EVALUATION OF SWAT IN SIMULATING NITRATE NITROGEN AND ATRAZINE FATES IN A WATERSHED WITH TILES AND POTHOLES

B. Du, A. Saleh, D. B. Jaynes, J. G. Arnold

ABSTRACT. *We evaluated a version of the Soil Water Assessment Tool (SWAT-M) that was modified to more accurately simulate tile drainage and water flow in a landscape dominated by closed surface depressions or potholes at a watershed scale using ten years of measured nitrate-nitrogen (NO_3-N) and atrazine data in stream discharge in the Walnut Creek watershed (WCW). The model was calibrated during the period of 1992 to 1995 and validated during the period of 1996 to 2001. Stream sites in the middle and outlet of the WCW were selected to assess overall performance of the model, while one drainage district drain was used for investigating chemical loads in subsurface flows. With the introduction of an independent tile drain lag time parameter, the performance of SWAT-M for daily flow simulation was improved. In comparison to our previous results, the Nash-Sutcliffe E values for the calibrated daily flow at the mid-watershed and outlet simulated by the enhanced SWAT model rose from 0.55 to 0.69 and from 0.51 to 0.63, respectively. Of special note, the E value for calibrated flow rose from −0.23 to 0.40 for the drainage district drain, which was dominated by tile and subsurface flow. Both the predicted corn yields and N uptake by corn were very similar to the measured data. The predicted yield and N uptake by soybean were relatively lower than the measured values. The monthly NO_3-N loads in stream discharges at the center and outlet of the Walnut Creek watershed were accurately predicted with good Nash-Sutcliffe E values of 0.91/0.80 and 0.85/0.67 in calibration/validation, respectively. Nevertheless, the model's simulation of the daily NO_3-N loads was not as good as the monthly simulation. The good agreement between the simulated and measured monthly NO_3-N loads from the drainage district site leads us to conclude that SWAT can reasonably simulate tile flow from pothole-dominated landscapes, although the model needs to be improved in the simulation of daily subsurface NO_3-N fluxes. The enhanced SWAT-M model simulated the NO_3-N loads in a watershed with intensive tile drainage systems much more accurately than the original SWAT2000 version. A second pesticide degradation half-life in soil was added for SWAT-M, which greatly improved the model performance for predicting atrazine losses from the watershed. Overall, SWAT-M is capable of simulating atrazine loads in the stream discharge of the WCW and is a much-improved tool over SWAT2000 for predicting both daily and monthly atrazine losses in nearly level, tile-drained watersheds.*

Keywords. *Atrazine, Chemical pollution, Modeling, Nitrate, Pesticide, Pothole, Subsurface drainage, SWAT, Tile drains, Water quality, Watershed.*

High application rates of chemical fertilizers and accumulative uses of pesticides in agricultural fields have increasingly led to great concerns about their pollution of water sources, although they have brought benefits to crop yields. Numerous areas in the Midwestern U.S. are characterized by tile and pothole drainage systems that are used to reduce poor drainage problems in crop fields (Hatfield et al., 1999). Agricultural contamination of the environment through these subsurface or tile drainage systems has been intensively investigated over the past several decades (Baker et al., 1975; Logan et al., 1994). Studies have shown that nitrate nitrogen (NO_3-N) is one of the main pollutants produced primarily from the tile drainage (Baker and Johnson, 1981; Jaynes et al., 1999; Cambardella et al., 1999) in these areas.

With its affordability, broad adaptability, and effectiveness, atrazine has been one of the most widely used pesticides in the Midwest for the past several decades (Miller et al., 1999). However, it also carries risks to human health. In the U.S. Environmental Protection Agency's "Overview of Atrazine Risk Assessment" (EPA, 2002), a wide range of dangers such as human health risk, environmental fate and transport risk, and ecological risk from use of atrazine were stated. A statewide survey in Iowa pointed out that atrazine contamination of drinking water is resulting in risk to human reproductive health (Munger et al., 1997). Jaynes and Miller (1999) and Jaynes et al. (2004) conducted a multi-year study of atrazine and other pesticides in the Walnut Creek watershed (WCW), located in central Iowa, for many years. Atrazine losses in surface runoff under various tillage operations were investigated using the rainfall simulation

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method (Basta et al., 1997). Hence, atrazine is representative of pesticide pollution of drinking water and was selected to evaluate the SWAT model in this study.

Modeling nutrient and pesticide fate in a watershed and their transport from point and, especially, nonpoint sources into streams is an efficient method for predicting contamination by agrochemicals and evaluating Best Management Practices (BMPs) for reducing environmental pollution. Therefore, numerous simulation models have been developed for simulating nutrient and pesticide processes at the watershed scale. The Soil Water Assessment Tool (SWAT) (Arnold et al., 1998) is representative of these models, and SWAT is being continuously developed and broadly applied in many watersheds. Recently, the SWAT model has been modified by Du et al. (2005) to simulate landscapes with tile drainage and pothole systems. They also evaluated the hydrology of the modified SWAT (SWAT-M) for accuracy using the data from the Walnut Creek watershed (WCW) of Iowa. Du et al. (2005) concluded that the simulation of the flow by SWAT-M was greatly improved for tile-drained and potholed systems as compared to the unmodified version of SWAT (SWAT2000).

The main objective of this study was to further enhance and then evaluate SWAT-M for simulating nitrate (NO_3-N) and atrazine losses from fields into streams using measured data from the Walnut Creek watershed (WCW). Additionally, the modified version (SWAT-M) was compared to the original version (SWAT2000) to evaluate the improvement in the prediction capabilities of SWAT-M for nearly level, tile-drained watersheds.

MATERIALS AND METHODS

WATERSHED DESCRIPTION AND SAMPLING

The 5130 ha WCW (fig. 1) is located in Story County, central Iowa, on poorly drained soils with numerous closed surface depressions or potholes. Over 60% of the watershed area has had tile drainage systems installed over the past 120 years. The watershed has an average elevation of about 300 m above sea level. The average annual precipitation in the simulated 10 years was approximately 782 mm, with 1993 being an extremely wet year (1268 mm). The time period with freezing temperature at night usually lasted from late October to early April during the simulation period, and the minimum and maximum temperature were −33.3°C and 37.6°C, respectively. A corn-soybean rotation cropping system is predominately used in the watershed.

