Evaluation of Phosphorus Transport and Transformations in GLEAMS 3.0

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Thesis submitted to the faculty of Virginia Polytechnic Institute and State University in
partial fulfillment of the requirements for the degree of

Master of Science
In
Biological Systems Engineering

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February 21, 2006
Blacksburg, Virginia

Keywords: modeling, nutrients, erosion, runoff, leaching

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ABSTRACT

The overall goal of this research was to improve simulation of soil phosphorus (P) transport and transformations in GLEAMS 3.0, a non-point source model that simulates edge-of-field and bottom-of-root-zone loadings of nutrients from climate-soil-management interactions to assess management alternatives. The objectives of this research were to identify the state of the science for P transport and transformations, determine appropriate relationships for inclusion in GLEAMS, and determine if modifications to GLEAMS improved predictions of P loss in runoff, sediment, and leachate.

The state of the science review revealed numerous equations available to predict dissolved P loss in runoff and leachate from a soil's nutrient status. These equations use a single variable to predict P loss and were developed for site-specific conditions based on empirical data. Use of these equations in GLEAMS is not reasonable as transport factors must also be considered when predicting P loss.

Results from the sensitivity analysis showed that GLEAMS prediction of leached P were extremely sensitive to changes in the P partitioning coefficient (CPKD). Runoff PO_4-P output was slightly to moderately sensitive, sediment PO_4-P was moderately sensitive to sensitive, and sediment organic P was moderately sensitive to changes in CPKD whereas plant uptake of P was insensitive to slightly sensitive. The weakness of GLEAMS to estimate CPKD has been documented. Upon further investigation, it was determined that CPKD was highly over-estimated in GLEAMS as compared to measured values found during the literature review. Furthermore, this over-estimation caused under-estimation of the P extraction coefficient (β_p); the value of β_p remained constant at 0.10 and did not vary over the simulation period.

Expressions for CPKD and β_p were modified in GLEAMS. Data from three published studies (Belle Mina, Gilbert Farm, and Watkinsville) were used in the analyses of three modifications to GLEAMS: GLEAMS β_p, GLEAMS CPKD, and GLEAMS β_p+CPKD. GLEAMS β_p investigated the change in β_p as a function of soil clay content, GLEAMS CPKD attempted to improve GLEAMS' estimation of CPKD, and GLEAMS β_p+CPKD assessed the combined effects of changes to β_p and CPKD.

Over the respective study periods, GLEAMS over predicted runoff PO_4-P for Belle Mina by 193 to 238% while under-predicting runoff PO_4-P at Gilbert Farm by 41% and Watkinsville by 81%. Sediment P was over-predicted by GLEAMS for Belle Mina by 225 to 233% and Gilbert Farm by 560%, while sediment P was under-predicted by 62% at Watkinsville. Leached PO_4-P was both over- and under-predicted by GLEAMS; Belle Mina was the only data set with observed leached P values.

Simulation results from the model changes were inconclusive. There was no clear evidence supporting use of one model over another. Modifications increased predicted dissolved P in runoff and leachate, while decreasing predicted sediment-bound P in runoff. The original GLEAMS model best predicted runoff and leached PO_4-P at the Belle Mina sites. GLEAMS CPKD was the best predictor of runoff PO_4-P and sediment P at Gilbert Farm. GLEAMS β_p+CPKD best predicted runoff PO_4-P at Watkinsville. Overall, the proposed improvements to GLEAMS did not improve GLEAMS predictions.

In conclusion, GLEAMS should not be used for quantitative estimates of hydrology, sediment, and nutrient loss for specific management practices. As recommended by the GLEAMS model developers, GLEAMS should only be used to predict relative differences in alternative management systems. It is recommended that future research focus on developing a better correlation between CPKD, clay mineralogy and content, and organic matter content, as CPKD has been identified as a vital component of the GLEAMS P sub-model that requires further examination.

ACKNOWLEDGEMENTS

I would like to thank my husband Winston Matthews; my parents Ricky and Beckey, my sisters Amanda and Valerie, and my brother-in-law Gerald. I would also like to thank Vicky Barone, Katie Flahive, Amanda Reinke, Mardi Russell, Tone Nordberg, Stefanie Brady, and John Klote for their friendship, support, and encouragement during my time at Virginia Tech. I especially would like to thank Tamie Veith for her technical expertise, computer programming knowledge, and friendship.

I would like to thank my committee members Drs. Wolfe, Dillaha, Alley, and Mullins as well as Drs. Mostaghimi, Zelazny, and Perumpral for their guidance and advice. And all the Biological Systems Engineering Staff, friendly people, and smiling faces that made my experience at Virginia Tech memorable.

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CHAPTER 1: INTRODUCTION

Phosphorus (P) is an essential element in the environment and is important to plant and animal physiology. Studies have shown that soil P levels can exceed local crop requirements in areas of intensive agricultural and livestock production (Schoumans and Groenendijk, 2000; Sharpley and Tunney, 2000). Nitrogen (N)-based nutrient management in these areas has resulted in over-application and increased levels of P in soils. Excess P concentrations in the soil can harm surrounding bodies of water and do not provide agronomic benefits to crops. Water quality impairment, such as eutrophication, can result from the transport of P from agricultural land to surface waters.

Phosphorus soil tests, such as Mehlich-3 (Mehlich, 1984), Bray-1 (Bray and Kurtz, 1945), and Olsen (Olsen et al., 1954), provide an index of plant available P in soils. Soil test P (STP) results are typically used to identify the soil's nutrient status, which is then used to estimate crop response and determine fertilizer requirements (Havlin et al., 1999; Pierzynski, 2000). High STP levels do not necessarily mean that an area has a high potential for P loss to surface water. Soil tests alone cannot be used to identify lands that might adversely affect water quality (Sims et al., 2000). Due to variability in site conditions, factors such as runoff volume and erosion should also be accounted for in determining P loss potential (Sharpley et al., 1996).

Transport of nutrients from agricultural fields to water bodies can be evaluated through the use of on-site monitoring or computer simulation models. On-site monitoring can be costly and several years may pass before results can be evaluated. Computer simulation models allow users to quickly and inexpensively evaluate and identify potential nutrient losses. By providing a simplification of what actually occurs in the complex real-world environment, computer simulation models provide a means to compare different management scenarios without the added costs and time involved with monitoring or field experimentation.

Several simulation models, such as ANSWERS (Areal Non-point Source Watershed Environmental Response Simulation) (Beasley et al., 1980) and AGNPS (Agricultural Non-Point Source) (Young et al., 1989), are available to predict nutrient losses in runoff from agricultural areas. Scientists with the United States Department of Agriculture-Agricultural Research Service (USDA-ARS) developed the CREAMS model to simulate movement of chemicals, runoff, and erosion from agricultural management systems on a field-scale (Knisel, 1980). The CREAMS model was modified to allow for simulation of groundwater loadings resulting in the GLEAMS, Groundwater Loading Effects of Agricultural Management Systems (Leonard et al., 1987), model. The GLEAMS model is a field-scale mathematical model that simulates edge of field and bottom-of-root-zone loadings of water, sediment, pesticides, and plant nutrients from climate-soil-management interactions to assess management alternatives. Phosphorus mineralization, immobilization, and plant uptake processes are simulated in GLEAMS. Dissolved and sediment P losses through surface runoff and dissolved P leaching through the soil profile are included in P simulation equations, however, loss of particulate P through preferential transport through the root zone is not simulated (Shirmohammadi et al., 1998).

The GLEAMS model is available for distribution to the public at a USDA-ARS website (http://www.cpes.peachnet.edu/sewrl/Gleams/gleams_y2k_update.htm). The website offers access to the GLEAMS model, source code, user manual, and updates. Example files are also provided that allow users to practice running GLEAMS and generate data output. Users can customize model input files using the hydrology, erosion, nutrient, and/or pesticide editors. Though technical support is not available for GLEAMS users, program “bugs” and glitches are periodically repaired and updates are performed to meet the demand and need of model users.

The intended use of GLEAMS is comparison of different management scenarios (Knisel, 1993). As stated by Shirmohammadi et al. (1998)**, “**GLEAMS can do a reasonable job in simulating long-term averages, thus rendering itself to be a viable management and decision making model regarding the assessment of the relative impacts of different agricultural management systems.” Knisel and Turtola (2000) also noted that GLEAMS should not be used for absolute predictions but only for relative comparisons of alternate management systems. The nutrient component in GLEAMS was not meant to be a quantitative predictor of nutrient loss from agricultural fields, but simply a relative predictor between different management practices. Yet, GLEAMS and other models that have adapted CREAMS components, such as EPIC - Erosion-Productivity Impact Calculator (Williams et al., 1984) and AGNPS (Young et al., 1989), have been used to quantitatively predict nutrient losses (Reyes et al., 1997; Shirmohammadi et al., 1998; Suttles et al., 2003; Yoon et al., 1992; Yoon et al., 1994).

Advances in the state of the science of soil P transport and transformations have been made since GLEAMS development began in 1984. For example, the P saturation level of a soil has been shown to be better than STP measurements for predicting concentrations of soil P loss in runoff (Sharpley, 1995). An increase in the degree of P saturation in soils increases the likelihood of P transport to surface waters (Sims et al., 2000). The GLEAMS model currently predicts P loss by calculating daily P mass balances based on P additions and losses to various P pools.

Accurately representing the soil P cycle in the environment is important because the fate of P in agricultural systems affects soil nutrient availability, fertilizer application, and off-site water quality. It is important to account for P inputs and outputs in the soil system for improved management of nutrient applications. Incorporating new knowledge of soil P interactions into computer models, such as GLEAMS, can improve prediction of agricultural P movement. Conceivably, through incorporation of the state of the science of P transport and transformations, GLEAMS can be used to estimate quantitative P losses from agricultural fields. A review of the state of the science is needed to assess current knowledge of soil P transport and transformations to make improvements to GLEAMS.

The overall goal of this research was to improve simulation of soil P transport and transformations in GLEAMS 3.0. The objectives were:

(1) To identify the state of the science for P transport and transformations to determine if GLEAMS P relationships are reasonable,
(2) To determine appropriate relationships for inclusion in GLEAMS, and
(3) To determine if modifications to GLEAMS improve predictions of P loss through runoff, erosion, and leaching.

CHAPTER 2: LITERATURE REVIEW

A literature review was performed on the topics of P mineralization, immobilization, plant uptake, leaching, runoff, and GLEAMS modeling. This chapter contains information from the literature review on the soil P cycle, water quality issues, and studies evaluating the predictive capability of GLEAMS. The GLEAMS user manual was reviewed to determine the equations and assumptions used in the simulation of P transport and transformations (Chapter 3). A list of symbols and acronyms used throughout this thesis can be found in Appendix A.

2.1 ENVIRONMENTAL CONCERNS RELATED TO PHOSPHORUS

Crop producers and confined animal operators utilize P to enhance crop yields and livestock production, respectively (Hedley and Sharpley, 1998). Organic wastes from confined animal facilities can be recycled as fertilizers and land applied. Due to high transportation costs, animal waste is usually applied close to the source (Sharpley et al., 1993). Elevated STP levels in areas receiving long-term land application of animal wastes have been documented (Combs and Burlington, 1992; Motschall and Daniel, 1982; Sharpley et al., 1991). Long-term application of animal waste on the basis of supplying crop N needs can result in excess amounts of P in soils and increased concentrations of P in surface runoff (Sharpley et al., 1996). The N:P ratio of animal waste can vary from 2:1 to 6:1 while the N:P crop uptake ratio ranges from 7:1 to 11:1; application of animal waste on a N-basis means that more P is generally applied than is required for optimum crop growth (Gburek et al., 2000). Some STP levels are so high that it make take a significant amount of time (8 to 10 years) before crop response to P is negatively impacted (McCollum, 1991). Sharpley et al. (1993) advised use of P-based manure application on land having STP levels of medium or above and indicating potential for runoff to occur. Soil test calibrations vary by region, crop type, and STP method. For example, medium STP values for Bray-1 P, Mehlich-3 P, and Olsen P may range from 13-25, 15-28, and 8-11 ppm, respectively (Havlin et al., 1999).

Transport of P to surface waters from agricultural land can cause eutrophication. Algal blooms, which are part of the eutrophication process in surface waters, are caused by P concentrations ranging from 0.01 to 0.03 mg L^{-1} (U.S. Environmental Protection Agency, 1994a). Soils with STP levels near those recommended for optimum crop growth have the potential to release bioavailable P to surface waters above concentrations that promote algal growth (Pote et al., 1996). Implementing measures to control P concentrations in surface runoff is recommended to minimize eutrophication (Sharpley et al., 1994).

2.2 SOIL PHOSPHORUS CYCLE

Various inputs and soil processes involved in the soil P cycle are shown in Figure 2.1. Phosphorus can be removed from soil by plant uptake and transported with erosion, runoff, and leaching. Inputs into the soil system include organic and commercial fertilizers, plant residues, agricultural wastes, and municipal and industrial by-products. Plants uptake P from the soil in the form of orthophosphate ions ($H_2PO_4^-$, HPO_4^{2-}). Sorption and desorption reactions can occur on clays, aluminum (Al) oxides, and iron (Fe) oxides to attach or remove orthophosphate ions, respectively, from soil surfaces. Primary and secondary P minerals can dissolve into soil solution. Secondary P minerals, which are formed from chemical weathering of primary minerals, can also precipitate from the soil solution. Organic P in the forms of soil biomass, soil organic matter, and soluble organic P are mineralized or immobilized to and from the soil solution (Havlin et al., 1999).

Increases in the concentration of P in the soil solution can increase the potential for P transport (McDowell and Sharpley, 2001a). Many factors influence P losses through runoff and leaching. Sharpley et al. (1981a) identified four variables that directly influence dissolved P transport: STP concentration, runoff volume, depth of soil-runoff interaction, and soil bulk density. Additionally, the loss of P in runoff is influenced by the rate and method of fertilizer application, type of fertilizer, intensity of rainfall or irrigation, and vegetative cover (Sharpley et al., 1993). The zone of interaction between soil and runoff is usually within the top 5 cm (Sharpley et al., 1996). Phosphorus loss through leaching depends mostly on the extent of P saturation in the soil. Potential P leaching from soils depends on the extent of phosphate-adsorbing mineral surfaces, the species of P in solution, and the method of transport through the soil profile. Phosphorus movement through the soil profile can occur by preferential flow through natural macropores or artificial drainage channels (Simard et al., 2000). Phosphate sorption is influenced by pH, ionic strength, type of P compound, and solution species competing with phosphate for adsorption (Hansen et al., 1999).

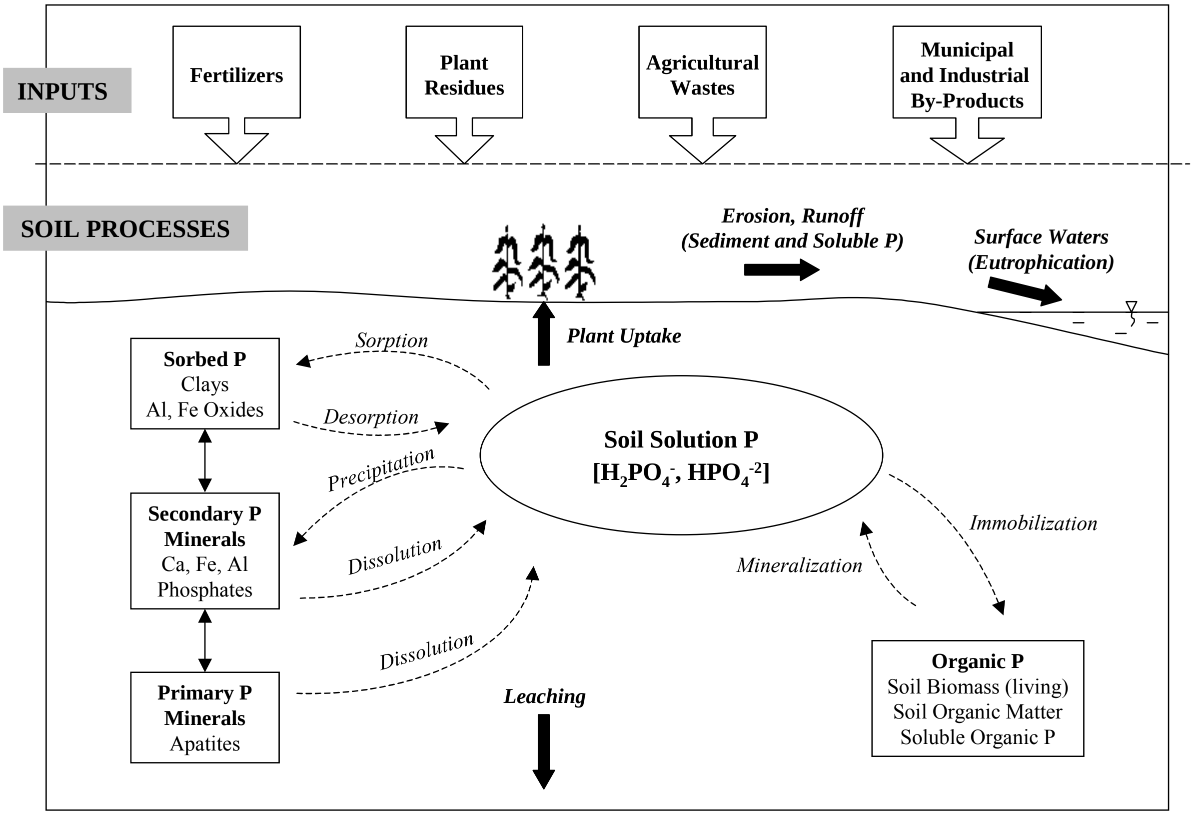

Figure 2.1 The soil P cycle (adapted from Pierzynski et al., 1994).

The concentration of P in runoff decreases due to water dilution and sediment deposition as runoff mixes with receiving waters. Through sorption and desorption processes combined with preferential transport of clay-sized particles, the fraction of P that is bioavailable may increase (Sharpley et al., 1993). Sharpley et al. (1996) stressed the importance of understanding that concentrations of P loss in runoff are not entirely related to soil P extracting method and added that variable site-specific conditions concerning hydrology and topography must not be overlooked.

Fertilizer application timing and duration of rainfall events are important factors affecting the loss of P from agricultural lands. Sharpley et al. (1993) reported the majority of P loss in runoff occurs during one or two intense storm events per year. This makes the timing of fertilizer application very important relative to the occurrence of intense storm events producing runoff. Quinton et al. (2001) reported that smaller erosion events should not be ignored. Over a six-year study period, Quinton et al. (2001) observed that 50% of the P lost was transported with 25% of total soil lost. Phosphorus concentrations in runoff increased as peak runoff increased but decreased as the duration of the rainfall/runoff event increased (Quinton et al., 2001).

2.3 SOIL TEST PHOSPHORUS

Soil P testing is the most commonly used method to identify soils with high risks for P loss (Maguire and Sims, 2002). Various STP methods exist and each is designed to extract P from soils of different types and chemistry (Pierzynski, 2000). Agronomic methods such as Bray-1, Mehlich-1, Mehlich-3, and Olsen (Table 2.1) measure an index of plant available P in the soil to help identify a deficiency or abundance of soil P which is then used to determine crop fertilizer P requirements. The level of soil P has been related to crop response to fertilizer and manure amendments (Sims et al., 2002). Mehlich-1 P is used in Virginia to classify levels of soil fertility. Virginia uses the following levels to assess soil nutrient status: low (0 to 6 mg P kg^{-1}), medium (6 to 18 mg P kg^{-1}), high (18 to 55 mg P kg^{-1}), and very high (> 55 mg P kg^{-1}) (Donohue, 2000). Delaware uses a fertility index value based on Mehlich-3 P to assess soil fertility as low (0 to 25), medium (26 to 50), optimum (51 to 100), and excessive (> 100) (Sims et al., 2002). The likelihood of adverse environmental effects due to transport of P to adjacent water bodies may increase in soils with very high or excessive STP levels. The Mehlich-3 P value is approximately 1.5 to 2 times Mehlich-1 P (Sims, 1989).

Table 2.1 Agronomic soil test P methods (Pierzynski, 2000).

STP Method	Region	Best Suited Conditions	Optimum for Crop Growth (mg P kg^{-1} soil)
Bray-1	Midwestern and North Central US	Acidic and neutral soils	25 to 30
Mehlich-1	Southeastern and mid-Atlantic states	Acidic soils (pH < 6.5), low cation exchange capacity (< 10 cmol kg^{-1}), and low organic matter (<5%)	20 to 25
Mehlich-3	US and Canada	Acidic and basic soils	45 to 50
Olsen	North Central and western US	Calcareous soils (>2% calcium carbonate)	10

Other STP methods such as water extractable, ammonium oxalate (NH_4-oxalate) extractable, and iron-strip P have been correlated to loss of dissolved reactive P in runoff (Fang et al., 2002; Gaston et al., 2003; McDowell and Sharpley, 2001a; Pote et al., 1996;

Robinson et al., 1994; Torbert et al., 2002). Iron-strip P measures desorbable P (Pautler and Sims, 2000).

Equations for relating soil P tests to one another have been developed (Gascho et al., 1990; McDowell and Sharpley, 2001a; Pautler and Sims, 2000; Wolf and Baker, 1985). Equations for converting from one soil test P extractant method to another are shown in Table 2.2.

Table 2.2 Equations for relating one soil P extractant method to another.

Reference	**Number of Samples**	**Soil Type**	**Equation**	**Y**	**X**	**R^2**
Gascho et al. (1990)				---------------------mg kg^{-1}---------------------		
	450	Range of sand to sandy clay loams	$Y = 1.46x + 4.78$	Mehlich-3 P	Mehlich-1 P	0.85
			$Y = 1.84x + 1.74$	Bray-1 P	Mehlich-1 P	0.86
			$Y = 1.22x – 3.14$	Bray-1 P	Mehlich-3 P	0.95
Pautler and Sims (2000)				---------------------mg kg^{-1}---------------------		
	122	Range of textural classes	$Y = 0.46x^{0.98}$	Fe-Oxide Strip P	Mehlich-1 P	0.81
			$Y = 0.03x + 0.21$	0.01 M $CaCl_2$-P	Mehlich-1 P	0.50
			$Y = 1.97x +112$	NH_4-oxalate P	Mehlich-1 P	0.70
			$Y = 0.06x + 0.0006x^2-0.63$	0.01 M $CaCl_2$-P	Fe-Oxide Strip P	0.76
McDowell and Sharpley (2001a)				-----------mg L^{-1}-----------	----------mg kg^{-1}----------	
	43	Calvin channery silt loam	$Y = 0.011x-0.03$	H_2O-extractable P	Mehlich-3 P	0.86
			$Y =0.062x-0.34$	0.01 *M* $CaCl_2$-extractable P	Mehlich-3 P	0.82
Wolf and Baker (1985)				---------------------ppm---------------------		
	91	Variety	$Y = 1.52x + 0.62$	Mehlich-1 P	Olsen P	0.87
			$Y = 3.31x – 9.65$	Bray-1 P	Olsen P	0.72
			$Y = 1.99x – 6.75$	Bray-1 P	Mehlich-1 P	0.68
			$Y = 0.87x + 4.21$	Mehlich-3 P	Bray-1 P	0.97
			$Y = 3.08x – 6.91$	Mehlich-3 P	Olsen P	0.79
			$Y = 1.85x – 4.33$	Mehlich-3 P	Mehlich-1 P	0.75

2.4 PHOSPHORUS TRANSFORMATIONS

2.4.1 MINERALIZATION AND IMMOBILIZATION REACTIONS

Phosphorus mineralization and immobilization reactions occur simultaneously in the soil system and are affected by the following soil factors: temperature, moisture content, pH, aeration, tillage practices, and P fertilization (Havlin et al., 1999). Mineralization is the conversion of organic forms of P to inorganic forms and immobilization is the conversion of inorganic, potentially plant-available P into organic (non plant-available) forms. Phosphatase enzymes initialize the P mineralization process and are sensitive to changes in the soil organic carbon (C) content. Enzyme activity increases as soil organic C content increases, thus soil organic P and C contents are highly correlated (Havlin et al., 1999). An increase in soil organic C is coupled with an observed increase in soil organic P, signifying an increase in P mineralization (Sharpley, 1985).

Cyclic soil moisture conditions (drying and rewetting process) can affect microbial activity and biomass (Kieft et al., 1987), which in turn affects P mineralization. Microbial activity can immobilize commercial inorganic fertilizer applied to the soil. A wide range, 25 to 100%, of applied inorganic fertilizer is immobilized (Havlin et al., 1999). In grassland soils, 5-24% of total soil organic P is in microbial biomass (Brookes et al., 1984).

Grierson et al. (1999) examined the effects of water potential, temperature, and fertilizer application on P mineralization rates for the surface horizon of a Florida Spodosol planted to loblolly pine (*Pinus taeda L.*). This soil type was chosen because of its inability to sorb mineral P due to a low number of adsorptive surfaces (Ballard and Fiskell, 1974; Fox et al., 1990), thus allowing for better measurement of P mineralization rates. Sorption of P from the soil solution to mineral surfaces complicates measurement of P mineralization rates (Grierson et al., 1999). Fertilized soil samples received 24 kg P ha^{-1} $year^{-1}$. Grierson et al. (1999) conducted laboratory incubations of soil samples for 14 and 42 days at temperatures of 15, 25, and 38°C. Water potentials varied from -0.1, -3, -8, -10, and -1500 kPa. Phosphorus mineralization was measured by changes in potassium chloride (KCl)-extractable inorganic P. Results indicated that as water potential and temperature increased, P mineralization rates increased. Mean P mineralization rates observed by Grierson et al. (1999) are shown in Table 2.3 for a range of water potentials at three temperatures. Higher P mineralization rates were observed during the first 14 days as compared to the 42-day incubation period, suggesting that P mineralization is initially fast followed by a decrease over time. The unfertilized treatment was significantly different from the fertilized treatment at P<0.001.

Table 2.3 Mean P mineralization rates for water potentials ranging from -0.1 to -1,500 kPa for an incubation study conducted at three temperatures (Grierson et al., 1999).

Temperature (°C)	**Unfertilized Treatment**		**Fertilized Treatment** (24 kg P ha^{-1} year^{-1})	
	14 days	**42 days**	**14 days**	**42 days**
	- - - - - - - - - -Mean P mineralization rate (mg P kg^{-1} day^{-1}) - - - - - - - - -			
15	0.325	0.091	0.355	0.126
25	0.288	0.062	0.337	0.106
38	0.371	0.139	0.471	0.145

Grierson et al. (1998) studied the kinetics of P mineralization in a sandy Florida Spodosol planted to loblolly pine. This research focused on the effects of cyclic soil moisture conditions on P mineralization kinetics. Soil samples were wetted to field capacity and kept at 38°C for 14 days prior to incubation. One treatment included drying and rewetting soil samples over the 26-day incubation period. In the other treatment, no additional moisture was applied. Net P mineralized was measured as the increase in KCl-extractable inorganic P over the incubation period. Zero- and first-order kinetic models were evaluated to determine which best described P mineralization kinetics for the study conditions. The zero-order kinetic model is given as:

$$P_{\min} = k_o t \qquad [2.1]$$

where P$_{\min}$ is the net P mineralized (mg kg^{-1}), k_o is the mineralization rate constant (mg kg^{-1} hr^{-1}), and t is time (hr). First-order kinetic models follow the equation:

$$P_{\min} = P_1\left(1 - e^{-k_1 t}\right) \qquad [2.2]$$

where P$_1$ is the pool of mineralizable P made available (mg kg^{-1}), and k_1 is the mineralization rate constant of P$_1$ (mg kg^{-1} hr^{-1}).

A segmented two-pool kinetic model was also evaluated:

$$\begin{aligned} P_{\min} &= P_1\left(1 - e^{-k_1 t}\right) && \text{for } t < 192 \text{ hours} \\ P_{\min} &= k_o t - b_m && \text{for } t \geq 192 \text{ hours} \end{aligned} \qquad [2.3]$$

where b_m is the intercept corresponding to the net P mineralization after the lag phase. The lag phase refers to a period where immobilization occurs or there is no net mineralization. The time of 192 hours was observed as the time when the rate of net P mineralization was at a minimum.

Results from Grierson et al. (1998) indicated that a zero-order kinetic model, with k_o equal to 0.009 mg kg^{-1} hr^{-1} ($R^2 = 0.884$), best described P mineralization for undried sandy soils. Phosphorus mineralization in sandy soils that were dried and rewetted over the incubation period was best described by a segmented, two-pool, kinetic model with P_1 equal to 5.952 mg kg^{-1}, k_1 equal to 4.018 mg kg^{-1} hr^{-1}, k_o equal to 0.011 mg kg^{-1} hr^{-1}, and b_m equal to 4.134 ($R^2 = 0.923$). Net P mineralization rates observed over the incubation period are shown in Table 2.4. Overall, P mineralization was greater in the dried/rewet samples than in the undried soils.

Table 2.4 Net P mineralized in fertilized and unfertilized soil samples incubated for 26 days at 38°C (Grierson et al., 1998).

Moisture Treatment	**Unfertilized**	**Fertilized** (24 kg P ha^{-1} year^{-1})
	P mineralized (mg P kg^{-1})	
Dried and Rewet	4.11	5.43
Undried*	1.57	1.96
	P mineralization rate (mg P kg^{-1} day^{-1})	
Dried and Rewet	0.158	0.209
Undried*	0.060	0.075

* Note: “Undried” means that the soil samples were wetted to field capacity and conditioned at 38°C for 14 days prior to incubation.

Zou et al. (1992) estimated rates of gross P mineralization and immobilization in soils. Four soils (3 forest and 1 grassland) with textures ranging from loamy sand to clay loam were subjected to radiation, autoclaving, and incubation procedures in an effort to separate mineral P solubilization, solution P immobilization, and organic P mineralization processes. Radiation was applied for ten hours, autoclaving lasted five minutes, and incubation was performed for a period of one day. The radiation treatment served to halt immobilization whereas autoclaving stopped the mineralization process. Anion exchange resin bags were used to measure P release. Phosphorus mineralized was estimated as the difference between resin P from the radiation and radiation plus autoclaving treatments. Measured net P transformation rates are shown in Table 2.5. The Alfisol (forest, silty clay loam) had the highest immobilization rate at 4.3 mg P kg^{-1} day^{-1} while the Andisol (forest, silty clay loam) had the lowest rate. Mineralization rates were highest in the Alfisol at 3.8 mg P kg^{-1} day^{-1} and lowest in the Ultisol (forest, loamy sand) at 0.6 mg P kg^{-1} day^{-1}. Results also showed that mineralization of organic P to solution P was 20-60% of the total available P in forest soils and 6% in the grassland soil.

Table 2.5 Phosphorus transformation rates observed by Zou et al. (1992).

Soil	**Texture**	**Total Soil P (mg g^{-1})**	**P Transformation Rate (mg P kg^{-1} day^{-1})**		
			Solubilization (Inorganic P →Solution P)	**Immobilization (Solution P→ Organic P)**	**Mineralization (Organic P→ Solution P)**
Alfisol	Silty clay loam	1	2.6	4.3	3.8
Mollisol	Sandy loam	0.3	22.2	1.7	1.3
Ultisol	Loamy sand	0.03	2.1	1.2	0.6
Andisol	Silty clay loam	2	3.2	0	1.3

Organic P mineralization rates were investigated by Oehl et al. (2004) from agricultural soils in Switzerland. Soil samples were taken from a long-term field experiment that received three fertilizer treatments over 20 years: (1) mineral fertilizer (MIN), (2) aerobically composted farmyard manure and slurry (DYN), and (3) slightly aerobically rotted farmyard manure and slurry (ORG). Phosphorus mineralization rates after seven days were 1.5 mg P kg^{-1} day^{-1} (MIN), 1.7 mg P kg^{-1} day^{-1} (ORG), and 2.5 mg P kg^{-1} day^{-1} (DYN).

Results from four studies measuring P mineralization and immobilization rates were presented in this section. In the study of P mineralization kinetics on forest soils by Grierson et al. (1998), mineralization rate constants of 0.009 mg kg^{-1} hr^{-1} (0.216 mg kg^{-1} day^{-1}) and 0.011 mg kg^{-1} hr^{-1} (0.264 mg kg^{-1} day^{-1}) were measured. Grierson et al. (1999) reported mineralization rates of 0.288 to 0.471 mg P kg^{-1} day^{-1} on forest soils. Mineralization rates of 0.06 to 0.209 mg P kg^{-1} day^{-1} were observed by Grierson et al. (1998) for forest soils whereas mineralization rates of 0.6 to 3.8 mg P kg^{-1} day^{-1} were reported by Zou et al. (1992) for three forest and one grassland soil. Oehl et al. (2004) observed P mineralization rates of 1.5 to 2.5 mg P kg^{-1} day^{-1} for agricultural soils. Zou et al. (1992) observed P immobilization rates ranging from 0 to 4.3 mg P kg^{-1} day^{-1}. Lower amounts of P were mineralized from the forest soils than from the agricultural soils. This may be due to greater amounts of soil organic P in agricultural soils due to additions of organic P from manure.

2.4.2 FLOW RATES BETWEEN PHOSPHORUS POOLS

Phosphorus pool sizes along with transformation rates play a major role in determining P availability (Zou et al., 1992). The size of the soil solution P pool is influenced by the equilibrium between soil sorption, soil solution, and precipitated P compounds (McDowell and Sharpley, 2003). In acidic soils, Al, Fe, and clay content dominate the P release rate, while calcium carbonate ($CaCO_3$) and clay content control the rate of P release in calcareous soils (Sharpley, 1983).

A study by Reddy et al. (1999) on a Vertisol with very fine clay loam (hyperthermic Typic Haplustert) in a semi-arid tropical climate found the ratio of labile P to moderately labile P to stable P pools to be 1: 2.9: 7.6. Inorganic and organic labile P extracted by sodium bicarbonate ($NaHCO_3$) was approximately 5.1% and 3.6% of the total soil P, respectively. The moderately labile P extracted with sodium hydroxide (NaOH) made up 10.1% (inorganic) and 15.2% (organic) of the total soil P. Stable P forms made up approximately 29.3% (HCl-extractable P) and 36.7% (residual-P) of total soil P.

Phosphorus pool sizes were measured by Zou et al. (1992) for four soil types to estimate daily P transformation rates (Table 2.6). A Mollisol (grassland, sandy loam) had the highest net change in the solution P pool whereas an Ultisol (forest, loamy sand) had the lowest. Generally, net changes in the organic P pool were relatively low.

Table 2.6 Net changes in P pool sizes after one day of incubation as measured by Zou et al. (1992).

Soil	**Net Changes in P Pool Size (mg P kg^{-1} soil)**	
	Solution P Pool	**Organic P Pool**
Alfisol	+ 2.1	+0.5
Mollisol	+21.8	+0.4
Ultisol	+ 1.5	+0.6
Andisol	+ 4.5	-1.3

McDowell and Sharpley (2003) studied the rate of P release to solution by desorption and dissolution reactions for three soils under varying STP concentrations. A power-function equation (Aharoni and Sparks, 1991) best described the kinetics of P release:

$$Q_p = \alpha t^{\beta} \qquad [2.4]$$

where Q_p is the amount of P released (mg kg^{-1}) in the desorption time t (min), α is the concentration of the initial P pool, and β is the rate of change in P release with time. Overall, results indicated that α increases with increasing STP values as measured by Olsen P while β decreases.

2.4.3 PHOSPHORUS SORPTION

Phosphorus sorption is the attachment of phosphate ions to soil surfaces. Initially, desorption reactions from soil surfaces are the major processes contributing to P release, however, over time a large part of P released will be due to dissolution from soil particles (McDowell and Sharpley, 2003). The P sorption process occurs rapidly in the first hours or days after the addition of P to the soil, but then ultimately decreases (Maguire et al., 2001a). The size and stability of soil aggregates (Linquist et al., 1997a) as well as clay content (He et al., 1999) affect P sorption-desorption reactions.

Phosphorus sorption is also affected by organic acids produced during decomposition of organic fertilizers (Siddique and Robinson, 2003). Organic acids can adsorb to soil particles, decreasing the number of available sites for P adsorption (Grossl and Inskeep, 1991) and thereby increasing P availability in the soil solution (Siddique and Robinson, 2003). Reactions of organic acids with Fe and Al form stable compounds that compete with P for available P retention sites (Cavallaro et al., 1993; Hue, 1991).

A model to describe the desorption kinetics of P release to surface runoff was developed by Sharpley et al. (1981b):

$$P_d = K_k \, P_o \, t^{\alpha_k} \, W^{\beta_k} \qquad [2.5]$$

where P_d is the amount of P desorbed over time t, W is the water to soil ratio, P_o is the amount of initial desorbable P, and K_k, α_k, and β_k are soil specific constants. Sharpley et al. (1981a) modified eqn. 2.5 to account for higher water to soil ratios over longer periods of time, which would make the model more applicable to describe P desorption from soil surfaces during rainfall events. The modified equation given by Sharpley et al. (1981a) is:

$$C_{ro} = \frac{\left[K_k \, P_o \, S \, t^{(\alpha_k - 1)} \, W^{\beta_k}\right]}{r_r} \qquad [2.6]$$

where C_{ro} is the concentration of desorbed P in runoff, S is the mass of soil in the zone of interaction, r_r is the rate of rainfall, and K_k, P_o, W, t, α_k, and β_k are as defined previously.

Hansen et al. (1999) developed a 'lag-linear' empirical model to describe P sorption kinetics and distinguish between the fast reaction, lag phase, and slow reaction:

$$\begin{array}{lll} \text{Fast Reaction}: & \ln P_{sol} = A - B \times \ln(t+1) & \\ \text{Lag Phase}: & \ln P_{sol} = A & \mathit{for}\ 0 \le t \le t_L \\ \text{Slow Reaction}: & \ln P_{sol} = A - B \times \ln\left(\dfrac{t+1}{t_L+1}\right) & \mathit{for}\ t > t_L \end{array} \qquad [2.7]$$

where P_{sol} is the concentration of P in solution (μM), A is the amount of fast-adsorbed P, B is an adsorption rate parameter, and t_L is the duration of the lag in the initiation of the slow adsorption reaction (min). The fast reaction occurs during the first minute. The lag phase occurs during the transition from fast to slow reaction. The slow adsorption reaction represents P adsorption over time when the amount of sorption remains relatively constant.

The Langmuir equation is the most common means of describing solid to solution reactions in soils (Vadas and Sims, 1999). The Langmuir equation can be expressed as (Castro and Rolston, 1977):

$$X = \frac{b_{\max} K C_w}{1 + K C_w} \qquad [2.8]$$

where X is the P sorption by the soil (mg P kg^{-1} soil), C_w is the concentration of P in solution at equilibrium (mg P L^{-1}), b_{max} is the P sorption maximum on the soil (mg P kg^{-1} soil), and K is the constant related to binding strength.

The Freundlich equation has also been used to describe P adsorption to soils and is given by the equation (Havlin et al., 1999):

$$X = a_f (C_w)^{b_f} \qquad [2.9]$$

where a_f and b_f are soil dependent coefficients. The Freundlich equation does not include a P adsorption maximum as in the Langmuir equation.

The P sorption-desorption process was studied by He et al. (1999) to assess the potential of P leaching in a fertilized sandy soil in Florida. Phosphate sorption was measured for P solution concentrations of 0, 2.5, 5, 7.5, 10, 15, and 20 mg P L^{-1}. Using the Langmuir equation, He et al. (1999) found that the amount of P sorbed increased with increasing solution P concentrations to about 10 mg L^{-1} (Figure 2.2). At solution P concentrations of 10 to 14 mg L^{-1} the increase in P sorption began to decline with the maximum sorption occurring at solution P concentrations of 14 to 18 mg L^{-1}. Results from He et al. (1999)

indicate that the Riviera fine sandy soil has a low capacity to sorb P and a high potential to leach P due in part to the low clay content of the soil.

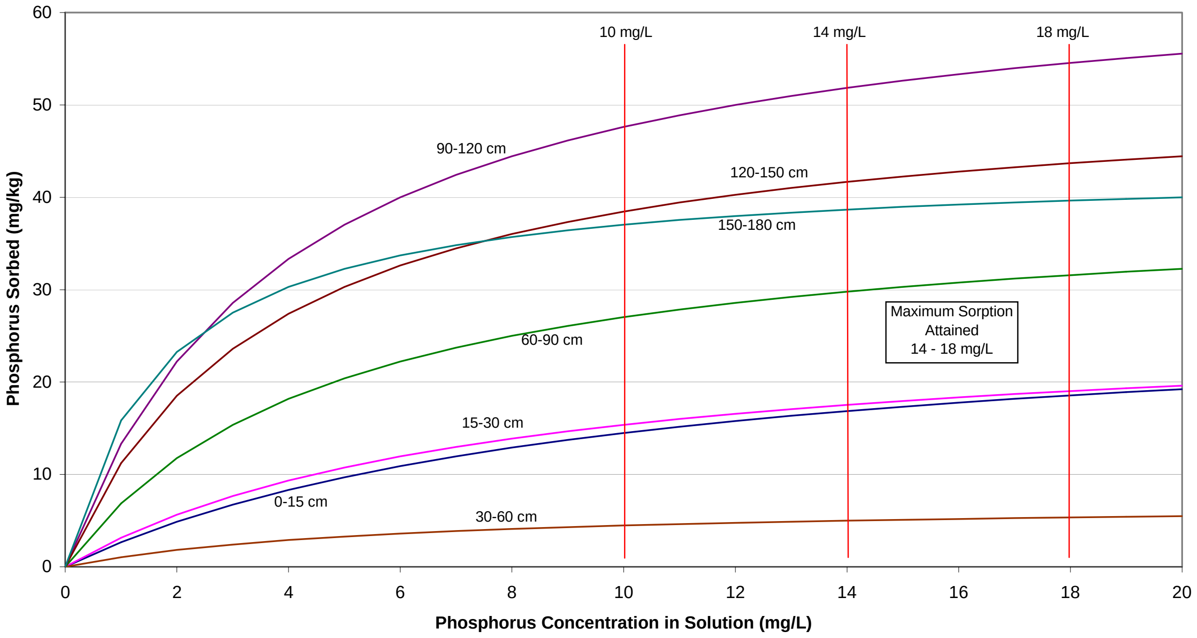

Figure 2.2 Phosphate sorption isotherms developed from the Langmuir equation by He et al. (1999) for a fertilized sandy soil.

Akhtar et al. (2003) developed P adsorption isotherms while studying preferential transport of solution P. Five different soils ranging from sandy loam to clay loam textures were sampled. Soil columns 36 cm in diameter were subjected to low intensity rainfall enriched with inorganic and organic P and ponding conditions. The P adsorption partitioning coefficient (k_d) was calculated by finding the tangent to the Langmuir isotherm at a concentration of 10 mg P L^{-1} in solution at equilibrium. Equation [2.8] was differentiated with respect to C_w:

$$\frac{dX}{dC_w} = \frac{b_{\max} K}{1 + KC_w} - \frac{b_{\max} K^2 C_w}{(1 + KC_w)^2} \qquad [2.10]$$

and simplified as:

$$k_d = \frac{1}{1 + KC_w}\left[b_{\max} K - \frac{b_{\max} K^2 C_w}{(1 + KC_w)}\right] \qquad [2.11]$$

Phosphorus adsorption coefficients are presented in Table 2.7. These values ranged from 1.4 to 26.1 L kg^{-1}. The Genesse and Lackawanna soils had the highest P partitioning coefficients and sorbed the most P. Results from Akhtar et al. (2003) indicated the adsorption coefficient only partially explained P transport through the soil profile in drainage water and that P loss through leaching is also dependent on soil structure and moisture content.

Table 2.7 Phosphorus adsorption parameters as determined by Akhtar et al. (2003).

Soil Series	Soil Texture	Adsorption Partitioning Coefficient, k_d (L kg^{-1})	Maximum soil P sorption, b_{max} (mg P kg^{-1} soil)	Constant Related to Binding Strength, K (L mg^{-1})
Surface Horizon A(p)				
Arkport	Very fine sandy loam	4.8	556	0.011
Hudson	Silt loam	6.5	526	0.017
Honeoye	Loam	12.4	1250	0.013
Genesse	Silt loam	22.6	1430	0.025
Lackawanna	Channery silt loam	19.5	1250	0.023
Subsurface Horizon (Bw, B/E)				
Arkport	Loamy fine sand	1.4	910	0
Hudson	Silty clay	10.7	1670	0
Honeoye	Loam	4.6	1430	0
Genesse	Loam	24.7	1670	0.02
Lackawanna	Channery loam	26.1	1250	0.04

Siddique and Robinson (2003) evaluated P sorption and availability on five soils fertilized with organic and inorganic sources of P. Soils were planted to wheat (*Tritucum aestvium*) and corn (*Zea mays L.*) and amended with four organic wastes: cattle slurry, poultry litter, poultry manure, and sewage sludge. Potassium phosphate (KH_2PO_4) was the inorganic fertilizer P applied. The binding energy, K, was determined from the Langmuir P sorption isotherm (Table 2.8). Addition of P fertilizer in both organic and inorganic forms significantly ($P<0.05$) reduced the soil's P binding energy. Addition of P in the form of cattle slurry and KH_2PO_4 resulted in larger decreases in P binding energy than did applications of poultry litter, poultry manure, and sewage sludge. Phosphorus adsorption coefficients were not measured. Applying eqn. 2.11 to parameters measured by Siddique and Robinson (2003) yielded estimated values for P adsorption partitioning coefficients at 10 mg P L^{-1} concentration in solution at equilibrium ranging from 0.4 to 18.2 L kg^{-1} (Table 2.9).

Table 2.8 Soil phosphorus binding energy as determined by the Langmuir equation (Siddique and Robinson, 2003).

Soil Series	Clay Content	Olsen P	P Source Added at Rates Equivalent to 100 mg P kg^{-1}					
			Control	Poultry Litter	Poultry Manure	Cattle Slurry	Sewage Sludge	KH_2PO_4
	%	mg kg^{-1}	P Binding Energy of Soil, K (L mg^{-1})					
Yattendon	25	15	0.160	0.143	0.140	0.095	0.132	0.120
Swanwick	18	44	0.142	0.103	0.100	0.048	0.105	0.056
Wickham	20	62	0.145	0.112	0.110	0.040	0.108	0.041
Sonning (I)	14	92	0.060	0.049	0.078	0.011	0.081	0.051
Sonning (II)	15	134	0.039	0.036	0.042	0.019	0.043	0.023

Table 2.9 Estimated phosphorus adsorption partitioning coefficients for data collected by Siddique and Robinson (2003).

Soil Series	P Source Added at Rates Equivalent to 100 mg P kg^{-1}					
	Control	Poultry Litter	Poultry Manure	Cattle Slurry	Sewage Sludge	KH_2PO_4
	Estimated Phosphorus Adsorption Partitioning Coefficient, k_d (L kg^{-1})					
Yattendon	18.2	17.3	17.3	14.7	17.5	15.5
Swanwick	6.7	6.4	6.5	4.9	6.2	5.4
Wickham	7.6	6.4	6.4	4.5	6.7	5.2
Sonning (I)	3.4	2.1	2.5	0.4	2.1	1.3
Sonning (II)	3.9	3.3	3.7	1.6	3.2	2.1

Fang et al. (2002) estimated the sorption energy constant while studying the effectiveness of P sorption saturation and STP methods to predict P loss in runoff from ten calcareous soils. Soils were collected from land planted to corn and soybean [*Glycine max* (L.) Merr.] and used as pasture for sheep. An expanded Langmuir model was used to calculate the sorption energy constant. Values of the sorption energy constant as well as other soil properties are shown in Table 2.10. Fang et al. (2002) did not measure P adsorption coefficients, therefore eqn. 2.11 was used to estimate the P adsorption partitioning coefficients for these data at a concentration of 10 mg P L^{-1} in solution at equilibrium. Estimated P adsorption partitioning coefficients ranged from 0.6 to 2.2 L kg^{-1}.

Table 2.10 Soil phosphorus sorption parameters for Fang et al. (2002).

Soil	Clay (%)	Total P (mg kg^{-1})	Sorption Maximum (mg kg^{-1})	Sorption Energy Constant (L mg^{-1})	Estimated P Adsorption Partitioning Coefficient, k_d (L kg^{-1})[a]
Morris East Up	41	782	245	1.25	1.7
Morris East Mid	36	1,110	340	1.37	2.2
Morris East Low	33	871	268	1.44	1.6
Morris West Up	41	643	237	1.77	1.2
Morris West Mid	42	585	226	1.77	1.1
Ivanhoe Up	54	661	224	1.57	1.3
Ivanhoe Low	57	774	281	1.79	1.4
Lamberton Mid	36	453	182	2.55	0.7
St. Peter Mid	33	351	202	3.00	0.6
St. Peter Low	49	627	225	2.44	0.9

[a] Phosphorus adsorption coefficients were not measured by Fang et al. (2002) and were estimated with equation 2.11.

He et al. (1999) studied P sorption reactions to assess the leaching potential of a Riveria fine sand in Florida. The Langmuir equation was used to estimate P sorption parameters. These parameters were input into Eqn. 2.11 to estimate the P adsorption partitioning coefficient of the soil at an equilibrium concentration of 10 mg P L^{-1} (Table 2.11). Results showed that clay content of the Riveria fine sand was correlated (R^2=0.87) to the soil's maximum sorption capacity, suggesting that soils with lower clay contents have a lower capacity for phosphate sorption.

