AnnAGNPS Model Application for the Future Midwest Landscape Study

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Abstract: The Future Midwest Landscape (FML) project is part of the US Environmental Protection Agency (EPA)'s new Ecosystem Services Research Program, undertaken to examine the variety of ways in which landscapes that include crop lands, conservation areas, wetlands, lakes, and streams affect human well-being. The goal of the FML project is to quantify current and future ecosystem services across the region and to examine changes expected to occur as a result of the growing demand for biofuels. This study is one of several pilots taking place under the umbrella of the FML research project. In this study, the USDA Annualized Agricultural Non-Point Source Pollution (AnnAGNPS) model was applied to the East Fork Kaskaskia River watershed (289.3 km^2) located in the Kaskaskia River Basin within the Upper Mississippi River Basin in Illinois. The effect of different spatial resolutions on model performance was investigated by comparing the observed runoff with the AnnAGNPS simulated results. Alternative future scenarios such as meeting future biofuel target and evaluating conservation practices were also simulated and analyzed. All delineations of the study area (coarser to finer) produced satisfactory results in simulating monthly and annual runoff. However, the size of the delineation does impact the simulation results. Finer delineations better represented the actual landscape and captured small critical areas that would be homogenized in coarser delineation. Those small critical areas are important to target to achieve maximum environment benefit. Simulations of alternative future scenarios showed that as corn production increases to meet future biofuel needs, total nitrogen loss increases. Conservation practices are needed to reduce total nitrogen loss from the watershed. Simulations of split fertilizer application vs. one time application showed that split fertilizer application reduced nitrogen loss by about 20%. Additional conservation practices such as constructed wetland should be implemented for further nitrogen loss reduction. However, the model can not simulate the benefit would accrue through implementation of the wetland as run for this study. This study provides an important foundation for the larger FML region modeling effort by addressing challenging FML landscape modeling issues such as model selection, need for further model development, and spatial resolution.

Keywords: Future Midwest Landscape study — AnnAGNPS— watershed modeling— runoff, sediment, nitrogen and phosphorous simulation— Conservation practices.

The Future Midwest Landscape (FML) study is part of the US Environmental Protection Agency (EPA)'s new Ecosystem Services Research Program, undertaken to examine the variety of ways in which landscapes that include crop lands, conservation areas, wetlands, lakes, and streams affect human well-being. The goal of the FML project is to quantify current ecosystem services across the Midwest region and to examine changes expected to occur as a result of the growing demand for biofuels. Studies are also being conducted to seek alternative management options to mitigate degradation of ecosystem services caused by meeting future biofuel production goals through implementation of conservation programs.

Various conservation programs have been adopted to reduce sediment and pollutant losses from agricultural areas. Data on how conservation programs and practices are affecting ecosystem services are needed to help decision makers determine a cost/benefit ratio of conservation program implementation. Monitoring programs are often used to evaluate land management effects on non-point source pollution (Shih et al., 1994). Long-term monitoring better reflects multi-year climatic variability and helps assure that a range of events and conditions are covered (Stone et al., 2000; Borah et al., 2003). Because long-term monitoring is expensive and often limited by personnel and financial resources, short-term monitoring with complimentary simulation modeling may be used as an alternative for watershed evaluation.

Models such as the USDA-Agricultural Research Service (ARS) Annualized Agricultural Non-Point Source Pollution model (AnnAGNPS) (Bingner et al., 2003) have been developed to aid in the evaluation of watershed response to agricultural management practices. Through a continuous simulation of runoff, sediment and pollutant loadings from watersheds, conservation programs can be evaluated. Many studies have demonstrated AnnAGNPS's capability in predicting runoff, sediment and nutrient losses (Yuan et al., 2001; Yuan et al., 2003; Suttles et al., 2003; Baginska et al., 2003; Yuan et al., 2005; Shrestha et al., 2006; Licciardello et al., 2007). However, all those AnnAGNPS applications were performed at relatively small watersheds, for which the watershed can be delineated as detail as needed to account for the variation of landuse and soil as well as the need for implementing conservation practices while remaining computational feasible. The FML study area includes 12 states of the USA, and to apply AnnAGNPS at larger watersheds, the level of detail a model represents has to be optimized because of the limitation on computational power of a computer. Thus, there is a need to evaluate the level of spatial detail a model represents on the accuracy of model results.

