MODELING AND RISK ANALYSIS OF NONPOINT-SOURCE POLLUTION CAUSED BY ATRAZINE USING SWAT

G. Vazquez-Amabile, B. A. Engel, D. C. Flanagan

ABSTRACT. *The SWAT (Soil Water Assessment Tool) model was calibrated and validated to evaluate its performance to predict atrazine loads in streams for the period 1996-2004 at eleven sampling sites in the St. Joseph River watershed in northeast Indiana. This watershed encompasses 280,000 ha, and 60% the area is in agricultural crops of corn and soybeans. Daily streamflow calibration and validation were completed before starting pesticide calibration. During the validation period, Nash-Sutcliffe values varied from 0.33 to 0.60 for daily streamflow and between 0.64 and 0.74 for monthly streamflow. The estimation of the timing of atrazine application was very important in the calibration-validation process, and it proved to be a key input for predicting the amount and timing of pesticide released to streams. Monthly atrazine concentrations were predicted with average R^2 values of 0.60 and 0.49 and average Nash-Sutcliffe coefficients of 0.38 and −0.91 for the calibration and validation periods, respectively. The total mass of atrazine released by the whole basin between 2000 and 2003, for the period April to September, was closely predicted by the model. The observed average amount of atrazine released during the four seasons was 1002.1 kg/season, and SWAT predicted 950.1 kg/season. Risk analysis was performed based on the outputs generated by the model by computation of exceedance probability curves and thematic and probability maps. The model was suitable to estimate levels of atrazine released to streams in rural watersheds and to conduct NPS pollution risk analysis at a basin scale to evaluate long-term effects of management practices and environmental changes.*

Keywords. *NPS pollution, Pesticide, Runoff, Risk analysis, SWAT.*

Agriculture is the main cause of nonpoint-source (NPS) pollution that affects streams and aquifers throughout the country (Yu et al., 2004). The driving force of NPS pollution is the rainfall-runoff process, which tends to be a complex non-linear, time-varying, and spatially distributed process in agricultural watersheds. This and other related processes may be quantified by means of physical hydrologic models. Likewise, hydrologic modeling is often the first step in the development of a spatial decision support system suitable for identifying areas that are vulnerable to nutrient and pesticide contamination (Lim et al., 2001), evaluating the effect of management practices, and performing risk analyses for different scenarios.

In agricultural watersheds, variable amounts of pesticides can be released to streams and aquifers through surface runoff and leaching, jeopardizing sources of drinking water. On the other hand, pesticides make high agricultural yields possible. Atrazine is a key input in corn production throughout the world. However, it is easily carried to streams by rainfall runoff because of its high solubility. Modeling is a valuable tool in the analysis of the risk of contamination caused by atrazine or other pesticides, and in evaluating the effect of management practices in that process.

The USDA-ARS National Soil Erosion Research Laboratory (West Lafayette, Indiana) is working on a comprehensive water quality monitoring and best management practice (BMP) research and assessment project for the Source Water Protection Initiative in the St. Joseph River watershed (Flanagan et al., 2003). The goal of the project is to study the transport and fate of agricultural chemicals in the sources of the water supply, as well as the impact of best management practices (BMPs) implementation, in the St. Joseph River watershed.

The St. Joseph River watershed is located in northeast Indiana, northwest Ohio, and south central Michigan and encompasses 2808.5 km^2. Since 1995, agricultural chemicals have been detected in the St. Joseph River at Fort Wayne, Indiana. The St. Joseph River represents the source of drinking water for approximately 200,000 residents in Fort Wayne (SJRWI, 2004). Peak levels of atrazine higher than 3 ppb, the EPA drinking water standard, have been reported at different sites in the watershed between 1995 and 1998 by the Environmental Working Group (EWG, a network of environmental groups) and the St. Joseph River Watershed Initiative (SJRWI).

Water quality data recorded by SJRWI between 1996 and 2003 and by the Three Rivers water treatment plant at Fort Wayne between 2000 and 2004 offer the possibility for calibration and validation of hydrologic models for the whole watershed, which may be used to simulate the impact of different management practices or any other kind of scenarios.

The SWAT (Soil Water Assessment Tool) model (Arnold et al., 1998) allows simulation of the impact of different

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scenarios on the levels of atrazine over time and space. Thus, SWAT constitutes a valuable tool to study the impact of fertilizer and pesticide use on water sources, as well as the impact of management practices and potential land use changes. In previous evaluations, SWAT has shown good results when predicting runoff (Saleh et al., 2000; Spruill et al., 2000) and nitrogen and phosphorus levels in streams (Saleh et al., 2000; Saleh and Du, 2004). SWAT daily predictions for atrazine were evaluated in Sugar Creek, Indiana (242 km^2) by Neitsch et al. (2002), who reported a daily R^2 of 0.21 and 0.41 in the calibration and validation periods, respectively.

The National Agricultural Pesticide Risk Analysis (NAPRA) system (Lim and Engel, 2003) uses GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) to perform NPS pollution risk analysis and works at the field level, computing the pesticide released at the edge of the field. Thus, it cannot be applied to large watersheds because it does not route the pesticides downstream to the basin outlet. Conversely, SWAT routes sediment, nutrients, and pesticides from the hydrologic response units to the subbasin and basin outlets, but does not compute NPS pollution risk analysis.

The primary goal of this study was to analyze the capabilities and performance of the SWAT model to predict atrazine levels in streams. A secondary goal was to conduct an NPS pollution risk analysis based on the SWAT outputs for this pesticide. If SWAT performs at an acceptable level, it could be used in the future as a complement to the NAPRA-GLEAMS system at basin scales.

Literature Review

Atrazine Chemical Properties and Metabolites

Atrazine (2-chloro-4-ethylamino-6-iso-propylanmin-s-triazine) is a selective soil-applied herbicide extensively used in corn production, and other crops, for control of broadleaf weeds. It belongs to the triazines group, along with cyanazine and simazine. The average rate used in corn fields in Indiana between 1990 and 2002 has been 1.45 kg ai/ha (NASS, 2004a). Once the herbicide reaches the soil, it is solved into the soil water to be absorbed later by the plant roots. Some species, like corn or sorghum, can detoxify the active ingredient, but photosynthesis is affected by atrazine in many other plant species, stopping their growth. Atrazine is moderately soluble in water (33 mg/L at 25°C and 28 mg/L at 20°C). Microbial activity and other chemicals may break down atrazine in soil and water, particularly in alkaline conditions. Sunlight and evaporation do not reduce its presence. It may bind to some soils, but it generally tends to leach to groundwater.

Atrazine has a long residual activity in soil, with a half-life in the topsoil of about 60 days, but its half-life is significantly longer in subsurface soils or in groundwater (Christensen and Ziegler, 1998). Even though atrazine is adsorbed by soil particles, it is easily desorbed from the solid phase, passing to the soil solution, which makes it possible to be transported to streams by surface runoff and to the aquifers by leaching.

Contamination Caused by Atrazine

High levels of atrazine residues have been found in groundwater and streams in the U.S., Canada, and European countries (Takacs et al., 2002). This has caused large concerns because of the potential environmental effects, such as endocrine disruption and chromosomal damage in animals and humans (Takacs et al., 2002).

Atrazine losses due to runoff may reach 18% of the applied amount but tend to be less than 3% (Huber, 1993). A loss of up to 15% of applied atrazine has been determined in Miami silt loam soil, 95.4% of which occurred in the dissolved phase (Zhang et al., 1997). Christensen and Ziegler (1998) found that approximately 1% of the atrazine applied in the Little Arkansas River watershed, in Kansas, was transported annually in surface runoff to the river in the period 1995-1997. Ninety percent of the runoff load occurred during a very short period of time, of about 15 to 40 days, generally following the application of herbicides in late spring and summer.

Tillage system effects on herbicide losses vary with year and rainfall patterns. The rainfall timing and intensity within the first month after pesticide application appear to be much more important than tillage system differences in controlling pesticide losses (Klavidko et al., 2001).

The U.S. Environmental Protection Agency has established 3 ppb (or μg/L) as the MCL for atrazine in drinking water, but other countries have adopted even lower maximum contaminant levels. In Canada, the Canadian Water Quality Guideline establishes a maximum concentration of atrazine in surface water of 1.8 μg/L for the protection of aquatic life. In Germany, atrazine use was banned in 1991 because groundwater concentrations exceeded the allowable level of 0.1 μg/L (Takacs et al., 2002). On 31 January 2003, the EPA released the atrazine Interim Re-registration Eligibility Decision (IRED) and announced an innovative and aggressive program to protect vulnerable community drinking water systems from contamination by atrazine (EPA, 2003).

