

# PHOSPHORUS COMPONENT IN ANNAGNPS

Y. Yuan, R. L. Bingner, F. D. Theurer, R. A. Rebich, P. A. Moore

**ABSTRACT.** *The USDA Annualized Agricultural Non-Point Source Pollution model (AnnAGNPS) has been developed to aid in evaluation of watershed response to agricultural management practices. Previous studies have demonstrated the capability of the model to simulate runoff and sediment, but not phosphorus (P). The main purpose of this article is to evaluate the performance of AnnAGNPS on P simulation using comparisons with measurements from the Deep Hollow watershed of the Mississippi Delta Management Systems Evaluation Area (MDMSEA) project. A sensitivity analysis was performed to identify input parameters whose impact is the greatest on P yields. Sensitivity analysis results indicate that the most sensitive variables of those selected are initial soil P contents, P application rate, and plant P uptake. AnnAGNPS simulations of dissolved P yield do not agree well with observed dissolved P yield (Nash–Sutcliffe coefficient of efficiency of 0.34,  $R^2$  of 0.51, and slope of 0.24); however, AnnAGNPS simulations of total P yield agree well with observed total P yield (Nash–Sutcliffe coefficient of efficiency of 0.85,  $R^2$  of 0.88, and slope of 0.83). The difference in dissolved P yield may be attributed to limitations in model simulation of P processes. Uncertainties in input parameter selections also affect the model's performance.*

**Keywords.** *AnnAGNPS, Model calibration and validation, Phosphorus simulation, Sensitivity analysis, Watershed modeling.*

Phosphorus (P) is an essential nutrient for all life forms. Research has shown that a deficiency of P in soils limits crop production (Maples and Heogh, 1973), whereas higher levels of P in soils often lead to loss via surface runoff (Sharpley, 1995; Sharpley et al., 1996; Pote et al., 1996, 1999). An abundance of P in fresh water will lead to algal blooms, which have many detrimental effects on natural ecosystems. Odors and discoloration caused by decay of algae interfere with recreational and aesthetic water use, algae blooms shade submerged aquatic vegetation and reduce or eliminate photosynthesis and productivity, and algae may clog water treatment plant filters (Sharpley et al., 1994).

Phosphorus does not occur as abundantly as nitrogen (N) in soil. Total P in surface soils ranges from 0.005% to 0.15% (Halvin et al., 1999). Phosphorus is not as mobile as N, although it can be leached, particularly in sandy soils. Phosphorus is generally strongly adsorbed by soil. The P adsorbed by sediment particles may be transported in overland flow. Phosphorus can also be dissolved as orthophosphate in the water and transported by surface and sub-surface flow (Smith, 1990). Surface runoff is the primary mechanism by which P is exported from most catchments (Sharpley and Syers, 1979).

Simulation of P processes at a watershed scale has been very challenging because of complexities and uncertainties related to the processes. A complete understanding of various P pools, including their chemical, physical, and biological interactions in the soil profile, is essential for a full description of the P cycle in soils and plants (Jones et al., 1984). A model based on mathematical descriptions of fundamental chemical, physical, and biological mechanisms of soil P behavior would be ideal for P modeling.

Generally, there are six pools of P available in the soil profile: three pools each in organic P and inorganic P (fig. 1). Phosphorus may be added to the soil by inorganic fertilizer, organic fertilizer (manure), or residue application. Phosphorus is removed from the soil by plant uptake, runoff, soil erosion, and leaching. The solution inorganic P in soil supplies plant growth. When the plant is mature, plant residue (or manure residue) is added back to the soil in the fresh organic P pool (Jones et al., 1984). Recent studies have shown that a small portion of manure residue is soluble P, which is easily carried away by surface runoff (Sharpley and Moyer, 2000; Delaune et al., 2004). Transformations of crop residue into other forms are very complicated and limited by many factors in soil. For inorganic P, the labile pool (solution) equilibrates rapidly, within days to weeks, with the active pool, but the active pool equilibrates slowly with the stable pool (Jones et al., 1984).

Decomposition is the breakdown of fresh organic residue into simpler organic components. Mineralization is the microbial conversion of plant-unavailable organic P to plant-available inorganic P, while immobilization is the reverse process (fig. 1). The decomposition and mineralization processes are controlled by the carbon-nitrogen (C:N) ratio and carbon-phosphorus (C:P) ratio in the residue, soil temperature, soil water content, soil pH value, cultivation intensity, P fertilization, and composition of crop residues. Studies (Havlin et al., 1999) have shown that mineralization occurs most readily when the C:P ratio is less than 200:1, and immobilization occurs when the ratio is greater than 300:1.

---

Article was submitted for review in July 2004; approved for publication by the Soil & Water Division of ASABE in October 2005.

The authors are **Yongping Yuan**, ASABE Member Engineer, Postdoctoral Research Scientist, and **Ronald L. Bingner**, ASABE Member Engineer, Agricultural Engineer, USDA–ARS National Sedimentation Laboratory, Oxford, Mississippi; **Fred D. Theurer**, ASABE Member Engineer, Agricultural Engineer, USDA–NRCS National Water and Climate Center, Beltsville, Maryland; **Richard A. Rebich**, Hydrologist, USGS Water Resource Division, Pearl, Mississippi; and **Philip A. Moore**, Soil Scientist, USDA–ARS Poultry Production and Product Safety Research Unit, Fayetteville, Arkansas. **Corresponding author:** Yongping Yuan, USDA–ARS–NSL, P.O. Box 1157, Oxford, MS 38655; phone: 662-232-2913; fax 662-281-5706; e-mail: yyuan@msa-oxford.ars.usda.gov.

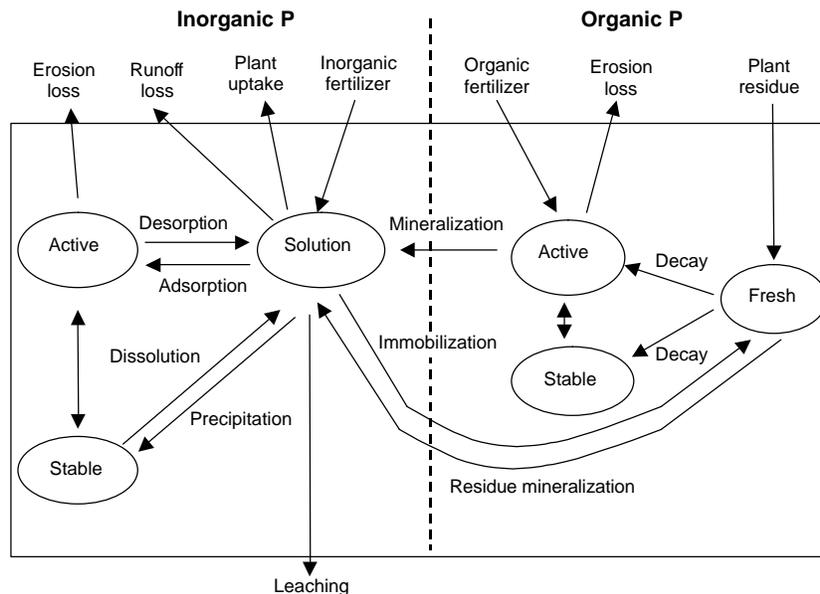


Figure 1. A simplification of P processes in soil (Havlin et al., 1999).

