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Application of the Soil and Water Assessment Tool and Annualized Agricultural Non-Point Source models in the St. Joseph River watershed

G.C. Heathman, D.C. Flanagan, M. Larose, and B.W. Zuercher

Abstract: This study evaluated the performance of two water quality models in accordance to specific tasks designated in the USDA Agricultural Research Service Conservation Effects Assessment Project. The Soil and Water Assessment Tool (SWAT) and the Annualized Agricultural Non-Point Source (AnnAGNPS) models were applied uncalibrated to the Cedar Creek watershed within the St. Joseph River watershed in northeastern Indiana to predict streamflow and atrazine losses. In order to ultimately assess the benefits of conservation practices in agricultural watersheds (which is one of the major goals of the Conservation Effects Assessment Project), proper application of the SWAT and AnnAGNPS models is essential including baseline comparisons made in an uncalibrated mode aimed at eliminating bias due to parameter optimization. Streamflow prediction results show that SWAT model performance was superior to AnnAGNPS, with SWAT model efficiency values ranging from 0.66 to 0.25 and AnnAGNPS model efficiency values ranging from 0.13 to -2.06 for monthly and annual streamflow, respectively. For uncalibrated conditions, neither model was able to adequately simulate atrazine loss concentrations. Overall results suggest that for Conservation Effects Assessment Project modeling applications at the Cedar Creek watershed scale in this study, the use of the SWAT model would be preferable to AnnAGNPS in terms of overall model performance and model support technology (e.g., model interface and documentation).

Key words: Annualized Agricultural Non-Point Source (AnnAGNPS)—atrazine—Conservation Effects Assessment Project (CEAP)—hydrologic modeling—Soil and Water Assessment Tool (SWAT)—streamflow—water quality

The dynamic nature of soil-plant-atmosphere processes, coupled with changing land use, different management practices, variations in climate, and limited observational data are only a few of the issues that must be considered in understanding and assessing the impact of conservation practices on water quality. Mathematical models are useful analysis tools in providing a means of simulating the complex nature of these interactions, albeit through simplification in most cases. Watershed scale models that incorporate climatic, soil, topographic, and land use characteristics are capable of addressing multiple issues related to water quality concerns and environmental assessments. The Soil and Water Assessment Tool (SWAT) (Arnold et al. 1993; Arnold and Fohrer 2005), and the Annualized Agricultural Non-Point Source (AnnAGNPS) model (Bingner and Theurer 2005) are two notable models that have been designated for use as assessment tools in the USDA Agricultural Research Service (ARS) Conservation Effects Assessment Project (CEAP).

As a result of the 2002 Farm Bill, CEAP was initiated in 2003 as a USDA nationwide program involving the cooperation of the Natural Resources Conservation Service (NRCS) and the USDA ARS to quantify the environmental effects of soil conservation practices on water quality (USDA NRCS 2008a, 2008b) (Mausbach and Dedrick 2004). The CEAP is comprised of two main components: a national assessment that provides model estimates of conservation benefits for annual reporting and a watershed assessment component aimed at quantifying the environmental benefits from specific conservation practices at the watershed scale (Mausbach and Dedrick 2004). Both the USDA NRCS and ARS have tasks and responsibilities in each component of the overall CEAP project. The USDA NRCS has posted a detailed description of CEAP and information on each of the project watersheds (USDA NRCS 2008a, 2008b). In this study, we report findings in regards to the USDA ARS watershed assessment component of CEAP that may ultimately impact the national assessment.

The five-year USDA ARS CEAP Watershed Assessment Study (WAS) Project Plan provides detailed descriptions of research studies at 12 (later expanded to 14) benchmark watersheds in the United States (USDA ARS 2004). The five major objectives of this USDA ARS portion of CEAP are (1) develop a web-based database system for archiving, retrieving and reporting data from USDA ARS benchmark watershed studies, (2) measure and quantify the effects of conservation practices on water quality and other environmental parameters, (3) validate water quality models and determine their uncertainty at predictions of water quality parameters in the benchmark watersheds, (4) develop and apply policy planning tools including economic analyses to maximize economic as well as environmental benefits of conservation practices, and (5) develop new water quality models that can be applied in future regional assessments. Each of the 14 watersheds has a particular area of special emphasis, due in part to watershed location and regional water quality issues. Thus, in some watersheds the greatest water quality concerns are related to sediment losses, in others nutrients [e.g., nitrate-N (N) and/or phosphate-P (P)] or pesticide losses dominate (USDA ARS 2004).

Gary C. Heathman is a soil scientist and Dennis C. Flanagan is an agricultural engineer at the National Soil Erosion Research Laboratory, USDA Agricultural Research Service, West Lafayette, Indiana. Myriam Larose is a research graduate assistant in the Agronomy Department, Purdue University, West Lafayette, Indiana. Ben W. Zuercher is a biologist at the National Soil Erosion Research Laboratory, USDA Agricultural Research Service.

The St. Joseph River watershed (SJRW) was designated in 2004 as one of the CEAP benchmark watersheds because of existing source water protection research studies in watershed monitoring and modeling being conducted by the USDA ARS National Soil Erosion Research Laboratory in West Lafayette, Indiana. Original research objectives in the SJRW were focused on atrazine herbicide losses (Flanagan et al. 2003); however, as part of the WAS project plan objective 2, new SJRW studies have focused on field and subbasin nutrient/pesticide water quality data collection in addition to project level data management (USDA ARS 2004). Another important aspect of the WAS project plan is to validate the accuracy of water quality models used to conduct the national assessment (objective 3). As part of the first phase of watershed assessments, both the SWAT and AnnAGNPS models are to be utilized to conduct comparative evaluations of environmental benefits associated with different management practices (USDA ARS 2004). In order to achieve the first phase, it was imperative to initially evaluate the performance of each model for estimating streamflow based on comparable input data sets and to apply both models without calibration, thus eliminating any ambiguities pertaining to the use of different optimized model parameter values.

SWAT (Arnold et al. 1998; Arnold and Fohrer 2005) is a river basin-scale model that allows the user to divide a watershed into any number of subbasins. The SWAT model can simulate and estimate pollution generation at the source and subsequent movement from the source area to the receiving water body, providing flow and concentration histograms at various points in the watershed and entry points into the receiving water body. The AnnAGNPS model (Theurer and Cronshey 1998; Bingner and Theurer 2005; USDA ARS 2006) was developed by the USDA ARS and NRCS to predict sediment and chemical delivery from ungaged agricultural watersheds up to 300,000 ha (741,000 ac) (Bosch et al. 2001). The AnnAGNPS model is a continuous simulation, grid-based, batch-process computer program where runoff, sediment, nutrients and pesticides are routed from their origins in upland grid cells through a channel network to the outlet of the watershed (Bingner and Theurer 2005).

The SWAT model has been used extensively within the United States, as well as internationally to study streamflow, sediment yields, and nutrient transport (Srinivasan et al. 1997; FitzHugh and Mackay 2000; Spruill et al. 2000; Arnold and Fohrer 2005; Borah et al. 2006). Gassman et al. (2007) provides an extensive review of the large number of model applications, including evaluation of SWAT hydrology (115 reported studies), sediment/suspended solids (28 reported studies), and nutrient (N, P) loss (30 reported studies). However, only very limited pesticide simulation using SWAT has been attempted, and Gassman et al. (2007) reported just two studies with model pesticide calibration/validation results available in the literature (Du et al. 2006; Vasquez-Amabile et al. 2006).

Du et al. (2006) evaluated the performance of SWAT2000 and a version of the model (SWAT-M) modified to better predict hydrology and pollutant loadings in landscapes dominated by tile drainage and pothole topography in the 5,130 ha (12,670 ac) Walnut Creek watershed in central Iowa. Original SWAT2000 model predictions were poor, especially for N and atrazine herbicide losses with both having negative Nash-Sutcliffe (1970) model efficiency (ENS) values. The SWAT-M modifications to SWAT2000 included those described by Du et al. (2005), as well as modifying the tile drainage lag time and adding a second pesticide degradation half-life (Du et al. 2006). With the modifications, predictions for flow discharge, nitrate-N loss, and atrazine loss were greatly improved. For the entire Walnut Creek watershed, ENS values were 0.86/0.50 (calibrated/validated) for monthly flow discharge, 0.85/0.67 for monthly nitrate-N loads, and 0.50/0.53 for monthly atrazine loads (Du et al. 2006).

Vasquez-Amabile et al. (2006) applied SWAT2000 to the 2,808 km^2 (1,084 mi^2) SJRW in northeast Indiana, and examined predictions of both streamflow and atrazine discharges. The model was able to satisfactorily predict streamflow discharge in both calibration and validation periods using US Geological Survey (USGS) data at four gauging stations from 1989 to 2002 (ENS values ranged from 0.64 to 0.74 in the monthly streamflow validation period). The SWAT predictions for atrazine were evaluated at 11 locations within the basin, using data collected by the St. Joseph River Watershed Initiative (SJRWI) and the Ft. Wayne water treatment plant. The model adequately approximated atrazine loss trends, although individual storm and monthly predictions sometimes had negative ENS values. The predicted total mass of atrazine released to the St. Joseph River for the period 2000 to 2003 was within approximately 5% of the measured value, and the correct timing of atrazine application in model inputs was found to be critical in obtaining satisfactory results (Vasquez-Amabile et al. 2006).

Larose et al. (2007) reported satisfactory results in application of a calibrated SWAT2000 model to the 707 km^2 (274 mi^2) Cedar Creek watershed (CCW) in northeast Indiana for both predicted monthly streamflow (E_{NS} = 0.56) and atrazine concentrations (E_{NS} = 0.43) during the validation phase. Neitsch et al. (2002) also reported acceptable results of flow and atrazine loss predictions for the 242 km^2 (93 mi^2) Sugar Creek watershed in Indiana, with an E_{NS} = 0.74 for daily streamflow during validation and r^2 = 0.41 for predicted atrazine concentrations after streamflow calibration.

In the literature, the AnnAGNPS model has in general been used to a much lesser degree than SWAT (mainly by researchers in the United States and Canada), and there is a single thesis and no peer-reviewed publications describing pesticide prediction performance. Tagert (2006) performed AnnAGNPS simulations in the 13,200 ha (32,600 ac) Upper Pearl River Basin to validate pesticide loading of atrazine and metolachlor against measured grab sample data. The event-based results showed an r^2 of 0.095 for atrazine and 0.062 for metolachlor when comparing measured and simulated concentrations. Although there was poor correlation, it was concluded that much of the error could be attributed to sampling frequency of measured data and pesticide application timing in the model inputs.

The AnnAGNPS hydrologic, nutrient, and sediment components have been documented to a somewhat greater extent (Yuan et al. 2001; Baginska et al. 2003; Suttles et al. 2003; Yuan et al. 2003; Das et al. 2007; Sadeghi et al. 2007). Yuan et al. (2001) evaluated the model on the 82 ha (203 ac) Deep Hollow watershed in Mississippi and found acceptable prediction of runoff and sediment for three years of field observations (r^2 = 0.90 and 0.50 for daily streamflow discharge and sediment loss, respectively). Baginska et al. (2003) evaluated AnnAGNPS performance on a 255-ha (630-ac) watershed near

Sydney, Australia, and obtained good results for event-based runoff and monthly predictions for streamflow and nutrient (N, P) losses. Suttles et al. (2003) conducted simulations with AnnAGNPS in the 333 km^2 (129 mi^2) Little River Research watershed in south central Georgia to examine sediment and nutrient loads. They found that average annual runoff, sediment, and nutrient loads were underpredicted by 37% to 58% in the upper part of the watershed. In the lower part of the watershed, predicted runoff was close to the observed, but sediment and nutrients were overestimated by up to a factor of 16.7 of the observed. Yuan et al. (2003) describe application of AnnAGNPS to the Deep Hollow watershed in Mississippi to evaluate N loadings and reported that overall predicted N losses were not statistically different from observed.