Table 2.11 Soil phosphorus sorption parameters determined from the Langmuir equation for a Riveria fine sand (He et al., 1999).

Depth (cm)	Clay (%)	Olsen P (mg kg^{-1})	Sorption Binding-Energy Constant (L mg^{-1})	Sorption Maximum (mg kg^{-1})	Estimated P Adsorption Partitioning Coefficient, k_d (L kg^{-1}) [a]
0-15	1.4	6.42	0.103	28.4	0.7
15-30	1.4	4.12	0.130	27.1	0.7
30-60	0.4	10.00	0.142	7.0	0.2
60-90	1.5	11.50	0.207	40.4	0.9
90-120	22	5.35	0.271	65.7	1.3
120-150	18	6.27	0.277	52.2	1.0
Ultisol	--	--	1.374	606.4	3.8
Goethite	--	--	6.060	3,482	5.6

[a] Phosphorus adsorption coefficients were not measured by He et al. (1999) and were estimated with equation 2.11.

2.5 PHOSPHORUS TRANSPORT

2.5.1 PHOSPHORUS LOSS IN RUNOFF

Phosphorus in surface runoff can be in dissolved and particulate forms. The majority of dissolved P is orthophosphate ($H_2PO_4^-$ or HPO_4^{2-}) and is readily available for algal growth (Walton and Lee, 1972). In contrast, organic and colloidal forms of P are not immediately bioavailable (Lean, 1973; Rigler, 1968). Particulate forms of P in runoff are caused by erosion and consist of P adsorbed to soil surfaces and organic matter. In fields under conventional tillage management, 75-95% of P loss is in particulate form (Sharpley et al., 1994).

2.5.1.1 DISSOLVED PHOSPHORUS LOSS IN RUNOFF

A number of researchers (Andraski and Bundy, 2003; Andraski et al., 2003; Daverede et al., 2003; Fang et al., 2002; Gaston et al., 2003; McDowell and Sharpley, 2001a; Pote et al., 1996; Robinson et al., 1994; Torbert et al., 2002) have analyzed the relationship between soil P measurements and dissolved P losses through surface runoff. Several variables such as dissolved P, dissolved reactive P (DRP), soluble P, and dissolved molybdate reactive P are used to describe solution forms of P. It is important to identify which P analysis method is used so that there is no confusion or room for misinterpretation (Pierzynski, 2000). The analysis methods used to measure P loss in runoff for each reference cited in this section are shown in Table 2.12.

Table 2.12 Phosphorus analysis method used to determine concentrations of dissolved P in runoff. All runoff samples for references were filtered prior to P analysis.

Reference	**Variable Used**	**Phosphorus Analysis Method**	**Phosphorus Analysis Method Reference**
Andraski and Bundy (2003)	Dissolved P	Ascorbic acid	Murphy and Riley (1962)
Andraski et al. (2003)	Dissolved P	Ascorbic acid	Murphy and Riley (1962)
Daverede et al. (2003)	Dissolved Reactive P [a]	Ascorbic acid	American Public Health Association (1995)
Fang et al. (2002)	Soluble Reactive P	Ascorbic acid	Murphy and Riley (1962), American Public Health Association (1995)
Gaston et al. (2003)	Dissolved P	Method 4500-P B and Method 4500-P D [b]	American Public Health Association (1995)
McDowell and Sharpley (2001a)	Dissolved Reactive P [a]	Not Available	Murphy and Riley (1962)
Pote et al. (1996)	Dissolved Reactive P [a]	Molybdenum-blue	Murphy and Riley (1962)
Robinson et al. (1994)	Dissolved P	Colorimetric determination	Murphy and Riley (1962)
Torbert et al. (2002)	Dissolved molybdate reactive P	Colorimetrically with ascorbic acid reduction	Pote and Daniel (2000)

[a] Dissolved reactive P refers to the fraction of P that is immediately available for algal uptake (Walton and Lee, 1972; Peters, 1981).

[b] Method 4500-P B refers to a sulfuric-nitric acid digestion; Method 4500-P D is the colorimetric determination of orthophosphate with the stannous chloride method (American Public Health Association, 1995).

Relationships developed to associate concentrations of dissolved P in surface runoff with STP methods are shown in Table 2.13. Andraski and Bundy (2003) conducted field experiments on three soils planted to corn in Wisconsin: a forest-derived silty soil, a prairie-derived silty soil, and a forest-derived clayey soil. The purpose of the study was to determine the effect of four treatments (tillage, manure additions, STP method, and soil sampling depth) on the relationship between STP levels and P concentrations in surface runoff. Simulated rainfall was applied at a rate of 75 mm h^{-1}. Equations presented in Table 2.13 are for STP levels sampled from 0-15 cm depth.

Table 2.13 Equations describing the relationships between STP methods and dissolved P in surface runoff.

Reference	Crop/Location	# of Data Points	Soil Type	Equation	Y	X	R^2
Andraski and Bundy (2003)							
	No-till and chisel-plowed corn/Wisconsin	98	Lancaster and Arlington; well-drained silt loam	$Y = 0.0024x + 0.015$	Dissolved P in Runoff (mg L^{-1})	Bray-1 P (mg kg^{-1})	0.65
		28	Fond du Lac; poorly drained silty clay loam	$Y = 0.012x - 0.08$	Dissolved P in Runoff (mg L^{-1})	Bray-1 P (mg kg^{-1})	0.66
Andraski et al. (2003)							
	Chisel-plowed corn/Wisconsin	14	Plano silt loam	$Y = 1.03x + 11$	Dissolved P load in Runoff (g ha^{-1})	Bray-1 P (mg kg^{-1})	0.64
		16	Rozetta silt loam	$Y = 0.93x + 3.41$	Dissolved P load in Runoff (g ha^{-1})	Bray-1 P (mg kg^{-1})	0.52
Daverede et al. (2003)							
	No-till; corn-soybean rotation/Illinois	29	Tama silty clay loam	$Y = \frac{0.8}{\left[1+\exp\left(-\frac{x-167}{59.2}\right)\right]}$	Dissolved Reactive P in Runoff (mg L^{-1})	Bray-1 P (mg kg^{-1})	0.87
	Chisel-plowed; corn-soybean rotation/Illinois	24	Tama silty clay loam	$Y = 0.0008x - 0.01$	Dissolved Reactive P in Runoff (mg L^{-1})	Bray-1 P (mg kg^{-1})	0.85
Torbert et al. (2002)							
	Permanent pasture/Texas	6	Windthorst sandy loam and Blanket clay loam (non-calcareous)	$Y = (2.276 \times 10^{-2})\,x + 0.2225$	Dissolved P in runoff (mg L^{-1})	Water extractable P (mg kg^{-1})	0.87
		6	Purves clay and Houston Black clay (calcareous)	$Y = (1.013 \times 10^{-2})\,x + 0.1493$	Dissolved P in runoff (mg L^{-1})	Water extractable P (mg kg^{-1})	0.55
		6	Windthorst sandy loam and Blanket clay loam (non-calcareous)	$Y = (3.395 \times 10^{-3})\,x + 0.3550$	Dissolved P in runoff (mg L^{-1})	Mehlich-3 P (mg kg^{-1})	0.68
		6	Purves clay and Houston Black clay (calcareous)	$Y = (1.176 \times 10^{-3})\,x + 0.1486$	Dissolved P in runoff (mg L^{-1})	Mehlich-3 P (mg kg^{-1})	0.67

Table 2.13 continued

Reference	Crop/Location	# of Data Points	Soil Type	Equation	Y	X	R^2
Fang et al. (2002)							
	Corn, soybean, and pasture/ Minnesota	10	Clay loam, silty clay loam, and clay	Y = 5.83x – 67.83	Soluble Reactive P in Runoff (μg L^{-1})	Mehlich-3 P (mg kg^{-1})	0.96
				Y = 9.41x – 63.61	Soluble Reactive P in Runoff (μg L^{-1})	Olsen P (mg kg^{-1})	0.95
				Y = 5.69x – 216.09	Soluble Reactive P in Runoff (μg L^{-1})	NaOH P (mg kg^{-1})	0.81
				Y = 64.47x – 40.62	Soluble Reactive P in Runoff (μg L^{-1})	Water Extractable P (mg kg^{-1})	0.93
				Y = 16.45x – 194.79	Soluble Reactive P in Runoff (μg L^{-1})	Iron oxide paper (mg kg^{-1})	0.78
				Y = 9.86x – 7.64	Soluble Reactive P in Runoff (μg L^{-1})	Bray-1 P (mg kg^{-1})	0.61
				Y = 1.07x – 463.14	Soluble Reactive P in Runoff (μg L^{-1})	Total P (mg kg^{-1})	0.75
Robinson et al. (1994)							
	Native grass and no-till wheat, sorghum, peanuts/OK and TX	20	Cobb fine sandy loam, Kirkland silt loam, Pullman clay loam, Woodward loam	Y = 0.75x + 0.01	Fe-oxide strip P (mg L^{-1})	Dissolved P in runoff (mg L^{-1})	0.98
	Conventionally tilled wheat/OK and TX	20	Kirkland silt loam and Pullman clay loam	Y = 0.90x + 0.04	Fe-oxide strip P (mg L^{-1})	Dissolved P in runoff (mg L^{-1})	0.98
Pote et al. (1996)							
	Fescue/Arkansas	54	Captina silt loam	Y = 0.0026x + 0.30	DRP in runoff (mg L^{-1})	Mehlich-3 P (mg kg^{-1})	0.72
			Captina silt loam	Y = 0.0022x +0.31	DRP in runoff (mg L^{-1})	Bray-Kurtz-1 P (mg kg^{-1})	0.75
			Captina silt loam	Y = 0.0088x +0.11	DRP in runoff (mg L^{-1})	Olsen P (mg kg^{-1})	0.72
			Captina silt loam	Y = 0.0118x + 0.10	DRP in runoff (mg L^{-1})	Water extractable P (mg kg^{-1})	0.82
			Captina silt loam	Y = 0.0013x + 0.19	DRP in runoff (mg L^{-1})	NH_4-oxalate (mg kg^{-1})	0.85
			Captina silt loam	Y = 0.0077x + 0.10	DRP in runoff (mg L^{-1})	Fe_2O_3 paper (mg kg^{-1})	0.82

Table 2.13 continued

Reference	Crop/Location	# of Data Points	Soil Type	Equation	Y	X	R^2
Gaston et al. (2003)							
	Bermudagrass/ Louisiana	11	Malbis fine sandy loam, Sacul very fine sandy loam, and Darley gravelly fine sandy loam	Y = 0.00218x + 2.47	Dissolved P in Runoff (mg L^{-1})	Total P (mg kg^{-1})	0.39
			Malbis, Sacul, and Darley	Y = 0.00498x + 2.81	Dissolved P in Runoff (mg L^{-1})	Bray-1P (mg kg^{-1})	0.35
				Y = 0.00519x + 2.55	Dissolved P in Runoff (mg L^{-1})	Bray-2 P (mg kg^{-1})	0.46
				Y =0.00505x + 2.64	Dissolved P in Runoff (mg L^{-1})	Mehlich-3 P (mg kg^{-1})	0.36
				Y = 0.0169x + 2.43	Dissolved P in Runoff (mg L^{-1})	Resin-exchangeable P (mg kg^{-1})	0.54
				Y = 0.136x + 1.52	Dissolved P in Runoff (mg L^{-1})	Water-extractable P (mg L^{-1})	0.64
McDowell and Sharpley (2001a)							
	Soybean/ Pennsylvania	52	Alvira, Berks, Calvin, and Watson channery silt loams	Y = 0.41x + 0.09	DRP in surface runoff (mg L^{-1})	Water extractable P (mg L^{-1})	0.86
	Wheat and grassland/ United Kingdom	16	Denbigh silt loam	Y = 0.36x	DRP in surface runoff (mg L^{-1})	Water extractable P (mg L^{-1})	0.92
	Soybean/ Pennsylvania	16	Calvin channery silt loam	Y =0.0017x + 0.14	DRP in surface runoff (mg L^{-1})	Mehlich-3 P (mg kg^{-1})	0.65
	Soybean/ Pennsylvania	16	Watson channery silt loam	Y = 0.0019x + 0.03	DRP in surface runoff (mg L^{-1})	Mehlich-3 P (mg kg^{-1})	0.62
	Wheat/ United Kingdom	8	Denbigh silt loam	Y =0.004x – 0.03	DRP in surface runoff (mg L^{-1})	Olsen P (mg kg^{-1})	0.95
	Grassland/ United Kingdom	8	Denbigh silt loam	Y =0.069x + 2.36	DRP in surface runoff (mg L^{-1})	Olsen P (mg kg^{-1})	0.95

In another study, the effects of long-term manure application and tillage on dissolved P losses in runoff were examined by Andraski et al. (2003). Steel frames (91 cm by 91 cm by 30 cm) were used to contain runoff in plots planted to corn. Rainfall was simulated at a rate of 75 mm h^{-1}. STP values and dissolved P loads in runoff from soils under no-till conditions were poorly correlated ($R^2 = 0.13$) (data not shown). Dissolved P loads in runoff under chisel plow systems were related to STP values for a silt loam soil (Table 2.13).

A study by Daverede et al. (2003) also observed the effects of tillage and STP levels on P in runoff. A randomized complete block design with two replications was used where each block consisted of eight 9-m by 6-m plots planted to a corn-soybean rotation. Rainfall was simulated at a rate of 95±12 mm h^{-1}. Unlike Andraski et al. (2003), Daverede et al. (2003) found an exponential relationship between STP levels as measured by Bray-1 and DRP concentrations in runoff under no-till conditions. A linear relationship between STP and dissolved reactive P in runoff ($R^2 = 0.85$ to 0.87) was found for plots under chisel-plow tillage (Table 2.13).

Dissolved molybdate reactive P (DMRP) in surface runoff was related to two STP methods of distilled water and Mehlich-3 by Torbert et al. (2002). Calcareous and non-calcareous soils under permanent pasture in Texas were sampled at varying depths in six surface runoff plots, each measuring 2 m by 3 m. Rainfall simulation was employed at a rate of 50 mm h^{-1} to produce 30 min of surface runoff. Results showed that calcareous soils had lower concentrations of DMRP in runoff than non-calcareous soils, which was attributed to P reactions with free $CaCO_3$ that resulted in less soluble soil P at higher levels of total P (Torbert et al., 2002).

Soluble reactive P in runoff from calcareous soils was analyzed by Fang et al. (2002). Ten soil samples (0-20 cm depth) were collected from five sampling sites planted to corn, soybean, and pasture. Each sample was placed in a box (0.61 m by 0.15 m by 0.10 m) and received simulated rainfall at a rate of 60 mm h^{-1} for 30 min. Linear relationships between several STP methods and soluble reactive P in runoff were determined.

Robinson et al. (1994) collected runoff samples from 20 agricultural watersheds under natural rainfall in Oklahoma and Texas during a three-year period. Watershed areas ranged from 1.6 to 5.6 ha and slopes were between 1 and 8%. Linear relationships between dissolved P in runoff and Fe-oxide strip P were developed for conventionally tilled wheat and no-till wheat, sorghum (*Sorghum vulgare*), peanuts (*Arachis hypogea*) and native grass watershed management and are shown in Table 2.13.

Pote et al. (1996) completed a plot study (54 plots, each 1.5 m by 6 m with 5% slope) on a Captina silt loam planted to fescue to compare soil P extraction methods with concentrations of dissolved reactive P in runoff for soils with a mean Mehlich-3 P value of 198 mg P kg^{-1}. Rainfall was simulated at 100 mm h^{-1} intensity to generate 30 min of runoff. The mean DRP concentration in runoff ranged from 0.31 to 1.81 mg P L^{-1} and was 83% of the bioavailable P runoff concentration (Pote et al., 1996).

Correlations (R^2 ranging from 0.35 to 0.64) between dissolved P in runoff and STP methods were found by Gaston et al. (2003) at four sites in north Louisiana. Soils categorized as fine, very fine, and gravelly fine sandy loams were planted to bermudagrass (*Cynodon dactylon*). Experimental plots were 2.1 m^2 and received simulated rainfall at a rate of 74±8 mm h^{-1}. Results indicated the predominant form of P in total runoff was dissolved orthophosphate (volume-averaged concentration of 96%). Table 2.14 shows the concentration of total and dissolved P in runoff. Gaston et al. (2003) noted that the use of STP methods to predict dissolved P concentrations in runoff for multiple soil types does not account for variation in infiltration rates.

Table 2.14 Soil P and runoff P concentration results from Gaston et al. (2003).

		Soil P Concentration (mg kg^{-1})		Runoff Concentration (mg L^{-1})	
Site	Date	Total P	Mehlich-3 P	Total P	Dissolved P
1	June 1998	86	9	5.12	4.85
	June 1999	50	5	2.22	2.20
	Dec 1999	73	13	0.84	0.76
2	June 1998	139	55	7.26	7.12
	June 1999	162	64	2.03	2.03
	Dec 1999	170	68	1.50	1.32
3	June 1998	623	323	6.18	5.93
	June 1999	457	240	5.53	5.49
	Dec 1999	479	292	3.81	3.76
4	June 1998	887	477	7.83	7.65
	June 1999	888	462	5.34	5.34

McDowell and Sharpley (2001a) developed relationships to predict DRP in runoff as a function of three STP methods. Soil was collected from 72 sites in a 39.5 ha sub-watershed in Pennsylvania and 16 sites in a 9.5 ha sub-watershed located in Devon, United Kingdom. Soil samples were placed inside impermeable boxes (Pennsylvania: 100 cm by 15 cm by 15 cm with 5% slope; United Kingdom: 100 cm by 15 cm by 7.5 cm with 5% slope). Simulated rainfall was applied for 30 min at an intensity of 50 mm h^{-1}. Results indicated positive correlations (R^2 =

0.62 to 0.95) between DRP in runoff and water extractable P, Mehlich-3 P, and Olsen P STP methods (Table 2.13).

In a study investigating the dependence of runoff P on extractable soil P, Sharpley (1995) applied poultry litter collected from broiler houses to soils placed in impermeable-bottom boxes (1 m by 0.15 m by 0.15 m). Poultry litter was applied at varying rates ranging from 0 to 20 Mg ha^{-1} and was incorporated into the top 5 cm of soil. Soils were sampled from LeFlore and McCurtain counties in Oklahoma. Historically, these soils annually received10 Mg ha^{-1} poultry litter under fescue. The impermeable-bottom boxes received simulated rainfall applications. The objective was to quantify the relationship between runoff and soil P with respect to soil type under constant rainfall intensity, slope, and management (Sharpley, 1995). The dissolved P concentration in runoff was well correlated (R^2 of 0.90 to 0.96) to the Mehlich-3 P surface soil concentration one week after application of poultry litter. Sharpley (1995) reported increases in the concentrations of dissolved, particulate, and bioavailable P in runoff as the rate of P applied as poultry litter increased.

The relationships presented in this section attempted to predict dissolved P in runoff based on a single variable, STP. Each equation was determined for site-specific conditions. Applicability of these relationships to a wide variety of soils is unknown. The transport of dissolved P is not solely related to STP; other factors such as hydrology and topography play a major role in P transport (Sharpley et al., 1996).

2.5.1.2 BIOAVAILABLE PHOSPHORUS IN RUNOFF

Bioavailable P is that available for algae growth and may contain dissolved and sediment-bound P (Sharpley, 1993). Bioavailable P loss as dissolved and particulate P in runoff has a significant impact on surface water quality (Sharpley et al., 1994; U.S. Environmental Protection Agency, 1994b). Bioavailable particulate P represents a variable 10 to 90% of the total particulate P in runoff (DePinto et al., 1981; Dorich et al., 1985, Sharpley et al., 1992). Dissolved P, which is comprised of inorganic ortho-P ions, is mostly bioavailable (Peters, 1981; Walton and Lee, 1972).

Andraski et al. (2003) and Pote et al. (1996) correlated bioavailable P in runoff with different STP methods. In the same study in which Pote et al. (1996) determined linear relationships between P extractant methods and dissolved P in runoff, relationships for STP values and bioavailable P concentration in surface runoff were also established. These relationships as well as those developed by Andraski et al. (2003) and Fang et al. (2002) are shown in Table 2.15. Bioavailable P concentrations in runoff ranging from 0.37 to 2.18 mg L^{-1} were observed by Pote et al. (1996).

A quadratic relationship was developed by Daverede et al. (2003) to predict the concentration of algal-available P in runoff from a Tama silty clay loam soil (25% clay content) in Illinois. The relationship uses sediment concentration in runoff and STP concentration to find the concentration of algal-available P in runoff:

$$\begin{aligned} AAP &= 0.1 + 0.0013(B1) - 0.035(SED) + 0.00044(B1xSED) - 5.7x10^{-7}(B1)^2 \\ R^2 &= 0.82 \end{aligned} \qquad [2.12]$$

where AAP is the algal-available P concentration in runoff (mg L^{-1}), B1 is the Bray-1 P value (mg kg^{-1}), and SED is the sediment concentration in runoff (g L^{-1}). The interaction between sediment concentration in runoff and Bray-1 P soil level is represented by B1xSED. The algal-available P concentration was measured using the Fe-oxide strip P method (Sharpley, 1993). Application of this relationship to other soils may not be feasible since particle size is important for transport of sediment-bound P in runoff. Finer clay size particles (< 2 μm) have a greater number of adsorption sites and may be preferentially transported over coarser sand (0.05 to 2.0 mm).

Table 2.15 Relationships between STP values and bioavailable P concentration in surface runoff.

Reference	Crop/Location	# of Data Points	Soil Type	Equation	Y	X	R^2
Andraski et al. (2003)							
	Chisel plow; corn/Wisconsin	14	Plano silt loam	Y = 1.28x + 48	Bioavailable P load in Runoff (g ha^{-1})	Bray-1 P (mg kg^{-1})	0.72
		7	Rozetta silt loam	Y = 2.75x + 41	Bioavailable P load in Runoff (g ha^{-1})	Bray-1 P (mg kg^{-1})	0.37
Fang et al. (2002)							
	Corn, soybean, and pasture/ Minnesota	10	Clay loam, silty clay loam, and clay	Y = 6.58x + 32.44	Bioavailable P in Runoff (μg L^{-1})	Mehlich-3 P (mg kg^{-1})	0.86
				Y = 10.05x + 57.31	Bioavailable P in Runoff (μg L^{-1})	Olsen P (mg kg^{-1})	0.77
				Y = 5.86x – 87.23	Bioavailable P in Runoff (μg L^{-1})	NaOH P (mg kg^{-1})	0.61
				Y = 72.77x + 62.76	Bioavailable P in Runoff (μg L^{-1})	Water Extractable P (mg kg^{-1})	0.83
				Y = 19.55x – 139.12	Bioavailable P in Runoff (μg L^{-1})	Iron oxide paper (mg kg^{-1})	0.78
				Y = 9.58x + 143.93	Bioavailable P in Runoff (μg L^{-1})	Bray-1 P (mg kg^{-1})	0.41
				Y = 1.15x – 375.87	Bioavailable P in Runoff (μg L^{-1})	Total P (mg kg^{-1})	0.62
Pote et al. (1996)							
	Fescue/Arkansas	54	Captina silt loam	Y = 0.0030x + 0.39	Bioavailable P in runoff (mg L^{-1})	Mehlich-3 P (mg kg^{-1})	0.72
				Y = 0.0025x + 0.41	Bioavailable P in runoff (mg L^{-1})	Bray-Kurtz-1 P (mg kg^{-1})	0.73
				Y = 0.0102x + 0.17	Bioavailable P in runoff (mg L^{-1})	Olsen P (mg kg^{-1})	0.72
				Y = 0.0136x + 0.16	Bioavailable P in runoff (mg L^{-1})	Distilled H_2O (mg kg^{-1})	0.82
				Y = 0.0014x + 0.27	Bioavailable P in runoff (mg L^{-1})	NH_4-oxalate (mg kg^{-1})	0.82
				Y = 0.0090x + 0.16	Bioavailable P in runoff (mg L^{-1})	Fe_2O_3 paper (mg kg^{-1})	0.82

2.5.1.3 Sediment-Bound P in Runoff

Phosphate ions can remain in the soil solution or adsorb to the surface of clay particles. These particles can potentially erode, transporting the adsorbed P with them (Quinton et al., 2001). Erosion of soil containing sediment-bound P (or particulate P) is an important pathway for P loss from agricultural fields to receiving waters (Burwell et al., 1977; Catt et al., 1998; Garbrecht and Sharpley, 1992; Schuman et al., 1973) as particulate P represents 75 to 90% of P transported through runoff (Schuman et al., 1973; Sharpley et al., 1987). Finer soil particles, such as clay, are more likely to be preferentially transported in runoff due to a greater surface area per unit weight (McIsaac et al., 1991). Phosphorus enrichment ratios provide a means to quantify the amount of P eroded compared to the total soil lost.

Fang et al. (2002) and Sharpley (2003) developed relationships for predicting particulate P loss in runoff (Table 2.16). Fang et al. (2002) found a correlation between particulate P and total suspended solids in runoff whereas Sharpley (2003) observed exponential relationships between P enrichment ratio and sediment discharge loads of overland flow. The P enrichment ratio was calculated as particulate P in overland flow divided by total soil P. Sharpley (2003) found that, with an increase in sediment discharge, there was a decrease in preferential transport of clay-sized particles resulting in a decrease in the P enrichment ratio.

Table 2.16 Equations relating particulate P in runoff with total suspended solids in runoff and P enrichment ratio with sediment discharge.

Reference	Soil Type	Equation	Y	X	R^2
Fang et al. (2002)					
	Clay loam, silty clay loam, and clay	$Y = 1.25x + 451.13$	Runoff particulate P ($\mu g\ L^{-1}$)	Runoff Total Suspended Solids ($mg\ L^{-1}$)	0.93
Sharpley (2003)					
	Loam; plowed corn-soybean;	$Y = 14.62\ x^{(-0.29)}$	P Enrichment Ratio for soils with high STP [a]	Sediment Discharge ($kg\ ha^{-1}$)	0.79
	Loam; unplowed corn-soybean;	$Y = 6.30\ x^{(-0.41)}$	P Enrichment Ratio for soils with low STP [b]	Sediment Discharge ($kg\ ha^{-1}$)	0.63
		$Y = 8.08\ x^{(-0.32)}$	P Enrichment Ratio for soils with high STP [a]	Sediment Discharge ($kg\ ha^{-1}$)	0.99

[a] High STP = 411-495 mg kg $^{-1}$ Mehlich-3 P; [b] Low STP = 25 mg kg $^{-1}$ Mehlich-3 P

McIsaac et al. (1991) studied P in eroded sediment from agricultural fields in Illinois. A Catlin silt loam (69% silt, 29% clay, and 2% sand) soil was planted to a corn-soybean rotation. Conventional, ridge, strip-till, sub-soil ridge, disk, and no-till treatments were employed. A quadratic relationship between the eroded Bray-1 P and soil loss was found for all tillage treatments except moldboard plowing, for which a linear relationship was found (Table 2.17). Use of the moldboard plow distributed fertilizer P deeper into the soil, thus reducing the surface Bray-1 P concentration by one-third from all other treatments (McIsaac et al., 1991).

Table 2.17 Bray-1 P content of soil loss from fields planted to corn-soybean rotation (McIsaac et al., 1991).

Treatment	# of Data Points	Equation	Y	X	R^2
Conventional, ridge, strip-till, sub-soil ridge, disk, and no-till (without moldboard plow)	140	$Y = 0.209x - 0.004x^2 + 0.026$	Bray-1 P Loss in Sediment (kg P ha^{-1})	Soil Loss (Mg ha^{-1})	0.92
Conventional tillage with moldboard plow	16	$Y = 0.070x + 0.032$	Bray-1 P Loss in Sediment (kg P ha^{-1})	Soil Loss (Mg ha^{-1})	0.84

Quinton et al. (2001) found a correlation (R^2=0.89) between the percentage of clay-sized particles and particulate P concentration in runoff for all samples taken during a six-year study period:

$$y = 55.9x + 417.9 \qquad R^2 = 0.89 \qquad [2.13]$$

where y is the sediment P content (mg kg^{-1}) and x is the clay content of the eroded sediment (%). Phosphorus was selectively transported with clay particles. Eroded sediment became enriched with P with the preferential transport of clay-sized particles.

2.5.2 PHOSPHORUS LOSS THROUGH LEACHING

Phosphorus losses through subsurface transport have become an environmental concern as recent studies indicate P leaching losses are greater than previously thought (Heckrath et al, 1995; Sims et al., 1998; Hooda et al., 1999). Vertical movement of P in the soil profile and loss through leaching were not believed to be a major concern due to the high capacity of most soils to adsorb P (Heckrath et al., 1995; Sims et al., 1998; Sui et al., 1999). However, in certain conditions such as sandy soils, soils with high organic matter content, presence of preferential flow pathways, and over-fertilized soils, P leaching can occur (Eghball et al., 1996; Sims et al., 1998). Subsurface P losses can be enhanced by preferential flow through cracks and earthworm burrows (Heathwaite and Dils, 2000; Simard et al., 2000). As the degree of P saturation increases, the potential for P loss by leaching increases (Maguire et al., 2001b; McDowell and Sharpley, 2001b; Hooda et al., 2000).

Brye et al. (2002) presented a summary of field studies that compared soil P solution concentrations with P loss through leaching. P leaching losses have been estimated to be as high as 30.7 kg P ha^{-1} yr^{-1} as molybdate-reactive ortho-P under a tile drainage system (Duxbury and Peverly, 1978) and 32 kg P ha^{-1} yr^{-1} as total P measured with a zero-tension lysimeter (Sui et al., 1999).

Leinweber et al. (1999) and Maguire and Sims (2002) found correlations ($R^2= 0.684$ to 0.731 and $R^2= 0.78$ and 0.87, respectively) between the degree of P saturation and P loss through leaching. Two studies (Maguire and Sims, 2002; McDowell and Sharpley, 2001a) related STP methods to DRP concentrations in leachate. The equations for these relationships and others are shown in Table 2.18.

Maguire and Sims (2002) observed "change points" while developing relationships to predict DRP in leachate by STP methods. Leachate DRP concentrations increased slowly up until the "change point" at which time the increase became more rapid (Maguire and Sims, 2002). The leachate concentrations and the corresponding mean STP values observed by Maguire and Sims (2002) are shown in Table 2.19. For low STP levels, a linear relationship with relatively low slopes best described DRP in leachate whereas at higher STP levels, DRP concentrations in leachate sharply increased. Heckrath et al. (1995) observed a "change point" of 60 mg Olsen P kg^{-1} for P concentrations from tile drain subsurface flow. Brye et al. (2002) suggest that neither water-extractable nor Bray-extractable STP methods can reliably predict P concentrations in leachate which is likely attributed to macropore flow in the soil profile that may have prevented P adsorption of labile P.

Table 2.18 Linear equations describing the relationship between STP values and DRP concentrations in leachate.

Reference	Crop/ Location	# of Data Points	Soil Name	Equation	Y	X	R^2
Maguire and Sims (2002)							
	Unknown/ Delmarva Peninsula	111	Butlerstown, Evesboro, Matapeake, Pocomoke, and Sassafras	For $x<42.6$, $Y = 0.001x+0.097$ For $x\geq 42.6$, $Y = 0.07x-2.85$	DRP in leachate (mg L^{-1})	Iron-strip P (mg kg^{-1})	0.80
				For $x<8.6$, $Y = 0.025x-0.002$ For $x\geq 8.6$, $Y = 0.12x-0.80$	DRP in leachate (mg L^{-1})	Water-soluble P (mg kg^{-1})	0.85
				For $x<1.59$, $Y = 0.034x-0.049$ For $x\geq 1.59$, $Y = 0.25x-0.30$	DRP in leachate (mg L^{-1})	0.01 *M* $CaCl_2$-P (mg kg^{-1})	0.84
				For $x<81$, $Y = -0.0003x-0.0896$ For $x\geq 81$, $Y = 0.019x-1.617$	DRP in leachate (mg L^{-1})	Mehlich-1 P (mg kg^{-1})	0.73
				For $x<181$, $Y = 0.0003x+0.0736$ For $x\geq 181$, $Y = 0.0124x-2.1068$	DRP in leachate (mg L^{-1})	Mehlich-3 P (mg kg^{-1})	0.58
				For $x<0.20$, $Y = 0.0098x+0.108$ For $x\geq 0.20$, $Y = 28.44x-5.71$	DRP in leachate (mg L^{-1})	Mehlich-3 P Saturation Ratio	0.78
McDowell and Sharpley (2001a)							
	Soybean/ Pennsylvania	13	Watson channery silt loam	$Y = 0.009x-0.18$	DRP in drainage water (mg L^{-1})	Mehlich-3 P (mg kg^{-1})	0.89
	Wheat/UK	4	Denbigh silt loam	$Y = 0.009x-0.18$	DRP in drainage water (mg L^{-1})	Olsen P (mg kg^{-1})	0.89
	Grassland/ UK	4	Denbigh silt loam	$Y = 0.005x-0.036$	DRP in drainage water (mg L^{-1})	Olsen P (mg kg^{-1})	0.93
	Soybean/ Pennsylvania	35	Alvira, Berks, Calvin, and Watson channery silt loams	$Y = 0.8x$	DRP in drainage water (mg L^{-1})	0.01 *M* $CaCl_2$-extractable P (mg L^{-1})	0.88
	Wheat and grassland/UK	8	Denbigh silt loam	$Y = 0.82x$	DRP in drainage water (mg L^{-1})	0.01 *M* $CaCl_2$-extractable P (mg L^{-1})	0.82
Schreiber (1999)							
	Corn/ Tennessee	308	Loring soil series	$Y = (-17.38/x) + 5.23$	PO_4-P Leachate concentration (mg L^{-1})	Stover (Residue) Loading Rate (t ha^{-1})	0.68

Table 2.19 Mean soil P values for different STP methods at varying ranges of leachate DRP concentrations (Maguire and Sims, 2002).

Leachate DRP Concentration (mg P L^{-1})	*Mean Soil Extractable P (mg P kg^{-1})*				
	Iron-strip P	***Water-soluble P***	***0.01 M $CaCl_2$ P***	***Mehlich-1 P***	***Mehlich-3 P***
<0.05	21	4.5	1.1	53	109
0.05-0.10	33	8.5	2.3	97	171
0.10-1.00	29	9.2	2.7	73	139
>1.00	90	34.1	14	263	401

Schreiber (1999) predicted concentrations of phosphate in leachate based on residue loading rates (Table 2.18). Simulated rainfall was applied to corn stover at varying rainfall intensities and durations. Results showed that phosphate concentrations in leachate decreased as rainfall intensity increased. This was attributed to longer contact times between stover and rainfall at lower intensities before leachate was initialized.

A lysimeter study in Germany by Leinweber et al. (1999) compared P soil characteristics with mean annual P concentrations lost through leaching. Leinweber et al. (1999) found that use of P sorption capacity and degree of P saturation were better predictors of P leaching losses than soil P tests. Results from soil measurements taken in March and December 1996 showed that on average the soil labile P concentration was 12-13% of the total P concentration in the soil whereas the residual P (stable organic P and insoluble inorganic P) concentration was approximately 13-16% of the total soil P concentration. The soils tested had average P sorption capacities of 17.5-20.4 mmol kg^{-1} and 57-61% P saturation.

2.5.3 PLANT UPTAKE OF PHOSPHORUS

Several studies observed that plant uptake of fertilizer P depends on the nature of the crop and soils. Thus, an estimated 10 to 25% of fertilizer P applied to agricultural fields is actually taken up by the intended crop (Higgs et al., 2000; Kanwar et al., 1982; Subba Rao et al., 1995). Plant roots absorb available nutrients for growth. The availability of nutrients is dependent upon the concentration and nature of nutrients in the soil solution as well as the amount of nutrients adsorbed to soil particles (Barber, 1995).

In its simplest form, a steady-state model for plant nutrient uptake as presented by Yanai (1994) is:

$$Plant\ Uptake = (2\pi r_o L)(\theta)(C_o)(\Delta t) \qquad [2.14]$$

where $2\pi r_o L$ is the root surface area (cm^2), θ is a linear root absorption coefficient (cm s^{-1}), C_o is the concentration of solute at the root surface (mol cm^{-3}), and Δt is the change in time. The concentration of labile nutrient at the root surface is based on the average concentration of nutrient in the soil solution. Steady-state models for plant nutrient uptake are best applied to low solute conditions in the soil system. For saturated conditions, α is calculated from Michaelis-Menten kinetics (as described below) to account for non-steady-state conditions.

The Barber-Cushman model is a non-steady-state nutrient uptake model and has been used by Chen and Barber (1990) and Ernani et al. (1994) to predict P uptake by corn. Plant uptake of nutrients is based on three processes: soil nutrient supply, root morphology, and root-uptake kinetics. The following equation is used in the Barber-Cushman model to calculate diffusion and mass flow of nutrients to plant roots (Jackson and Caldwell, 1996):

$$\frac{\partial C_l}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\, D_e \frac{\partial C_l}{\partial r} + \frac{r_o v_o C_l}{b_s} \right) \qquad [2.15]$$

where C_l is the nutrient concentration in soil solution (µmol cm^{-3}), t is time (s), r is the radial distance from the root axis (cm), D_e is the effective diffusion coefficient (cm^2 s^{-1}), r_o is the mean root radius (cm), v_o is the water influx rate (cm s^{-1}), and b_s is the soil buffering capacity (unitless). Calculation of nutrient uptake in the Barber-Cushman model follows Michaelis-Menten kinetics (Jackson and Caldwell, 1996):

$$J_r = \frac{I_{\max}\left(C_l - C_{\min}\right)}{K_m + \left(C_l - C_{\min}\right)} \qquad [2.16]$$

where J_r is the net nutrient uptake (µmol cm^{-2} s^{-1}), I_{max} is the maximum influx of nutrients (µmol cm^{-2} s^{-1}), C_{min} is the nutrient concentration where influx is zero (µmol cm^{-3}), and K_m is the nutrient concentration where influx is one-half of I_{max} (µmol cm^{-3}). The net nutrient uptake is then calculated for new and existing roots as (Jackson and Caldwell, 1996):

$$T = 2\pi r_o L_o \int_0^{t_m} J_r\left(r_o, S\right) dS + 2\pi r_o \int_0^{t_m} \frac{df}{dt} \int_0^{t_m - t} J_r\left(r_o, S\right) dS\, dt \qquad [2.17]$$

where T is the total net nutrient uptake (µmol cm^{-2} s^{-1}) as time, t_m (s), L_o is the initial root length (cm), $\frac{df}{dt}$ is the rate of root growth (cm s^{-1}), and $J_r(r_o,S)$ is the net nutrient uptake for a given root diameter and surface area (µmol cm^{-2} s^{-1}).

Chen and Barber (1990) observed P uptake by corn for nearly 19 days at varying pH levels. The results showed that predicted P uptake as determined by the Barber-Cushman model was correlated with observed values. A study by Ernani et al. (1994) tested the ability of the Barber-Cushman model to predict P uptake by 46-day-old corn from highly weathered soils at two levels of P (25 and 100 mg kg^{-1}). Although results indicated a correlation (R^2=0.92) between predicted and observed P uptake, the Barber-Cushman model predicted only 36% of the P absorbed by the corn plants.

In determining the P-supplying capacities of five Missouri soils, Aquino and Hanson (1984) correlated plant P removal with extractable P as measured by Bray-1, Bray-2, Mehlich-2, and Mehlich-3 STP methods. Soils were planted to grain sorghum for seven harvest cycles. Linear regression equations (Table 2.20) were developed for the five soils to predict plant P removal based on soil extractable P.

In a study of soybean and corn on a clay soil in Maui, Hawaii, Linquist et al. (1997b) monitored soil P levels for four years. Four crops received applications of commercial P fertilizer two months prior to planting during the build-up phase (years 1 and 2). Total P fertilizer additions over the first two years were 0, 155, 310, and 930 kg P ha^{-1} for the control, low, medium, and high P level plots, respectively. A residual phase was observed by not applying any additional sources of P to the crops during years 3 and 4. Linquist et al. (1997b) observed differences in crop dry matter yield and P uptake due to variations by crop and season. During the build-up phase, as applied P rates increased, P uptake and dry matter yield also increased. Phosphorus uptake by soybean declined by 32 to 53% in the residual phase, which was attributed to lower crop yields. Linquist et al. (1997b) observed a 6 to 10% recovery of fertilizer P in the labile (plant available) P pool.

Table 2.20 Equations from Aquino and Hanson (1984) describing relationships between STP methods and plant P removal in soils planted to grain sorghum.

Soil Type	**Equation (X is the STP method)**	**STP Method (mg kg^{-1}) (Y)**	**R^2**
Sharkey clay	Y = 90.6 – 0.54x	Bray-1 P	0.95
	Y = 135.6 – 0.37x	Bray-2 P	0.87
	Y = 71.1 – 0.49x	Mehlich-2 P	0.94
	Y = 59.3 – 0.39x	Mehlich-3 P	0.90
Mexico silt loam	Y = 51.9 – 0.11x	Bray-1 P	0.82
	Y = 307.5 – 0.75x	Bray-2 P	0.95
	Y = 46.1 – 0.18x	Mehlich-2 P	0.91
	Y = 249.0 – 0.70x	Mehlich-3 P	0.94
Kennebec silt loam	Y = 52.9 – 0.43x	Bray-1 P	0.97
	Y = 82.5 – 0.48x	Bray-2 P	0.97
	Y = 48.7 – 0.47x	Mehlich-2 P	0.96
	Y = 57.6 – 0.48x	Mehlich-3 P	0.95
Broseley loamy fine sand	Y = 136.2 – 0.82x	Bray-1 P	0.87
	Y = 175.9 – 1.06x	Bray-2 P	0.90
	Y = 101.2 – 0.58x	Mehlich-2 P	0.87
	Y = 92.7 – 0.58x	Mehlich-3 P	0.86
Tiptonville silt loam	Y = 55.8 – 0.57x	Bray-1 P	0.92
	Y = 95.5 – 0.73x	Bray-2 P	0.93
	Y = 46.3 – 0.60x	Mehlich-2 P	0.96
	Y = 70.6 – 0.61x	Mehlich-3 P	0.90

2.6 FERTILIZER PHOSPHORUS

Inorganic P from commercial fertilizers and organic P from animal wastes add to soil P pools. Fertilizer P can be absorbed by plant roots or remain in the soil system and potentially be lost through surface runoff or leaching. Crops utilize an estimated 20% of fertilizer P (Kanwar et al., 1982; Subba Rao et al., 1995). Whether these additions of P are surface applied, incorporated, or applied through fertigation, application methods affect the concentrations of P loss in surface runoff and leachate (Kleinman et al., 2002). Results from Kleinman et al. (2002) showed that 64% of the total soil P surface-applied through inorganic fertilizer and manure on no-till soils was lost as DRP in runoff whereas only 9% of total P from soils with incorporated P additions was lost. Soils that did not receive inorganic or organic sources of P lost 9% of the total soil P as DRP in runoff. Surface-applied soil amendments were identified as the major source of DRP in runoff (Kleinman et al., 2002).

No-till versus chisel plow management effects on P concentrations in runoff were studied by Andraski et al. (2003). For no-till management on a well-drained silt loam soil, remaining crop residue on the soil surface led to increased infiltration and decreased erosion resulting in a reduction of P losses through runoff (57% for dissolved P, 70% for bioavailable P, and 91% for total P) as compared to chisel-plow management. Manure history was also considered and did not affect runoff volumes at low surface residue levels (13 to 25 %) for plots under chisel-plow management. However, runoff volumes were 60% lower with increasing surface residue (41 to 80%) observed in the no-till treatments with a history of manure application.

Additions of P fertilizer to soil can change the amount of extractable P potentially lost from the soil system through runoff, leaching, plant uptake, and crop harvest. Application of organic P fertilizers may lower a soil's level of P saturation (Sharpley et al., 1984a; Hue, 1990) by providing additional adsorption sites (McGechan and Lewis, 2002). Johnston et al. (1991) related the change in Bray-1 P six weeks after fertilizer application to the percent clay content for soils in South Africa for 54 soils, including Vertisols, Mollisols, Oxisols, Ultisols, and Alfisols. The change in Bray-1 P was given by:

$$CB1P = \exp(-0.033 \times CL) \qquad [2.18]$$

where CB1P is the change in Bray-1 P per kg of fertilizer P applied, and CL is the percent of clay in the soil. The change in Bray-1 P represents the change in labile P based on percent of soil clay content.

Cox (1994) related the change in Mehlich-3 extractable P per unit of applied P to the percent clay content for Ultisols in North Carolina and Oxisols in Brazil one year after fertilizer application. Three rates of P fertilizer were applied to six experimental plots to study the resulting change in soil extractable P. Experimental plots were planted with crop rotations consisting of corn, wheat, soybean, sorghum, and peanut. Soils on the plots varied in clay content from 8% to 68%. The following relationship was developed from 14 sites comprised of Ultisols and Oxisols:

$$CM3P = \exp(-0.040 \times CL) \qquad [2.19]$$

where CM3P is the change in Mehlich-3 extractable P per kg of fertilizer P applied.

Results from Cox (1994) indicated a 70% increase in Mehlich-3 extractable P per unit of applied P is expected for soils with 10% clay content. In this study with kaolinitic and gibbsitic soils containing greater than 40% clay, the change in Mehlich-3 extractable P per unit of applied P decreased to less than 20%. Results from Cox (1994) and Johnston et al. (1991) showed that lower amounts of P were extracted from soils with higher clay contents due to P adsorption to the clay surface. These studies showed that a change in STP level due to applied P is exponentially related to the clay content of the soil.

2.7 PHOSPHORUS SATURATION

Phosphorus saturation is a measure of P that has accumulated on soil particles through adsorption, relative to the number of active sites available for P retention. Saturating a soil with P can take away from the number of available sites where P adsorption can occur resulting in excess labile P in the soil-solution (Reddy et al., 1999). Phosphorus sorption saturation is a ratio of the extractable soil P to the P sorption capacity (Sharpley, 1995; Sharpley et al., 1996).

Paulter and Sims (2000) related the degree of soil P saturation with several STP methods (Table 2.21). Of the STP methods used on 122 topsoil samples from Delaware, the dilute salt-soluble P (0.01 M $CaCl_2$-P Soluble P) test had the highest correlation with degree of P saturation compared to water extractable, Mehlich-1, or iron-oxide strip P methods. The degree of soil P saturation determined by Langmuir P sorption isotherm ($DPS_{Langmuir}$) was calculated by:

$$DPS_{Langmuir} = \frac{P_{OX}}{PSC_t} \times 100 \qquad [2.20]$$

where P_{OX} is the amount of P already sorbed and PSC_t is the total P sorption capacity and is calculated as:

$$PSC_t = P_{OX} + PSC_r \qquad [2.21]$$

where PSC_r is the remaining P sorption capacity. Paulter and Sims (2000) used the P sorption maxima from the Langmuir equation to estimate PSC_r.

Table 2.21 Relationship between several STP methods and degree of P saturation (Pautler and Sims, 2000). X is the degree of P saturation determined from the Langmuir P isotherm.

Equation	**Y (mg kg^{-1})**	**R^2**
$Y = 0.026 \exp(0.061x)$	0.01 M $CaCl_2$-P Soluble P	0.82
$Y = 1.73 \exp(0.028x)$	Water extractable soluble P	0.66
$Y = 5.66 \exp(0.037x)$	Mehlich-1 P	0.76
$Y = 3.69 \exp(0.033x)$	Fe-oxide Strip P	0.65

Using P saturation as a predictor of dissolved P in surface runoff is preferable to using STP values because STP and dissolved P in runoff relationships vary with soil type (Sharpley, 1995). Pote et al. (1996, 1999) and Sharpley (1995) measured dissolved P in runoff and related these values to the degree of P saturation in the surface soil (Table 2.22). Pote et al. (1996) observed a mean P saturation value of 39% for 54 study plots with a mean Mehlich-3 P value of 198 mg kg^{-1}.

Fang et al. (2002) predicted soluble P in runoff based on soil sorption capacity indicators such as desorbability (release of added P as labile P to soil), soil equilibrium P concentration (P concentration at which no net sorption or desorption occurs), P saturation index based on sorption maximum, and P saturation index based on sorptivity. Fang et al. (2002) reported significant correlations ($r^2 = 0.50 – 0.89$) between soil sorption capacity indicators and soluble P in runoff.

Table 2.22 Relationship between soil P saturation and dissolved P in runoff.