NPS Pollution Modeling

NPS pollution models are valuable tools in environmental studies to evaluate the effects of pesticide and fertilizer losses caused by land use changes and management practices. The GLEAMS model (Leonard et al., 1987) has been run by the National Resources Inventory program (NRI) for 170,000 NRI sample points to determine annual concentrations of pesticides at the bottom of the root zone and the edge of the field for a 20-year period, and compared to water quality standards (Goebel, 1998). NRI sample points were treated as "representative fields" to determine which watersheds had the greatest potential for pesticide losses to groundwater and streams.

The NAPRA system (National Agricultural Pesticide Risk Analysis), which incorporates the GLEAMS model, has been used by NRCS to estimate pesticide leaching and runoff loss at 1,940 NRI sample points within three river basins (Kellogg et al., 1998). The NAPRA-GLEAMS system allows analysis of pesticide losses for different management scenarios, generating 50 years of climate data to estimate the exceedance probability of mass loading, or concentration, in groundwater or runoff water at the edge of the field. In this way, the NAPRA-GLEAMS system performs risk analysis at the watershed level using information from farm fields. The NAPRA WWW (World-Wide-Web) system is a web-based approach (Lim and Engel, 2003) developed to estimate the effect of site-specific land use and management practices, defined on-line by the user, on water pesticide levels. NAPRA WWW was enhanced, incorporating the QUAL2E model to simulate in-stream processes, and new features of GLEAMS 3.0: crop rotations, multiple pesticide simulation, grass waterways, and tillage operations associated soil erodibility factors.

A different approach is the multipurpose environmental analysis system created by the U.S. EPA for use by regional, state, and local agencies in performing watershed and water quality based studies (EPA, 2004a). This system has been named BASINS (Better Assessment Science Integrating point and Nonpoint Sources). The latest version, BASINS 3.0 (EPA, 2004b) runs under ArcView and integrates into one package an in-stream water quality model (QUAL2E), a simplified GIS-based nonpoint-source annual loading model (PLOAD), and two watershed loading and transport models (SWAT and HSPF − Hydrological Simulation Program FORTRAN). Each of these four models can be used independently of one another. SWAT is the most convenient model in the package, since it includes all the processes computed in HSPF, QUAL2E, and PLOAD.

SWAT is a comprehensive river basin or watershed scale model developed by Dr. Jeff Arnold of the USDA-ARS (Arnold et al., 1998). This distributed, continuous model uses a daily time step. SWAT was created to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soil, land use, and management conditions over long periods of time (Neitsch et al., 2001). AVSWAT2000, the latest SWAT model version, is a GIS interface extension developed in ArcView by Di Luzio et al. (2001). In this version, some inputs, such as soils, land use, elevation, streams, outlets, and gauges, are introduced as ArcView files (shapes and grids).

SWAT computes runoff as well as nutrient (N and P) and pesticide transport with sediments, to streams, and to water bodies (e.g., ponds, wetlands, and reservoirs). Even though the model uses a daily step, it can be run to assess sub-daily precipitation data. In its GIS version, SWAT divides the watershed into subbasins, which are composed of smaller units called hydrologic response units (HRUs). The model computes all the processes daily for every HRU. Therefore, the level of detail of the analysis depends on the size of the HRUs, which in turn depends on the size of the soil and land use units. Thus, the more detailed the soil information, the more detailed are the model results. This means that very detailed soil information might produce HRUs comparable to farm field units. HRUs are generally generated from the STATSGO soil database (approximate scale 1:250,000) so that SWAT results will constitute a complement, at a smaller scale, of the site-specific NAPRA-GLEAMS system (Lim and Engel, 2003).

SWAT Algorithms for Pesticides

SWAT algorithms for pesticide fate and transport were adapted from the GLEAMS and EPIC (Erosion Productivity Impact Calculator) (Williams, 1995) model equations. These processes include plant wash-off, leaching, and degradation, along with movement of soluble pesticides and transport of sorbed pesticides to the streams.

Pesticide components of the GLEAMS model (Leonard et al., 1987) are essentially the same as those of the CREAMS model (Knisel, 1980), but some modifications were made for pesticide extraction into runoff, and pesticide evaporation and uptake. In GLEAMS, the pesticide is partitioned into soil and solution phases. Leonard and Wauchope (1980) described the pesticide distribution as a simple linear adsorption isotherm:

$$Kd = Cs / Cw \tag{1}$$

where Kd is the partitioning coefficient, Cs is the concentration in the solid phase (mg/kg), and Cw is the concentration in the solution phase (mg/L). Kd depends on the pesticide characteristics and soil organic carbon. Therefore, Kd has to be normalized by the soil organic carbon content by a constant denominated linear adsorption coefficient for organic carbon (Koc):

$$Kd = Koc \times \mathrm{OC}/100 \tag{2}$$

For atrazine, Koc has been determined as 100 g/mL (SCS, 1990). However, Koc is not available for all pesticides and can be computed using the relationship with water solubility (WS), proposed by Kenaga and Goring (1980), which is reliable for pesticides with solubility between 100 to 300 mg/L:

$$\log 10Koc = 3.64 - 0.55 \times \log 10WS \tag{3}$$

The solid and water soluble transported mass are defined as Y:

$$Y = CwV + CsB \tag{4}$$

where V is the volume of water per unit volume of runoff interface, and B is the soil mass per unit volume of overland flow.

Evaporation and transpiration are calculated using partitioning related to the leaf area index of the plant species. Pesticide evaporation and uptake are computed using the pesticide concentration in soil solution. Thus, the mass of pesticide uptake will be the pesticide fraction of the mass of water transpired. Pesticides transported by soil evaporation are only moved into the layer directly above the computational layer, and movement from layer 1 into the atmosphere is not modeled in the system.

For pesticide modeling, the main difference between GLEAMS and SWAT is that SWAT incorporates routing and in-stream pesticide transformations, as well as reservoir transformations (Neitsch et al, 2001). These processes are based on the equations proposed by Chapra (1997). The model assumes a well-mixed layer of water overlying a sediment layer, and only one pesticide can be routed through the stream network. In-stream pesticide transformation includes solid-liquid partitioning, degradation, volatilization, and settling of pesticides in the water; and degradation, re-suspension, diffusion, and burial of pesticides in the sediment. These processes are also modeled in reservoirs, but not in other water bodies, such as ponds and wetlands.

Even though SWAT can model only one pesticide at a time, the main advantage is that SWAT includes pesticide field and in-stream processes in the same model. GLEAMS can model more than one pesticide simultaneously, but it does not model in-stream processes, and in-stream models, like QUAL2E (Lim et al., 2001), have to be used to model water quality in the stream network.

Materials and Methods

For this study, the GIS version of the SWAT model was used (AVSWAT2000; Di Luzio et al., 2001). The project consisted of two parts: model calibration-validation, and risk analysis. First, daily flow was calibrated and validated at four USGS gauges, and then atrazine levels in streams were calibrated and validated at ten sampling sites along the St. Joseph River watershed. Additionally, SWAT was validated for the whole basin at the main outlet, for the period 2000-2004, using a more detailed dataset recorded daily from the St. Joseph River by personnel of the Three Rivers water treatment plant at Fort Wayne.

A risk analysis of NPS pollution from atrazine was accomplished for the study area, similarly to the GLEAMS-NAPRA system. Two main tools were considered for the analysis: the quantification of atrazine levels (concentration) over time and throughout the watershed, and the exceedance probability. Both were presented in thematic and probability maps along with probability curves for different scenarios.

Study Area and Datasets

The St. Joseph River watershed is located in northeast Indiana, northwest Ohio, and south central Michigan and encompasses 280,000 hectares. Its boundaries are defined by the USGS 8-digit HUA No. 04100003. It includes portions of the counties of Allen, Steuben, Dekalb, and Noble in Indiana; Hillsdale and Branch in Michigan; and Williams and Defiance in Ohio. The main stream of the watershed is the St. Joseph River, approximately 100 km long, which runs in a NE-SW direction until joining the Maumee River at Fort Wayne (fig. 1).