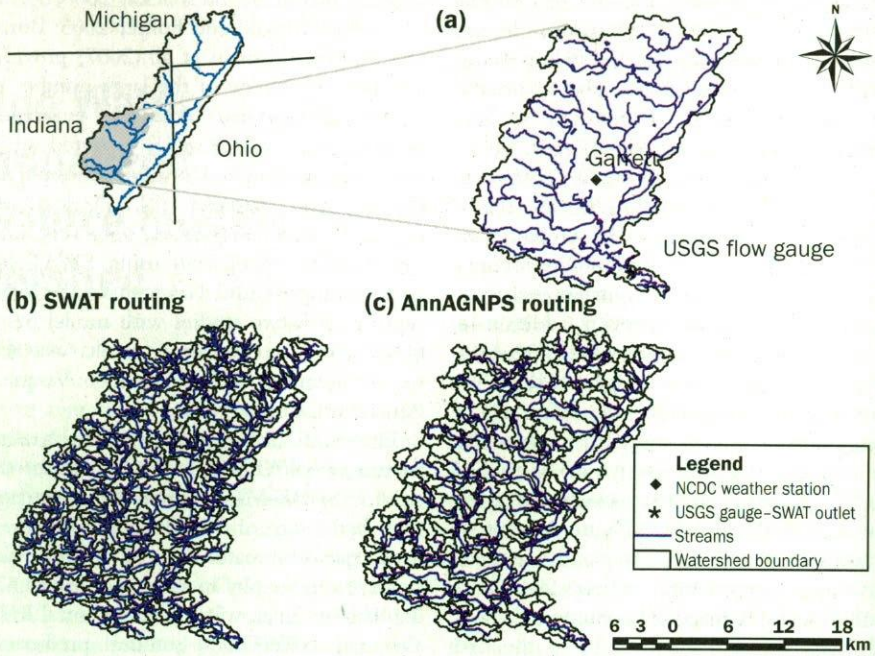
A few studies in the literature present results for concurrent evaluation of both SWAT and AnnAGNPS. In Ontario, Das et al. (2007) compared the performance of the models for prediction of runoff and sediment loss from the Canagagigue Creek watershed. AnnAGNPS had E_{NS} values of 0.79 and 0.69 for monthly runoff predictions in the calibration and validation periods, respectively (SWAT values were 0.70 and 0.57). For monthly sediment losses, AnnAGNPS E_{NS} values were 0.53 and 0.35 for the calibration and validation periods, respectively (SWAT values were 0.41 and 0.24). Sadeghi et al. (2007) also compared results from the SWAT and AnnAGNPS models for the 1,036 km^2 (400 mi^2) Choptank River watershed in Maryland. AnnAGNPS better predicted streamflow (E_{NS} = 0.49) than SWAT (E_{NS} = -0.28). Neither model performed well for nitrate-N loss prediction (AnnAGNPS E_{NS} = 0.13; SWAT E_{NS} = -1.61).

The primary motivation for this research was to accomplish specific tasks outlined in the WAS project plan, including portions of tasks 3.2.4 and 3.3.2a under objective 3. The goal of task 3.2.4 is to "compare SWAT and AnnAGNPS models to identify the range of implementation subwatersheds over which the models provide comparable results," and the goal of task 3.3.2a is to "complete model scenario runs using uncalibrated model default parameter sets" (USDA ARS 2004). The specific objective of this study was to test the accuracy and applicability of the SWAT2005 and AnnAGNPS models for estimating streamflow and atrazine loss in the CCW in northeastern Indiana. The CCW is within the SJRW and is the largest tributary of the St. Joseph River, which supplies drinking water for approximately 250,000 people (SJRWI 2004) in the city of Fort Wayne, Indiana. Concentrations of atrazine (3.7 to 10.0 μg L^{-1} [ppb]) exceeding the safe drinking water standard (3.0 μg L^{-1}) were found in the tap water of Fort Wayne in 1995 (Environmental Working Group 1995). Costly treatment of the intake source water and/or reduction of atrazine transport to the source water is required if the safe drinking water standard for atrazine is to be met. Approximately 76% of the SJRW is under extensive corn production, and it is believed that most of the pesticide found in streams comes from agricultural areas within the watershed due to corn production. Thus, effective watershed management requires a comprehensive understanding of hydrologic and chemical processes within the watershed as well as the application of simulation models for assessing the effects of various management practices on water quality at the watershed scale.

The study is unique in that there are to our knowledge no peer-reviewed journal articles that present this particular type of model comparison and evaluation at the watershed scale. Since both models were designed to be applied to ungaged watersheds, the study also considers possible sources of error and uncertainty associated with these estimates based on non-calibrated model parameters, model configuration, and input data sets.

Figure 1

(a) Cedar Creek watershed stream network, weather station, and US Geological Survey gauging station within the St. Joseph River Basin; and Cedar Creek watershed flow routing for (b) SWAT and (c) AnnAGNPS.



Notes: SWAT = Soil and Water Assessment Tool. AnnAGNPS = Annualized Agricultural Non-Point Source model.

Materials and Methods

Study Area. The CCW is located within the SJRW in northeastern Indiana (41°04'48" to 41°56'24" N and 84°52'12" to 85°19'48"W). The watershed drains two 11-digit hydrologic unit code watersheds, the Upper (04100003080) and Lower Cedar (04100003090), covering approximately an area of 708 km^2 (273 mi^2) (figure 1). The topography of the watershed varies from rolling hills in Noble County to nearly level plains in DeKalb and Allen Counties with a maximum altitude above sea level of 326 m (1,046 ft) and average land surface slope of 3%. Soil types on the watershed were formed from compacted glacial till and fluvial materials. The predominate soil textures in the immediate Cedar Creek are silt loam, silty clay loam, and clay loam. The

majority of the Soil Survey Geographic (SSURGO) database soils along Cedar Creek are the Morley-Blount and Eel-Martinsville-Genesee associations. The Morley-Blount association usually occurs on the uplands and indicates deep, moderately to poorly drained, nearly level to steep, medium-textured soils. The Eel-Martinsville-Genesee association consists of deep, moderately well drained, nearly level, and medium to moderately fine-textured soils on bottom lands and stream terraces (SJRWI 2004). The average annual precipitation in the watershed is approximately 900 mm (35 in). The average temperature during crop growth seasons ranges from 10°C to 23°C (50°F to 73.4°F). Approximately 44% of the watershed area is agriculture, 36% is pasture lands including Conservation Reserve Program, 12% is forested lands, and 2% is urban (USDA National Agricultural Statistics Service [NASS] 2001). The majority of the agricultural lands are rotationally tilled predominantly with corn and soybeans, with lesser amounts of wheat and hay.

SWAT2005 Hydrology and Pesticide Overview. The SWAT model was developed to simulate the hydrologic response of a large watershed with numerous subwatersheds. It is a spatially distributed, physically based hydrological model, and can operate on a daily as well as an annual time step for long-term simulation up to 100 years. The SWAT model is a modification of the Simulator for Water Resources in Rural Basins (SWRRB) model that incorporates a new routing structure, flexibility in watershed configuration, irrigation water transfer, a lateral flow component, and a ground water component (Arnold et al. 1993). The SWAT model also incorporates shallow ground water flow, reach routing transmission losses, sediment transport, chemical transport, and transformations through streams, ponds, and reservoirs. The main purpose of the SWAT model is to predict the effect of different management practices on hydrology, sediment, and agricultural chemical yields in large ungaged watersheds (Arnold et al. 1998; Arnold and Fohrer 2005).

Hydrologic processes simulated by the model include evapotranspiration (ET), infiltration, percolation losses, surface runoff, lateral shallow aquifer flow, and deep aquifer flow. The minimum weather inputs required by the model are maximum and minimum air temperature and precipitation. The hydrologic cycle as simulated by SWAT for the land phase is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \ , \quad (1)$$

where SW_t is the final soil water content (mm H_2O), SW_0 is the soil water content on day i (mm H_2O), t is time (days), R_{day} is the amount of precipitation on day i (mm H_2O), Q_{surf} is the amount of surface runoff on day i (mm H_2O), E_a is the amount of evapotranspiration on day i (mm H_2O), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm H_2O), and Q_{gw} is the amount of return flow on day i (mm H_2O).

The Soil Conservation Service runoff curve number (SCS CN) (USDA SCS 1986) method or Green and Ampt (1911) infiltration model is used to estimate surface runoff from precipitation. While the Green-Ampt method needs sub-daily rainfall data, the SCS CN is adjusted according to moisture condition in the watershed. Evapotranspiration in SWAT is calculated by the Priestly-Taylor (Priestly and Taylor 1972), Penman-Monteith (Monteith 1965), or Hargreaves methods (Hargreaves et al. 1985). Daily average soil temperature is simulated as a function of the maximum and minimum daily air temperatures, surface temperature, and damping depth (Saleh et al. 2000).

The SWAT model uses algorithms from the GLEAMS (Ground water Loading Effects on Agricultural Management Systems) model (Leonard et al. 1987) to simulate pesticide movement and fate in land areas. The process is divided into three components: (1) pesticide processes in land areas, (2) transport of pesticide from land areas to the stream network, and (3) in-stream pesticide processes. Algorithms governing movement of soluble and sorbed forms of pesticide from land areas to the stream network were taken from the Environmental Policy Integrated Climate (EPIC) model (Williams et al. 1984). The SWAT model incorporates a simple mass-balance method developed by Chapra (1997) to model the transformation and transport of pesticides in streams. The model assumes a well-mixed layer of water overlying a homogenous sediment layer. Only one pesticide can be routed through the stream network in a given simulation (Neitsch et al. 2001). The partitioning of pesticide between the solution and soil phase and extraction into runoff is based on algorithms in the GLEAMS model for both SWAT and AnnAGNPS according to the equation:

$$K_p = \frac{C_{solid}}{C_{solute}} \ , \quad (2)$$

where K_p is the soil adsorption (mg kg^{-1}), C_{solid} is the concentration of pesticide sorbed to the solid phase (mg chemical kg^{-1} solid material), and C_{solute} is the concentration of pesticide in solution (mg chemical L^{-1} solution). In SWAT, pesticide in the soluble phase may be transported with surface runoff as a function of time, concentration, and amount of flow according to the equation:

$$\frac{dpst_{s,ly}}{dt} = 0.01 \cdot C_{solute} \cdot w_{mobile} \ , \quad (3)$$

where $pst_{s,ly}$ is the amount of pesticide in the soil layer (kg ha^{-1}), C_{solute} is the concentration of pesticide in solution (mg chemical L^{-1} solution), and w_{mobile} is the amount of mobile water on a given day (mm H_2O).