Reference	Soil Type/ Location	# of Data Points	Equation	Y (mg L^{-1})	X (%)	R^2
Pote et al. (1996)						
	Captina silt loam/ Arkansas	54	Y = 0.0238x + 0.07	Dissolved P in runoff	Surface Soil P saturation	0.769
Pote et al. (1999)						
	Captina silt loam/ Arkansas	54	Y = 0.035x + 0.269	DRP in runoff	Soil P Saturation calculated by the H_2O-P sorption index (PSI) method	0.822
Sharpley (1995)						
	Six soil textures/ Oklahoma	60	Y = 0.0288x – 0.0328	Dissolved P in runoff	Surface Soil P sorption saturation	0.86
Fang et al. (2002)						
	Clay loam, silty clay loam, and clay/ Minnesota		Y = 29.10x – 383.6	Soluble Reactive P in Runoff	Desorbability (%)	0.75
			Y = 1.11x – 100.69	Soluble Reactive P in Runoff	Soil Equilibrium P Concentration (μg L^{-1})	0.89
			Y = 14.83x – 237.63	Soluble Reactive P in Runoff	P Saturation Index based on Sorption Maximum (%)	0.50
			Y = 23.61x – 192.83	Soluble Reactive P in Runoff	P Saturation Index based on Sorptivity	0.88

2.8 GLEAMS BACKGROUND REVIEW

In an effort to improve the simulation of soil P transport and transformations in GLEAMS 3.0, a literature review was necessary to determine the predictive capabilities of P loss in GLEAMS compared to field data. Several studies tested the predictive capability of GLEAMS with respect to P loss in surface runoff and subsurface flow (Knisel and Turtola, 2000; Reyes et al., 1997; Shirmohammadi et al., 1998; Yoon et al., 1994).

Shirmohammadi et al. (1998) simulated monthly dissolved and particulate P losses via subsurface drain tiles for a Lanna clay soil (clay content ranged from 46.5% to 60.6%) in southwest Sweden. These results are shown in Table 2.23. Each plot was 0.5 ha on flat topography. Surface runoff was prevented by boundaries surrounding the three study plots to ensure that all P losses were through subsurface drainage. Measured subsurface water loss from all three plots was used to calibrate the hydrology component. Field capacity and wilting point water content values were adjusted during hydrology calibration. One plot (plot 3) was used to calibrate the nutrient component because initial soil nutrient values were unavailable. Plots 4 and 5 were simulated using the same initial nutrient values as plot 3. Knisel et al. (1991) indicated that hydrology calibration in CREAMS is not required, but that, when possible, observed data should be compared to predicted values. This should also hold true for GLEAMS which is a modified version of CREAMS that allows for groundwater loadings of nutrients.

Results from Shirmohammadi et al. (1998) (Table 2.23) showed that, on a yearly average, the calibrated GLEAMS version 2.10 under-predicted dissolved P concentrations in subsurface drainage (yearly average percent error for plots 3, 4, and 5 were -10.8%, -54%, and -44.4%, respectively), except in 1992 on plot 5 and 1995 on plot 3 where the model over-predicted. Differences between measured and predicted dissolved P in subsurface drainage may have been caused by a weakness in GLEAMS to simulate cold weather conditions (Rekolainen and Posch, 1994). Observed particulate P losses in drainage water were on average higher than their dissolved P counterpart; average annual particulate P loss over the four-year study period for plots 3, 4, and 5 were 0.059, 0.089, and 0.099 kg ha^{-1}, respectively. The subsurface drainage tiles provided a means of preferential flow allowing soil erosion and subsequent transport of particulate P to occur within the soil profile (Ulen, 1995). Because loss of particulate P below the root zone is not simulated in GLEAMS, the submodel PARTLE was developed to simulate particulate P loss via drainage (Shirmohammadi et al., 1998).

Table 2.23 Observed and GLEAMS predicted dissolved P loss via subsurface drain tiles (Shirmohammadi et al., 1998).

		Dissolved P Loss (kg ha^{-1})		
Plot No.	**Year**	**Observed**	**Predicted**	**% Error**
3*	1992	0.023	0.020	-13.0
	1993	0.035	0.030	-14.3
	1994	0.071	0.040	-43.7
	1995	0.020	0.040	100.0
	Average	0.037	0.033	-10.8
4	1992	0.033	0.010	-69.7
	1993	0.054	0.030	-44.4
	1994	0.080	0.020	-75.0
	1995	0.034	0.030	-11.8
	Average	0.050	0.023	-54.0
5	1992	0.015	0.020	33.3
	1993	0.047	0.030	-36.2
	1994	0.081	0.020	-75.3
	1995	0.038	0.030	-21.1
	Average	0.045	0.025	-44.4

* Nutrient calibration plot

Knisel and Turtola (2000) simulated P losses through runoff and leaching using GLEAMS version 2.10 on a heavy clay soil (clay content ranging from 61% to 90%) under different management scenarios in Finland. Plots A and D were used for model calibration whereas plots B and C were used for model validation. The drainage area for each plot was 0.46 ha and the mean slope was 2%. The study was conducted from 1987 to 1993. Leachate loss was through subsurface drain tiles spaced 16.5 m apart at the beginning of the study, but in June 1991 plastic drain tubing with 0.3 m spacing was installed to improve drainage. Small, gravel bottom channels collected surface runoff. Flow from surface and subsurface drainage was directed through pipes to a recording tipping bucket inside an adjacent observation building. Observed data were recorded for both time periods (1987–May 1991 and June 1991–1993) where subsurface drainage differed.

Hydrology calibration was achieved by adjusting sensitive model parameters such as soil porosity, field capacity, and curve number to obtain the best water balance estimate. Runoff predictions in GLEAMS can be improved by adjusting the moisture condition-II curve numbers (Ma et al., 1998). In addition, Knisel and Turtola (2000) identified rooting depth as a sensitive parameter in hydrology calculations and assumed this value to be the depth of the drain tile (1 m). After hydrology calibration was completed, erosion calibration was performed through adjustment of soil loss ratios and Manning's 'n' for overland flow to obtain the best sediment yield estimate. Particulate P losses through drainage were calculated externally from GLEAMS with the PARTLE sub-model. Average parameter values from calibration were used in GLEAMS simulation to determine predicted total P loss through leaching and runoff.

Phosphorus leaching values were reported as total P which included leached particulate P as predicted by PARTLE (Knisel and Turtola, 2000). Observed and predicted values did not distinguish between dissolved and particulate P, therefore an analysis of the capability of GLEAMS to predict P loss through leaching could not be performed. The GLEAMS model over-predicted total P loss in runoff for plot B during both test periods (Table 2.24). After the installation of plastic drain tubing, predicted values for plot C more closely agreed with observed runoff P values. Large variations from month-to-month between observed and predicted total P losses in runoff and drainage water were also reported (Knisel and Turtola, 2000).

Table 2.24 Observed and GLEAMS predicted loss of P (dissolved and particulate) in leaching and runoff (Knisel and Turtola, 2000).

Subsurface Total Phosphorus Loss (kg ha^{-1})				
Plot	**Year**	**Observed**	**Predicted***	**% Error**
B	1987-May 1991	0.84	1.38	64.3
	June 1991-1993	1.62	1.56	-3.7
C	1987-May 1991	0.75	1.17	56.0
	June 1991-1993	1.53	0.50	206.0
	* Predicted values of total P loss with leaching are the sum of dissolved P leached as predicted by GLEAMS and particulate P leached as predicted by PARTLE.			

Surface Total Phosphorus Loss (kg ha^{-1})				
Plot	**Year**	**Observed**	**Predicted**	**% Error**
B	1987-May 1991	4.78	7.45	55.9
	June 1991-1993	0.37	0.67	81.1
C	1987-May 1991	4.48	4.44	-0.9
	June 1991-1993	0.37	0.43	16.2

Note: Subsurface drain tiles were used from 1987-May 1991. Subsurface plastic drain tubing was used from June 1991 – 1993.

Reyes et al. (1997) evaluated the capability of GLEAMS to predict nutrient losses in surface runoff on a poorly drained Commerce clay loam from a plot study in south Louisiana. Predicted values from GLEAMS were compared to predictions made by GLEAMS-SWAT, a submodel designed for poorly drained soils with artificial subsurface drainage and shallow water table conditions. The GLEAMS-SWAT model simulates the effects of artificial subsurface drainage on surface runoff, water table depth, and soil water movement. In GLEAMS, percolation calculations assume that no shallow water table exists and that the soil moisture content can reach a state of field capacity. In conditions where a shallow water table is present, soil water cannot freely drain and therefore field capacity cannot be achieved. In situations where shallow water tables exist, GLEAMS may underestimate soil moisture content, thus under-predicting runoff (Reyes et al., 1994).

The two study plots, each with an area of 1.5 ha and slope of 0.14%, were surface drained. One plot was also drained by subsurface drain tubes. No hydrology or erosion calibration was performed prior to GLEAMS nutrient model simulation. Runoff volumes were under-predicted by 54% and soil losses were under-predicted by 76% for plots lacking subsurface drainage. For the plots with surface and subsurface drainage, runoff volumes and soil losses were under-predicted by 30 and 61%, respectively. Results showed that both GLEAMS and GLEAMS-SWAT generally under-predicted P loss in surface runoff (Table 2.25) likely attributed to under-predictions of sediment yield in the erosion sub-model (Reyes et al., 1997).

In the Reyes et al. (1997) study, the GLEAMS-predicted values of P loss in surface runoff were the same regardless of whether the plots employed subsurface drainage or not (Table 2.25) possibly due to GLEAMS' inability to simulate P losses by preferential flow (Djodjic et al., 2002). Subsurface preferential flow can be artificial (drain tile, pipe, or tubing) or natural (macropores, soil cracks, and fissures) (Heathwaite, 1997; Stamm et al., 1998). Rapid transport of suspended soil particles through the soil profile can occur in the presence of macropores (Heathwaite, 1997). Artificial subsurface drainage increases water infiltration and may reduce overland flow (Simard et al., 2000). Phosphorus movement through preferential flow in the soil profile was not considered during the calculation of P loss in surface runoff in GLEAMS, resulting in an under-prediction of P loads in surface runoff.

Table 2.25 Prediction of total P in surface runoff for fields under shallow water table conditions (Reyes et al., 1997).

	Phosphorus loss in surface runoff (kg ha^{-1})				
Year	**Observed**	**GLEAMS Predicted**	**GLEAMS % Error**	**GLEAMS-SWAT Predicted**	**GLEAMS-SWAT % Error**
Plot with surface drainage					
1981	0.8	0.7	-12.5	1.0	25.0
1982	5.0	1.4	-72.0	1.9	-62.0
1983	9.3	1.8	-80.6	2.9	-68.8
1984	6.5	0.5	-92.3	0.7	-89.2
1985	16.2	1.7	-89.5	1.9	-88.3
1986	6.7	1.6	-76.1	2.1	-68.7
Average	7.8	1.3	-83.3	1.8	-76.9

	Phosphorus loss in surface runoff (kg ha^{-1})				
Year	**Observed**	**GLEAMS Predicted**	**GLEAMS % Error**	**GLEAMS-SWAT Predicted**	**GLEAMS-SWAT % Error**
Plot with surface and subsurface drainage					
1981	0.4	0.7	75.0	0.8	100.0
1982	3.1	1.4	-54.8	1.4	-54.8
1983	7.0	1.8	-74.3	2.2	-68.6
1984	3.0	0.5	-83.3	0.6	-80.0
1985	10.8	1.7	-84.3	1.7	-84.3
1986	3.3	1.6	-51.5	1.7	-48.5
Average	4.7	1.3	-72.3	1.4	-70.2

GLEAMS' capability to predict nutrient losses in surface and subsurface runoff was studied by Yoon et al. (1994). Plots, each 0.1 ha, were planted to conventionally tilled corn harvested for grain with a cereal rye cover crop in the winter on a Decatur silty clay (clay content ranged from 33% to 58%). Four replications of three fertilizer treatments were applied to the plots: commercial fertilizer (450 kg ha^{-1} ammonium nitrate and 122 kg ha^{-1} triple superphosphate), 18 t ha^{-1} poultry litter (PL18), and 9 t ha^{-1} poultry litter (PL9).

Monthly observed and GLEAMS predicted losses of dissolved and sediment P were presented by Yoon et al. (1994) in graphical terms. Runoff (dissolved and sediment) and leachate P values estimated from the graphs are presented in Tables 2.26 through 2.28. Results indicated that GLEAMS was unable to accurately predict monthly dissolved P loss in surface runoff for the plots receiving the commercial fertilizer treatment; simulated monthly dissolved P loss in runoff was near zero from June 1991 through November 1992 (Table 2.26). In the plots that received 9 t ha^{-1} poultry litter, GLEAMS-predicted monthly dissolved

P loss in runoff was within ±15% of observed values for 10 months during the 21-month study period. On plots receiving 18 t ha^{-1} poultry litter, GLEAMS predictions of monthly dissolved P in runoff were within ±15% of observed values for six months during the study period. In general, the GLEAMS model over-predicted dissolved P loss in surface runoff for the poultry litter plots while under-predicting dissolved P on the plots receiving commercial fertilizer.

Table 2.26 Median observed and GLEAMS predicted monthly dissolved P losses in runoff (Yoon et al., 1994).

Month	Dissolved Losses in Surface Runoff (kg ha^{-1})								
	Commercial Fertilizer			Poultry Litter (9 t ha^{-1})			Poultry Litter (18 t ha^{-1})		
	Observed	Predicted	% Error	Observed	Predicted	% Error	Observed	Predicted	% Error
Mar-91	0	0.04	*	0.01	0.05	400	0.17	0.04	-76
Apr-91	0	0.04	*	0.09	0.08	-11	0.09	0.15	67
May-91	0	0.04	*	0	0.17	*	0.04	0.33	725
Jun-91	0	0	*	0	0.01	*	0	0	*
Jul-91	0	0	*	0	0	*	0	0	*
Aug-91	0	0	*	0	0	*	0	0.01	*
Sep-91	0.08	0	-100	0.01	0.01	0	0.02	0.09	350
Oct-91	0	0	*	0	0	*	0	0.01	*
Nov-91	0	0	*	0	0	*	0	0.04	*
Dec-91	0	0	*	0.02	0.50	2,400	0.09	1.10	1,122
Jan-92	0.04	0	-100	0	0	*	0	0.04	*
Feb-92	0	0	*	0	0	*	0	0	*
Mar-92	0.04	0	-100	0.03	0	-100	0.02	0.09	350
Apr-92	0	0	*	0	0	*	0	0	*
May-92	0.04	0	-100	0.01	0.05	400	0.02	0.12	500
Jun-92	0.04	0	-100	0.09	1.40	1,456	0.55	2.60	373
Jul-92	0.08	0	-100	0.04	0.20	400	0.06	0.33	450
Aug-92	0	0	*	0.02	0.01	-50	0	0.09	*
Sep-92	0.08	0	-100	0.09	0.25	178	0.25	0.55	120
Oct-92	0	0	*	0	0	*	0	0	*
Nov-92	0.08	0	-100	0.04	0.09	125	0.09	0.09	0

* Denotes where percent error was divisible by zero.

Mean monthly sediment P loss in runoff was always over-predicted but was within observed ranges (data not given) for all months on plots receiving commercial fertilizer applications. As with soluble P loss in surface runoff, there were several months during which the GLEAMS-predicted sediment P loss value did not fall within observed values (data not given) for treatments receiving 9 and 18 t ha^{-1} poultry litter (Table 2.27). In addition, dissolved P loss in leachate (Table 2.28) was simulated by GLEAMS and compared to observed values (Yoon et al., 1994). For all treatments, observed dissolved P in leachate data varied from 0 to 0.25 mg L^{-1}. However, GLEAMS predictions were low at a nearly constant 0.02 mg P L^{-1}. In general, GLEAMS-predicted losses of P in surface runoff (dissolved and sediment P) and leachate (dissolved P) did not vary with observed variations (Yoon et al., 1994).

Table 2.27 Median observed and GLEAMS predicted monthly sediment P losses in runoff (Yoon et al., 1994).

Month	Sediment P Losses in Surface Runoff (kg ha^{-1})								
	Commercial Fertilizer			Poultry Litter (9 t ha^{-1})			Poultry Litter (18 t ha^{-1})		
	Observed	Predicted	% Error	Observed	Predicted	% Error	Observed	Predicted	% Error
Mar-91	0.16	0.27	69	0.18	0.45	150	0.50	0.70	40
Apr-91	0.10	0.25	150	0.14	0.47	236	0.22	0.72	227
May-91	0.13	0.25	92	0.18	0.47	161	0.18	0.75	317
Jun-91	0	0	*	0	0	*	0	0	*
Jul-91	0	0	*	0	0	*	0	0	*
Aug-91	0	0.08	*	0	0.05	*	0	0.08	*
Sep-91	0	0.10	*	0.02	0.18	800	0.01	0.20	1,900
Oct-91	0	0	*	0	0.05	*	0	0	*
Nov-91	0	0	*	0	0.02	*	0	0	*
Dec-91	0.08	0.20	150	0.10	0.25	150	0.10	0.47	370
Jan-92	0	0.01	*	0	0	*	0	0	*
Feb-92	0	0.05	*	0	0	*	0	0	*
Mar-92	0	0	*	0	0	*	0	0	*
Apr-92	0	0	*	0	0.05	*	0	0.05	*
May-92	0.01	0.10	900	0.02	0.14	600	0.02	0.25	1,150
Jun-92	0.13	0.50	285	0.14	2.20	1,471	0.25	3.9	1,460
Jul-92	0	0.10	*	0	0.20	*	0	0.30	*
Aug-92	0	0	*	0	0.04	*	0	0.08	*
Sep-92	0	0.05	*	0.01	0.25	2,400	No data	0.50	*

* Denotes where percent error was divisible by zero.

Table 2.28 Median observed and GLEAMS predicted dissolved P concentrations in leachate (Yoon et al., 1994).

Date	Dissolved P Concentration in Leachate (mg L^{-1})								
	Commercial Fertilizer			Poultry Litter (9 t ha^{-1})			Poultry Litter (18 t ha^{-1})		
	Observed	Predicted	% Error	Observed	Predicted	% Error	Observed	Predicted	% Error
4/12/1991	0.1	0.02	-80	0.12	0.02	-83	0.13	0.02	-85
5/2/1991	0.092	0.02	-78	0.10	0.02	-80	0.14	0.02	-86
5/22/1991	0	0.02	*	0	0.02	*	0.02	0.02	0
6/11/1991	0.02	0.02	0	0	0.02	*	0	0.02	*
6/27/1991	0.083	0	-100	0.02	0	-100	0.033	0	-100
7/23/1991	0	0	*	0.02	0	-100	0	0	*
10/15/1991	0	0.028	*	0	0.028	*	0	0.02	*
11/15/1991	0	0.028	*	0	0.022	*	0	0.02	*
12/6/1991	0	0.019	*	0	0.02	*	0	0.02	*
12/19/1991	0	0.02	*	0	0.02	*	0	0.02	*
1/7/1992	0	0.02	*	0.001	0.02	1,900	0	0.02	*
1/21/1992	0	0.02	*	0	0.02	*	0	0.02	*
2/4/1992	0	0.02	*	0	0.02	*	0	0.02	*
2/18/1992	0	0.02	*	0	0.02	*	0	0.02	*
3/3/1992	0.017	0.02	18	0	0.02	*	0	0.02	*
3/18/1992	0.004	0.02	400	0.013	0.019	46	0.033	0.02	-39
4/2/1992	0.028	0.02	-29	0	0.019	*	0.02	0.019	-5
4/17/1992	0	0	*	0	0	*	0	0	*
4/30/1992	0	0.02	*	0	0.02	*	0	0.02	*
5/15/1992	0	0.02	*	0	0.02	*	0	0.02	*
6/1/1992	0	0	*	0	0	*	0	0	*
6/17/1992	0	0.02	*	0	0.02	*	0	0.02	*

* Denotes where percent error was divisible by zero.

Studies using GLEAMS to simulate P loss in surface runoff and subsurface flow have shown varying results (Knisel and Turtola, 2000; Reyes et al., 1997; Shirmohammadi et al., 1998; Yoon et al., 1994). Calibration of GLEAMS hydrology and erosion input files may increase the accuracy of GLEAMS prediction of P loss in runoff and leaching. However, differences between observed and predicted P loss values still remained after calibration (Knisel and Turtola, 2000; Shirmohammadi et al., 1998; Yoon et al., 1994). Study results show that regardless of hydrology and/or erosion calibration, GLEAMS is not always able to accurately predict P losses through surface runoff and subsurface leaching.

The intended use of GLEAMS is to compare different management scenarios (Knisel, 1993). As concluded by Shirmohammadi et al. (1998)**, "**GLEAMS can do a reasonable job in simulating long-term averages, thus rendering itself to be a viable management and decision making model regarding the assessment of the relative impacts of different agricultural management systems." This conclusion was based on simulation of P loss over a four-year study period for which predicted average annual dissolved P loss in leachate ranged from -44% to 7% of the observed annual data. Comparison of monthly observed P loss to GLEAMS-predicted values may not produce favorable results as demonstrated by Yoon et al. (1994). The nutrient component in GLEAMS was not meant to be a quantitative predictor of nutrient loss from agricultural fields but simply a relative predictor among different management practices (Knisel and Turtola, 2000).

2.9 SUMMARY

Excess P in soils and subsequent runoff can result in eutrophic conditions in surface waters that can cause algal blooms, which are harmful to aquatic organisms; thus, understanding the dynamics of P in soil and water is vital to management decisions. Relationships between dissolved P loss in runoff and STP methods have been developed for site-specific combinations of tillage, manure applications, soil type, and soil sampling depth. Phosphorus loss in leachate has also been predicted by STP and the degree of P saturation. Though STP and P saturation have been shown to be good indicators of P loss, site characteristics concerning hydrology and topography must also be considered when estimating concentrations of P loss in runoff. These equations were developed for site-specific conditions and applicability to a wide variety of soils is unknown.

The GLEAMS model simulates P loss in surface runoff and subsurface flow to predict the effects of various parameters on P loss. Several simulations have produced varying results including underestimation of dissolved P concentrations in subsurface drainage, inability to predict P loss through leaching, overestimation of total P loss in runoff, and inability to simulate P losses by preferential flow. Some authors suggest calibration of GLEAMS hydrology and erosion components to enhance the model's predictive capability with respect to P loss in runoff and leaching. However, calibration did not always improve model results. The GLEAMS model is intended for use in relative comparison of management scenarios. Attempts to absolutely quantify P loss from agricultural sites using GLEAMS may be beyond the scope of this model. Modifications and improvements to the GLEAMS model are necessary for estimating quantitative P loss.

CHAPTER 3: GLEAMS 3.0 SIMULATION OF PHOSPHORUS

The overall goal of this research was to improve simulation of soil P processes and transformations in GLEAMS. In order to achieve this goal, literature was reviewed with respect to P mineralization, immobilization, uptake, evaporation, leaching, and runoff to determine the current state of the science (Chapter 2). The equations and relationships used in GLEAMS for P simulation in the soil system are presented in this chapter. They are evaluated with respect to the current state of the science to determine if changes are necessary to improve GLEAMS.

The P component in GLEAMS (Figure 3.1) simulates P losses, additions, and internal reactions within the soil system. The soil system is defined by the soil surface as the upper boundary and the bottom of the root zone as the lower boundary. The GLEAMS model simulates a maximum of five soil layers in the root zone, which is divided into a maximum of 12 computational layers (Knisel and Turtola, 2000). Crop residue is considered part of the soil surface and is therefore within the soil system. Phosphorus transformations simulated within the soil system include mineralization, immobilization, crop uptake, and flow between various P pools.

Fresh organic P in crop residue is mineralized to organic humus P and labile P. Organic P in the soil system from animal waste can also be mineralized to organic humus P and labile P. Organic humus P is further mineralized to labile P. The only immobilization reaction occurring in the soil system is the conversion of labile P to fresh organic P. Flow rates between stable and active inorganic P pools as well as active inorganic and labile P pools are also included in the P sub-model. Additions of P to the soil system are in the form of fertilizers and organic P from animal waste. Phosphorus losses can be in the form of dissolved and sediment-bound P in surface runoff, dissolved P in percolation (potential leaching), and by crop harvest.

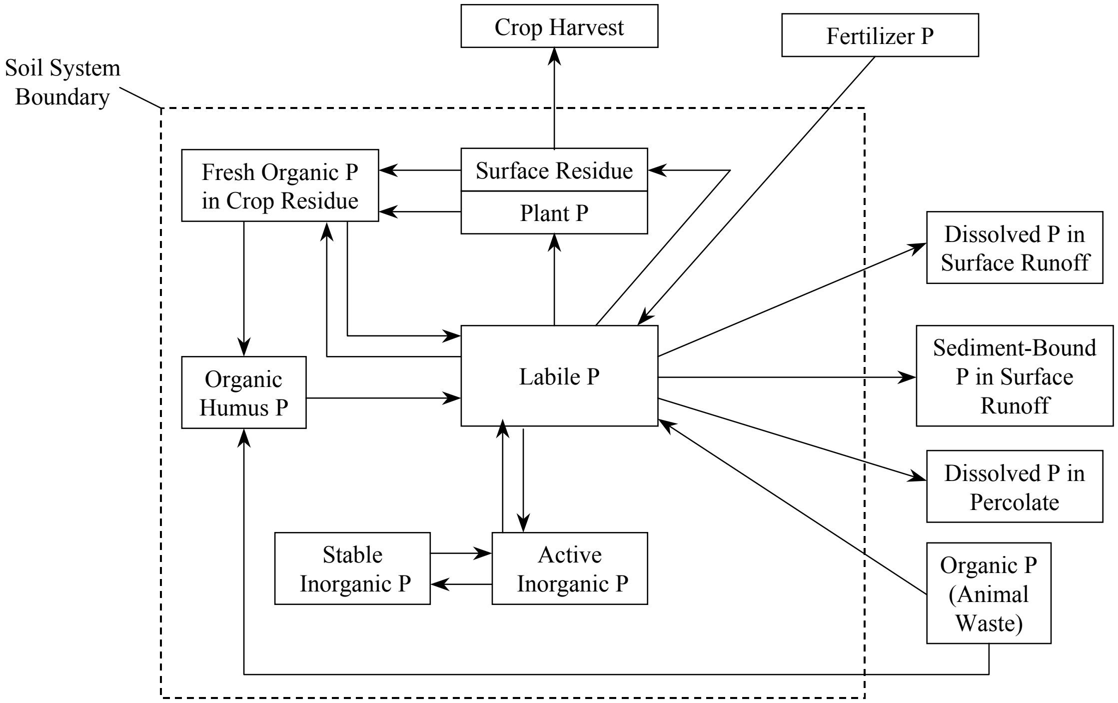

Figure 3.1 GLEAMS simulation of phosphorus (adapted from Knisel and Davis, 1999).

The P component in GLEAMS was divided into five categories for this state of the science review:

1. Plant uptake of labile P and removal through crop harvest;
2. Phosphorus loss in runoff and leaching;
    a. Dissolved P in surface runoff
    b. Sediment-bound P in surface runoff
    c. Dissolved P in percolate
3. Mineralization and immobilization reactions within the soil system;
4. Flow rate between the different P pools within the soil system; and
5. Phosphorus additions to the soil system from fertilizers.

All equations given in the following sections are from the GLEAMS version 2.10 (Knisel, 1993) and version 3.0 (Knisel and Davis, 1999) user manuals. Additional features that are included in version 3.0 that were not in version 2.10 of the GLEAMS model include:

- Year 2000 compliance to allow use of a four-digit year instead of a two–digit year,

- Simultaneous simulation of up to 366 pesticides,
- A two-compartment pesticide degradation component,
- Increased pesticide database in the pesticide parameter editor,
- Removal of biomass in the top 1 cm of soil with sod harvest,
- Reduced rainfall energy in northern and southern latitudes, and
- Input of solar radiation in metric units.

3.1 PLANT UPTAKE OF LABILE PHOSPHORUS AND REMOVAL THROUGH CROP HARVEST

Percolation is the downward movement of water through the soil profile. During percolation, some water is retained by the soil and other water is subject to eventual loss from the root zone through leaching. Some of the soil storage water eventually moves upward by capillary action to plant roots, stems, and leaves to satisfy the growing requirements of the crop.

The GLEAMS model simulates capillary action by plant roots to acquire water needed for growth based on the P demand estimation used in EPIC (Erosion/Productivity Impact Calculator) (Sharpley and Williams, 1990). This process in which plant available P is transported under capillary action to the plant root is termed "evaporation" in GLEAMS model documentation (Knisel, 1993). This term can be confusing since P is not actually lost from the soil surface through vaporization.

GLEAMS calculates evapotranspiration using the Penman-Monteith or Priestly-Taylor method. Upward movement of P to plant roots is estimated using the total water transported by capillary action of soil-water solution calculated in the hydrology sub-model and the concentration of labile P in the soil-water solution for each layer. Phosphorus carried upward by capillary action is removed from the labile P concentration of that layer and added to the labile P concentration of the soil layer above.

The concentration of P in crop biomass is dependent on the concentration of N and the N:P ratio in the crop biomass. The concentration of N in crop biomass is estimated daily using a crop growth ratio along with two empirical coefficients. The crop growth ratio is based on incoming solar radiation and whether solar radiation is absorbed by plant leaves or directly by the soil. Leaf area index is the leaf area per unit land and indicates whether plants or soil will absorb more radiation. Accumulated and potential leaf area indices are used to calculate the crop growth ratio. Total dry matter is calculated from the growth ratio, potential yield of the harvestable portion of the crop, and ratio of the total dry matter to harvestable yield.

The total dry matter P content of a crop is calculated using the concentration of P in the crop biomass and the total dry matter. The daily optimum P demand is then determined as the difference between the total dry matter P values on successive days.

Plant uptake of labile P is calculated for each layer where transpiration occurs using the concentration of labile P in the soil-water solution and the transpiration equivalent depth in the soil. The total uptake is the sum of plant uptake of labile P over all layers where transpiration occurs. The daily optimum P demand for a crop and the total uptake of P are used to find a P demand factor that is in turn used to estimate an adjusted uptake of P value. The adjusted plant uptake of P value is subtracted from the labile P mass in the soil for each layer.

The concentration of N in crop biomass is calculated daily from the relation:

$$CN = (C1)(GRT)^{C2} \tag{3.1}$$

where CN is the concentration of N in crop biomass (%), C1 and C2 are empirical coefficients, and GRT is a crop growth ratio defined as:

$$GRT = \frac{SUMLAI}{POTLAI} \tag{3.2}$$

where SUMLAI is the accumulated leaf area index ($m^2\ m^{-2}$), and POTLAI is the potential leaf area index for a crop on the day of harvest ($m^2\ m^{-2}$). The value of POTLAI is the sum of the idealized daily leaf area index over the growing period without water or N stress. The growth ratio is then used to calculate total dry matter (TDM) (kg ha^{-1}) as:

$$TDM = (GRT)(PY)(DMY) \tag{3.3}$$

where PY is potential yield of the harvestable portion of the crop (kg ha^{-1}), and DMY is the dry matter ratio, i.e., ratio of the total dry matter to harvestable yield.

The concentration of P in the crop biomass is estimated from the concentration of N in crop biomass and the N:P ratio in crop biomass as:

$$CP = \frac{CN}{NPR} \tag{3.4}$$

where CP is the concentration of P in the crop biomass (%), CN is the concentration of N in crop biomass (%), and NPR is the N:P ratio in crop biomass.

Total dry matter P is:

$$TDMP = 0.01(CP)(TDM) \tag{3.5}$$

where TDMP is the total dry matter P (kg ha^{-1}). The constant 0.01 is a units conversion factor. The P demand is then determined as the difference between the TDMP values on successive days as:

$$DEMP_d = TDMP_d - TDMP_{d-1} \tag{3.6}$$

where DEMP is the daily optimum P demand of a crop (kg ha^{-1}), and the subscript *d* represents the day.

Uptake of labile P is estimated for each layer *i* where transpiration occurs by:

$$UPLP_i = 0.1(CPLABW_i)(TR_i) \tag{3.7}$$

where UPLP is the uptake of labile P (kg ha^{-1}), CPLABW is concentration of labile P in the soil-water solution (mg L^{-1}), and TR is the transpiration equivalent depth (cm). The constant 0.1 is a units conversion factor.

The total uptake is determined as the sum over all layers where transpiration occurs:

$$UPP = \sum(UPLP_i) \quad for\ i = 1, ntl \tag{3.8}$$

where UPP is the total uptake of P (kg ha^{-1}), and *ntl* is the number of transpiration layers.

A demand factor for P is calculated using the ratio of daily optimum P demand of a crop to the total uptake of P as:

$$DMPFAC = \frac{DEMP}{UPP} \tag{3.9}$$

where DMPFAC is the P demand factor.

The uptake of labile P and the P demand factor are used to calculate an adjusted uptake of P for each layer *i* as:

$$AJUPP_i = (UPLP_i)(DMPFAC) \tag{3.10}$$

The adjusted uptake is subtracted from the labile P mass in the soil for each layer.

Phosphorus is moved upward with evaporation one computational soil layer. Phosphorus loss is not allowed out of the surface layer by evaporation. The upward movement of P by evaporation is estimated as:

$$EVP_i = 0.1\ (EVAP_i)(CPLABW_i) \qquad [3.11]$$

where EVP is the upward movement of labile P (kg ha^{-1}), and EVAP is the water evaporation calculated in the hydrology sub-model (cm). EVP$_i$ is subtracted from PLAB$_i$ and added to PLAB$_{i-1}$. The constant 0.1 is a unit conversion factor.

3.2 PHOSPHORUS LOSS IN RUNOFF AND LEACHING

Simulation of P in surface runoff and percolation through the root zone begins with the initial labile concentration of P in each soil layer. This value is input by the model user for each soil layer as CLAB in ppm. Ideally, the labile concentration of P in the soil should be known from soil tests for site-specific information. Labile P is the readily available fraction of the STP value. If the value for CLAB is not known and left blank in the nutrient input file, GLEAMS estimates CLAB from the soil organic P humus value in each layer based on three soil groups: calcareous, slightly weathered, and highly weathered. For calcareous, slightly weathered, and highly weathered soils, mean CLAB is estimated to be 10%, 8.7%, and 5.6% of soil organic humus P, respectively (Sharpley et al., 1984b).

The fraction of labile P concentration in the soil that is available for transport through surface runoff and percolation is dependent on the concentration of labile P in the soil, P partitioning coefficient, infiltrating water, and initial abstraction of rainfall, as well as soil porosity. Phosphorus partitioning and extraction coefficients, together with the calculated available labile P concentration in the soil, are used to estimate concentration of labile P in the soil solution. The labile P concentration in the soil solution is used in the calculations of dissolved and sediment-associated labile P in surface runoff.

The mass of P in percolation is the amount of P that has the potential for loss through leaching. As the percolating soil solution moves downward through the root zone, some P is adsorbed to sediment within the soil profile. Phosphorus not adsorbed during downward movement remains in the soil solution. The amount of P remaining in the soil solution after passage through the root zone is the amount of P that potentially could be lost from the agricultural system by way of leaching.

A daily time step is used in GLEAMS calculations. At the beginning of the day, there is an initial mass of labile P available for transport in each soil layer. The occurrence of rainfall initializes the hydrologic cycle and starts the simulation of P loss through surface runoff and leaching by way of percolation. When the rainfall rate exceeds the infiltration rate, ponding occurs on the soil surface and may initiate runoff. The GLEAMS model simulates runoff using a modified SCS curve number method (U.S. Soil Conservation Service, 1972) in the hydrology sub-model. Infiltrating water percolates downward through the surface layer into the next soil layer. A percolation mass of P out of the surface layer (layer 1) is calculated. This, along with the depth of percolation in layer 1, is used to estimate the concentration of labile P in percolate leaving layer 1. The vertical distance traveled by the percolate in layer *i* is assumed to be equal to the depth of soil in layer *i*. Although the active surface layer varies with time and management, for simplification, the surface layer is fixed at a thickness of 1 cm (Knisel, 1993).

Only a fraction of labile P is available for transport through runoff and percolation. At the end of the day, new concentrations of labile P are calculated for each soil layer. The remaining concentration of labile P in the surface layer at the end of the day is calculated as the initial (beginning of day) concentration of labile P minus all P that was lost from the layer through runoff and percolation. The remaining concentration of labile P for all non-surface layers at the end of the day is determined as the initial concentration of labile P plus the concentration of labile P in percolate from the layer above the soil layer of interest. The concentration of P in the soil solution available for further percolation, capillary action, and plant uptake is then calculated. This value becomes the initial concentration of labile P to be used in simulation of the next P transformation. Figure 3.2 depicts the simulation of P in surface runoff and through the root zone by percolation.

Partitioning of P between the soil and water phase is related to the percent clay in the soil as:

$$CPKD_i = 100 + 2.5(CL_i) \qquad [3.12]$$

where CPKD is the P partitioning coefficient between the soil and water phases, and CL is the percent clay content in the soil. The subscript *i* denotes the computational soil layer.

The extraction coefficient for P (β_p) into surface runoff and percolate depends on the value of the P partitioning coefficient as:

$$\begin{aligned} &\beta_p = 0.50 \quad for\ CPKD \le 1.0 \\ &\beta_p = 0.5979\exp(-0.17883 \times CPKD) \quad for\ 1.0 < CPKD < 10.0 \qquad [3.13] \\ &\beta_p = 0.10 \quad for\ CPKD \ge 10.0 \end{aligned}$$

The calculation of β_p follows the same equation as the ammonia extraction coefficient used in GLEAMS for N modeling.

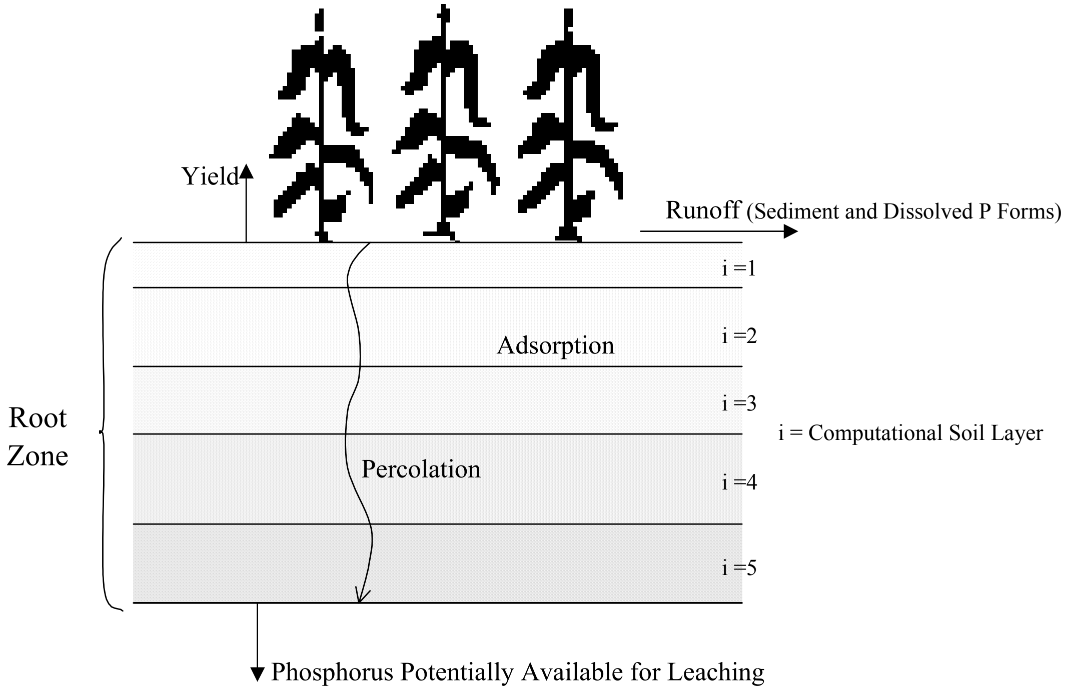

Figure 3.2 Simulation of P in surface runoff and leaching through the soil layers adapted from GLEAMS 3.0 description (Knisel and Davis, 1999). The number of computational soil layers can vary from 3 to 12.

The concentration of P in the surface layer of soil available for runoff and percolation into layer 2 is given by:

$$(C_{av})_p = (CPLAB_i)\exp\left[\frac{-(F-ABST)}{CPKD_1\left(\frac{1-POR_1}{2.65}\right)+POR_1}\right] \qquad [3.14]$$

where $(C_{av})_p$ is the P concentration in the soil available for runoff and percolation (μg g^{-1}), CPLAB is the concentration of labile P in the soil based upon the dry weight of the soil (μg g^{-1}), F is the infiltrating water or rainfall minus runoff (cm), ABST is initial abstraction of rainfall (cm), and POR is the porosity of the soil (cm^3 cm^{-3}). The subscript *p* denotes the plow layer, while the subscript *i* denotes the computational soil layer. The initial abstraction of rainfall (ABST) is calculated as:

$$ABST = 0.2(SAT_i - SW_i) \qquad [3.15]$$

where SAT is the volumetric soil water content at saturation (cm cm^{-1}), and SW is the volumetric soil water content (cm cm^{-1}).

The concentration of labile P in solution is:

$$CPLABW_1 = \frac{(C_{av})_p \beta_p}{1 + (CPKD_1)\beta_p} \qquad [3.16]$$

where CPLABW is the concentration of labile P in the water (mg L^{-1}).

Labile P in runoff is:

$$ROLP = 0.1(CPLABW_1)(Q) \qquad [3.17]$$

where ROLP is the labile P in runoff (kg ha^{-1}), and Q is the runoff depth (cm). The constant 0.1 is a units conversion factor.

The sediment-associated labile P is:

$$SEDLP = 0.1(SY)(ER)(CPKD_1)(CPLABW_1) \qquad [3.18]$$

where SEDLP is the sediment-associated labile P (kg ha^{-1}), SY is the sediment yield (kg ha^{-1}), and ER is the sediment enrichment ratio. The constant 0.1 is a units conversion factor.

The sediment enrichment ratio is calculated as the ratio of specific surface area of eroded sediment to the specific surface area of residual soil:

$$ER = \frac{SS_{sed}}{SS_{soil}} \qquad [3.19]$$

where SS_{sed} is the specific surface area of sediment leaving the field, and SS_{soil} is the specific surface area of remaining soil. Baver (1965) reported the specific surface area of sand and silt as 0.05 m^2 g^{-1} and 4.0 m^2 g^{-1}, respectively. These values as well as the specific surface area of organic matter (2,000 m^2 g^{-1}) are fixed in GLEAMS. Mineralogy affects the specific surface area of clay particles. The specific surface area of kaolinite is 20 m^2 g^{-1} while montmorillonite has a specific surface area of 800 m^2 g^{-1} (Baver, 1965). Due to the large variation in specific surface areas of clay particles, the GLEAMS model user must enter a specific surface area value for clay.

The sediment-associated loss of active mineralizable P is calculated as:

$$SEDMP = \frac{(SY)(ER)(PMINP_1)}{SOILMS_1} \qquad [3.20]$$

where SEDMP is the sediment-associated mineralizable P (kg ha^{-1}), PMINP is the active mineral P (kg ha^{-1}), and SOILMS is the soil mass (Mg ha^{-1}).

The sediment-associated loss of P in animal waste is:

$$SEDOP = \frac{(SY)(ER)(ORGPW_1)}{SOILMS_1} \qquad [3.21]$$

where SEDOP is sediment-associated organic P (kg ha^{-1}), and ORGPW is the organic P in animal waste (kg ha^{-1}).

Loss of sediment-associated stable soil P is:

$$SEDSP = \frac{(SY)(ER)(SOILP_1)}{SOILMS_1} \qquad [3.22]$$

where SEDSP is the sediment-associated stable soil P (kg ha^{-1}), and SOILP is stable soil P (kg ha^{-1}).

Sediment-associated organic humus P is calculated as:

$$SEDHP = (SY)(ER)(SORGP_1) \qquad [3.23]$$

where SEDHP is sediment-associated organic humus P (kg ha^{-1}), and SORGP is soil organic humus P (kg ha^{-1}).

The total sediment-associated P (SEDP, kg ha^{-1}) is:

$$SEDP = SEDLP + SEDHP + SEDOP + SEDMP + SEDSP \qquad [3.24]$$

The initial mass of labile P available in layer 1 is:

$$AVLPMS_1 = (CPLAB_1)(SOILMS_1) \qquad [3.25]$$

where AVLPMS is the available mass of labile P (kg ha^{-1}), and SOILMS is the soil mass (Mg ha^{-1}).

The percolation mass of P out of layer 1 is:

$$PRLPMS_1 = AVLPMS_1 - \left[(C_{av})_p (SOILMS_1) \right] \qquad [3.26]$$

where PRLPMS is the labile P mass in percolate (kg ha^{-1}).

The concentration of labile P in the percolate out of layer 1 is:

$$PERCLP_1 = \frac{0.1(PRLPMS_1)}{PERC_1} \qquad [3.27]$$

where PERCLP is the concentration of percolation labile P (mg L^{-1}), and PERC is the depth of percolation (cm). The constant 0.1 is a units conversion factor.

The labile P mass remaining in layer 1 after a runoff event is:

$$PLAB_1 = (PLAB_1)_o - ROLP - SEDLP - PRLPMS_1 \qquad [3.28]$$

where PLAB is the labile P mass in the soil (kg ha^{-1}). The subscript *o* denotes the value at the beginning of the day.

For layers 2 through *ncl*, total number of computational layers, the labile P mass in soil layer i is:

$$PLAB_i = PLAB_i + \left[(PERCLP_{i-1})(PERC_{i-1}) \right] \qquad [3.29]$$

The concentration of P in the soil-water solution available for further transport through percolation or capillary action is:

$$CPLABW_i = \frac{10 \times PLAB_i}{(CPKD_i)(SOILMS_i) + WM_i} \qquad [3.30]$$

where WM is the water mass (depth) in the soil (cm). The constant 10 is a units conversion factor.

3.3 PHOSPHORUS MINERALIZATION AND IMMOBILIZATION REACTIONS

3.3.1 MINERALIZATION

Mineralization of P refers to the conversion of organic forms of P to inorganic forms. Crop residue and animal waste on the soil surface and in the root zone are organic materials that undergo the mineralization process. Phosphorus mineralization is a first-order process (Jones et al., 1984). GLEAMS models P mineralization from crop residue, soil organic matter, and animal waste.

Mineralization from fresh organic P in crop residue occurring in soil computational layer *i* is defined as:

$$RMP_i = (DCR_i)(FOP_i) \qquad [3.31]$$

where RMP is the mineralization rate for fresh organic P (kg ha^{-1} d^{-1}), DCR is the residue decay rate (d^{-1}), and FOP is fresh organic P in crop residue (kg ha^{-1}). Fresh organic P in the crop residue is estimated in the model as 10 kg ha^{-1} and is uniformly distributed through the root zone. Seventy-five percent of mineralization from fresh organic P is added to the labile P pool and the remaining 25% is added to the organic humus P pool (SORGP). Soil organic humus P (SORGP, μg g^{-1}) is calculated as a function of total N (TN, %) based on equations derived by Sharpley et al. (1984b):

$$\begin{aligned} SORGP &= 44.4 + 1130(TN) && \textit{for surface layer} \\ SORGP &= 1464(TN) && \textit{all other soil horizons} \end{aligned} \qquad [3.32]$$

Twenty-five percent of organic P from crop residue and animal waste is assumed to remain organic and is added to the soil organic humus P pool, while 75% of organic P is assumed to be mineralized into inorganic form and is added to the labile P pool.

Decay rate constant for fresh organic P, DCR, is:

$$DCR_s = (CNP_s)(RC_s)\left[(SWFA_1)(TFA)\right]^{0.5} \qquad [3.33]$$

where CNP is based on either the C:N ratio of crop residue (CNR) or the C:P ratio of crop residue (CPR), RC is a residue composition factor, SWFA is the soil water factor for ammonification, TFA is the temperature factor for ammonification, and *s* denotes the surface layer. Use of the term "ammonification" in the description of the variables SWFA and TFA in the GLEAMS user manual can be confusing. This merely means that the same ambient conditions are assumed during the P mineralization and N ammonification processes.

The C:P ratio (CPR) and C:N ratio (CNR) of crop residue are needed to find CNP:

$$CNP = \text{minimum}\begin{cases} \exp\left[\dfrac{-0.693(CNR-25)}{25}\right] \\ \exp\left[\dfrac{-0.693(CPR-200)}{200}\right] \\ 1.0 \end{cases} \qquad [3.34]$$

where

$$CPR = \frac{0.58(FRES_i + OMAW_i)}{FOP_i + ORGPW_i + PLAB_i} \qquad [3.35]$$

and

$$CNR = \frac{0.58(FRES_i + OMAW_i)}{FON_i + ORGNW_i + SNO3_i + AMON_i} \qquad [3.36]$$

and FRES is fresh crop residue (kg ha^{-1}), OMAW is organic matter in animal waste (kg ha^{-1}), FOP is fresh organic P in crop residue (kg ha^{-1}), ORGPW is organic P in animal waste (kg ha^{-1}), PLAB is labile P (µg g^{-1}), FON is fresh organic N in crop residue (kg ha^{-1}), ORGNW is organic N in animal waste (kg ha^{-1}), SNO3 is the nitrate-N content of soil (kg ha^{-1}), and AMON is the NH_4-N content of soil (kg ha^{-1}). Fresh organic N in crop residue in GLEAMS is fixed at 40 kg ha^{-1}. If the user does not enter a value for SNO3, GLEAMS assumes the nitrate-N concentration of all soil layers as 10 μg g^{-1}. The value for concentration of NH_4-N of soil is fixed internally within the model as 2 μg g^{-1}.