NO_3-N and atrazine concentrations and water flow were intensively monitored throughout the watershed from 1992 to 2001 by the USDA-ARS National Soil Tilth Laboratory (Jaynes et al., 1999). In this study, we include data from the stream outlet (site 330, fig. 1), a mid-watershed stream site (site 310), and from a 52 cm diameter drainage district drain outlet (site 210). Discharge loads rather than concentrations of nitrate nitrogen and atrazine were considered in the assessment of the SWAT versions. The sampled daily NO_3-N (S) and atrazine (S) loads and the corresponding monthly NO_3-N (S) and atrazine (S) loads were compared to the results of the model simulations for the purpose of model evaluation, where S represents only the days that nitrate and atrazine samples were taken. Comparisons between the total monthly loads, measured vs. model prediction, were also conducted. Since the daily water quality measurements were limited in a month, but flow measurements were continuous and averaged daily, a time-centered scheme was used based on the time of water sample collection (Jaynes et al., 1999) in order to calculate total monthly loads from the available data. Load concentrations below the detection limits for NO_3-N and atrazine were treated as zero values. Thus, the calculated total loads represent minimum estimates.

Daily precipitation data from 17 rain gauges distributed across the watershed were used in the simulations. Daily maximum and minimum temperatures from two weather stations within the watershed and daily solar radiation from one of the stations were used as additional input to the models.

MODEL IMPROVEMENTS

Du et al. (2005) described several modifications made to SWAT2000 to better simulate water flow for nearly level, intensively drained watersheds like Walnut Creek. We build on the improvements described by Du et al. (2005) by adding a slight change to the routing of water in the tile drains and by increasing the complexity of how pesticide-soil interactions are simulated.

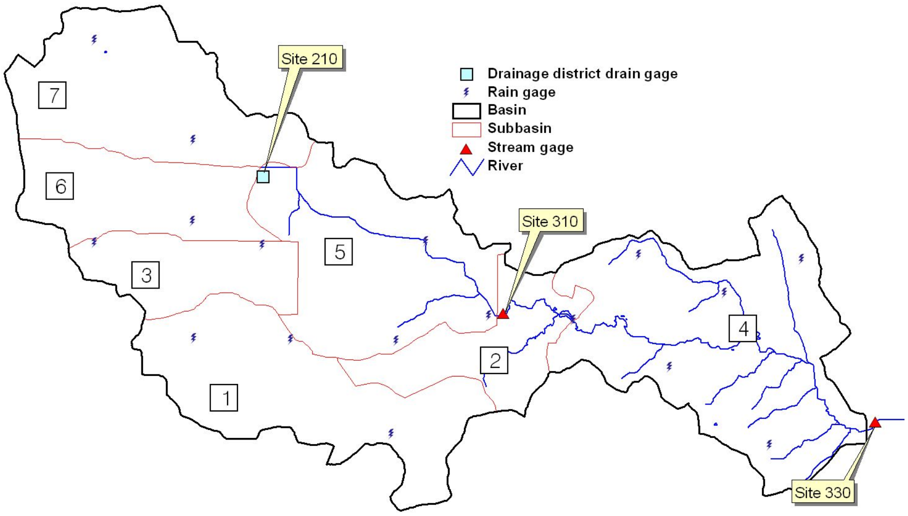

Figure 1. Sub-basins and measurement sites in the Walnut Creek watershed.

Tile Drainage Lag

Surface runoff takes time to reach a receiving stream, so the surface runoff lag time (*surlag*) plays an important role in calibrating daily flow. Similarly, the tile flow lag time is a crucial parameter affecting daily tile flow calibration. In the first version of SWAT-M, the tile flow lag time was combined with the lateral flow lag time and was not sensitive to tile flow (Du et al., 2005). Here, we introduce a drainage coefficient (*tiletime*) that determines the portion of the flow from the tile drains into the streams on a daily basis:

$$tiletime = 1 - \exp\left[-\frac{24}{g_{drain}}\right] \tag{1}$$

where g_{drain} is the drain tile lag time (h).

Pesticide Degradation Factor

The equations used in SWAT to model pesticide cycling in farmland were adopted from GLEAMS (Neitsch et al., 2002; Leonard et al., 1987). The movement of the pesticide is controlled by its solubility, degradation half-life, and soil organic carbon adsorption coefficient. A single factor of pesticide soil half-life (*hlife_s*) is used by SWAT to calculate the rate of pesticide degradation in all soil layers. The default value of *hlife_s* is 60 days (d) for atrazine. The half-life of atrazine in soil is affected by many factors, such as soil type, temperature, soil moisture, organic matter content, and soil pH values. Therefore, the half-life varies with the soil environment to which atrazine is exposed in the soil profile. Buhler et al. (1993) reported that average atrazine concentration in tile water did not decline in the 18 months following the atrazine application. In the study by Jaynes and Miller (1999), a substantial amount of atrazine was still detected one year after atrazine application. It was reported that at 25°C, an increase in pH will slow the hydrolysis half-life from 64 d at 5 pH to more than 200 d at 7 pH (Wagenet et al., 2005). It was also discovered that using a single degradation rate for the entire soil profile may not correctly depict atrazine fate (Moorman et al., 1994; Jaynes and Miller, 1999). Therefore, a second pesticide degradation half-life in soil (*hlife_s2*) was added for SWAT, which applies to soil layers below the surface soil layer. The second factor of pesticide degradation in soil layers is governed by first-order kinetics:

$$pst_{s,ly,t} = pst_{s,ly,o} \cdot \exp\left[\frac{0.693}{hlife\_s2} \cdot t\right] \tag{2}$$

where $pst_{s,ly,t}$ is the amount of pesticide in the soil layer (*ly*) at time *t* (kg pst/ha), $pst_{s,ly,o}$ is the initial amount of pesticide in the soil layer (kg pst/ha), and *t* is the time elapsed since the initial pesticide amount was determined (days).

PREPARING INPUT DATA FOR THE MODEL

Measured data such as digital elevation, land use, soil, daily precipitation, temperature, and solar radiation for the watershed were provided to the SWAT models. The Penman-Monteith method was selected for potential evapotranspiration (ET) calculation. Other input data were defaults assigned by the model. The watershed was delineated into seven sub-basins (fig. 1), which included 65 hydrologic response units (HRUs). An HRU has unique soil, land use, and land management. In the land use categories, corn and soybean 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 corn-soybean area, while the remaining 85% of this area was in a corn-soybean rotation (Hatfield et al., 1999).

The scheduled management operation input data were prepared as follows. The optimum time period for corn planting is April 20 to May 5, so a planting date of April 25 was set for the simulation years. While spring application of nitrate (N) fertilizer was employed in a small portion of the watershed, most areas of the WCW received nitrogen fertilizers, which were applied in the fall in the form of anhydrous ammonia. The fertilizer application rates from 1992 to 2001 for the entire WCW were determined from farmer surveys (Hatfield et al., 1999; Jaynes et al., 2004). Note that when a general date of fertilizer application is used for a watershed or a sub-basin, the date should be manually checked to see if there was rainfall on or near that day because SWAT does not automatically check on these special situations. Farm machines do not operate in fields under wet conditions, and it is also not appropriate to set a pesticide application one or two days prior to a heavy rainfall, which likely would have been avoided by the farmer using local weather forecasts. The annually averaged N fertilizer rate for corn fields was 165 kg/ha. The annual phosphorous fertilizer (P_2O_5) rate was 45 kg/ha. A general scheme of annual farming practices for the corn-soybean rotation is stated in table 1. The heat unit method is not appropriate for determining soybean grain development, since soybeans are day-length sensitive and do not respond to air temperatures as corn does (KSU, 2006). Therefore, the heat unit for soybean was set at 0.