Mineralization increases with the total organic P content; therefore, the P mineralization decreases with continued cultivation because the organic P decreases.

Adsorption refers to the binding of P to soil particles. Adsorbed P is bound only to the surface of minerals. The solution P is usually in a form of  $\text{HPO}_4^{-2}$  or  $\text{H}_2\text{PO}_4^{-}$ , which attaches strongly to positively charged minerals. Because minerals become more positively charged at lower pH, more phosphate is adsorbed at lower soil pH values, whereas more phosphate is available for plant uptake at higher soil pH values (Havlin et al., 1999). In addition, as more P fertilizer is added, more P is available for plant uptake. Phosphorus adsorption is generally increased with increased temperature (Barrow and Shaw, 1975; Jones and Jacobsen, 2002). The release of soil-adsorbed P is called desorption, which is the opposite of adsorption. As soil pH value affects adsorption, increasing the soil pH value increases the P concentration in soil solution. However, the desorption process depends on the complex nature of adsorption. Release of adsorbed P may be extremely slow or impossible depending on the formation structure of the adsorption (Havlin et al., 1999).

Precipitation is the process through which soluble P is converted to mineral P. The solubility of P minerals controls the available P concentrations. Calcium phosphate is the dominant mineral in neutral to high pH soils. There are numerous forms of calcium phosphate in soil, ranging from very soluble to very insoluble. Usually, after fertilizing with P in a neutral or high pH soil, calcium phosphate forms in order from high to low solubility, and the time for each mineral to form is highly dependent on temperature (Jones and Jacobsen, 2002). Aluminum phosphate and ferric phosphate are the dominant minerals in soils with pH levels below 6.5 (Havlin et al., 1999). Unlike calcium phosphate, the solubility of these minerals decreases at lower pH. Therefore, P is most available around pH 6.5 (Havlin et al., 1999).

The USDA-ARS Annualized Agricultural Non-Point Source Pollution model (AnnAGNPS) (Bingner et al., 2003) has been developed to facilitate assessment of watershed response to agricultural management practices. Through a

continuous simulation of runoff, sediment, and pollutant yields from watersheds, best management practices (BMPs) can be evaluated with AnnAGNPS. Previous studies have been performed to evaluate AnnAGNPS performance on runoff, sediment, and nitrogen (Yuan et al., 2001, 2003; Suttles et al., 2003; Baginska et al., 2003). AnnAGNPS performance on phosphorus (P) simulation was also evaluated in a Coastal Plain agricultural watershed in Georgia (Suttles et al., 2003) and a small experiment catchment in the Sidney region of Australia (Baginska et al., 2003).

Information on total P presented by Suttles et al. (2003) was limited to annual average. Their study showed that AnnAGNPS underpredicted total P in the upper part of the watershed because of poor landcover discretization, which caused an underestimation of agricultural cropland. In contrast, AnnAGNPS overpredicted total P in the lower part of the watershed where extensive riparian forests and forest wetland areas existed. The model did not have a riparian buffer function; thus, nonpoint-source pollution attenuation by the riparian buffer was not simulated (Suttles et al., 2003). In comparison, the evaluation of AnnAGNPS nutrient simulation by Baginska et al. (2003) was limited to an Australian catchment where a different local condition exists; therefore, this study's results may not be applicable to locations in the U.S. The limitations of these two studies indicate that more studies should be conducted to evaluate AnnAGNPS performance on P simulation.

The objective of this article is to introduce the P component of AnnAGNPS and evaluate the performance of AnnAGNPS on P simulation using comparisons with measurements from the Deep Hollow (DH) watershed of the Mississippi Delta Management Systems Evaluation Area (MDMSEA) project.

## METHODS AND PROCEDURES

### ANNAGNPS MODEL OF PHOSPHORUS PROCESSES

AnnAGNPS is a continuous simulation, daily time step, pollutant loading model that includes significantly more

advanced features than AGNPS (Young et al., 1989). Because of the continuous nature of AnnAGNPS, daily climate information, which includes daily precipitation, maximum and minimum temperatures, dewpoint temperature, sky cover, and wind speed, is needed to account for temporal weather variations. The spatial variability of soils, land use, and topography within a watershed is accounted for by dividing the watershed into user-specified, homogeneous, drainage-area-determined cells. AnnAGNPS simulates runoff, sediment, nutrients, and pesticides leaving the land surface and being transported through their watershed channel system to the watershed outlet.

In general, the chemical component in AnnAGNPS exists in two phases: dissolved (solution) in the surface runoff, and attached (adsorbed) to clay-size particles resulting from sheet and rill erosion carried into the stream system by the surface runoff. To simulate P yield, daily soil mass balances of P are maintained for each computational area (AnnAGNPS cell). The mass balance portion of the model adapts the P model in EPIC (Sharpley et al., 1984; Sharpley and Williams, 1990).

Phosphorus is partitioned into inorganic P and organic P, and a separate mass balance is maintained for each. Inorganic P is further broken down into three classes: (1) labile P (P readily available for plant uptake), (2) active P (P that is more or less reversibly adsorbed to the soil), and (3) stable P (adsorbed P that is "fixed" as discrete insoluble P minerals or relatively irreversibly chemisorbed to the soil adsorption complex). The model simulates the effect of P adsorption, which controls P availability to plant uptake and runoff loss, and P movements between the three classes. Sediment-attached P is estimated from soil erosion, is assumed to be associated with the clay-size fraction of the soil, and consists of both organic and inorganic P. Major processes considered are residue decomposition and mineralization, fertilizer application, plant uptake, and runoff and erosion losses. Plant uptake of P is modeled through a simple crop growth stage index specified by either the user or the model (Bingner et al., 2003).

Comparison of soil P processes (fig. 1) with the P processes simulated in AnnAGNPS (fig. 2) demonstrates that AnnAGNPS maintains only one organic P pool. AnnAGNPS simulates the reaction between solution pool and active pool and between active pool and stable pool, but not between

solution pool and stable pool. Precipitation, dissolution, immobilization, and leaching are not simulated.

Phosphorus losses from AnnAGNPS cell are transported to AnnAGNPS reach (no P transport between AnnAGNPS cells). Phosphorus in the reach is re-equilibrated between dissolved P and sediment-attached P during transport to the watershed outlet.

#### STUDY WATERSHED AND MONITORING INFORMATION

Data collected at the Deep Hollow (DH) watershed were available for this study. The DH watershed, which is located in Leflore County, Mississippi, is one of three watersheds studied in the Mississippi Delta Management Systems Evaluation Area project (MDMSEA). The MDMSEA project seeks to develop and assess alternative innovative farming systems for improved water quality and ecology in the Mississippi Delta. The main crops grown in the DH watershed are cotton and soybeans. The watershed contains 15 soil series varying in texture from loamy sand to silty clay, but three series, which are Dundee (fine-silty), Forestdale (fine), and Dowling (very fine), cover 80% of the total area (Yuan et al., 2001). Detailed records of agricultural operations including tillage, planting, harvesting, fertilization, cover crop planting, and pesticide usages have been maintained since 1996 (Yuan et al., 2001). For cotton fields, fertilizer was applied with equipment that "knives in" the material at a depth of 100 mm without further mixing with soil (table 1). Fertilizer was not applied on the soybean fields or during the winter wheat cover crop growth period. A field, defined as an area that has the same management operations, can be further delineated into several AnnAGNPS cells based on topography and soils.