The residue composition factor value is based upon the stage of residue decay and is given by:

$$\begin{aligned} &RC = 0.8 && \mathit{for}\ DECOMP \le 20\% \\ &RC = 0.05 && \mathit{for}\ 20\% < DECOMP \le 90\% \\ &RC = 0.0095 && \mathit{for}\ DECOMP > 90\% \end{aligned} \tag{3.37}$$

where DECOMP refers to the percent of initial fresh residue that has decomposed. Stages of residue decomposition are grouped into three categories: the first 20% of fresh residue decomposed relates to carbohydrate-like material; 20-90% relates to decomposition of cellulose-like material; and the remaining 10% of fresh residue decomposed refers to lignin (Sharpley and Williams, 1990).

SWFA is defined as:

$$SWFA = \frac{(SW_i - WP_i)}{(FC_i - WP_i)} \quad \mathit{for}\ SW \le FC \tag{3.38}$$

where SW is the volumetric soil water content, WP is the volumetric water content at 1500 kPa (wilting point), and FC is the volumetric water content at 33 kPa (field capacity).

The temperature factor for ammonification (TFA) is a function of soil temperature:

$$TFA = \begin{cases} \dfrac{T_i}{T_i + \exp(9.93 - 0.312\, T_i)} & \mathit{for}\ T_i > 0 \\ TFA = 0 & \mathit{for}\ T_i \le 0 \end{cases} \tag{3.39}$$

where T is soil temperature (°C), and the subscript *i* denotes the computational soil layer. Again, use of the term "ammonification" refers to the ambient conditions used during P mineralization and N ammonification processes.

Mineralization from soil organic humus P is simulated as:

$$PMN_i = (CMN)(SORGP_i)\left(\frac{POTMN_i}{SOILN_i}\right)\left[(SWFA_i)(TFA_i)\right]^{0.5} \tag{3.40}$$

where PMN is P mineralization rate from active inorganic P (kg ha^{-1} d^{-1}), CMN is mineralization constant, which is assumed to be equal to 0.0001 kg ha^{-1} day^{-1}, SORGP is soil organic humus P (kg ha^{-1}), POTMN is potentially mineralizable soil N (kg ha^{-1}), and SOILN is stable soil N (kg ha^{-1}). The mineralization constant (0.0001 kg ha^{-1} day^{-1}) is also used during the N mineralization process in GLEAMS.

Mineralization rate for P in animal waste is determined from:

$$PMNAW_i = (AWDCR_i)(ORGPW_i)\left[(SWFA_i)(TFA_i)\right]^{0.5} \qquad [3.41]$$

where PMNAW is the mineralization rate for P in animal waste (kg ha^{-1} d^{-1}), AWDCR is the decomposition rate constant, and ORGPW is the organic P in animal waste (kg ha^{-1}). Division of the total daily P mineralized from organic P in animal waste is similar to that for fresh organic P; seventy-five percent of P mineralized from animal waste is added to the labile P pool and 25% is assumed to remain organic and is added to the soil organic humus P pool.

Animal waste decomposition rate is calculated using the same form as the decay rate constant for fresh organic P and is defined as:

$$AWDCR_i = (CNP_i)(AWRC_i)\left[(SWFA_i)(TFA_i)\right]^{0.5} \qquad [3.42]$$

where AWRC is an animal waste residue composition factor based on decomposition stage:

$$\begin{aligned} &AWRC = 0.8 && for\ DECOMP \le 20\% \\ &AWRC = 0.05 && for\ 20\% < DECOMP \le 90\% \\ &AWRC = 0.0095 && for\ DECOMP > 90\% \end{aligned} \qquad [3.43]$$

3.3.2 IMMOBILIZATION

Immobilization is the conversion of inorganic, potentially plant-available P into organic (non plant-available) forms. Immobilization of labile P in the soil is initialized when the crop residue C:P ratio exceeds 200 (Jones et al., 1984). Immobilized P is defined as:

$$WIMP_i = (DCR_i)(FRES_i)\left[0.16PLI_i - (c_{pfr})_i\right] \qquad [3.44]$$

where WIMP is the P immobilization rate (kg ha^{-1} d^{-1}), DCR is the residue decay rate (kg ha^{-1} d^{-1}), FRES is the fresh crop residue (kg ha^{-1}), PLI is the labile P immobilization factor, and c_{pfr} is the P concentration in fresh residue (kg kg^{-1}).

Labile P immobilization factor is defined as:

$$\begin{aligned} &PLI_i = 0.01 + 0.001CPLAB_i && for\ CPLAB \le 10 \\ &PLI_i = 0.02 && for\ CPLAB > 10 \end{aligned} \qquad [3.45]$$

where CPLAB is the concentration of labile P in the soil (μg g^{-1}). During P immobilization, it is assumed that 40% of the fresh crop residue is carbon (C) and that soil microorganisms assimilate 40% of the C. The concentration of P in the fresh residue, c_{pfr} (kg kg^{-1}) is:

$$(c_{pfr}) = \frac{FOP}{FRES_i} \qquad [3.46]$$

If the amount of P immobilized per day exceeds 95% of the labile P concentration in the soil, an adjusted decay rate, DCRPR, is calculated as:

$$DCRPR_i = \frac{0.95(PLAB_i)}{FRES_i\left[0.16PLI_i - (c_{pfr})_i\right]} \qquad [3.47]$$

The total amount of immobilized P is subtracted from the labile P concentration in the soil layer and subsequently added to fresh organic P.

If the immobilization value exceeds the amount of labile P in the surface layer, an adjusted surface residue decay rate is calculated as:

$$DCRPR_s = \frac{0.95(PLAB_1) + SOLP}{RESDW\left[0.16PLI_i - (c_{pfr})_s\right]} \qquad [3.48]$$

where $DCRPR_S$ is the adjusted surface residue decay rate (kg ha^{-1} d^{-1}), SOLP is the soluble P concentration on the soil surface layer (kg ha^{-1}), and RESDW is the crop residue mass on the soil surface (kg ha^{-1}). The value for RESDW is input by the model user.

3.4 FLOW RATES BETWEEN PHOSPHORUS POOLS

Transfer of inorganic P occurs between the labile and active inorganic P pools (sorption and desorption reactions) and between the active and stable inorganic P pools (precipitation and dissolution reactions). The active inorganic P pool represents P adsorbed to clays and Al and Fe oxides. The stable inorganic P pool signifies insoluble P found in secondary minerals such as Ca, Fe, and Al phosphates and adsorbed to primary minerals such as quartz and micas.

Flow between the labile and active inorganic P pools is determined by the following equation for each soil layer:

$$MPR_i = 0.1(SWFA_i)\exp(0.115T_i - 2.88)\left[PLAB_i - (PMINP_i)\left(\frac{PSP_i}{1 - PSP_i}\right)\right] \qquad [3.49]$$

where MPR is the inorganic P flow rate (kg ha^{-1} d^{-1}), SWFA is the soil water factor for ammonification, T is soil temperature (°C), PLAB is the labile P mass in the soil (kg ha^{-1}), PMINP is the active inorganic P in the soil (kg ha^{-1}), and PSP is a P sorption coefficient.

The P sorption coefficient takes into account an initial rapid P sorption reaction that occurs when fertilizer P enters the soil system and is the portion of fertilizer P remaining in the labile pool after sorption (Williams et al., 1984). Phosphorus sorption coefficients are calculated based on three soil categories (calcareous, slightly weathered, and highly weathered) using equations developed by Sharpley and Williams (1990) and are defined as:

$$\begin{aligned} PSP_i &= 0.58 - 0.0061(CACO3_i) && \textit{for calcareous soils} \\ PSP_i &= 0.0054(BSAT_i) + 0.116(PH_i) - 0.73 && \textit{for slightly weathered soils} \\ PSP_i &= 0.46 - 0.0916\ln(CL_i) && \textit{for highly weathered soils} \end{aligned} \quad [3.50]$$

where CACO3 is the calcium carbonate content of the soil (μg g^{-1}), BSAT is base saturation (%), PH is soil pH, and CL is the clay content (%). The value of PSP ranges from 0.05 to 0.75.

At equilibrium, stable inorganic P is assumed to be four times the active inorganic P pool (Sharpley and Williams, 1990). The flow rate between active and stable inorganic P pools is given as:

$$ASPR_i = \omega_i (4 \times PMINP_i - SOILP_i) \quad [3.51]$$

where ASPR is the P flow rate between active and stable inorganic P pools, ω_i is a P flow coefficient, PMINP is the active inorganic P (kg ha^{-1}), and SOILP is the stable inorganic P (kg ha^{-1}). The P flow coefficient is defined by Jones et al. (1984) as:

$$\begin{aligned} \omega_i &= 0.00076 && \textit{for calcareous soils} \\ \omega_i &= \exp(-1.77 \times PSP_i - 7.05) && \textit{for noncalcareous soils} \end{aligned} \quad [3.52]$$

3.5 FERTILIZER PHOSPHORUS

In GLEAMS, fertilizer P in the form of inorganic commercial or animal waste can be surface applied, incorporated, injected, or applied through fertigation. Inorganic fertilizer is assumed to be instantaneously soluble and therefore added to the labile P pool. Surface applied P fertilizer is added to the soluble P pool (SOLP). When rainfall or irrigation occurs, the soluble P pool is moved into the soil surface layer. Incorporated, injected, or fertigation applied fertilizer are mixed into the soil surface layer on the date of application (Knisel, 1993). Both the application rate and depth of incorporation are input by the model user and are sensitive parameters affecting plant uptake and potential leaching losses (Knisel and Davis, 1999).

3.6 PARAMETER SENSITIVITY

Sensitivity of GLEAMS parameters is site-specific and may change with differences in soil characteristics, climate, and management (Knisel, 1993). Users are urged to obtain site-specific data and rely on default values only when no other data are available.

GLEAMS output may be sensitive to initial values of labile P if significant rainfall occurs shortly after simulation. Model output may also be sensitive to crop characteristics, such as potential yield, leaf area index, and current crop rooting depth. Plant uptake of nutrients may be sensitive to the crop coefficient and exponent in highly fertilized systems. The method of application and composition of animal waste can cause sensitivity in model output. The depth of incorporation of fertilizers can affect nutrient loads in runoff and leaching (Knisel, 1993).

3.7 DISCUSSION

Equations and relationships used by GLEAMS to simulate P transport and transformations were presented in this chapter. GLEAMS simulation of plant uptake of P is based on a P demand factor that is calculated from the ratio of daily optimum P demand of a crop to the total P uptake. The state of the science review showed that the Barber-Cushman model has been used by Chen and Barber (1990) and Ernani et al. (1994) to predict plant uptake of P. Use of the Barber-Cushman model in GLEAMS is not feasible because the model requires root morphology and uptake kinetics that are specific for each crop and must be determined experimentally. Aquino and Hansen (1984) developed linear relationships to predict plant P removal with STP, but these relationships are only applicable to grain sorghum. Therefore, changes to plant uptake of P calculations in GLEAMS are not feasible at this time.

Simulation of P loss through runoff and leaching in GLEAMS begins with the initial soil labile P concentration. The P partitioning coefficient (CPKD) determines the amount of P in the soil and water phases and is used to estimate the P extraction coefficient and concentration of P available for loss in runoff and percolation. During review of equations used by GLEAMS to simulate P, an error was observed in the calculation of the P partitioning and extraction coefficients. The P partitioning coefficient is calculated by Eqn. 3.12 and is then used to determine the P extraction coefficient in Eqn. 3.13. Regardless of clay content, the P partitioning coefficient will always be greater than 100 resulting in the assumption that the P extraction coefficient is always 0.10, possibly contributing to underestimates of dissolved P loss through leachate and total P loss through runoff. Consideration must be given to soils with low clay contents and high P saturation values to account for more P available for transport through runoff and leaching. Also, based on values found in the literature review, CPKD is highly overestimated in GLEAMS. Changes to calculations of the P partitioning and extraction coefficients should be considered in GLEAMS. Sensitivity of GLEAMS-predicted P in runoff and leachate to the P partitioning and extraction coefficients is described in Chapter 4.

The equation given in the GLEAMS user manual for calculation of the concentration of labile P in solution (CPLABW) did not agree with the equation hard-coded in the GLEAMS Fortran files; an extra variable (CPKD) was included in the numerator of the equation presented in the user manual. Upon further investigation, it was determined that the equation in the Fortran source code was correct.

The state of the science review revealed numerous relationships that have been developed to predict dissolved P loss in runoff and leachate based on a single variable, such as STP and P saturation. Use of these equations in GLEAMS may not be feasible; the equations were developed for site-specific conditions and are applicable for a given set of soil and management characteristics. Transport factors must also be considered when predicting P loss.

Phosphorus mineralization is a factor of soil organic C and P content. GLEAMS considers these factors by calculating the C:P and C:N ratios of crop residue to help determine P mineralization. Fresh organic P and N are assumed to equal 10 kg ha^{-1} and 40 kg ha^{-1}, respectively. Also the mineralization constant is assumed to be 0.0001 kg ha^{-1} day^{-1}. No sources or explanations for these assumptions were given in the user manual. Sensitivity of the GLEAMS P output to these constants is unknown but was determined and is presented in Chapter 4. Immobilization is affected by microbial activity, and GLEAMS considers the correlation between C and P content in fresh residue when calculating immobilization.

GLEAMS does simulate the general trends of P mineralization and immobilization reactions. Results from the sensitivity analysis, presented in Chapter 4, should indicate if any changes to the constant, CMN, should be made.

Phosphorus pool sizes along with transformation rates are important in estimating P availability. The equilibrium between soil sorption, solution, and precipitated compounds and soil mineralogy are important factors when determining the size of the P pools and the flow between them. GLEAMS calculates a P sorption coefficient based on the calcium carbonate content of calcareous soils, the base saturation and pH of slightly weathered soils, and the clay content of highly weathered soils. The P sorption coefficient is then used to estimate flow between the active and stable inorganic P pools. Though the amount of clay in soil plays a factor in GLEAMS-predicted P pool sizes, the type of clay (i.e., 1:1 and 2:1 clay layer type) is not considered. Since no new advances to the estimation of P pool sizes were found, changes to GLEAMS calculation of P pool sizes were not considered.

GLEAMS also simulates additions to the soil system in the form of plant residue and fertilizers. The type and rate of fertilizer application affect plant uptake of P and potential P leaching losses. The state of the science review did not reveal any new knowledge on simulating fertilizer P in the soil system, therefore no changes to fertilizer P calculations in GLEAMS should be considered.

CHAPTER 4: GLEAMS SENSITIVITY ANALYSIS

A literature review of the state of the science for P transport and transformations was presented in Chapter 2. Chapter 3 reviewed GLEAMS 3.0 simulation of P. Chapter 4 presents the sensitivity analysis that was conducted as a component of this study to determine how changes in selected variables affect GLEAMS-predicted P in runoff and leachate. Data sets from two studies utilizing CREAMS and GLEAMS to predict nutrient losses (Yoon et al., 1992; 1994) were selected to assess GLEAMS P modeling capability. These two studies at Belle Mina and Gilbert Farm in North Alabama documented parameters necessary to create the GLEAMS hydrology, erosion, and nutrient input files. The sample data set distributed with GLEAMS for the Watkinsville P-2 watershed (Georgia) is also presented. The Watkinsville P-2 data were not used in the sensitivity analysis but were used in the model change analysis described in Chapter 5.

4.1 MODEL PARAMETERS INVESTIGATED

A sensitivity analysis of GLEAMS 3.0 was conducted to determine how changes in the variables FOP, FON, CMN, CPKD, and β_p affect GLEAMS-predicted values of dissolved and sediment P in runoff, leached P, and P uptake by plants. These variables are hard-coded within the Fortran source code. The analysis was done by adjusting the GLEAMS Fortran code and compiling changes into an executable program. No studies were found reporting the sensitivity of GLEAMS output to these variables.

The value of FOP is used in the calculation of the mineralization rate of fresh organic P, the C:P ratio of crop residue, and the concentration of P in fresh residue. Likewise, FON is used to calculate the mineralization rate of fresh organic N, the C:N ratio of crop residue, and the concentration of N in fresh residue. No explanations or references were given in the GLEAMS user manual (Knisel and Davis, 1999) that indicate why 10 kg ha^{-1} and 40 kg ha^{-1} were used as constants for FOP and FON, respectively. Fresh organic P was changed from the original GLEAMS value of 10 kg ha^{-1} to 0, 20, 50, and 100 kg ha^{-1} to cover a wide range of possible values. The sensitivity of GLEAMS P output to FON was considered because FON is used in the calculation of the decay rate constant for FOP (eqn. 3.33) when CNP is a function of CNR (eqn. 3.34). The value of FON was varied in GLEAMS from the default value of 40 kg ha^{-1} to 0, 20, 80, and 160 kg ha^{-1}.

The mineralization constant, CMN, is used to calculate mineralization of soil organic humus P to labile P and is fixed at 0.0001 kg ha^{-1} day^{-1} within GLEAMS. Zou et al. (1992) observed P mineralization rates for four soils, three forest and one grassland. A silty clay loam forest Alfisol mineralized organic P to solution P at a rate of 3.8 mg kg-$soil^{-1}$ day^{-1}. A forest Ultisol with loamy sand texture mineralized organic P to solution P at a rate of 0.6 mg kg-$soil^{-1}$ day^{-1}. A sandy loam Mollisol from a grassland and a silty clay loam forest Andisol both mineralized organic P to solution P at a rate of 1.3 mg kg-$soil^{-1}$ day^{-1}. Comparison of CMN to mineralization constants reported in current literature is problematic due to differing units. The value of CMN was changed to 0.0000, 0.0005, 0.0010, 0.0050, 0.0075, and 0.0100 kg ha^{-1} d^{-1} to determine sensitivity of GLEAMS P output. Because the value of CMN is the same for N and P mineralization, changing CMN for the purpose of studying the sensitivity of P output also affects N calculations in GLEAMS.

The value of CPKD is important for calculations of labile P in soil and soil-water solutions, which in turn are used to estimate concentrations of labile P in runoff and percolation. Frere et al. (1980) acknowledged weaknesses of the CREAMS nutrient sub-model in estimating partitioning coefficients; assumptions were developed in the absence of experimental data and this weakness was carried over to GLEAMS. The GLEAMS 2.10 documentation (Knisel, 1993) noted concerns of possible errors in CPKD estimation and stated: "Assumptions presently made are that CPKD is related only to the clay content of soil and not to P status, degree of clay surface coverage by adsorbed P, or the nature of the surface. While this assumption may be valid for agricultural soils, CPKD may be overestimated for soils with inherently low adsorptive capacity receiving large P loadings such as from animal waste." The value of CPKD is calculated as a function of clay content (CPKD = 100 + 2.5 x CL from Eqn. 3.12). In turn, the extraction coefficient, β_p, is calculated as a function of CPKD (Eqn. 3.13).

The value of CPKD as computed in GLEAMS is always greater than 100, which results in the assumption that, regardless of clay content, the P extraction coefficient is always 0.10 implying that only 10% of available P can be separated from the soil system and be lost through runoff, leaching, and plant uptake ($\beta_p = 0.10$; Eqn. 3.13). This does not give consideration to soils with low clay contents where a larger proportion of the total soil P may be available for transport through runoff and leaching. Soils with lower clay contents may have potential for more P to be available due to a lower number of P adsorption sites. This apparent error in implementation of the equation used to estimate CPKD causes a possible underestimation of the extraction coefficient for P in soils with low clay content. The following changes to CPKD, with the resulting values of β_p, were evaluated:

- CPKD = 1, $\beta_p = 0.50$
- CPKD = 3, $\beta_p = 0.35$
- CPKD = 5, $\beta_p = 0.24$
- CPKD = 7, $\beta_p = 0.17$
- CPKD = 15, $\beta_p = 0.10$
- CPKD > 100, $\beta_p = 0.10$ (default GLEAMS value)

Sensitivity of the variable β_p was also evaluated independent of a change in CPKD. The P extraction coefficient was varied from the GLEAMS default value, as calculated by Eqn. 3.13, to 0.25, 0.50, 0.75, and 1.00.

Relative sensitivity (S_R) was used to evaluate model output and was calculated as:

$$S_R = \frac{(New\ Output - Baseline\ Output)}{(New\ Input - Baseline\ Input)} x \frac{(Baseline\ Input)}{(Baseline\ Output)} \qquad [4.1]$$

Storm et al. (1988) defined five levels of relative sensitivity: insensitive ($S_R < |0.01|$), slightly sensitive ($|0.01| \leq S_R < |0.10|$), moderately sensitive ($|0.10| \leq S_R < |1.00|$), sensitive ($|1.00| \leq S_R < |2.00|$), and extremely sensitive ($S_R \geq |2.00|$). These levels were used to evaluate the relative sensitivity of GLEAMS 3.0. The data sets used in the sensitivity analysis are described in the following sections.

4.2 FIELD DATA

4.2.1 BELLE MINA, ALABAMA

Field data from Yoon et al. (1994) were used to evaluate P losses in surface runoff and subsurface leaching from GLEAMS. The site was located at Belle Mina, AL in Limestone County. Historical daily rainfall and temperature data were obtained from the National Climatic Data Center (NCDC) website (NCDC, n.d.). The closest weather station with records for the study period (January 1991 to December 1992) was identified as Belle Mina 2N weather station in Belle Mina, AL. Field observed monthly rainfall data were given by Yoon et al. (1994), however, daily rainfall values required for GLEAMS simulations were not included. Field observed monthly rainfall totals were compared to monthly values from the Belle Mina 2N weather station data with notable differences (Table 4.1). The daily rainfall values from Belle Mina 2N weather station were then adjusted proportionally by multiplying each by the ratios of the monthly rainfall values (field observed to weather station data).

Table 4.1 Monthly precipitation data for Belle Mina, AL. On-site observed rainfall data are from Yoon et al. (1994); Belle Mina 2N weather station data are from NCDC (n.d.).

Month	Precipitation (cm)		
	Belle Mina On-site Observed Rainfall	Belle Mina 2N Weather Station Data	Ratio of Monthly On-site to Weather Station Data
Mar-91	19.0	21.7	0.88
Apr-91	19.5	23.0	0.85
May-91	23.0	24.2	0.95
Jun-91	4.5	4.5	1.00
Jul-91	5.0	5.3	0.94
Aug-91	5.5	5.1	1.08
Sep-91	9.5	9.3	1.02
Oct-91	5.0	5.8	0.86
Nov-91	9.0	7.9	1.14
Dec-91	32.5	32.3	1.01
Jan-92	7.5	7.5	1.00
Feb-92	8.0	8.1	0.99
Mar-92	12.5	12.1	1.03
Apr-92	5.0	4.5	1.11
May-92	6.2	5.8	1.07
Jun-92	20.0	22.8	0.88
Jul-92	14.5	16.0	0.91
Aug-92	8.5	10.9	0.78
Sep-92	12.5	13.3	0.94
Oct-92	7.5	7.1	1.06
Nov-92	12.5	12.9	0.97
Total	247.2	260.0	*

* No ratio for total values

Field plots were 0.1 ha in size. Since field plot dimensions were not given by Yoon et al. (1994), the plots were assumed to be rectangular (43.74 m long and 22.86 m wide) with a 5% slope. The assumption affects the slope length in the erosion sub-model and may allow more or less sediment to be lost than what was observed. Data given by Yoon et al. (1994) include averages of four replications of three fertilizer treatments: commercial fertilizer (450 kg ha^{-1} ammonium nitrate and 122 kg ha^{-1} triple superphosphate), 18 t ha^{-1} poultry litter (PL18), and 9 t ha^{-1} poultry litter (PL9).

Soil type for the Yoon et al. (1994) study site was Decatur silty clay. Soil depth, percent clay, percent silt and percent organic matter were taken from soil physical properties as reported by Yoon et al. (1994). The Soil Survey Geographic Database (http://www.ncgc.nrcs.usda.gov/products/datasets/ssurgo/) (SSURGO, n.d.) was used to determine a range of soil properties for inclusion in the GLEAMS input files. The Soil Texture Triangle (http://www.bsyse.wsu.edu/saxton/soilwater/#AW) (Saxton, n.d.) was used to determine the soil textural class based on the soil clay, silt, and sand content given by Yoon et al. (1994) and to estimate soil parameters not provided by Yoon et al. (1994) such as wilting point, field capacity, bulk density, porosity, and saturated hydraulic conductivity. Soil erodibility factors from SSURGO data (SSURGO, n.d.) were used. Soil property values listed in Table 4.2 were used in the initial hydrology input file prior to calibration.

Table 4.2 Soil properties used in GLEAMS hydrology input files for Belle Mina data set prior to calibration.

Soil Property	Soil depth (cm)			
	0 - 5	5 - 10	10 - 40	40 - 100
Percent Clay (%) [a]	33	35	43	58
Percent Silt (%)[a]	50	48	43	32
Organic Matter (%)[a]	1.8	1.8	1.2	0.8
Bulk Density (g cm^{-3}) [b]	1.29	1.28	1.24	1.19
Soil Erodibility Factor [c]	0.32	0.32	0.28	0.24
Field Capacity (cm^3 cm^{-3}) [b]	0.35	0.36	0.40	0.45
Porosity (cm^3 cm^{-3}) [b]	0.51	0.52	0.53	0.55
Wilting Point (cm^3 cm^{-3}) [b]	0.18	0.19	0.24	0.34
Hydraulic Conductivity (cm hr^{-1}) [b]	0.42	0.37	0.27	0.24

Data sources: [a] Yoon et al. (1994), [b] Saxton (n.d.), [c] SSURGO (n.d.)

The criterion for selection of the best agreement between observed and simulated data for calibration was based on percent relative error. The relative error from observed data was given by Storm et al. (1988) and calculated as:

$$\text{Relative Error } \% = \frac{(Simulated - Observed)}{Observed} \times 100 \qquad [4.2]$$

A negative percent error indicates an under-prediction whereas a positive percent error represents an over-prediction. A parameter set was selected as being calibrated if, on average, it had the lowest percent error among calibration trials.

GLEAMS hydrology for treatment PL9 was calibrated by adjusting field capacity and wilting point to produce the closest agreement between observed and simulated runoff values for March 1991 to November 1992 (Figure 4.1). During calibration, each adjusted parameter was not changed more than ±15 percent of the original initial value and the SCS curve number for antecedent moisture condition II (CN2) was decreased from 85 to 78. For hydrologic soil group B (Decatur silty clay) and straight row crops in poor condition, curve number values range from 78 to 85. Annual observed runoff values in 1991 and 1992 were 20.8 cm and 8.1 cm, respectively. The calibrated hydrology input file produced GLEAMS runoff predictions of 7.9 cm in 1991 and 5.1 cm in 1992. Annual runoff was under-predicted by 62% in 1991 and 37% in 1992. The GLEAMS simulation period began on January 1, 1991, allowing two months for initialization of soil conditions. A possible reason for the large variation (-96 to -175%) between observed and predicted monthly runoff from March through May 1991 may be due to compacted soil conditions from farm machinery; compacted soil may have reduced infiltration rates and allowed more runoff to occur.

GLEAMS erosion for treatment PL9 was calibrated for March 1991 to August 1992 by adjusting the soil loss ratio and contouring factor for overland flow at certain times of the year (Figure 4.2). The soil loss ratio (C-factor) and the contouring factor (P-factor) are from the Universal Soil Loss Equation. Annual observed sediment values were 1.05 t ha^{-1} in 1991 and 0.28 t ha^{-1} in 1992. GLEAMS predictions from the calibrated erosion input file were 0.83 t ha^{-1} in 1991 and 0.28 t ha^{-1} in 1992. Annual sediment loss was under-predicted by 21% in 1991; the relative percent error between observed and predicted annual sediment loss in 1992 was <1%.

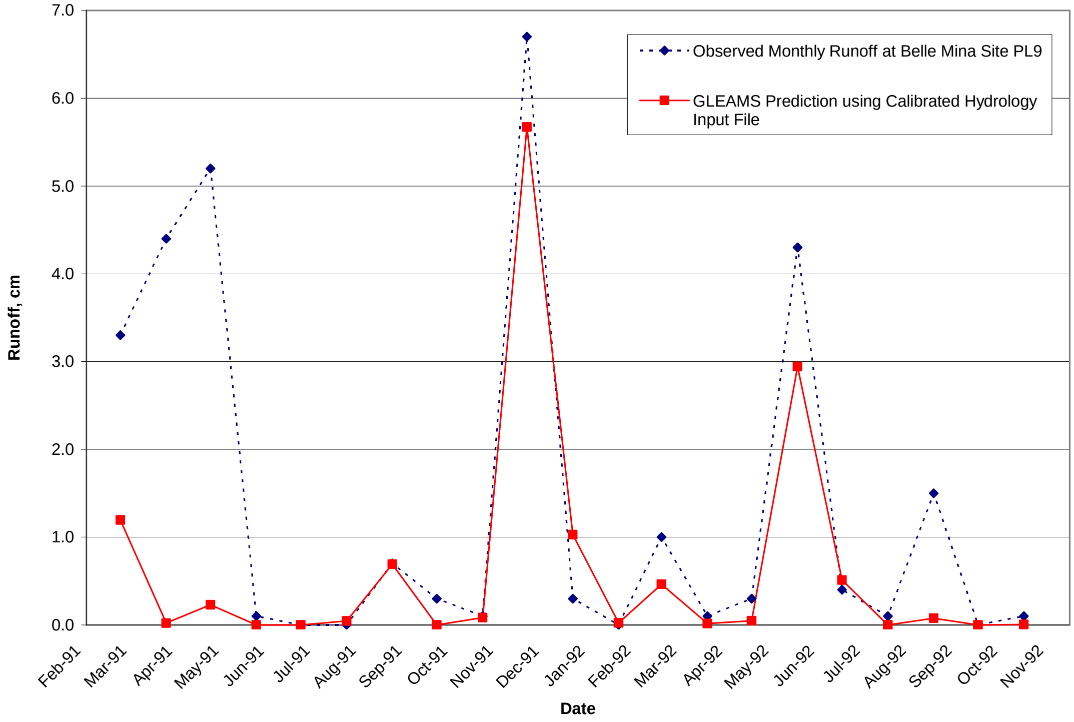

Figure 4.1 Surface runoff calibration for Belle Mina, AL, treatment PL9.

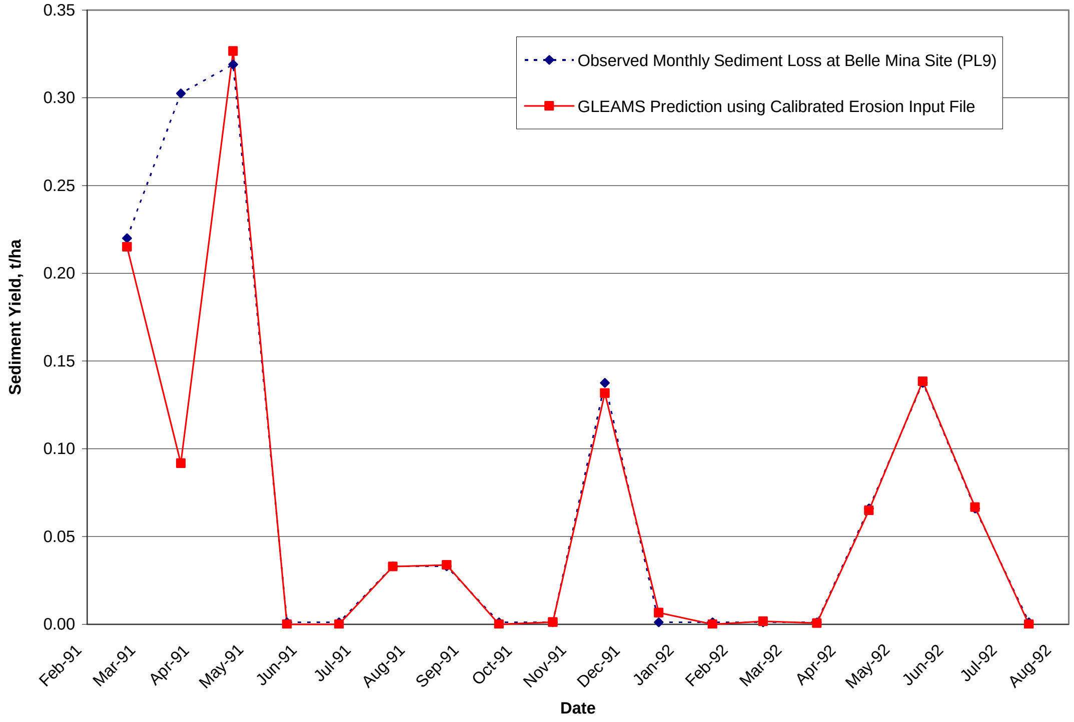

Figure 4.2 Sediment loss calibration for Belle Mina, AL, treatment PL9.

Attempts were made to calibrate a nutrient input file based on observed data for PL9. This file would then be used for the PL18 nutrient input file (with 18 t ha^{-1} poultry litter applied as opposed to 9 t ha^{-1}). Calibration of P loss in runoff and leachate proved difficult due to the lack of soil nutrient data presented by Yoon et al. (1994). Information such as poultry litter characteristics, fertilizer application method and date of application were given, but soil nutrient status was not. An initial nutrient input file was created. Efforts to calibrate dissolved P loss in runoff through changes in the total P, labile P, and organic P content were unsuccessful. An error from underflow of P mineralization was often encountered when varying these parameters during calibration. Also, changes made to the nutrient input file to accommodate calibration of dissolved P loss affected calibration of sediment P loss. Therefore, soil nutrient input parameters in all soil horizons were assumed to be equal:

- Total P – 0.026%,
- Labile P – 10 ppm, and
- Initial organic P content in soil – 0.042%.

Figure 4.3 shows the loss of dissolved P in runoff as predicted by GLEAMS versus observed data. Annual observed dissolved P values were 0.13 kg ha^{-1} in 1991 and 0.32 kg ha^{-1} in 1992. GLEAMS predictions from the calibrated nutrient input file were 0.17 kg ha^{-1} in 1991 and 1.15 kg ha^{-1} in 1992. Annual dissolved P loss in runoff was over-predicted by 32% in 1991 and 259% in 1992. These over-predictions are not explained by the under-predictions in annual runoff. Predicted monthly dissolved P loss in runoff in December 1991 and June 1992 dominated the annual over-predictions. GLEAMS simulated a 2.9 cm runoff event on June 26, 1992, which was the highest predicted daily runoff amount over the study period from March 1991 through November 1992. The amount of observed runoff for this date (June 26, 1992) is unknown because Yoon et al. (1994) only presented monthly values. All of the predicted runoff PO_4-P (0.94 kg ha^{-1}) lost in June 1992 was from a single runoff event; 0.09 kg ha^{-1} of runoff PO_4-P was observed in June 1992.

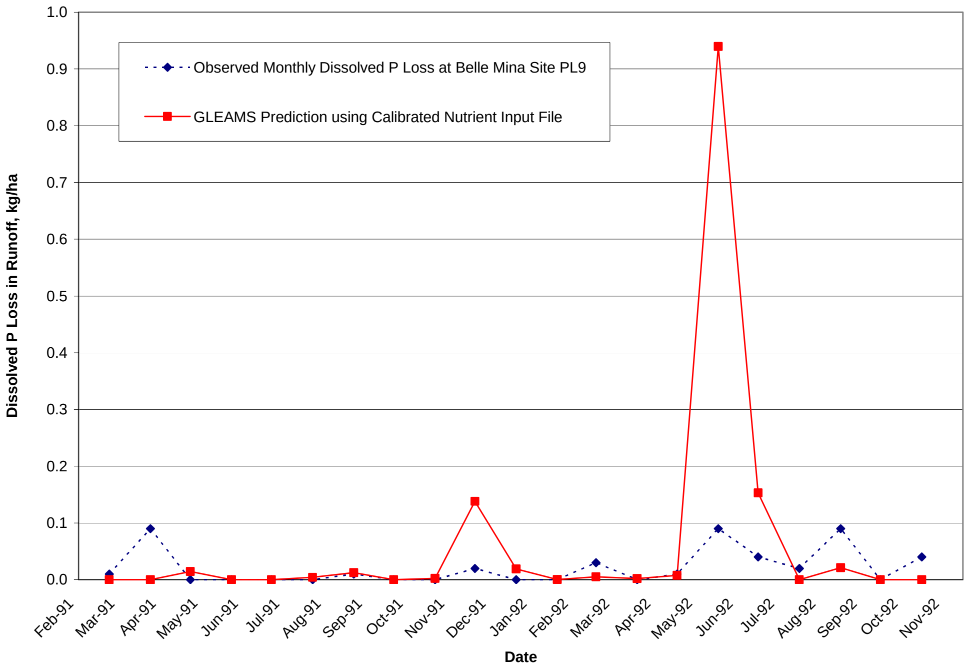

Figure 4.3 Dissolved P in runoff for Belle Mina, AL, treatment PL9.

Figures 4.4 and 4.5 show predictions of sediment P in runoff and dissolved P in leachate, respectively, for Belle Mina treatment PL9. Annual observed sediment P in runoff was 0.62 kg ha^{-1} in 1991 and 0.17 kg ha^{-1} in 1992. GLEAMS sediment P in runoff predictions from the calibrated nutrient input file were 1.68 kg ha^{-1} in 1991 and 0.88 kg ha^{-1} in 1992. GLEAMS over-predicted annual sediment P loss by 172% (1991) and 418% (1992). Though annual sediment loss was under-predicted by 21% in 1991, GLEAMS-predicted sediment loss was within <1% of observed in 1992. This does not explain the over-predictions of monthly sediment P loss in March through May 1991 and May through July 1992.

Annual observed values of dissolved P in leachate totaled 0.26 mg L^{-1} in 1991 and 0.023 mg L^{-1} in 1992. Total GLEAMS predicted dissolved P in leachate for 1991 and 1992 were 0.14 mg L^{-1} and 0.016 mg L^{-1}, respectively. GLEAMS under-predicted annual dissolved P in leachate by 47% and 32% in 1991 and 1992, respectively. Total leachate volumes were not presented by Yoon et al. (1994), therefore, a comparison between GLEAMS-predicted and observed leachate could not be done.

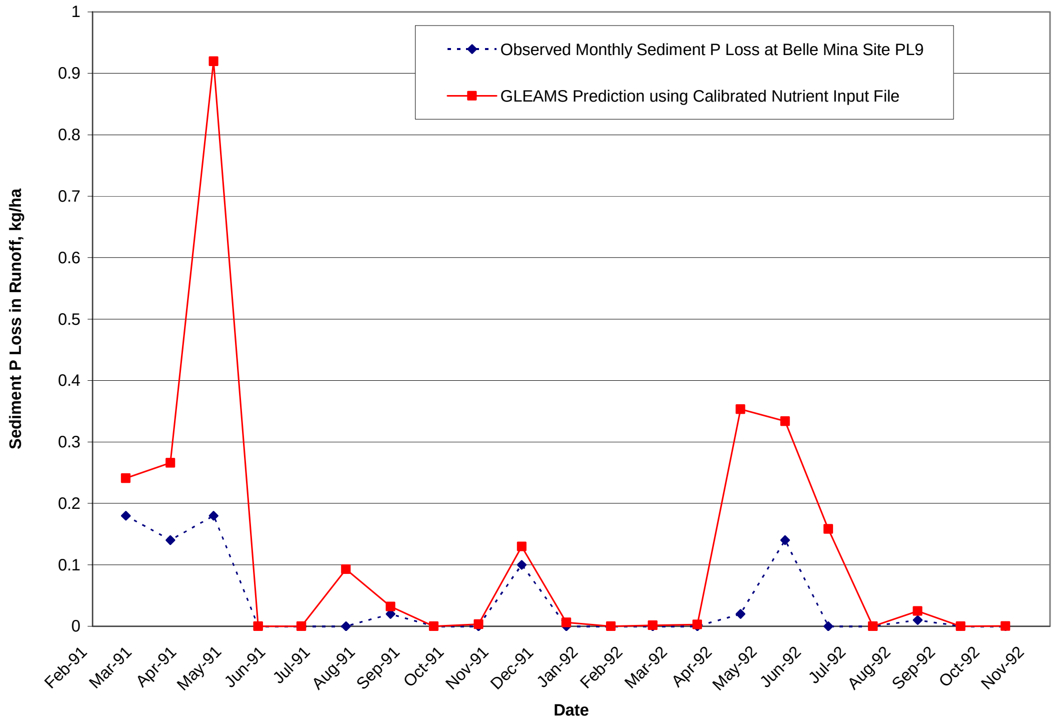

Figure 4.4 Sediment P in runoff for Belle Mina, AL, treatment PL9.

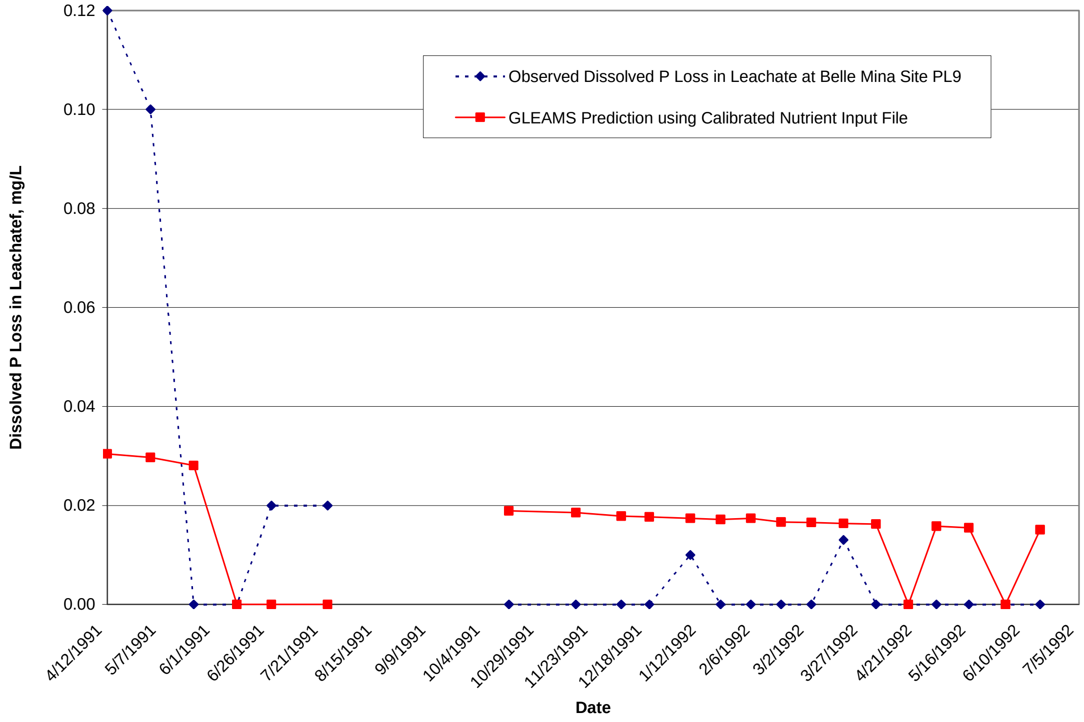

Figure 4.5 Dissolved P in leachate for Belle Mina, AL, treatment PL9.

All treatments at Belle Mina received the same amount of rainfall, however, runoff volumes varied. Initial calibration of hydrology for treatment PL18 was performed using the calibrated hydrology file from PL9. Soil water storage capacity was adjusted to calibrate PL18 hydrology. Surface runoff calibration for PL18 is shown in Figure 4.6. Annual observed surface runoff values totaled 25.3 cm in 1991 and 7.5 cm in 1992 compared to GLEAMS predicted values of 3.2 cm in 1991 and 2.0 cm in 1992. GLEAMS under-predicted runoff by 87% in 1991 and 73% in 1992. As in the PL9 data, soil on the study plots may have been compacted from farm machinery, resulting in decreased infiltration and increased runoff.

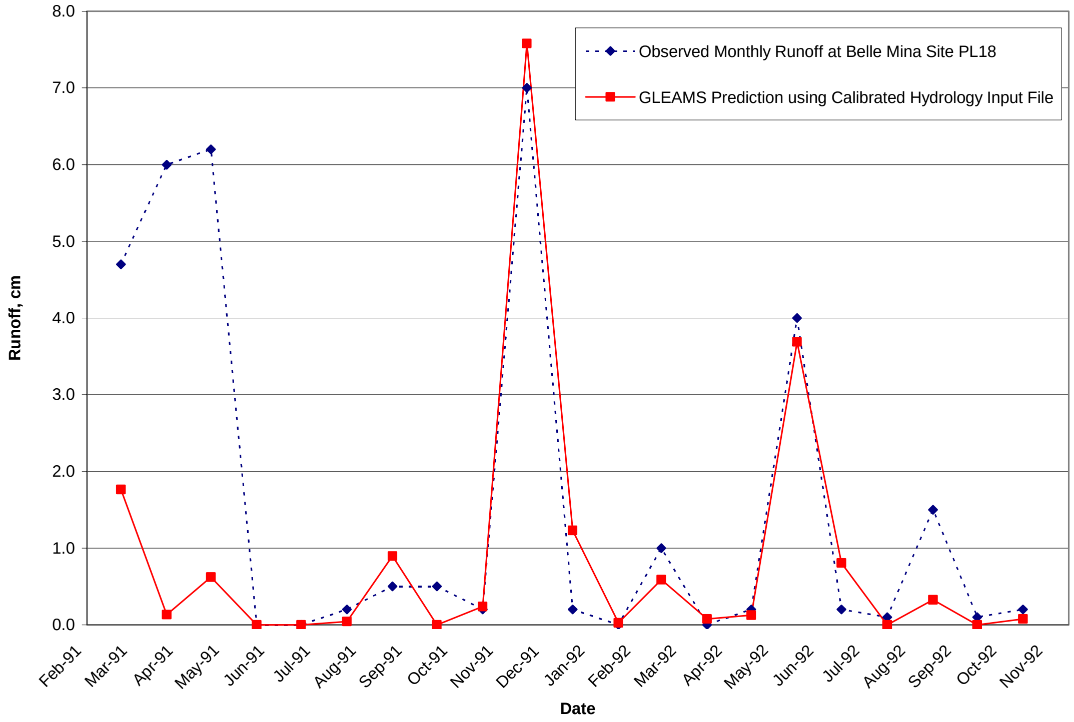

Figure 4.6 Surface runoff calibration for Belle Mina, AL, treatment PL18.

Sediment loss for PL18 was calibrated by adjusting soil loss ratio. Annual observed sediment loss in 1991 and 1992 was 1.41 t ha^{-1} and 0.13 t ha^{-1}, respectively (Figure 4.7). Predicted annual values totaled 1.25 t ha^{-1} in 1991 and 0.13 t ha^{-1} in 1992. GLEAMS under-predicted sediment loss by only 12% in 1991 and less than one percent in 1992; however runoff was under-predicted by 83% over the study period.

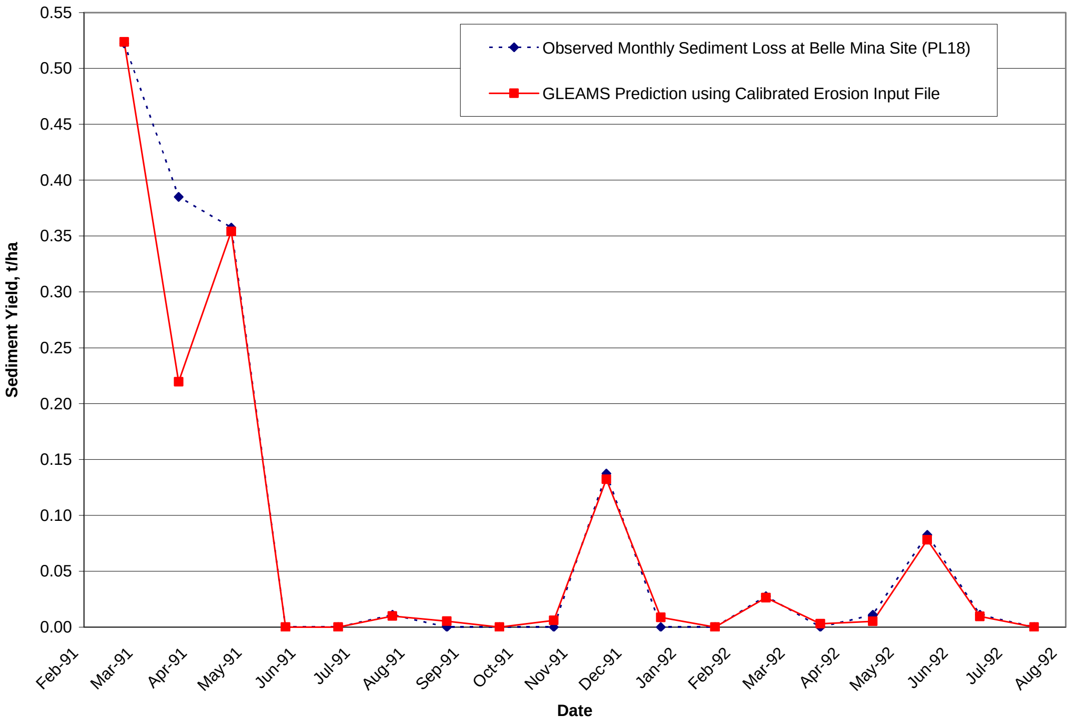

Figure 4.7 Sediment loss calibration for Belle Mina, AL, treatment PL18.