MODEL EVALUATION METHODS

The applied N is mainly distributed among plant uptake, storage in soils, and losses in stream discharge, while the N losses in other ways are relatively small. It is important to look at each of these components of the N balance and keep them in reasonable ranges, since errors in their representations could result in unreasonable simulation of in-stream nitrogen loads. Furthermore, one of the main applications of the model is to investigate the effects of farming practices on the environment. This investigation is to a large extent based on the correct levels of N in the soil. It is evident that the possibly misleading outputs of models can be avoided if at

Table 1. SWAT inputs for soybean-corn rotation timings and management operations.

Date	Operation
Corn year	
April 14	P_2O_5 application, 90 kg/ha
April 15/22	Chisel plow and field cultivation
April 25	Atrazine banded, 0.438 kg/ha
April 25	Corn planting, 1800 heat unit
June 1	Row cultivation
October 15	Corn harvesting
Soybean year	
May 5	Chisel plow and field cultivation
May 15	Metolachlor broadcast, 1.588 kg/ha
May 15	Soybean planting
June 12/24	Row cultivation
September 21	Soybean harvesting
November 1	Anhydrous ammonia, 148 to 188 kg/ha[a]

[a] The rates for 1992 through 2001 were 152.5, 148, 152.8, 152.8, 164, 164, 188, 182, 174, and 174 kg/ha, respectively.

least two of the three main N-receiving resources are evaluated. In this study, therefore, the model simulation of crop yield was first evaluated in order to ensure that plant uptake of N is correct, and then the NO_3-N loads were calibrated and validated.

First, the calibration and validation of SWAT-M for flow were upgraded using ten years of data. Then the model was calibrated for the period of 1992 to 1995, and validated for the period of 1996 to 2001, for NO_3-N and atrazine loads at stream monitoring sites.

Stream sites 310 and 330, which are located mid-watershed and at the outlet of Walnut Creek, respectively, were selected to evaluate overall simulation of NO_3-N in stream discharge. Subsurface NO_3-N and atrazine losses from drainage district outlet site 210 were measured and exclusively used to evaluate the SWAT-M model simulation of subsurface chemical loads.

The Nash-Sutcliffe model efficiency (E) (Nash and Sutcliffe, 1970) and relative mean error (RME) or prediction error were used as the indicators during the calibration process of NO_3-N and atrazine loads and subsurface tile flow when comparing the model output values to measured values. E and RME are calculated as follows:

$$\mathrm{E} = 1 - \frac{\sum_{i=1}^{n}(X_{mi} - X_{pi})^2}{\sum_{i=1}^{n}(X_{mi} - \overline{X}_m)^2} \tag{3}$$

where E is the efficiency (goodness of fit) of the model, X_{mi} are measured values, X_{pi} are predicted values, $\overline{X}_m$ are average measured values, and n is the number of predicted/measured values. E ranges from $-\infty$ to 1. A value of E = 1.0 indicates that the pattern of model prediction perfectly matches the measured data. The farther away from 1 the E value becomes, the bigger the error in the predicted pattern as compared to the observations.

$$\mathrm{RME} = \frac{\sum_{i=1}^{n}(X_{mi} - X_{pi})}{\sum_{i=1}^{n}(X_{mi})} \tag{4}$$

where RME is the relative mean error. A value of RME = 0 indicates that the predicted total amount of flow or loads equals the measured value.

For the comparison of the SWAT-M and SWAT2000 models, the same input data were employed.

The parameter values for flow calibration were described in Du et al. (2005). *Nperco* (nitrate percolation coefficient) is usually used for NO_3-N calibration. In this study, *tdrain* (time to drain soil to field capacity) and *gdrain* (drain tile lag time) were also used because of the tile drain and pothole features of the WCW. Additionally, *cmn* (mineralization factor of active organic nutrients) and *rtn* (fraction of organic nitrogen in the active pool) were found to play an important role in controlling NO_3-N losses under the tile drainage conditions. Pesticide losses are heavily impacted by peak surface runoff, so the combined adjustment of both *surlag* and *percop* (pesticide percolation coefficient) was needed for pesticide load calibration. E and RME values were used as the indicator of model performance during the calibration of flow and both NO_3-N and atrazine loads. The values of the main calibrated parameters for NO_3-N and atrazine are listed in table 2.

Table 2. Nitrate and atrazine calibration parameters.

Parameter	Default	Calibrated
Nitrate percolation coefficient[a]	0.20	0.97
Drain tile lag time (hours)[b]	96	24-244
Fraction of organic nitrogen in the active pool[c]	0.02	0.04
Rate factor for humus mineralization[d]	0.0003	0.0019
Pesticide percolation coefficient[e]	0.5	0.015
Soil adsorption coefficient[f]	100	81
Wash-off fraction[g]	0.45	0.45
Foliar half-life (days)[h]	5	5
Atrazine half-life (days) in soil layer 1[i]	60	137
Atrazine half-life (days) in soil below layer 1[j]	60	315
Application efficiency[k]	0.85	0.89
Water solubility (mg/L)[l]	33	33

[a] Controls the amount of nitrate removed from the surface layer in runoff relative to the amount removed via percolation.
[b] The amount of time between the transfer of water from the soil to the drain tile and the release of the water from the drain tile to the reach.
[c] The fraction of humus nitrogen in the active pool.
[d] The rate coefficient for mineralization of the humus active organic nutrients.
[e] The ratio of the concentration of pesticide in runoff and lateral flow from the top 10 mm to the concentration in percolation.
[f] The ratio of the pesticide concentration in the soil or solid phase to the pesticide concentration in the solution or liquid phase.
[g] The fraction of the pesticide on the foliage that is washed-off by rainfall events.
[h] A lumped parameter describing the loss rate of pesticides on the plant canopy.
[i] The number of days required for a given pesticide concentration to be reduced by one-half in the top soil layer.
[j] The number of days required for a given pesticide concentration to be reduced by one-half in the soil layers below the top soil layer.
[k] The fraction of pesticide applied that is deposited on the foliage and soil surface (0.1 to 1.0). The remainder is lost.
[l] The highest concentration of pesticide that can be reached in the runoff and soil pore water.