In 1995-1996, the U.S. Geological Survey (USGS) installed a gauging station to monitor runoff, sediment yield, and nutrient and pesticides loadings at one of the inlets to the DH Lake (Yuan et al., 2001). Data collected at the outlet of this monitoring site were used for this study. The drainage area for the monitored site was 11 ha. Runoff was monitored using a critical flow flume. Composite samples were taken during rainfall events for sediment and nutrient analyses. Rainfall was monitored at the flume using a tipping-bucket rain gauge.

Total P and orthophosphate concentrations were determined for composite samples, whereas total P and ortho-

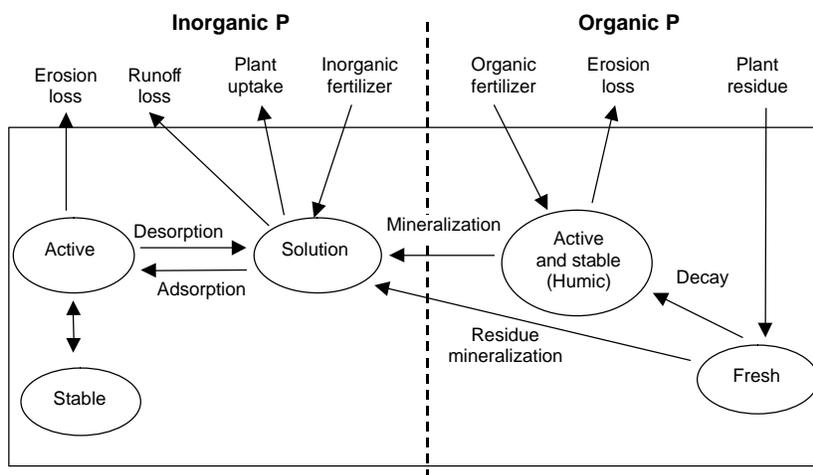


Figure 2. Phosphorus processes simulated in AnnAGNPS.

**Table 1. Fertilizer application and reference information for simulation period. Fertilizer was applied with equipment that “knives in” the material at the depth of 100 mm without completely mixing with soil.**

Application Date	Fertilizer Information			
	Fertilizer Type	Application Rate (kg ha <sup>-1</sup> )	Mineralizable N (%)	Mineralizable P (%)
29 Apr. 1996	Urea-ammonium nitrate	100.8	32	0
13 May 1997	Anhydrous ammonia	107.2	82	0
18 May 1997	Urea-ammonium nitrate	33.6	32	0
9 Apr. 1998	Urea-ammonium nitrate	115.7	32	0
6 Oct. 1998	Phosphate 0-30-0	72.9	0	30
30 Apr. 1999	Urea-ammonium nitrate	102.2	32	0

phosphate mass loads were calculated using sample concentration and total volume from each runoff event. Dissolved P yield for each rainfall event was calculated using the P fraction of orthophosphate.

**INPUT DATA PREPARATION**

Established input files for model runoff and sediment evaluation, including watershed topography, soil type, climate data, and actual field operations and management (Yuan et al., 2001), were modified for this study. Yuan et al. (2001) has described the development of input information for AnnAGNPS simulations, and complete information on input file preparation can be found at the AGNPS website ([www.ars.usda.gov/Research/docs.htm?docid=5199](http://www.ars.usda.gov/Research/docs.htm?docid=5199)). The subwatersheds (AnnAGNPS cells), land use, soil information, and stream network for the monitoring site are presented in figure 3 and table 2. Based on this input file, fertilizer application was created according to actual field records (table 1). Fertilizer application reference information was set up based on AnnAGNPS guidelines and databases.

Detailed soil information was obtained from the Soil Survey Geographic (SSURGO) Database (NRCS, 2005). SSURGO provides most of soil parameters needed for AnnAGNPS simulation, such as soil texture, erosive factor, hydraulic properties, pH value, and organic matter. However, information on soil nutrient contents was not available from this database.

Determining initial soil nutrient values needed for this study was a very difficult task. Soil testing is one way of gaining soil nutrient values. Location, timing, and method of

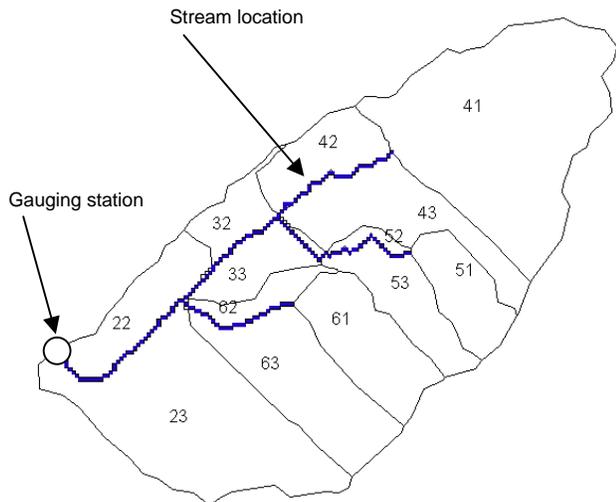
sampling impact the nutrient values that would be obtained from soil testing (Self and Soltanpour, 2004). However, soil testing may not be a feasible way to gain soil nutrient values at a watershed scale because of limited resources. First, a watershed may include thousands of fields. Second, each field has different soil types and field managements. Third, nutrient level may vary from one spot to another within a field. Consequently, obtaining representative values for the watershed is challenging. Therefore, a sensitivity analysis is needed to identify how initial soil nutrient levels impact the simulation result. Literature searches have found that total P in surface soils ranges from 50 to 1500 mg kg<sup>-1</sup> and decreases with depth (Halvin et al., 1999). Organic P typically varies between 15% and 90% of the total P in soils. Thus, as base values for sensitivity analysis, initial soil organic P content was set to 500 mg kg<sup>-1</sup> for the top layer and 250 mg kg<sup>-1</sup> for the subsequent layers, and initial soil inorganic P content was set to 250 mg kg<sup>-1</sup> for all soil layers (table 3).

**Table 2. Land use and soil information of subwatersheds (cells) in the monitoring site (Yuan et al., 2001).**

Cell	Area (ha)	Soil Type	Hydrologic Soil Group	Land Use
22	0.62	284B Tensas silty clay loam	D	Soybeans
23	2.2	284B Tensas silty clay loam	D	Cotton
32	0.32	284B Tensas silty clay loam	D	Soybeans
33	0.39	284B Tensas silty clay loam	D	Soybeans
41	2.85	178A Dundee loam	C	Cotton
42	0.53	284B Tensas silty clay loam	D	Soybeans
43	0.94	284B Tensas silty clay loam	D	Cotton
51	0.53	164B Dubbs very fine sandy loam	B	Cotton
52	0.12	12A Alligator clay	D	Cotton
53	0.59	178A Dundee loam	C	Cotton
61	0.81	178A Dundee loam	C	Cotton
62	0.24	12A Alligator clay	C	Soybeans
63	1.15	284B Tensas silty clay loam	D	Cotton

**Table 3. Input parameters considered in the sensitivity analysis.**

Input Parameter	Values		
	A	B (base value)	C
P mixing code	YES	NO	
P application rate (kg ha <sup>-1</sup> )		72.9	353.0
Initial soil P content in the top soil layer (mg kg <sup>-1</sup> )			
Organic P	50	500	
Inorganic P	25	250	
Plant P uptake (ratio)			
Cotton	0.0003	0.0023	0.0043
Soybean	0.0075	0.0095	0.0115
Winter wheat	0.0005	0.0025	0.0045