The GLEAMS-predicted and observed values of dissolved P loss in runoff are shown in Figure 4.8. Annual observed dissolved P loss in runoff values were 0.41 kg ha^{-1} in 1991 and 0.99 kg ha^{-1} in 1992. GLEAMS predicted annual values were 1.84 kg ha^{-1} in 1991 and 2.89 kg ha^{-1} in 1992. Annual dissolved P in runoff was over-predicted by 349% in 1991 and 192% in 1992.

Observed and predicted values of sediment P loss in runoff are shown in Figure 4.9. Annual observed values totaled 1.01 kg ha^{-1} in 1991 and 0.27 kg ha^{-1} in 1992. GLEAMS-predicted annual sediment P values were 3.75 kg ha^{-1} and 0.49 kg ha^{-1} in 1991 and 1992, respectively. Annual sediment-bound P in runoff was over-predicted by 271% in 1991 and 81% in 1992.

Dissolved P loss in leachate for PL18 is shown in Figure 4.10. Observed dissolved P in leachate values in 1991 and 1992 were 0.32 mg L^{-1} and 0.053 mg L^{-1}, respectively. GLEAMS predicted annual values of 0.15 mg L^{-1} in both 1991 and 1992. GLEAMS under-predicted dissolved P loss in leachate in 1991 by 54% and over-predicted this value by 180% in 1992. All GLEAMS input files are included in Appendix B.

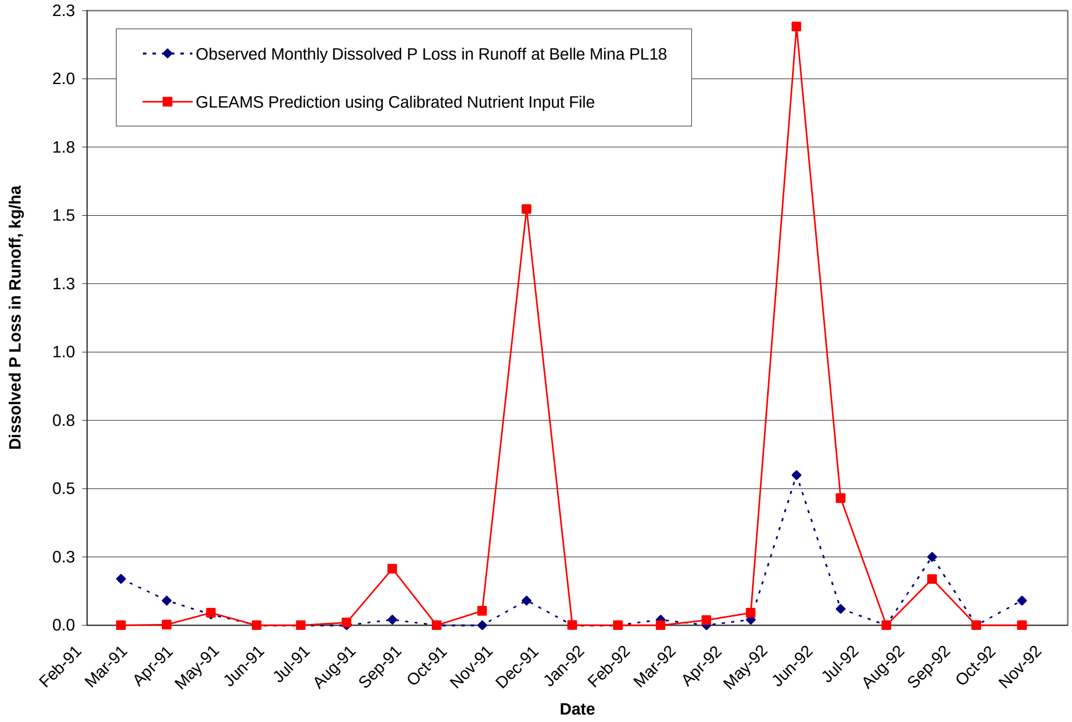

Figure 4.8 Dissolved P loss in runoff for Belle Mina, AL, treatment PL18.

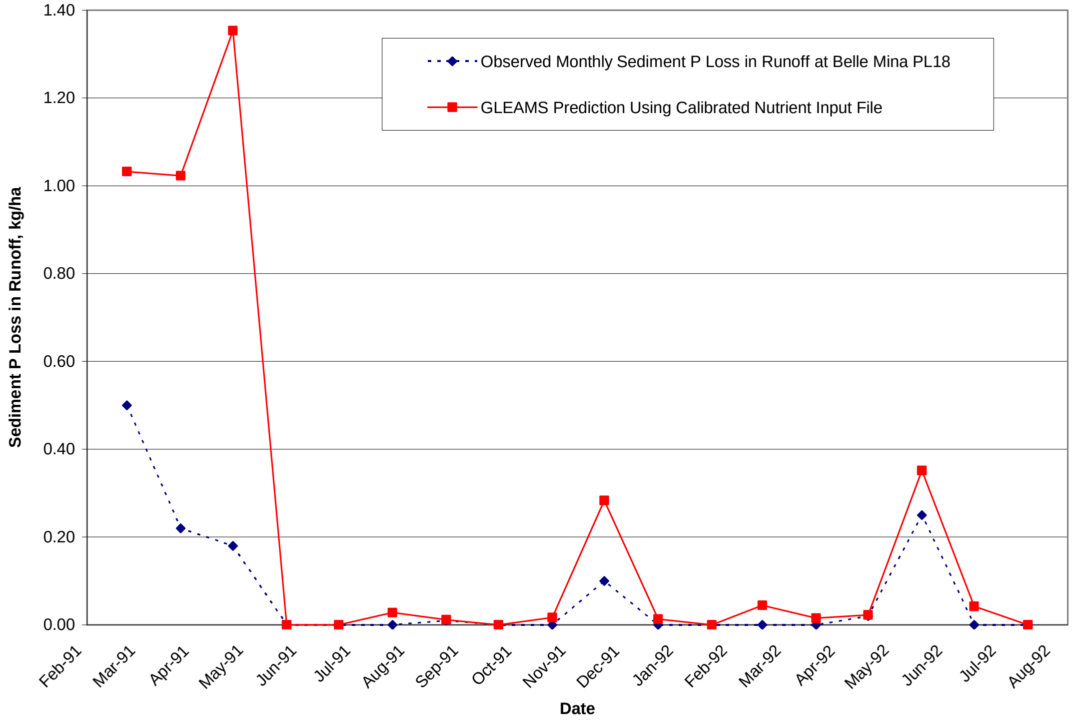

Figure 4.9 Sediment P loss in runoff for Belle Mina, AL, treatment PL18.

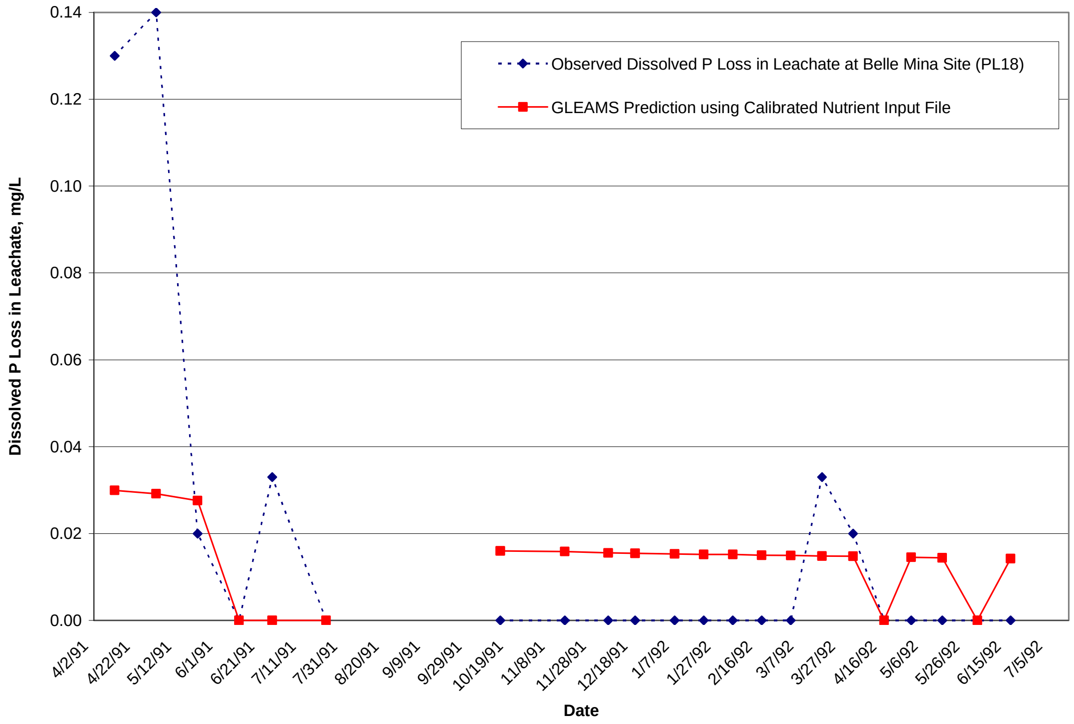

Figure 4.10 Dissolved P loss in leachate for Belle Mina, AL, treatment PL18.

4.2.2 GILBERT FARM, ALABAMA

Data from Yoon et al. (1992) were used to evaluate P loss in surface runoff from GLEAMS. The watershed under study (Gilbert Farm) was located in Colbert County, AL. Historical daily precipitation and temperature data were obtained from NCDC (n.d.) for 1984 through 1989 for the Muscle Shoals Regional Airport weather station in Colbert County. This weather station was the nearest to the field location (less than 16 km east of watershed) collecting continuous daily rainfall data during the study period. Annual precipitation data for Gilbert Farm watershed are shown in Table 4.3.

The field-sized watershed (3.8 ha) with a 6% slope was planted to cotton. Conventional tillage was implemented from 1984-1986 with conservation tillage used in 1987-1989. Rye was planted as a cover crop during the winters of 1987 and 1988. A 10- to 15-m wide grassed strip bordered the field.

Table 4.3 Annual precipitation data for Gilbert Farm watershed. On-site observed rainfall data are from Yoon et al. (1992).

Year	Precipitation (cm)	
	Gilbert Farm On-site Data	Muscle Shoals Regional Airport Weather Station Data
1984	121.03	120.35
1985	111.94	108.59
1986	133.07	143.10
1987	112.83	99.52
1988	106.45	106.73
1989	161.04	175.87
Total	746.45	754.15

Soil properties were taken from SSURGO data (SSURGO, n.d.) where available. As with the Belle Mina data set, the soil texture triangle (http://www.bsyse.wsu.edu/saxton/soilwater/#AW) (Saxton, n.d.) was used to determine the soil textural class based on the soil clay, silt, and sand content and to estimate values for soil properties not reported by Yoon et al. (1992). Table 4.4 lists soil properties used for the Gilbert Farm data set.

Table 4.4 Soil properties for Gilbert Farm data set.

Soil Property	Soil depth (cm)		
	0 – 18	18 - 51	51 - 183
Percent Clay (%)	22 [a]	48 [c]	60 [c]
Percent Silt (%)	59 [a]	35 [c]	20 [c]
Organic Matter (%)[a]	2	1.5	1.5
Bulk Density (g cm^{-3}) [b]	1.35	1.23	1.21
Soil Erodibility Factor [#]	0.28	0.24	0.32
Field Capacity (cm^3 cm^{-3}) [b]	0.30	0.43	0.48
Porosity (cm^3 cm^{-3}) [b]	0.49	0.54	0.54
Wilting Point (cm^3 cm^{-3}) [b]	0.13	0.28	0.35
Hydraulic Conductivity (cm hr^{-1}) [b]	0.96	0.22	0.19

Data sources: [a] Yoon et al. (1992), [b] Saxton (n.d.), [c] SSURGO (n.d.)

Hydrology and erosion calibrations were performed on the Gilbert Farm watershed data set. Preliminary simulation results revealed the largest difference between observed annual runoff and GLEAMS simulated values occurred in 1985; therefore, the best parameter set for hydrology calibration was selected based on all years except 1985. Surface runoff calibration for Gilbert Farm watershed was performed by changing the soil's field capacity; the results are shown in Figure 4.11. Average annual observed runoff was 23.5 cm compared to GLEAMS' prediction of 26.2 cm. GLEAMS over-predicted runoff the first three years of simulation by 19% in 1984, 207% in 1985, and 37% in 1986 and under-predicted runoff for the last three years by 31% in 1987, 5% in 1988, and 20% in 1989.

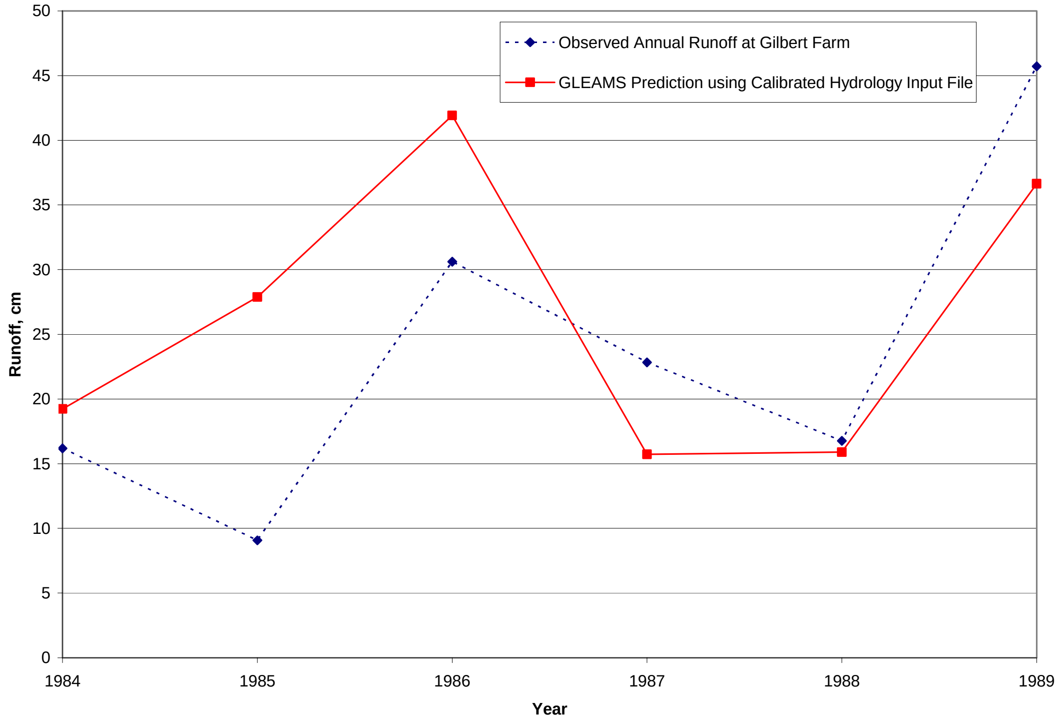

Figure 4.11 Surface runoff calibration for Gilbert Farm watershed.

Sediment yield was calibrated by varying soil erodibility and Manning's 'n' for overland flow. Manning's 'n' affects flow velocity, which is used to calculate transport capacity and shear stress. Throughout all calibration trials, the sediment loss in 1989 was highly over-predicted. Calibration was performed by adjusting parameter values that resulted in the best agreement between observed and simulated sediment loss from 1984-1988. Sediment loss calibration for Gilbert Farm is shown in Figure 4.12. Observed average annual sediment loss was 2.1 t ha^{-1} over the six year period compared to GLEAMS-predicted 2.8 t ha^{-1}. GLEAMS under-predicted annual sediment loss by 29% in 1984 and 7% in 1986.

Over-predictions of sediment loss were made by GLEAMS in years 1985 (15%), 1987 (2%), 1988 (64%), and 1989 (262%).

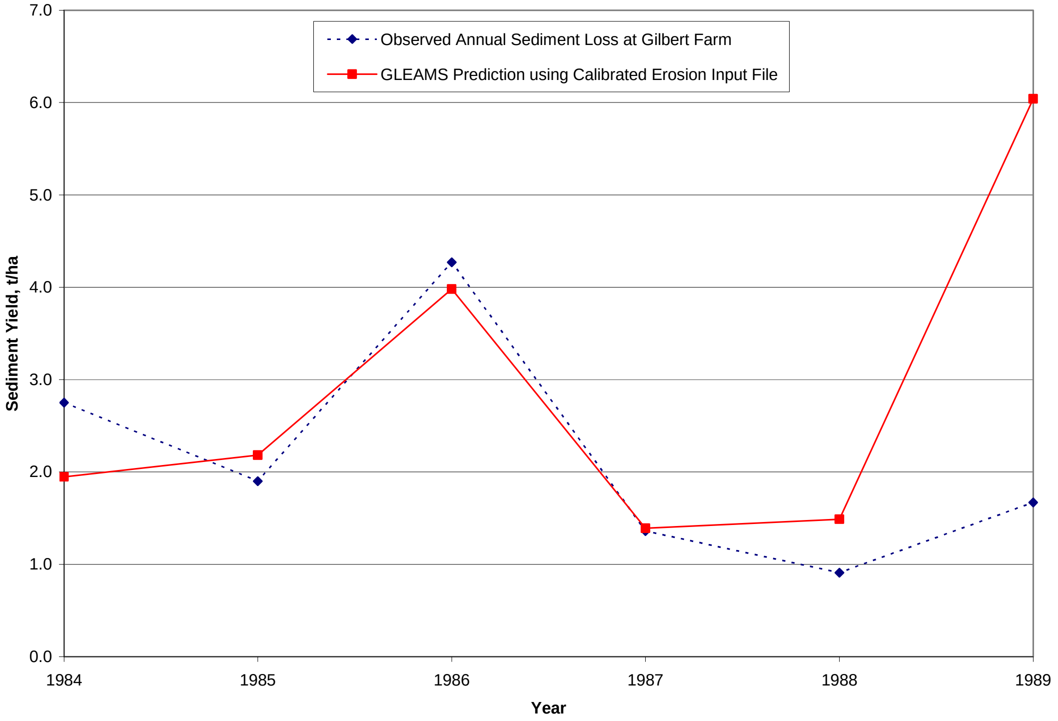

Figure 4.12 Sediment loss calibration for Gilbert Farm watershed.

A GLEAMS nutrient input file was created based on the site-specific nutrient conditions given by Yoon et al. (1992). Figure 4.13 shows the dissolved P loss in runoff at Gilbert Farm. The average annual observed dissolved P in runoff was 1.80 kg ha^{-1} compared to GLEAMS-prediction of 1.06 kg ha^{-1}. GLEAMS under-predicted annual dissolved P in runoff in four of the six years of the study period.

Figure 4.14 shows the sediment P loss in runoff. The observed average annual sediment-bound P in runoff was 0.24 kg ha^{-1}; GLEAMS predicted an average of 1.56 kg ha^{-1} annually. GLEAMS over-predicted sediment P throughout the study period.

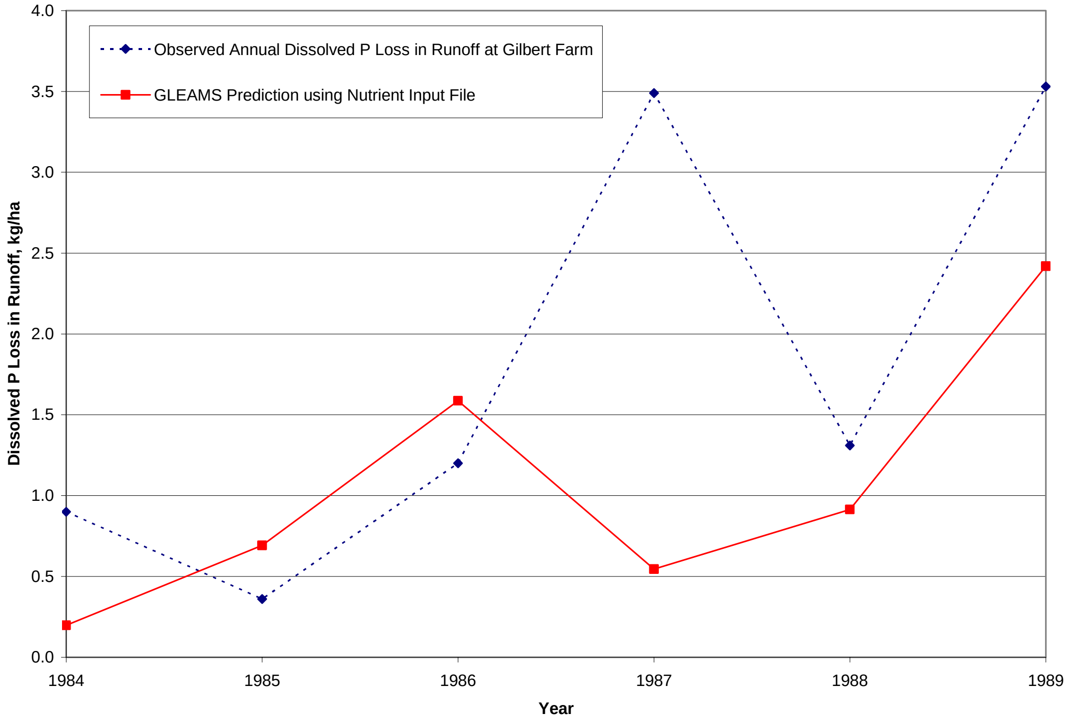

Figure 4.13 Dissolved P loss in runoff for Gilbert Farm watershed.

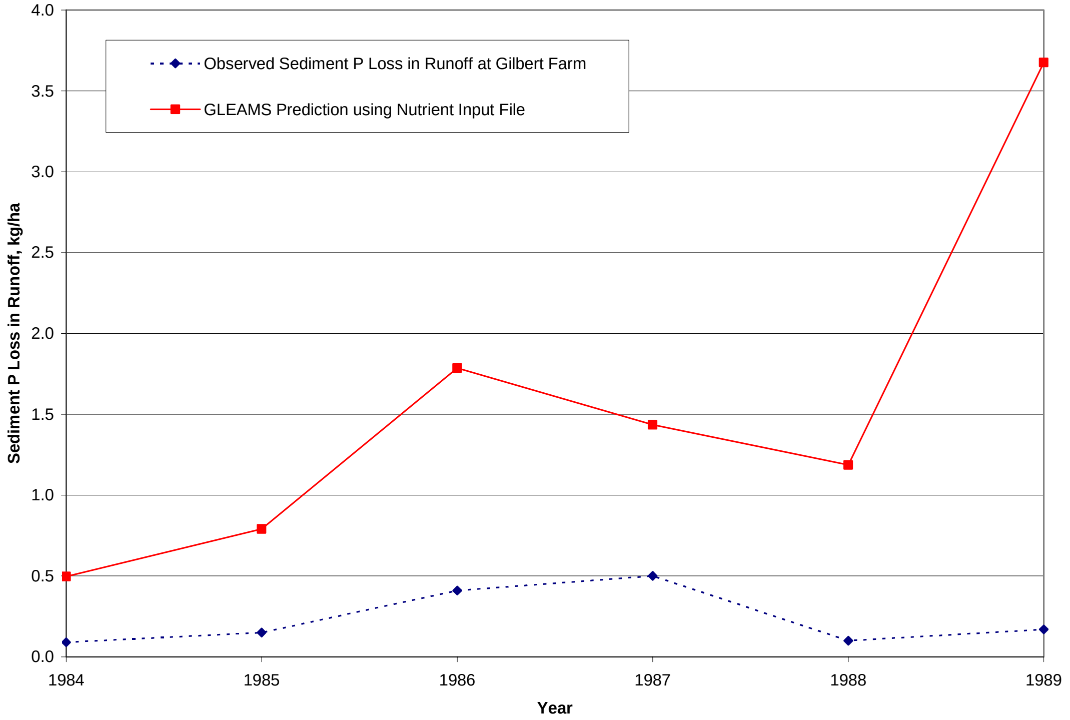

Figure 4.14 Sediment P loss in runoff for Gilbert Farm watershed.

4.2.3 WATKINSVILLE, GEORGIA

The Watkinsville P-2 sample data set distributed in the GLEAMS 3.0 software package was not used in the sensitivity analysis but was used in Chapter 5 to evaluate modifications to GLEAMS. Details of this data set are presented in the GLEAMS Version 2.1 User Manual (Knisel, 1993). The Watkinsville P-2 watershed is 1.3 ha in size. Conventionally-tilled corn was grown over a three-year period (1973-1975) on a Cecil sandy loam. Runoff and sediment measurements were taken for all three years. Nutrients were not measured the first year of the study.

Hydrology calibration was performed by adjusting field capacity and wilting point by no more than ±15 percent from the initial value. Table 4.5 shows the original values for these parameters and the changes made. Calibration trials showed that surface runoff for years 1973 and 1974 could be adjusted to within ±20% of observed values. However, there were large differences (100 to 350% error) between observed and simulated annual runoff in 1975 during calibration trials. Though there was more precipitation in 1975 (154.6 cm) than in 1973 (124.9 cm) and 1974 (102.3 cm), no major differences were noted between crop type and management practice for each year to explain this. The hydrology input file was calibrated with the closest agreement between observed and simulated runoff values for years 1973 and 1974 (Figure 4.15). Average annual observed runoff was 11.7 cm compared to GLEAMS-predicted 17.1 cm. GLEAMS over-predicted surface runoff volumes in 1973 and 1975 by 18% and 196%, respectively; runoff was under-predicted by 8% in 1974.

Table 4.5 Hydrology parameters adjusted for calibration of Watkinsville P-2 runoff data.

Hydrology Parameter	Original Value	New Value	Percent Change
Field Capacity in Soil Horizon 1	0.38	0.33	-13.2
Field Capacity in Soil Horizon 2	0.38	0.33	-13.2
Field Capacity in Soil Horizon 3	0.38	0.33	-13.2
Field Capacity in Soil Horizon 4	0.38	0.33	-13.2
Field Capacity in Soil Horizon 5	0.40	0.34	-15.0
Wilting Point in Soil Horizon 1	0.20	0.17	-15.0
Wilting Point in Soil Horizon 2	0.20	0.17	-15.0
Wilting Point in Soil Horizon 3	0.23	0.20	-13.0
Wilting Point in Soil Horizon 4	0.23	0.20	-13.0
Wilting Point in Soil Horizon 5	0.28	0.24	-14.3

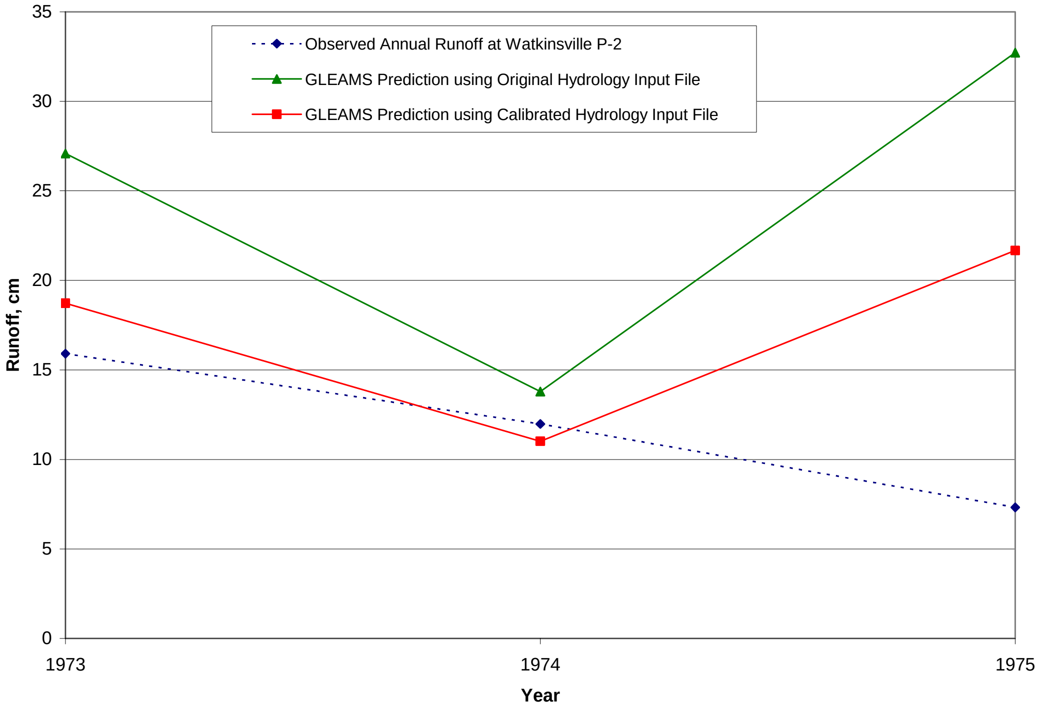

Figure 4.15 Surface runoff calibration for Watkinsville P-2.

Erosion for the Watkinsville P-2 data set was calibrated by adjusting the soil loss ratio (Universal Soil Loss Equation C-factor) for overland flow in years 1974 and 1975 of the simulation. The soil loss ratio is not averaged in GLEAMS and is specific for given dates during simulation. Reduction of soil loss ratio values by 30% from original values in 1974 resulted in a decrease in annual sediment yield in year 1973. The soil loss ratio was 0.20 on November 5, 1973 and remained 0.20 until April 23, 1974 (day 113) when the value was changed to 0.62 in the original erosion input file. Changes made to soil loss ratio (reduced by 75 to 92%) in year 1975, also resulted in a reduction of annual sediment yield in year 1974. It is not clear why changes made in 1974 and 1975 impacted results from 1973 and 1974, respectively. An input parameter must have been inadvertently changed in 1973 to cause this to occur. The calibrated erosion file incorporated all changes in years 1974 and 1975. Original versus calibrated values are given in Table 4.6. Annual sediment loss for the original and calibrated erosion input file are shown in Figure 4.16. Over-estimation of surface runoff in 1975 contributed to an over-estimation of sediment loss during the same year. The observed average annual sediment yield was 4.4 t ha^{-1} with GLEAMS predicting 13.2 t ha^{-1}.

Table 4.6 Soil loss ratio adjusted for calibration of Watkinsville P-2 sediment yield data.

Simulation Day	**Management/ Tillage Practice**	**Soil Loss Ratio**		
		Original Value	**New Value**	**% Change**
		--------------------- 1974 ---------------------		
113	Chisel/disk tillage	0.62	0.44	-29
119	Corn planted	0.54	0.38	-30
140	Corn – spring cover	0.42	0.30	-29
160	Corn – spring cover	0.30	0.21	-30
200	Corn – spring cover	0.20	0.14	-30
259	Corn harvested	0.20	0.14	-30
268	Weeds – winter cover	0.20	0.14	-30
	--------------------- 1975 ---------------------			
114	Chisel/disk tillage	0.62	0.05	-92
141	Plant corn	0.54	0.05	-91
160	Corn – spring cover	0.42	0.05	-88
200	Corn – spring cover	0.30	0.05	-83
250	Corn – spring cover	0.20	0.05	-75
276	Harvest corn	0.20	0.05	-75
288	Weeds – winter cover	0.20	0.05	-75

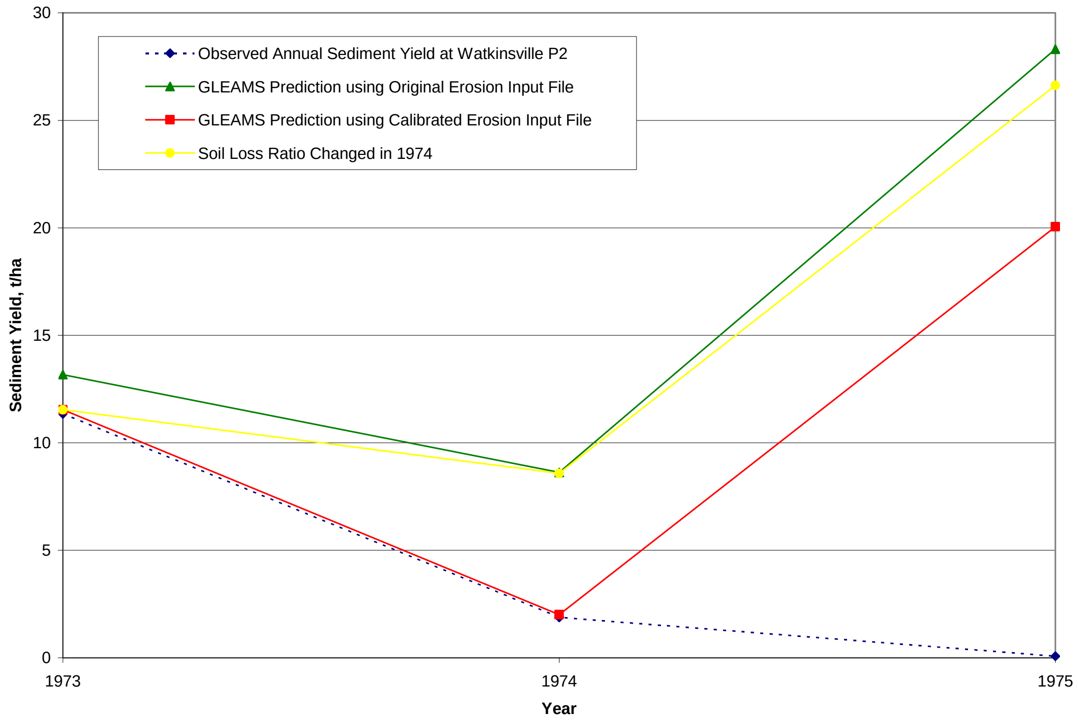

Figure 4.16 Sediment loss calibration for Watkinsville P-2.

The nutrient file supplied with the GLEAMS 3.0 package was used unaltered. Dissolved and sediment P in runoff measurements were available for years 1974 and 1975, but not for 1973. Figure 4.17 shows the annual dissolved P loss in runoff. The average annual observed dissolved P in runoff was 0.48 kg ha^{-1} compared to GLEAMS-predicted 0.12 kg ha^{-1}. GLEAMS under-predicted dissolved P in runoff by 88% in 1974 and 14% in 1975.

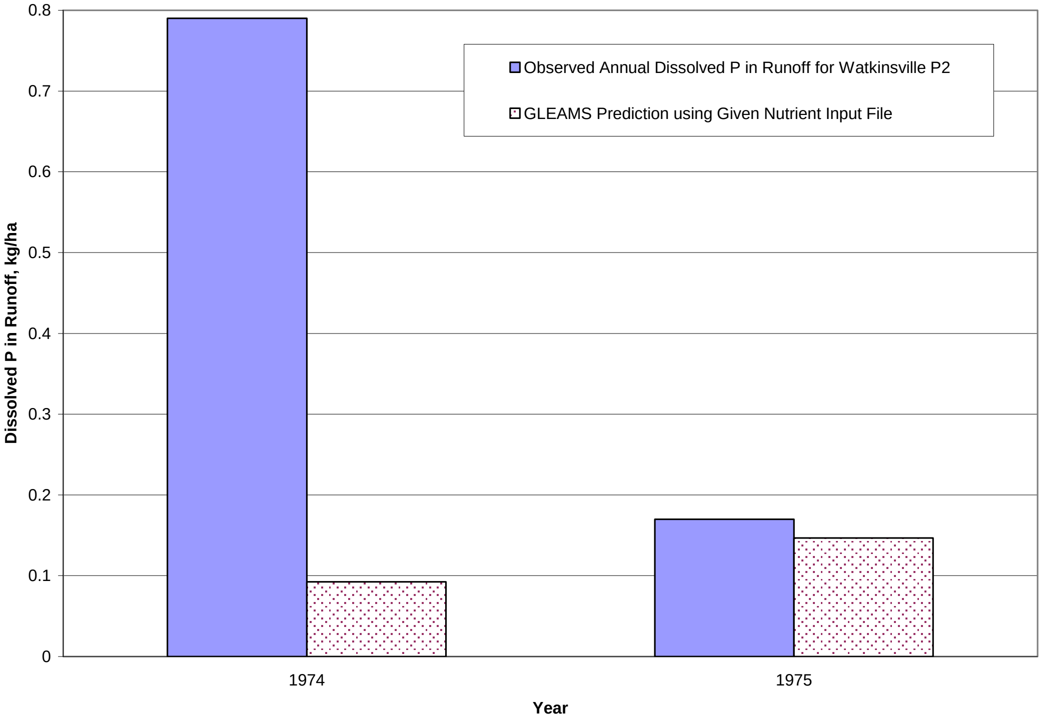

Figure 4.17 Dissolved P loss in runoff for Watkinsville P-2.

Sediment P loss in runoff in 1974 and 1975 is shown in Figure 4.18. GLEAMS over-predicted sediment P in 1974 by 24% and under-predicted this value by 48% in 1975. The average annual GLEAMS-predicted sediment P loss was 2.1 kg ha^{-1}, while the average annual observed value was 2.8 kg ha^{-1}. There was a large variation in observed values while GLEAMS predicted similar values for both years.

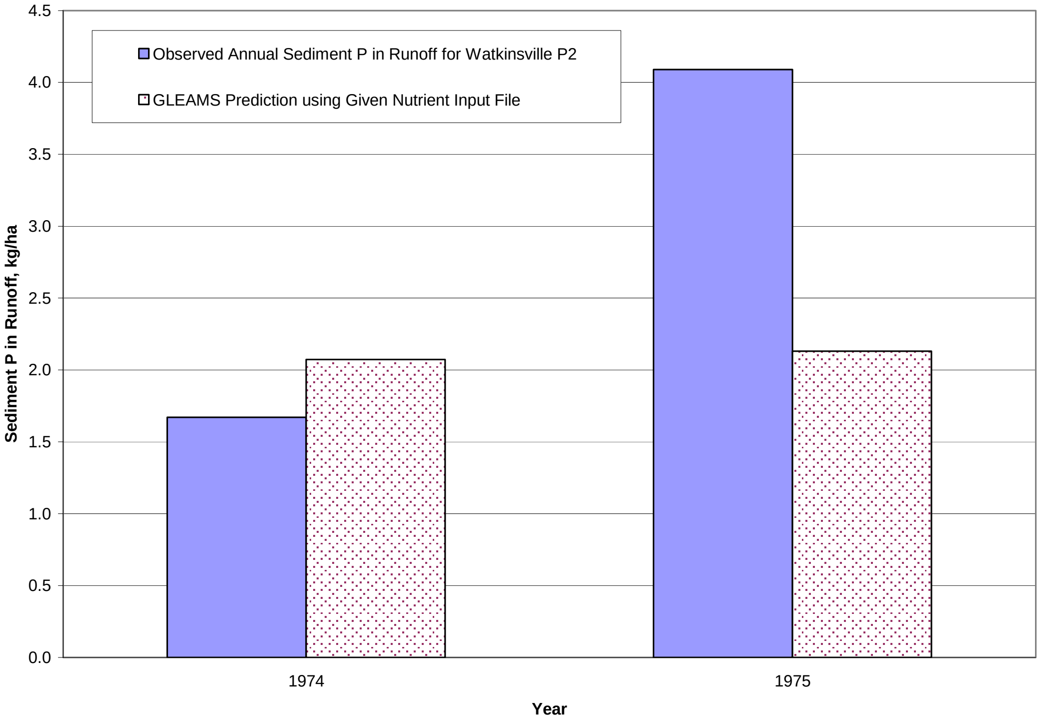

Figure 4.18 Sediment P loss in runoff for Watkinsville P-2.

4.3 SENSITIVITY ANALYSIS RESULTS

4.3.1 RESULTS FROM BELLE MINA PL9 AND PL18 DATA SETS

The sensitivity of average annual P output to various parameters was investigated over a 10-year simulation period. While the monthly values of runoff PO_4-P (selected variable code 2912) produced results, the use of GLEAMS selected variable code for annual runoff PO_4-P (code 3912) resulted in output of zero values over the 10-year simulation period possibly caused by a programming error in the GLEAMS source code. Therefore, the monthly values for runoff PO_4-P were totaled each simulation year to generate the GLEAMS annual runoff PO_4-P output.

The CLIGEN model was used to generate weather data for the Belle Mina data set over a 10-year period. The nearest CLIGEN station to Belle Mina, AL, was Huntsville WSO Ap, AL, in Madison County (station #4064). Maximum and minimum daily temperatures were averaged and used for GLEAMS daily temperature input.

Tables 4.7 through 4.11 show the average annual results for selected P outputs and the relative sensitivity of each parameter for both the PL9 and PL18 data sets. Table 4.12

shows a summary of the levels of sensitivity of selected P outputs to FOP, FON, CMN, CPKD, and β_p. Changes to FOP, FON, CMN, and β_p had little effect on P output, however, changes to CPKD did affect model P output. The P partitioning coefficient (CPKD) varied from 182.5 for the surface layer to 245.0 for the lowest soil layer. The value of 182.5 was used as the baseline for comparison. Results from the sensitivity analysis showed that runoff PO_4-P output was slightly to moderately sensitive to changes in CPKD for the PL9 and PL18 data sets. Sediment PO_4-P output was moderately sensitive to sensitive for both PL9 and PL18 data sets. In addition, sediment organic P output was moderately sensitive for both Belle Mina data sets whereas plant uptake of P was insensitive to slightly sensitive to changes in CPKD. The amount of PO_4-P leached was extremely sensitive to changes in CPKD with $|S_R|$ ranging from 16 to 235 for PL9 and from 17 to 281 for PL18. Figures 4.19 through 4.23 depict the changes in average annual P output with change in CPKD for the PL9 and PL18 data sets Detailed results from the sensitivity analysis are located in Appendix C.

Table 4.7 Results of sensitivity analysis of GLEAMS P output with changes to fresh organic phosphorus (FOP) for Belle Mina PL9 and PL18 data sets.

Input Parameter, FOP (kg/ha)	% Change in Input Parameter	PL9		PL18	
		% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity
Runoff PO_4-P					
0	-100	-0.1	0.00	0.0	0.00
10	Baseline				
20	100	-0.1	0.00	0.0	0.00
50	400	1.6	0.00	0.6	0.00
100	900	1.6	0.00	0.6	0.00
Sediment PO_4-P					
0	-100	-0.1	0.00	0.0	0.00
10	Baseline				
20	100	-0.1	0.00	0.0	0.00
50	400	0.5	0.00	1.2	0.00
100	900	0.6	0.00	1.6	0.00
Sediment Organic P					
0	-100	-0.1	0.00	-0.1	0.00
10	Baseline				
20	100	0.1	0.00	0.1	0.00
50	400	0.3	0.00	-0.1	0.00
100	900	0.2	0.00	0.1	0.00
PO_4-P Leached					
0	-100	0.0	0.00	0.0	0.00
10	Baseline				
20	100	0.0	0.00	0.0	0.00
50	400	-0.1	0.00	-0.2	0.00
100	900	-0.1	0.00	0.0	0.00
Plant Uptake of P					
0	-100	0.2	0.00	0.0	0.00
10	Baseline				
20	100	0.2	0.00	0.0	0.00
50	400	0.1	0.00	0.0	0.00
100	900	0.3	0.00	0.1	0.00

Table 4.8 Results of sensitivity analysis of GLEAMS P output with changes to fresh organic nitrogen (FON) for Belle Mina PL9 and PL18 data sets.

Input Parameter, FON (kg/ha)	% Change in Input Parameter	PL9		PL18	
		% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity
		Runoff PO_4-P			
0	-100	-0.1	0.00	0.0	0.00
20	-50	-0.5	0.01	0.0	0.00
40	-------------------------------------Baseline--------------------------------------				
80	100	-0.5	-0.01	0.6	0.01
160	300	1.5	0.01	-0.3	0.00
		Sediment PO_4-P			
0	-100	-0.1	0.00	0.0	0.00
20	-50	0.1	0.00	0.0	0.00
40	-------------------------------------Baseline--------------------------------------				
80	100	-4.1	-0.04	1.1	0.01
160	300	0.2	0.00	-0.2	0.00
		Sediment Organic P			
0	-100	-0.1	0.00	0.0	0.00
20	-50	0.0	0.00	0.0	0.00
40	-------------------------------------Baseline--------------------------------------				
80	100	-0.8	-0.01	0.0	0.00
160	300	0.1	0.00	0.4	0.00
		PO_4-P Leached			
0	-100	0.0	0.00	0.1	0.00
20	-50	0.0	0.00	0.0	0.00
40	-------------------------------------Baseline--------------------------------------				
80	100	0.0	0.00	-0.1	0.00
160	300	-0.1	0.00	-0.2	0.00
		Plant Uptake of P			
0	-100	0.0	0.00	-0.1	0.00
20	-50	0.1	0.00	0.0	0.00
40	-------------------------------------Baseline--------------------------------------				
80	100	0.5	0.00	0.0	0.00
160	300	0.7	0.00	0.0	0.00

Table 4.9 Results of sensitivity analysis of GLEAMS P output with changes to the mineralization constant (CMN) for Belle Mina PL9 and PL18 data sets.

Input Parameter, CMN (kg/ha/d)	% Change in Input Parameter	PL9		PL18	
		% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity
Runoff PO_4-P					
0.0000	-100	-0.1	0.00	0.0	0.00
0.0001	------------------------------------Baseline------------------------------------				
0.0005	400	0.0	0.00	0.4	0.00
0.0010	900	0.1	0.00	0.4	0.00
0.0050	4,900	0.4	0.00	1.4	0.00
0.0075	7,400	4.6	0.00	2.1	0.00
0.0100	9,900	4.7	0.00	2.3	0.00
Sediment PO_4-P					
0.0000	-100	-0.2	0.00	0.0	0.00
0.0001	------------------------------------Baseline------------------------------------				
0.0005	400	-0.1	0.00	0.0	0.00
0.0010	900	0.0	0.00	-0.3	0.00
0.0050	4,900	0.4	0.00	2.1	0.00
0.0075	7,400	-0.3	0.00	3.4	0.00
0.0100	9,900	-0.4	0.00	3.6	0.00
Sediment Organic P					
0.0000	-100	0.0	0.00	0.0	0.00
0.0001	------------------------------------Baseline------------------------------------				
0.0005	400	0.0	0.00	-0.1	0.00
0.0010	900	0.0	0.00	-0.1	0.00
0.0050	4,900	-0.1	0.00	-0.2	0.00
0.0075	7,400	0.3	0.00	-0.3	0.00
0.0100	9,900	0.2	0.00	-0.4	0.00
PO_4-P Leached					
0.0000	-100	-0.1	0.00	-0.1	0.00
0.0001	------------------------------------Baseline------------------------------------				
0.0005	400	0.2	0.00	0.3	0.00
0.0010	900	0.6	0.00	0.6	0.00
0.0050	4,900	3.1	0.00	3.3	0.00
0.0075	7,400	4.5	0.00	5.1	0.00
0.0100	9,900	6.0	0.00	6.8	0.00
Plant Uptake of P					
0.0000	-100	0.2	0.00	0.0	0.00
0.0001	------------------------------------Baseline------------------------------------				
0.0005	400	0.7	0.00	0.0	0.00
0.0010	900	1.0	0.00	0.0	0.00
0.0050	4,900	2.7	0.00	0.2	0.00
0.0075	7,400	3.8	0.00	0.3	0.00
0.0100	9,900	4.1	0.00	0.4	0.00

Table 4.10 Results of sensitivity analysis of GLEAMS P output with changes to the phosphorus partitioning coefficient (CPKD) for Belle Mina PL9 and PL18 data sets.

Input Parameter, CPKD	% Change in Input Parameter	PL9		PL18	
		% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity
Runoff PO_4-P					
1	-99	-88	0.88	-76	0.77
3	-98	-40	0.41	-3	0.03
5	-97	-13	0.13	34	-0.35
7	-96	-1	0.01	48	-0.50
15	-92	28	-0.31	76	-0.83
182.5	------------------------------Baseline------------------------------				
Sediment PO_4-P					
1	-99	-100	1.00	-100	1.00
3	-98	-98	1.00	-98	1.00
5	-97	-95	0.98	-95	0.97
7	-96	-92	0.96	-92	0.96
15	-92	-81	0.88	-80	0.87
182.5	------------------------------Baseline------------------------------				
Sediment Organic P					
1	-99	-18	0.18	-16	0.16
3	-98	-17	0.17	-15	0.15
5	-97	-16	0.17	-15	0.15
7	-96	-15	0.16	-15	0.15
15	-92	-13	0.14	-12	0.13
182.5	------------------------------Baseline------------------------------				
PO_4-P Leached					
1	-99	23,408	-235	27,949	-281
3	-98	7,607	-77	7,865	-80
5	-97	4,579	-47	4,660	-48
7	-96	3,280	-34	3,324	-35
15	-92	1,508	-16	1,519	-17
182.5	------------------------------Baseline------------------------------				
Plant Uptake of P					
1	-99	-2.4	0.02	-1.07	0.01
3	-98	-0.3	0.00	-0.33	0.00
5	-97	0.2	0.00	0.09	0.00
7	-96	0.2	0.00	0.04	0.00
15	-92	0.2	0.00	0.04	0.00
182.5	------------------------------Baseline------------------------------				

Table 4.11 Results of sensitivity analysis of GLEAMS P output with changes to the phosphorus extraction coefficient (β_p) for Belle Mina PL9 and PL18 data sets.