The St. Joseph River watershed is largely agricultural, with major crops being corn and soybeans. Land uses were grouped in five major classes, where agriculture represented 59.2% of the total area, pastures 20.7 %, forest classes 13.1%, wetlands 3.9%, and urban classes 3.1%.

The soils of the watershed are generally somewhat poorly drained, and the parent material is compacted glacial till. The predominant soil textures are silt loam, silty clay loam, and clay loam. Soil associations include Miami-Morley, Morley-Glynwood-Blount, and Blount-Pewamo. The topography of the watershed varies from rolling hills in Hillsdale, Williams, Noble, and Steuben counties to nearly level plains in Dekalb and Allen counties. Erosion and oversaturation are the major soil limitations (SJRWI, 2004), and subsurface drainage is an important practice in some portions of the basin. The average slope varies from 0% to 2%, and the predominant soil hydrologic groups are classes B and C, with 24.1% and 72.6% of the area, respectively. Class A represents 3.3% of the soils, and class D is not present in the watershed at the STATSGO scale.

Input files for SWAT were organized based on GIS data supplied by the St. Joseph River Watershed Initiative. However, weather and streamflow daily data were downloaded from the National Climate Data Center (NCDC) and U.S. Geological Survey (USGS) websites, respectively. Topographic (DEM), land use, soil, and stream network data required by SWAT were provided by the St. Joseph River Watershed Initiative GIS system, created in ArcView 3.2, with a UTM 16 NAD 83 coordinate system. This system includes additional layers of information such wetlands, road and railroad networks, and geological data.

The source of the elevation data was the National Elevation Dataset (NED NAD 83) developed by USGS. Soil data from the State Soil Geographic Database for the Conterminous United States (STATSGO) was used, as well as land use data called EROS 1998 National Land Data Cover developed by the Earth Resources Observation Systems (EROS) Data Center (EDC) at Sioux Falls, South Dakota, using Landsat TM data acquired between the years 1988 and 1994.

Weather data were adapted to SWAT. Locations of weather stations (table 1) and stream gauges (table 2) are depicted in figure 1. Data collected by USGS at the gauge station at Fish Creek near Artic was used only for validation because its records started in 1998.

Since 1996, SJRWI has been collecting water quality data at 40 sampling stations throughout the watershed. For this study, we selected ten sampling stations that provide

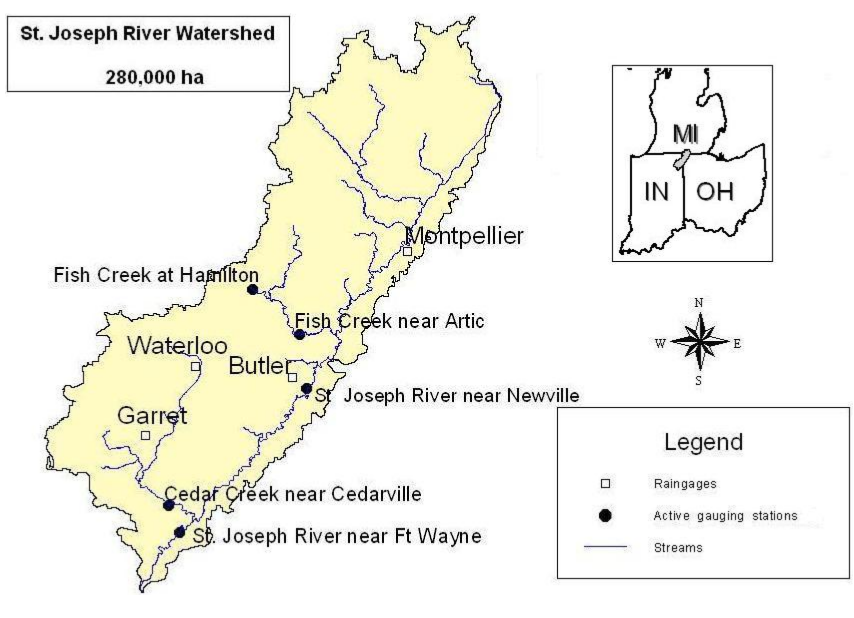

Figure 1. St. Joseph River watershed location and USGS gauges and NCDC stations.

Table 1. NCDC weather stations for the St. Joseph River watershed.

NCDC Gauges	Cooperative ID	Period of Records
Waterloo, Indiana	129271	1939-2004
Montpellier, Ohio	335438	1948-2004
Garret, Indiana	123207	1989-2004
Butler, Indiana	121187	1999-2004

Table 2. USGS gauge stations at the St. Joseph River watershed.

Stream Gauges	USGS No.	Period of Records
Cedar Creek near Cedarville	4178000	1946-2003
St. Joseph River near Newville	4180000	1946-2003
Fish Creek at Hamilton	4177720	1969-2003
St. Joseph River near Fort Wayne	4180500	1983-2003
Fish Creek near Artic	4177810	1998-2003

continuous sets of observations for the period 1996-2002. Model calibration and validation for atrazine were conducted at the sampling sites 100, 104, 123,124, 125, 126, 127,128, 130, and 131, which are depicted in figure 3. The remaining stations present incomplete datasets or do not include atrazine among the analyzed constituents.

Different sampling techniques have been used by the St. Joseph River Watershed Initiative for the collection of pesticide data. Samples were collected weekly for eight months out of the year. In 1996, 1997, and 1998, composite samples were collected for analysis. In 1999 and 2000, both composite and single samples were collected for analysis, and in 2001 and 2002, only single samples were analyzed. SJRWI personnel ran paired t-tests on the 1999 and 2000 single-sample and composite data. No significant difference (t-test, $P = 0.297$) was detected between the two sampling techniques. From this, we can safely deduce that comparisons can be made between the composite data collected in 1997 and 1998 with single-sample data collected from 1999-2002 (SJRWI, 2004).

To compute monthly atrazine concentrations, weekly observations were average weighted by streamflow. Additionally, data recorded by the Three Rivers water treatment plant at Fort Wayne were used to validate the model at the main outlet of the watershed for the period 2000-2004. This dataset was supplied by the Office of the Indiana State Chemist.

As for crop acreage, corn and soybean areas were assigned based on the proportion they represented in the watershed according to the information supplied by the USDA-NASS for corn and soybean area by county between 1986 and 2002(NASS, 2004a). The area-weighted crop percentage was 48% for corn and 52% for soybean.

Since SWAT cannot grow two different crops in the same HRU in the same year, two rotations (corn-soybean and soybean-corn) were assigned to different HRUs. This was done in order to get an average constant area of corn and soybeans according to the actual crop distribution. This is very important to construct a more realistic simulation of pesticide (atrazine in corn) and nutrients (N and P in corn and soybeans), since both crops require different rates and produce different biomass. Usual tillage, planting dates, and rates of application were set according to current farm practices and information published by USDA-NASS (NASS, 2004a; NASS, 2004b).

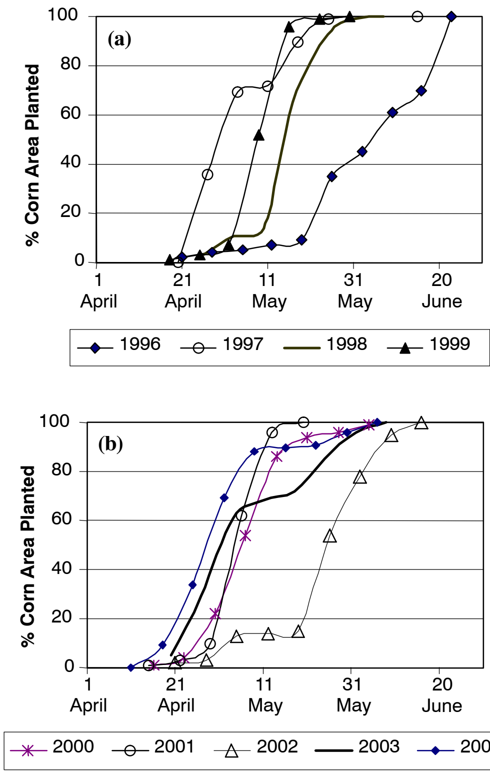

Figure 2. Planting date distribution according to USDA-NASS (NASS, 2004a) for northeast Indiana for the (a) calibration period and (b) validation period.