RESULTS AND DISCUSSIONS

MODEL CALIBRATION AND VALIDATION FOR FLOW AT SITES 310, 330, AND 210 OF THE WCW

The results of flow calibration and validation are summarized in table 3. A detailed discussion of the results for SWAT-M and its comparison to SWAT2000 can be reviewed in Du et al. (2005). In comparison to the previous results for SWAT-M (Du et al., 2005), the E values (min/max) for the calibrated daily flow at sites 310 and 330 simulated by the further modified SWAT-M rose from 0.55 to 0.69 and from 0.51 to 0.63, respectively. Most noticeably, at site 210, where monitoring largely reflected tile drainage, the E value rose from −0.23 to 0.40, indicating that the introduction of *tiletime* improved the performance of SWAT-M. After SWAT-M was calibrated for flow, the NO_3-N and atrazine calibration and validation process was conducted.

MODEL PREDICTION OF CROP YIELDS

The corn yields predicted by SWAT-M ranged from 7767 kg/ha to 8956 kg/ha. A soybean-corn rotation HRU was randomly selected for yield evaluation. The corn yield in the selected HRU was 8865 kg/ha in 1996, with a total biomass of about 12471 kg/ha. The corn plant uptake of N in the HRU

Table 3. Values of E, RME, mean, and SD for daily and monthly flows of 1992-2001 at sites 310, 330 and 210 of the WCW.

			Daily Flow				Monthly Flow			
			E[a]	RME[b] (%)	Mean (mm/day)	SD[c]	E	RME (%)	Mean (mm/month)	SD
Site 310		Measured	--	--	0.91	1.97	--	--	27.73	43.95
	Calibration	SWAT-M	0.69	−11	0.81	1.43	0.87	−11	24.67	37.30
		SWAT2000	0.58	−38	0.57	1.77	0.82	−38	17.20	31.41
		Measured	--	--	0.50	1.24	--	--	15.34	25.86
	Validation	SWAT-M	0.66	4	0.52	0.94	0.78	4	15.91	21.13
		SWAT2000	0.59	−47	0.26	1.09	0.71	−47	8.06	17.36
Site 330		Measured	--	--	0.95	2.18	--	--	28.80	45.56
	Calibration	SWAT-M	0.63	−18	0.77	1.48	0.86	−18	23.51	34.96
		SWAT2000	0.46	−40	0.56	1.91	0.78	−40	17.16	31.66
		Measured	--	--	0.39	0.89	--	--	11.81	17.35
	Validation	SWAT-M	0.31	35	0.52	1.01	0.50	35	15.96	19.81
		SWAT2000	0.38	−33	0.26	1.06	0.70	−33	7.87	16.17
Site 210		Measured	--	--	0.69	1.12	--	--	20.96	27.43
	Calibration	SWAT-M	0.43	−12	0.61	1.11	0.65	−12	18.54	29.77
		SWAT2000	−0.78	−23	0.53	1.83	0.66	−23	16.10	31.21
		Measured	--	--	0.40	0.88	--	--	12.20	19.05
	Validation	SWAT-M	0.40	−10	0.36	0.68	0.61	−10	11.00	15.18
		SWAT2000	−0.25	−41	0.24	1.04	0.49	−41	7.24	15.49

[a] E = Nash-Sutcliffe model efficiency.
[b] RME = relative mean error.
[c] SD = standard deviation.

was 109 kg/ha. This compares with a recorded corn grain yield in a field within the watershed of 8320 kg/ha, with an N uptake of 95.8 kg/ha. Adding a stalk nitrate content of 3500 mg/kg creates a total N uptake of 109.8 kg/ha, assuming 4000 kg of stalks at harvest. The average corn yield for the Iowa conditions reported by Bakhsh et al. (2004) was 8615 kg/ha. Cambardella et al. (1999) reported that N uptake by corn grain ranged from 105 to 115 kg/ha. Therefore, both the predicted corn yields and the predicted N uptake by the corn plants were close to measured data. For soybean, the reported average yield (Bakhsh et al., 2004) in Iowa was 2388 kg/ha, and the predicted yields by SWAT-M ranged from 1356 to 2245 kg/ha. In the soybean year (1997) within the selected HRU, the predicted yield was 2135 kg/ha (biomass 4449 kg/ha) and the predicted N uptake was 115 kg/ha. Measurements in a soybean field in the WCW showed a harvest of 2510 kg/ha, with an N uptake of 156 kg/ha in the grain. The predicted yield and N uptake by the soybean crop were therefore somewhat lower than the measured values. Overall, the predicted yield and N uptake by corn and soybean were within a reasonable range.

MODELING NO_3-N LOADS AT SITES 310 AND 330 OF THE WCW

Figures 2a and 2b illustrate the monthly simulated vs. measured NO_3-N (S) loads from 1992 to 2001 at the mid-watershed (site 310) of Walnut Creek during 1992 to 2001. As these figures show, the monthly NO_3-N (S) loads predicted in both the calibration and validation periods were close to the measured values. The agreement was further demonstrated by the high E values (up to 0.91 and 0.80 for monthly NO_3-N (S) for the calibration and validation periods, respectively) and by the standard deviation (SD) values of the predicted monthly NO_3-N (S) loads, similar to those of the measured values (table 4). The RME values of the model were as low as −8% and 0% in the calibration and validation periods, respectively. For the simulations of daily NO_3-N (S) loads, although the model performed reasonably well (E = 0.61) during the calibration period, the accuracy (E = 0.41) of the daily NO_3-N (S) prediction declined in the validation period.

At the outlet (site 330) of the WCW, even though the model slightly underestimated the NO_3-N (S) loads in most months during 1992 and 1993 (fig. 2c), the E value for the calibrated NO_3-N (S) loads still reached 0.85, indicating that the model was well calibrated. The slight underestimation of NO_3-N (S) loads during 1992 and 1993 contributed a −25% RME for the total NO_3-N (S) load in calibration. In validation, both the graph (fig. 2d) and the statistical analysis (monthly E = 0.67; RME of the total NO_3-N (S) load = 8%) suggest that the monthly NO_3-N (S) loads were predicted relatively well. However, the model's simulation of the daily NO_3-N (S) loads at this site was not as good as the monthly values. The E value for the daily NO_3-N (S) load was 0.53 in calibration but only 0.26 in validation (table 4).