Input Parameter, β_p	% Change in Input Parameter	PL9		PL18	
		% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity
Runoff PO_4-P					
0.10	------Baseline------				
0.25	150	3.1	0.02	3.2	0.02
0.50	400	4.2	0.01	4.3	0.01
0.75	650	4.5	0.01	4.6	0.01
1.00	900	4.7	0.01	4.8	0.01
Sediment PO_4-P					
0.10	------Baseline------				
0.25	150	3.1	0.02	3.2	0.02
0.50	400	4.2	0.01	4.3	0.01
0.75	650	4.6	0.01	4.7	0.01
1.00	900	4.8	0.01	4.8	0.01
Sediment Organic P					
0.10	------Baseline------				
0.25	150	0.2	0.00	0.1	0.00
0.50	400	0.3	0.00	0.2	0.00
0.75	650	0.3	0.00	0.2	0.00
1.00	900	0.4	0.00	0.2	0.00
PO_4-P Leached					
0.10	------Baseline------				
0.25	150	0.0	0.00	0.0	0.00
0.50	400	0.0	0.00	0.0	0.00
0.75	650	0.0	0.00	0.0	0.00
1.00	900	0.0	0.00	0.0	0.00
Plant Uptake of P					
0.10	------Baseline------				
0.25	150	0.2	0.00	0.0	0.00
0.50	400	0.2	0.00	0.0	0.00
0.75	650	0.2	0.00	0.0	0.00
1.00	900	0.2	0.00	0.0	0.00

Table 4.12 Summary of levels of sensitivity to FOP, FON, CMN, CPKD, and β_p on P output for Belle Mina PL9 and PL18.

Input	Average Annual Output				
	Runoff PO_4-P	Sediment PO_4-P	Sediment Organic P	PO_4-P Leached	Plant Uptake of P
FOP	Insensitive	Insensitive	Insensitive	Insensitive	Insensitive
FON	Insensitive to Slightly Sensitive	Insensitive to Slightly Sensitive	Insensitive to Slightly Sensitive	Insensitive	Insensitive
CMN	Insensitive	Insensitive	Insensitive	Insensitive	Insensitive
CPKD	Slightly to Moderately Sensitive	Moderately Sensitive to Sensitive	Moderately Sensitive	Extremely Sensitive	Insensitive to Slightly Sensitive
β_p	Insensitive to Slightly Sensitive	Insensitive to Slightly Sensitive	Insensitive	Insensitive	Insensitive

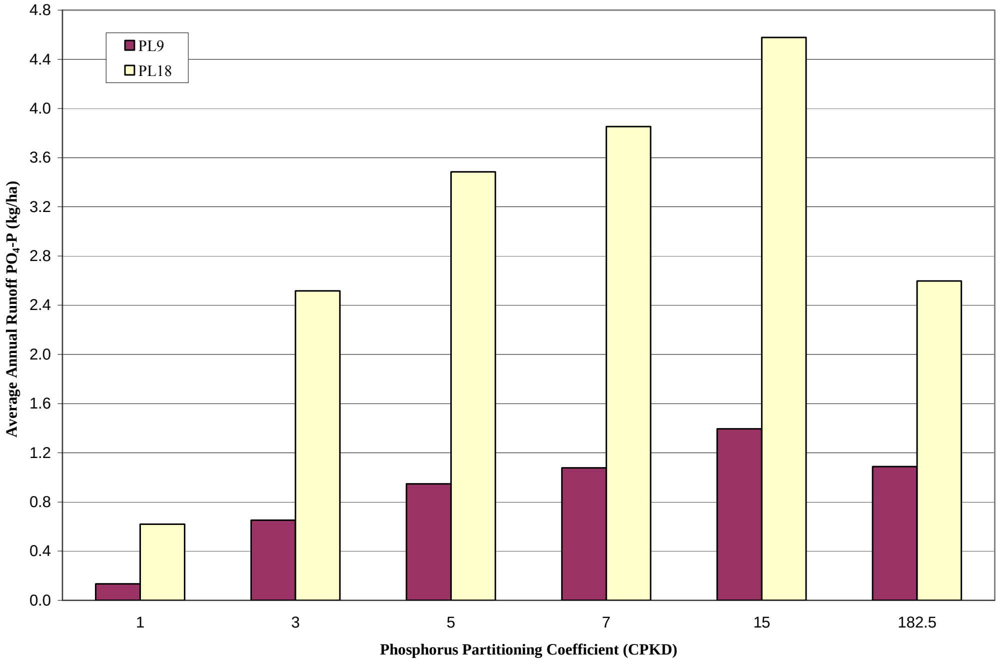

Figure 4.19 Average annual runoff PO_4-P predicted by GLEAMS for Belle Mina data sets PL9 and PL18 over 10-year simulation period with change in P partitioning coefficient.

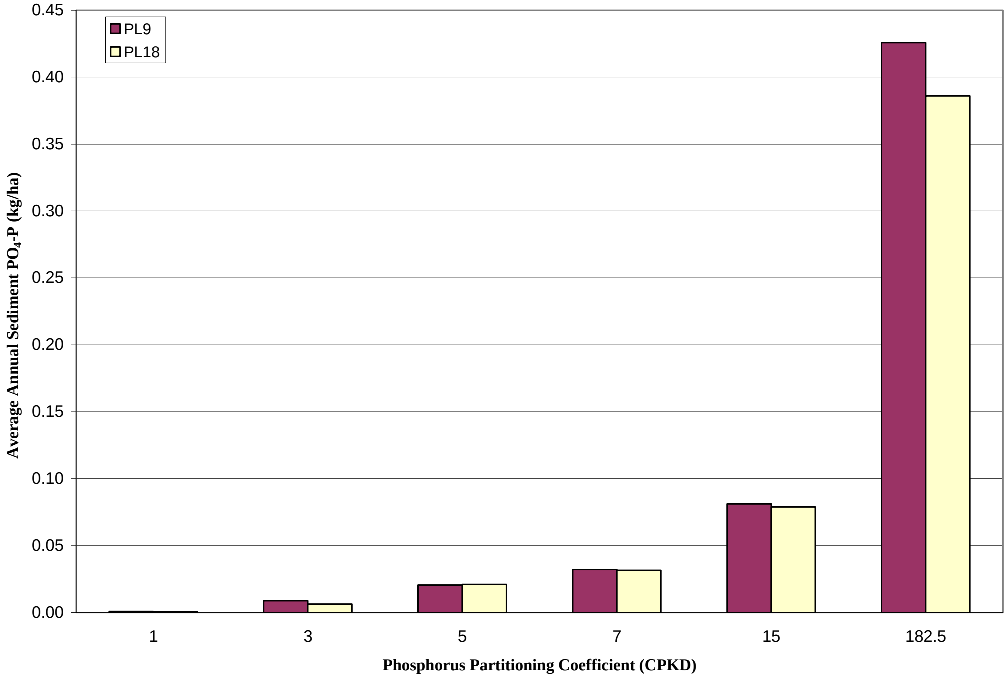

Figure 4.20 Average annual sediment PO_4-P predicted by GLEAMS for Belle Mina data sets PL9 and PL18 over 10-year simulation period with change in P partitioning coefficient.

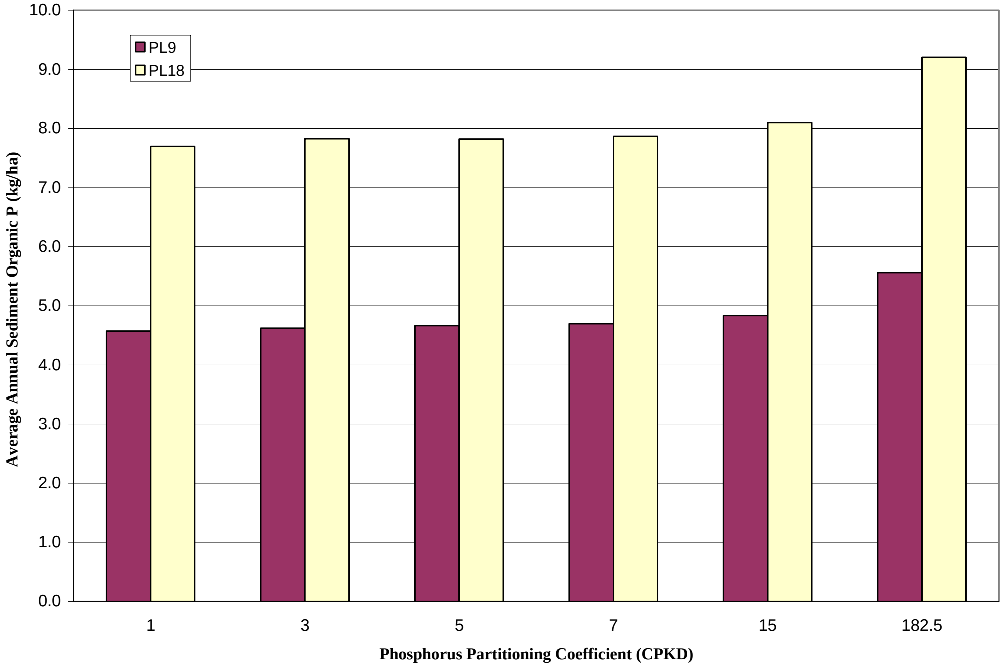

Figure 4.21 Average annual sediment organic P predicted by GLEAMS for Belle Mina data sets PL9 and PL18 over 10-year simulation period with change in P partitioning coefficient.

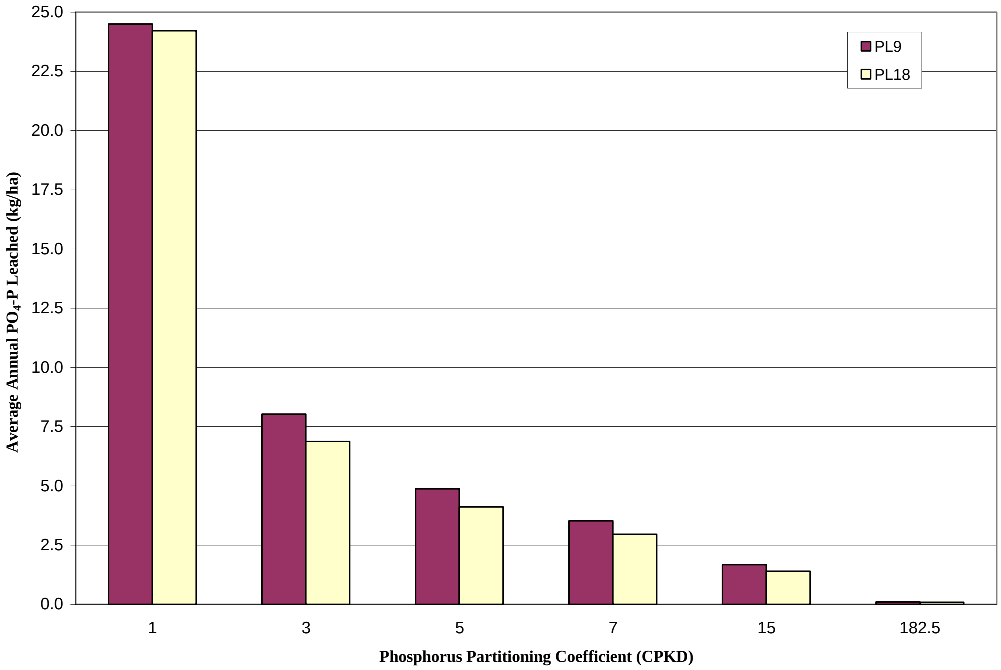

Figure 4.22 Average annual PO_4-P leached predicted by GLEAMS for Belle Mina data sets PL9 and PL18 over 10-year simulation period with change in P partitioning coefficient.

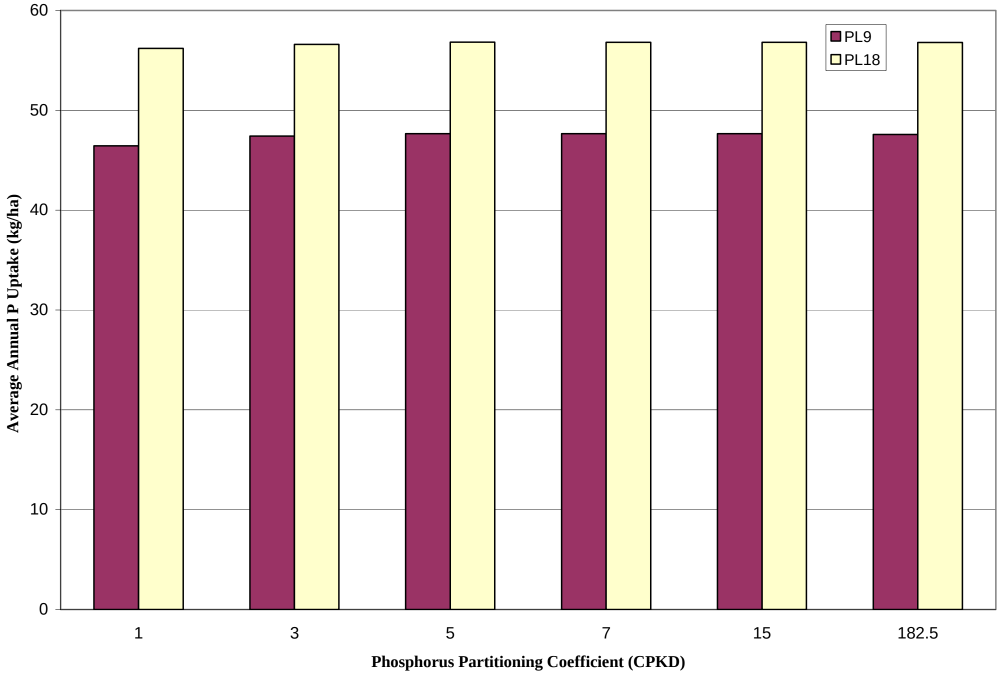

Figure 4.23 Average annual P uptake predicted by GLEAMS for Belle Mina data sets PL9 and PL18 over 10-year simulation period with change in P partitioning coefficient.

4.3.2 RESULTS FROM GILBERT FARM DATA SET

Sensitivity of average annual GLEAMS P output was also investigated for the Gilbert Farm data. The CLIGEN model was used to generate weather data for the Gilbert Farm data set over a six-year period. A 10-year simulation was attempted but errors were encountered after year six. The CLIGEN station closest to Gilbert Farm in Colbert County, AL, was Muscle Shoals CAA AL (station # 5749).

Changes to FOP ≥ 20 kg ha^{-1} resulted in error N2 (underflow in P initialization). The GLEAMS user manual states that a possible cause for this error may be negative values encountered in the variables total P, labile P, and organic P in animal waste (Knisel and Davis, 1999). For model runs where FOP was equal to 0 kg ha^{-1}, average annual runoff PO_4-P, sediment PO_4-P, sediment organic P, and plant uptake of P were slightly sensitive to the change in FOP while PO_4-P leached was insensitive (Table 4.13). Changes to the variables FON and CMN had little impact on average annual P output; selected P model output was insensitive to slightly sensitive (Tables 4.14 and 4.15). Runoff PO_4-P and sediment PO_4-P were slightly sensitive to changes in the P extraction coefficient; sediment organic P, PO_4-P leached, and plant uptake of P were insensitive (Table 4.16). Table 4.17 shows a summary of the levels of sensitivity of selected P outputs to FOP, FON, CMN, CPKD, and β_p.

Table 4.13 Results of sensitivity analysis of GLEAMS P output with changes to fresh organic P (FOP) for Gilbert Farm data set.

Input Parameter FOP (kg/ha)	% Change in Input Parameter	Runoff PO_4-P		Sediment PO_4-P		Sediment Organic P		PO_4-P Leached		Plant Uptake of P	
		% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity
0	-100	-2.1	0.02	-1.4	0.01	-0.7	0.01	0.1	0.00	-1.0	0.01
10	Baseline										
20	100	Error N2		Error N2		Error N2		Error N2		Error N2	
50	400	Error N2		Error N2		Error N2		Error N2		Error N2	
100	900	Error N2		Error N2		Error N2		Error N2		Error N2	

* Error N2 is GLEAMS error for underflow in phosphorus initialization

Table 4.14 Results of sensitivity analysis of GLEAMS P output with changes to fresh organic N (FON) for Gilbert Farm data set.

Input Parameter FON (kg/ha)	% Change in Input Parameter	Runoff PO_4-P		Sediment PO_4-P		Sediment Organic P		PO_4-P Leached		Plant Uptake of P	
		% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity
0	-100	-1.3	0.01	-0.9	0.01	-0.6	0.01	0.1	0.00	-1.8	0.02
20	-50	0.7	-0.01	1.1	-0.02	0.4	-0.01	0.1	0.00	-0.2	0.00
40	Baseline										
80	100	8.8	0.09	5.9	0.06	4.0	0.04	-0.2	0.00	0.3	0.00
160	300	10.5	0.03	7.8	0.03	0.1	0.00	-0.7	0.00	0.4	0.00

Table 4.15 Results of sensitivity analysis of GLEAMS P output with changes to the mineralization constant (CMN) for Gilbert Farm.

Input Parameter CMN (kg/ha/d)	% Change in Input Parameter	Runoff PO$_4$-P		Sediment PO$_4$-P		Sediment Organic P		PO$_4$-P Leached		Plant Uptake of P	
		% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity
0.0000	-100	1.8	-0.02	1.9	-0.02	0.6	-0.01	-0.7	0.01	-0.9	0.01
0.0001	----------Baseline----------										
0.0005	400	-1.7	0.00	-2.2	-0.01	-0.8	0.00	2.8	0.01	2.0	0.00
0.0010	900	5.9	0.01	1.8	0.00	2.4	0.00	6.3	0.01	4.7	0.01
0.0050	4,900	8.9	0.00	2.9	0.00	2.5	0.00	34	0.01	16	0.00
0.0075	7,400	12.1	0.00	5.6	0.00	4.1	0.00	51	0.01	19	0.00
0.0100	9,900	15.6	0.00	8.5	0.00	5.6	0.00	68	0.01	21	0.00

Table 4.16 Results of sensitivity analysis of GLEAMS P output with changes to the P extraction coefficient (β_p) for Gilbert Farm.

Input Parameter β_p	% Change in Input Parameter	Runoff PO$_4$-P		Sediment PO$_4$-P		Sediment Organic P		PO$_4$-P Leached		Plant Uptake of P	
		% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity
0.10	----------Baseline----------										
0.25	150	3.5	0.02	3.5	0.02	0.7	0.00	0.0	0.00	0.0	0.00
0.50	400	4.7	0.01	4.7	0.01	0.9	0.00	0.0	0.00	0.0	0.00
0.75	650	5.1	0.01	5.1	0.01	1.0	0.00	0.0	0.00	0.0	0.00
1.00	900	5.3	0.01	5.3	0.01	1.0	0.00	0.0	0.00	0.0	0.00

Table 4.17 Summary of levels of sensitivity to changes in FOP, FON, CMN, CPKD, and β_p on P output for Gilbert Farm.

Input	Average Annual Output				
	Runoff PO_4-P	Sediment PO_4-P	Sediment Organic P	PO_4-P Leached	Plant Uptake of P
FOP	Slightly Sensitive	Slightly Sensitive	Slightly Sensitive	Insensitive	Slightly Sensitive
FON	Slightly Sensitive	Slightly Sensitive	Insensitive to Slightly Sensitive	Insensitive	Insensitive to Slightly Sensitive
CMN	Insensitive to Slightly Sensitive	Insensitive to Slightly Sensitive	Insensitive to Slightly Sensitive	Slightly Sensitive	Insensitive to Slightly Sensitive
CPKD	Moderately Sensitive	Moderately Sensitive to Sensitive	Moderately Sensitive	Extremely Sensitive	Slightly Sensitive
β_p	Slightly Sensitive	Slightly Sensitive	Insensitive	Insensitive	Insensitive

For the Gilbert Farm data set, CPKD varied from 155.0 (surface layer) to 250.0 for the lowest soil layer, thus the surface layer value of 155.0 was used as the baseline for the sensitivity analysis. The average annual amount of PO_4-P leached was extremely sensitive to changes in CPKD (Table 4.18). Runoff PO_4-P and sediment organic P output were moderately sensitive. Sediment PO_4-P output was moderately sensitive to sensitive while plant uptake of P was slightly sensitive to changes in CPKD. Figure 4.24 depicts the changes in average annual runoff PO_4-P, sediment organic P, and PO_4-P leached. Average annual sediment organic P gradually increased with increasing CPKD, while PO_4-P leached decreased. Figure 4.25 shows the average annual sediment PO_4-P and Figure 4.26 shows the average annual plant uptake of P with change in P partitioning coefficient for the Gilbert Farm data set. Sediment PO_4-P increased with the increase in CPKD.

Table 4.18 Results of sensitivity analysis of GLEAMS average annual P output with changes to the P partitioning coefficient (CPKD) for Gilbert Farm.

Input Parameter CPKD	% Change in Input Parameter	Runoff PO_4-P		Sediment PO_4-P		Sediment Organic P		PO_4-P Leached		Plant Uptake of P	
		% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity	% Change in Output	Relative Sensitivity
1	-99	-45	0.46	-100	1.00	-46	0.46	20,371	-205	0.8	-0.01
3	-98	26	-0.27	-97	0.98	-44	0.45	7,615	-78	1.7	-0.02
5	-97	42	-0.43	-94	0.97	-41	0.43	4,670	-48	1.9	-0.02
7	-95	40	-0.42	-91	0.96	-39	0.41	3,353	-35	2.0	-0.02
15	-90	39	-0.43	-83	0.92	-33	0.37	1,541	-17	1.7	-0.02
155	---Baseline---										

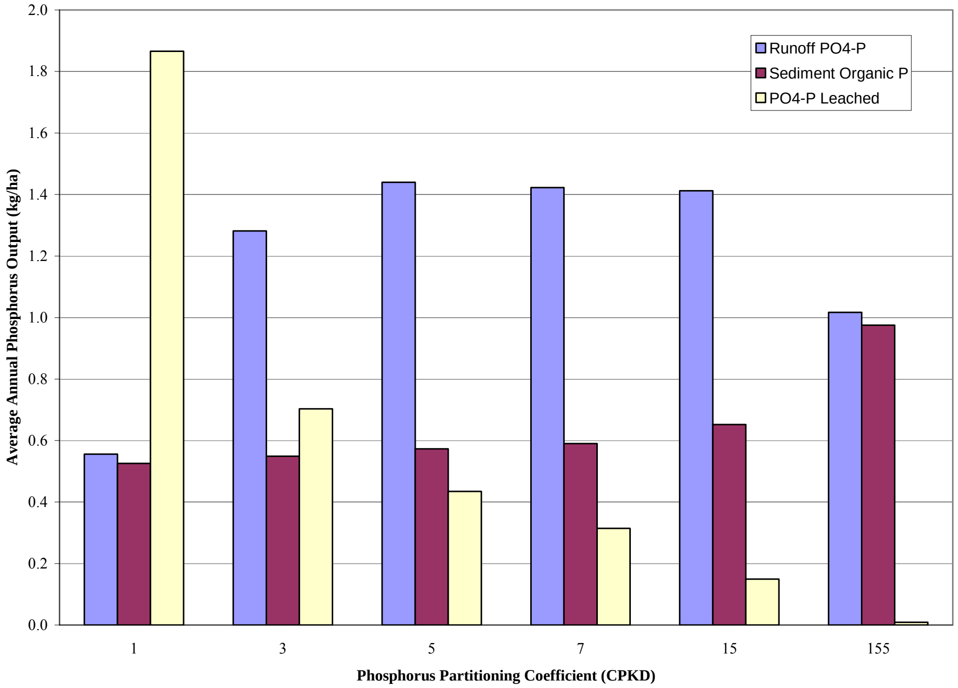

Figure 4.24 Average annual runoff PO_4-P, sediment organic P, and PO_4-P leached for Gilbert Farm over six year simulation period with change in P partitioning coefficient.

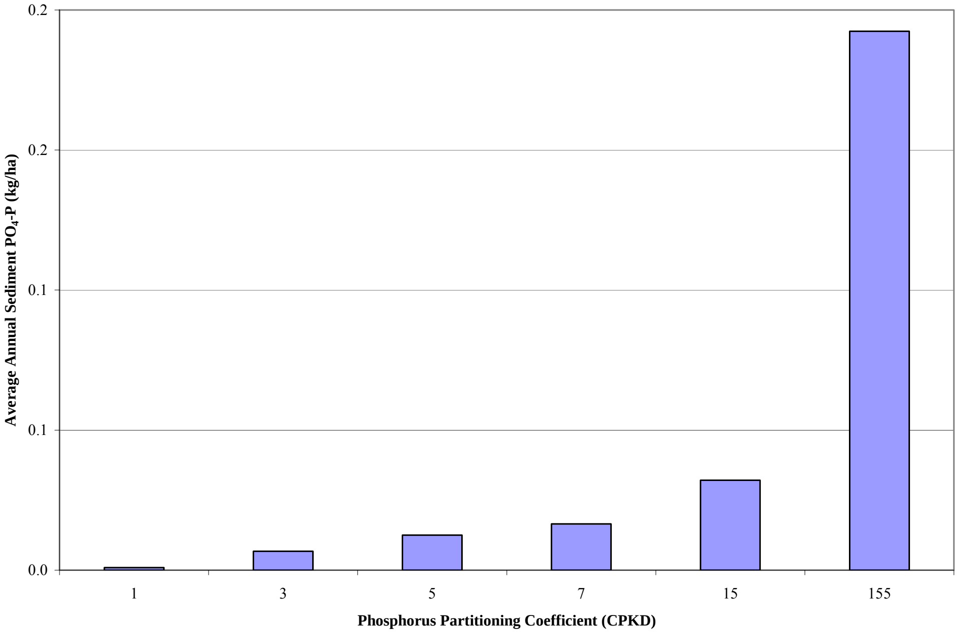

Figure 4.25 Average annual sediment PO_4-P for Gilbert Farm over six year simulation period with change in P partitioning coefficient.

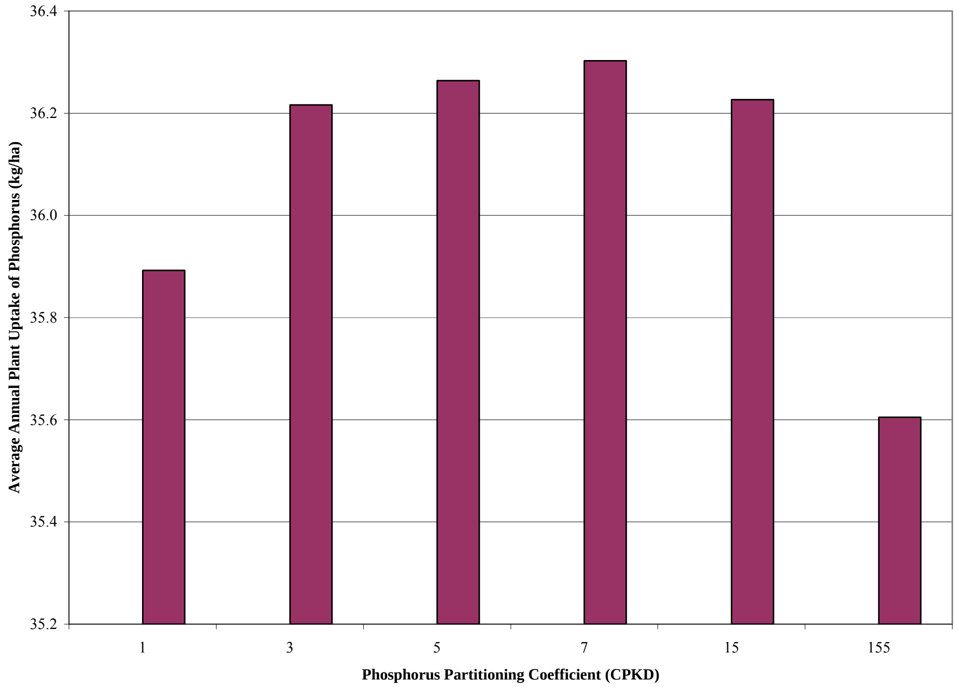

Figure 4.26 Average annual plant uptake of P for Gilbert Farm over six year simulation period with change in P partitioning coefficient.

4.5 CONCLUSIONS

The sensitivity analysis shows that GLEAMS 3.0 selected P outputs were insensitive to slightly sensitive to changes in FOP, FON, CMN, and β_p. Changes to the P partitioning coefficient had a dramatic effect on GLEAMS 3.0 P output. Leached PO_4-P was extremely sensitive to changes in the variable CPKD. Runoff PO_4-P output was slightly to moderately sensitive, sediment PO_4-P was moderately sensitive to sensitive, and sediment organic P was moderately sensitive to changes in CPKD whereas plant uptake of P was insensitive to slightly sensitive.

As shown by the sensitivity analysis, changing the way GLEAMS calculates CPKD had a substantial impact on P loss through runoff and leaching. Because the P extraction coefficient (β_p) is calculated as a function of CPKD in GLEAMS, changes made to CPKD induced changes to β_p. However, selected P output was insensitive to slightly sensitive to changes in β_p. Based on information presented in the literature review in Chapter 2, GLEAMS overestimates CPKD.

As presented in Chapter 2, studies utilizing GLEAMS to simulate P loss in surface runoff and subsurface flow have shown varying results (Knisel and Turtola, 2000; Reyes et al., 1997; Shirmohammadi et al., 1998; Yoon et al., 1994). Under-predictions of dissolved P loss in leachate by Shirmohammadi et al. (1998) may be attributed to the overestimation of CPKD. Reyes et al. (1997) reported under-predictions of P losses in runoff by GLEAMS, but runoff and sediment loss were also under-predicted. Knisel and Turtola (2000) reported over-predictions of total P (sum of dissolved and sediment P) loss in runoff by GLEAMS. This may be explained by an overestimated CPKD. Results from the sensitivity analysis indicate the importance of CPKD in GLEAMS prediction of P loss. Therefore, potential changes to calculations of CPKD and β_p are needed. These modifications are evaluated in Chapter 5.

CHAPTER 5: MODIFICATIONS TO GLEAMS 3.0

Incorporation of new knowledge for modeling soil P can potentially increase the capability of GLEAMS 3.0 to accurately predict P losses in surface runoff and leachate. Overall, there are no consistent conclusions about GLEAMS' capability to simulate P loss based on the studies presented in Sec 2.8. The state of the science review revealed numerous relationships available to predict P losses in runoff and leaching based on STP and P saturation values. The use of these relationships in GLEAMS may not be feasible considering the equations were developed for site-specific conditions and may not be applicable to a wide variety of soils. Phosphorus loss is also dependent on transport factors such as hydrology and topography and not solely on one variable.

As identified in the sensitivity analysis described in Chapter 4, the P partitioning coefficient (CPKD) is a critical component used in GLEAMS to predict P loss in runoff and leachate. GLEAMS currently overestimates CPKD as shown by data presented in the literature review, and the P extraction coefficient (β_p) is calculated as a function of CPKD. The P partitioning coefficient is used to estimate P available for loss in the calculations used by GLEAMS to simulate P loss in runoff and leaching. Potential changes to CPKD and β_p in an attempt to make GLEAMS a better predictor of P loss are evaluated in this chapter. The GLEAMS 3.0 Fortran source code was modified to evaluate proposed changes. GLEAMS was the baseline model for comparison of modifications. Three modifications to GLEAMS were made: GLEAMS β_p is the baseline model with modified β_p, GLEAMS CPKD is the baseline model with modified CPKD, and GLEAMS β_p+CPKD is the baseline model with modified β_p and CPKD.

5.1 MODEL CHANGES

5.1.1 GLEAMS β_P

The amount of P available for loss through runoff is dependent on the P extraction coefficient (β_p). As presented in Chapter 3, the value of β_p is always 0.1 because of an overestimation of the P partitioning coefficient (CPKD). One approach to modify β_p in GLEAMS is to relate β_p to the change in Mehlich-3 P over time. Mehlich-3 P provides an index of extractable P in the soil. Soil clay content and Mehlich-3 P data from Andraski and Bundy (2003), Fang et al. (2002), Gaston et al. (2003), Sharpley (1996), and Sharpley (1995) are plotted in Figure 5.1. Data from Gaston et al. (2003) showed high (59 to 726 mg P kg^{-1} soil) Mehlich-3 P values for soils of less than 10 percent clay content. Kaolinitic soils were present at one of the four sites; clay type was not given for remaining sites. An exponential trend can be seen among all data presented between a soil's Mehlich-3 P value and percentage of clay content. Other factors such as fertilizer application history, tillage practices, and level of P saturation come into play. The relationship found between the change in Mehlich-3 P over time with clay content by Cox (1994) is also plotted in Figure 5.1. The exponential relationship between the amount of extracted residual P (difference between initial Mehlich-3 P and value one year after fertilizer application) and clay content was given by the equation:

$$CM3P = \exp(-0.040 \times CL) \qquad [2.20]$$

where CM3P is the change in Mehlich-3 extractable P per unit of fertilizer P applied and CL is the clay content. Estimation of CM3P is dependent on the amount but not the type of clay and does not take into account the amount of fertilizer P applied. The variable CM3P can be considered to be equivalent to the P extraction coefficient in that it is a measure of the amount of available P that can be potentially lost through runoff. In an effort to allow β_p to change with varying clay contents, the following relationship was incorporated into GLEAMS:

$$\beta_P = \exp(-0.040 \times CL) \qquad [5.1]$$

This change makes β_p dependent on clay content and not CPKD. This change in calculation of β_p would allow more dissolved P to become available for loss through runoff and leaching at lower clay contents than is currently calculated in GLEAMS. This relationship only considers the clay content and not the type of clay. Though GLEAMS considers the specific surface area of clays for calculation of sediment P, the model does not differentiate between 1:1 and 2:1 clay layer types.

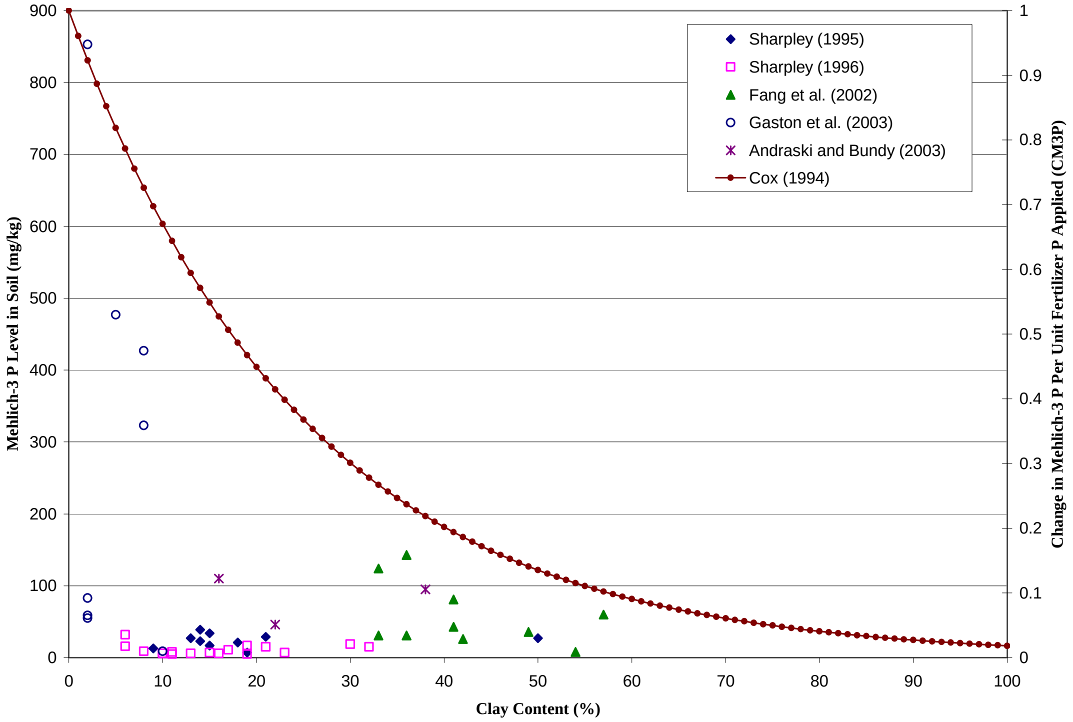

Figure 5.1 Relationship between Mehlich-3 P soil level (left axis), CM3P (right axis), and clay content (Andraski and Bundy, 2003; Cox, 1994; Fang et al., 2002; Gaston et al., 2003; Sharpley, 1996; and Sharpley, 1995). Phosphorus extraction coefficient calculated from the equation $\beta_p = \exp(-0.040 * \text{clay content})$.

5.1.2 GLEAMS CPKD

Phosphorus adsorption coefficients presented in Chapter 2 ranged from 0.2 to 26.1 L kg^{-1}. These values are much lower than the GLEAMS estimate (100 for 0% clay content to 350 for 100% clay content) for partitioning P between the solid and water phases. Based on this information, GLEAMS overestimates CPKD. No studies were found that examined the correlation between clay content and CPKD.

Soil clay content, total P, and Olsen P data from Siddique and Robinson (2003) and Fang et al. (2002), along with P partitioning coefficients, were analyzed statistically in Systat 11 (Systat, 2004) to determine if there is a relationship between clay content, total P, Olsen P, and CPKD. A General Linear Model was applied to the 300 data points and the results are shown in Table 5.1. Only Olsen P was significant at the $P<0.05$ level. Figures 5.2 through 5.4 show plots of CPKD versus clay content, Olsen P, and total P. Phosphorus partitioning coefficients were estimated from Eqn. 2.11 for assumed equilibrium P concentrations of 1 to 20 mg P L^{-1}. A relationship to predict CPKD based on clay, Olsen P, and total P was not found.

Table 5.1 Results from general linear model to determine relationship of the P partitioning coefficient with clay content, Olsen P, and total P (n = 300).

Effect	Coefficient	Standard Error	Standard Coefficient	P
CONSTANT	31.713	28.381	0.000	0.265
CLAY	-1.073	0.863	-1.052	0.215
TP	0.012	0.040	0.260	0.767
OLSENP	-0.657	0.226	-1.731	0.004
TP*CLAY	0.001	0.001	0.496	0.586
OLSENP*CLAY	0.009	0.008	0.549	0.294
OLSENP*TP	0.000	0.000	0.567	0.595
OLSENP*TP*CLAY	-0.000	0.000	-0.154	0.847

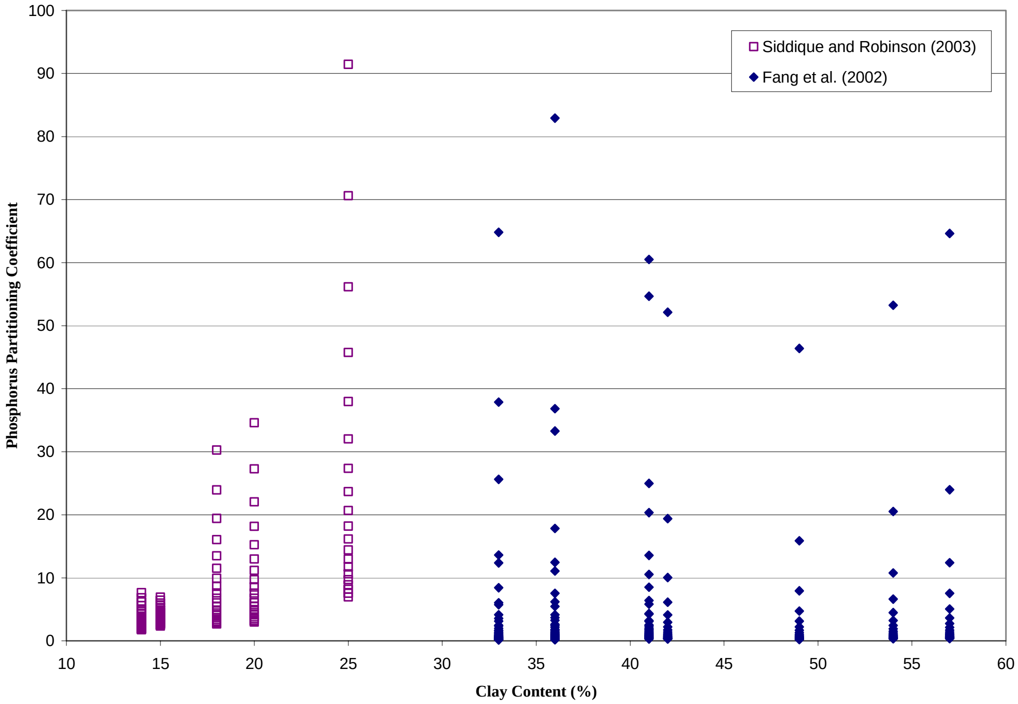

Figure 5.2 Phosphorus partitioning coefficient with respect to clay content for data collected by Siddique and Robinson (2003) and Fang et al. (2002).

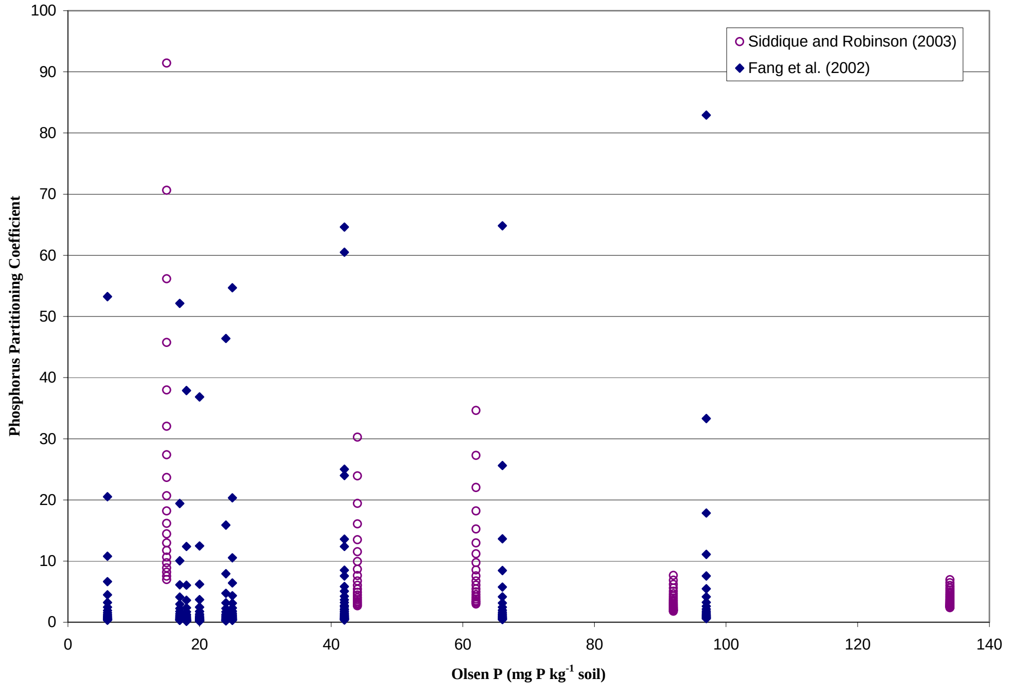

Figure 5.3 Phosphorus partitioning coefficient with respect to Olsen P for data collected by Siddique and Robinson (2003) and Fang et al. (2002).

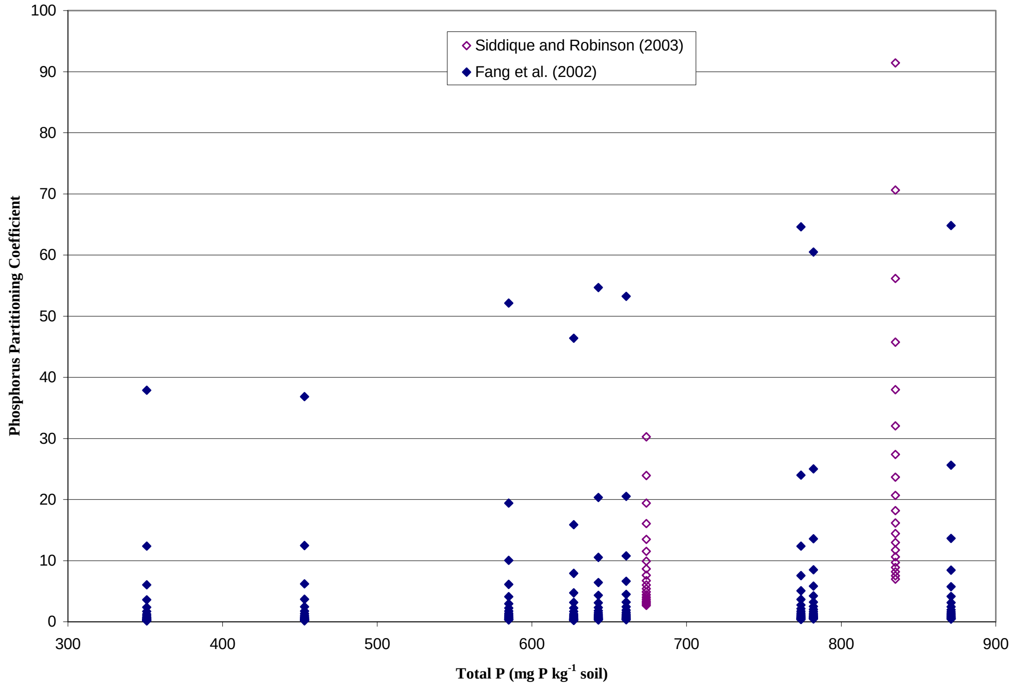

Figure 5.4 Phosphorus partitioning coefficient with respect to total P for data collected by Siddique and Robinson (2003) and Fang et al. (2002).

Use of equation 2.11 alone to estimate CPKD was not feasible because the maximum soil P sorption and constant related to binding strength are site- and soil-specific. These constants must be determined experimentally for each soil type. In the absence of experimental data, the following relationship was incorporated into GLEAMS and used to evaluate CPKD as a function of clay content (CL) for each computational soil layer, *i*:

$$CPKD_i = 0.75 \times CL_i \qquad [5.2]$$

This equation is not based on experimental data and was created in an effort to reduce the magnitude of CPKD used in GLEAMS, so that CPKD would more closely agree with reported values. Eqn 5.2 does not take into account soil mineralogy or soil P levels. The value of CPKD would range from 0 to 75 using eqn. 5.2. This equation was applied to all soil conditions. Reduction of CPKD from GLEAMS-estimated 100 – 350 (Eqn 3.12) to 0 – 75 (Eqn 5.2) would cause an increase in the concentration of labile P in solution, thus increasing the amount of dissolved P lost in runoff and leachate and decreasing the amount of sediment P.

5.1.3 GLEAMS β_P+CPKD

Equations 5.1 and 5.2 were incorporated into GLEAMS to evaluate the combined effects of these changes on model output.

5.2 MODEL SIMULATIONS

Data sets for Belle Mina, Gilbert Farm, and Watkinsville as presented in Chapter 4 were used in this analysis. The results of all simulations are presented first followed by a discussion of results.

5.2.1 BELLE MINA, AL RESULTS

5.2.1.1 BELLE MINA PL9

Creation and calibration of the GLEAMS hydrology, erosion, and nutrient input files for the Belle Mina PL9 data set were presented in Sec 4.1. This data set was input into the four models (GLEAMS, GLEAMS β_p, GLEAMS CPKD, and GLEAMS β_p+CPKD) for analysis.

The values of β_p and CPKD for each of the models are given in Table 5.2. Predicted P losses over the study period are given in Table 5.3. Total runoff PO_4-P values were closer to observed in the unmodified GLEAMS model than in the other models though the percent difference between observed runoff PO_4-P and GLEAMS-predicted was high at 193%. Annual runoff was under-predicted both years at the Belle Mina PL9 site. Total observed runoff was 28.9 cm over the study period from March 1991 to November 1992 while GLEAMS hydrology predicted 13.0 cm. An under-prediction in runoff would better explain under-predictions in runoff PO_4-P loss, but not the over-predictions seen in the model runs. Reducing the value of CPKD from 182.50 to 24.75 increased the total amount of runoff PO_4-P predicted by GLEAMS CPKD. Increasing the constant β_p from 0.10 to 0.27 also increased the total amount of PO_4-P loss in runoff. Figure 5.5 shows the change in monthly runoff PO_4-P over the study period for all model runs. A large variation (944% for GLEAMS, 979% for GLEAMS β_p, 3,564% for GLEAMS CPKD, and 4,367% for GLEAMS β_p+CPKD) between observed and predicted runoff PO_4-P was seen in June 1992 for all models. This is a result of GLEAMS hydrology sub-model simulating a large (2.9 cm) runoff event on June 26, 1992, which was the highest predicted daily runoff amount over the study period from March 1991 through November 1992. Daily observed runoff values were not provided by Yoon et al. (1994) preventing comparison of simulated versus observed daily runoff. All models predicted that more PO_4-P was lost in this single runoff event than any other runoff event over the simulation period causing the large variation between predicted and observed.

Table 5.2 Phosphorus partitioning and extraction coefficients used in Belle Mina PL9 simulation.

Model	Phosphorus Partitioning Coefficient (CPKD) for Surface Layer	Phosphorus Extraction Coefficient (β_p)
GLEAMS	182.50	0.1000
GLEAMS β_p	182.50	0.2671
GLEAMS CPKD	24.75	0.1000
GLEAMS β_p+CPKD	24.75	0.2671

Table 5.3 Observed and predicted P loss over study period from March 1991 through November 1992 for Belle Mina PL9 data set.