Atrazine Application Rates and Dates

After establishing the corn and soybean areas for the basin, two rotation scenarios were set to input the distribution of atrazine application according to the planting dates for every year in the period 1996-2004, as supplied by the USDA-NASS (NASS, 2004a). The progress of the corn-planted area, reported weekly for northeast Indiana, was used to set the application dates of atrazine for each year. Atrazine was applied three days after the reported planting date, at a rate of 1.46 kg/ha in only one application, according to the average use of that pesticide in northeast Indiana between 1996-2002 (NASS, 2004b). In every HRU planted with corn, atrazine was applied weekly proportionally to the increment of the planted area. For example, an increment of 10% of planted area resulted in an application of 0.146 kg/ha, which means that 1.46 kg/ha of atrazine was applied randomly to 10% of the corn area. Thus, atrazine was applied from April to June according to the progress of corn planting, which had a different pattern every year due to weather conditions.

This input information was extremely important in the calibration process. Model predictions improved when atrazine was applied following the actual pattern of corn planting in every season, instead of using an overall average pattern of application. As can be observed in figures 2a and 2b, the planting distribution was different from one year to the next, which had an effect on the application of atrazine and its release to the stream.

Calibration and Validation

The model was first calibrated and validated for streamflow and then for atrazine. For streamflow, the model was calibrated for the period 1989-1998 at three USGS gauges:

Cedar Creek near Cedarville, and the St. Joseph River near Fort Wayne and near Newville. Streamflow validation was accomplished for the period 1999-2002 at those gauges as well as at Fish Creek near Artic, with records since 1998 (table 2). Data from Fish Creek near Hamilton were not used in this study because of the presence of Hamilton Lake and the lack of information to calibrate the reservoir, which has an area of 300 ha.

As for atrazine, data from ten sampling sites (SJRWI) were used for model calibration, and eleven sampling sites were used for validation. The calibration period was 1996-1999 and the validation period was 2000-2003 for SJRWI stations. Furthermore, the whole basin was validated at the main outlet for the period 2000-2004, using data recorded by the Three Rivers water treatment plant at Fort Wayne. All model runs were started three years before the period of analysis to be sure the model results were stabilized at the beginning of the study period.

Streamflow calibration was accomplished by adjusting the model for all subbasins simultaneously, without creating different settings for each subbasin. This strategy was adopted for two reasons. First, the watershed is fairly uniform in terms of landscape, slope, drainage pattern, and land use. Thus, there is no reason to calibrate the model for different subbasins. Second, if SWAT is calibrated for the whole watershed regardless of the subbasin boundaries, then the model results will not depend on the watershed subdivisions, and the model settings will be the same if a different criterion is adopted to define subbasins. That was important in this project because USGS gauges and SJRWI sampling sites were placed at different locations. Since SWAT computes pesticide load in streams at every subbasin outlet, different subbasin subdivisions were used for streamflow and atrazine calibration.

For streamflow calibration and validation, a SWAT project was created defining six subbasins for the five USGS gauges and the main outlet of the St. Joseph River watershed (HUA 8-digit No. 04100003). After finishing streamflow calibration, a new SWAT project was built for atrazine calibration, keeping the model settings but redefining subbasin boundaries, using the ten water quality sampling sites as subbasin outlets. Figure 3 shows the subbasin outlets for streamflow and for atrazine calibration. Two discretization schemes were necessary for streamflow and atrazine calibration since not all observations of flow and atrazine were at the same locations. The calibrated coefficients for streamflow for each subbasin were assigned to all smaller subwatersheds of the second scheme according to their location in the basin.

Risk Analysis

After model validation, SWAT was run to simulate 50 years in order to compute monthly exceedance probability and average atrazine concentration. SWAT was run for three scenarios (early planting, average planting, and late planting) using observed weather data of the 56-year period 1948-2003 and discarding the results of the first six years. This analysis takes into account the effect of the year-to-year variability due to weather and the effect of planting date on the amount of pesticide released to streams.

The early, average, and late planting scenarios were built according to the 2004, 1999, and 2002 corn planting seasons,

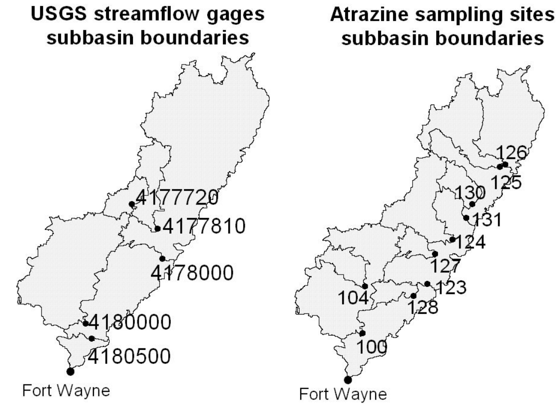

Figure 3. Subbasin boundaries for streamflow and atrazine calibration.

respectively, as shown in figure 4. Monthly atrazine concentration and exceedance probability of the critical value of 3 ppb (Dorsey and Portier, 2000) were presented in plots for the whole basin and in thematic and probability maps for all subbasins.

Results and Discussion

Daily and Monthly Streamflow: Calibration and Validation

Prior to calibrating SWAT for atrazine, streamflow was calibrated. Daily streamflow calibration is very important to predict atrazine release to the streams during and after every precipitation event. A good calibration for monthly streamflow is not useful to predict atrazine movement to the streams if the model is not reasonably calibrated for daily streamflow. In the calibration process, the curve number (CN) and Manning's coefficients for overland flow and the main and tributary channels were adjusted, as well as the groundwater inputs.

In the calibration period (1989-1998), the Nash-Sutcliffe model efficiencies for streamflow (Nash and Sutcliffe, 1970) ranged between 0.46 and 0.65 for daily intervals and between 0.64 and 0.74 for monthly time intervals. In table 3, R^2 values and model efficiencies (R^2_N) are presented for the validation period (1999-2002) at four USGS gauges for daily and monthly streamflow. Figure 5 partially depicts daily predicted and observed streamflow values for the validation period at the USGS stream gauge located on the St. Joseph River near Fort Wayne.

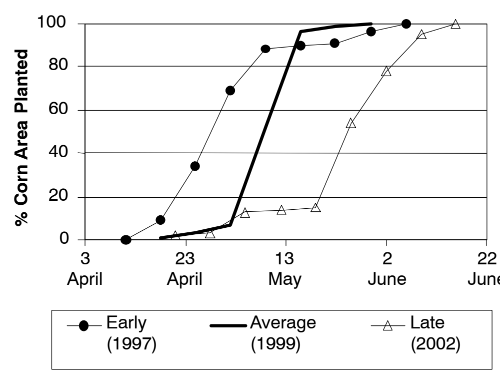

Figure 4. Corn planting scenarios for risk analysis.

Table 3. Nash-Sutcliffe model efficiency and R^2 for daily and monthly streamflow predictions for the validation period (1999-2002).

Validation Sites (1999-2003)	Drainage Area (ha)	Daily R^2	Daily R^2_N	Monthly R^2	Monthly R^2_N
Fish Creek near Artic (4177810)	24,430	0.62	0.60	0.73	0.72
Cedar Creek near Cedarville (4178000)	64,039	0.60	0.53	0.73	0.64
St. Joseph River near Newville (4180000)	148,108	0.50	0.33	0.73	0.68
St. Joseph River near Fort Wayne (4180500)	255,310	0.66	0.59	0.76	0.74

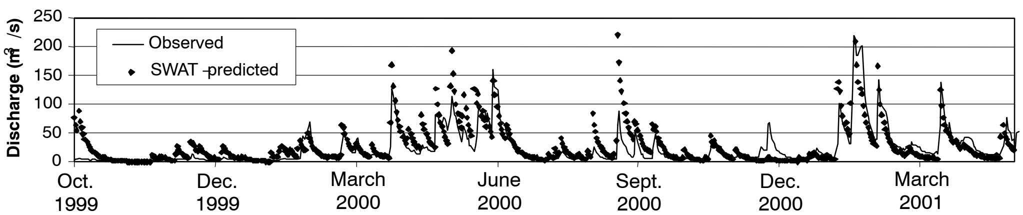

Figure 5. Observed and SWAT-predicted daily streamflow for a portion of the validation period, St. Joseph River near Fort Wayne.