**Figure 3. Subwatersheds (cells) and stream network in the monitoring site (Yuan et al., 2001).**

Detailed crop information such as crop yield, growth period, and amount of residue produced was imported from the RUSLE crop database (Renard et al., 1997). However, plant nutrient uptake information was not available from this database. Determining plant nutrient uptake for this study was another challenge because information on plant nutrient uptake is usually not available at a watershed scale. AnnAGNPS requires plant nutrient uptake through the crop data section. Plant nutrient uptake is expressed as a ratio (weight of P to weight of harvest unit). AnnAGNPS converts the plant P uptake value into a daily value based on crop growth stage. To gain information on plant nutrient uptake, an intensive literature search was conducted. Research on various cottons in Alabama and Louisiana showed that an average of 58 kg N ha<sup>-1</sup> and 9.1 kg P ha<sup>-1</sup> were removed when seed cotton was harvested under optimum fertilization condition (Mullins and Burmester, 1990; Bassett et al., 1970; Boquet and Breitenbeck, 2000). Thus, cotton N uptake was set at 0.017 and cotton P uptake was set at 0.0023 (Mullins and Burmester, 1990; Boquet and Breitenbeck, 2000). Similarly, soybean N uptake was set at 0.092 and soybean P uptake was set at 0.0095 (Flannery, 1986), while winter wheat N uptake was set at 0.022 and winter wheat P uptake was set at 0.0025 (Baethgen and Alley, 1989). Taking these as base values, a sensitivity analysis is also needed to identify how plant P uptake impacts the simulation result.

#### SENSITIVITY ANALYSIS

The purpose of a sensitivity analysis is to investigate input parameters, especially those that are difficult to measure or whose expected effect on model output is unclear (Lane and Ferreira, 1980). The purpose of this sensitivity analysis was to evaluate if calibration is possible with user modification of selected input parameters given the use of standard NRCS input parameters of soil and crop.

In a study of Water Erosion Prediction Project (WEPP) model sensitivity, Nearing et al. (1990) used a single value to represent sensitivity of the output parameter over the entire range of the input parameter tested. The sensitivity index (*S*) described by equation 1 (Nearing et al., 1990) was selected for sensitivity testing of the AnnAGNPS P yield component:

$$S = \frac{\frac{O_2 - O_1}{O_{12}}}{\frac{I_2 - I_1}{I_{12}}} \quad (1)$$

where

$I_1, I_2$  = least and greatest values of input used, respectively

$I_{12}$  = average of  $I_1$  and  $I_2$

$O_1, O_2$  = output values for the two input values

$O_{12}$  = average of  $O_1$  and  $O_2$ .

The parameter *S* represents the ratio of a relative normalized change in output to a normalized change in input. An index of one indicates a one-to-one relationship between the input and the output, such that a 1% relative change in the input leads to a 1% relative change in the output. A negative value indicates that input and output are inversely related. The greater the absolute value of the index, the greater the impact that an input parameter has on a particular output. Because it is dimensionless, *S* provides a basis for comparison among input variables.

Soil nutrient content and plant nutrient uptake are difficult parameters to measure. Because the impact of fertilizer application on nutrient losses is a public concern, sensitivity analysis was performed for inorganic fertilizer application. The study investigated the sensitivity of the P output to changes in the following input parameters: (1) P mixing code, (2) P application rate, (3) initial P content in the top soil layer, and (4) plant P uptake. Phosphorus mixing code reflects how well the applied fertilizer is mixed within the depth of application. If the P mixing code is set to "YES," then applied fertilizer is well mixed within the depth of application. If the P mixing code is set to "NO," then the entire applied fertilizer is placed at the bottom of the applicator knife.

Values used for sensitivity analysis are listed in table 3. For the P application rate, the actual amount of fertilizer applied (table 1) was used as the base value. Base value selections for initial soil P content and plant P uptake were discussed earlier in the Input Data Preparation section. Each parameter varied individually within a range, as reported in the literature (Mullins and Burmester, 1990; Bassett et al., 1970; Boquet and Breitenbeck, 2000; Baethgen and Alley, 1989). The lower limit for plant P uptake is under deficient fertilization condition, whereas the upper limit is under excessive fertilization condition.

The AnnAGNPS sensitivity analysis simulation was performed for a four-year period. Annual average P yield was used as the output parameter for the sensitivity analysis. To evaluate the sensitivity of P mixing code (table 4), four AnnAGNPS simulations were performed: two for P application rate B, and two for P application rate C. The base values listed in table 3 were used for initial soil P content and plant P uptake for all four simulations. No sensitivity index can be calculated for this analysis because no quantitative number is associated with P mixing code "YES" or "NO." A percent error, which indicates relative changes of P yields from P mixing code "YES" to "NO," was calculated (table 4). First, the difference between P yields from P mixing codes "YES" and "NO" was calculated, and then the percent error was calculated as the ratio between the difference and the P yield from P mixing code "NO." The impact of P application rate on model predictions (table 5) was performed using P application rates of 72.9 and 353 kg ha<sup>-1</sup>, and the base values listed in table 3 were used for initial soil P content and plant P uptake. The sensitivity index (*S*) was calculated using equation 1 for sediment-attached P and dissolved P (table 5). Similarly, the impact of initial soil P content and plant P uptake on model predictions was performed (table 5).

**Table 4. Sensitivity analysis for the effect of mixed code on P yields.**

P Mixing Code	Annual Average P yields (kg ha <sup>-1</sup> )			
	P Application Rate B <sup>[a]</sup>		P Application Rate C <sup>[a]</sup>	
	Attached P	Dissolved P	Attached P	Dissolved P
YES	1.683	15.610	1.707	18.713
NO	1.680	16.514	1.695	22.702
Percent Error <sup>[b]</sup>	0.001	-0.055	0.007	-0.176

<sup>[a]</sup> Application rate B refers to table 1; application rate C adds 280 kg ha<sup>-1</sup> more for metaphos application, as listed in table 3. Initial soil P content and plant P uptake remain as the base values listed in table 3.

<sup>[b]</sup> The percent error is calculated as the ratio of the difference between results from P mixing codes "YES" and "NO" and results from P mixing code "NO."

**Table 5. Sensitivity indexes (S) of selected parameters on P yields.**

Input Parameter	Sensitivity index (S) for P Mixing Code "YES"		Sensitivity index (S) for P Mixing Code "NO"	
	Attached P	Dissolved P	Attached P	Dissolved P
P application rate (kg ha <sup>-1</sup> )	72.9	0.01	0.01	0.24
	353.0			
Initial soil P content in the top soil layer (mg kg <sup>-1</sup> )				
Organic P	500	0.54	0.57	0.05
	50			
Inorganic P	250	0.19	0.22	0.84
	25			
Plant P uptake (ratio)				
Cotton	0.0003	-0.003	-0.003	-0.03
	0.0043			
Soybean	0.0075	-0.014	-0.013	-0.11
	0.0115			
Winter wheat	0.0005	-0.004	-0.004	-0.03
	0.0045			

## MODEL SIMULATION

AnnAGNPS has been developed to utilize input parameters such as climate, soil, and crop information taken from databases created by NRCS for any location in the U.S. This is meant to reduce users' effort in input data preparation and the need for calibration for ungauged watershed, where site-specific information is usually not available. AnnAGNPS was not calibrated for runoff and sediment simulation (Yuan et al., 2001). However, for the P study, soil P content was not available from the NRCS soil database, and it can exist in a wide range in soils (Havlin et al., 1999). Furthermore, initial soil P content had the greatest impact on P yields among the parameters tested for sensitivity (table 5). Therefore, initial soil P content was adjusted to give good correspondence with the observed P yields.

