This is not a peer-reviewed article.

Paper Number: 032164
An ASAE Meeting Presentation

Application of Soil and Water Assessment Tool (SWAT) to Landscapes with Tiles and Potholes. Part II. Validation of New Procedures. Case of Walnut Creek Watershed (Iowa)

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Written for presentation at the
2003 ASAE Annual International Meeting
Sponsored by ASAE
Riviera Hotel and Convention Center
Las Vegas, Nevada, USA
27- 30 July 2003

Abstract. *The SWAT model with modified tile drain and pothole components (SWAT-M) was evaluated at a watershed scale using 9 years of measured flow and nitrate nitrogen (NO_3-N) data sets in Walnut Creek watershed (WCW). The model was calibrated during the period of 1992 to 1995 and validated during the period of 1996 to 1999. In addition, comparisons between the modified version and 2000 version (SWAT2000) of SWAT models were conducted. In assessing overall performance of SWAT models, the center location (site 310) and outlet (site 330) of WCW were selected. Nash-Sutcliffe E values of the simulated monthly flows and NO_3-N loads were 0.69 to 0.78 and 0.52 to 0.79, respectively, indicating that SWAT-M reasonably well estimated the monthly flows and NO_3-N loads in the large flat landscape of WCW with tile drains and potholes. SWAT-M was capable of simulating daily flow and NO_3-N loads but with smaller E values (0.31 to 0.50 and 0.20 to 0.46, respectively), compared to the monthly results. By investigating site 210, which was exclusively selected for the evaluation of subsurface tile drain, it was concluded that the simulated monthly subsurface flows and NO_3-N loads(E values ranging from 0.71 to 0.79 and 0.72 to 0.78, respectively) were reasonably well matched to the measured values. Nevertheless, SWAT-M's simulations of daily subsurface flows (E values of 0.09 to 0.18) and NO_3-N loads (E values of 0.37 to 0.43) were less accurate than monthly results. SWAT-M estimated daily and monthly flows, NO_3-N loads, subsurface tile drains and subsurface tile NO_3-N loads better than SWAT2000.*

Keywords. Water quality, modeling, tile drains, pothole, watershed, SWAT.

Introduction

Computer simulation models are increasingly being developed and applied for the assessment and prediction of the effects of agricultural production on the environment due to their cost-effectiveness, efficienct advantages (Saleh et al., 2000; Spruill et al., 2000). Among the representatives of those models that calculate pollutant loads of point and nonpoint sources at watershed level are the continuous-time (often hourly-based) Hydrological Simulation Program FORTRAN (HSPF) (Bicknell et al., 2000), the daily-based (runoff and channel routing at 15min time steps) Soil Water Assessment Tool (SWAT) (Arnold et al., 1998), and a simplified GIS based nonpoint source annual load model (PLOAD) (CH2M HILL), which have all been incorporated into the Better Assessment Science integrating point and Nonpoint Sources (BASINS) (BASINS 3, 2001) system. In the application of these models, users can easily utilize Geographic Information System (GIS) techniques to automate model inputs from national databases of topography, land use, chemicals and soils data. On the other hand, field-scale models have been developed to predict the impact of point and non point source pollution on water quality at the field level. Some examples of these models include Erosion-Productivity Impact Calculator (EPIC) (Williams et al., 1984), Agricultural Policy/Environmental eXtender (APEX) (Williams et al., 2000), Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) (Knisel et al. 1980), Ground Water Load Effects on Agricultural Management Systems (GLEAMS) (Leonard et al. 1987), in-stream water quality (QUAL2E), Root Zone Water Quality Model (RZWQM) (Singh et al., 1996), Agricultural Non-point Source (AGNPS) (Young et al. 1989),

However, these agricultural and environmental models are being continuously improved because of their applications in various circumstances. Numerous areas in the Midwestern United States are characterized by tile and pothole drainage systems that are used to reduce poor drainage problems in crop fields (Hatfield et al., 1998). While the tiles were added to improve drainage, the potholes are naturally occurring enclosed depressions in this geologically young landscape. Agricultural contamination of the environment through these subsurface or tile drainage systems has been intensively investigated over past decades (Baker et al., 1975; Logan et al., 1994). Many studies have shown that NO_3-N is one of main pollutants produced primarily from the tile drainage (Baker et al., 1981; Jaynes et al., 1999; Cambardella et al., 1999) in these areas. Cropping systems in pothole regions employing tile drainage systems have unique hydrologic and nitrogen transport characteristics (Eidem et al., 1999). Therefore, it is necessary to develop models capable of simulating landscapes with tile drainage systems. Some mathematical models have been developed to calculate the water balance and its corresponding nutrient loads in these systems (Duffy et al., 1975). Singh (1996) explored a component of subsurface drainage in the Root Zone Water Quality Model (RZWQM). Arnold (1999) developed the subsurface tile flow component in the SWAT model (Arnold et al., 1999). Chung et al. (2002) evaluated the EPIC model modified with a tile drain component.

However, there has not been an assessment of the applicability of the models with tile and pothole components at watershed level. The objective of this study was to evaluate the enhanced SWAT model (SWAT-M) with new tile drainage and pothole surface storage components, developed during the first part of this study (Arnold et al., 2003), using measured data from Walnut Creek watershed (WCW) located in the central Iowa. In addition, comparisons between the SWAT-M and the version 2000 of SWAT (SWAT2000) were conducted.