Model Calibration and Validation to Predict Atrazine Concentration in Streams

Predicted atrazine values are given by the model in milligrams per day. Thus, atrazine concentration in ppb was computed by dividing the pesticide mass (mg) by the total daily volume of water (computed from flow in m^3/sec). Daily and monthly predicted values were computed for atrazine load at the ten sampling sites and at the basin main outlet. During the calibration process, many adjustments were explored, such as modifying pesticide solubility (g/L), application efficiency, and delaying atrazine application to 3, 5, and 8 days after planting. However, the only adjustments that had a large impact on the model predictions were the PERCOP (pesticide percolation coefficient) and the distribution and rate of atrazine throughout the planting season. The PERCOP parameter was set at 0.04, and the atrazine application dates and rates were set for each year, delaying it by three days after planting, according to the progress of the corn-planted area reported by USDA-NASS for northeast Indiana (NASS, 2004a). Even though there were different applications dates, there was just one corn planting date, since SWAT does not allow more than one crop growing at the same time in the same HRU. Therefore, the last application of atrazine might be on a crop that was planted earlier, and some pesticide might be intercepted by leaves. SWAT monitors the amount of pesticide intercepted by foliage and washed off during rain events according to a pesticide constant called WOF or "wash-off fraction for the pesticide." To solve this problem, WOF was set to 1 for atrazine, to wash off all the pesticide remaining on the crop leaves in the following rain event. Thus, PERCOP and WOF were the only model parameters modified after streamflow calibration to predict atrazine concentration in streams.

As for runoff, the CN was not changed after planting, so that corn growing during planting season did not affect surface runoff for applications made in the last weeks of the period.

In the calibration period, the mean area-weighted Nash-Sutcliffe model efficiency was 0.14 for daily time intervals and 0.42 for monthly time intervals. Table 4 presents the R^2 value, Nash-Sutcliffe model efficiency (R^2_N), and root mean squared error (RMSE) for daily, monthly, and three-month running average, between April and September, for the validation period. Table 4 shows the upstream area corresponding to each sampling station or subbasin outlet. In some cases, the sampling stations were placed on the very stream of the St. Joseph River (123, 131, and Fort Wayne). In other cases, samples were taken in a tributary stream before joining

Table 4. Model validation results for atrazine concentration at the SJRWI sampling stations (2000-2003) and at the water treatment plant at Fort Wayne (2000-2004).

Site	Upstream Area (ha)	Daily R^2	Daily R^2_N	Daily RMSE (ppb)	Monthly R^2	Monthly R^2_N	Monthly RMSE (ppb)	Three-Month Running Average R^2	Three-Month Running Average R^2_N	Three-Month Running Average RMSE (ppb)
100	64,180	0.77	−2.49	2.57	0.63	−2.01	1.99	0.45	−0.64	0.85
104	9,909	0.80	−2.37	2.95	0.20	−2.08	2.40	0.20	0.03	0.95
123	162,000	0.25	0.40	1.44	0.53	0.40	1.15	0.25	−0.01	0.63
124	27,280	0.73	−1.94	2.56	0.39	−2.11	1.88	0.54	−3.54	1.99
125	27,880	0.35	0.21	1.29	0.63	0.36	0.90	0.66	0.32	0.93
126	38,660	0.81	−0.70	1.70	0.58	−0.28	1.20	0.71	−0.50	1.21
127	6,252	0.63	−0.78	2.51	0.38	−1.25	2.14	0.17	−1.81	1.87
128	6,770	0.66	−1.02	2.70	0.61	−3.69	2.60	0.72	−4.76	1.58
130	9,348	0.30	0.09	2.15	0.33	0.17	1.32	0.66	0.10	1.21
131	96,100	0.10	0.05	2.10	0.48	0.18	1.48	0.20	−0.88	1.62
Fort Wayne (main outlet)	262,000	0.27	−0.31	1.06	0.59	0.28	1.34	0.58	0.24	0.91
Mean	−−	0.52	−0.80	2.09	0.49	−0.91	1.67	0.46	−1.17	1.28
Mean, area−weighted	−−	0.35	−0.40	1.59	0.33	−0.22	0.91	0.23	−0.39	0.68

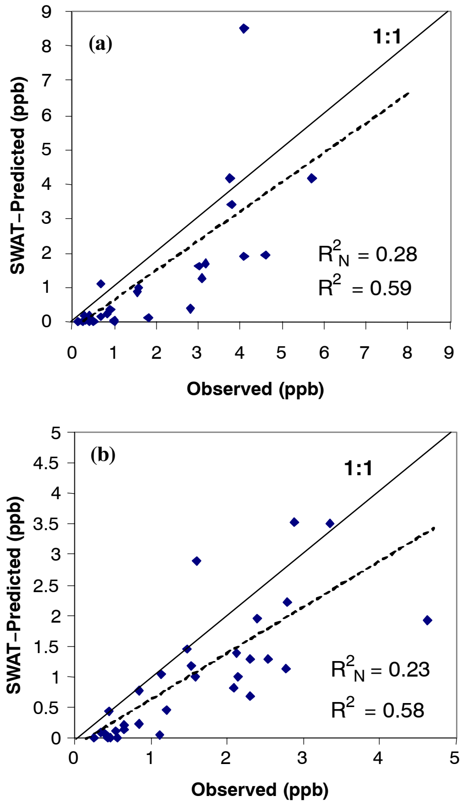

Figure 6. (a) Monthly and (b) three-month running average observed and SWAT-predicted atrazine concentrations (ppb) at the main outlet of the St. Joseph River watershed.

the St. Joseph River. For that reason, at some points, the observed atrazine load comes from the pesticide released in one subbasin, while at other points, the observed load comes from the atrazine routed from more than one upstream subbasin.

SWAT performed better for monthly predictions than for daily predictions, and the R^2 values were also better than the Nash-Sutcliffe model efficiencies because of the disagreement with the 1:1 line between observed and predicted values. Figures 6a and 6b show observed versus SWAT-predicted atrazine concentrations, as monthly values and three-month running averages, respectively, at Fort Wayne for the validation period.

There are many sources of uncertainty when modeling NPS pollution caused by atrazine. Some of them come from the input data, and others come from the model itself. It is important to specify the atrazine application rate and dates accurately. The quality of the recorded data regarding the frequency of water sampling during and between rainfall events is also a key element of the calibration-validation process. Precipitation data is also of importance because of the spatial variability of this variable and the consequent variation of runoff and NPS pollution throughout the watershed.

Figures 7 and 8 depict observed and SWAT-predicted atrazine concentrations over time at Fort Wayne, for daily and monthly time intervals, respectively, for the validation period. Both figures show that the model reproduced the general trend of the atrazine concentration in the stream.

As for the model, some modifications might be tried in order to improve the simulation of atrazine movement. Like GLEAMS and CREAMS, SWAT does not model the fraction of pesticide taken up by the crop over the growing season. Instead, SWAT uses a pesticide constant, called H-LIFE_S (half-life of pesticide in soil), to gradually reduce the amount of atrazine available for runoff. Furthermore, SWAT does not change the pesticide solubility as a function of temperature, but uses a constant solubility for the pesticide throughout the year. Since daily temperature is a model input, SWAT might easily update the pesticide solubility according to the temperature, if a solubility-temperature function is included in the model. Both crop uptake and solubility impact the mass

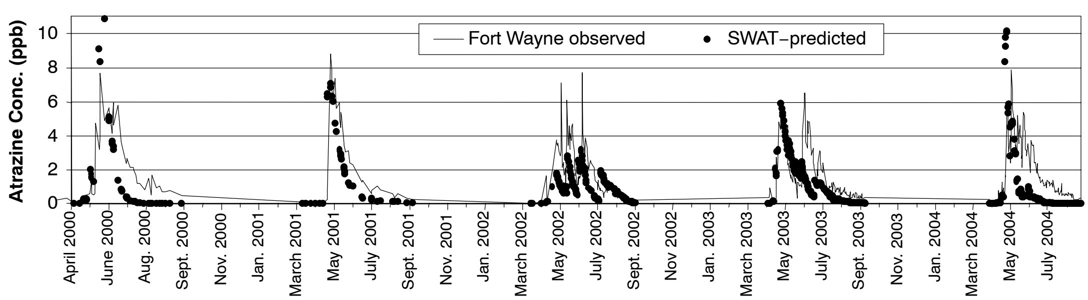

Figure 7. Observed and SWAT-predicted daily atrazine concentration in the St. Joseph River at Fort Wayne for the validation period.