MODELING NO_3-N LOADS IN SUBSURFACE FLOW OF SITE 210

Most of the chemical loads at site 210 came from subsurface flow or tile drainage. Figure 2e demonstrates that the simulated NO_3-N (S) loads were higher than the measured values in some months and lower in other months during the calibration period. However, the model simulated monthly NO_3-N (S) loads reasonably well during the calibration period, since the E value was 0.73 and the RME 13% (table 4). In validation, high overestimations of NO_3-N (S) loads were found in May and June of 1996 (fig. 2f). The reasons for the discrepancy could be some abnormal farming activities during that time period in the drainage area above this site, which was not considered due to the use of general field operation information. For example, the measured nitrate load at upstream site 210 contributed up to 41% of that

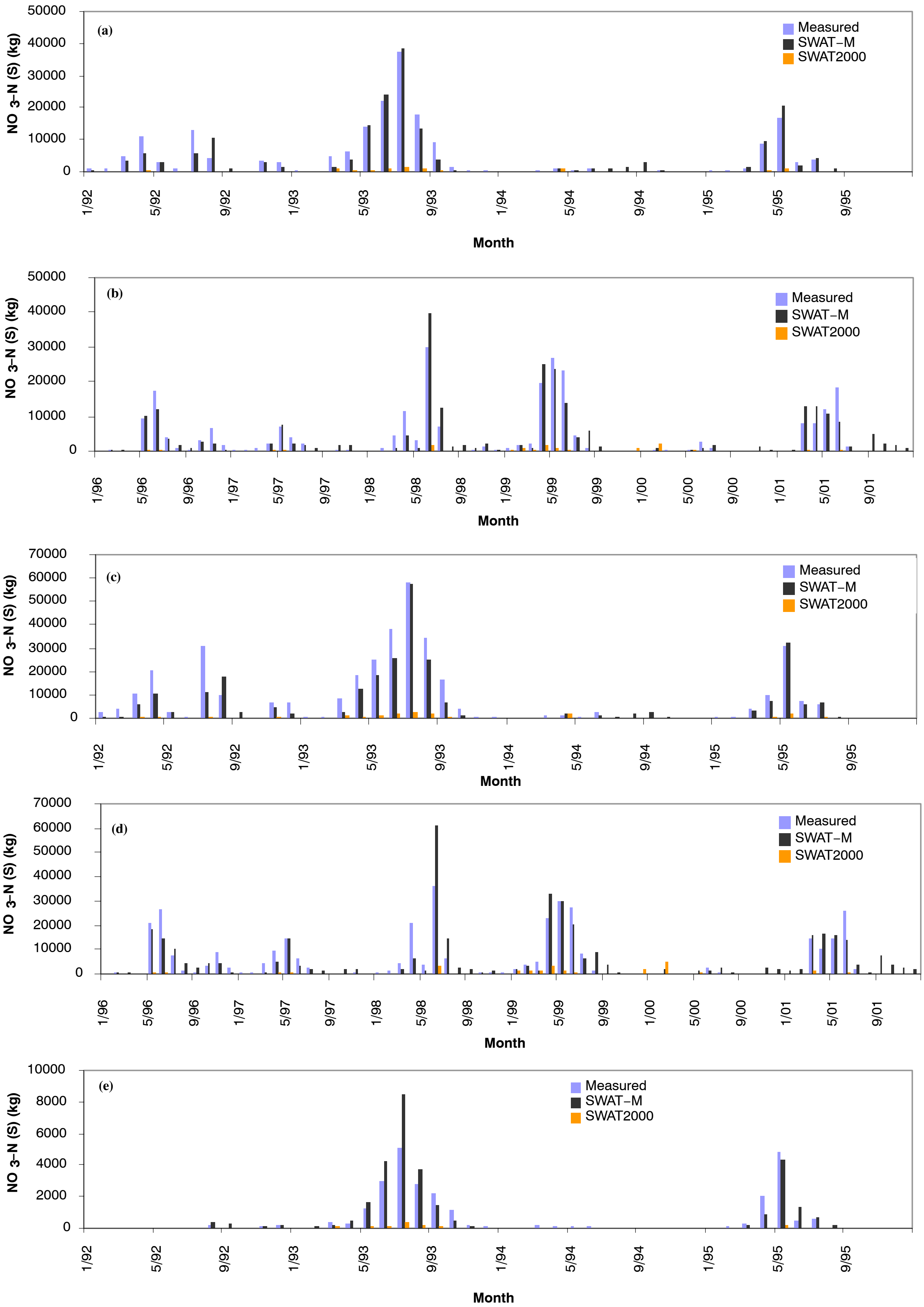

Figure 2. Measured vs. predicted monthly NO_3-N (S) loads in calibration/validation at: (a, b) site 310, (c, d) site 330, and (e, f) site 210 of the WCW (cont).

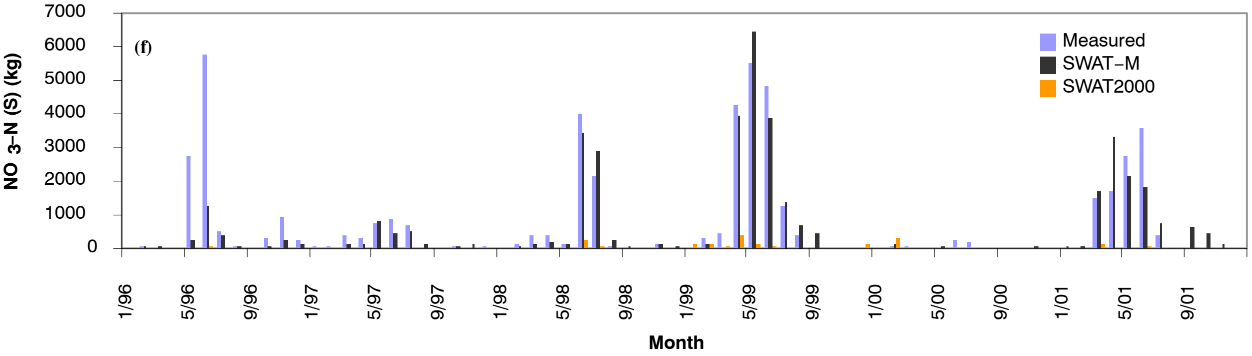

Figure 2. (cont) Measured vs. predicted monthly NO_3-N (S) loads in calibration/validation at: (a, b) site 310, (c, d) site 330, and (e, f) site 210 of the WCW.

at downstream site 310 and 29% of that at outlet site 330 on May 25, 1996, but the area of site 210 was only 21% of site 310 and 10% of site 330. No unusual farming practices in the drainage area above site 210 were observed to account for this disproportionately large discharge of nitrate in terms of its area. Similarly, the measured nitrate load at site 210 in June 1996 was up to 33% of that at site 310 and 21% of that at site 330, which was disproportionately large compared to the area. The predicted NO_3-N (S) loads in most months, however, matched those measured during the validation period, as shown in figure 2f. The model performed well, with an E value of 0.71 and a RME of −17% in validation (table 4).