Materials and Methods

Model description

SWAT has developed into a comprehensive simulation model, which can assist farmers, water resource managers, and policymakers in assessing the effects of field and water management on environmental contamination. It simulates water movement, sediment, nutrient and pesticide loads in fields, ponds/reservoirs and streams. Its main components are composed of weather, soil, crop growth, hydrology, sedimentation, nutrients, pesticides, agricultural land and field management, forest land, urban land, ponds/reservoirs and channels (Arnold et al., 1998).

A watershed simulation using SWAT can include up to seven types of objects: subbasins, hydrologic response units (HRU), reach/main channels, tributary channels, ponds/reservoirs, potholes, and point sources. HRU is a unique concept in setting up the simulation models of hydrology and water quality. SWAT aggregates areas of land with homogeneous landuse/management/soil into one HRU. A Pothole, a depression without an outlet, is designated as a special HRU within a subbasin. Using a similar method of setting up a HRU, potholes within a subbasin are aggregated into one pothole. A proportion of surface runoff from other HRUs in the same subbasin will contribute to the designated HRU as a pothole within each subbasin. The tile drain and potholes were added to the system of hydrology including surface runoff, evapotranspiration (ET), lateral flow, ground water flow, transmission loss, percolation, pond/reservoir routing and channel routing.

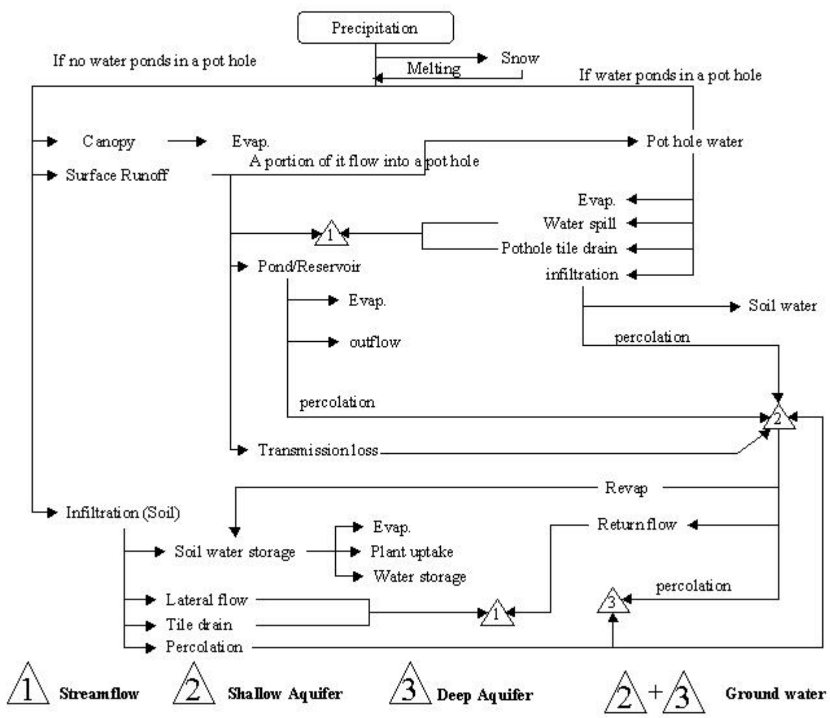

Figure 1 schematic diagram of hydrological cycle with tile drain and potholes

Within SWAT-M, the tile drain and pothole routines were enhanced (Arnold et al., 2003). Except for the modifications of equations regarding subsurface tile flow, NO_3-N in subsurface tile and pothole flows, the hydrologic cycle of the model related to potholes was also improved. When there is no water ponded in potholes, the water balance of a HRU in SWAT-M is expressed as the distribution of precipitation to soil water increase, canopy and soil evaporation and plant uptake of water (ET), water yield, and percolation. The water yield within SWAT-M consists of surface runoff, lateral flow, tile drainage and ground water return flow after subtracting transmission losses. Otherwise, precipitation equals the summation of pothole water increase, soil water increase, water yield and percolation when there is water ponding in potholes, where water yield consists of pothole tile drain, lateral flow, and ground water return flow. The schematic diagram of the modified hydrological cycle with an addition of tile drain and pothole is shown in Figure 1.

Watershed Description

The 5130 ha WCW, located in Story county, central Iowa, is typical of the poorly drained, gently rolling landscapes of central Iowa row cropping areas. This landscape was formed on young till plane and contains numerous closed depressions or potholes as a result of a poorly developed geologically young surface drainage network. These potholes often fill with water, especially during snowmelt and after heavy rainfall, which can result in a reduction in crop yields. The upland soils are underlain by a dense unoxidized till that restricts vertical drainage resulting in poorly drained soils in the lower elevation areas. A corn-soybean rotation cropping system is predominately used in this area.

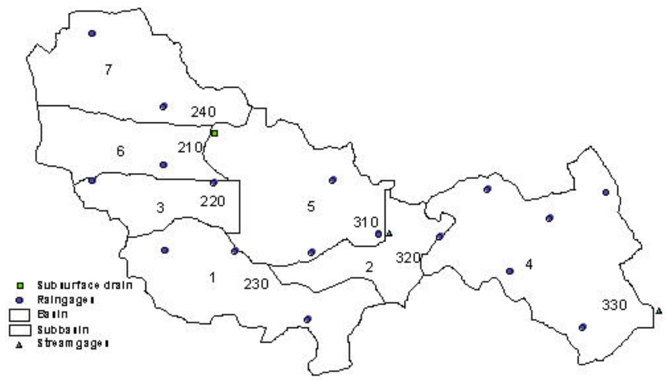

Figure 2. Subbasins, sites and measurement gages in WCW, IA, used by SWAT

The watershed has an average elevation above sea level of about 300 m. The average annual precipitation in the simulated 9 years was approximately 820 mm, and the average temperature during crop growth seasons ranged from 9.0 to 23.0 ^{o}C. These beneficial weather conditions, plus the fertile soil in the area, lead to high crop yields of corn and soybean.