Model	Runoff PO_4-P (kg ha^{-1})	Sediment P (kg ha^{-1})	PO_4-P Leached[a] (mg L^{-1})	(kg ha^{-1})	Plant Uptake of P (kg ha^{-1})
Observed	0.45	0.79	0.28	*	**
GLEAMS	1.32	2.57	0.33	0.15	70.51
GLEAMS β_p	1.36	2.58	0.33	0.15	69.82
GLEAMS CPKD	4.19	2.30	1.83	0.85	69.82
GLEAMS β_p+CPKD	5.10	2.35	1.83	0.85	69.82

[a] April through July 1991 and October 1991 through June 1992; * Observed data were given as concentration, ** No observed data

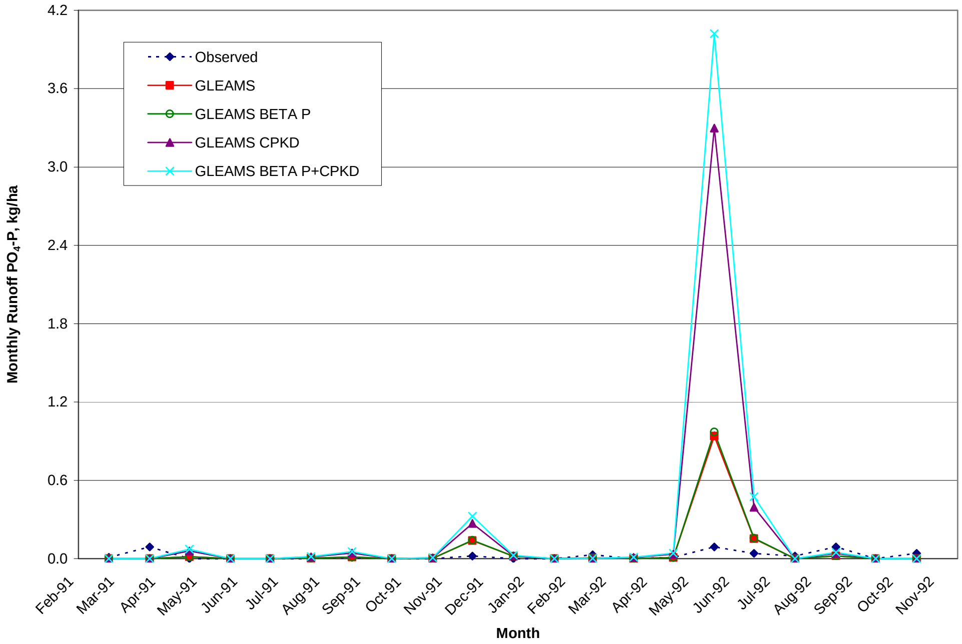

Figure 5.5 Monthly runoff PO_4-P loss over study period from March 1991 through November 1992 for Belle Mina PL9.

The total sediment P loss over the study period was over-predicted by all models. Predicted annual sediment loss closely agreed with observed data, with 21% under-prediction in 1991 and 1% over-prediction in 1992. Total sediment loss was under-predicted by 15%. The original GLEAMS model over-predicted sediment P by 225%. The decrease of CPKD in the surface layer from 182.50 to 24.75 reduced the total sediment P loss over the study period. Even with this reduction, the GLEAMS CPKD and GLEAMS β_p + CPKD models still over-predicted total sediment P loss by 191% and 197%, repsectively. The change in monthly sediment P loss over time is shown in Figure 5.6.

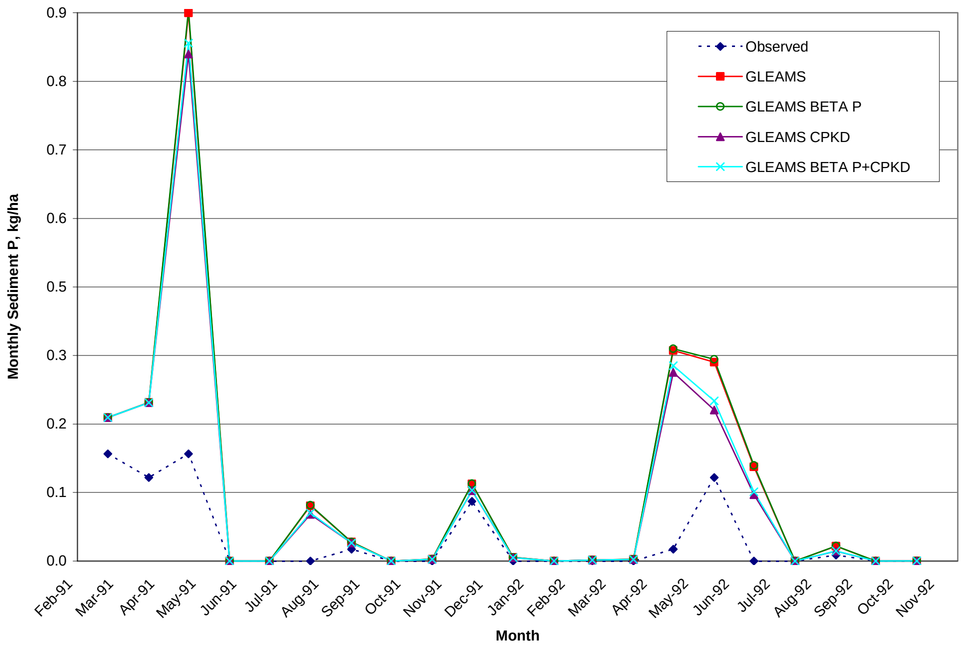

Figure 5.6 Monthly sediment P loss over study period from March 1991 through November 1992 for Belle Mina PL9.

GLEAMS produced the same results as GLEAMS β_p when predicting total PO_4-P leached concentrations. Similarly, GLEAMS CPKD produced the same results as GLEAMS β_p+CPKD. Changing β_p from 0.10 in GLEAMS to 0.27 in GLEAMS β_p had no effect on the total PO_4-P concentrations leached (Table 5.3). Observed data were collected bi-weekly with flow-weighted concentrations given. Daily PO_4-P concentrations leached for all models were flow-weighted for two weeks prior to each sample date for comparison to observed data. Total PO_4-P concentrations leached from GLEAMS and GLEAMS β_p were 18% higher than observed totals. Decreasing CPKD from 182.5 to 24.75 in GLEAMS CPKD and GLEAMS β_p+CPKD increased the total amount of PO_4-P leached to 554% over observed values. Figure 5.7 shows the change in PO_4-P leached over time.

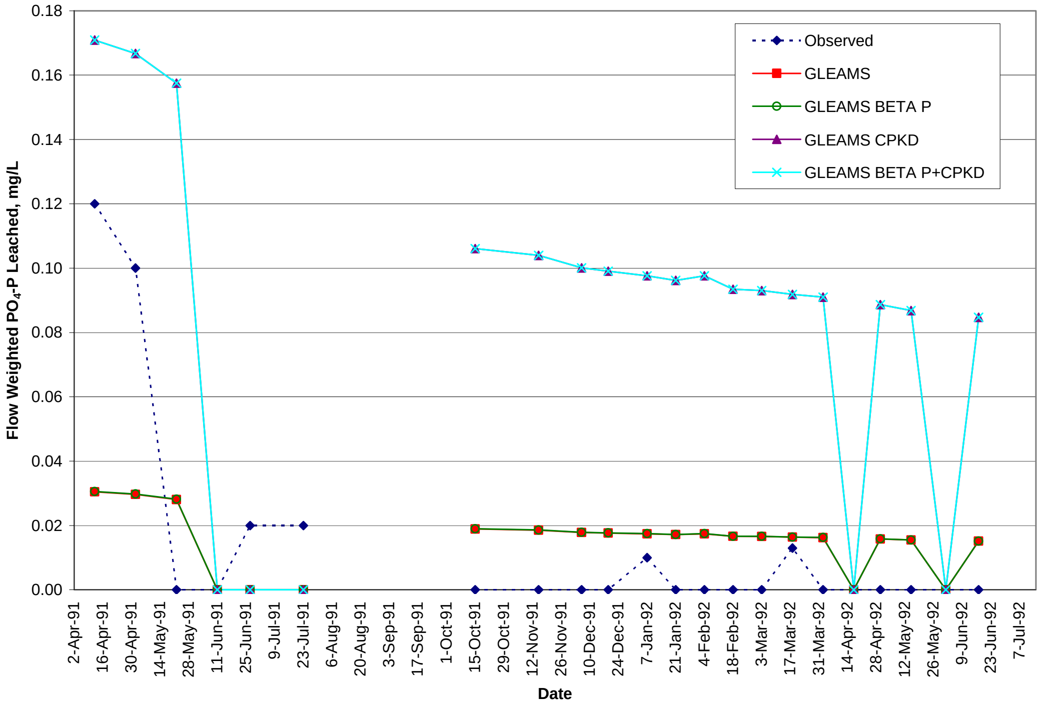

Figure 5.7 PO_4-P leached from April 1991 through July 1991 and October 1991 through June 1992 for Belle Mina PL9 data set.

There were no observed data for plant uptake of P for comparison to simulated values for the Belle Mina PL9 data set. A decrease in CPKD from 182.5 to 24.75 and increase in β_p from 0.10 to 0.27 slightly decreased the total amount of plant uptake of P over the study period by less than one percent (Table 5.3). Figure 5.8 depicts the change in monthly plant uptake of P. All models produced similar monthly results except in July 1991 when GLEAMS predicted higher plant uptake of P values than the other models.

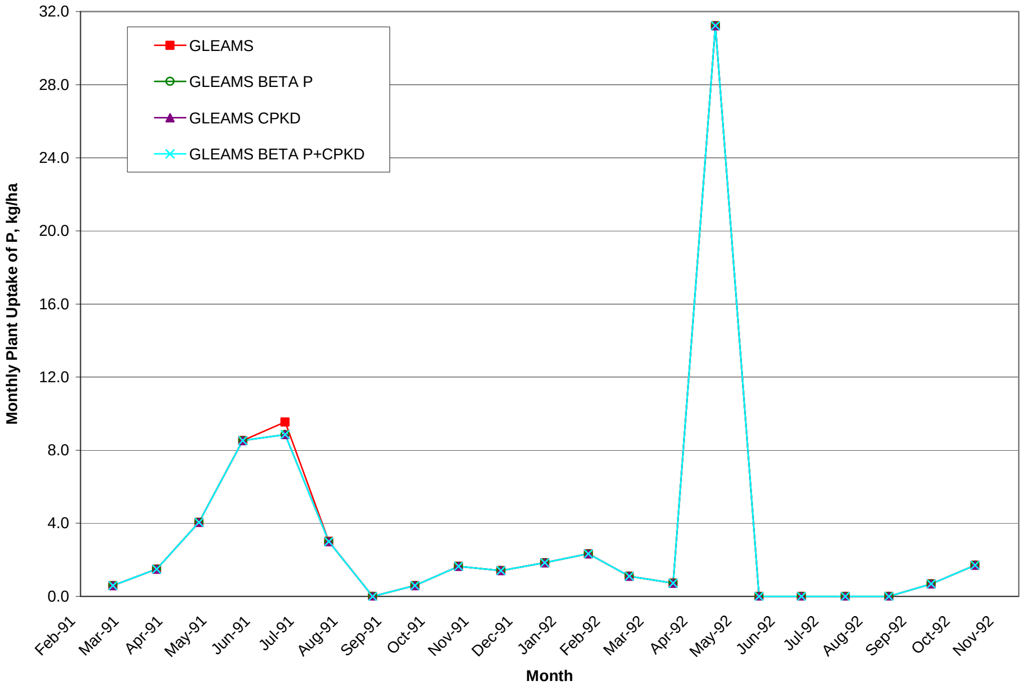

Figure 5.8 Monthly plant uptake of phosphorus from March 1991 through November 1992 for Belle Mina PL9 data set.

5.2.1.2 BELLE MINA PL18

Data used to create and calibrate the GLEAMS hydrology, erosion, and nutient input files for Belle Mina PL18 were presented in Sec 4.1. This data set was input into the four models (GLEAMS, GLEAMS β_p, GLEAMS CPKD, and GLEAMS β_p+CPKD) for analysis.

The values of CPKD and β_p for Belle Mina PL18 were the same as Belle Mina PL9 (Table 5.2). Table 5.4 shows the predicted P loss over the study period for Belle Mina PL18. Total runoff PO_4-P values from GLEAMS had the lowest percent difference (238%) as compared with observed values. Runoff was under-predicted by 87% in 1991 and 73% in 1992. This under-prediction does not explain why runoff PO_4-P was over-predicted. The same trend was observed as in the Belle Mina PL9 data; a decrease in CPKD from 182.5 to 24.75 and an increase in β_p from 0.10 to 0.27 resulted in greater amounts of runoff PO_4-P. The monthly runoff PO_4-P loss over the study period is shown in Figure 5.9. Large variations between observed and simulated runoff PO_4-P for all models were found in September and December 1991 and June 1992. GLEAMS hydrology predicted a total of 43 runoff events during the study period from March 1991 to Novemner 1992. Ten of those events occurred in December 1991 resulting in an increase in predicted PO_4-P loss in runoff. The maximum simulated runoff event (3.6 cm) over the study period occurred on June 26, 1992. This large event carried more predicted runoff PO_4-P from the site than in any other month.

Table 5.4 Observed and predicted P loss over study period from March 1991 through November 1992 for Belle Mina PL18 data set.

Model	Runoff PO_4-P (kg ha^{-1})	Sediment P^a (kg ha^{-1})	PO_4-P Leached ^{b}		Plant Uptake of P (kg ha^{-1})
			(mg L^{-1})	(kg ha^{-1})	
Observed	1.40	1.28	0.38	*	**
GLEAMS	4.73	4.24	0.30	0.14	101.7
GLEAMS β_p	4.88	4.25	0.30	0.14	102.2
GLEAMS CPKD	12.84	3.96	1.67	0.76	102.2
GLEAMS β_p+CPKD	15.56	4.00	1.67	0.76	102.2

[a] March 1991 through August 1992; [b] April through July 1991 and October 1991 through June 1992;
* Observed data was given as concentration, **No observed data

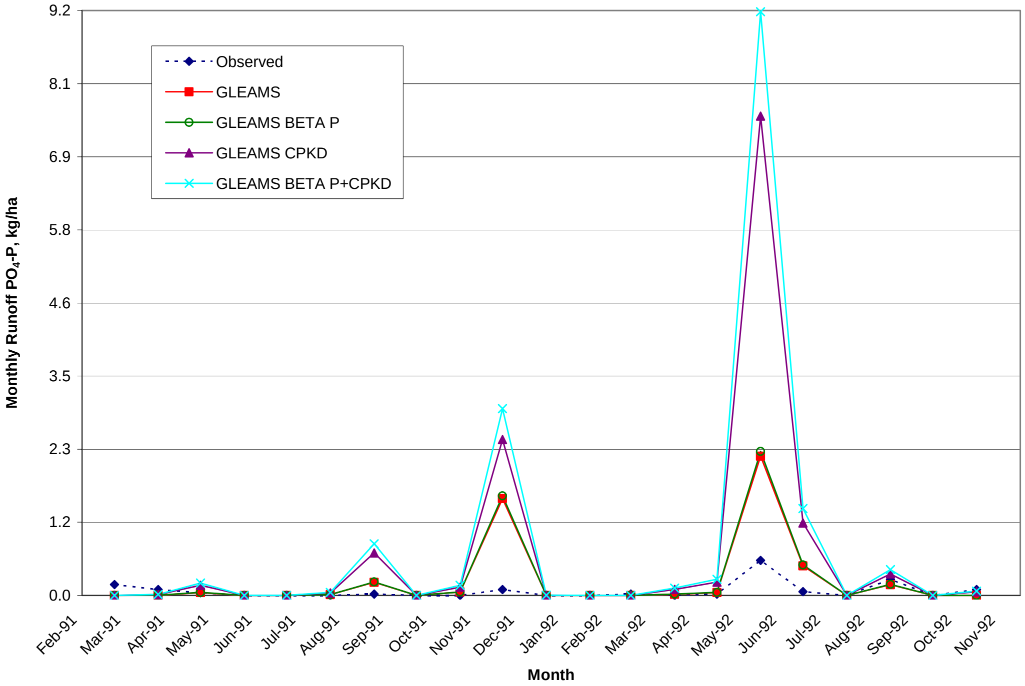

Figure 5.9 Monthly runoff PO_4-P loss over study period from March 1991 through November 1992 for Belle Mina PL18 data set.

GLEAMS under-predicted sediment loss by 12% in 1991 and about 1% in 1992. Total sediment loss from March 1991 to August 1992 was under-predicted by 8%.

GLEAMS CPKD generated the lowest percent difference of 209% from observed values for total sediment P loss out of all models. Total sediment P loss over the study period decreased with a reduction of CPKD. An increase in β_p from 0.10 to 0.27 led to a slight increase in total sediment P loss. Monthly sediment P loss over time is shown in Figure 5.10. Large variations (106 to 652%) between predicted and observed sediment P occurred in March through May 1991 for all models.

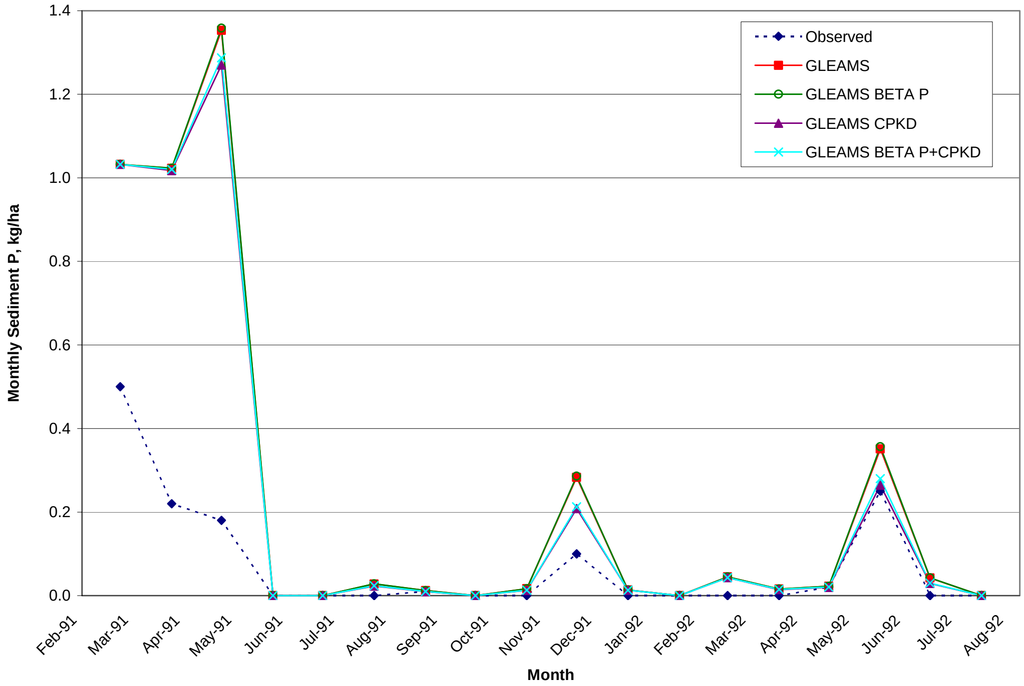

Figure 5.10 Monthly sediment P loss over study period from March 1991 through August 1992 for Belle Mina PL18 data set.

As with the Belle Mina PL9 data, change in β_p from 0.10 in GLEAMS to 0.27 in GLEAMS β_p had no effect on the total PO_4-P concentration leached (Table 5.4). Total PO_4-P concentration leached from GLEAMS and GLEAMS β_p were 21% lower than observed totals. GLEAMS CPKD and GLEAMS β_p+CPKD over-predicted the total concentration of PO_4-P leached by 339%. Figure 5.11 shows the change in PO_4-P concentration leached over time for Belle Mina PL18. All models predicted that the total concentration of PO_4-P leached over the study period was lower in Belle Mina PL18 than PL9. Organic fertilizer in the form of poultry litter was applied on both Belle Mina sites on March 27, 1991 and April

11, 1992 with 9 t ha^{-1} more poultry litter applied to PL18. The incorporation of more organic P at PL18 did not cause an increase in the amount of labile P lost in leachate as predicted by GLEAMS. Observed data indicated otherwise. GLEAMS hydrology may explain the lower predicted dissolved P loss in leachate at PL18 than PL9. The hydrology input files for PL9 and PL18 were not the same since the PL18 site experienced more runoff than PL9. GLEAMS hydrology simulated 8 cm more percolation for PL9 (total percolation = 121 cm) than PL18 (total percolation = 113 cm) over the study period from March 1991 through November 1992 (Figure 5.12).

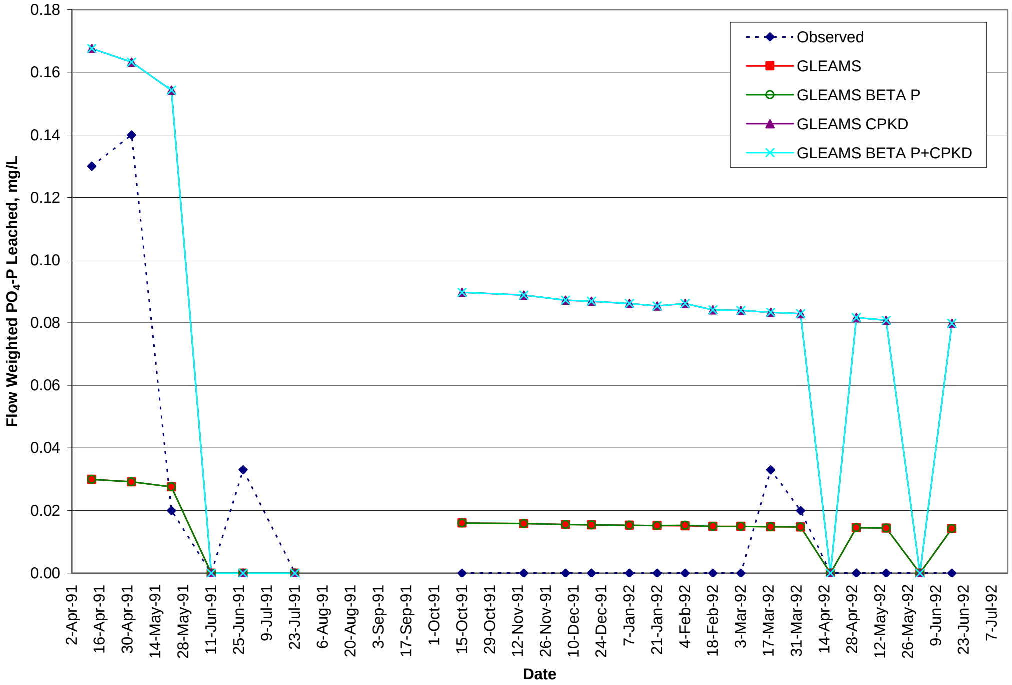

Figure 5.11 PO_4-P leached over study period from April 1991 through July 1991 and October 1991 through June 1992 for Belle Mina PL18 data set.

The Belle Mina PL18 data set did not include observed values for plant uptake of P. Change in calculation of β_p (GLEAMS β_p) resulted in a small increase in total plant uptake of P as compared to GLEAMS (Table 5.4). Subsequent changes made in GLEAMS CPKD and GLEAMS β_p+CPKD had the same effect on total plant uptake of P as in GLEAMS β_p. Figure 5.13 shows the monthly change in plant uptake of P over the study period.

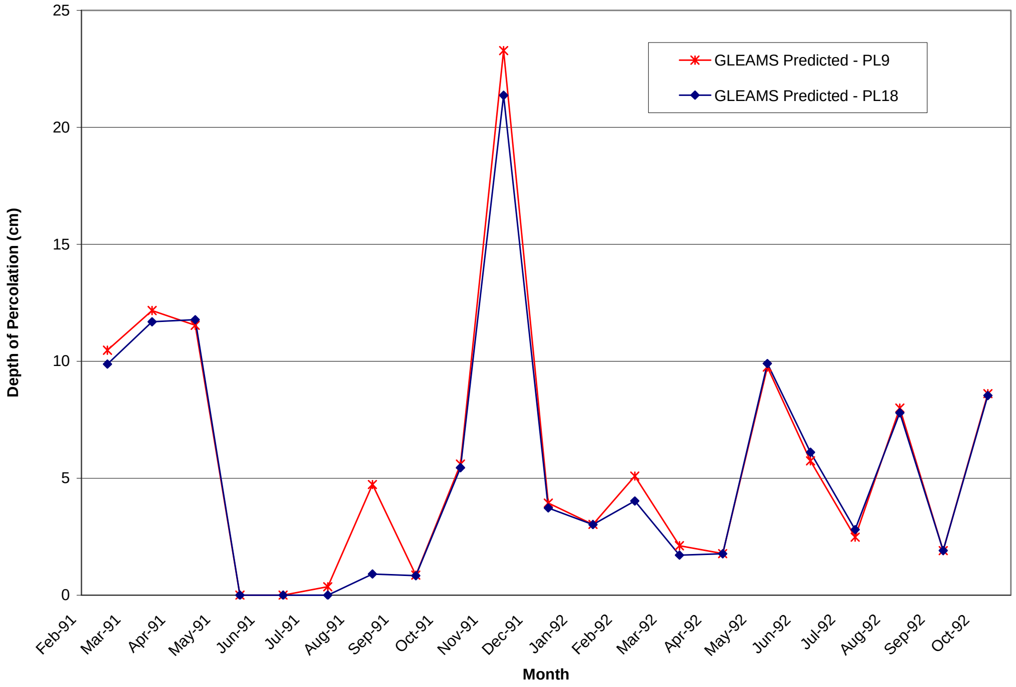

Figure 5.12 Monthly depth of percolation for Belle Mina PL9 and PL18 data sets.

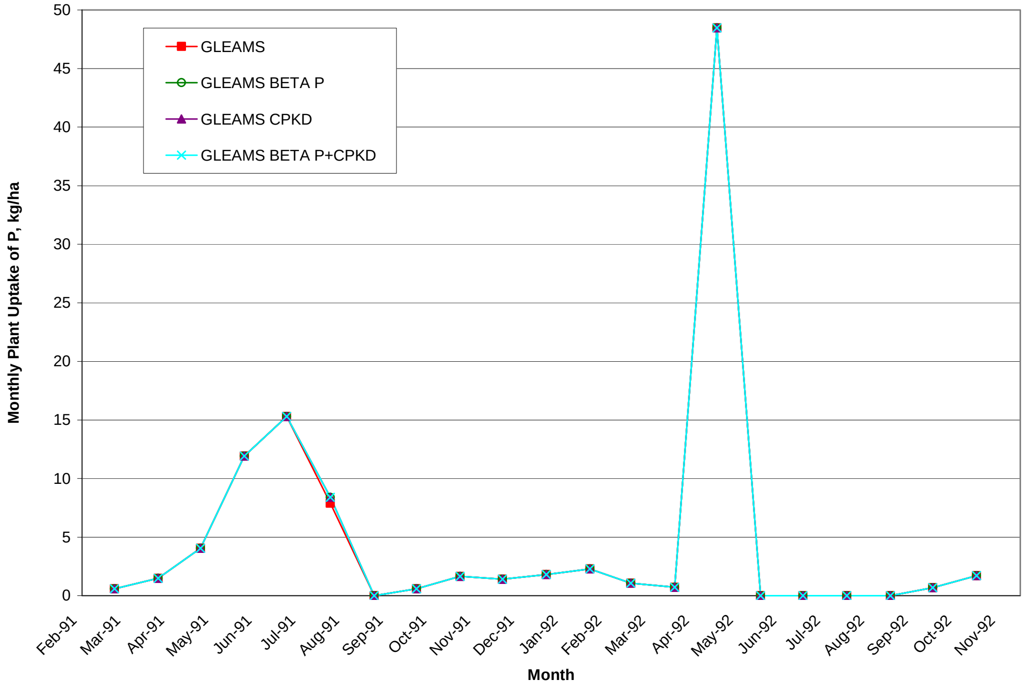

Figure 5.13 Monthly plant uptake of phosphorus over study period from March 1991 through November 1992 for Belle Mina PL18 data set.

5.2.2 GILBERT FARM RESULTS

Data for Gilbert Farm were presented in Sec. 4.2 and were input into the four models for analysis. Table 5.5 lists the values of β_p and CPKD for each of the models. Predicted average annual P loss for all model runs over the six-year study period are shown in Table 5.6. GLEAMS and GLEAMS β_p under-predicted runoff PO_4-P loss by 41% and 38%, respectively. Runoff was over-predicted by GLEAMS the first three years (1984-1986) of simulation and under-predicted the last three (1987-1989). GLEAMS hydrology over-predicted total runoff by 11% over the study period. Both GLEAMS β_p and GLEAMS CPKD increased the average annual runoff PO_4-P from that predicted by the unmodified GLEAMS. GLEAMS CPKD, with a decrease in CPKD from 155 to 16.5, had the smallest percent difference out of all models at 13% with respect to average annual values. This can be misleading since GLEAMS CPKD closely agreed with observed values for three years (-15% difference in 1984, 5% difference in 1988, and 4% difference in 1989), while exhibiting large variations (576% difference in 1985, 181% difference in 1986, and -85% difference in 1987) from observed data for the remaining three years. Annual runoff PO_4-P is shown in Figure 5.14.

Table 5.5 Phosphorus partitioning and extraction coefficients used in Gilbert Farm simulation.

Model	Phosphorus Partitioning Coefficient (CPKD) for Surface Layer	Phosphorus Extraction Coefficient (β_p)
GLEAMS	155.00	0.1000
GLEAMS β_p	155.00	0.4148
GLEAMS CPKD	16.50	0.1000
GLEAMS β_p+CPKD	16.50	0.4148

Table 5.6 Observed and predicted average annual P loss for Gilbert Farm over six-year study period.

Model	Runoff PO_4-P	Sediment P	PO_4-P Leached	Plant Uptake of P
	(kg ha^{-1})			
Observed	1.80	0.24	*	*
GLEAMS	1.06	1.56	0.007	39.15
GLEAMS β_p	1.11	1.58	0.007	39.27
GLEAMS CPKD	2.03	0.91	0.038	40.33
GLEAMS β_p+CPKD	2.70	0.94	0.038	40.23

* No observed data

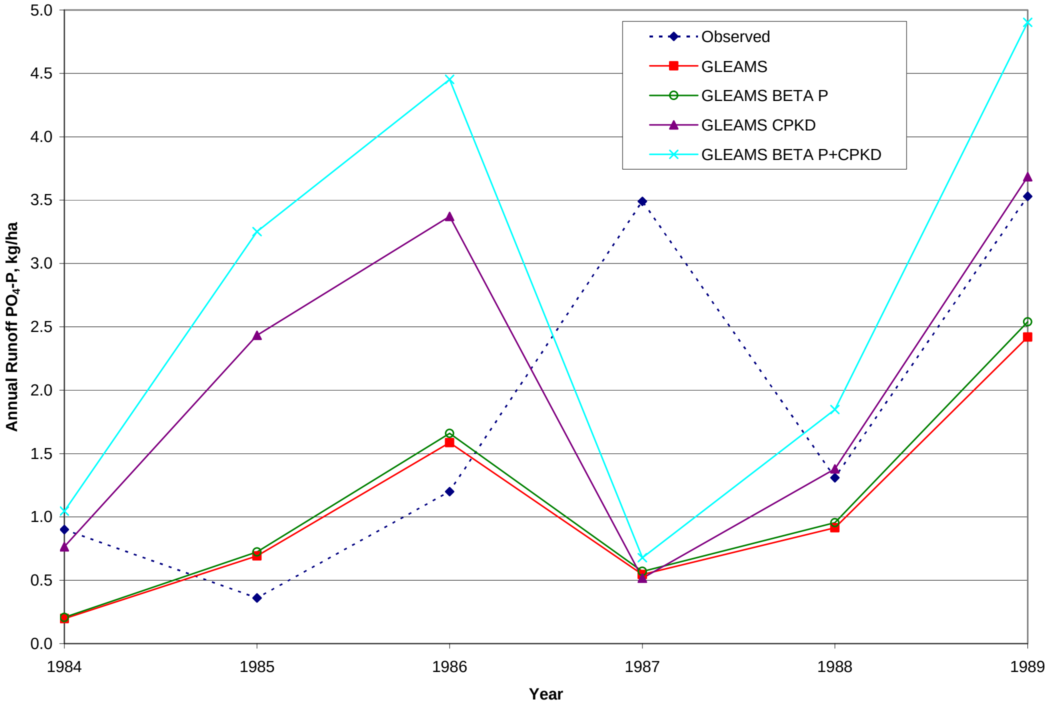

Figure 5.14 Annual runoff PO_4-P loss for Gilbert Farm over six-year study period.

Predicted average annual sediment P loss ranged from 0.91 kg ha^{-1} (GLEAMS CPKD) to 1.58 kg ha^{-1} (GLEAMS β_p). Annual sediment P loss of the six-year study period is shown in Figure 5.15. GLEAMS under-predicted annual sediment loss by 29% in 1984 and 7% in 1986, while over-predicting by 15% in 1984, 2% in 1987, 64% in 1988, and 262% in 1989. The GLEAMS erosion sub-model over-predicted total sediment loss by 32% during the study period. All models over-predicted annual sediment P which may be attributed to sediment yield over-predictions. GLEAMS CPKD caused average annual sediment P loss predictions to decrease as compared to GLEAMS.

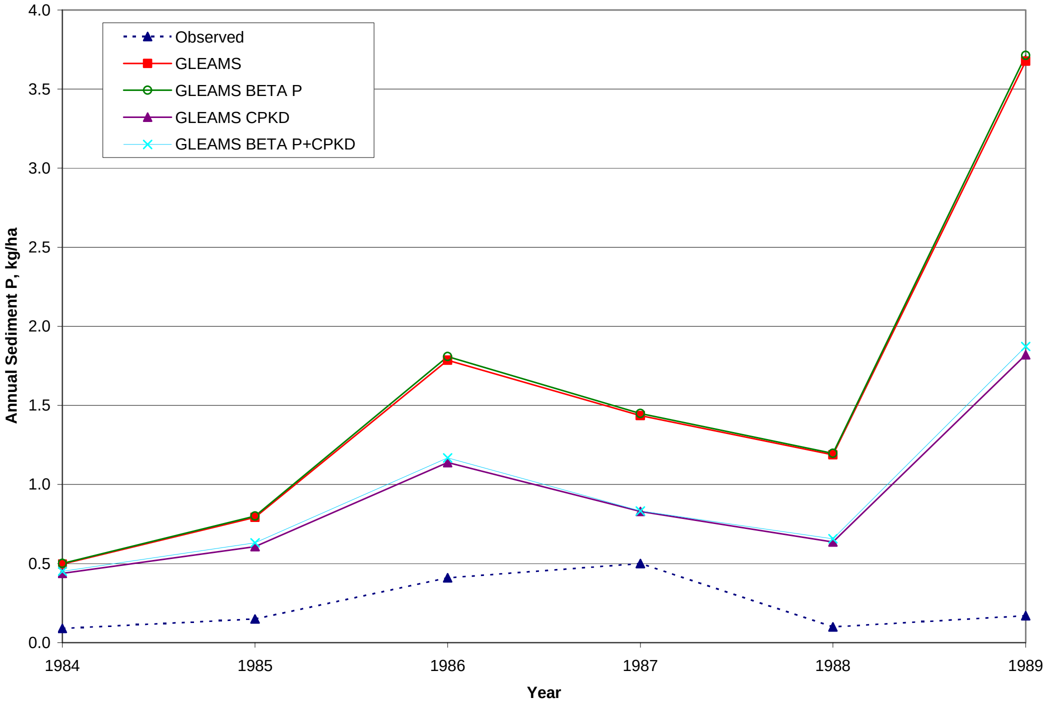

Figure 5.15 Annual sediment P loss for Gilbert Farm over six-year study period.

There were no observed data for leached P and plant uptake of P. Figure 5.16 shows the variation in PO_4-P leached over time. GLEAMS and GLEAMS β_p produced the same annual PO_4-P leached results. GLEAMS CPKD and GLEAMS β_p+CPKD also produced similar results. Change in β_p from 0.10 to 0.41 in GLEAMS β_p did not affect the annual amount of PO_4-P leached. The change in CPKD from 155 to 16.5 in GLEAMS CPKD and GLEAMS β_p+CPKD caused an increase in the average annual PO_4-P leached. Average annual plant uptake of P increased with an increase in β_p and decrease in CPKD. Annual values of plant uptake of P are shown in Figure 5.17.

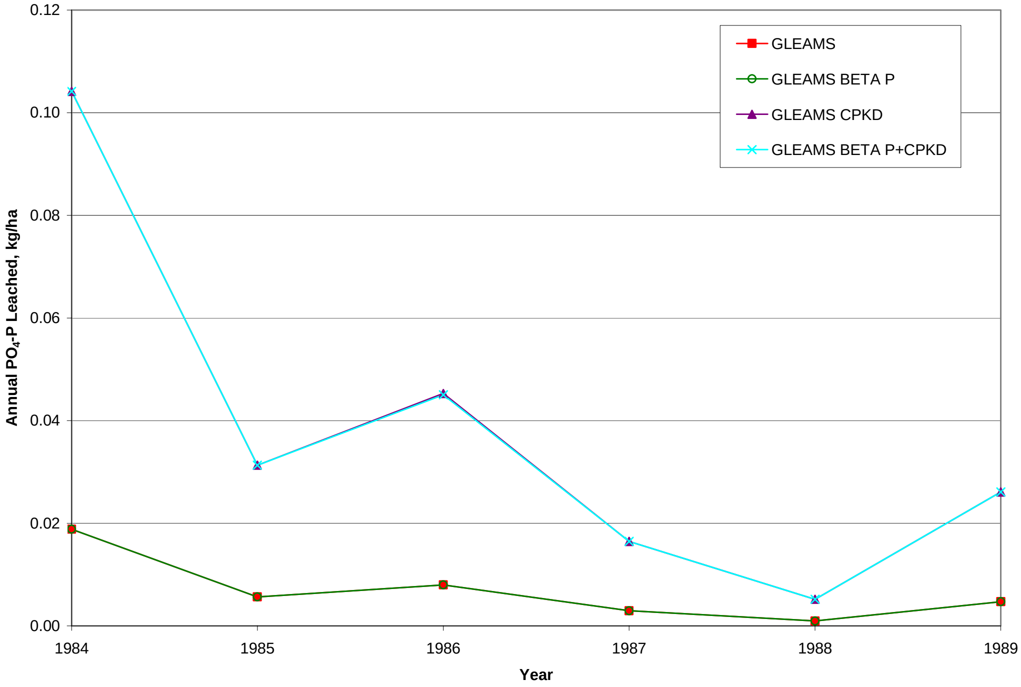

Figure 5.16 Annual PO_4-P leached for Gilbert Farm over six-year study period.

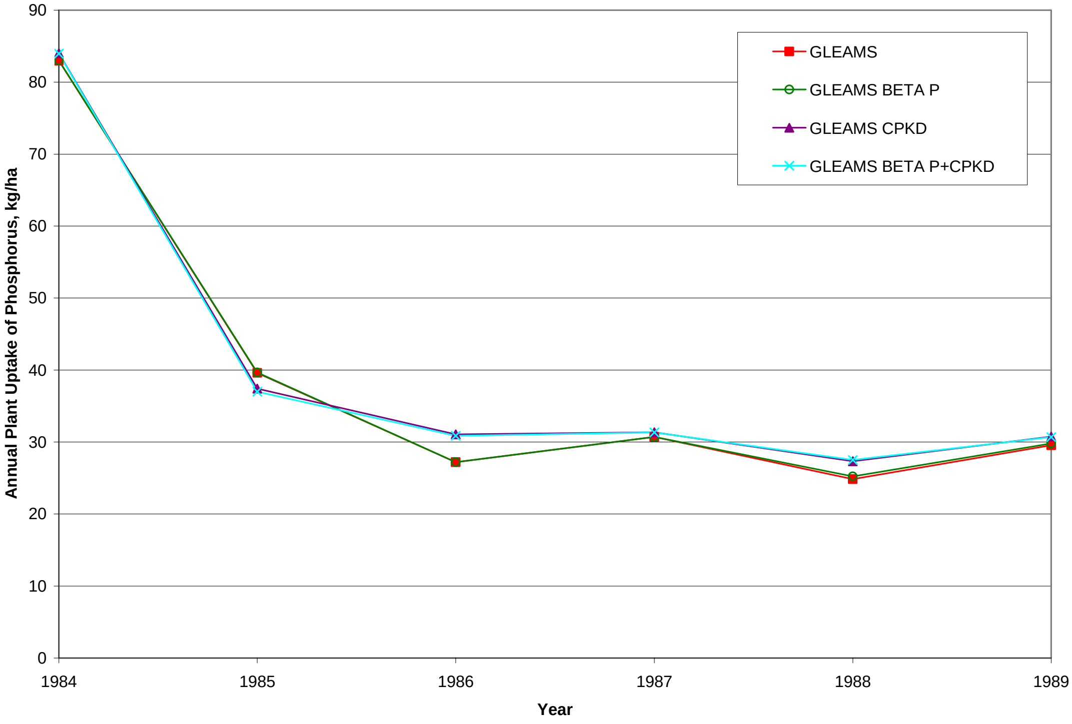

Figure 5.17 Annual plant uptake of phosphorus for Gilbert Farm over six-year study period.

5.2.3 WATKINSVILLE RESULTS

The sample data set provided with the GLEAMS software was also used for analysis of the four models. Table 5.7 shows the values of β_p and CPKD for each model for the Watkinsville data set. There were no observed data for runoff PO_4-P and sediment P in 1973. Average annual P output for years 1974 and 1975 is given in Table 5.8. The percent error for runoff PO_4-P was lowest in GLEAMS β_p+CPKD (4%) and highest in GLEAMS (-81%). Annual runoff PO_4-P loss is shown in Figure 5.18. Surface runoff was over-predicted by 18% in 1973 and 196% in 1975. In 1974, GLEAMS under-predicted surface runoff by 8%. Over the three-year study period, total runoff was over-predicted by 46%. Predictions of average annual runoff PO_4-P were low in GLEAMS and GLEAMS β_p compared to GLEAMS CPKD and GLEAMS β_p+CPKD. The reduction of CPKD from 132.5 to 9.75 decreased the estimation of P in the solid phase, increasing the amount of P available for loss through runoff.

Table 5.7 Phosphorus partitioning and extraction coefficients used in Watkinsville simulation.

Model	Phosphorus Partitioning Coefficient (CPKD) for Surface Layer	Phosphorus Extraction Coefficient (β_p)
GLEAMS	132.50	0.1000
GLEAMS β_p	132.50	0.5945
GLEAMS CPKD	9.75	0.1046
GLEAMS β_p+CPKD	9.75	0.5945

Table 5.8 Average annual P output over two years (1974 and 1975) for Watkinsville P2.

Model	Runoff PO_4-P	Sediment P	PO_4-P Leached	Plant Uptake of P
	(kg ha^{-1})			
Observed	0.48	2.88	*	*
GLEAMS	0.09	1.09	0.006	40.97
GLEAMS β_p	0.10	1.10	0.006	40.97
GLEAMS CPKD	0.30	1.01	0.047	40.71
GLEAMS β_p+CPKD	0.50	1.02	0.047	40.68

* No observed data

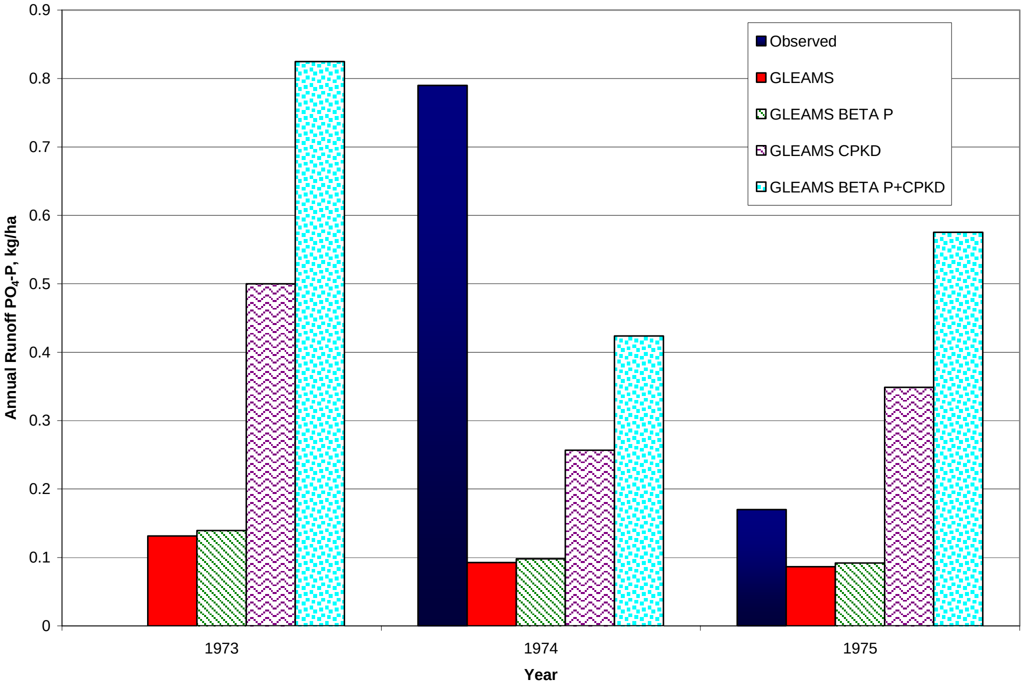

Figure 5.18 Annual runoff PO_4-P loss for Watkinsville P2 data set.

Average annual sediment P values for years 1974 and 1975 ranged from 1.01 kg ha^{-1} (GLEAMS CPKD) to 1.10 kg ha^{-1} (GLEAMS β_p). Annual sediment P loss in runoff is shown in Figure 5.19. Increase of β_p from 0.10 to 0.59 in GLEAMS β_p increased average annual sediment P loss by less than one percent over GLEAMS' prediction. Change in calculation of CPKD decreased GLEAMS' prediction of sediment P. Over-estimation of surface runoff in 1975 contributed to an over-estimation of sediment loss during the same year. The observed average annual sediment yield was 4.4 t ha^{-1} with GLEAMS predicting 13.2 t ha^{-1}. Yet, all models under-predicted average annual sediment P loss by 62 to 65%.

No observed data were available for leached PO_4-P and plant uptake of P for Watkinsville. The decrease in CPKD from 132.5 to 9.75 in GLEAMS CPKD and GLEAMS β_p+CPKD greatly increased the average annual amount of PO_4-P leached as compared to GLEAMS and GLEAMS β_p (Figure 5.20). The value of β_p had no effect on PO_4-P leached, so the change was due solely to CPKD. This trend was seen among all four data sets studied. Plant uptake of P varied little among all four models (Figure 5.21).

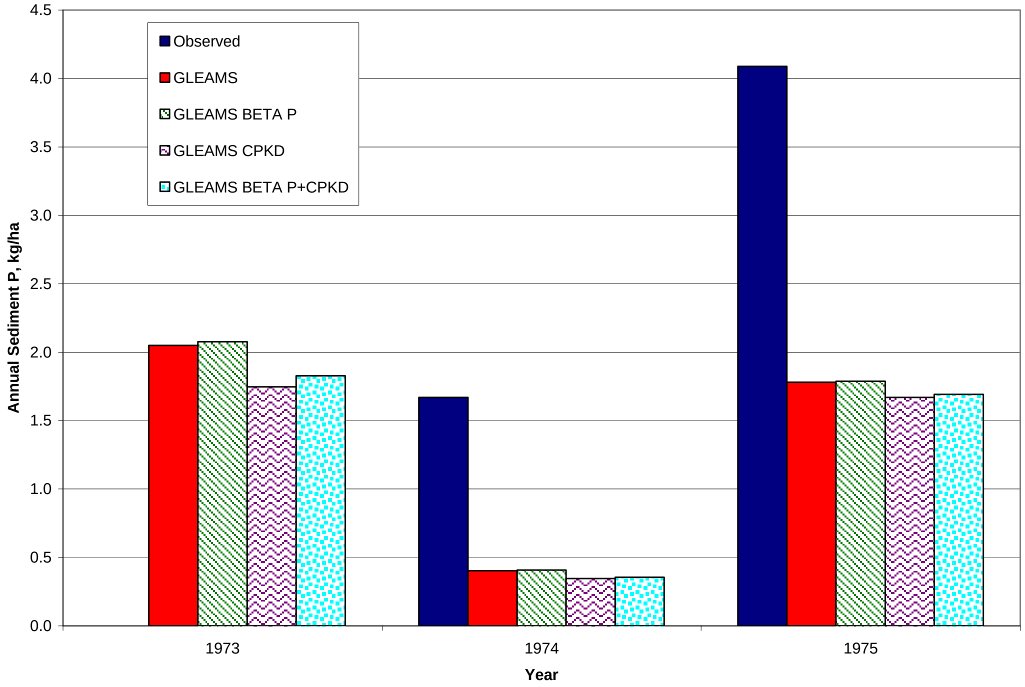

Figure 5.19 Annual sediment P loss for Watkinsville P2 data set.