AnnAGNPS 3.3 Hydrology and Pesticide Overview. The AnnAGNPS model (USDA ARS 2006) is based upon the single storm AGNPS model (Young et al. 1989) and was created by a team of USDA ARS and NRCS scientists starting in the early 1990s. Model development focused on long-term sediment and chemical transport in ungaged predominately agricultural watersheds (Bingner and Theurer 2005). The AnnAGNPS model provides simulations for hydrology, sediment, pesticide, and nutrient transport. The climatic data requirements for AnnAGNPS include daily maximum and minimum temperature, precipitation, average daily dew point temperature and wind speed, and sky cover (Bingner and Theurer 2005). The AnnAGNPS model incorporates the Generation of weather Elements for Multiple applications climate generation model (USDA NRCS 2005), which produces daily precipitation, maximum and minimum temperature, and solar radiation. In addition, users also have the option to input measured climate data.

The AnnAGNPS model's hydrology is based on a simple bookkeeping of inputs and outputs of water during the daily time steps (Bingner and Theurer 2005). The hydrologic processes simulated in the model include interception evaporation, surface runoff, and ET. Recent enhancements to the model have included simulation of subsurface

lateral flow and subsurface drainage (Yuan et al. 2006). In AnnAGNPS, runoff is predicted using the SCS CN technique (USDA SCS 1986). The soil moisture balance is calculated on a sub-daily time step using a simple constant-time step procedure for both the tillage and below tillage composite soil layers (Bingner and Theurer 2005):

$$SM_{t+1} = SM_t + \frac{WI_t - Q_t - PERC_t - ET_t - Q_{lat} - Q_{tile}}{Z}, \quad (4)$$

where S_{Mt} is the moisture content for each soil layer at the beginning of the time period (fraction); S_{Mt+1} is the moisture content for each soil layer at the end of the period (fraction); WI_t is water input, consisting of precipitation or snowmelt plus irrigation water (mm); Q_t is surface runoff (mm); $PERC_t$ is percolation of water out of each soil layer (mm); ET_t is potential evapotranspiration (mm); Q_{lat} is the subsurface lateral flow (mm); Q_{tile} is tile drainage flow (mm); Z is thickness for soil layer (mm); and t is the time period.

The AnnAGNPS model simulates the transport and fate of pesticides using a modified version of the GLEAMS pesticide component (Bingner and Theurer 2005). A pesticide mass balance in each cell is performed daily and accounts for materials applied to a field, foliage wash-off, transport in the soil profile, degradation, and soluble and sediment adsorbed material that moves in surface runoff (Bosch et al. 2001; Bingner and Theurer 2005). Pesticide available for loss in runoff is based on the equation:

$$C_{av}B = C_w + C_s B, \quad (5)$$

where C_{av} is the available pesticide concentration (mg L^{-1}), B is the soil mass per unit volume of overland flow (kg L^{-1}), C_w is the pesticide concentration in solution (mg L^{-1}), and C_s is pesticide concentration in the soil or solid phase (mg kg^{-1}). More detailed information regarding pesticide transport equations for SWAT or AnnAGNPS is available in Neitsch et al. (2001) or Leonard et al. (1987), respectively.

SWAT2005 and AnnAGNPS Initialization and Common Data Sets. A warm-up period for SWAT is recommended to initialize and approach reasonable starting values for model variables. Mamillapalli (1998) used a five-year warm-up period to minimize SWAT96.2 model initialization problems. Tolson and Shoemaker (2004) used a two-year warm-up period for SWAT2000 in order to provide reasonable initial channel sediment levels. In a SWAT2000 sensitivity analysis by White and Chaubey (2005), initial values were established by simulating a three-year period, allowing the model to stabilize during the first three years and considering the fourth year to be representative of conditions in the watershed. In our study, a three-year warm-up period was used for SWAT and AnnAGNPS model simulations. Unfortunately, there is no documentation regarding AnnAGNPS warm-up periods; however, the three-year period in this study was considered sufficient based on AnnAGNPS developer recommendation (R.L. Bingner, personal communication).

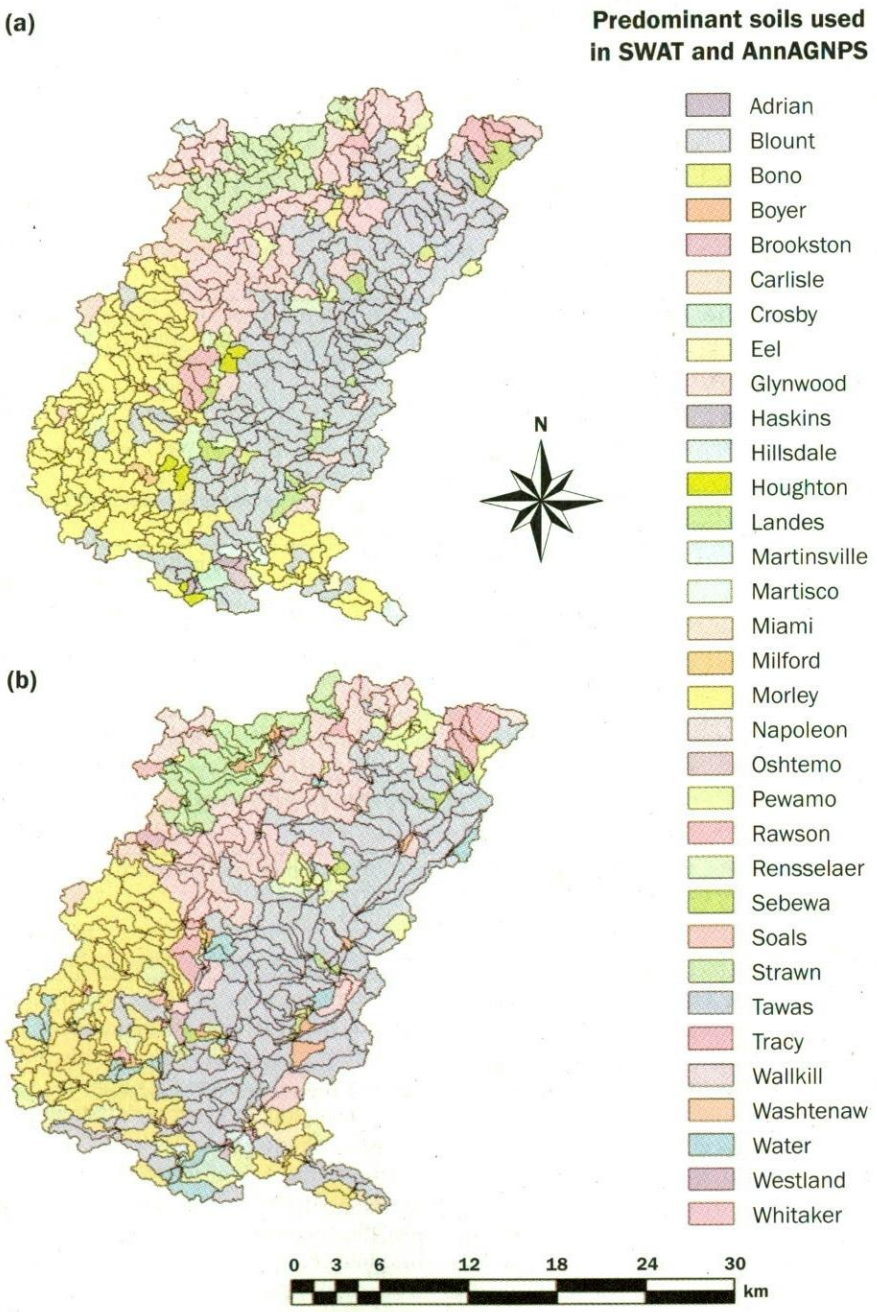
In order to compare SWAT and AnnAGNPS, it was essential to utilize the same data sets whenever possible. For both models, a Digital Elevation Model (DEM) was obtained from the USGS at a resolution of 1/3 arc-second with an elevation resolution of ± 7m (23 ft) to delineate the subwatershed slopes, stream network, and the watershed and subbasin boundaries (figure 1). The DEM was projected to Universal Transverse Mercator NAD83, Zone 16 for the state of Indiana. The St. Joseph Watershed Initiative sampling site 100 is co-located with the USGS streamflow gauge station (figure 1a), thus the same delineation was used for both streamflow and atrazine concentration. Daily historical precipitation and maximum and minimum air temperatures from 1989 to 2005 were obtained from the National Oceanographic and Atmospheric Administration National Climate Data Center (National Oceanographic and Atmospheric Administration National Climate Data Center 2004) for the Garrett meteorological station located within the watershed (figure 1).

Historical measured data for streamflow and atrazine concentration from the USGS and the SJRWI, respectively, were used to conduct the simulation process. Both the SWAT and AnnAGNPS models were run for 1989 to 2005 using measured streamflow data from Cedar Creek Gauge 04180000 (41°13'08" N, 85°04'35" W) Cedarville, Indiana. Simulated atrazine values were analyzed from 1996 to 2004 using measured values from SJRWI Site 100 (41°13'08" N, 85°04'37" W) located at the outlet of the watershed. While flow data was available year-round, atrazine measurements were only taken at SJRWI Site 100 during the months of April through September. Furthermore, the measured atrazine data was obtained from single grab samples taken during storm runoff events, which is a fairly coarse measurement. Both the measured flow data from the USGS and SWAT simulation flow output are composed of baseflow and streamflow. Baseflow is the groundwater contribution to streamflow, which had to be separated out so that measured surface flow can be compared to simulated values. Therefore, the baseflow filter program (Arnold and Allen 1999) was used to separate streamflow from baseflow in SWAT and the USGS measured streamflow data. Flow data from AnnAGNPS does not have a baseflow contribution.

The SSURGO database spatial data (USDA NRCS 2004) was utilized to determine the predominant soil in each hydrologic response unit (HRU) for SWAT and each cell for AnnAGNPS (figure 2 and table 1). As a point of clarification, for AnnAGNPS the watershed was delineated into 498 cells with each cell representing a subbasin. In SWAT, the watershed was delineated into 498 HRUs with each HRU representing a subbasin. Thus, both models have the same number of subbasins. The SSURGO spatial data consists of county-level maps, metadata, and tables which define the proportionate extent of the component soils and their properties for each map unit. For the counties intersecting the watershed, the SSURGO soil database is at a map-scale of 1:12,000, and was created primarily for farm, landowner, township, or county natural resource planning and management. Forty-five soil SSURGO series are present in the CCW with Blount being dominant (25% of the watershed), followed by Morley (16%), Pewamo (16%), and Glynwood (10%). Although the soils within the CCW are considered highly productive, the majority are comprised of slowly permeable glacial till material that require agricultural producers to use artificial drainage (Smith and Pappas 2007). Approximately 80% to 90% of the cropland in DeKalb County is tile-drained (DeKalb County Department of Watershed Management 2008). Thus, tile drainage was specified in both models for cropland areas in the watershed and held constant throughout the simulation with no optimization.

A description of land use in the CCW was determined from the USDA NASS

Figure 2
SSURGO geographic information system soil map layer for (a) SWAT hydrologic response units and (b) AnnAGNPS subbasins within the Cedar Creek watershed.