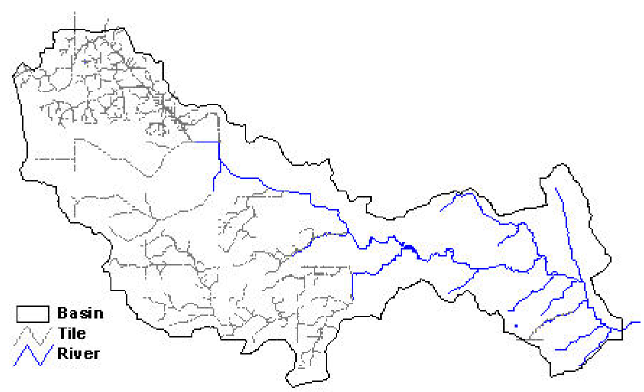

Figure 3. Distributions of subsurface drains and streams across WCW

Data collections

Weather, streamflows and NO_3-N concentrations have been intensively monitored at a number of sites within the watershed since 1991 by USDA-ARS, National Soil Tilth Lab. Streamflow was calculated from water stage data recorded on a CR-10 datalogger. Water quality samples of one-liter were collected several times a week when flow occurred at each site. The more detailed introduction of the data measurements and computations can be found in Jaynes et al. (1999).

Precipitation data measured by 17 weather gages within the watershed (Fig. 2) were used in SWAT. The maximum and minimum temperature data sets were measured every day at two locations within the watershed and solar radiation data at one station. Other measured data used in this study were streamflow data from 1991 to 1999 for site 330 and site 310, subsurface drain data from 1991 to 1999 for site 210 and NO_3-N concentration data from 1992 to 1998 for sites 330, 310 and 210. Discharge loads rather than concentrations of NO_3-N were considered in the assessment of the models. The monthly NO_3-N loads were the summation of the scattered measured daily values.

Sites 310 and 330 are near the central portion and at the outlet of WCW, respectively. Subsurface flow from site 210 were measured and exclusively used to evaluate SWAT models' simulation of subsurface flow and NO_3-N load.

Input data and Model assumptions

The digital elevation, land use, and soils maps, and measured daily precipitation, temperature and solar radiation for the watershed were provided during the initial setup of the input data files for SWAT using the ArcView interface for SWAT2000 (AVSWAT) (DiLuzio et. al., 2001). Other input data such as daily wind speed and relative humidity were generated by SWAT from long term monthly statistics. Penman/Monteith method within SWAT was selected for potential ET calculation.

In the land use categories, corn and soybeans occupied 87% of the total area while other crops, roads and forest occupied 13% of the area. Continuous corn production occurred on 15 % of the total farmland while 85% of the area was in a corn-soybean rotation (Hatfield et al., 1999).

The seven predominated soils of Clarion, Webster, Canisteo, Lester, Harps, Okoboji and Lester were used. The very poorly drained Okoboji and Harps soils were assigned to potholes. Based on the Figure 3 and Hatfield et al. (1999), it was assumed that about 66% of the total watershed area were tile drained and 57% of the total surface runoff directly flowed into potholes. Total pothole area occupied 10% of the total land use. Table 1 shows the overall outline of landuse, soils, tiles and potholes used by SWAT.

Table 1 Soils, land use, tiles and potholes used in SWAT

Soil (percentage)	
CANISTEO	18.0
CLARION	30.0
HARPS	6.1
OKOBOJI	3.6
NICOLLET	14.0
WEBSTER	18.7
LESTER	9.6
Land use, tile and pothole (percentage)	
Total area with tiles	66.3
Area of total runoff flowing to Potholes	57.4
Total Potholes Area	9.7
Total farm land	87.0
Corn area of farm land	14.7
corn-soybean area of farm land	85.3
Total forest and others land	13.0

In constructing SWAT management files, the amount of fertilizer applied from 1991 to 1994 in the entire WCW, as determined from farmer surveys, was used (Hatfield et. Al., 1999). The annually averaged nitrogen fertilizer rate of 126 kg/ha and phosphorous fertilizer rate of 24 kg/ha in the period of 1991 to 1994 were applied for the period of 1996 to 1999 for which actual use rates were not available.

A standard tile drain depth of 1.2 m was used in this study. The initial number of soil layers in soil files created from the State Soil Geographic (STATSGO) soils data for WCW varied from 3 to 4, and the distribution of layer depths of soils varied. To set up tile drains at a depth of 1.2 m , the number of soil layers was modified to 7 for all soils. Tile drains are usually designed to reduce the water content to field capacity within 48 hours, so the initial value of tile drain or tdrain (time to drain soil to field capacity) was set at 48 hours, which was calibrated later.

An average daily outflow to main channel from tile flow pot_tile of 3.0 m3/s and a maximum volume of water stored in the pothole pot_volx of 600.0x104 m3 were assumed.