The overall objectives of this study were: 1) to explore the applicability of the AnnAGNPS model on a large scale through exploring the model spatial resolutions and accuracy; 2) to apply the model to current and future landscape scenarios to look at potential runoff, sediment and nutrient loading changes caused by meeting the 2022 biofuel targets; 3) to apply the model to estimate the need for conservation practices and evaluate the benefits that could be realized if appropriate conservation practices were implemented.

Materials and Methods

AnnAGNPS model description

AnnAGNPS is an advanced simulation model developed by the USDA-ARS and NRCS to help evaluate watershed response to agricultural management practices (Bingner et al., 2003). It is a continuous simulation, daily time step, pollutant loading model designed to simulate water, sediment and chemical movement from agricultural watersheds (Bingner et al., 2003). The AnnAGNPS model evolved from the original single event AGNPS model (Young et al., 1989), but includes significantly more advanced features than AGNPS. The spatial variability of soils, land use, and topography within a watershed can be determined by dividing the watershed into many user-specified, homogeneous, drainage-area-determined cells. From individual cells, runoff, sediment and associated chemicals can be predicted from precipitation events that include rainfall, snowmelt and irrigation. AnnAGNPS simulates runoff, sediment, nutrients and pesticides leaving the land surface and being transported through the watershed channel system to the watershed outlet on a daily time step basis. The model routes the physical and chemical constituents from each AnnAGNPS cell into the stream network and finally to the watershed outlet and has the capability to identify the sources of pollutants at their origin and track them as they move through the watershed system. The complete suite of AnnAGNPS model, which include programs, pre and post-processors, technical documentation, and user manuals, are currently available at http://www.ars.usda.gov/Research/docs.htm?docid=5199 .

Required input parameters for application of the model include climate data, watershed physical information, and land management operations such as planting, fertilizer and pesticide applications, cultivation events, and harvesting (Figure 1). Daily climate information is required to account for temporal variation in weather and multiple climate files can be used to describe the spatial variability of weather. Output files can be produced to describe runoff, sediment and nutrient loadings on a daily, monthly, or yearly basis. Output information can be specified for any desired watershed source location such as specific cells, reaches, feedlots, or point sources. Additional information describing AnnAGNPS can be found in Bingner et al. (2003).