Low daily E values of 0.25/0.42 in calibration/validation indicated that further improvement of the SWAT model is needed for the simulation of daily NO_3-N (S) loads in subsurface flow.

The simulation improvements from the enhancements to SWAT can be demonstrated by comparing SWAT-M and SWAT2000. Both figures 2a through 2f and the values of mean and SD in table 4 demonstrate that SWAT2000 seriously underpredicted NO_3-N (S) loads in this watershed with heavily installed tile drainage systems, and SWAT-M simulated the NO_3-N (S) loads much more accurately than SWAT2000.

The predictive capabilities of the model for nitrate loss simulation for every day of a month, as opposed to sampling days, are summarized in table 4. In spite of the decrease in E values for the calibration/validation periods at all sites (table 4), all E values were above 0.50 except in the validation period of site 330, indicating that the model is capable of simulating monthly NO_3-N loads in stream discharge of the WCW. However, it is important to note that the statistical methods used to estimate the missing measured daily values within a month could affect the model verification process.

Table 4. Values of E, RME, mean, and SD for daily and monthly NO_3 of 1992-2001 at sites 310, 330, and 210 of the WCW.

		Daily NO_3-N (S[a])				Monthly NO_3-N (S)				Monthly NO_3-N			
		E[b]	RME[c] (%)	Mean (kg/day)	SD[d]	E	RME (%)	Mean (kg/month)	SD	E	RME (%)	Mean (kg/month)	SD
Site 310													
Calibration	Measured	--	--	361.4	506.1	--	--	4119	7269	--	--	6485	8562
	SWAT-M	0.61	−8	333.8	444.9	0.91	−8	3804	7406	0.76	−8	5934	9502
	SWAT2000	−0.37	−95	17.9	40.9	−0.21	−95	204	354	−0.46	−95	311	405
Validation	Measured	--	--	163.7	340.0	--	--	3562	6560	--	--	4582	6978
	SWAT-M	0.41	0	164.2	337.2	0.80	0	3574	6729	0.59	−1	4545	7825
	SWAT2000	−0.14	−95	8.9	36.6	−0.21	−95	193	428	−0.34	−95	219	426
Site 330													
Calibration	Measured	--	--	683.7	932.3	--	--	7663	12599	--	--	11923	15747
	SWAT-M	0.53	−25	512.3	650.7	0.85	−25	5742	10717	0.79	−25	8929	13709
	SWAT2000	−0.41	−95	34.9	84.3	−0.26	−95	392	644	−0.45	−95	597	784
Validation	Measured	--	--	233.3	440.3	--	--	5013	8559	--	--	6535	9287
	SWAT-M	0.26	8	251.3	490.5	0.67	8	5399	9588	0.33	7	7013	11377
	SWAT2000	−0.18	−92	17.9	81.2	−0.22	−92	385	848	−0.37	−93	438	838
Site 210													
Calibration	Measured	--	--	68.0	76.6	--	--	540	1175	--	--	951	1361
	SWAT-M	0.25	13	77.0	86.0	0.73	13	612	1552	0.60	3	978	1733
	SWAT2000	−0.60	−95	3.6	7.6	−0.08	−95	29	73	−0.35	−95	52	85
Validation	Measured	--	--	35.7	78.2	--	--	676	1357	--	--	905	1474
	SWAT-M	0.42	−17	29.5	54.2	0.71	−17	559	1177	0.58	−14	779	1267
	SWAT2000	−0.16	−96	1.4	6.4	−0.19	−96	27	68	−0.31	−96	35	72

[a] Sampling days only.
[b] E = Nash-Sutcliffe model efficiency.
[c] RME = relative mean error.
[d] SD = standard deviation.

Modeling Atrazine Loads at Sites 310 and 330 of the WCW

Measured atrazine losses were below 1000 g/ha in most months, but in some months they exceeded 10,000 g/ha; hence, atrazine loads were plotted on a log scale. The predicted and measured atrazine loads at site 310 are plotted in figures 3a and 3b. Figure 3a shows that SWAT-M did not simulate higher atrazine losses (>1000 g/ha) as accurately as lower losses in calibration. Overall, the model was adequately calibrated for monthly atrazine (S) loads, at an E value of 0.73 and as demonstrated in figure 3a. The underestimation of heavy atrazine (S) loads (>1000 g/ha) in June and July of 1993 resulted in a −34% RME (table 5). The model greatly underpredicted the monthly atrazine (S) load in June of 1998 (fig. 3b), which caused a decrease in the E value (0.58) during the validation period. Figure 3b shows that other predicted atrazine load peaks during the verification period closely followed the measured values. The RME for the total atrazine (S) load in validation was the same as in calibration (table 5). In comparison to SWAT2000, SWAT-M has been greatly improved in predicting large event-associated atrazine losses, as shown in figures 3a and 3b. The E values in calibration/validation for the monthly atrazine (S) loads predicted by SWAT2000 were only 0.02/0.06 and the RMEs were up to −93%/−77%. The daily simulation of atrazine (S) loads by SWAT-M has also been improved with E values of 0.47/0.12 in calibration/validation as compared to SWAT2000 with E values of only 0.05/0.02.

Although SWAT-M predicted atrazine (S) loads in most months of the calibration period at site 330 (fig. 3c) reasonably well, it seriously underpredicted the heavy atrazine (S) load in June 1993, which produced a big impact on the E value (only 0.50) in calibration. The −28% RME by SWAT-M in calibration was mainly caused by this underestimation in June. During the validation period, SWAT-M overpredicted the level of atrazine (S) loads in most months (fig. 3d), which led to a 29% RME. However, the E value still reached 0.53 (table 5), indicating that SWAT-M was capable of simulating atrazine (S) loads at site 330. The simulation of daily atrazine (S) loads by SWAT-M (table 5) was poor, with E values of 0.21/0.41 in calibration/validation. Nevertheless, figure 3c and 3d, and the E and RME values, illustrate that SWAT-M is a much better tool for predicting both daily and monthly atrazine (S) losses than SWAT2000.

Modeling Atrazine Loads in Subsurface Flow at Site 210 of the WCW

The monthly atrazine (S) loads during the calibration period at site 210 predicted by SWAT-M were very well matched to the measured loads, with an E value of 0.92 (fig. 3e). The RME was as low as 6%. The model predicted especially accurately the largest load (in June 1993) during the calibration period. The simulation of daily (S) loads in calibration was also in agreement with the measured data in terms of the E value (0.51). As at the other sites, there were one or two months when the model could not accurately simulate large atrazine loads at this site. The model missed the highest monthly atrazine (S) load (June 1999) during the validation period. The E value for the monthly load prediction during validation was tremendously reduced to 0.31 by this underprediction in June 1999. This same underprediction also led to the RME increasing to −44% for the validation period. The reason for the poor model performance was unusual atrazine occurrences in the stream discharge at this site on three days (June 4, 10, and 11), which were 206, 145, and 207 g/day, respectively. The monthly precipitations in June 1993, June 1996, and June 1998 were similar to or higher than those in June 1999, but none of the daily atrazine loads in those years exceeded 100 g.