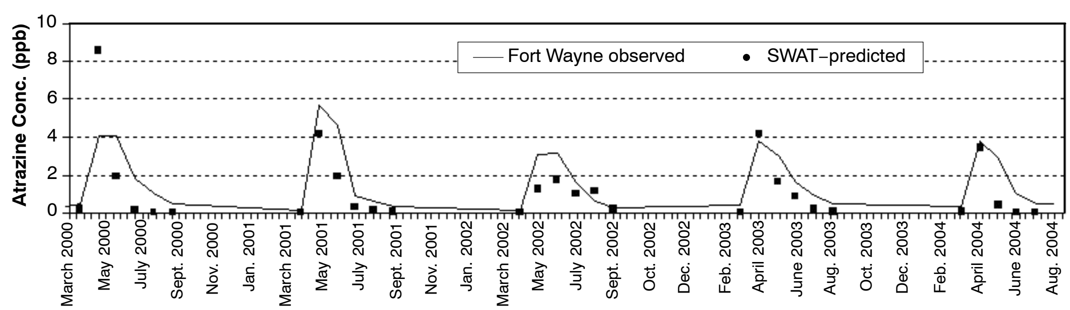

Figure 8. Observed and SWAT-predicted monthly atrazine concentration in the St. Joseph River at Fort Wayne for the validation period.

Table 5. Total mass of atrazine released during the crop season to St. Joseph River in the period 2000-2003.

Year	Total Mass (kg) of Atrazine Released to Streams for the Period April-September	
	Observed	SWAT-Predicted
2000	1,391.0	1,864.9
2001	989.9	531.4
2002	698.8	354.8
2003	928.9	1,052.8
Total	4,008.5	3,803.9
Average	1002.1	951.0

Table 6. Estimated proportion of total mass of atrazine released during the crop season to St. Joseph River for the period 2000-2003.

Year	Proportion (%) of the Total Applied Mass of Atrazine Released to Streams for the Period April-September	
	Observed (%)	SWAT-Predicted (%)
2000	1.15	1.55
2001	0.82	0.44
2002	0.58	0.29
2003	0.77	0.87
Total	0.83	0.79

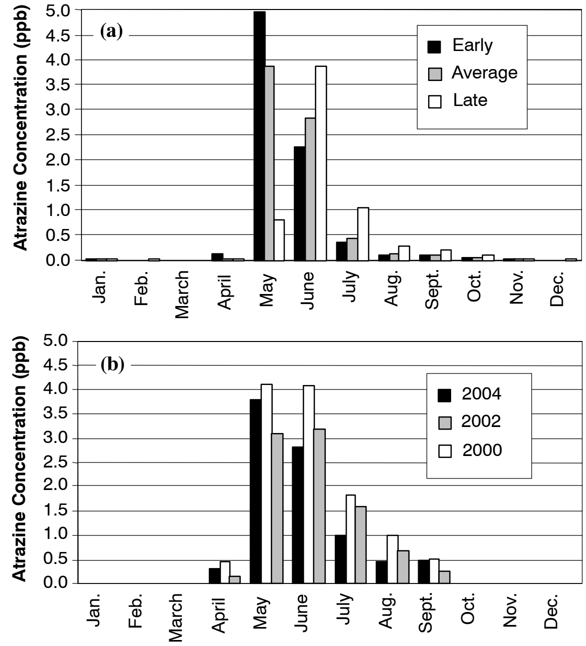

Figure 9. (a) Estimated 50-year monthly average atrazine concentration at Fort Wayne computed from SWAT outputs, and (b) observed monthly average atrazine concentration at Fort Wayne, recorded by personnel of the water treatment plant at Fort Wayne during the period 2000-2004 (2004 = early application, 2000 = intermediate application, and 2002 = late application).

of atrazine available to runoff. Regarding pesticide leaching, SWAT does not have any output variable that estimates the amount of atrazine in shallow groundwater, which is important to predict atrazine loads in-stream between rainfall events, especially in those watersheds that have a large network of subsurface drains.

SWAT estimates resembled the general pattern of daily and monthly atrazine loads in streams over time, but SWAT either underpredicted or overpredicted daily and monthly loads (figs. 7 and 8). Part of the error was due to the prediction of streamflow, which combines with the error in the atrazine load prediction.

As for the total mass of atrazine released by the whole basin to the river during the crop season (April-September) in the period 2000-2003, table 5 shows the SWAT-predicted values and the observed values at Fort Wayne. Even though we know the atrazine concentration for the 2004 crop season, the total mass of atrazine was not computed because the USGS flow data were unavailable at the time this research was completed.

Assuming an average annual mass of atrazine of 120,000 kg applied to the whole basin, which comes from a rate of 1.46 kg /ha applied to the corn-planted area, representing approximately 50% of the agriculture area, the released mass of the pesticide would represent around 0.8% of the total applied (table 6). This proportion agrees with values reported by other researchers (Huber, 1993; Zhang et al., 1997; Christensen and Ziegler, 1998).

Risk Analysis

The SWAT model does not perform a risk analysis, but it generates enough information to accomplish such an analysis outside the program. This makes it possible to use SWAT as a complement of the NAPRA-GLEAMS system to carry out an NPS pollution risk analysis for atrazine at a basin scale. In this section, a risk analysis based on the SWAT model outputs is presented.

After validation, SWAT was run to compute average monthly atrazine concentration and the exceedance probability for the EPA critical value of 3 ppb. These values were computed for the whole basin, at the main outlet, and for every subbasin, based on the results of three simulations of 50 years. SWAT simulations were carried out using weather data from the period 1954-2003, instead of using the weather generator.

The analysis was conducted for three corn planting season scenarios: early, average, and late. The early scenario followed the pattern recorded for 2004, the average scenario followed the pattern of 1999, and the late scenario resembled the pattern of 2002. In a strict sense, it is not correct to apply any weather dataset to all three scenarios, since a planting schedule is closely related to each year's particular weather conditions, particularly the amount and distribution of precipitation. However, it is also difficult to estimate a corn planting schedule, and then atrazine application dates, according to the conditions without introducing a new source of uncertainty. Thus, all three scenarios were run for the same 50-year period, and their results were processed to compute monthly atrazine concentration as well as exceedance probability.

Figure 9a shows the 50-year average monthly atrazine concentration for the whole basin at Fort Wayne for the early, average, and late planting season scenarios. Average atrazine concentration observed at the main outlet of the basin, for the period 2000-2004, is presented in figure 9b, to be compared with the SWAT results presented in figure 9a.

Figure 9b presents separately the values for 2004 or early planting, 2002 or late planting, and 2000, which is similar to 1999 and resembles an intermediate situation. Even though the plots are not strictly comparable, because SWAT was run for the three scenarios for all weather conditions, it can be observed that in any planting schedule, in both figures, the critical value of 3 ppb atrazine was exceeded in May, in June, or in both months. However, the observed data (fig. 9b)

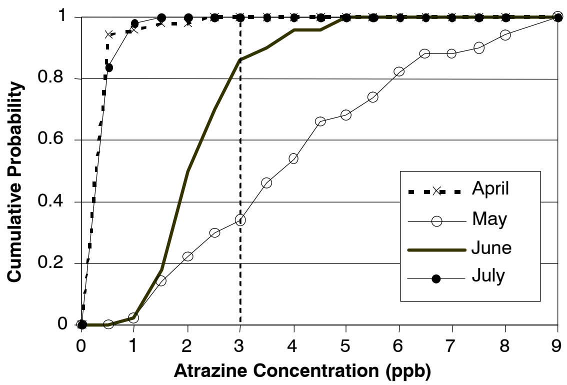

Figure 10. Cumulative probability computed from SWAT outputs for the early planting scenarios.

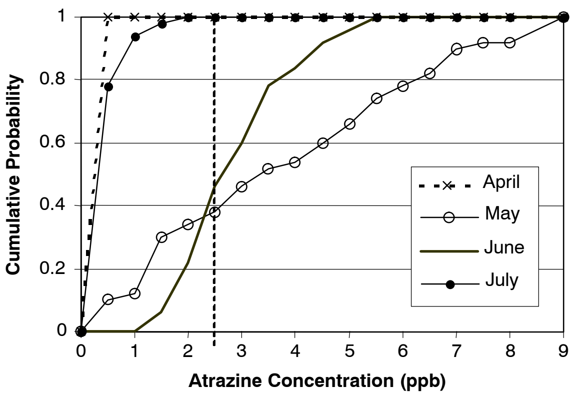

Figure 11. Cumulative probability computed from SWAT outputs for the average planting scenarios.