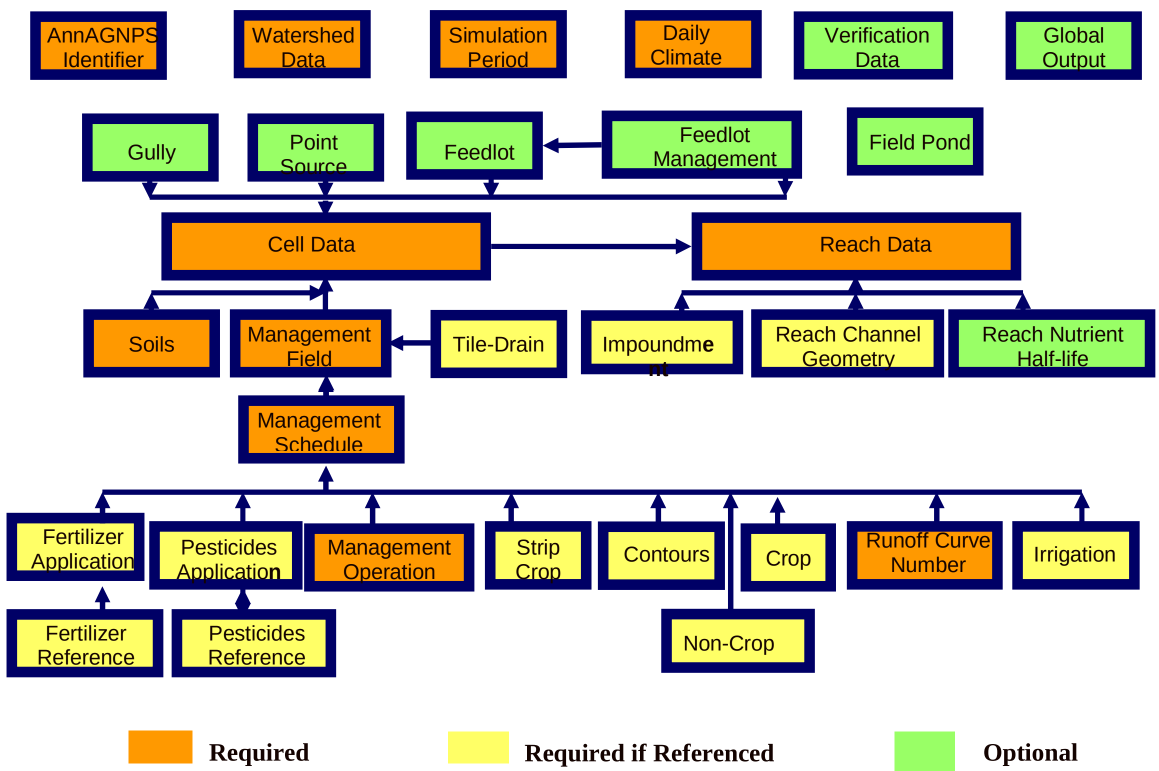

Figure 1. All available AnnAGNPS input data sections

USGS Stream Gauge Station 05592900 and Data Summary

The USGS stream gauge station 05592900 East Fork Kaskaskia River near Sandoval (38° 41' 20'' and 89° 06' 00'') is located in Marion County, Illinois and is a part of the Kaskaskia River Basin (figure 2) which directly drains to the Mississippi River. The USGS 05592900 drains 289.3 km^2, with elevations ranging from 142 m to 194 m above sea level. The study area has a dominant landuse of agriculture (61%), and major crops are corn/soybeans. The other landuse include forest (26%), urban (9%), wetland (3%) and barren (1%).

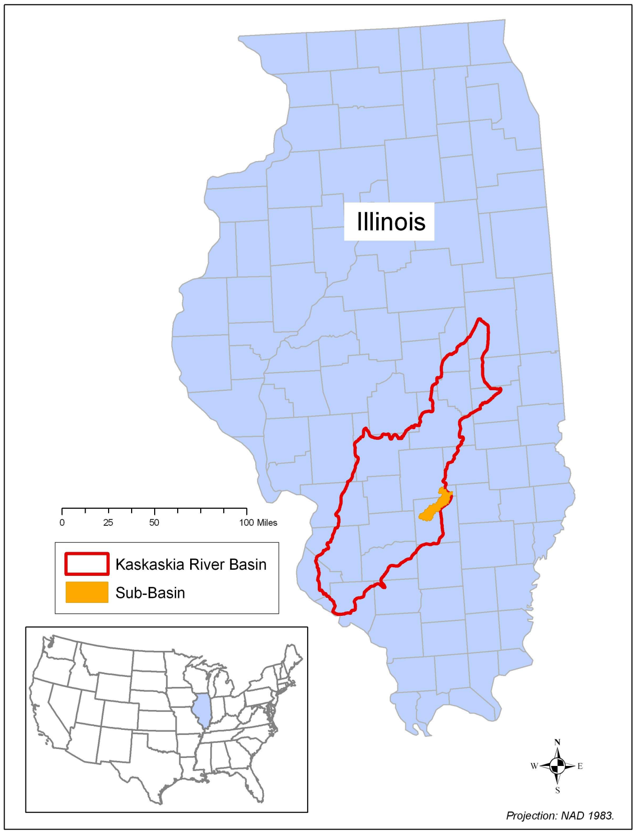

Figure 2. Location of the watershed.

Daily total stream discharge at station 05592900 was downloaded from the U. S. Geological Survey (USGS) National water Information System (NWIS). The station has a complete record from 1980 to 2006. The USGS monthly Water quality data were obtained from the USGS National Stream Quality accounting Network (NASQAN) for the period of 1985 to 1996. Water quality parameters measured include turbidity, total N, total P and dissolved P. Baseflow Filter Program (Arnold et al., 1995; Arnold and Allen, 1999) was used to separate baseflow from total streamflow. In order to estimate pollutant loadings, pollutant concentrations are needed for days when no sample result is available. Therefore, statistical regression methods available in the USGS (2004) LOADEST software were used to estimate pollutant concentrations and calculate monthly and annual pollutant loadings. Daily stream discharge together with LOADEST estimated pollutant loadings were used to evaluate the performance of AnnAGNPS.