Initial soil P content selection for calibration was based on many studies of P summarized in Havlin et al. (1999). The first simulation was performed using 100 mg kg<sup>-1</sup> for initial soil organic P content and 15 mg kg<sup>-1</sup> for initial soil inorganic P content, which represents the lower level of soil P content. The second simulation was performed using 500 mg kg<sup>-1</sup> for initial soil organic P content and 250 mg kg<sup>-1</sup> for initial soil inorganic P content, which represents the average level of soil P content. The third simulation was performed using 1000 mg kg<sup>-1</sup> for initial soil organic P content and 500 mg kg<sup>-1</sup> for initial soil inorganic P content, which represents the high level of soil P content. The selection of initial soil P contents involved many trials and errors. The first 27 months were used to calibrate the model, and the last 22 months were used to validate the model. For plant P uptake, base values used for sensitivity analysis (table 3) were chosen because these values were typical values under optimum fertilization. It was assumed that fertilizer applied in this study was the optimum value for crop uptake. AnnAGNPS predicts P yield in dissolved phase and sediment-attached phase; thus, the predicted total P yield was generated by summing dissolved and sediment-attached P yields (table 6). The predicted and observed P yields listed in table 6 do not include all P yields generated from the watershed. Although an attempt was made to collect samples for every storm event, some storm events were not sampled due to unforeseen circumstances, such as equipment malfunctions. Therefore, comparisons between model simulations and observations were made only when monitoring data were available. Linear regression and

the Nash-Sutcliffe coefficient of efficiency (Nash and Sutcliffe, 1970) were calculated to evaluate the model's performance (table 6). The Nash-Sutcliffe coefficient of efficiency (E) ranges from minus infinity to one, with one indicating the model is perfect (Nash and Sutcliffe, 1970).

## RESULTS AND DISCUSSION

### SENSITIVITY ANALYSIS

Sensitivity analysis results (table 5) indicate that the most sensitive variables of those selected for analysis of P yields were initial soil P contents. This is consistent with many previous studies (Sharpley, 1995; Pote et al., 1996, 1999; Fang et al., 2002), which demonstrated that P losses to surface runoff were significantly correlated with soil P levels. Evaluation of AnnAGNPS nitrogen (N) simulation showed that initial soil N content was the most sensitive variable for N simulation. However, selecting initial soil P values at the watershed scale is very challenging. Taking literature values or calibrating literature values with observed data is a possible method of gaining input information on soil P levels. Soil P testing is another possible way to provide models with reliable inputs; however, for a watershed with thousands of fields, labor and resources may prohibit soil P testing for each field. Furthermore, because soil P level may vary from one spot to another in a real field, uncertainties related to the soil P tests have to be considered.

Attached P yield is more sensitive to the initial soil organic P than soil inorganic P, but is not sensitive to fertilizer application rate and plant P uptake (table 5). In contrast, dissolved P yield is very sensitive to the initial soil inorganic P, less sensitive to P application rate, and not sensitive to plant P uptake (table 5). Because no sensitivity index can be calculated for the P mixing code, the sensitivity of P yields to P mixing code differs from the other parameters analyzed. It is similar, however, to P application rate in that the dissolved P is sensitive to the P mixing code while the attached P is not. The sensitivity of P yields to the P mixing code increases with the increase of P application rate (table 4), as expected.

The plant uptake of P depends on many factors, such as types of land use, crop rotation, soils, climate conditions, farming technology, irrigation and drainage, amount of

**Table 6. Monthly observed rainfall, observed and predicted runoff, sediment yield, dissolved P and total P yields.**

Year	Month <sup>[a]</sup>	Rainfall (mm)	Runoff (mm)		Sediment Yield (Mg ha <sup>-1</sup> )		Dissolved P yield (g ha <sup>-1</sup> )		Total P yield (g ha <sup>-1</sup> )						
			Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted					
<b>Calibration Period</b>															
1996	October	63.8	4.8	25.6	0.02	0.15	23	65	23	164					
	November	122.4	27.4	49.5	0.07	0.09	67	196	115	254					
	December	127.5	70.6	71.2	0.13	0.18	59	131	211	261					
1997	January	182.1	129.5	101.4	0.70	0.23	145	126	437	269					
	February* <sup>110</sup>	81.8	70.4	45.8	0.23	0.07	64	179	231	229					
	March* <sup>170.7</sup>	0.0	0.0	0.0	0.00	0.00	0	0	0	0					
	April	86.5	30.9	26.3	0.15	0.04	115	123	262	169					
	May	152.4	82.7	70.8	1.10	0.57	123	124	768	388					
	June	130.3	37.6	31.4	1.24	0.33	117	124	925	291					
	July	41.1	4.1	3.1	0.12	0.02	9	0	47	0					
	August* <sup>58</sup>	49.1	0.0	5.7	0.00	0.00	0	0	0	0					
	September* <sup>76</sup>	0.0	0.0	0.0	0.00	0.00	0	0	0	0					
	October	85.6	5.5	21.2	0.05	0.19	5	127	37	162					
	November	56.4	13.1	16.6	0.06	0.29	19	63	124	106					
	December	133.3	56.8	73.9	0.72	0.37	41	178	314	265					
1998	January* <sup>142</sup>	106.6	59.3	69.6	0.58	0.51	39	121	378	174					
	February* <sup>98</sup>	90.0	36.5	35.3	0.47	0.22	41	55	389	69					
	March* <sup>95</sup>	88.7	37.7	18.9	0.18	0.08	9	119	86	216					
	April	130.8	72.6	48.9	0.46	0.43	101	177	468	305					
	May	111.5	84.6	64.3	0.81	2.08	13	63	748	524					
	June	31.0	12.3	7.8	0.29	0.09	27	61	144	86					
	July	166.1	53.6	48.8	0.23	0.42	142	242	255	463					
	August* <sup>29</sup>	0.0	0.0	0.0	0.00	0.00	0	0	0	0					
	September* <sup>74</sup>	0.0	0.0	0.0	0.00	0.00	0	0	0	0					
	October	27.2	0.0	0.0	0.00	0.00	0	0	0	0					
	November	141.2	39.9	50.8	0.11	0.70	262	129	394	573					
	December	205.2	155.0	134.4	0.51	1.51	454	258	1092	1331					
Total <sup>[b]</sup>							1992	2661	7446	6299					
Regression <sup>[b]</sup>							$y = 0.52x + 62.3$ $R^2 = 0.45$		$y = 0.71x + 38.5$ $R^2 = 0.61$						
Nash–Sutcliffe E <sup>[b]</sup>							0.35		0.58						
<b>Validation Period</b>															
1999	January	224.3	214.8	147.3	1.68	1.89	187	250	1532	1601					
	February	50.0	7.2	8.1	0.04	0.04	6	56	46	73					
	March	120.4	58.1	45.9	0.24	0.22	45	122	288	270					
	April	110.0	65.4	47.5	0.19	0.30	313	122	569	314					
	May	73.7	6.5	7.0	0.10	0.12	56	51	132	70					
	June	29.8	0.0	2.2	0.00	0.00	0	0	0	0					
	July	7.1	0.0	0.1	0.05	0.01	0	0	0	0					
	August	0.0	0.0	0.0	0.00	0.00	0	0	0	0					
	September	40.5	0.0	3.6	0.00	0.00	0	0	0	0					
	October	24.4	0.0	0.7	0.00	0.00	0	0	0	0					
	November	96.0	1.0	2.7	0.03	0.01	18	65	30	93					
	December	64.0	11.6	8.9	0.08	0.01	49	123	154	137					
2000	January	52.3	9.2	3.4	0.10	0.01	26	0	116	0					
	February	47.2	7.8	1.3	0.07	0.01	25	0	95	0					
	March	156.0	77.0	50.5	0.12	0.08	306	127	457	204					
	April	289.3	213.6	210.0	0.37	0.35	1073	242	1152	592					
	May	34.8	0.0	0.0	0.00	0.00	0	0	0	0					
	June	103.6	28.8	26.6	0.28	0.04	99	125	316	162					
	July	23.9	0.0	0.0	0.00	0.00	0	0	0	0					
	August	2.0	0.0	0.0	0.00	0.00	0	0	0	0					
	September	50.5	0.0	0.0	0.00	0.00	0	0	0	0					
	October	9.4	0.0	0.0	0.00	0.00	0	0	0	0					
Total <sup>[c]</sup>							4019.8	1785.9	1587.1	11.58	11.66	2203	1283	4888	3516
Regression <sup>[c]</sup>							$y = 0.82x + 2.63$ $R^2 = 0.94$		$y = 0.89x + 0.03$ $R^2 = 0.51$		$y = 0.24x + 34.2$ $R^2 = 0.51$		$y = 0.83x - 24.1$ $R^2 = 0.88$		
Nash–Sutcliffe E <sup>[c]</sup>							0.91		0.22		0.34		0.85		