Model evaluation and calibration methods

To compare the model output values to measured values, the Nash-Sutcliffe model efficiency (E) (Nash et. al., 1970) was calculated as follows:

$$E = 1 - \frac{\sum_{i=1}^{n} (X_{mi} - X_{ci})^2}{\sum_{i=1}^{n} (X_{mi} - \overline{X}_m)^2}$$

where E = the efficiency (goodness of fit) of the model, X_{mi} = measured values, X_{ci} = predicted values, $\overline{X}_m$ = average measured values, and n= the number of predicted/measured values.

The same input data were used for both SWAT-M and SWAT2000 for the purpose of comparison.

Typically, there are three main adjustable parameters used for the calibration of flow and NO_3-N in SWAT (Arnold et al., 1999). These parameters are *esco* (a soil evaporation compensation coefficient) and *cn2* (condition II runoff curve number) for the ET and flow calibration, and *nperco* (nitrate percolation coefficient) for NO_3-N calibration. However, because of the complicacy associated with the simulation of a watershed with tile drainage and pothole, herein more parameters were used for the flow calibration. Both versions of SWAT were calibrated for the period of 1992 to 1995 and validated for the period of 1996 to 1999. The *esco* was adjusted to calibrate the annual ET predicted by SWAT. The *tdrain* and *gdrain* (drain tile lag time) were used for flow calibration. The groundwater parameters, such as *gwqmn* (threshold depth of water in the shallow aquifer required for return flow to occur), *gw_revap* (groundwater revap coefficient) and *revapmn* (threshold depth of water in the shallow aquifer for revap to occur), were also used for flow calibration. The E value was used as the indicator ending the calibration process of flow, subsurface tile drain, and NO_3-N load.,

Results and Discussions

Water Balance

Initial calibrations of SWAT were performed based on the measured annual ET and stream discharge data at the outlet of WCW from 1992 to 1995 (Hatfield et al., 1999) (Table 2 and Figure 4). The annually averaged stream discharge (305.3 mm) at the outlet of WCW and annually averaged ET (478.7 mm) simulated by SWAT-M for the period of 1992 to 1995 were close to measured values (345.8 mm and 435.0 mm, respectively).

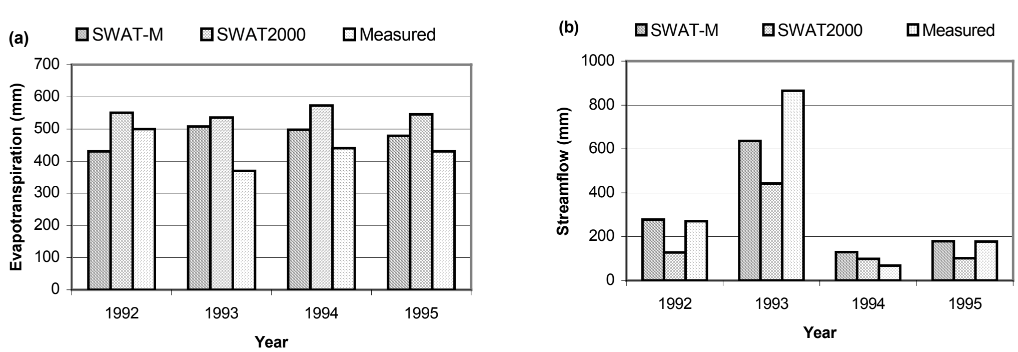

Figure 4 Simulated and measured annual ETs and streamflows of WCW

Both E values (Table 2) and Figure 4 demonstrate that improvement of hydology routine within SWAT-M resulted in better prediction of annual stream discharge and ET compared to SWAT2000.

Table 2. Comparisons of measured and simulated water balances between SWAT-M and SWAT2000 for WCW

	ET			stream discharge		
	----- mm -----					
Year	SWAT-M	SWAT2000	Measured	SWAT-M	SWAT2000	measured
1992	430.4	550.6	500.0	277.5	127.4	271.0
1993	507.9	535.6	370.0	636.1	442.4	865.0
1994	497.3	572.8	440.0	129.4	98.3	69.0
1995	479.3	545.1	430.0	178.3	101.9	178.0
average	478.7	551.0	435.0	305.3	192.5	345.8

A significant change in distribution of water balance component , including surface runoff, ground water flow and tile flow, was found in the outputs of SWAT-M (Table 3). Similar to actual field measurements, there were more tile and groundwater flows and less surface runoff in SWAT-M than in SWAT2000.

Table 3. Comparisons of water components of SWAT-M and SWAT2000 for WCW

	Surface runoff		Ground water		Tile flow	
	----- mm -----					
Year	SWAT-M	SWAT2000	SWAT-M	SWAT2000	SWAT-M	SWAT2000
1992	94.0	105.3	65.2	8.3	116.5	12.8
1993	170.5	255.7	200.7	92.7	260.7	91.7
1994	56.1	87.6	25.1	3.4	47.4	6.8
1995	56.0	73.1	51.2	13.0	70.0	15.1
Average	94.1	130.4	85.5	29.4	123.6	31.6

