identifies the hydrologic processes that produce the precipitation-runoff response. Hortonian (infiltration-excess) overland flow also is simulated in WEBMOD when the precipitation rate is greater than the infiltration rate. Within the WEBMOD structure, soil water that exceeds field capacity can either move vertically downward or be diverted directly to the stream as lateral preferential flow. Water that recharges the shallow aquifer can reach the stream through exfiltration or direct ground-water flow into the stream. Exfiltration represents water from the shallow aquifer that reaches the stream after it re-emerges on the hillslope where the water table intersects the land surface, simulating the process evident at a seepage face.

In addition to WEBMOD, the widely used Soil and Water Assessment Tool (SWAT) (Neitsch et al., 2002a) was applied to the ACT watersheds. SWAT uses the same input data as WEBMOD, but there are some fundamental differences in how SWAT simulates water movement to the stream. The Soil Conservation Service curve number (CN) method (McCuen, 1982) used by SWAT partitions rainfall into either infiltration or runoff that is directly received by the stream. As the CN increases, a greater part of precipitation is apportioned to direct runoff. Before leaving the soil profile vertically, infiltrated water can reach the stream through lateral flow. Water percolating from the soil profile that reaches the shallow aquifer can travel to the stream through ground-water discharge or be lost to the deeper, regional ground-water system.

WEBMOD and SWAT have been applied to each of the five ACT watersheds. The influences of agricultural management practices, such as irrigation, tile drainage, and use of retention ponds, on chemical transport are being explored with each model. This paper, however, presents only the results of hydrologic modeling for the Maryland watershed. The application of the models is presented, and the dominant hydrologic processes in the watershed are discussed. Simulations incorporating chemical transport are not included in this paper.

### **Site Description**

The Morgan Creek watershed is in a coastal, agricultural region of the Delmarva Peninsula in Maryland. The area of the watershed is about 32 km<sup>2</sup>. Comparison of data from several weather stations showed minimal climatological variability in the watershed. The closest weather station is near Chestertown, Maryland, about 12 km southwest of the watershed centroid. Precipitation is the sole input of water to the watershed, and mean annual precipitation during 1951 to 1980 was 112 cm (James, 1999). Sloto (2002) indicated that mean annual evapotranspiration for 1998 and 1999 in the Big Elk Creek drainage, just north of the Morgan Creek watershed, is about 77 cm. Mean annual stream discharge from the watershed during 1951–2002 was 27 cm (James et al., 2002).

The Morgan Creek watershed is underlain by a hydraulically restrictive geologic layer that dips to the southeast. This forces ground-water loss across the southeastern topographic boundary from the Morgan Creek watershed to the neighboring Chesterville Branch watershed. The quantity of ground-water loss from Morgan Creek is estimated to be about 7% of mean annual precipitation, or about 8 cm. Ground-water loss (Loss) was estimated as the remainder of the

difference between mean annual precipitation (P) and the sum of annual mean evapotranspiration (ET) and streamflow (Q), such that  $Loss = P - (ET + Q)$ .

Through comparing observed discharge to observed precipitation, it is apparent that the watershed responds quickly to precipitation events. However, about 68% of the watershed drains into retention ponds, which would retard the response of the watershed to precipitation. This suggests that lateral preferential flow may constitute a substantial part of the watershed's quick response to precipitation events. Observed perennial seepage faces, also indicate that shallow, near-surface, saturated flow is a major source of streamflow.

## METHODS

### Preprocessing

WEBMOD and SWAT both require the same spatial data inputs: a digital elevation model (DEM), a land-use grid, and a grid of soil map units. A 3-m-resolution DEM was available for the Morgan Creek watershed. The spatial representation of land use was a 30-m-resolution grid of the enhanced National Land Cover Database (Vogelmann et al., 2001). The map-unit grid corresponding to the State Soil Geographic (STATSGO) database (Schwarz and Alexander, 1995) had a 30-m-resolution. Default parameter files were created by using each data grid and the preprocessors specific to each model.