(continued)

**Table 6 (cont.). Monthly observed rainfall, observed and predicted runoff, sediment yield, dissolved P and total P yields.**

- [a] Asterisks (\*) indicate months when not all storms were successfully monitored for runoff and sediment. The number after the asterisk is the total rainfall (mm) during that month. Rainfall values reported in the Rainfall column reflects only the amount of rainfall associated with monitored data; y refers to predicted, and x refers to observed.
- [b] Indicates total P yield, regression equation, and Nash-Sutcliffe coefficient of efficiency (E) for the first 27 months of calibration for P
- [c] Indicates total P yield, regression equation, and Nash-Sutcliffe coefficient of efficiency (E) for the last 22 months of validation for P. The validation period for runoff and sediment was 49 months because no calibration was performed for runoff and sediment simulation. Thus, the total, regression, and Nash-Sutcliffe coefficient under runoff and sediment are for the entire simulation period.

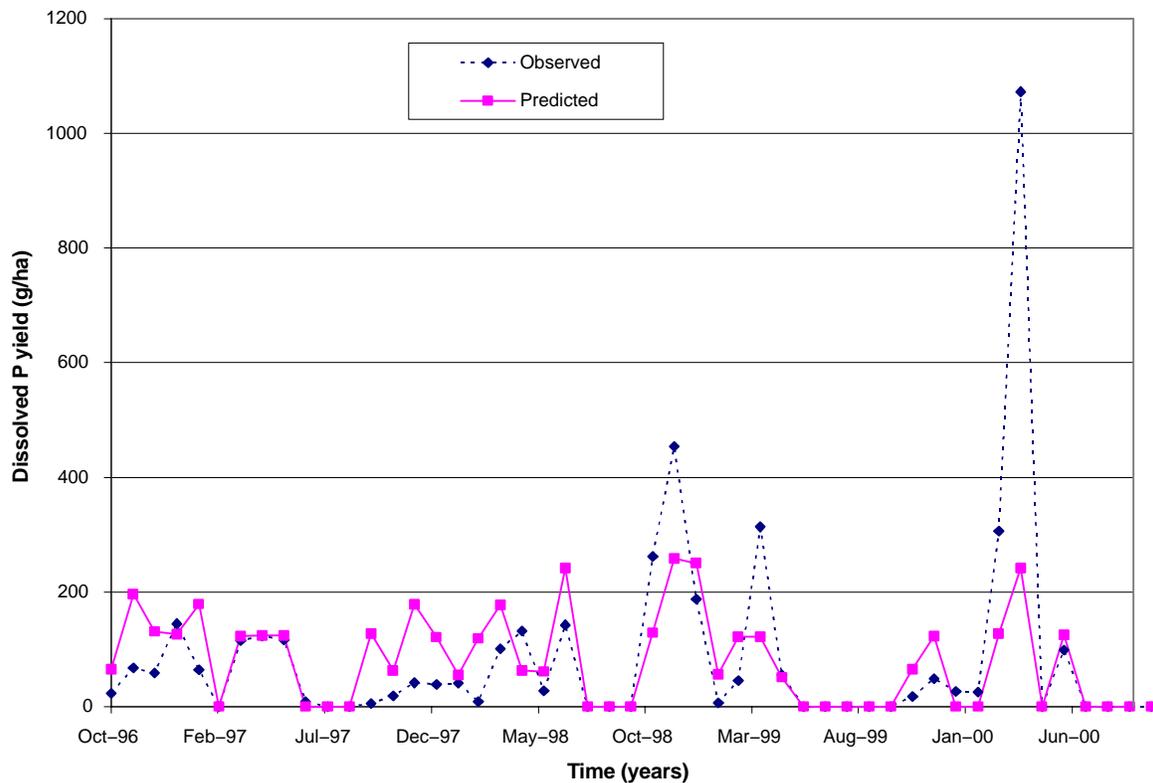
fertilizer application, and timing of application. For this study, available literature values were used, and they were not calibrated for model evaluation.

**PREDICTED VERSUS OBSERVED P YIELDS**

Calibration results show that AnnAGNPS underpredicts total P yield and overpredicts dissolved P yield. Calibration demonstrated that increase in either organic or inorganic initial soil P content increased both dissolved and sediment-attached P yields. Based on sensitivity analysis, attached P yield is more sensitive to the initial soil organic P than soil inorganic P. Thus, attempts were made to increase total P yield by increasing the initial soil organic P content, which resulted in an increase in the dissolved P yield. Because dissolved P yield is more sensitive to the initial soil inorganic P than soil organic P, attempts were also made to decrease the dissolved P yield by decreasing the initial soil inorganic P content, which resulted in a decrease in the total P yield. Initial soil organic P of 750 mg kg<sup>-1</sup> and initial soil inorganic P of 25 mg kg<sup>-1</sup> were used for the final calibration simulation. Because of the complex and contradictory response of changing initial soil P contents, the regression of monthly predicted dissolved P yield with observed dissolved P yield resulted in an R<sup>2</sup> value of 0.45 and a slope of 0.52 (table 6). The Nash-Sutcliffe coefficient of efficiency (E) was 0.35.

Regression of monthly predicted total P yield with observed total P yield resulted in an R<sup>2</sup> value of 0.61 and a slope of 0.71. The E value was 0.58.