AnnAGNPS input preparation

Various GIS data layers of the watershed are needed for the AnnAGNPS model. These include data on land surface topography, soils, land use, stream network, and climate. Using the GIS digital data layers of digital elevation model, soils, and land use, a majority of the large data input requirements of AnnAGNPS were developed by using a customized ArcView GIS interface (Bingner, 2003). Inputs developed from the ArcView GIS interface include physical information of the watershed and subwatershed (AnnAGNPS cell), such as boundary and size, land slope and slope direction, and channel reach (AnnAGNPS reach) descriptions. The ArcView GIS interface also assigned a soil and land-use type to each cell by using the generated subwatershed and the soil and land-use GIS data layers. Additional steps to provide the model with the necessary inputs included developing the soil layer attributes to supplement the soil spatial layer, establishing the different crop operation and management data, and providing channel hydraulic characteristics. Those inputs can be organized using the AnnAGNPS Input Editor (Bingner, 2003), a graphical user interface designed to aid users in selecting appropriate input parameters. Management information includes various field management operations such as planting, cultivation, fertilization, pesticides and harvesting, much of which can be obtained from RUSLE (Renard et al., 1997) databases or from actual activities implemented. Climate data for AnnAGNPS simulation can be historically measured, synthetically generated using the climate generator program (Johnson et al., 2000), or created through a combination of the two.

AnnAGNPS cell and reach parameters produced with the customized ArcView GIS interface depend on two stream network generation parameters which are Critical Source Area (CSA) and Minimum Source Channel Length (MSCL). Usually, the finer the delineation is, the better characterization of the variation of landuse and soil. To evaluate the cell sizes as subwatersheds on AnnAGNPS model hydrologic and water quality predictions, various combinations of CSA and MSCL were used for watershed delineation (table 1), and numbers of cells and reaches generated from each combination of CSA and MSCL values are also listed in table 1.

Table 1. Cell and reach numbers within the study area using different CSA and MSCL values

Type of delineation	*CSA parameter (hectares)	*MSCL parameter (meters)	Number of cells	Number of reaches
1	500	2000	48	20
2	200	500	188	76
3	100	200	367	148
4	20	40	1728	721

* CSA is Critical Source Area, and MSCL is the Minimum Source Channel Length. The total area for the watershed is 28707 ha.

Detained soil information was obtained from the USDA-NRCS Soil Survey Geographic (SSURGO) Database (Natural Resources Conservation Service, 2009). The USGS 2001 National Land Cover Database (NLCD) was selected as a basis for base year data layer. To differentiate crop type and rotation, the USDA National Agriculture Statistical Survey (NASS) Cropland Data Layer (CDL) was collected for years of 2004-2007 to expand the "Single cultivated crops" land use within the NLCD into multiple cropping types and rotational information. Base year landuse information for the study area is listed in table 2. Base year landuse information was also used for simulation of 1980 to 2006 for model evaluation. Landuses of different delineations for AnnAGNPS simulations are also listed in table 2. For crop management practices, RUSLE2 crop management database downloaded at http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm was used to develop the AnnAGNPS Management Schedule Data Section. Nitrogen and P applied for major crops corn, soybean and wheat are listed in table 3.

Model evaluation and simulations of alternative scenarios

The Nash-Sutcliffe coefficient of efficiency (Nash and Sutcliffe, 1970), the relative error, the Willmott index of agreement d (Willmott, 1984) and visual data analysis were used to evaluate the model's performance. The Nash-Sutcliffe coefficient of efficiency (NSE) ranges from minus infinity to one, with one indicating the model is perfect (Nash and Sutcliffe, 1970). The relative error (RE) is the ratio between the total difference and the total observed value, and it ranges from minus one to infinity. Zero indicates that there is no difference between model simulation and field observation. The smaller the absolute value of a relative error, the better performance of the model is. The index of agreement (d) was developed by Willmott (1984) as a standardized measure of the degree of model prediction error and varies between 0 and 1. A computed value of 1 indicates a perfect agreement between the measured and predicted values, and 0 indicates no agreement at all (Willmott, 1984). To address how resolution would affect the performance of the model, Simulation results from different delineations resulted from various combinations of CSA and MSCL values were compared with the observed data from the USGS gauging station. The Nash-Sutcliffe coefficient (NSE), relative error (RE) and the index of agreement d were computed for all delineations.