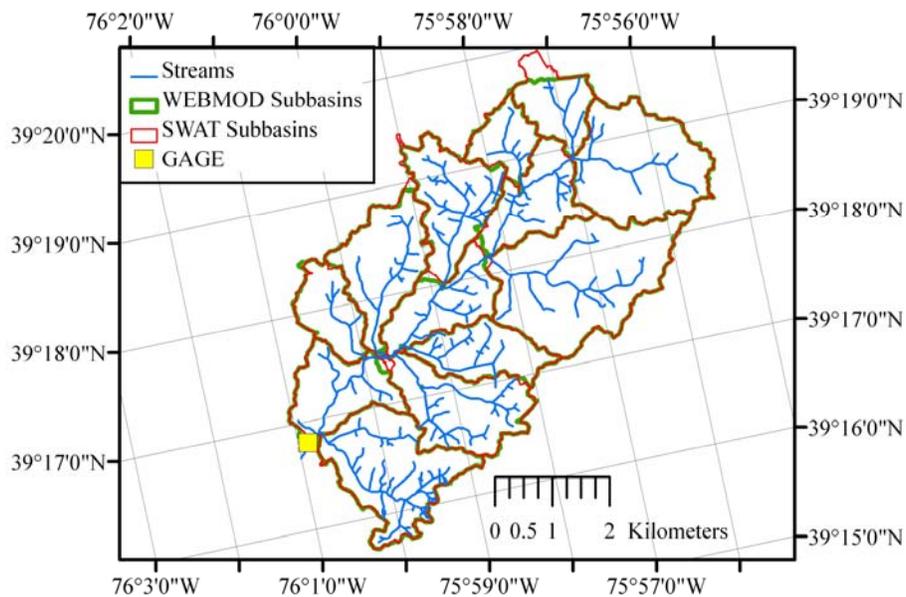


Figure 1 Morgan Creek watershed with WEBMOD subbasins delineated in green and SWAT subbasins in red.

Prior to any modeling, WEBMOD uses the GIS WEASEL (Viger et al., 1998) to create a default parameter file. Flow directions were derived using the DEM for the Morgan Creek watershed. Elevation data were used to derive WEBMOD parameters such as the TWI values, slope, and aspect for each modeling response unit (MRU). MRUs, in the case of WEBMOD, refer to the right and left banks of subbasins that have unique parameter values and, consequently, unique

runoff responses. Prior to parameterization, 26 MRUs were created from 13 subbasins, which are depicted in figure 1.

The SWAT (version SWAT 2000) model is part of the Environmental Protection Agency's Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) software (USEPA, 2004). The watershed was subdivided into 13 subbasins, as illustrated in figure 1. Because land-use and soils vary in the Morgan Creek watershed, multiple hydrologic response units (HRUs) were created in each subbasin. Similar to the MRUs of WEBMOD, each HRU had a unique parameter set. In any one subbasin, no more than four HRUs were created. In multi-year simulations, areas initially designated as corn were specified as soybeans the following year, then back to corn in the successive year. This annual rotation was applied to every year of a simulation with a complementary rotation used in areas where soybeans were the initial designated land use.

### **Model Calibration**

The period from 10/01/1994 to 09/30/1998 was used for calibration, while the period from 10/01/1999 to 09/30/2003 was used for validation. The models were considered calibrated when the Nash-Sutcliffe (NS) value (Nash and Sutcliffe, 1970) exceeded 0.5, similar to criteria used by Neitsch et al. (2002b). The first year of each simulation was not included in assessing the calibration because that year was needed as an initialization period to reduce the effect of the assumed initial condition specified for soil moisture.