Because P movement depends on runoff and sediment movement, the results of runoff and sediment simulation (Yuan et al., 2001) are also presented in table 6. No calibration was performed for runoff and sediment simulation. Over the 49-month simulation period, AnnAGNPS-predicted runoff was 89% of the observed total runoff, and AnnAGNPS-predicted dissolved P yield was 94% of the observed total dissolved P yield (table 6). However, AnnAGNPS-predicted dissolved P yield was only 58% of the observed dissolved P yield for the validation period. AnnAGNPS-predicted monthly runoff matched well with observed monthly runoff, but the predicted monthly dissolved P yield did not match well with the observed monthly dissolved P yield. The regression of the monthly predicted dissolved P yield with the observed dissolved P yield was fair, with an R<sup>2</sup> value of 0.51 and a slope of 0.24. The E value was 0.34, which also indicated a fair model performance in predicting dissolved P yield. A time series comparison of observed and predicted dissolved P yield at the study site (fig. 4) shows both overpredictions and underpredictions by AnnAGNPS.



**Figure 4. Time series comparison of observed and predicted dissolved P yield.**

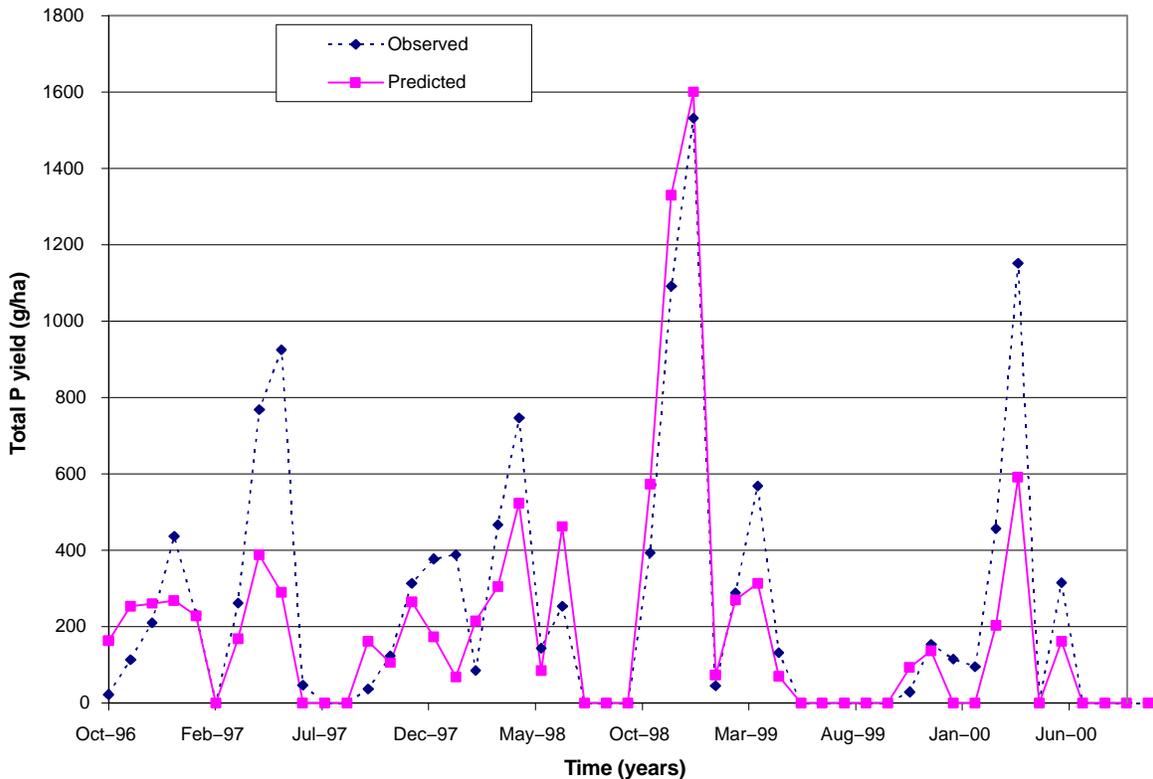


Figure 5. Time series comparison of observed and predicted total P yield.

AnnAGNPS-predicted total P yield during the validation period was 72% of the observed total P yield (table 6). The E value was 0.85, which indicated that the model's performance in predicting total P yield was good. The regression of the monthly predicted total P yield with the observed total P yield resulted in an  $R^2$  value of 0.88 and a slope of 0.83 (table 6). Although a time series comparison of observed and predicted total P yield at the study site (fig. 5) shows both overpredictions and underpredictions by AnnAGNPS, observed and predicted total P yield generally coincided better than observed and predicted dissolved P yield (figs. 4 and 5).

Both runoff prediction and sediment prediction impact the total P yield prediction. AnnAGNPS-predicted sediment yield over the 49-month simulation period was 101% of the observed sediment yield (table 6). Sediment-attached P yield during the validation period was 83% of the observed sediment-attached P yield. The observed sediment-attached P yield was calculated as the difference between the total P yield and the dissolved P yield.

The difference in the agreement of P yields may be attributed to limitations in AnnAGNPS simulation of P processes, such as P movement between organic and inorganic, and movement of inorganic P between solution pool and active pool and between active pool and stable pool. Such processes are very complicated and difficult to describe mathematically. AnnAGNPS characterizes the adsorption and desorption processes (reaction between solution pool and active pool) using a P availability index, which is calculated based on soil physical and chemical properties such as content of  $\text{CaCO}_3$ , organic carbon, clay, base saturation, and soil pH value. Uncertainties in those soil variables, which were obtained from SSURGO database, would impact the accuracy of P availability index calculation. The flow rate

between solution pool and active pool is calculated based on soil moisture, temperature, P availability index, and the amount of P in each pool. As more soluble P moves to active P, less soluble P is available for runoff loss.

Simulation results may be improved through a better determination of input parameters. For example, actual field analysis of crop information at harvest may provide a better estimation of plant P uptake parameters than using literature values. Further, after calibration of initial soil P contents, additional calibration of plant P uptakes may also improve simulation results. Plant P uptakes directly impact the prediction of dissolved P yield because the crop utilizes dissolved P for growth. The variation of the solution P would impact the P loss to runoff and sediment because the amount of P in the solution pool would impact the transfer among the three inorganic pools. In addition, improving the prediction of runoff and sediment would improve the prediction of P yields.

## CONCLUSIONS

This study demonstrates that AnnAGNPS adequately simulates monthly total P. The simulation of monthly dissolved P is not as satisfactory as monthly total P. The differences between simulated and observed results may be attributed to the simplification of P processes in AnnAGNPS and uncertainties in input selections. Initial soil P contents are the most sensitive parameters of those selected for sensitivity analysis in determining P yields.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution of the MDMSEA project committee in funding and data

collection support. The authors also wish to thank Vance Justice for his help in model simulation and the associate editor and reviewers whose comments helped to improve the manuscript.