Table 2. Landuse defined by the final GIS landuse layer and by AnnAGNPS cells of different delineations.

Landuse Type	Landuse assigned to AnnAGNPS Cells (hectares)					Landuse from GIS Layer (hectares)	
	1	2	3	4			
Corn	0	0	1.4	14.6	0.1%	780.7	2.7%
Corn/Soybean	16582.8	18269.5	16529.9	15871.2	55.3%	11665.6	40.6%
Corn/Wheat	0	0	0	0	0.0%	80.7	0.3%
Soybean	0	0	0	130.3	0.5%	613.1	2.1%
Soybean/other	0	190.0	206.8	611.1	2.1%	1704.9	5.9%
Soybean/Wheat	0	0	160.4	277.5	1.0%	666.5	2.3%
Wheat	0	0	0	0	0.0%	95.9	0.3%
Grain	0	0	3.5	19.0	0.1%	239.9	0.8%
Pasture/Hay	0	43.7	0	244.3	0.9%	896.0	3.1%
Fallow/idle	0	292.4	264.1	603.1	2.1%	721.3	2.5%
Barren	0	0	8.5	0.6	0.0%	209.3	0.7%
Forest	12124.9	9687.0	11075.0	9862.4	34.4%	7555.6	26.3%
Developed	0	215.1	448.0	870.9	3.0%	2637.7	9.2%
Wetland	0	0	0	0	0.0%	11.3	0.0%
Flood plain	0	10.1	10.1	96.1	0.3%	693.4	2.4%
Open Water	0	0	0	106.6	0.4%	136.0	0.5%
Total	28707.7	28707.7	28707.7	28707.7	100%	28707.7	100%

Table 3. Fertilizer application for base year and biofuel target scenarios (All fertilizers were one time application and applied before planting)

Crop Name	Application Rate (kg/ha.)	
	Nitrogen (N)	Phosphorus (P_2O_5)
Corn	165.3	72.5
Soybean	4.5	17.4
Wheat	115.5	76.8

After AnnAGNPS simulations were evaluated based on the observed data from the USGS gauging station, AnnAGNPS simulation was performed to estimate runoff, sediment and nutrient transport in the watershed for the base year (BY) scenario. Results from this simulation were used as a baseline or a reference for additional simulations of biofuel target (BT) scenarios to meet the biofuel target as well as to evaluate the impact of biofuel production on water quality. The final scenario, multiple service (MS) simulations were performed to look for strategies to reduce nutrient loadings from the study area.

Results and Discussion

AnnAGNPS simulated monthly runoff and annual runoff from delineation 4 (CSA=20, MSCL=40), and the observed monthly runoff and annual runoff at the USGS gauging station are displayed in figures 3 and 4. Calculated NSE, RE and the index of agreement d are also shown in figures 3 and 4. AnnAGNPS simulated monthly runoff and annual runoff from other delineations (figures not shown) were also compared with the observed monthly runoff and annual runoff at the USGS gauging station, and the calculated NSE, RE and the index of agreement d are given in table 4. AnnAGNPS simulated annual total N and annual total N computed using the observed daily stream flow and observed monthly total N concentrations are displayed in figure 5, and AnnAGNPS simulated annual total P and annual total P computed using the observed daily stream flow and observed monthly total P concentrations are displayed in figure 6. NSE, RE and the index of agreement were not calculated because N and P concentration at a monthly interval is not good enough for model calibration and evaluation (Rode and Suhr, 2007). Results of BY simulation from different delineations are given in table 5. Results from alternative scenario simulations are given in table 6.