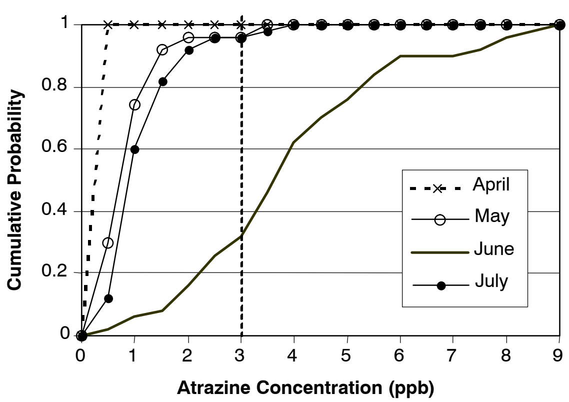

Figure 12. Cumulative probability computed from SWAT outputs for the late planting scenarios.

showed that atrazine levels in the stream exceeded the critical value either in May or June, regardless of the planting schedule, but SWAT delayed the atrazine release according to the delay in corn planting (fig. 9a). SWAT predicted the largest peak of pesticide for early plantings, and observed data showed the largest peak for late planting.

Figures 10 through 12 show the cumulative probability curves for the early, average, and late scenarios, respectively, for the months of April, May, June, and July. The highest values of exceedance probability occurred in May for the early planting scenario (0.66) and for average planting scenario (0.52), and in June for the late planting scenario (0.68).

It was not possible to validate the exceedance probability because the short period of observed records was not sufficient to estimate this parameter. However, both observed and simulated data showed that shifting the planting date only shifted the peak dates, and it might not have a significant effect on reducing the pesticide exceedance level. This agrees with the researchers who pointed out the importance of precipitation timing and intensity within the first month after pesticide application (Klavidko et al., 2001). However, in this analysis, only rainfall timing was evaluated, not the effect of rainfall intensity, because of the lack of hourly precipitation data. Further modeling using hourly precipitation data might show differences in the average level of atrazine concentration or the exceedance probability due to differences in the rainfall intensity in April, May, and June.

Figures 7 to 12 estimate what happens at the main outlet, giving useful information for the basin as a whole, but they do not provide information on pesticide levels of the individual subbasins. Therefore, another analysis was completed at the subbasin level in order to identify potential differences within the basin. By processing the SWAT output files, atrazine concentration was computed, for each scenario, at the outlet of every subbasin, independently of the atrazine released upstream by other subbasins. Then, a monthly average concentration and exceedance probability were computed for each subbasin in order to create risk maps that help to identify areas more susceptible to NPS pollution due to atrazine. Average monthly concentration and exceedance probability maps were computed for the months of April, May, June, and July (Vazquez-Amabile, 2005). The remaining months of the year were not mapped since they had values close to zero. Figure 13 shows the maps that depict the monthly atrazine level and exceedance probability for June.

In figure 13, it can be observed that the subbasins located in the northern part of the basin have lower concentrations of atrazine and lower exceedance probabilities than the other subbasins, because of the presence of soils of hydrologic groups A and B. Thus, the biggest contrasts between subbasins were largely due to soil differences.

Summary and Conclusions

SWAT performed well in predicting the general trend of atrazine concentration in streams over time for daily and monthly time intervals in the St. Joseph River watershed. That makes the model suitable to evaluate management scenarios and long-term effects of management practices and environmental changes, such land use or climate changes on runoff and NPS pollution caused by atrazine.

Daily streamflow calibration and validation had to be accomplished before starting pesticide calibration. During the validation period, the Nash-Sutcliffe values varied from 0.33 to 0.60 for daily flow and between 0.64 and 0.74 for monthly flow. Even though the model was not accurate for predicting atrazine levels at specific points, showing low Nash-Sutcliffe values, SWAT was consistent in obtaining high coefficients of determination (R^2) while overpredicting or underpredicting observed values. Monthly atrazine predictions were better than daily predictions, but three-month running averages were not better predicted than monthly average concentrations.

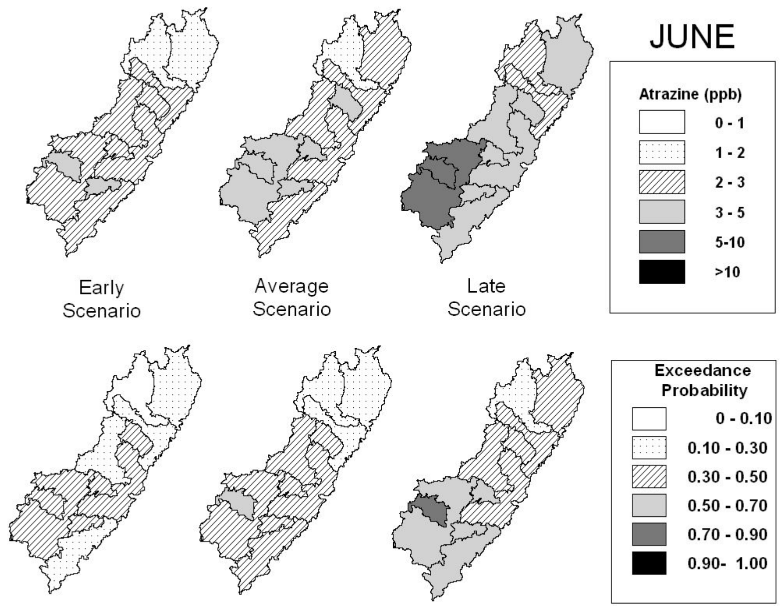

Figure 13. Estimated subbasin atrazine concentrations and exceedance probability for June, computed from SWAT for 50 years.

During the calibration period, monthly atrazine concentrations were predicted with an average R^2 of 0.60 and an average Nash-Sutcliffe coefficient of 0.38. In the validation period, daily atrazine concentration was predicted with an average R^2 of 0.49 and an average Nash-Sutcliffe efficiency of −0.91. These results agree with those reported by Neitsch et al. (2002) in Sugar Creek in east central Indiana.Large watersheds were not consistently better predicted than smaller watersheds, or vice versa. For validation, the total mass of atrazine released by the whole basin between 2000 and 2003, for the period April-September, was closely predicted by the model in two of the four years. The observed average amount of atrazine released during the four years was 1002.1 kg per season, and SWAT predicted 950.1 kg per season. Likewise, both observed and predicted values showed that atrazine concentration in the river exceeded the MCL (3 ppb) any time between May and July.

Dates and rates of application were very important model inputs to predict the amounts of atrazine released to the streams. Considering that NASS data were used for every year in this study, SWAT predictions might be improved if more detailed data, from surveys of farmers for example, were used in the processes of calibration and validation. The effect of planting date on the level of contamination caused by atrazine should be analyzed, studying the intensity of precipitation during the planting season. The SWAT model should be tested using hourly precipitation inputs in order to determine if the model can predict this effect, which could be useful in assessing the impact of early and split applications of atrazine in stream concentrations.

Since application timing is an important input to predict atrazine concentration in streams, remote sensing data periodically collected during the planting season might provide more accurate information than NASS surveys to estimate the corn-planted area, and therefore the periodical change of the atrazine applied in the watersheds during the planting season. Additional studies might use remote sensing data for crop management inputs.

Likewise, the model was suitable to carry out an NPS pollution risk analysis for atrazine, to be used as a complement of the NAPRA-GLEAMS system, at the basin scale. Even though the model does not perform a risk analysis, it generates enough information to accomplish such an analysis outside the program.

Additional research will be necessary to evaluate the model's ability to predict the effects of best management practices on NPS pollution. That represents a key issue for NPS pollution modeling and an essential step before using SWAT as a tool for comparing different management scenarios.

As a recommendation for future research and model improvements, the model should generate an output variable that describes the level of pesticides in shallow groundwater. This would be important for predicting pesticide loads in shallow aquifers and in the baseflow between rainfall events, particularly in those watersheds that deliver pesticides through tile drain systems. In this way, the model would provide the complete spectrum of the NPS pollution in rural watersheds for pesticides.

Finally, the amount of atrazine released to the St. Joseph River during the period 2000-2003 represented about 1% of the total applied in the whole basin. Therefore, model inputs required to predict such a proportion have to be as accurate as possible, as well as the sampling method and frequency of observed data, so as not to introduce additional sources of uncertainty into the processes of model calibration and validation.