Notes: SSURGO = Soil Survey Geographic database. SWAT = Soil and Water Assessment Tool. AnnAGNPS = Annualized Agricultural Non-Point Source model.

(2001) Indiana Cropland Data Layer for SWAT and AnnAGNPS (figure 3 and table 2). This land use is a raster, geo-referenced, categorized land cover data layer produced using satellite imagery from the Thematic Mapper instrument on Landsat 5 and the Enhanced Thematic Mapper on Landsat 7. The imagery was collected between the dates of April 29, 2001 and September 5, 2001. The approximate scale is 1:100,000 with a ground resolution of 30 m by 30 m (98.4 ft by 98.4 ft). As listed in table 2, the major percentages of NASS 2001 land use for SWAT and AnnAGNPS, respectively are 18.8% and 17.49% for corn, 27.25% and 24.47% for soybeans, 40.92% and 43.36% for pasture, and 10.57% and 8.79% for forests. For both models, the initial value for the SCS CN corresponding to each soil group and land use for each management practice was obtained from Technical Release 55 (USDA SCS 1986).

Conservation tillage has been widely adopted in the watershed. In DeKalb County, 28% of all corn and 82% of all soybeans planted in 2004 were under a no-till system (Indiana Conservation Tillage Reports 2004). The tillage practices in Noble and Allen counties differed only slightly from that in DeKalb County. However, the Noble and Allen County Soil and Water Conservation District offices regard tillage in the Cedar Creek portion of their county to be similar to that of neighboring DeKalb County. In general, all three counties exhibit similar agricultural trends within the watershed. For agricultural management data, area-specific information on SWAT and AnnAGNPS management input scenarios was in accordance with the most current data available as provided by the SJRWI, Soil and Water Conservation Districts of Allen, DeKalb, and Noble Counties, Indiana Agricultural Statistics Service, and Indiana Conservation Tillage Reports. Table 3 shows the management dates, operation types, and fertilizer and pesticide types and amounts used for a typical two-year corn-soybean (the predominant crops in the CCW) rotation. Corn and soybeans are usually planted between late April and early May (Indiana Agricultural Statistics Service 2003). Nitrogen fertilizer is primarily applied as anhydrous ammonia to corn, phosphorus is usually applied to corn and soybeans in granular form blended in various combinations with other nutrients, and atrazine-based herbicides are widely used to

Table 1
SWAT and AnnAGNPS predominant soil types in the Cedar Creek watershed based on SSURGO data.

			SWAT		AnnAGNPS	
SSURGO soil series	Texture	Hydrologic group	Area (km²)	Percent	Area (km²)	Percent
Blount	SIL-SIC-SICL	C	268.94	38.82%	268.36	37.67%
Boyer	LS-L-GR-S	B	5.52	0.8%	8.06	1.13%
Glynwood	SIL-C-CL	C	102.22	14.75%	130.19	18.27%
Miami	SIL-CL-L	B	16.88	2.44%	9.54	1.34%
Morley	SIL-CL-SICL	C	171.44	24.75%	139.56	19.59%
Pewamo	SIL-SIC-CL	C	18.65	2.69%	42.74	5.99%
Rawson	SL-SLC-SIC	B	16.06	2.32%	19.53	2.74%
Rensselaer	SIL-SCL-L-SIL	B	8.48	1.22%	4.36	0.611%
Sebewa	L-SCL-GR--S	B	9.84	1.42%	4.25	0.60%
Strawn	L-SICL-CL	B	40.32	5.82%	40.29	5.66%
Water	NA	NA	NA	NA	20.30	2.85%

Notes: SWAT = Soil and Water Assessment Tool. AnnAGNPS = Annualized Agricultural Non-Point Source model. SSURGO = Soil Survey Geographic database. Only SSURGO soils with coverage greater than 1% of Cedar Creek watershed total area are shown. SIL = silt loam. SIC = silty clay. SICL = silty clay loam. LS = loamy sand. L = loam. GR = gravel. S = sand. C = clay. CL = clay loam. SLC = silty loam clay. NA = not applicable.

control weeds in corn and are surface applied as a liquid solution (table 3). Glyphosate-tolerant corn hybrids are becoming increasingly popular in the area so the amount of atrazine applied is being reduced over time. The DeKalb County Soil and Water Conservation District estimated that greater than 75% of all soybeans planted in the watershed are glyphosate-tolerant cultivars.

The timing, average rate, and number of atrazine applications were determined based on the seasonal progress of crop development and farm activities for northeastern Indiana reported by the NASS Agricultural Chemical Database. On average, the NASS reported 1.01 atrazine applications per corn grid cell over a seven-year period from 1996 to 2002 with a rate of 1.46 kg ha^{-1} (1.30 lb ac^{-1}) for northeastern Indiana (USDA NASS 2004). For the CCW, the timing of atrazine application was modified to account for the actual temporal application of pesticide in the watershed. Applications before, during, and after planting with an amount equal to the percentage of seasonal progress of crop development were used (table 3). Table 4 lists the properties and parameter values for atrazine that were used as input for each model.

SWAT2005 Inputs. The ArcView 3.3 SWAT2005 GIS interface (DiLuzio et al. 2001) was used for expediting SWAT model input and output. To obtain the proper stream path delineation, the 11-digit USGS boundaries of the CCW (the upper and lower Cedar) were used as a mask, and the stream delineation from the National Hydrograph Data set was overlain on the DEM and used to burn in the location of the streams in the watershed. The AVSWAT-X GIS interface can accept either the USDA NRCS STATSGO (from the 1:250,000 scale underlying map) or the SSURGO (from the 1:12,000 to 1:63,000 scale underlying map) geospatial soil databases. For this study, the SSURGO spatial data set was used as input for soil types in the CCW.

Table 2
SWAT and AnnAGNPS predominant land cover distribution in the Cedar Creek watershed based on USDA NASS (2001) data.

	SWAT		AnnAGNPS	
Land cover	Area (km²)	Percent	Area (km²)	Percent
Corn	130.24	18.80%	124.63	17.49%
Soybeans	191.09	27.25%	174.32	24.47%
Pasture/farmstead	283.52	40.92%	308.91	43.36%
Fallow/Conservation Reserve Program	2.79	0.40%	9.90	1.39%
Forest	73.23	10.57%	62.65	8.79%
Urban	11.93	1.72%	11.73	1.65%
Water			20.30	2.85%

Notes: SWAT = Soil and Water Assessment Tool. AnnAGNPS = Annualized Agricultural Non-Point Source model. NASS = National Agricultural Statistics Service.

Typically, HRUs are determined in SWAT by the unique combination of land use and soils within each subbasin based on threshold values the user sets for soil and land use (e.g., 10% and 10%). Thus, a subbasin may have any number of HRUs depending on the threshold values. However, for comparative evaluation with AnnAGNPS in this study, threshold values were not assigned and HRUs were determined by the dominant soil type (figure 2) and land use (figure 3). Accordingly, for SWAT a stream threshold minimum value of 75 ha (185.3 ac) was used to delineate 498 subbasins which, for this study, are synonymous with HRUs (figure 2). This provided a means to derive comparable soil, and land use GIS input data sets for both models.

Due to the lack of measured data, SWAT default values were used for those parameters affecting baseflow and groundwater, i.e., baseflow recession constant (ALPHA_BF = 0.05 days), delay time for aquifer recharge (GW_DELAY = 31 days), threshold water level in the shallow aquifer for return flow to occur (GWQMN = 0.0 mm), coefficient for controlling the movement of water into the overlying unsaturated zone (GW_REVAP = 0.02), and threshold water level in the shallow aquifer for movement of water to the unsaturated zone or percolation to

Table 3
SWAT and AnnAGNPS management input information for a typical two-year corn-soybean rotation in the Cedar Creek watershed.

Year	Month	Day	Operation/crop	Implement	Fertilizer (kg ha^{-1})	Pesticide (kg ha^{-1})
No-till						
1	May	3	Fertilizer	Surface applied	95 (10-34-00)	
1	May	3	Tillage	No-till mixing		
1	May	4	Corn			
1	May	4	Pesticide			1.5 (atrazine)
1	May	25	Fertilizer	Injected	145 (ANH-NH_3)	
2	April	20	Fertilizer	Surface applied	32 (Elemental P)	
2	May	20	Tillage	No-till mixing		
2	May	20	Soybean			
2	June	1	Pesticide			0.7 (Roundup)
2	October	1	Harvest and kill			
Conventional tillage						
1	April	1	Tillage	Spring plowing		
1	April	15	Tillage	Field cultivator		
1	May	3	Fertilizer	Surface applied	95 (10-34-00)	
1	May	4	Corn			
1	May	4	Pesticide			1.5 (atrazine)
1	May	25	Fertilizer	Injected	145 (ANH-NH_3)	
1	October	30	Harvest and kill			
1	November	1	Tillage	Fall plowing		
2	April	15	Tillage	Tandem disk		
2	April	20	Fertilizer	Surface applied	32 (Elemental P)	
2	May	20	Soybean			
2	June	1	Pesticide			0.7 (Roundup)
2	September	20	Harvest and kill			

Notes: SWAT = Soil and Water Assessment Tool. AnnAGNPS = Annualized Agricultural Non-Point Source model. ANH-NH_3 = anhydrous ammonia.

Table 4
List of SWAT and Annualized AnnAGNPS input parameter values critical for Cedar Creek watershed streamflow and atrazine concentration prediction.

Model	Land use and soil	Hydrologic soil group	CN	SOL_AWC (mm mm^{-1})	SOL_K (mm h^{-1})	PERCOP	WOF	AP_EF	Foliar half-life (days)	Soil half-life (days)	Soil adsorption coefficient (mg kg^{-1}) (mg L^{-1})$^{-1}$	Water solubility (mg L^{-1})
SWAT	USDA NASS 2001	A	55	0.36	186.8	0.5	0.45	0.75	5	60	100	33
	SSURGO	B	72	0.14	57.6	0.5	0.45	0.75	5	60	100	33
		C	80	0.16	32.3	0.5	0.45	0.75	5	60	100	33
AnnAGNPS	USDA NASS 2001	B	74	0.12	53.8	NA	0.45	NA	5	60	100	33
	SSURGO	C	82	0.14	32.6	NA	0.45	NA	5	60	100	33
		D	88	0.05	10.16	NA	0.45	NA	5	60	100	33

Notes: SWAT = Soil and Water Assessment Tool. AnnAGNPS = Annualized Agricultural Non-Point Source model. CN = curve number. SOL_AWC = soil available water capacity. SOL_K = soil saturated hydraulic conductivity. PERCOP = coefficient for partitioning pesticide removal between percolate and surface runoff. WOF = pesticide wash-off fraction. AP_EF = pesticide application efficiency. NASS = National Agricultural Statistics Service. SSURGO = Soil Survey Geographic database. NA = not applicable.

the deep aquifer (REVAPMN = 1.0 mm). Additionally, in SWAT, water entering tiles is treated like lateral flow with the input variables defined in the management (.mgt) input files. Parameters describing tile drainage include the average depth of the tile drain area (DDRAIN = 90 mm), drainage time after a rain for the soil to reach field capacity (TDRAIN = 48 hr), and the drain tile lag time (GDRAIN = 2 hr). Table 4 lists other properties and parameter values critical for streamflow and atrazine concentration prediction that were used as input for SWAT.