Results of simulations using default parameter sets (figure 2) indicated that each model over-predicted streamflow peaks; WEBMOD commonly produced an excess of peak volume, and SWAT regularly simulated maximum streamflow values in excess of observed streamflow peak. Also, the generally high baseflow levels simulated by both models illustrated the need to remove water from the watershed either by increasing evapotranspiration or activating the ground-water loss components of each model.

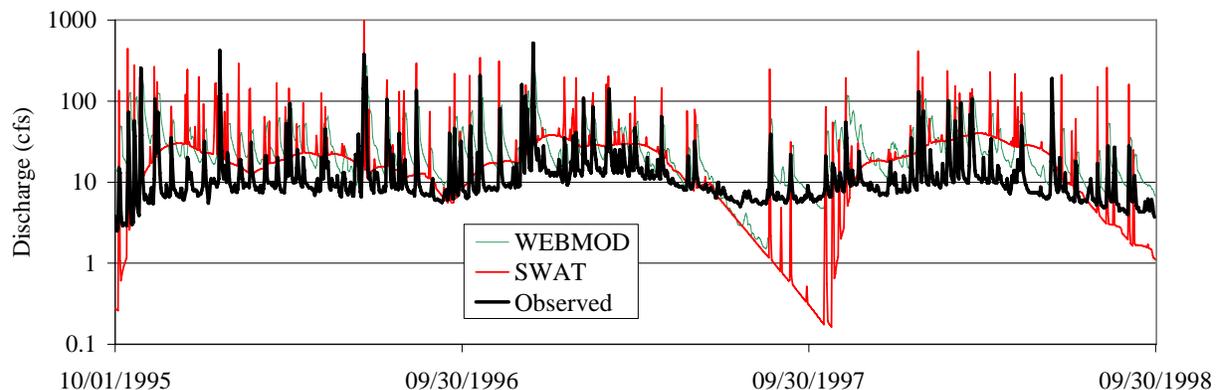


Figure 2 Comparison of observed discharge at the Morgan Creek gage with WEBMOD and SWAT discharge simulated using default parameter files.

WEBMOD simulations indicated that excessive Hortonian overland flow was the source of overly large peak discharge, which resulted from default soil physical properties that inhibited infiltration. Increasing the saturated hydraulic conductivity of the soil to about 6 cm/hr increased

infiltration in the model. When simulated infiltration was increased, however, WEBMOD predicted that the mean water table of the watershed was within 1 m of land surface. Field observations, in contrast, indicated the mean depth of the water table was about 3 m. To increase the thickness of the unsaturated zone, the average depth to the restrictive layer was increased from the default value of 1.5 m to 12 m, which is similar to depths observed in the field. Simulations conducted after adjusting the depth to the restrictive layer produced hydrographs in which the magnitudes of the large streamflow peaks were similar to observed peak flows. The simulated smaller event responses still exceeded those in the observed hydrograph, while others were not simulated at all. Commonly, the missing simulated discharge peaks occurred during the early growing season when the model simulated excessive ground-water influx to the stream. To produce the peaks that were not simulated, percolating water was partitioned by increasing the volume and velocity of water apportioned to lateral preferential flow. In addition, the rates of percolation and transmissivity of the soil were decreased.

The magnitude of direct runoff in the SWAT model was controlled using the CN specific for each HRU. The CNs for each land use were decreased to the minimum values recommended by SWAT. In addition to adjusting the CN values, the hydraulic conductivities were increased, generally by an order of magnitude to about 18 cm/hr, so that they were similar to those developed by Wolock (1997). Following these adjustments, the magnitude and temporal distribution of streamflow peaks were similar to those of the observed discharge (figure 3).

After calibrating to the runoff peaks in each model, attempts were made to match simulated base flow to observed base flow. To decrease the amount of ground-water influx to the stream in WEBMOD, a head-dependent loss parameter was used to remove water from the shallow aquifer. This allowed water in the shallow aquifer to be removed from the topographical boundary of the basin, consistent with the effects of the dipping confining layer that transfers ground water from the Morgan Creek watershed to the Chesterville Branch watershed. By initiating ground-water losses, simulated baseflow conditions matched observed baseflow conditions during periods of low streamflow. However, simulated baseflow discharges during the growing season exceeded those observed during the same periods.