Table 4. Monthly and Annual runoff comparisons for different delineations

Type of delineation	Monthly comparison			Annual Comparison			Number of cells
	NSE	RE (%)	d	NSE	RE	d	
1	0.73	16	0.91	0.76	8	0.93	48
2	0.73	8	0.92	0.76	8	0.93	188
3	0.73	13	0.91	0.76	8	0.93	367
4	0.73	10	0.91	0.76	8	0.93	1728

Table 5. Annual average over the entire watershed based on a 30-year simulation for BY scenario

Type of delineation	Runoff (mm/year)	Sediment (Tons/ha/yr)	Total N (kg/ha/yr)	Total P (kg/ha/yr)	Number of cells
1	184.5	1.35	11.3	0.33	48
2	201.2	1.34	12.8	0.41	188
3	190.6	1.02	11.3	0.38	367
4	195.9	0.71	11.2	0.36	1728

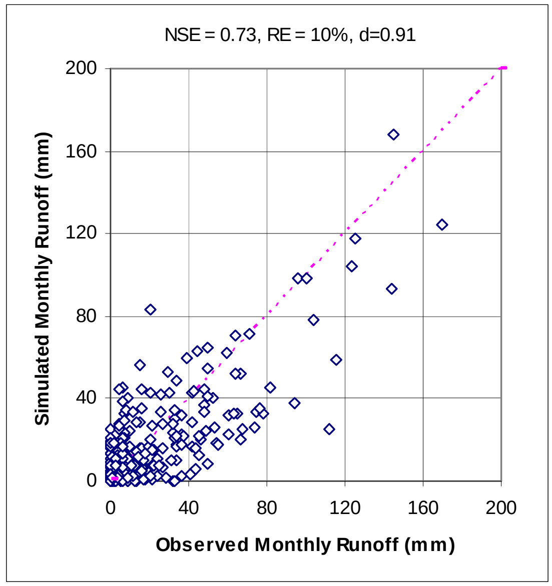

Figure 3. Comparison of observed and simulated monthly runoff for the period of 1980 to 2006.

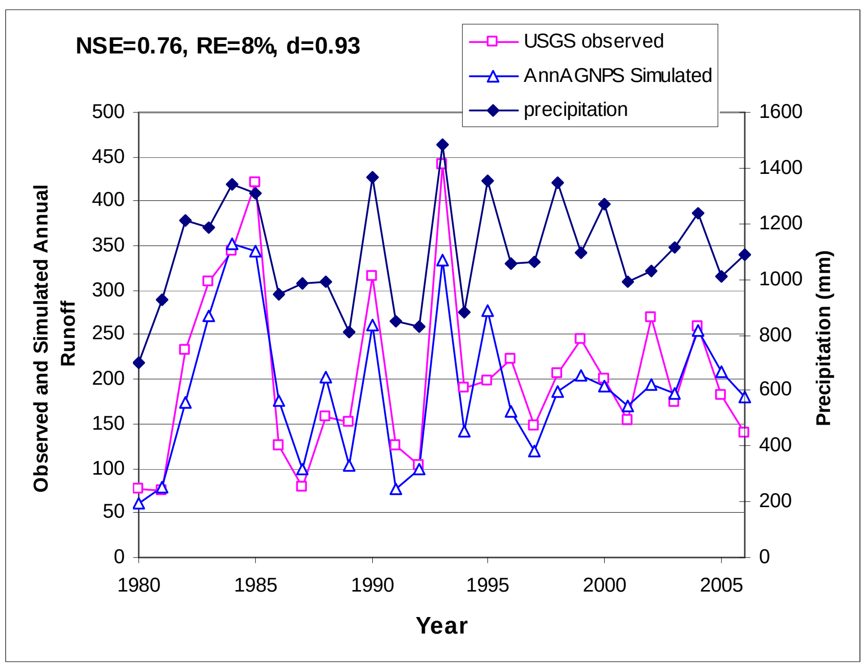

Figure 4. Comparison of observed and simulated Annual runoff from the USGS gauging station

Model evaluation

Comparisons between the simulated and observed monthly runoff at the USGS gauging station produced a NSE of 0.73, RE of 0.1 and index of agreement d of 0.91 (figure 3). Comparisons between the simulated and observed annual runoff at the USGS gauging station produced a NSE of 0.76, RE of 0.1 and index of agreement d of 0.93 (figure 4). Moriasi et al. (2007) thoroughly reviewed literature on model application and recommended model evaluation methods, and they concluded that model simulation can be judged as satisfactory if NSE is greater than 0.50; very good if NSE is greater than 0.75 for runoff. Because of the overall good model performance as values of NSE, RE and index of agreement d shown in figures 3 and 4, no further model calibration was performed. This analysis reflects the capability of AnnAGNPS to estimate runoff that would be typical for ungauged watersheds, where data for calibration are usually not available.