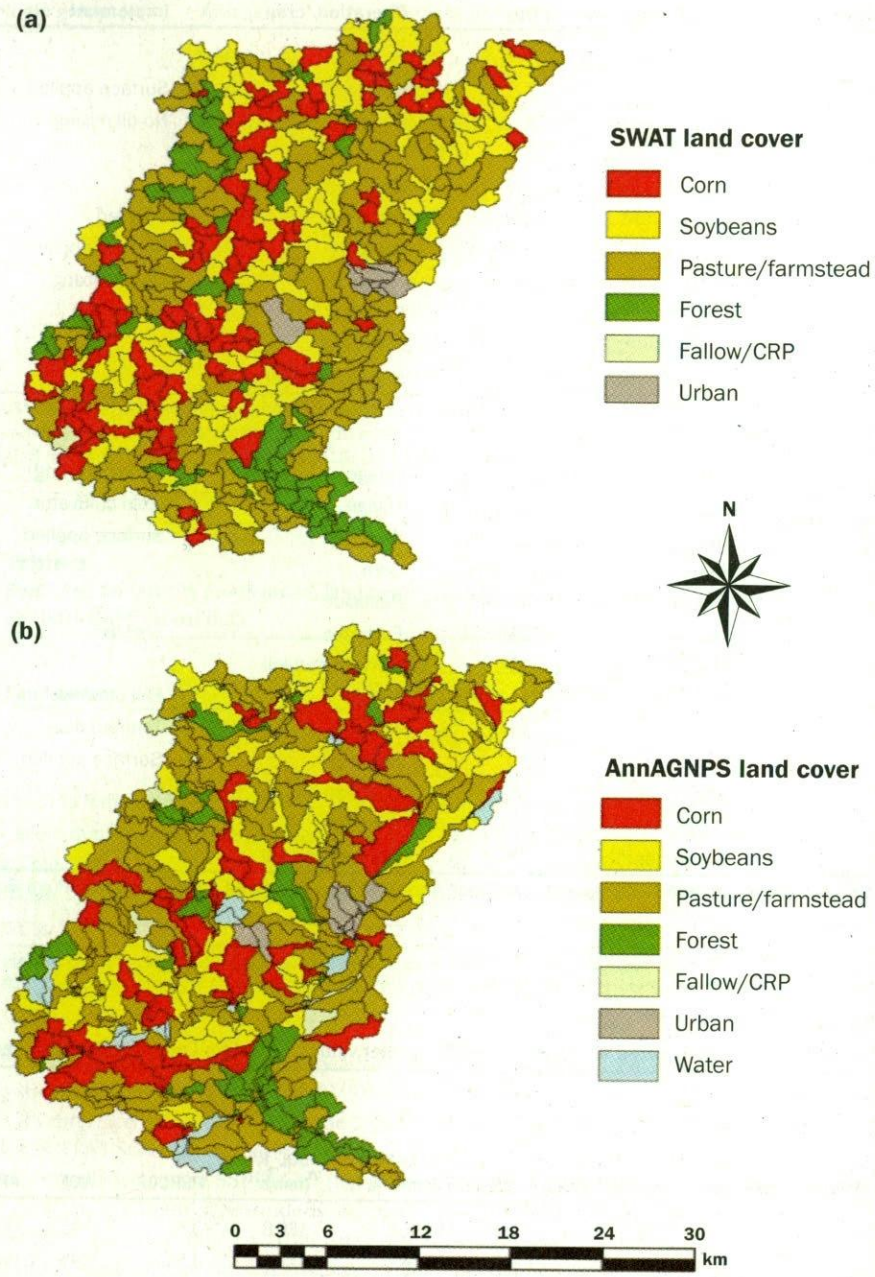
The CCW data set was set up to run on a daily time step for streamflow and atrazine concentration. The Penman-Monteith method was selected to compute ET in order to capture the effects of wind and relative humidity. The SCS CN was used to calculate surface runoff. The SWAT model default values for SCS CN were used for the land management of forest, pasture, and urban areas. The SWAT model is capable of generating climatic data for temperature, precipitation, wind, solar radiation and relative humidity, or the data can be inputted. For this study, information on solar radiation, wind speed, and relative humidity were generated by SWAT. The channel water routing needed to predict the changes in the magnitude of the peak and the corresponding stage of flow as a flood wave moves downstream was based on the Muskingum routing method (Cunge 1969).

AnnAGNPS Model Inputs. The AnnAGNPS watershed was delineated using the TopAGNPS program (Garbrecht et al. 2001) within the AnnAGNPS ArcView 3.3 interface (USDA ARS 2006) and a USGS 1/3 arc-second DEM that was resampled to an exact 10 m (32.8 ft) grid, burned in 1 m (3.3 ft) with the stream networks from the National Hydrograph Data set. A critical source area of 175 ha (432.4 ac) and minimum source channel length of 200 m (656.2 ft) were used to delineate the same number of 498 cells (or subbasins in this case) as was obtained with SWAT HRU delineation. Flow routing in AnnAGNPS is based on the downslope flow routing concept that defines the drainage and flow direction on the landscape as the steepest downslope path from the cell of interest to one of its adjacent cells (Garbrecht et al. 2001).

The AnnAGNPS ArcView 3.3 interface (USDA ARS 2006) was also used to extract the cell and reach data from the DEM.

Figure 3

USDA NASS (2001) geographic information system land cover map layer for (a) SWAT hydrologic response units and (b) AnnAGNPS subbasins within the Cedar Creek watershed.



Notes: NASS = National Agricultural Statistics Service. SWAT = Soil and Water Assessment Tool. AnnAGNPS = Annualized Agricultural Non-Point Source model. CRP = Conservation Reserve Program.

The dominant soils for the subbasins were determined using the intersect soils feature in the AnnAGNPS ArcView interface with the SSURGO spatial data set. Soil properties for the representative soils were retrieved in an AnnAGNPS input format using the National Soil Information System (NASIS) soil database. The AnnAGNPS interface requires that land use be in Environmental Systems Research Institute shapefile format (Environmental Systems Research Institute 1998). Therefore, the USDA NASS (2001) Indiana Cropland Data Layer was converted from a raster file to an Environmental Systems

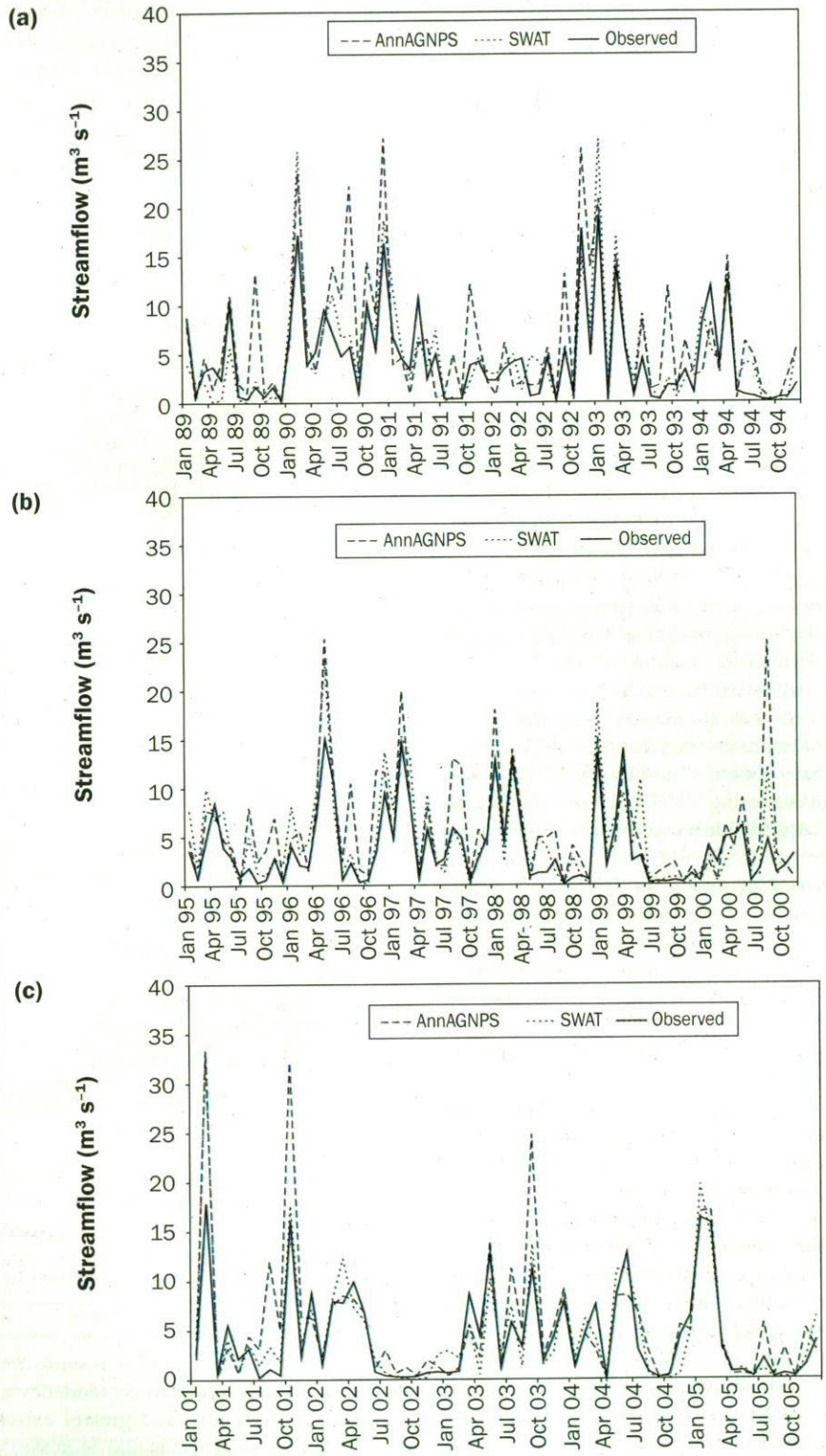
Research Institute shapefile using ArcView. Dominant land use was then determined by intersecting the delineated subwatersheds with the converted land use shapefile in the AnnAGNPS ArcView interface.

The AnnAGNPS model has the capability of generating climate data for temperature and precipitation through the use of the Generation of weather Elements for Multiple applications model (USDA NRCS 2005) from the ArcView interface or the data can be uploaded to the model in the input editor. However, neither Generation of weather Elements for Multiple applications nor the observed climate data for CCW included the AnnAGNPS required data for sky cover, wind speed, and dew point temperature. For this study, sky cover, wind speed and dew point temperature were generated by processing the measured daily precipitation, and maximum and minimum air temperature data with the Complete_Climate program (USDA NRCS 1999) that is included with the AnnAGNPS model.

Because of the lack of measured data, default AnnAGNPS parameter values used in this study were 12.7 mm d^{-1} (0.5 in day^{-1}) for tile drainage rate, 1.0 for RUSLE sub P-factor of subsurface drainage, and 0.04 for cell concentrated flow Manning's "n". Table 4 lists other properties and parameter values critical for streamflow and atrazine concentration prediction that were used as input for AnnAGNPS. Management operation data (not shown) including residue cover remaining, area disturbed, initial random roughness, final random roughness, and operation tillage depth were imported from the RUSLE database. The RUSLE database was also utilized to import crop growth parameters and noncropland use data.