To account for the ground-water loss to the Chesterville Branch watershed in the SWAT model, recharge to the deep aquifer from all subbasins on the southern one-half of the watershed was maximized. In the SWAT model, ground water moving to a deep, regional aquifer does not directly contribute to streamflow.

## **RESULTS AND DISCUSSION**

For the models to be accepted as reasonable representations of hydrologic processes in Morgan Creek, it is expected that the simulated hydrographs be similar to the observed hydrograph and the estimated mass balances are consistent with the long-term means noted previously. The NS scores for the calibration period were 0.52 for WEBMOD and 0.52 for SWAT. When the same parameter files created during the calibration period were used for the validation period, simulations yielded NS scores of 0.53 and 0.50 for WEBMOD and SWAT, respectively. The simulated hydrographs for part of the validation period are shown in figure 3.

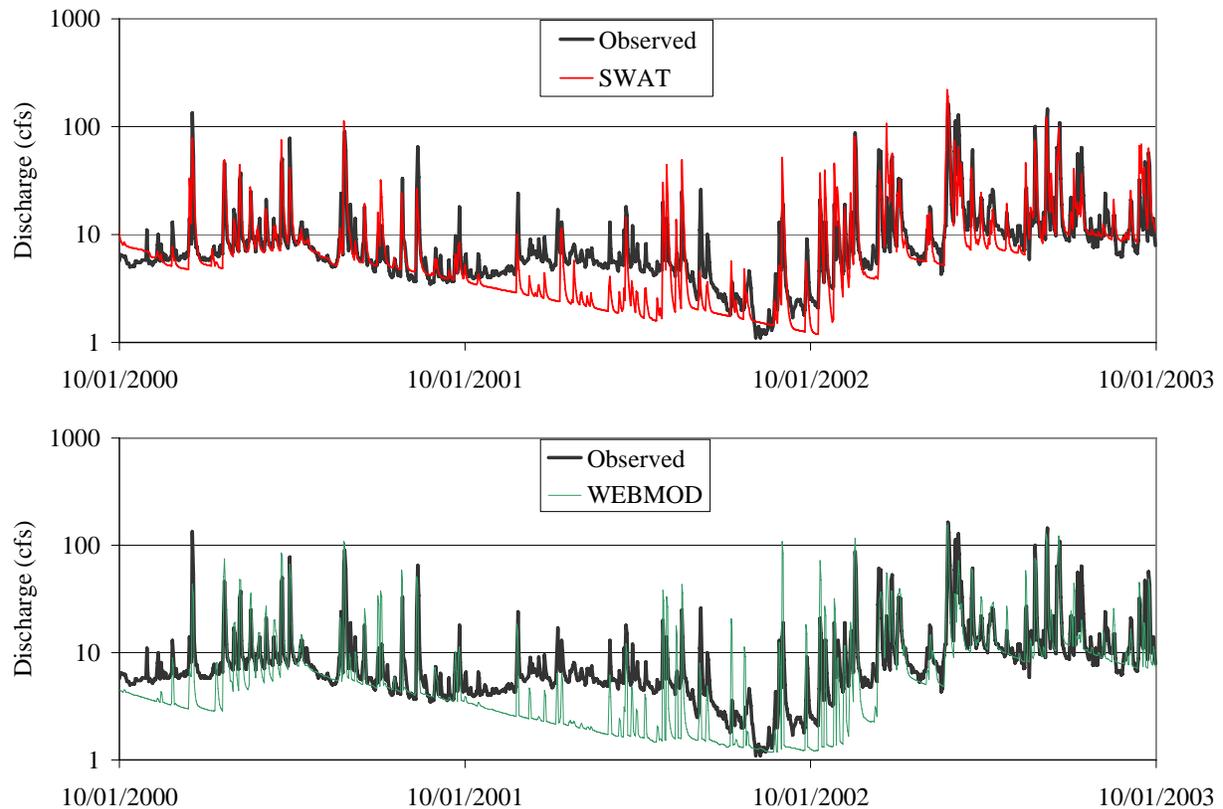


Figure 3 Comparison of calibrated SWAT and WEBMOD hydrographs to observed streamflow from Morgan Creek for the period between October 1, 2000, and September 30, 2003.