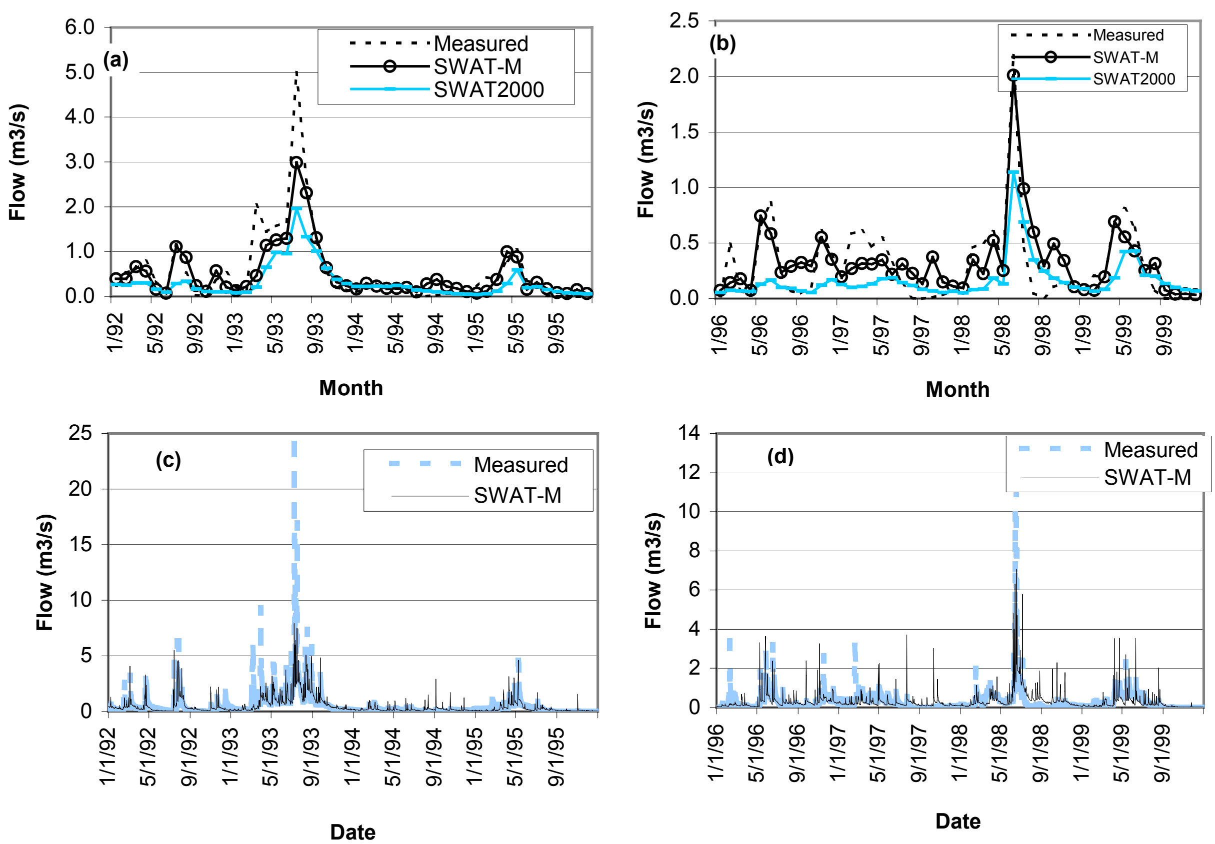

Figure 5 Simulated and measured monthly and daily flows at site 330 of WCW

Monthly Streamflow Simulation at site 310 and 330 of WCW

Figures 5a-b represent monthly measured and simulated streamflows at site 330 during the calibration and vaidation periods . It is apparent from these figures and the E values (Table 4) that the monthly simulated flows of SWAT-M at both sites during both calibration and validation periods were satisfactorily matched to the measured values in most months. However, the SWAT-M underestimated the flows in the extremely heavy rainfall during July 1993, while SWAT2000 underestimated the flows in most months. In comparing SWAT-M to SWAT2000, SWAT-M is a much better predictor of monthly flows at the two sites during both calibration and validation periods (Table 4) .

Table 4. E values for daily and monthly flows of 1992-1999 at sites 310 and 330 of WCW

	E values for daily flow			
	site 310		site 330	
	SWAT-M	SWAT2000	SWAT-M	SWAT2000
calibration (92-95)	0.47	0.36	0.50	0.35
validation (96-99)	0.39	0.36	0.31	0.39
	E values for monthly flow			
calibration (92-95)	0.77	0.43	0.78	0.50
validation (96-99)	0.73	0.31	0.69	0.34