SWAT2005 and AnnAGNPS Statistical Evaluation. The accuracy of SWAT and AnnAGNPS simulation results were determined by examination of the mean, standard deviation (sd), coefficient of determination (r^2), root mean square error (RMSE), and the Nash-Sutcliffe (1970) model efficiency coefficient (E_{NS}). A simple comparison of mean and standard deviation indicates whether the frequency distribution of model results is similar to the measured frequency distribution. The r^2 value is an indicator of the strength of the linear relationship between the observed and simulated values. The RMSE is indicative of the error associated with estimated streamflow or atrazine concentration.

Figure 4
Monthly Cedar Creek watershed observed versus SWAT and AnnAGNPS simulated streamflow for (a) 1989 to 1994, (b) 1995 to 2000, and (c) 2001 to 2005.



Notes: SWAT = Soil and Water Assessment Tool. AnnAGNPS = Annualized Agricultural Non-Point Source model.

E_{NS} simulation coefficient indicates how well the plot of observed versus simulated values fits the 1:1 line. The ENS can range from $-\infty$ to +1, with 1 being a perfect agreement between the model and real data (Santhi et al. 2001). The RMSE and E_{NS} statistics are defined as

$$\mathrm{RMSE} = \sqrt{\frac{\sum (X_p - X_o)^2}{n}}, \quad (6)$$

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n} (X_o - X_p)^2}{\sum_{i=1}^{n} (X_o - \overline{X_o})^2}, \quad (7)$$

where $\overline{X_0}$ is the average measured value during the simulation period, X_p is the simulated output on day *i*, and X_o is the observed data on day *i*.

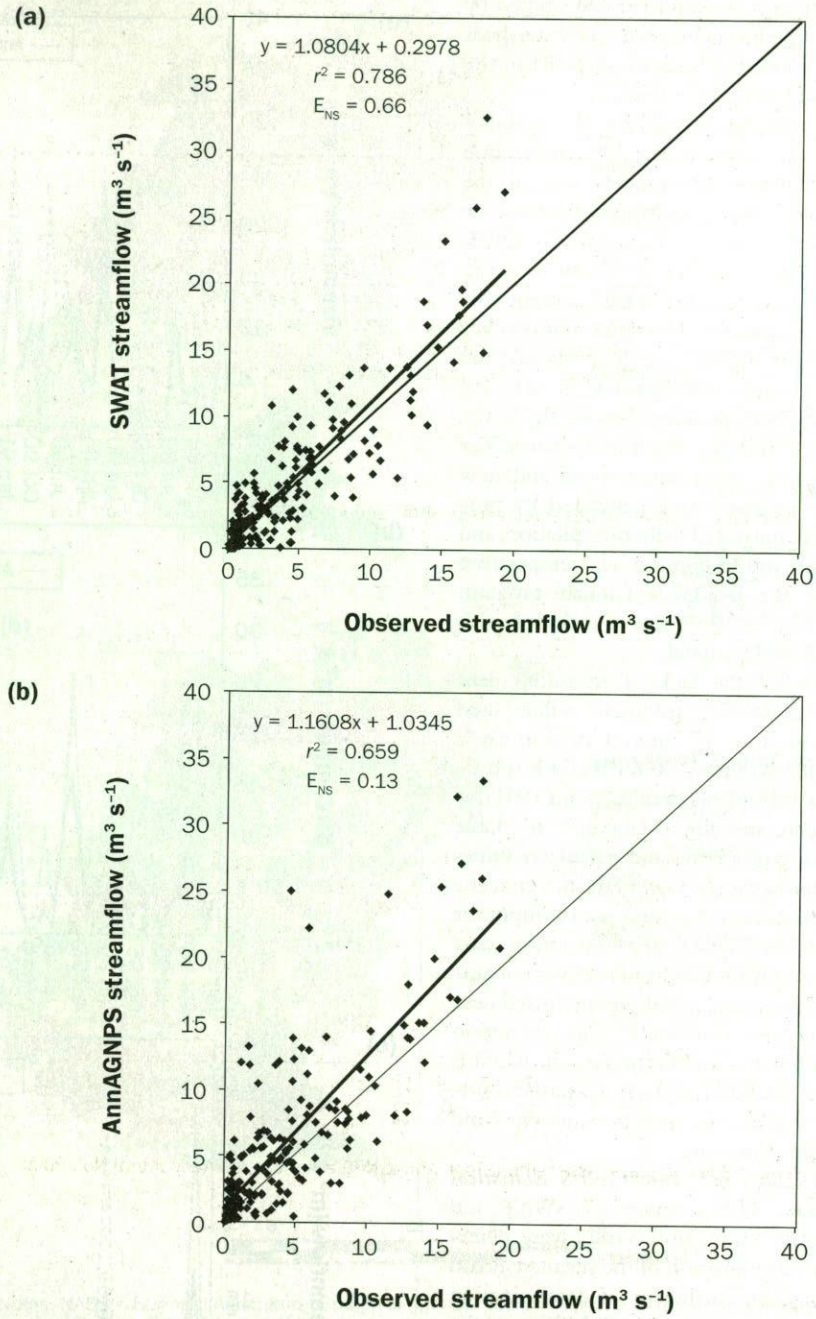
Gassman et al. (2007) reported that the most widely used statistics for SWAT hydrologic predictions are r^2 and E_{NS}. In a recent review of model statistics, Moriasi et al. (2007) proposed that E_{NS} values should exceed 0.50 for model performance to be considered satisfactory for hydrologic and pollutant loss evaluations. Although model performance is somewhat of a subjective area, we have chosen to use the above E_{NS} criteria in evaluating SWAT and AnnAGNPS. We also applied Tukey's statistical least significant difference (LSD) test at the $\alpha = 0.05$ level to determine significant differences between all possible pairs of means for simulated output and observed data. Tukey's LSD is a more suitable test for multiple comparisons than the simple t-test (Ott 1979).

Results and Discussion

Results. The observed monthly streamflow and values predicted by the SWAT and AnnAGNPS models are shown in figures 4a to 4c where the simulation period from 1989 to 2005 was separated into three subperiods for better visual interpretation of the data. Since AnnAGNPS does not simulate base flow, the SWAT base flow filter program (Arnold and Allen 1999) was used to separate base flow from SWAT predicted values and measured streamflow for comparisons with AnnAGNPS output. In general, both SWAT and AnnAGNPS captured the major trends seen in the observed data for timing of peak discharge occurrences (figures 4a to 4c), and to some degree, the magnitude of the observed monthly streamflow values. However, throughout the simulation period, AnnAGNPS displayed a tendency to overpredict streamflow to a greater extent than SWAT, particularly during high flows. This is also apparent in figures 5a and 5b where the SWAT and AnnAGNPS monthly simulated versus observed streamflow data are shown in 1:1 plots. Compared to the SWAT simulated streamflow data in figure 5a, the AnnAGNPS simulated streamflow data in figure 5b has a considerably higher amount of scatter, as well as a greater degree of overprediction as indicated by the larger deviation of the regression line from the

Figure 5

1:1 plot of monthly Cedar Creek watershed observed versus (a) SWAT and (b) AnnAGNPS simulated streamflow (1989 to 2005).



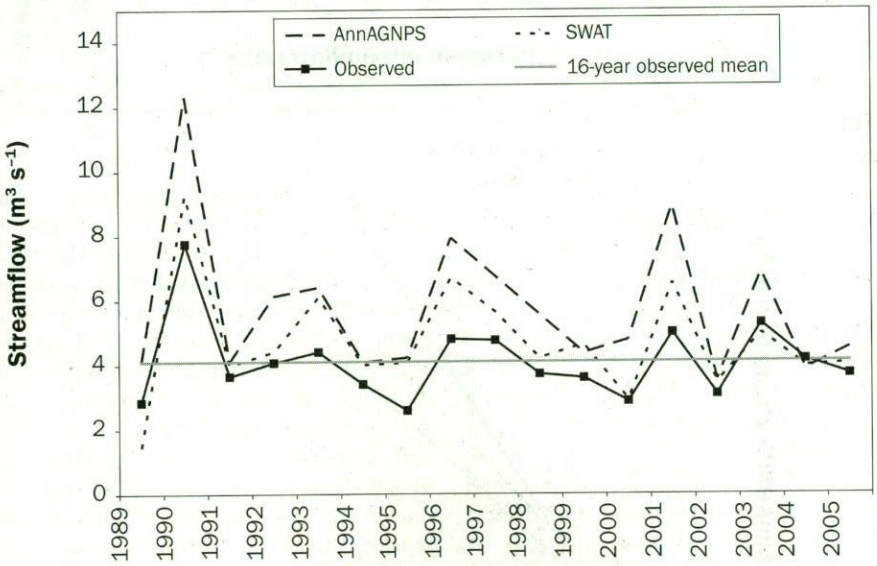
Notes: SWAT = Soil and Water Assessment Tool. AnnAGNPS = Annualized Agricultural Non-Point Source model.

Table 5
Statistical evaluation for monthly observed and simulated streamflow (1989 to 2005) and atrazine concentration (1996 to 2004) in the Cedar Creek watershed.

	Mean	sd	RMSE	E_{NS}	r^2
Streamflow ($m^3 s^{-1}$)					
Observed	4.11 b	4.42			
SWAT	4.74 ab	5.99	6.69	0.66	0.79
AnnAGNPS	5.81 a	6.32	4.11	0.13	0.66
Atrazine ($\mu g L^{-1}$)					
Observed	1.08 b	1.33			
SWAT	3.11 a	6.02	5.62	-17.15	0.40
AnnAGNPS	0.01 b	0.02	1.69	-0.64	0.34

Notes: Means followed by the same letter are not significantly different in Tukey's LSD test statistic with $\alpha = 0.05$. sd = standard deviation. RMSE = root mean square error. E_{NS} = Nash-Sutcliffe model efficiency coefficient. r^2 = coefficient of determination. SWAT = Soil and Water Assessment Tool. AnnAGNPS = Annualized Agricultural Non-Point Source model.

Figure 6
Annual Cedar Creek watershed observed versus SWAT and AnnAGNPS simulated streamflow (1989 to 2005).



Notes: SWAT = Soil and Water Assessment Tool. AnnAGNPS = Annualized Agricultural Non-Point Source model.

Table 6
Statistical evaluation for annual observed and simulated streamflow (1989 to 2005) in the Cedar Creek watershed.

	Mean	sd	RMSE	E_{NS}	r^2
Observed	4.10b	1.23			
SWAT	4.72ab	1.75	1.04	0.25	0.80
AnnAGNPS	5.79a	2.30	2.09	-2.06	0.84

Notes: Means followed by the same letter are not significantly different in Tukey's LSD test statistic with $\alpha = 0.05$. sd = standard deviation. RMSE = root mean square error. E_{NS} = Nash-Sutcliffe model efficiency coefficient. r^2 = coefficient of determination. SWAT = Soil and Water Assessment Tool. AnnAGNPS = Annualized Agricultural Non-Point Source model.