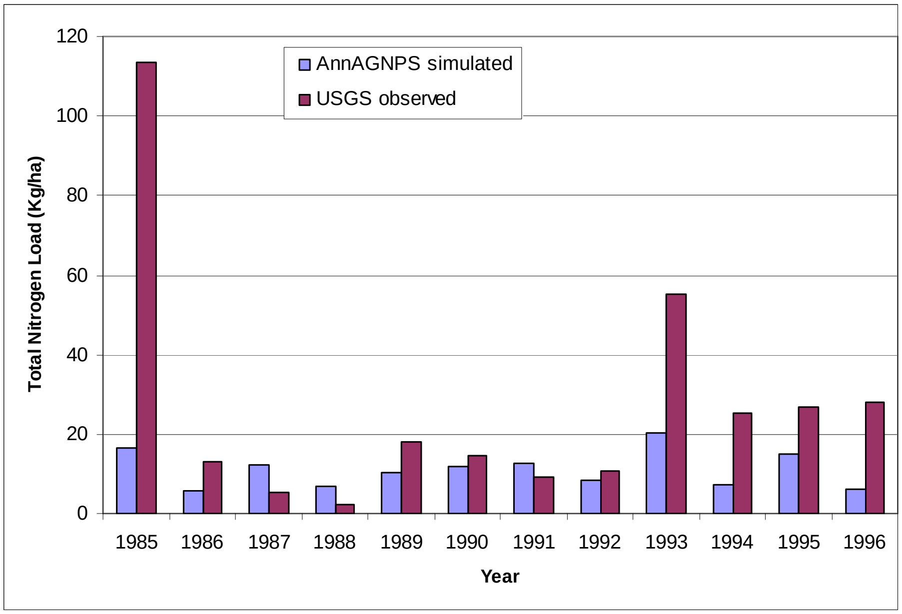

Figure 5. Comparison of observed and simulated total nitrogen load from the USGS gauging station

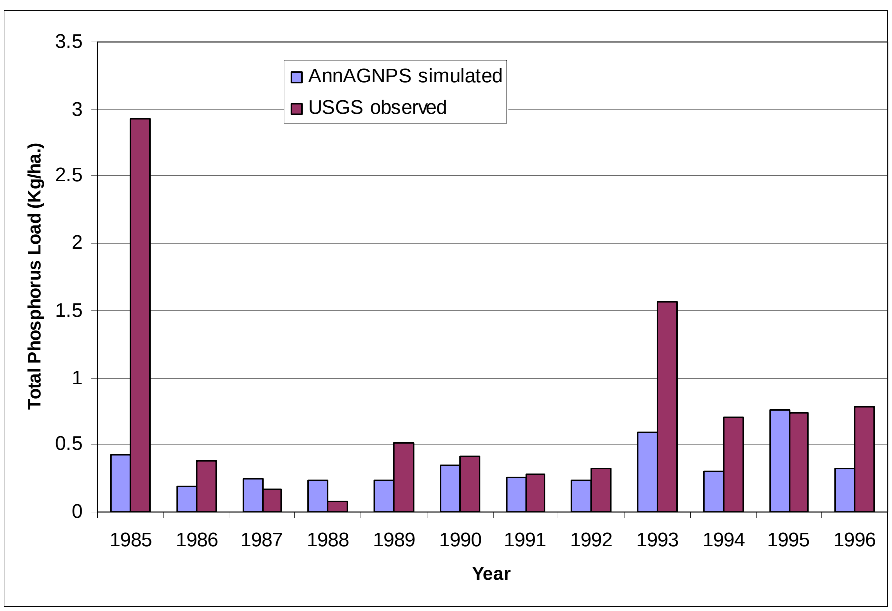

Figure 6. Comparison of observed and simulated total phosphorus load from the USGS gauging station

Comparisons of simulated monthly and annual runoff from other delineations (1, 2, and 3; table 1) with observed monthly and annual runoff all produced satisfactory results (table 4).

No calibration and validation was performed for total N and P because of uncertainties with the monthly water quality data (Rode and Suhr, 2007). Except the year of 1985 and 1993, simulated total N generally matches observed total N (figure 5). This is also true for total P (figure 6). The year of 1985 and 1993 had the highest observed flow (figure 4) which determined the high total N and P loading based on the LOADEST program. However, 116 kg/ha in 1985 is high comparing with the fertilizer application (table 3).