There may be some inherent difficulties in predicting daily loads of nitrate nitrogen and atrazine when relatively small watersheds or averages for dates and rates of chemical application are used in model simulation, while over large areas or longer times (months) averages may suffice. Over small areas and times, differences between what the farmers actually did and the average practice may cause substantial differences in model output. For example, some farmers may have applied atrazine just before a rain storm or applied at a very high rate compared to the average. In a watershed the size of WCW, one farmer can substantially affect the loads in the stream.

The predicted monthly atrazine loads with continuous days of data are summarized in table 5. Compared to the monthly atrazine (S) loads, the E values for the monthly atrazine loads at all sites (table 5) were the same or slightly lower, and the RME values were slightly higher or lower, but they still indicated that the model was capable of simulating monthly atrazine loads in stream discharge of the WCW.

SWAT-M was run without the introduction of the second pesticide degradation half-life in soil, and the results are listed in table 5 (SWAT-M*). Comparing model predictions with and without *hlife_s2*, the former achieved much higher

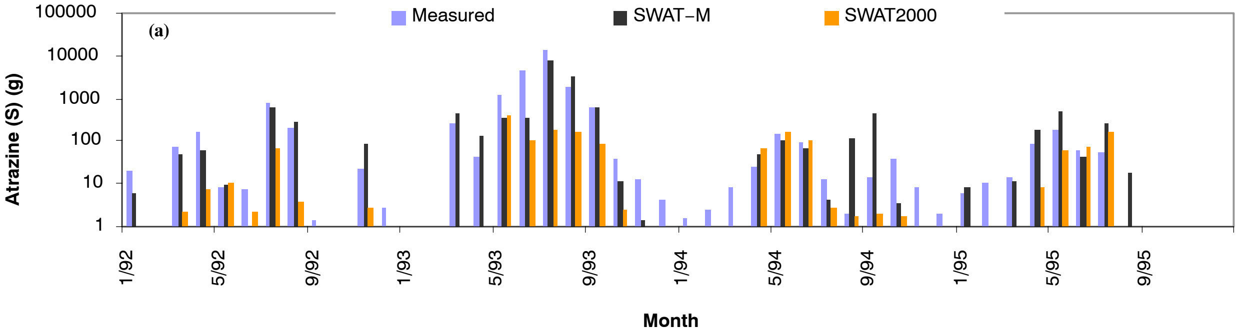

Figure 3. Measured vs. predicted monthly atrazine (S) loads in calibration/validation at: (a, b) site 310, (c, d) site 330, and (e, f) site 210 of the WCW. (cont)

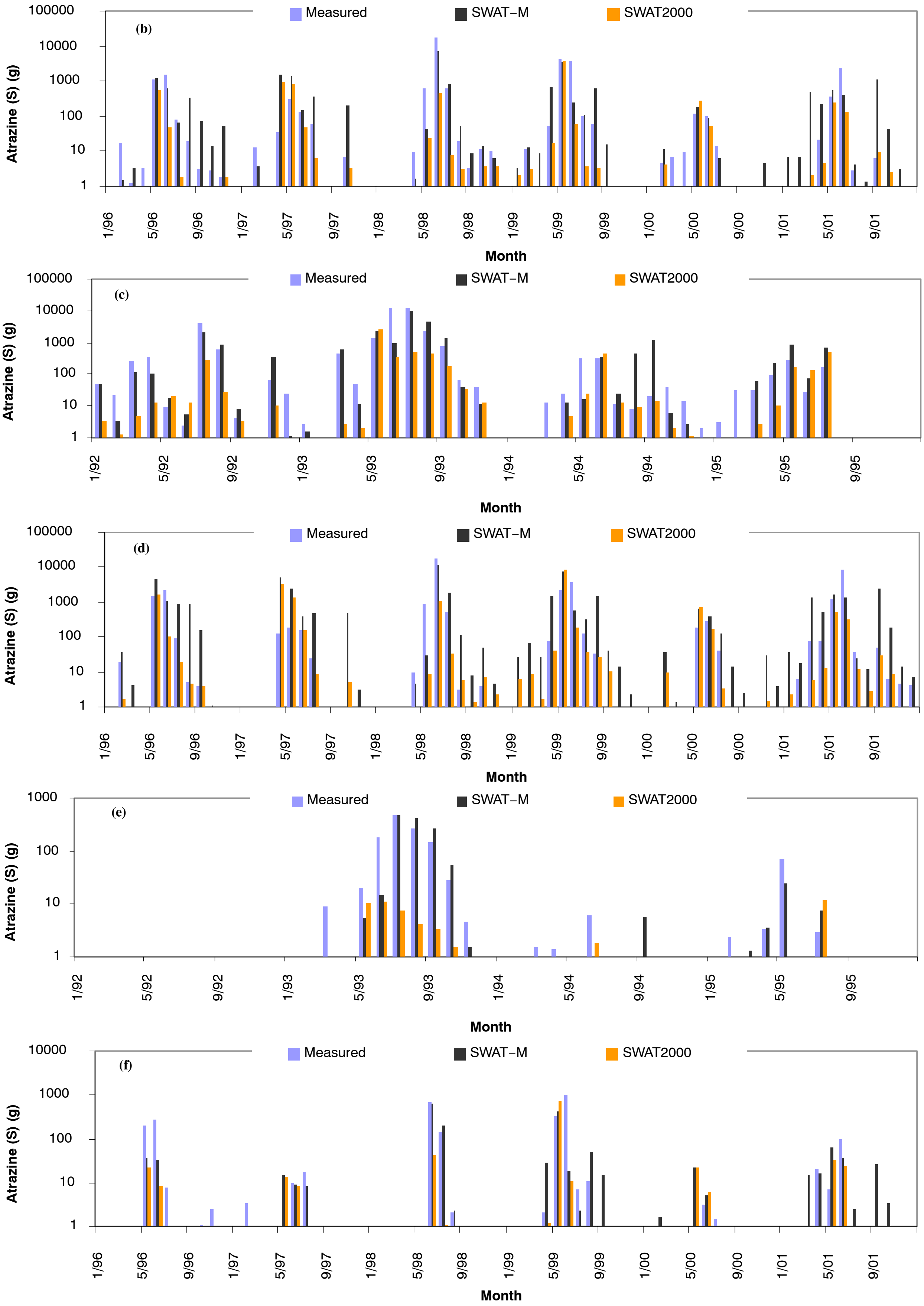

Figure 3. (cont) Measured vs. predicted monthly atrazine (S) loads in calibration/validation at: (a, b) site 310, (c, d) site 330, and (e, f) site 210 of the WCW.