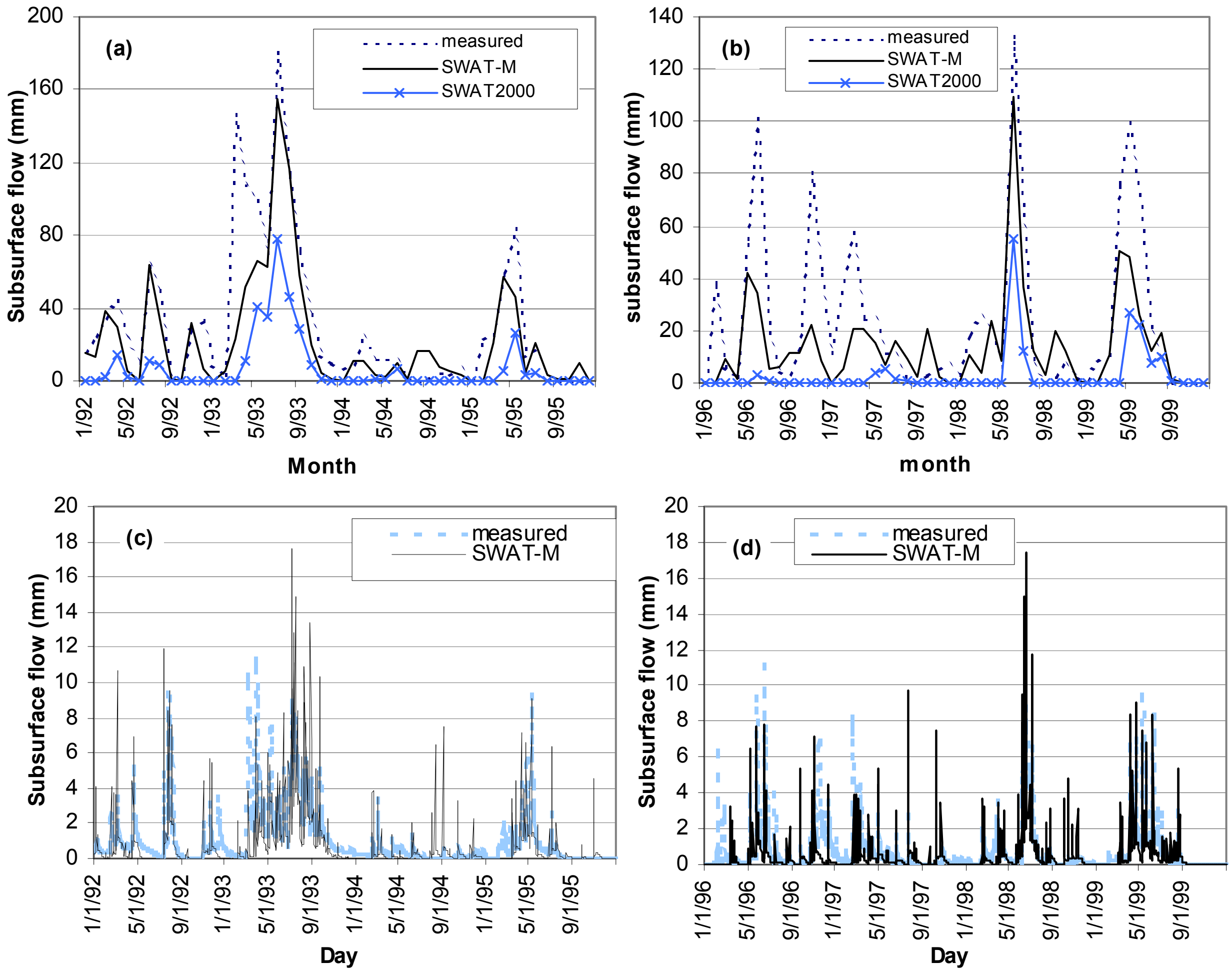

Figure 6 Simulated and measured subsurface flows at site 210 of WCW

Daily Streamflow at sites 310 and 330 of WCW

Although SWAT-M is able to accurately simulate most daily flows as shown in Figure 4c-d, it underpredicted the high peak flows occurring at site 330 on July 9, 1993, and June 14 and 18, 1998 when 75 mm, 71 mm and 64 mm precipitation occurred separately on those days.

It was also noticed that the daily flows occurring on March 3 and 30, 1993; February 10, 1996; February 18, 1997 seemed not predicted correctly by SWAT-M. By examining the daily data, we found that the temperatures were below zero oC before and after these days, but above zero oC on these days, which cauased snow melt. Also the big events before those days coincided with the temperature warming well above freezing. Therefore, it can be reasonably assumed that flows during these days were probably a combination of increased flow rate and ice damming at the station, which could have raised the stream level behind the weir and gave false high flow readings.

E values (Table 4) of the daily-simulated flows indicate that that SWAT-M flow prediction was slightly better than that of SWAT2000.

Table 5. E values for daily and monthly flows of 1992-1999 at site 210 of WCW

	E values for daily flow		E values for monthly flow	
	SWAT-M	SWAT2000	SWAT-M	SWAT2000
calibration (92-95)	0.18	0.09	0.79	0.43
validation (96-99)	0.09	-0.03	0.71	0.29

Subsurface flow simulation at site 210

E values of the monthly-simulated subsurface flows from site 210 during calibration and validation periods for SWAT-M were 0.79 and 0.71 (Table 5), respectively, indicating that