Watershed simulation of BY, BT and MS Scenarios

The 30-year simulation of BY with AnnAGNPS produced an annual average runoff of 195.9 mm, annual average sediment loss of 0.71 Mg/ha, annual average total N loss of 11.3 kg/ha, and annual average total P loss of 0.33 kg/ha over the entire watershed (table 5). Although all delineations produced satisfactory results for annual and monthly runoff simulation (table 4), results of base year simulation from other delineations (table 5) showed that the size of cells does impact the prediction results. The prediction results are impacted by how different delineations can accurately represent the actual landuse (table 2). Delineation 4 represented the actual landuse more closely than the other three delineations (table 2). However, the differences still exist between the real landuse and the landuse represented by delineation 4. For example, small percentage of landuse such as corn/wheat can not be captured by delineation 4. Further finer delineations would be possible to capture more actual landuse, but it would require significant more computational time. Delineation 2 produced the most amount of runoff because the delineation 2 had the most amount of cropland and the least amount of forest land (table 2). In contrast, delineation 1 produced the least amount of runoff because the delineation 1 had the most amount of forest land (table 2). Delineation 2 also produced the most amount of total N and total P loss because of the most amount of cropland it represented.

As shown in table 6, as corn production increases, total N loss increases. Converting all soybean production (130.3 ha.) to corn (BT_1) would result in 1% increase of total N; Converting one third of corn/soybean rotation (5290.4 ha.) to monoculture corn would result in 33% increase of total N loss. Total N loss would be more than doubled if converting all corn/soybean rotation (15871.2 ha.) to monoculture corn (BT_4 in table 6) comparing with the base year total N loss. From BT_1 to BT_5, corn production increases, so does the total N loss. BT_5 had a total N loss of 25.7 kg/ha. Because of the high total N loss resulting from the increases of corn production, additional management options must be sought to reduce total N loss from the study area. Simulation results (table 6) show that total N loss can be reduced by 20% by split N application (comparing MS_1 with BT_5).

Conclusions

AnnAGNPS runoff simulations of different delineations of watershed all produced satisfactory results comparing with the USGS observed runoff. However, cell size from different delineations does impact simulation results. The watershed should be delineated as detail as possible within the computation power because finer delineations better represented the actual landscape and captured small critical areas that would be homogenized in coarser delineation. Those small critical areas are important to target to achieve maximum environment benefit. As corn production increases to meet future biofuel needs, total nitrogen loss increases. Simulations of split fertilizer application vs. one time application showed that split fertilizer application could reduce nitrogen loss by about 20%. The model needs to be further enhanced to simulate additional conservation practices such as constructed wetland and riparian buffer for nitrogen loss reduction.

Table 6. Summary of simulation results for alternative BT scenarios (results reported in the table are based on delineation 4).

Scenarios		Runoff Volume [mm]	Total Sediment Loading [T/ha/yr]	Total Nitrogen Loading [Kg/ha/yr]	Total Phosphorus Loading [Kg/ha/yr]
ID	Description				
BY	Base Year	195.9	0.71	11.2	0.36
BT_1	All soybean (130.3 ha.) represented 0.5% of the entire study area by AnnAGNPS converted to corn	196.0	0.71	11.3	0.36
BT_2	1/3 of corn/soybean rotation (5290.4 ha.) represented 18.4% of the entire study area by AnnAGNPS converted to monoculture corn	196.2	0.65	16.1	0.29
BT_3	2/3 of corn/soybean rotation (10580.8 ha.) represented 36.8% of the entire study area by AnnAGNPS converted to monoculture corn	196.4	0.61	20.8	0.23
BT_4	All corn/soybean rotation (15871.2 ha.) represented 55.3% of the entire study area by AnnAGNPS converted to monoculture corn	196.6	0.49	24.9	0.17
BT_5	All fallow/idle (603.1 ha.) represented 2.1% of the entire study area by AnnAGNPS converted to corn	197.4	0.53	25.7	0.18
MS_1	Split fertilizer application	197.4	0.60	21.1	0.20

Notice: Although this work was reviewed by USEPA and approved for publication, it may not necessarily reflect official Agency policy. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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