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References

Arnold, J. G., R. Srinavasan, R. S. Muttiah, and J. R. Williams. 1998. Large-area hydrologic modeling and assessment part I: Model development. *J. American Water Resources Assoc.* 34(1): 73-89.

Chapra, S. C. 1997. *Surface Water Quality Modeling.* Boston, Mass.: WCB/McGraw-Hill.

Christensen, V. G., and A. G. Ziegler. 1998. Atrazine in source water intended for artificial ground-water recharge, south central Kansas. USGS fact sheet FS-074-98. Washington, D.C.: USGS.

Di Luzio, M., R. Srinavasan, and J. G. Arnold. 2001. ArcView interface for SWAT2000: User's guide. Temple, Texas: Blackland Research Center, Texas Agricultural Experiment Station. Available at: www.brc.tamus.edu/swat/doc.html.

Dorsey, L., and C. Portier. 2000. Atrazine: Hazard and dose-response assessment and characterization. FIFRA Scientific Advisory Panel Meeting, 27-29 June 2000. SAP Report No. 2000-05. Available at: www.epa.gov/oscpmont/sap/2000/june27/finalatrazine.pdf.

EPA. 2003 Atrazine Interim Re-registration Eligibility Decision (IRED) Q&A's – January 2003. Available at: www.epa.gov/pesticides/factsheets/atrazine.htm. Accessed 14 July 2004.

EPA. 2004a. Consumer fact sheet on atrazine. Available at: www.epa.gov/safewater/dwh/c-soc/atrazine.html. Accessed 7 July 2004.

EPA. 2004b. BASINS: Better Assessment Science Integrating point and Nonpoint Sources. Available at: www.epa.gov/waterscience/basins/basinsv3.htm. Accessed 10 July 2004.

Flanagan, D. C., S. J. Livingston, C. H. Huang, and E. A. Warnemuende. 2003. Runoff and pesticide discharge from agricultural watersheds in NE Indiana. ASAE Paper No. 032006. St. Joseph, Mich.: ASAE.

Goebel, J. J. 1998. The national resources inventory and its role in U.S. agriculture. In *Agricultural Statistics 2000: An International Conference on Agricultural Statistics*, 181-192. T. E. Holland and M. P. R. Van den Broecke, eds. Voorburg, The Netherlands: International Statistical Institute.

Huber, W. 1993. Ecological relevance of atrazine in aquatic systems. *Environ. Toxicol. Chem.* 12(10): 1865-1881.

Kellogg, R. L., S. Plotkin, J. Bagdon, E. Hesketh, M. Hugo, and S. Wallace. 1998. Prospects for reducing environmental-risk pesticide loss from farm fields using alternative farm management practices. In *53rd Annual Soil and Water Conservation Service (SWCS) Conference.* Washington, D.C.: USDA Natural Resources Conservation Service. Available at: www.nrcs.usda.gov/technical/land/pubs/naptext.html. Accessed May 2006.

Kenaga, E. E., and C. A. Goring. 1980. Relationship between water solubility, soil sorption, octanol-water partitioning, and concentration of chemicals in biota. In *Aquatic Toxicology*, 78-115. J. G. Eaton, P. R. Parrish, and A. C. Hendriks. eds. Philadelphia, Pa.: American Society for Testing Materials.

Klavidko, E. J., L. C. Brown, and J. L. Baker. 2001. Pesticide transport to subsurface tile drains in humid regions in North America. *Critical Reviews in Environ. Sci. and Tech.* 31(1): 1-62.

Knisel, W. G., ed. 1980. *CREAMS: A Field-Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems.* Conservation Research Report No. 26. Washington, D.C.: USDA Science and Education Administration.

Leonard, R. A., and R. D. Wauchope. 1980 The pesticide submodel. In *CREAMS: A Field-Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems*, 88-112. W. G. Knisel, ed. Conservation Research Report No. 26. Washington, D.C.: USDA Science and Education Administration.

Leonard, R. A., W. G. Knisel, and D. A. Still. 1987. GLEAMS: Groundwater loading effects of agricultural management systems. *Trans ASAE* 30(5): 1403-1418.

Lim, K. J., and B. A. Engel. 2003. Extension and enhancement of national agricultural pesticide risk analysis (NAPRA) WWW decision support system to include nutrients. *Computers and Electronics in Agric.* 38(3): 227-236.

Lim, K. J., B. Engel, and A. Hetzroni. 2001. Incorporation and evaluation of a river quality model to NAPRA WWW decision support system. ASAE Paper No. 012127, presented at the 2001 ASAE Annual International Meeting. St. Joseph, Mich.: ASAE.

Nash, J. E., and J. E Sutcliffe. 1970. River flow forecasting through conceptual models: Part 1. A discussion of principles. *J. Hydrology* 10(3): 282-290.

NASS. 2004a. Indiana agricultural statistics. Washington, D.C.: USDA-NASS. Available at: www.nass.usda.gov/in/publications.html. Accessed July 2004.

NASS. 2004b. NASS agricultural chemical use database. Washington, D.C.: USDA-NASS. Available at: www.pestmanagement.info/nass/app_usage.cfm. Accessed July 2004.

Neitsch, S. L., J. G. Arnold, J. R. Kiniry, and J. R. Williams. 2001. Soil and Water Assessment Tool: Theoretical documentation, version 2000. Temple, Texas: Blackland Research Center, Texas Agricultural Experiment Station. Available at: www.brc.tamus.edu/swat/doc.html. Accesed May 2006.

Neitsch, S., J. G. Arnold, and R. Srinavasan. 2002. Final report: Pesticides fate and transport predicted by the Soil and Water Assessment Tool (SWAT): Atrazine, metolachlor, and trifluralin in the Sugar Creek watershed. BRC Publication No. 2002-03. Washington, D.C.: U.S. EPA, Office of Pesticide Programs. Available at: www.brc.tamus.edu/swat/applications/SugarCreekIN.pdf.

Saleh, A., and B. Du. 2004 Evaluation of SWAT and HSPF within BASINS program for the upper North Bosque River watershed in central Texas. *Trans. ASAE* 47(4): 1039-1049.

Saleh A., J. G. Arnold, P. W. Gassman, L. M. Hauck, W. D. Rosenthal, J. R. Williams, and A. M. S. McFarland. 2000. Application of SWAT for the upper North Bosque River watershed. *Trans. ASAE* 43(5): 1077-1087.

SCS. 1990. SCS/ARS/CES pesticide properties database: Version 2.0 (summary). Syracuse, N.Y.: USDA Soil Conservation Service.

SJRWI. 2004. Fort Wayne, Ind.: St. Joseph River Watershed Initiative. Available at: www.sjrwi.org/watershed.htm. Accessed 12 February 2004.

Spruill, C. A., S. R. Workman, and J. L. Taraba. 2000. Simulation of daily and monthly stream discharge from small watersheds using the SWAT model. *Trans. ASAE* 43(6): 1431-1439.

Takacs, P., P. A. Martin, and J. Struger. 2002. Pesticides in Ontario: A critical assessment of potential toxicity of agricultural products to wildlife, with consideration for endocrine disruption: Volume 2. Triazine herbicides, glyphosate, and metolachlor. Technical Report Series No. 369. Ottawa, Ontario, Canada: Canadian Wildlife Service, Environmental Conservation Branch, Ontario Region. Available at: http://dsp-psd.communication.gc.ca/Collection/CW69-5-369E.pdf. Accessed 7 July 2004.

Vazquez-Amabile, G. G. 2005. Hydrologic and nonpoint-source pollution risk analysis on agricultural watersheds. PhD diss. West Lafayette, Ind.: Purdue University.

Williams, J. R. 1995 Chapter 25: The EPIC model. In *Computer Models of Watershed Hydrology*, 909-1000. V. P. Singh, ed. Highlands Ranch, Colo.: Water Resources Publications.

Yu, C., W. J. Northcott, and G. F. McIsaac. 2004. Development of an artificial neural network for hydrologic and water quality modeling of agricultural watersheds. *Trans. ASAE* 47(1): 285-290.

Zhang, X. C., L. D. Norton, and M. Hickman. 1997. Rain pattern and soil moisture content effects on atrazine and metolachlor losses in runoff. *J. Environ. Quality* 26: 1539-1547.