1:1 line. The Tukey's LSD test statistic ($\alpha = 0.05$) showed that there was no significant difference between mean monthly SWAT simulated streamflow and mean monthly observed streamflow (table 5). The Tukey's LSD test also found no significant difference between SWAT and AnnAGNPS simulated mean monthly streamflow; however, mean monthly AnnAGNPS simulated streamflow was significantly different from mean monthly observed streamflow (table 5). The AnnAGNPS model predicted a higher (but not statistically significant) mean monthly streamflow value (5.81 $m^3 s^{-1}$ [205 $ft^3 sec^{-1}$]) than SWAT (4.74 $m^3 s^{-1}$ [167 $ft^3 sec^{-1}$]) with the E_{NS} and r^2 for streamflow being higher for SWAT (E_{NS} = 0.66, r^2 = 0.79) than AnnAGNPS (E_{NS} = 0.13, r^2 = 0.66) (table 5). Table 5 also shows that SWAT monthly streamflow predictions had a slightly smaller standard deviation and larger RMSE compared to AnnAGNPS.

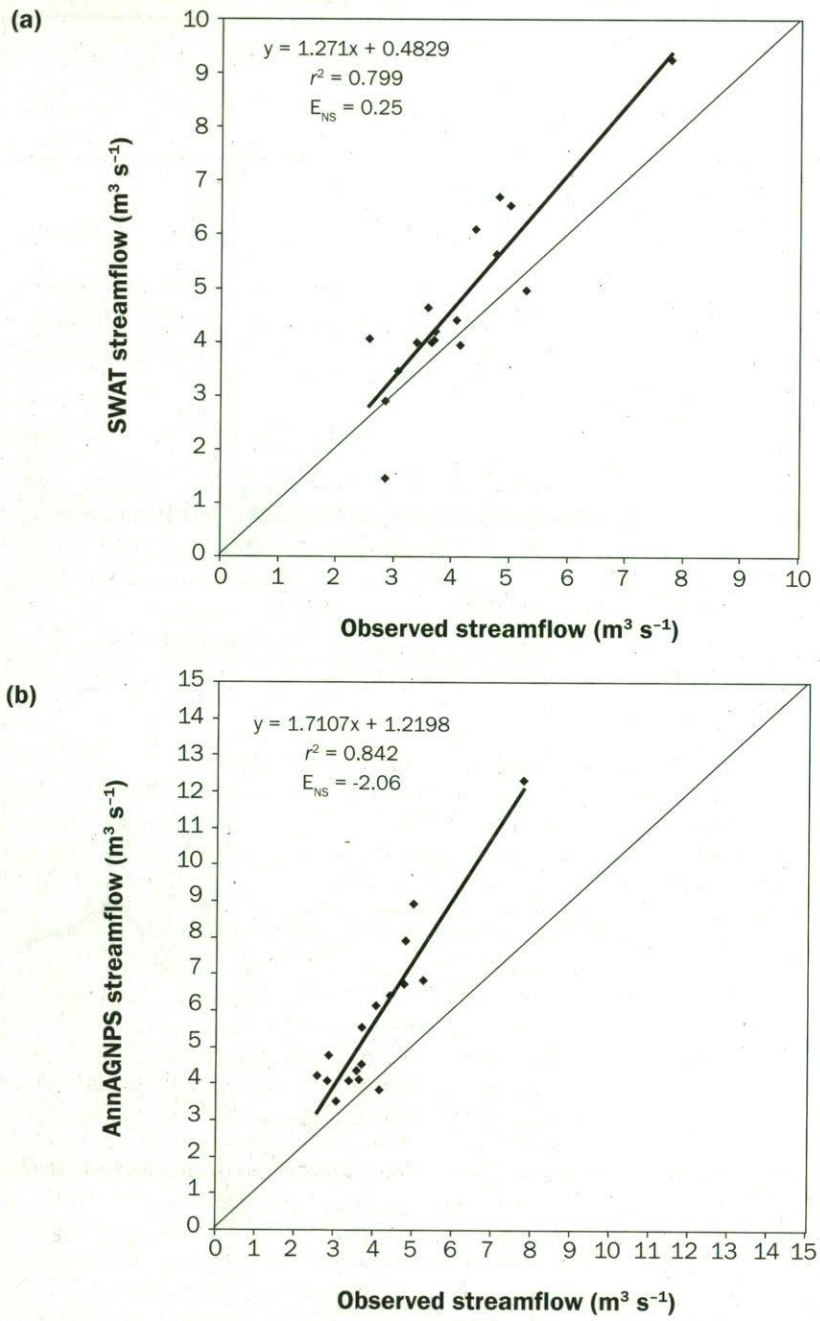
Annual observed and simulated streamflow results from 1989 to 2005 are displayed in figures 6 and 7. Similar to mean monthly SWAT and AnnAGNPS streamflow predictions, both models overpredicted annual streamflow. In addition, both SWAT and AnnAGNPS had lower annual streamflow E_{NS} values (table 6) as compared to the mean monthly streamflow E_{NS} values (table 5). This was somewhat surprising given the fact that model performance typically improves when going from finer to coarser time scales. However, for uncalibrated conditions this may not necessarily be the case and emphasizes the importance of evaluating model performance at different time scales. The observed annual streamflow in figure 6 shows the flow variability during the course of the 16-year study period with some years having relatively high or low flows. Both models simulated the general trend of measured annual streamflow but consistently overpredicted by approximately 15% for SWAT and 30% for AnnAGNPS.

The 1:1 comparisons for SWAT and AnnAGNPS simulated versus observed annual streamflow are presented in figures 7a and 7b, respectively. Annual streamflow predictions by SWAT resulted in a marginal E_{NS} value of 0.25, with r^2 equal to 0.80 (figure 7a and table 6). However, the statistical evaluation presented in table 6 indicates no significant difference between SWAT predicted (4.72 $m^3 s^{-1}$ [166 $ft^3 sec^{-1}$]) and

observed (4.10 $m^3 s^{-1}$ [145 $ft^3 sec^{-1}$]) mean annual streamflow using Tukey's LSD test (α = 0.05). The AnnAGNPS model overpredicted annual streamflow values to a greater extent than SWAT as shown in figures 6 and 7b. In table 6, AnnAGNPS simulated mean annual streamflow (5.79 $m^3 s^{-1}$ [204 $ft^3 sec^{-1}$]) was significantly different from observed mean annual streamflow (4.10 $m^3 s^{-1}$ [145 $ft^3 sec^{-1}$]) according to the Tukey's LSD test (α = 0.05). For AnnAGNPS, the r^2 value between simulated and observed annual streamflow was 0.84, while the ENS value was -2.06 indicating poor model performance (figure 7b and table 6). In addition, the standard deviation and RMSE were both larger for AnnAGNPS annual streamflow predictions compared to SWAT (table 6). However, it is apparent from the 1:1 graphs in figures 7a and 7b that neither model predicted annual streamflow satisfactorily with AnnAGNPS having a considerably lower ENS value of -2.06 compared to 0.25 for SWAT.

Monthly observed and simulated atrazine concentrations are presented in figures 8 and 9a-b. Stream sampling for atrazine was only conducted during April to September so it was not possible to determine annual values. Neither the uncalibrated SWAT nor AnnAGNPS models were able to adequately simulate monthly atrazine concentrations. Figures 8 and 9a-b show that there was considerable discrepancy between modeled atrazine concentrations since it was necessary to plot the output from each model using extremely different concentration scales. The SWAT model overpredicted monthly atrazine concentrations by approximately 2.8 times and had a very low E_{NS} value of -17.15 (table 5). The AnnAGNPS model, on the other hand, greatly underpredicted monthly atrazine concentrations (simulated values were approximately 1/100 of measured) and had an E_{NS} value of -0.64 (table 5). The data scatter in figures 9a and b, as well as the negative E_{NS} values, illustrates the inability of both SWAT and AnnAGNPS to adequately simulate atrazine concentrations. Although the mean monthly simulated and observed atrazine concentrations are very low in table 5, it is interesting to note that no significant difference was found between AnnAGNPS simulated and observed mean monthly atrazine concentration using the Tukey's LSD test (α = 0.05). To the contrary, using a simple t-test with α = 0.05 showed that all atrazine mean monthly concentrations in table 6 were significantly different (analysis not shown). Both SWAT and AnnAGNPS, however, were able to replicate the timing of the peak atrazine concentrations, if not the magnitude (figure 8). These results suggest that for the CCW it may not be possible to use either SWAT or AnnAGNPS in an uncalibrated mode for prediction of atrazine concentrations and losses. Again, it is important to note that the measured data being compared with model predictions is from single grab samples taken during storm runoff events. This is a fairly coarse mea-

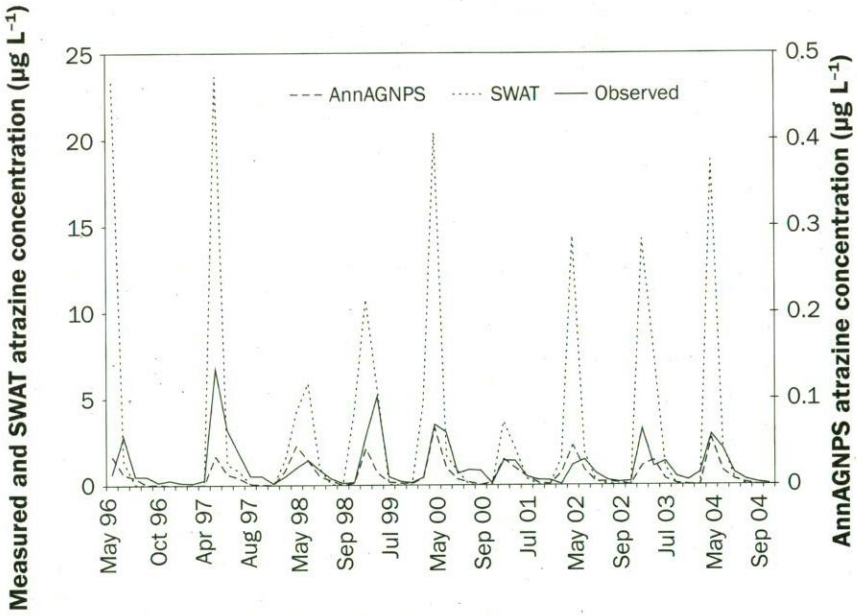
Figure 7
1:1 plot of annual Cedar Creek watershed observed versus (a) SWAT and (b) AnnAGNPS simulated streamflow (1989 to 2005).



Notes: SWAT = Soil and Water Assessment Tool. AnnAGNPS = Annualized Agricultural Non-Point Source model.

Figure 8

Monthly Cedar Creek watershed observed versus SWAT and AnnAGNPS simulated atrazine concentrations (May 1996 to September 2004).



Notes: SWAT = Soil and Water Assessment Tool. AnnAGNPS = Annualized Agricultural Non-Point Source model. Note the difference between scales for each y-axis.

surement, and the implications of using the atrazine grab sample data for SWAT and AnnAGNPS model evaluation are discussed further in the following section.