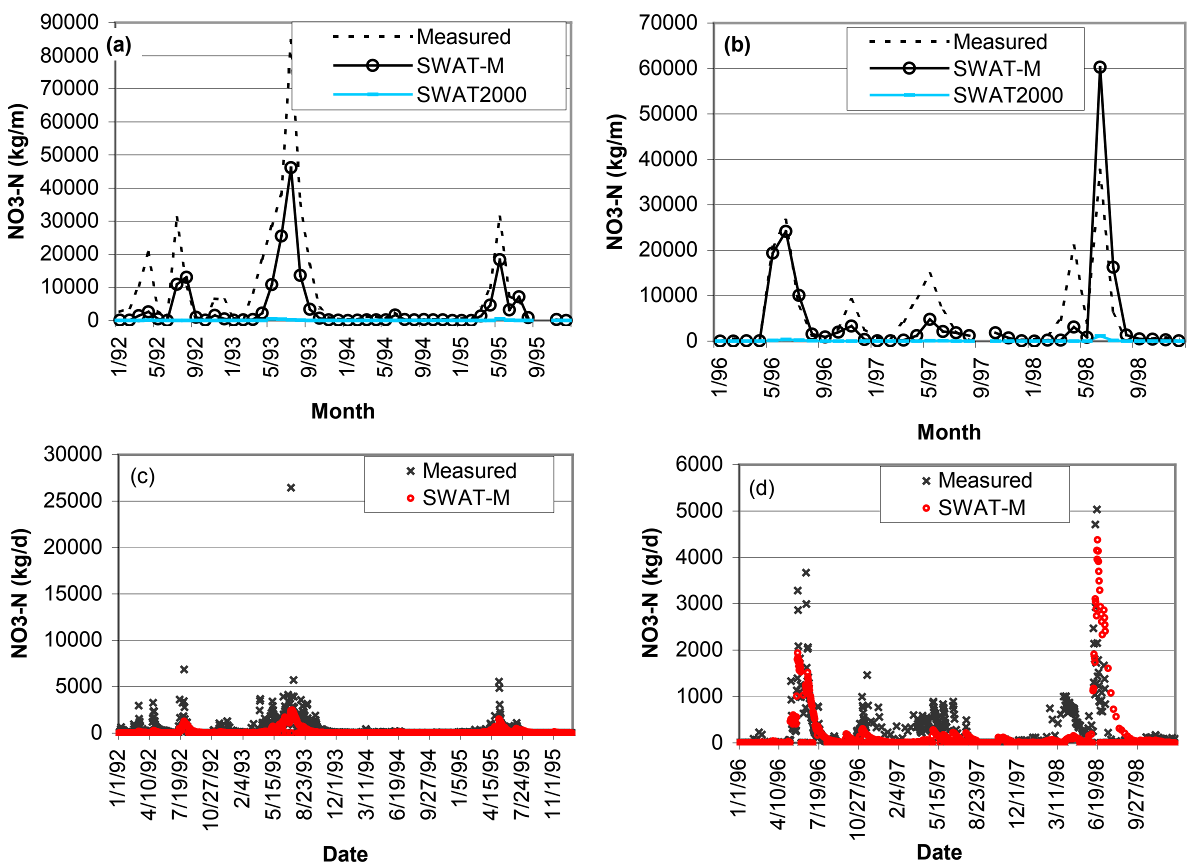

Figure 7 Simulated and measured monthly and daily NO_3-N loads at site 330 of WCW

SWAT-M satisfactorily simulated monthly subsurface flow. In contrast, as it is shown in Figure 6a-b and E values in Table 5, SWAT2000 greatly underestimated subsurface flow at this site. Therefore, we can conclude that the improvement of tile and pothole components of SWAT-M were important for better simulation of monthly subsurface discharge. Nevertheless, the lower daily E values (Table 5) indicate that the simulations of the daily subsurface flows by both versions of SWAT were not as good as that of the monthly ones. However, SWAT-M still produced better daily results than SWAT2000. Figures 6c-d show the simulation of daily subsurface flow at site 210 by SWAT-M.

Stream NO_3-N loads at sites 310 and 330 of WCW

Figures 7a-b show that SWAT-M slightly underestimated the monthly NO_3-N loads at site 330 during the calibration period and overestimated NO_3-N in June 1998 of the validation period. Because E values of the monthly NO_3-N loads predicted by SWAT-M at sites 310 and 330 during the calibration were 0.62 and 0.77, respectively, and 0.52 and 0.79 during the validation, respectively (Table 6), SWAT-M relatively well simulated the monthly NO_3-N loads. Similar to the flow results, the SWAT-M's simualtion of the daily NO_3-N loads was not as good as the monthly one. Nevertheless, E values of Table 6 demonstrate that SWAT-M simulated monthly and daily NO_3-N loads more accurately than SWAT2000. Figures 7c-d show the comparison of daily NO_3-N loads of SWAT-M to measured values at site 330.

Table 6. E values for daily and monthly NO_3-N loads of 1992-1998 at sites 310 and 330 of WCW

	E values for daily NO_3-N			
	site 310		site 330	
	SWAT-M	SWAT2000	SWAT-M	SWAT2000
calibration (92-95)	0.46	-0.51	0.20	-0.25
validation (96-98)	0.43	-0.41	0.20	-0.46
	E values for monthly NO_3-N			
Calibration (92-95)	0.77	-0.32	0.62	-0.31
Validation (96-98)	0.79	-0.30	0.52	-0.35

NO_3-N load in subsurface flow of site 210

Although Figures 8a-b shows that the simulated subsurface NO3-N loads were higher than the measured ones in some months during calibration and validation periods and vice vers in other months, SWAT-M simulated monthly subsurface NO3-N loads from site 210 reasonably well (E values of 0.72 for the calibration and 0.78 for the validation period; Table 7 and Figure 8). Lower daily E values of 0.37 for the calibration period and 0.43 for the validation period indicate the further improvement of SWAT model is needed for the simulationh of daily NO3-N loads in subsurface flow. SWAT-M still is a much better predictor on simulating subsurface NO3-N loads than SWAT2000 (Table 7 and Figures 8a-b). Figures 8c-d show the daily NO3-N loads in subsurface flows at site 210 simulated by SWAT-M.