The models provide information on the important hydrologic processes governing streamflow in the watershed. As an example, the processes identified by each model for water year 2003 were compared. WEBMOD contributions to the stream from the near surface are the sum of Dunnian overland flow, lateral preferential flow, and exfiltration flow processes, which compose 63% of simulated streamflow contributions (table 1). Shallow, near-surface flow processes of SWAT include, at least, lateral flow, which contributes 25% of simulated streamflow (table 1). However, ground-water flow in SWAT consists of flow from the shallow aquifer to the stream

Table 1 Contributions to streamflow simulated by SWAT and WEBMOD for the 2003 water year compared to observed streamflow.

Contributions to streamflow (cm)	Observed	SWAT	WEBMOD
Hortonian overland	--	--	12.6
Dunnian overland	--	--	0.5
Direct	--	17.5	--
Lateral preferential	--	--	12.7
Lateral	--	11.7	--
Exfiltration	--	--	14.9
Ground water	--	17.8	4.2
Total streamflow	46.3	47	44.9

and does not differentiate water that re-emerges on the hillslope (exfiltration) prior to reaching the stream. Although the direct runoff produced using curve numbers is commonly associated with Hortonian overland flow, it more accurately represents any rapid response to precipitation without considering its specific flow paths.

The simulated mass balance for water year 2003 illustrates the effect of a wetter than average year on gross components of the mass balance. Precipitation received by the Morgan Creek watershed was 173.1 cm, about 60 cm wetter than the mean annual precipitation (112 cm). However, the consumptive use of water should be similar to the mean annual evapotranspiration of 77 cm. Simulated evapotranspiration from WEBMOD was estimated as 79.9 cm and, 77.7 cm for SWAT. The total streamflow simulated by the models for water year 2003 (table 1) was about 20 cm greater than the mean annual discharge of 27 cm. Using the mass balance percentages of precipitation, evapotranspiration and streamflow obtained from mean annual values, ground-water losses were estimated as 7% of the water year 2003 annual water budget, or 12.1 cm. WEBMOD estimated ground-water losses as 9.5 cm, while the SWAT estimate was 13.5 cm. The remainder of the received water was used by the models to alleviate the soil moisture deficit accrued during water year 2002. The described mass balance indicates the models apportioned water similarly in a year inconsistent with a mass balance based on mean annual values. The continuity between the simulated discharge from each model and observed discharge, the components of water contributing to streamflow and the conceptual understanding of flow processes occurring, and the gross components of the mass balance simulated by each model support the reliability of the models to reproduce hydrologic processes occurring in an agricultural watershed.

## **CONCLUSIONS**

Spatially distributed precipitation-runoff models tend to have numerous parameters that can be adjusted to facilitate calibration. WEBMOD and SWAT exemplify this generality and 16 WEBMOD and 18 SWAT parameters were adjusted during calibration. The adjusted parameters represent intuitive physical characteristics that control flow processes that cause the precipitation-runoff response.

This study was motivated by the assumption that understanding the runoff processes occurring was paramount to revealing the hydrologic pathways by which agricultural chemicals reach streams. Both WEBMOD and SWAT were able to reproduce hydrographs and gross annual water budgets similar to observed conditions. Whether or not the runoff processes simulated by the models are realistic is being determined by analyzing the fate and transport of agricultural chemicals.

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