## REFERENCES

- Baethgen, W. E., and M. M. Alley. 1989. Optimizing soil and fertilizer nitrogen use by intensively managed winter wheat: I. crop nitrogen uptake. *Agronomy J.* 81(1): 116-120.
- Baginska, B., W. Milne-Home, and P. S. Cornish. 2003. Modeling nutrient transport in Currency Creek, NSW with AnnAGNPS and PEST. *Environ. Modeling and Software* 18(8): 801-808.
- Barrow, N. J., and T. C. Shaw. 1975. The slow reactions between soil and anions: 2. Effect of time and temperature on the decrease in phosphate concentration in soil solution. *Soil Sci.* 119(2): 167-177.
- Bassett, D. M., W. D. Anderson, and C. H. Werkhoven. 1970. Dry matter production and nutrient uptake in irrigated cotton (*Gossypium hirsutum*). *Agronomy J.* 62(2): 299-302.
- Bingner, R. L., F. D. Theurer, and Y. Yuan. 2003. AnnAGNPS Technical Processes. Washington, D.C.: USDA-ARS. Available at: [www.ars.usda.gov/Research/docs.htm?docid=5199](http://www.ars.usda.gov/Research/docs.htm?docid=5199). Accessed 20 June 2005.
- Boquet, D. J., and G. A. Breitenbeck. 2000. Nitrogen rate effect on partitioning of nitrogen and dry matter by cotton. *Crop Science* 40(6): 1685-1693.
- Delaune, P. B., P. A. Moore, D. K. Carman, A. N. Sharpley, B. E. Haggard, and T. C. Daniel. 2004. Development of a phosphorous index for pastures fertilized with poultry litter: Factors affecting phosphorous runoff. *J. Environ. Qual.* 33(6): 2183-2191.
- Fang, F., P. L. Brezonik, D. J. Mulla, and L. K. Hatch. 2002. Estimating runoff phosphorous losses from calcareous soils in the Minnesota River basin. *J. Environ. Qual.* 31(6): 1918-1929.
- Flannery, R. L. 1986. Plant food uptake in a maximum yield soybean study. Unpublished manuscript. Conway, Ark.: Potash and Phosphate Institute.
- Havlin, J. L., J. D. Beaton, S. L. Tisdale, and W. L. Nelson. 1999. *Soil Fertility and Fertilizers: An Introduction to Nutrient Management*. 6th ed. Upper Saddle River, N. J.: Prentice Hall.
- Jones, C. A., and J. Jacobsen. 2002. Phosphorus cycling, testing and fertilizer recommendations. Nutrient Management Module No. 4. Bozeman, Mont.: Montana State University Extension Service. Available at: [www.montana.edu/wwwpb/pubs/mt44494.pdf](http://www.montana.edu/wwwpb/pubs/mt44494.pdf). Accessed 23 April 2004.
- Jones, C. A., C. V. Cole, A. N. Sharpley, and J. R. Williams. 1984. A simplified soil and plant phosphorus model: I. Documentation. *SSSA J.* 48(4): 800-805.
- Lane, L. J., and V. A. Ferreira. 1980. Chapter 6: Sensitivity analysis. In *CREAMS: A Field-Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems*, 113-158. Conservation Report No. 26. W. G. Knisel, ed. Washington, D.C.: USDA-SEA.
- Maples, R., and J. L. Heogh. 1973. Phosphorus fertilization experiments with cotton on Delta soils of Arkansas. USDA-781. Fayetteville, Ark.: University of Arkansas, Division of Agriculture, Agricultural Experiment Station.
- Mullins, G. L., and C. H. Burmester. 1990. Dry matter, nitrogen, phosphorous accumulation by four cotton varieties. *Agronomy J.* 82(4): 729-736.
- Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models: Part I. A discussion of principles. *J. Hydrology* 10(3): 282-290.
- Nearing, M. A., L. Deer-Ascough, and L. M. Laflen. 1990. Sensitivity analysis of the WEPP hillslope profile erosion model. *Trans. ASAE* 33(3): 839-849.
- NRCS. 2005. Soil Survey Geographic (SSURGO) Database. Washington, D.C.: USDA-NRCS. Available at: [www.ncgc.nrcs.usda.gov/products/datasets/ssurgo/index.html](http://www.ncgc.nrcs.usda.gov/products/datasets/ssurgo/index.html). Accessed on 14 July 2005.
- Pote, D. H., T. C. Daniel, A. N. Sharpley, P. A. Moore Jr., D. R. Edwards, and D. J. Nichols. 1996. Relating extractable soil phosphorous to phosphorous losses in runoff. *SSSA J.* 60(3): 855-859.
- Pote, D. H., T. C. Daniel, D. J. Nichols, A. N. Sharpley, P. A. Moore Jr., D. M. Miller, and D. R. Edwards. 1999. Relationship between phosphorous levels in three Ultisols and phosphorous concentrations in runoff. *J. Environ. Qual.* 28(1): 170-175.
- Renard, K. G., G. R. Foster, G. A. Weesies, D. K. McCool, and D. C. Yoder, coordinators. 1997. Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). USDA Agriculture Handbook No. 703. Washington D.C.: USDA.
- Self, J. R., and P. N. Soltanpour. 2004. Soil sampling. Fort Collins, Colo.: Colorado State University Cooperative Extension. Available at: [www.ext.colostate.edu/pubs/crops/00500.html](http://www.ext.colostate.edu/pubs/crops/00500.html). Accessed on 14 July 2005.
- Sharpley, A. N. 1995. Dependence of runoff phosphorous on extractable soil phosphorous level. *J. Environ. Qual.* 24(5): 920-926.
- Sharpley, A. N., and B. Moyer. 2000. Phosphorous forms in manure and compost and their release during simulated rainfall. *J. Environ. Qual.* 29(5): 1462-1469.
- Sharpley, A. N., and J. K. Syers. 1979. Phosphorus inputs into a stream draining an agricultural watershed: II. Amounts and relative significance of runoff types. *Water, Air and Soil Pollution* 11(4): 417-428.
- Sharpley A. N., and J. R. Williams. 1990. EPIC - Erosion/Productivity Impact Calculator: I. Model documentation. USDA Technical Bulletin No. 1768. Washington D.C.: USDA.
- Sharpley, A. N., C. A. Jones, C. Gray, and C. V. Cole. 1984. A simplified soil and plant phosphorus model: II. Prediction of labile, organic, and sorbed phosphorus. *SSSA J.* 48(4): 805-809.
- Sharpley, A. N., S. C. Chapra, R. Wedepohl, J. T. Sims, T. C. Daniel, and K. R. Reddy. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. *J. Environ. Qual.* 23(3): 437-451.
- Sharpley, A. N., T. C. Daniel, J. T. Sims, and D. H. Pote. 1996. Determining environmentally sound soil phosphorous levels. *J. Soil Water Conserv.* 51(2): 160-166.
- Smith, A. E. 1990. WWF conservation yearbook 1987/88. *Biological Conserv.* 53(2): 161-182.
- Suttles, J. B., G. Vellidis, D. Bosch, R. Lowrance, J. M. Sheridan, and E. L. Usery. 2003. Watershed-scale simulation of sediment and nutrient loads in Georgia Coastal Plain streams using the Annualized AGNPS model. *Trans. ASAE* 46(5): 1325-1335.
- Young, R. A., C. A. Onstad, D. D. Bosch, and W. P. Anderson. 1989. AGNPS: A nonpoint-source pollution model for evaluating agricultural watersheds. *J. Soil Water Conserv.* 44(2): 168-173.
- Yuan, Y., R. L. Bingner, and R. A. Rebich. 2001. Evaluation of AnnAGNPS on Mississippi Delta MSEA watersheds. *Trans. ASAE* 44(5): 1183-1190.
- Yuan, Y., R. L. Bingner, and R. A. Rebich. 2003. Evaluation of AnnAGNPS nitrogen loading in an agricultural watershed. *J. American Water Res. Assoc.* 39(2): 457-466.