Discussion. In order to assess the application of SWAT and AnnAGNPS for modeling streamflow and atrazine losses in the CCW, it is beneficial to contrast the results of this study with similar studies. There is a considerable collection of literature that demonstrates the use of SWAT in effectively modeling monthly streamflow (e.g., Spruill et al. 2000; Cotter et al. 2003; Van Liew and Garbrecht 2003; Di Luzio et al. 2005; White and Chaubey 2005; Wang and Melesse 2006; Gassman et al. 2007; Larose et al. 2007). The statistical analysis results reported in this study for uncalibrated monthly streamflow predictions (E_{NS} = 0.66, r^2 = 0.79) fall within the range of those found throughout the literature. Van Liew and Garbrecht (2003) reported uncalibrated daily streamflow ENS values as low as -3.24 that were improved with calibration to values as high as 0.60 for the Little Washita River watershed in Oklahoma. In the same 15-year study by Van Liew and Garbrecht (2003), evaluation results showed that the SWAT model underestimated average annual streamflow by 18.4% using default values for model parameters affecting streamflow prediction. On a year-by-year basis, SWAT underestimated one year by as much as 98.4% while overestimating another year by 156.9%. More recently, a five-year study by Wang and Melesse (2006) showed that for the Elm River watershed in North Dakota, calibrated daily SWAT streamflow predictions ranged from 5% overprediction to 35% underprediction compared to the observed data. For a small watershed in Kentucky, Spruill et al. (2000) found that differences between observed and calibrated daily SWAT streamflow rates ranged between ±25 % over a two-year period and that the size of the drainage area influenced SWAT discharge predictions. Several of the other studies cited herein also report a considerable range in SWAT results for uncalibrated as well as calibrated streamflow (e.g., Di Luzio et al. 2005; White and Chaubey 2005; Wang and Melesse 2006; Larose et al. 2007).

Possible explanations for SWAT model overestimation of streamflow may be attributed to using default parameters that govern simulated flow through the shallow and deep aquifer, as well as to the tile drainage routine used in SWAT (Gassman et al. 2007). Although SWAT has been greatly enhanced from its original version, further improvement in the tile drainage components should increase the accuracy in estimating streamflow and atrazine losses in watersheds with tile drains such as those throughout the Midwest.

Studies involving the application of AnnAGNPS for estimating streamflow are not as prevalent in the literature as those for SWAT. Sarangi et al. (2007) used AnnAGNPS to predict runoff and sediment losses from forested and agricultural watersheds on the island of St. Lucia in the Caribbean. Based on calibration and validation of the model for different rainfall events, Sarangi et al. (2007) reported errors of 7% to 36% for annual streamflow prediction from the agricultural watershed, which are comparable to the AnnAGNPS noncalibrated streamflow error range in this study (14% to 38%). In a two-year study on a small watershed in Southern Ontario, Das et al. (2006) reported that mean annual runoff was underestimated by approximately 55% for noncalibrated conditions as opposed to the overpredictions obtained with AnnAGNPS in this study. Several additional sources of information from symposium proceedings report similar results for streamflow estimates using AnnAGNPS (Theurer and Cronshey 1998; Das et al. 2007; Sadeghi et al. 2007).

Considering both models, overprediction of monthly streamflow (especially during summer months) (figures 4a-c) may be due to the lack of measured data for solar radiation and wind speed which are needed to estimate potential ET based on the Penman equation in each model. Furthermore, the lack of available measured ET data for the study period makes it difficult to validate simulated ET results. Under- or over-estimates of ET could thereby affect the overall water balance, particularly during the summer months when ET demand is higher. In addition, use of the SCS CN approach represents an overall response of each HRU or cell and does not account for near-stream saturation associated with excess runoff.

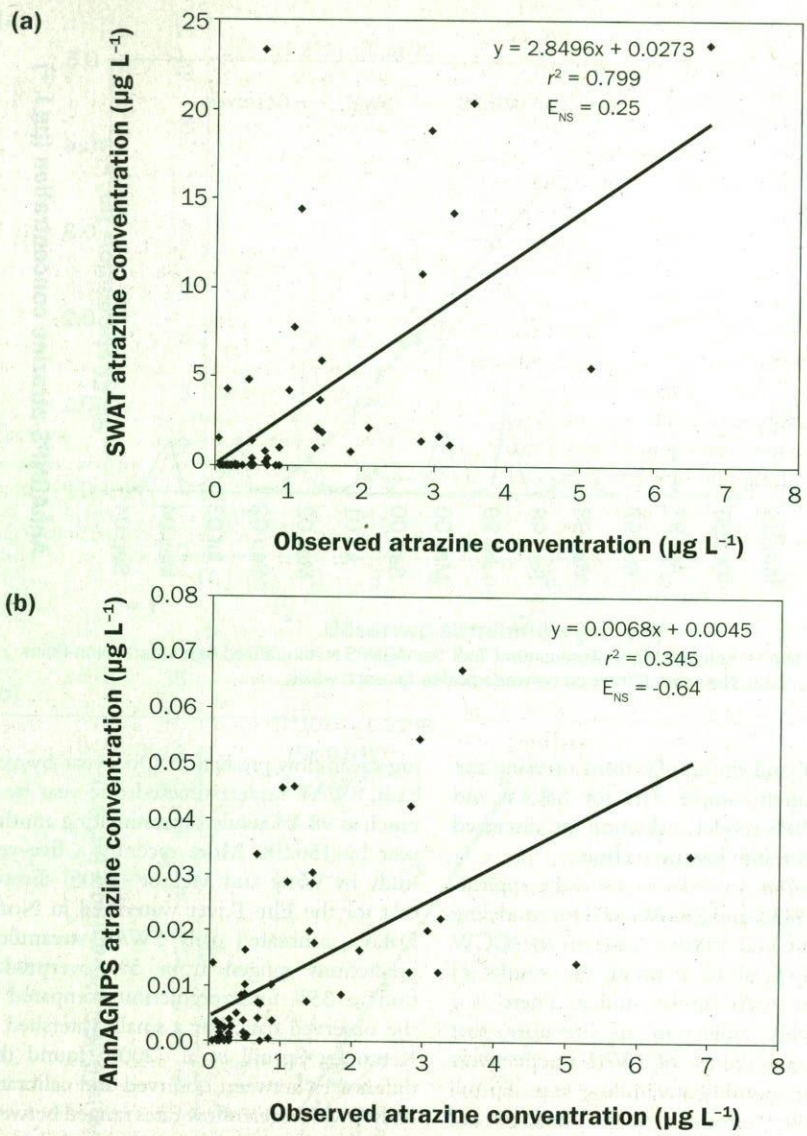
The availability of climate data also plays an important role in model performance and accuracy. Spatial variability of precipitation data represents one of the major limitations in large scale hydrologic modeling (Arnold et al. 1998). The subbasins in SWAT and cells in AnnAGNPS accessed data from the Garrett weather station located near the center of the watershed (figure 1), which may misrepresent the distribution of rainfall over the entire watershed and thus would

impact streamflow estimation. Upon closer inspection of the daily rainfall records for the Garrett weather station, spikes appeared in SWAT and AnnAGNPS simulated streamflow (due to a recorded rainfall event) with no response observed in the USGS discharge data at the watershed outlet. It is possible these were localized rainfall events not significantly contributing to total measured watershed streamflow. However, higher rainfall recorded at the Garrett weather station than what actually occurred would result in higher streamflow predictions (due to rainfall values at this station being distributed over the entire watershed). In addition, the streamflow simulation results for both SWAT and AnnAGNPS almost certainly would improve if additional stream gauge and weather station data were available.

Since neither SWAT nor AnnAGNPS was calibrated for streamflow (or atrazine transport) in this study, it was not surprising to see that atrazine losses were poorly simulated. However, it is important to understand that by applying the models uncalibrated, one can clearly ascertain the degree to which SWAT and AnnAGNPS differ in their estimates (while considering the fact that the pesticide components in both models were adapted from GLEAMS). In spite of having been developed from a common source, the difference in SWAT and AnnAGNPS atrazine loss predictions were substantial. On the other hand, both models captured the peak time periods of atrazine loss fairly well. Overestimation of atrazine loss by the SWAT model may be explained to a large degree by the overprediction of streamflow. However, this is not the case for AnnAGNPS where predicted atrazine concentrations were much lower than observed concentrations. Unfortunately, there is only one literature source on simulating atrazine loss using AnnAGNPS (Tagert 2006) and the atrazine predictions were very poor (r^2 = 0.095). The SWAT atrazine simulations would be improved with calibration, although, as noted in Larose et al. (2007), knowing the application dates plays a critical role in successfully modeling atrazine loss (especially if a runoff producing rainfall event occurs shortly after application). Future SWAT and AnnAGNPS simulation studies for the CCW and its subbasins will utilize much more detailed automated event-based water quality sampling data that is now being collected by the National Soil Erosion Research Laboratory.

Figure 9

1:1 plot of monthly Cedar Creek watershed observed versus (a) SWAT and (b) AnnAGNPS simulated atrazine concentrations (May 1996 to September 2004).



Notes: SWAT = Soil and Water Assessment Tool. AnnAGNPS = Annualized Agricultural Non-Point Source Pollution. Note the difference between scales for each y-axis.

Summary and Conclusions

As outlined in WAS project plan objectives, both SWAT and AnnAGNPS are to be utilized to conduct comparative evaluations of environmental benefits associated with different conservation management practices (USDA ARS 2004). In an attempt to accomplish specific CEAP tasks, we evaluated the application of the SWAT2005 and AnnAGNPS 3.3 models to estimate streamflow (1989 to 2005) and atrazine losses (1996 to 2004) in the 70,820 ha (174,925 ac) CCW. It was imperative to initially evaluate the performance of SWAT and AnnAGNPS for estimating streamflow and atrazine losses based on comparable input data sets and to apply both models without calibration, thus eliminating any uncertainties pertaining to the use of different optimized model parameter values.

Results of this study indicate that uncalibrated, the model performance statistics for SWAT were considerably better compared to

those of AnnAGNPS in estimating streamflow, e.g., E_{NS} values for SWAT ranged from 0.66 to 0.25, and E_{NS} values for AnnAGNPS ranged from 0.13 to -2.06 for mean monthly and annual streamflow, respectively. Neither the uncalibrated SWAT nor AnnAGNPS models adequately simulated monthly atrazine concentrations, with SWAT overpredicting concentrations by approximately 2.8 times and AnnAGNPS greatly underpredicting concentrations (i.e., simulated values were approximately 1/100 of measured). These results indicate that for the CCW modeled in this study, it would not be advisable to use either SWAT or AnnAGNPS in an uncalibrated mode for prediction of atrazine concentrations and losses. Finally, in evaluating the application of each model as an assessment tool in accomplishing the CEAP objectives, we also considered differences in technical and user documentation, model interfaces, input and output file descriptions, and model technical support. Use of SWAT was relatively straightforward and could be gleaned from an abundance of published materials, tutorial Internet sources, and extensive documentation. AnnAGNPS was more difficult to learn and understand, and documentation was limited. We also found that the AnnAGNPS software and interfaces were not at the level of refinement of those for SWAT. Thus, in considering all aspects of model applications involved in this study, the use of the SWAT model would be preferable to the AnnAGNPS model for simulating streamflow and atrazine concentration in the CCW. Further study is certainly warranted in evaluating the water quality application of each model when calibrated (at multiple scales) as well as quantifying model uncertainty, all of which are additional CEAP tasks. Ultimately, the results of this study imply that careful consideration must be given in the application of different hydrologic models being used in CEAP as a basis for accurately quantifying the environmental effects of soil conservation practices on off-site water quality.

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