Table 5. Values of E, RME, mean, and SD for daily and monthly atrazine of 1992-2001 at sites 310, 330, and 210 of the WCW.

		Daily Atrazine (S)[a]				Monthly Atrazine (S)				Monthly Atrazine			
		E[b]	RME[c] (%)	Mean (g/day)	SD[d]	E	RME (%)	Mean (g/month)	SD	E	RME (%)	Mean (g/month)	SD
Site 310													
Calibration	Measured	--	--	70.7	254.0	--	--	495	2008	--	--	598	2174
	SWAT-M	0.47	−34	46.6	124.3	0.73	−34	326	1172	0.71	−30	417	1258
	SWAT2000	−0.05	−93	5.1	13.2	−0.02	−93	35	75	−0.03	−88	71	185
	SWAT-M*[e]	0.27	−66	23.9	64.0	0.43	−66	167	602				
Validation	Measured	--	--	25.9	208.6	--	--	467	2158	--	--	510	2215
	SWAT-M	0.12	−34	17.1	83.8	0.58	−34	309	928	0.57	−29	362	981
	SWAT2000	−0.02	−77	5.9	60.6	0.06	−77	106	480	0.05	−77	115	495
	SWAT-M*	0.06	−58	10.8	67.4	0.36	−58	194	607				
Site 330													
Calibration	Measured	--	--	120.2	316.5	--	--	776	2609	--	--	971	3092
	SWAT-M	0.21	−28	86.8	170.7	0.50	−28	561	1573	0.50	−13	841	2077
	SWAT2000	−0.12	−85	18.4	65.2	−0.01	−85	119	380	−0.02	−77	223	555
	SWAT-M*	0.12	−58	50.5	98.4	0.32	−58	326	860				
Validation	Measured	--	--	31.2	213.5	--	--	554	2333	--	--	598	2410
	SWAT-M	−0.41	29	40.2	212.3	0.53	29	715	1869	0.49	48	886	2011
	SWAT2000	−0.39	−55	14.2	154.7	−0.04	−55	252	1064	−0.05	−53	279	1098
	SWAT-M*	−0.47	−10	28.2	194.6	0.39	−10	501	1407				
Site 210													
Calibration	Measured	--	--	9.2	13.1	--	--	35	146	--	--	41	149
	SWAT-M	0.51	6	9.8	14.5	0.92	6	38	157	0.87	26	52	165
	SWAT2000	−0.47	−97	0.3	0.9	−0.04	−97	1	3	−0.07	−83	7	27
	SWAT-M*	0.49	−41	5.4	8.2	0.78	−41	21	88				
Validation	Measured	--	--	2.4	13.3	--	--	40	157	--	--	44	167
	SWAT-M	0.09	−44	1.4	7.4	0.31	−44	23	89	0.32	−25	33	102
	SWAT2000	−0.46	−67	0.8	11.5	−0.06	−67	13	90	−0.06	−57	19	94
	SWAT-M*	0.01	−72	0.7	5.8	0.15	−72	11	50				

[a] Sampling days only.
[b] E = Nash-Sutcliffe model efficiency.
[c] RME = relative mean error.
[d] SD = standard deviation..
[e] SWAT-M* indicates the results of SWAT-M without the introduction of the second factor of pesticide degradation half-life in soil.

E and RME values than the latter, demonstrating that SWAT-M has been improved by including the *hlife_s2*.

SUMMARY AND CONCLUSIONS

SWAT with modified tile drain and pothole components was evaluated at a watershed scale, using 10 years of measured NO_3-N and atrazine data in stream discharge in the Walnut Creek watershed. The centrally located site (310) and the outlet (site 330) of the watershed were selected to investigate overall performance of the SWAT model, while site 210 was used exclusively to scrutinize the model's capability of simulating subsurface NO_3-N and atrazine loads. With the introduction of independent tile drain lag time, the performance of the SWAT model for daily flow simulation has been improved. In comparison to the previous results (Du et al., 2005), the E values for the calibrated daily flow at sites 310 and 330 simulated by SWAT-M increased from 0.55 to 0.69 and from 0.51 to 0.63, respectively. Of special note, at site 210 (dominated by tile drainage), the E value rose from −0.23 to 0.40.

After the model was calibrated for flow, evaluation of the model was conducted first in predicting crop yield and N uptake, and then in the simulation of NO_3-N and atrazine fate in the watershed. Both the predicted corn yields and N uptake by corn plant were close to the measured data. For soybean, both the predicted yield and N uptake were lower than the measured values.

Although SWAT-M underpredicted NO_3-N (S) loads in some sites and overpredicted them in other sites, the monthly NO_3-N (S) loads in stream discharges at the center and outlet of Walnut Creek watershed were predicted relatively well, with high E values of 0.91/0.80 and 0.85/0.67 for calibration/validation, respectively. Nevertheless, the model's simulation of the daily NO_3-N (S) loads was not as good as the monthly loads, as the E values of daily NO_3-N (S) loads at the center and outlet of the WCW were only 0.41 and 0.26 during the validation period, respectively. By especially investigating site 210, which was dominated by tile drainage, it was concluded that the model reasonably simulated monthly NO_3-N (S) loads in subsurface flow (E = 0.73/0.71 and RME = 13%/−17% in calibration/validation), although it needs to be improved in the simulation of daily subsurface NO_3-N (S) (E = 0.25/0.42 in calibration/validation). The enhancement of the SWAT model in this study was further proven by comparing SWAT-M and SWAT2000. Both figures and statistics demonstrated that SWAT-M simulated the NO_3-N loads in the watershed with widely installed tile drainage systems more accurately than SWAT2000.

A second pesticide degradation half-life in soil was added to SWAT to improve the model performance. Comparing model prediction with and without the second pesticide half-life factor, the former achieved much better E and RME values than the latter, demonstrating that SWAT-M was greatly improved. Overall, SWAT-M (with some exceptions of over- or underpredictions during the simulation periods) proved to be capable of simulating atrazine loads in stream discharge of the WCW with tile drains and potholes relatively well. The accuracy of atrazine loads predicted by SWAT-M at the daily time step was lower than that obtained at the monthly time step. Nevertheless, we have demonstrated that SWAT-M is a much better tool for predicting both daily and monthly atrazine losses in the WCW than SWAT2000.

Although the SWAT model has been greatly enhanced from its previous version (SWAT2000), its tile drain and pothole components need further improvement to obtain higher accuracy in predicting NO_3-N and atrazine loads in stream discharge of watersheds with tile drains and potholes.

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