Table 7. E values for daily and monthly NO_3-N loads of 1992-1998 at site 210 of WCW

	E values for daily NO_3-N		E values for monthly NO_3-N	
	SWAT-M	SWAT2000	SWAT-M	SWAT2000
calibration (92-95)	0.43	-0.77	0.78	-0.21
validation (96-98)	0.37	-0.43	0.72	-0.20

Summary and Conclusions

The SWAT model with modified tile drain and pothole components was evaluated at a watershed scale using 9 years of measured flow and NO3-N data in WCW. At the same time, the comparisons between SWAT-M and SWAT2000 were conducted. A centrally located site

(310) and outlet site (330) of WCW were selected to investigate overall performance of both versions of SWAT model, while site 210 was used to exclusively scrutinize SWAT-M's capability of simulating subsurface flow and NO3-N load. The initial calibrations of the models were carried out based on the measured annual ET and stream discharge of WCW. The annually averaged stream discharge at the outlet of WCW and annually averaged ET simulated by SWAT-M for the period of 1992 to 1995 were close to measured values. At sites 310 and 330 during both calibration and validation periods, E values up to 0.78 and 0.79 for the simulated monthly flow and NO3-N load, respectively, indicated that SWAT-M reasonably well estimated the monthly flow and NO3-N load in the gently rolling landscape of WCW with tile drain and pothole. SWAT-M was capable of simulating daily flow and NO3-N loads but with lower accuracy(E values from 0.31 to 0.50 and 0.20 to 0.46, respectively) compared to the monthly results. When the daily precipitation exceeded 64 mm, the simulated daily flows were much lower than the measured values, which also resulted in a lower estimation of the monthly flow in July of 1993 with the extremely heavy rainfall by SWAT-M. By investigating site 210, it was concluded that the simulated monthly subsurface flows and NO3-N, at E values ranging from 0.71 to 0.79 and 0.72 to 0.78, respectively, were reasonably well matched to the measured values. Nevertheless, SWAT-M's simulation of daily subsurface flows (E values of 0.09 to 0.18) and NO3-N loads (E values of 0.37 to 0.43) were not as good as the monthly results.

In comparing SWAT-M to SWAT2000, the former estimated daily and monthly flows better than the latter. The simulation of NO3-N of SWAT-M was more accurate than that of SWAT2000

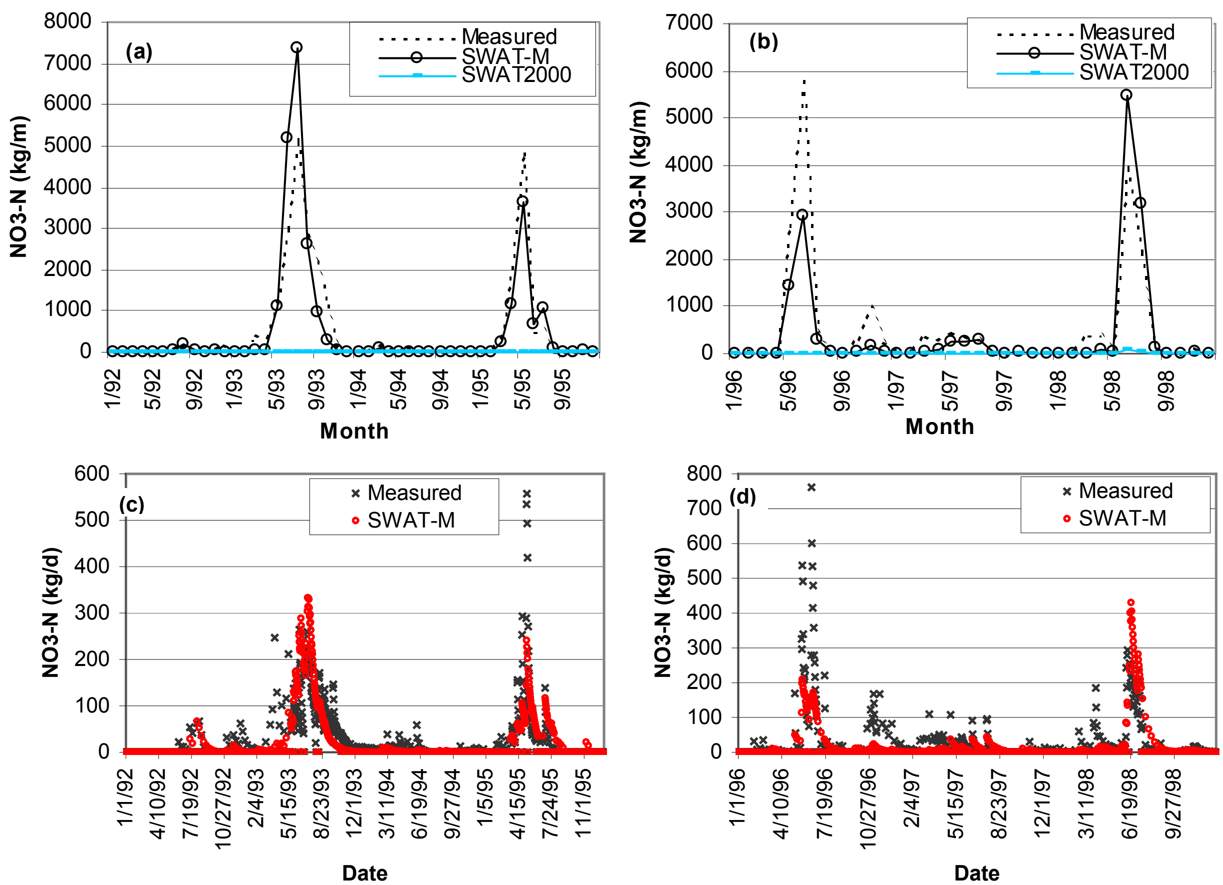

Figure 8 Daily and monthly simulated and measured NO_3-N loads at site 210 of WCW

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