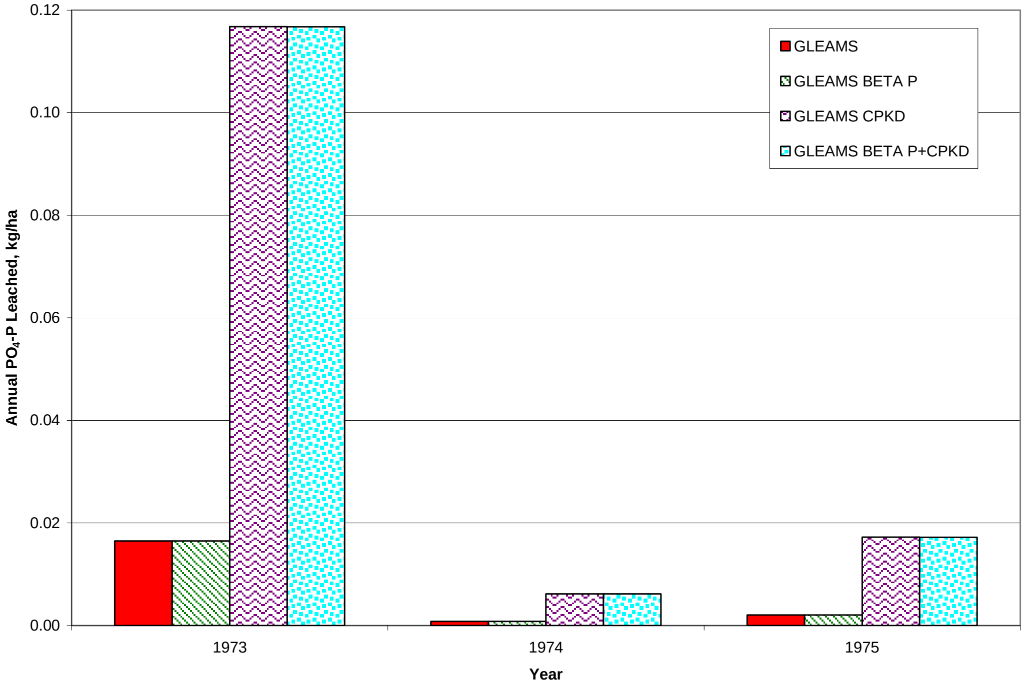

Figure 5.20 Annual PO_4-P leached for Watkinsville P2 data set.

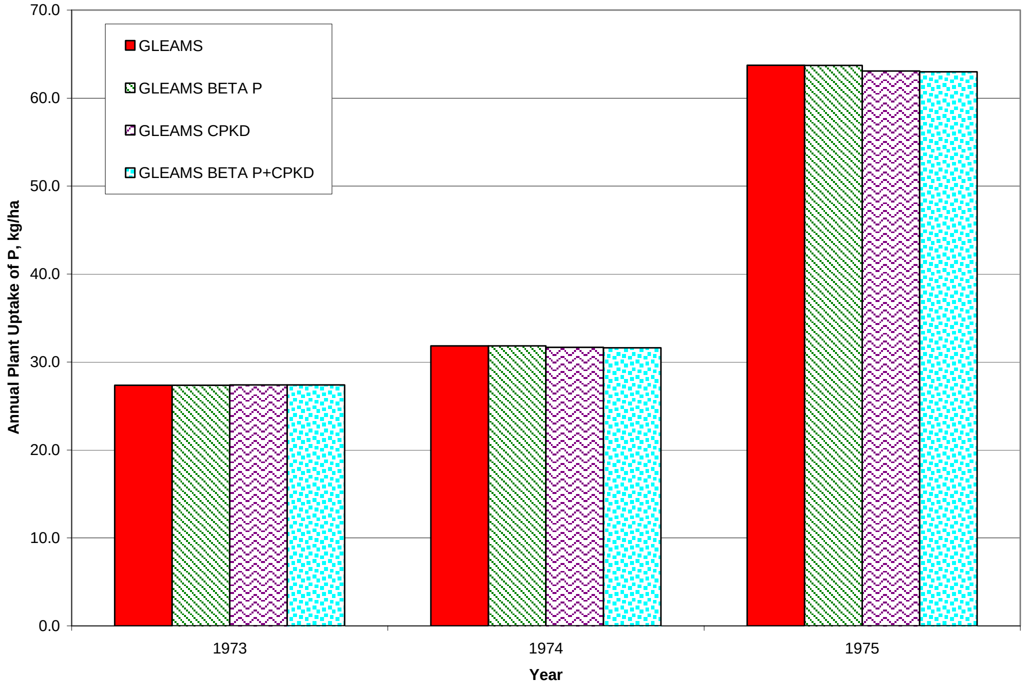

Figure 5.21 Annual plant uptake of phosphorus for Watkinsville P2 data set.

5.3 DISCUSSION

A definite conclusion about whether the modifications made to GLEAMS improved P predictions was difficult to determine. Table 5.9 presents the overall model predictions relative to observed data for each data set used in the analyses. The percent differences presented are with respect to the total sum of P loss over the study periods of each data set. Though hydrology and erosion calibrations were performed, GLEAMS under-predicted surface runoff and sediment yield totals for the Belle Mina PL9 and PL18 data sets and over-predicted for Gilbert Farm and Watkinsville.

Increased loss of dissolved P through runoff and leaching was expected with the modification to the P extraction coefficient (β_p) in GLEAMS β_p. This was the case with regard to PO_4-P loss in runoff as GLEAMS β_p increased predicted runoff PO_4-P in all four data sets analyzed, as compared to unmodified GLEAMS. Calculation of the P extraction coefficient (β_p) as a function of clay content made more P available for loss through runoff. But these increases in predicted runoff PO_4-P further increased the percent error between predicted and observed values for the Belle Mina PL9 and PL18 data sets. The anticipated increase in the concentration of PO_4-P leached at Belle Mina with the modification to β_p

(GLEAMS β_p) did not occur. GLEAMS β_p predicted the same total PO$_4$-P concentration in leachate as GLEAMS, suggesting that the P extraction coefficient is not critical to GLEAMS prediction of P loss through leaching. Results from the sensitivity analysis in Chapter 4 indicated that GLEAMS P output was insensitive to slightly sensitive to change in β_p.

Table 5.9 Overall performance of model predictions (under and over) for respective study period for each data set.

Parameter	**Model**	**Data Set**			
		Belle Mina PL9	**Belle Mina PL18**	**Gilbert Farm**	**Watkinsville**
Study Period		Mar 1991 - Nov 1992	Mar 1991 -Nov 1992	1984 - 1989	1973 - 1975
Hydrology Sub-model					
Runoff (cm)	GLEAMS	Under -55%	Under -83%	Over +11%	Over +46%
Erosion Sub-model					
Sediment Yield (t ha^{-1})	GLEAMS	Under -15%	Under -8%	Over +32%	Over +153%
Nutrient Sub-model					
Runoff PO$_4$-P (kg ha^{-1})	GLEAMS	Over +193%	Over +238%	Under -41%	Under -81%
	GLEAMS β_p	Over +202%	Over +248%	Under -38%	Under -80%
	GLEAMS CPKD	Over +831%	Over +817%	Over +13%	Under -36%
	GLEAMS β_p+CPKD	Over +1,033%	Over +1,011%	Over +50%	Over +4%
Sediment P (kg ha^{-1})	GLEAMS	Over +225%	Over +231%	Over +560%	Under -62%
	GLEAMS β_p	Over +226%	Over +232%	Over +567%	Under -62%
	GLEAMS CPKD	Over +191%	Over +209%	Over +285%	Under -65%
	GLEAMS β_p+CPKD	Over +197%	Over +213%	Over +295%	Under -64%
PO$_4$-P Leached (mg L^{-1})	GLEAMS	Over +18%	Under -21%	*	*
	GLEAMS β_p	Over +18%	Under -21%	*	*
	GLEAMS CPKD	Over +554%	Over +339%	*	*
	GLEAMS β_p+CPKD	Over +554%	Over +339%	*	*

*No observed data

The effect of GLEAMS β_p on sediment P loss was small; a slight increase in GLEAMS-predicted sediment P was seen in all model simulations. This slight increase was to the sediment-associated labile P pool. GLEAMS β_p further increased over-predictions in sediment P for Belle Mina and Gilbert Farm. GLEAMS under-prediction of sediment P at Watkinsville was slighty reduced.

The change to calculation of CPKD in GLEAMS CPKD was expected to cause an increase in dissolved P loss in runoff and leaching while decreasing the amount of sediment P loss in erosion. Reduction of the magnitude of CPKD lowered the estimate of P associated with the solid phase. As shown in the literature review, the value of CPKD is over-estimated in GLEAMS. The equation proposed to correct for this was not based on experimental data, but was an attempt to correct the problem in GLEAMS. The new calculation of CPKD had a marked effect on runoff PO_4-P and PO_4-P leached. Reduction of CPKD signifcantly increased predictions of P loss in runoff and leachate as anticipated. For the Belle Mina PL9 and PL18 data sets, these increased predictions in runoff PO_4-P and PO_4-P leached also increased the percent error between predicted and observed. In the Gilbert Farm and Watkinsville data sets, GLEAMS CPKD predictions more closely agreed with predicted runoff PO_4-P than GLEAMS predictions. Inorganic commercial fertilizers were applied annually and incorporated in soils at Gilbert Farm (0.05 t P ha^{-1}) and Watkinsville (0.03 t P ha^{-1}) whereas 9 and 18 t ha^{-1} of poultry litter was applied at Belle Mina. The larger application of fertlizer at Belle Mina combined with mineralization of organic P contributed to the soluble P pool and resulted in increases in predicted runoff and leached PO_4-P.

Decreasing the value of CPKD in GLEAMS CPKD, decreased sediment P predictions in GLEAMS. GLEAMS over-predicted sediment P loss in the Belle Mina and Gilbert Farm data sets. GLEAMS CPKD reduced these predictions to more closely agree with observed values. Total sediment P loss at Watkinsville was under-predicted by GLEAMS; these under-predictions were slightly worsened by 2% with the change in CPKD. Combining changes in β_p and CPKD further increased over-predictions of runoff PO_4-P by 840% at Belle Mina PL9, 77% at Belle Mina PL18, 91% at Glibert Farm, and 85% at Watkinsville over GLEAMS predicted values.

The model results were ranked to identify which model's output best agreed with observed average annual values. For each data set, the model predicting the best agreement with observed data was ranked as 1, while the model with the worst agreement to observed data was given a 4. Table 5.10 shows the summary of this ranking for runoff PO_4-P. The unmodified GLEAMS model showed to be the better predictor of average annual runoff PO_4-P for the Belle Mina PL9 and PL18 data sets. GLEAMS CPKD was the best predictor for the Gilbert Farm data set, while the combined GLEAMS β_p+CPKD was the best predictor of runoff PO_4-P for Watkinsville.

Table 5.10 Summary of model results for runoff PO_4-P.

Model	Belle Mina PL9[a]	Belle Mina PL18[a]	Gilbert Farm[b]	Watkinsville P2[b]
GLEAMS	1	1	3	4
GLEAMS β_p	2	2	2	3
GLEAMS CPKD	3	3	1	2
GLEAMS β_p+CPKD	4	4	4	1

[a] Based on total runoff PO_4-P values over study period; [b] Based on average annual values

Table 5.11 shows the ranking for model performance for predicting sediment P. GLEAMS CPKD proved to be the best predictor for Belle Mina PL9, Belle Mina PL18, and Gilbert Farm data sets. Sediment P for Watkinsville P2 was best predicted by GLEAMS β_p. Belle Mina PL9 and PL18 were the only data sets with observed P leached data. In both cases, GLEAMS was the best predictor of PO_4-P loss through leachate.

Table 5.11 Summary of model results for sediment P.

Model	Belle Mina PL9[a]	Belle Mina PL18[a]	Gilbert Farm[b]	Watkinsville P2[b]
GLEAMS	3	3	3	2
GLEAMS β_p	4	4	4	1
GLEAMS CPKD	1	1	1	4
GLEAMS β_p+CPKD	2	2	2	3

[a] Based on total sediment P values over study period; [b] Based on average annual values

Changes to β_p and CPKD were determined to be appropriate relationships for inclusion to GLEAMS. These modifications to GLEAMS showed varying results as there was no conclusive evidence to select one model over another. GLEAMS proved to best predict dissolved P in runoff and leachate for the Belle Mina data. Annual sediment P was better predicted by GLEAMS CPKD for three of the four data sets analyzed. Changes to CPKD greatly increased the percent error between predicted and observed runoff PO_4-P values for the Belle Mina data but reduced the percent error for Gilbert Farm and Watkinsville.

CHAPTER 6: CONCLUSIONS

The overall goal of this research was to improve simulation of soil P transport and transformations in GLEAMS 3.0. The first objective was to determine the state of the science for P transport and transformation to determine if GLEAMS P relationships are reasonable. This was accomplished during the literature review presented in Chapter 2. The P transport and transformations in GLEAMS were found to be overly simplistic and not based on current state of the science for P transport and dynamics. GLEAMS does not consider different types of clay (i.e., 1:1 or 2:1 clay layer types) when determining P pool sizes. Also, GLEAMS does not consider root morphology or uptake kinetics when estimating plant uptake of P. Although many relationships have been developed to predict dissolved P loss in runoff and leachate from STP and the degree of P saturation, the use of a single variable to predict P loss is not enough; transport factors must also be considered. GLEAMS is a tool intended for long-term average annual comparisons of management practices but it is commonly misused as a quantitative predictor of P loss.

The second objective of this research was to determine appropriate relationships for inclusion in GLEAMS. This objective was accomplished by comparing the state of the science to GLEAMS simulation of P and conducting a sensitivity analysis to determine which GLEAMS P parameters affect the P model predictions. During the review of GLEAMS P simulation described in Chapter 3, an error in calculation of the P partitioning coefficient (CPKD) and subsequent under-estimation in the P extraction coefficient (β_p) were observed. The weakness of GLEAMS to estimate CPKD has been documented by others. Sources for the constants fresh organic P (FOP), fresh organic N (FON), and the mineralization constant (CMN) were not provided in the GLEAMS user manual. A sensitivity analysis was performed to determine how changes in the variables FOP, FON, CMN, CPKD, and β_p affect GLEAMS-predicted P in runoff and leachate. Results from the sensitivity analysis showed the dramatic impact CPKD has on GLEAMS P output. The lack of experimental data made determining an appropriate CPKD relationship to include in GLEAMS difficult. An equation was developed in an effort to reduce the magnitude of GLEAMS-estimated CPKD to more closely agree with values found during the literature review. A new equation to estimate β_p was also proposed to eliminate the dependency of β_p on CPKD.

The third objective of this research was to determine if modifications to GLEAMS improved P predictions. Four data sets (Belle Mina PL9, Belle Mina PL18, Gilbert Farm, and Watkinsville) were used in the analysis of proposed model changes. The original GLEAMS model was used as a baseline for comparison of three modified GLEAMS models: GLEAMS β_p, GLEAMS CPKD, and GLEAMS β_p+CPKD. GLEAMS β_p investigated how the change in β_p as a function of soil clay content instead of CPKD affected P output. GLEAMS CPKD attempted to improve GLEAMS' estimation of CPKD, while GLEAMS β_p+CPKD assessed the combined effects of changes to β_p and CPKD on P output.

Simulation results from the model changes were inconclusive. There was no clear evidence supporting use of one model over another. The original GLEAMS model best predicted runoff PO_4-P and PO_4-P leached at the Belle Mina sites, while GLEAMS CPKD best predicted sediment P loss. For the Gilbert Farm data set, GLEAMS CPKD was the best predictor of runoff PO_4-P and sediment P. GLEAMS β_p+CPKD best predicted runoff PO_4-P at Watkinsville, while GLEAMS β_p performed better than the other models in predicting sediment P. Overall, the proposed improvements to GLEAMS did not improve GLEAMS predictions.

The results from this research indicate a need for further analysis on estimation of the variable CPKD in GLEAMS. CPKD has been identified as a vital component of GLEAMS simulation of P loss in runoff and leaching. Recommendations for future research are to:

- Conduct field or laboratory experiments to develop a better correlation between the P partitioning coefficient, clay mineralogy and content, and organic matter content, and further refine the estimate of the P partitioning coefficient in GLEAMS,
- Consider the degree of P saturation when comparing results from more than one data set to better determine the capacity of soils to potentially adsorb more P, and
- Collect P uptake field data to allow evaluation of GLEAMS simulation of P uptake.

The main conclusion of this research is that the GLEAMS model should not be used for quantitative estimates of hydrology, sediment, and particularly nutrient loss for specific management practices. The nutrient dynamics model in particular is too simplified to accurately predict nutrient losses. As recommended by the GLEAMS model developers, GLEAMS should only be used to predict relative differences in alternative management systems. Default values suggested in the GLEAMS user manual merely provide a starting point for developing model input files; the user should make every effort to enter site-specific data in order to increase the accuracy of comparisons of varying management practices.

CHAPTER 7: REFERENCES

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APPENDIX A: LIST OF SYMBOLS

$2\pi r_o L$ – root surface area, cm^2
α – concentration of initial P pool, mg kg^{-1}
α_k – soil specific constant for desorption kinetics of P release
β – rate of change in P release with time
β_k – specific constant for desorption kinetics of P release
β_p – phosphorus extraction coefficient
Δt – change in time
θ - linear root absorption coefficient, cm s^{-1}
ω_I – flow coefficient
a_f – soil dependent coefficient for Freundlich equation
b_f – soil dependent coefficient for Freundlich equation
b_m – intercept corresponding to net P mineralization after lag phase for segmented two-pool kinetic model
b_{max} – P sorption maximum on the soil, mg P kg^{-1} soil
b_s – soil buffering capacity
$(C_{av})_p$ – concentration of phosphorus in soil available for runoff and percolation, μg g^{-1}
c_{pfr} – concentration of phosphorus in fresh residue, kg kg^{-1}
d – subscript denoting day
df/dt – rate of root growth, cm s^{-1}
i – subscript denoting computational soil layer
i – subscript denoting initial condition
k_d – phosphorus partitioning coefficient
k_1 – mineralization rate constant of P_1, mg kg^{-1} hr^{-1}
k_o – mineralization rate constant, mg kg^{-1} hr^{-1}
ncl – total number of computational layers
ntl – number of transpiration layers
o – subscript denoting value at beginning of day
r – radial distance from root axis, cm
r_o – mean root radius, cm
r_r – rate of rainfall
s – subscript denoting the surface layer
t – time, hr
t_l – duration of the lag phase prior to initiation of slow adsorption reaction, min
t_m – time, sec
v_o – water influx rate, cm s^{-1}
A – amount of fast-adsorbed P
AAP – algal-available P concentration in runoff, mg L^{-1}
ABST – initial abstraction of rainfall, cm
AGNPS – Agricultural Non-Point Source
AJUPP – adjusted uptake of phosphorus, kg ha^{-1}
Al – Aluminum
AMON – NH_4-N mass in the soil, kg ha^{-1}
ANSWERS – Areal Non-point Source Watershed Environment Response Simulation
ARS – Agricultural Research Service

ASPR – phosphorus flow rate between mineral pools, kg ha^{-1} d^{-1}
AVLPMS – available mass of labile phosphorus, kg ha^{-1}
AWDCR – decomposition rate constant
AWRC – animal waste residue composition factor based on decomposition stage
B – adsorption rate parameter
B1 – Bray-1 P, mg kg^{-1}
BSAT – base saturation, %
C – carbon
C_1 – nutrient concentration in soil solution, μmol cm^{-3}
C_{min} – nutrient concentration where influx is zero, μmol cm^{-3}
C_o – concentration of solute at the root surface, mol cm^{-3}
C_{ro} – concentration of desorbed P in runoff
C_w – concentration of P in solution at equilibrium, mg P L^{-1}
C1, C2 – empirical coefficients
$CaCO_3$ – calcium carbonate
CACO3 – calcium carbonate content of the soil, μg g^{-1}
CB1P – change in Bray-1 phosphorus per kg of fertilizer phosphorus applied
CL – clay content of soil, %
CLAB – concentration of labile phosphorus in the soil, μg g^{-1}
CM3P – change in Mehlich-3 extractable phosphorus per kg of fertilizer phosphorus applied
CMN – mineralization constant, kg ha^{-1} d^{-1}
CN – concentration of nitrogen in crop biomass, %
CN2 – antecedent moisture condition II
CNP – carbon:nitrogen, carbon:phosphorus ratio of crop residue
CNR – carbon:nitrogen ratio of crop residue
CPKD – phosphorus partitioning coefficient between the soil and water phase
CP – concentration of phosphorus in crop biomass, %
CPLAB – concentration of labile phosphorus in soil, μg g^{-1}
CPLABW – concentration of labile phosphorus in the soil-water solution, mg L^{-1}
CPR – carbon:phosphorus ratio of crop residue
CREAMS – Chemicals, Runoff, and Erosion from Agricultural Management Systems
D_e – effective diffusion coefficient, cm^{2} s^{-1}
DCR – residue decay rate, kg ha^{-1} d^{-1}
DCRPR – adjusted residue decay rate, kg ha^{-1} d^{-1}
DECOMP – initial fresh residue that has decomposed, %
DEMP – daily optimum phosphorus demand of a crop, kg ha^{-1}
DMPFAC – phosphorus demand factor
DMY – ratio of total dry matter to harvestable portion of crop
$DPS_{Langmuir}$ – degree of soil P saturation determine by Langmuir sorption isotherm
DRP – dissolved reactive orthophosphate
EPIC – Erosion/Productivity Impact Calculator
ER – sediment enrichment ratio
EVAP – depth of evaporation, cm
EVP – evaporation of labile phosphorus, kg ha^{-1}
F – depth of water infiltration, cm
FC – field capacity, volumetric water content at 33 kPa, cm cm^{-1}

Fe – Iron
FON – fresh organic (crop residue) nitrogen, kg ha^{-1}
FOP – fresh organic (crop residue) phosphorus, kg ha^{-1}
FRES – fresh crop residue, kg ha^{-1}
GLEAMS – Groundwater Loading Effects of Agricultural Management Systems
GRT – crop growth ratio
I_{max} – maximum influx of nutrients, µmol cm^{-2} s^{-1}
J_r – net nutrient uptake, µmol cm^{-2} s^{-1}
$J_r(r_o,S)$ – net nutrient uptake for a given root diameter and surface area, µmol cm^{-2} s^{-1}
K – constant related to binding strength
K_k – soil specific constant for desorption kinetics of P release
K_m – nutrient concentration where influx is one-half of I_{max}, µmol cm^{-3}
L_o – initial root length, cm
MPR – mineral phosphorus flow rate, kg ha^{-1} d^{-1}
N – nitrogen
NaOH – sodium hydroxide
$NaHCO_3$ – sodium bicarbonate
NCDC – National Climatic Data Center
NH_4 – ammonium
NPR – nitrogen:phosphorus ratio in crop biomass
NRCS – Natural Resources Conservation Service
OMAW – organic matter in animal waste kg ha^{-1}
ORGNW – organic nitrogen in animal waste, kg ha^{-1}
ORGPW – organic phosphorus in animal waste, kg ha^{-1}
P – phosphorus
P_1 – pool of mineralizable P made available, mg kg^{-1}
P_d – amount of P desorbed over time, µg g^{-1}
P_{min} – net P mineralized, mg kg^{-1}
P_o – amount of initial desorbable P, µg g^{-1}
P_{ox} – amount of P already sorbed
P_{sol} – concentration of P in solution, µM
PERC – depth of water percolation, cm
PERCLP – labile phosphorus in the percolate, mg L^{-1}
PH – soil pH
PLAB – labile phosphorus mass in the soil, kg ha^{-1}
PLI –labile phosphorus immobilization factor
PMINP – active mineral phosphorus, kg ha^{-1}
PMN – phosphorus mineralization from active mineral P, kg ha^{-1}
PMNAW – phosphorus mineralization for animal waste
POR – soil porosity, cm^3 cm^{-3}
POTLAI – potential leaf area index for a crop, m^2 m^{-2}
POTMN – potentially mineralizable soil nitrogen, kg ha^{-1}
PRLPMS – labile phosphorus mass in percolate, kg ha^{-1}
PSC_r – remaining P sorption capacity
PSC_t – total P sorption capacity
PSP – phosphorus sorption coefficient

PY – potential yield, kg ha^{-1}
Q – runoff depth, cm
Q_p – amount of P released, mg kg^{-1}
R^2 – coefficient of determination
RC – residue composition factor
RESDW – crop residue mass on soil surface, kg ha^{-1}
RMP – phosphorus mineralization from crop residue, kg ha^{-1} d^{-1}
ROLP – labile phosphorus in surface runoff, kg ha^{-1}
S – mass of soil in the root zone of interaction,
S_R – relative sensitivity
SAT – volumetric soil water content at saturation, cm cm^{-1}
SED – sediment concentration in runoff, g L^{-1}
SEDHP – sediment-associated organic humus P, kg ha^{-1}
SEDLP – sediment-associated labile phosphorus in surface runoff, kg ha^{-1}
SEDMP – sediment-associated mineralizable P, kg ha^{-1}
SEDOP – sediment-associated organic P, kg ha^{-1}
SEDSP – sediment-associated stable soil P, kg ha^{-1}
SNO3 – nitrate-N content kg ha^{-1}
SOILMS – soil mass, Mg ha^{-1}
SOILN – stable soil nitrogen, kg ha^{-1}
SOILP – stable soil phosphorus, kg ha^{-1}
SOLP – soluble phosphorus on the soil surface, kg ha^{-1}
SORGP – soil organic humus phosphorus, kg ha^{-1}
SS_{sed} – specific surface area of sediment leaving the field, m^2 g^{-1}
SS_{soil} - specific surface area of remaining soil, m^2 g^{-1}
STP – soil phosphorus test
SUMLAI – accumulated leaf area index, m^2 m^{-2}
SW – volumetric soil water content, cm cm^{-1}
SWFA – soil water factor for ammonification
SY – sediment yield, kg ha^{-1}
T – soil temperature, °C
T_n – total net nutrient uptake, μmol cm^{-2} s^{-1}
TDM – total dry matter, kg ha^{-1}
TDMP – total dry matter phosphorus, kg ha^{-1}
TFA – temperature factor for ammonification
TP – total phosphorus in the soil horizon, %
TR – transpiration equivalent depth, cm
UPLP – uptake of labile phosphorus, kg ha^{-1}
UPP – total uptake of phosphorus, kg ha^{-1}
USDA – United States Department of Agriculture
W – water to soil ratio for desorption kinetics of P release
WIMP – immobilization rate for phosphorus, kg ha^{-1} d^{-1}
WM – water mass (depth) in the soil, cm
WP – volumetric soil water at wilting point (1500 kPa), cm cm^{-1}
X – P sorption by the soil, mg P kg^{-1} soil

APPENDIX B: GLEAMS INPUT FILES

Table B.1 GLEAMS calibrated hydrology input file PL9 Belle Mina, AL.

```
Yoon et al. 1994 (#10) Belle Mina Hydrology File; after calibration
9 ton/ha poultry litter applied, 0.1 ha
conventional till corn with cereal rye winter cover crop
 1991001       0       0       1       0       0       0       1       1       0
    2002

 0.24711    0.24     0.7     3.5      78 0.04877   1.914    40.0   600.0   34.66
       3       4     2.0     4.0    16.0    40.0
    0.51    0.52    0.53    0.55
    0.30    0.31    0.34    0.41
    0.20    0.23    0.29    0.39
    0.42    0.37    0.27    0.24
     1.8     1.8     1.2     0.8
    33.0    35.0    43.0    58.0
    50.0    48.0    43.0    32.0
   48.24   53.25   62.67   72.99   79.99   86.93   89.46   88.88   82.99   73.29
   62.20   52.34
   29.09   32.56   40.56   49.32   57.53   65.32   69.14   68.13   62.06   49.57
   40.27   32.93
   191.0   262.0   340.0   460.0   531.0   554.0   542.0   497.0   427.0   340.0
   241.0   180.0
   392.0   409.0   423.0   393.0   337.0   318.0   288.0   282.0   318.0   337.0
   366.0   394.0
   34.36   35.17   38.99   48.09   57.82   65.64   68.64   68.00   61.64   50.72
   39.72   33.99
    1991    1992       2
      51    0286    1079            39.0     3.2       0
       0
      20    1094    1246            39.0    4.92       0
       0
      51    1287    2086            39.0    3.20       0
       0
      20    2119    2269    2148    39.0    4.92       0
       0
      51    2287    3079            39.0    3.20       0
       0
       0
       0       0       0       0
      -1       0       0       0
```

Table B.2 GLEAMS calibrated erosion input file for PL9 Belle Mina, AL.

```
Yoon et al. 1994 (#10) Belle Mina, Alabama Site
Erosion File, 0.1 ha, conventionally tilled corn and
cereal rye winter cover crop
    1991    1992       0       1       0
    20.0
       1  0.2471
  143.52    0.05
       1     1.0    0.30
       2
     001     045     079     094     109     170     208     246     287     303
     004     045     086     119     134     195     233     269     287     303
       1     1.0
    0.50    0.40    0.16     1.0     1.0    0.55    0.34    0.07    0.05    0.05
    0.10    0.10    0.10     1.0    0.45    0.60    0.45    0.05    0.02    0.05
   0.042   0.042   0.042   0.030   0.030   0.030   0.030   0.030   0.042   0.042
    0.14    0.04    0.20    0.60    0.42    0.41    0.24    0.30    0.16    0.14
    0.01    0.01    0.01    0.50    0.01    0.02    0.01    0.01    0.01    0.01
   0.042   0.042   0.033   0.030   0.030   0.030   0.030   0.030   0.042   0.042
```

Table B.3 GLEAMS estimated nutrient input file for PL9 Belle Mina, AL.

```
Yoon et al. (1994) Belle Mina, Nutrient File, PL9 Calibration
Conventional till corn and cereal rye winter cover crop
9 ton/ha poultry litter applied, 0.1 ha
    1991    1992       1       2       1
   400.0     0.8     0.0     0.0
    0.06    0.06    0.06    0.06    0.06
    10.0    10.0    10.0    10.0    10.0
   262.0   262.0   262.0   262.0   262.0
    0.07
   0.026   0.026   0.026   0.026   0.026
    10.0    10.0    10.0    10.0    10.0
   0.042
    1001
       0       0    1079
      51                              75.0     5.7
    1080
       1       1    1246
      20                              80.0     5.9
    1086       1       1      15
     9.0    15.0     2.6    4.12  0.6652    1.48    2.85    77.7       1
    1086      12    15.0
    1247
       0       0    2086
      51                              75.0     5.7
    2087
       1       2    2269
      20                              80.0     5.9
    2101       1       1      15
     9.0    15.0     4.4    4.12  0.5898     3.4    2.85    77.7       1
    2101      12    15.0
    2148       5    10.0
    2270
       0       0    3079
      51                              75.0     5.7
       0
```

Table B.4 GLEAMS calibrated hydrology input file PL18 Belle Mina, AL.

```
Yoon et al. 1994 (#10) Belle Mina Hydrology File
18 t/ha poultry litter applied, 0.1 ha
conventional till corn with cereal rye winter cover crop
 1991001       0       0       1       0       0       0       1       1       0
    2002

 0.24711    0.24     0.7     3.5      78 0.04877   1.914    40.0   600.0   34.66
       3       4     2.0     4.0    16.0    40.0
    0.51    0.52    0.53    0.55
    0.34    0.35    0.38    0.45
    0.20    0.23    0.29    0.39
    0.42    0.37    0.27    0.24
     1.8     1.8     1.2     0.8
    33.0    35.0    43.0    58.0
    50.0    48.0    43.0    32.0
   48.24   53.25   62.67   72.99   79.99   86.93   89.46   88.88   82.99   73.29
   62.20   52.34
   29.09   32.56   40.56   49.32   57.53   65.32   69.14   68.13   62.06   49.57
   40.27   32.93
   191.0   262.0   340.0   460.0   531.0   554.0   542.0   497.0   427.0   340.0
   241.0   180.0
   392.0   409.0   423.0   393.0   337.0   318.0   288.0   282.0   318.0   337.0
   366.0   394.0
   34.36   35.17   38.99   48.09   57.82   65.64   68.64   68.00   61.64   50.72
   39.72   33.99
    1991    1992       2
      51    0286    1079            39.0     3.2       0
       0
      20    1094    1246            39.0    4.92       0
       0
      51    1287    2086            39.0    3.20       0
       0
      20    2119    2269    2148    39.0    4.92       0
       0
      51    2287    3079            39.0    3.20       0
       0
       0
       0       0       0       0
      -1       0       0       0
```

Table B.5 GLEAMS calibrated erosion input file PL18 Belle Mina, AL.

```
Yoon et al. (1994) Belle Mina Site Erosion File, PL18 Calibration
Conventionally tilled corn and cereal rye winter cover crop
18 ton/ha poultry litter applied, 0.1 ha
    1991    1992       0       1       0
    20.0
       1  0.2471
  143.52    0.05
       1     1.0    0.30
       2
     001     045     079     094     109     170     208     246     287     303
     004     045     086     119     134     195     233     269     287     303
       1     1.0
    0.50    0.40    0.31     1.0    0.50    0.05    0.10    0.01    0.01    0.04
    0.10    0.20    0.10     1.0    0.45    0.05    0.05    0.05    0.02    0.05
   0.042   0.042   0.042   0.030   0.030   0.030   0.030   0.030   0.042   0.042
    0.14    0.60    0.20    0.15    0.20    0.05    0.24    0.30    0.16    0.14
    0.01    0.01    0.01    0.01    0.01    0.02    0.01    0.01    0.01    0.01
   0.042   0.042   0.033   0.030   0.030   0.030   0.030   0.030   0.042   0.042
```

Table B.6 GLEAMS estimated nutrient input file for PL18 Belle Mina, AL.

```
Yoon et al. (1994) Belle Mina, calibrated nutrient file, PL18
Conventional till corn and cereal rye winter cover crop
18 ton/ha poultry litter applied, 0.1 ha
    1991    1992       1       2       1
   400.0     0.8     0.0     0.0
    0.06    0.06    0.06    0.06    0.06
    10.0    10.0    10.0    10.0    10.0
   262.0   262.0   262.0   262.0   262.0
    0.07
   0.026   0.026   0.026   0.026   0.026
    10.0    10.0    10.0    10.0    10.0
   0.042
    1001
       0       0    1079
      51                                75.0     5.7
    1080
       1       1    1246
      20                                80.0     5.9
    1086       1       1      15
    18.0    15.0     2.6    4.12  0.6652    1.48    2.85    77.7       1
    1086      12    15.0
    1247
       0       0    2086
      51                                75.0     5.7
    2087
       1       2    2269
      20                                80.0     5.9
    2101       1       1      15
     18.0    15.0     4.4    4.12  0.5898     3.4    2.85    77.7       1
    2101      12    15.0
    2148       5    10.0
    2270
       0       0    3079
      51                                75.0     5.7
       0
```

Table B.7 GLEAMS calibrated hydrology input file for Gilbert Farm watershed.

```
Yoon et al. 1992 Data for Gilbert Farm Watershed 1984-1989
Cotton, 1984-86-conventional till, 1987-1989 conservation till
Hydrologic Soil Group B, Hydrology Input File
 1984000       0       0       1       0       0       0       1       1       0
    3922    3928    3918

    9.39    0.20     0.3     3.5      84   0.016    1.89    30.0  538.06   34.75
       3       3     7.0    20.0    30.0
    0.43    0.47    0.46
    0.34    0.39    0.42
    0.12    0.24    0.30
    0.33    0.10    0.08
    1.50    1.50    1.50
    22.0    48.0    60.0
    59.0    35.0    20.0
   49.46   53.78   62.45   72.79   80.43   87.90   90.46   89.79   83.59   73.77
   61.73   52.53
   30.80   33.71   41.00   49.96   57.92   65.89   69.45   68.12   61.90   49.60
   40.11   33.64
   179.0   252.0   333.0   449.0   521.0   553.0   541.0   491.0   418.0   331.0
   233.0   170.0
   398.0   370.0   379.0   366.0   303.0   282.0   259.0   258.0   269.0   291.0
   347.0   372.0
   33.83   35.10   38.83   48.05   57.93   65.66   68.66   67.66   61.32   50.17
   39.17   33.83
    1984    1989       6
      19    0325    1103            30.0    3.28       1
       0
      24    1131    1321    1152    48.0    4.92       0
       0
      24    2108    2298    2152    48.0    4.92       0
       0
      24    3127    3317    3152    48.0    4.92       0
       0
      24    4118    4298            48.0    4.92       0
       0
      51    4301    5091            30.0    3.28       0
       0
      24    5111    5301            48.0    4.92       0
       0
      51    5315    6105            30.0    3.20       0
       0
      24    6136    6326            48.0    4.92       0
       0
       0       0       0       0
       0       0       0       0
       0       0       0       0
       0       0       0       0
       0       0       0       0
       0       0       0       0
      -1       0       0       0
```

Table B.8 GLEAMS calibrated erosion input file for Gilbert Farm watershed.

```
Yoon et al., 1992 Data for Gilbert Farm Watershed 1984-1989
Cotton, 1984-86-conventional till, 1987-1989 conservation till
Hydrologic soil group B, Erosion Input File
    1984    1989       0       3       0
    20.0
       3    9.39
  410.10   0.016  479.00   0.022   544.6   0.022
       1     1.0    0.24
       1       1                    9.39     0.0    20.0
   377.3  0.0070
    20.0    0.03    0.02
       6
     001     103     105     131     152     162     198     245     321
     091     108     152     175     222     298
     091     127     152     194     241     317
     118     185     232     298     301
     014     052     091     111     178     227     301     315
     018     066     105     136     203     326
       2     0.9     1.0
    0.02    0.02    0.74    0.69    0.74    0.69    0.54    0.28    0.40
    0.60    0.60    0.60    0.60    0.60    0.60    0.60    0.60    0.60
   0.088   0.088   0.037   0.037   0.032   0.037   0.046   0.060   0.033
    0.10    0.10    0.01    0.01    0.01    0.01    0.01    0.01    0.01
     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0
   0.029   0.029   0.029   0.029   0.029   0.029   0.029   0.029   0.029
    0.59    0.55    0.59    0.43    0.22    0.32
    0.60    0.60    0.60    0.60    0.60    0.60
   0.037   0.037   0.032   0.046   0.060   0.032
    0.01    0.01    0.01    0.01    0.01    0.01
     1.0     1.0     1.0     1.0     1.0     1.0
   0.029   0.029   0.029   0.029   0.029   0.029
    0.59    0.55    0.59    0.43    0.22    0.32
    0.60    0.60    0.60    0.60    0.60    0.60
   0.037   0.037   0.032   0.046   0.060   0.032
    0.01    0.01    0.01    0.01    0.01    0.01
     1.0     1.0     1.0     1.0     1.0     1.0
   0.029   0.029   0.029   0.029   0.029   0.029
    0.26    0.20    0.14    0.40    0.48
    0.60    0.60    0.60    0.60    0.60
   0.037   0.046   0.060   0.032   0.037
    0.01    0.01    0.01    0.01    0.01
     1.0     1.0     1.0     1.0     1.0
   0.029   0.029   0.029   0.029   0.029
    0.31    0.12    0.32    0.26    0.20    0.14    0.40    0.48
    0.60    0.60    0.60    0.60    0.60    0.60    0.60    0.60
   0.046   0.060   0.032   0.037   0.046   0.060   0.032   0.037
    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.01
     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0
   0.029   0.029   0.029   0.029   0.029   0.029   0.029   0.029
    0.31    0.12    0.32    0.26    0.20    0.14
    0.60    0.60    0.60    0.60    0.60    0.60
   0.046   0.060   0.032   0.037   0.046   0.060
    0.01    0.01    0.01    0.01    0.01    0.01
     1.0     1.0     1.0     1.0     1.0     1.0
   0.029   0.029   0.029   0.029   0.029   0.029
       1     1.0
    0.08    0.08    0.08    0.08    0.08    0.08    0.08    0.08    0.08
    0.05    0.05    0.05    0.05    0.05    0.05    0.05    0.05    0.05
    13.0    13.0    13.0    13.0    13.0    13.0    13.0    13.0    13.0
    0.08    0.08    0.08    0.08    0.08    0.08
    0.05    0.05    0.05    0.05    0.05    0.05
```

Table B.8 continued

```
    13.0     13.0     13.0     13.0     13.0     13.0
    0.08     0.08     0.08     0.08     0.08     0.08
    0.05     0.05     0.05     0.05     0.05     0.05
    13.0     13.0     13.0     13.0     13.0     13.0
    0.08     0.08     0.08     0.08     0.08
    0.05     0.05     0.05     0.05     0.05
    13.0     13.0     13.0     13.0     13.0
    0.08     0.08     0.08     0.08     0.08     0.08     0.08     0.08
    0.05     0.05     0.05     0.05     0.05     0.05     0.05     0.05
    13.0     13.0     13.0     13.0     13.0     13.0     13.0     13.0
    0.08     0.08     0.08     0.08     0.08     0.08
    0.05     0.05     0.05     0.05     0.05     0.05
    13.0     13.0     13.0     13.0     13.0     13.0
```

Table B.9 GLEAMS estimated nutrient input file for Gilbert Farm watershed.

```
Yoon et al., (1992) Data for Gilbert Farm Watershed 1984-1989
Cotton, 1984-1986-conventional till, 1987-1989 conservation till
Hydrologic soil group B, Nutrient Input File
    1984    1989       0       6       1
  1000.0     0.8     0.0     0.0
    0.08    0.08    0.08    0.08    0.08
   17.85   17.85   17.85   17.85   17.85
   500.0   500.0   500.0   500.0   500.0
   0.076
   0.015   0.015   0.015   0.015   0.015
   7.556    6.56    6.56    6.56    6.56
   0.002
    1001
       0       0    1103
      19          4480.0    1.35    24.0     5.0
    1104
       1       2    1321
      24          2200.0     6.5    80.0     5.8
    1117       0       1
    67.0            49.0    10.0
    1105      12    15.2
    1152       5    10.0
    1322
       1       2    2298
      24          2100.0     6.5    80.0     5.8
    2107       0       1
    67.0            29.0    10.0
    2091       4    15.2
    2152       5    10.0
    2299
       1       2    3317
      24          1600.0     6.5    80.0     5.8
    3097       0       1
    37.0            29.0    10.0
    3091       4    15.2
    3152       5    10.0
    3318
       1       0    4298
      24          1300.0     6.5    80.0     5.8
    4118       0       0
    78.0            25.0     0.0
    4299
       0       0    5091
      51                          75.0     5.7
    5092
       1       0    5301
      24          1270.0     6.5    80.0     5.8
    5105       0       0
    78.0            25.0     0.0
    5302
       0       0    6105
      51                          75.0     5.7
    6106
       1       0    6326
      24          1000.0     6.5    80.0     5.8
    6114       0       0
    78.0            25.0     0.0
       0
```

Table B.10 GLEAMS calibrated hydrology input file for Watkinsville P-2

```
GLEAMS Version 3.0 (NRCS v 3.0.1), calibrated hydrology
Watkinsville, GA, W/S P-2,1973-75  continuous corn w/winter weeds after harvest
Cecil sandy loam (Typic Hapludults)  Hydrologic soil group B
 1973000       0       0       1       0       0       0       1       1       0
    3002

     3.2     .09     .90     3.5      84    .022   1.881    24.0    690.   33.53
       3       5     3.0     6.0    12.0    18.0    24.0
     .43     .43     .40     .40     .43
     .33     .33     .33     .33     .34
     .17     .17      .2      .2     .24
    1.24    1.24    0.49    0.49    0.18
    1.29    1.29    1.00    1.00      .5
     13.     13.     21.     21.     37.
     21.     21.     20.     20.     16.
   53.91   58.68   67.56   75.34   82.30   88.37   90.54   89.67   84.74   75.94
   66.66   57.30
   32.94   35.18   42.86   49.91   57.70   64.79   68.43   67.96   62.69   51.28
   43.31   35.80
    232.    298.    384.    506.    551.    568.    538.    511.    420.    351.
    278.    211.
    362.    382.    385.    374.    321.    309.    295.    281.    304.    312.
    332.    346.
   34.48   35.73   40.49   49.23   59.26   65.50   69.50   68.75   63.75   52.75
   42.50   35.23
    1973    1975       3
      78    0275    1150    1108    12.0

      20    1131    1306            24.0

      78    1307    2150    2113    12.0

      20    2119    2259            24.0

      78    2260    3150    3140    12.0

      20    3141    3276            24.0

      78    3277    4150    4120    12.0

       0
       0       0
       0       0
      -1       0
```

Table B.11 GLEAMS calibrated erosion input file for Watkinsville P-2

```
GLEAMS Version 3.0 (NRCS v 3.0.1), calibrated erosion parameters, Watkinsville, GA,
Watershed P-2, 1973-75  continuous corn with winter weeds after harvest
Cecil sandy loam (Typic Hapludults)  Hydrologic soil group B
    1973    1975       0       3       0
    20.0
       4     3.2
    98.0     .02   125.0     .04   175.0     .03   206.0    .024
       1     1.0     .23
       5       4     2.4    2.25     3.2      .2    20.0
    46.0    .021   102.0    .032   217.0    .014   302.0    .018   371.0    .024
    20.0     .03     .02
       3
     001     108     131     155     180     200     302     309
     113     119     140     160     200     259     268
     114     141     160     200     250     276     288
       1     1.0
     .26     .62     .54     .42     .30     .20     .20     .20
     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0
     .03     .03     .01     .01     .01     .02     .03     .04
     .44     .38     .30     .21     .14     .14     .14
     1.0     1.0     1.0     1.0     1.0     1.0     1.0
    .034    .011    .011    .011    .011    .023    .034
     .05     .05    0.05     .05     .05     .05     .05
     1.0     1.0     1.0     1.0     1.0     1.0     1.0
     .03     .01     .01     .01     .01     .02     .03
       1     1.0
    .065     .04     .03     .03     .03     .03    .065    .065
     .33     .33    -99.   -99.0   -99.0   -99.0   -99.0   -99.0
   -10.0   -99.0   -99.0   -99.0   -99.0   -99.0   -99.0   -99.0
    .074    .046    .034    .034    .034    .034    .074
     .33     .33   -99.0   -99.0   -99.0   -99.0   -99.0
    10.0   -99.0   -99.0   -99.0   -99.0   -99.0   -99.0
    .065     .04     .03     .03     .03     .03    .065
     .33     .33   -99.0   -99.0   -99.0   -99.0   -99.0
   -99.0   -99.0   -99.0   -99.0   -99.0   -99.0   -99.0
```

Table B.12 GLEAMS estimated nutrient input file for Watkinsville P-2

```
GLEAMS Version 3.0 (NRCS v 3.0.1), sample nutrient parameters, Watkinsville, GA
Watershed P-2, 1973-75, continuous corn with winter weeds after harvest.
Cecil sandy loam (Typic Hapludults) Hydrologic soil group B
    1973    1975       1       3       1
  1000.0      .8
    .035    .035    .020    .009    .007
     5.0     5.0     5.0     5.0     5.0
   150.0   150.0   100.0    60.0    30.0
     0.0
    .012    .012    .008    .004    .002
    31.0    31.0     6.0     3.0     2.0
     0.0
    1001
               1    1108
      78          1000.0
    1108      19    20.0
    1109
       2       3    1306
      20          7200.0
    1131       0       1
     0.0    28.0    17.0    15.0     0.0
    1174       0       0
     0.0   112.0     0.0     0.0     0.0
    1131      10    15.0
    1131      22     3.0
    1306      25     0.0     0.0     0.0
    1307
               2    2113
      78          1000.0
    1309      23     0.0     0.0     0.0
    2113      10    15.0
    2114
       2       4    2259
      20          7200.0
    2119       0       1
     0.0    38.0    33.0    15.0
    2162      00       0
     0.0   100.7     0.0     0.0     0.0
    2115       4    20.0
    2119      10    15.0
    2119      22     3.0
    2259      23     0.0     0.0     0.0
    2260
       1       3    3114
      78          1000.0
    3114       0       1
    11.0    11.0    31.0    15.0
    2260      23     0.0     0.0     0.0
    3114      10    15.0
    3114      22     3.0
    3115
       1       1    3276
      20          7200.0
    3176      00       1
     0.0   112.0     0.0     0.0     0.0
    3276      24     0.0     0.0     0.0
```

APPENDIX C: RESULTS FROM SENSITIVITY ANALYSIS

Table C.1 GLEAMS 3.0 average annual output for Belle Mina PL9 data set with changes to fresh organic P (FOP)

Annual Output

FOP is 0 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.23	0.63	0.94	0.55	0.60	1.19	2.49	0.64	2.49	1.09
Sediment PO_4-P (kg/ha)	0.175778	0.32075	0.37216	0.19337	0.87531	0.40288	0.62422	0.87662	0.29828	0.11315	0.43
Sediment Organic P (kg/ha)	2.433223	1.93505	12.365	1.38375	17.0193	2.44523	8.33759	3.99225	4.51876	1.10635	5.55
PO_4-P Leached (kg/ha)	0.140925	0.10839	0.11011	0.10234	0.07411	0.07541	0.10574	0.12358	0.07068	0.13126	0.10
Plant Uptake of P (kg/ha)	36.74269	53.7138	35.2285	54.6305	50.2549	59.7246	29.5485	60.7119	38.9692	57.0996	47.66

FOP is 10 kg/ha (Baseline)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.24	0.64	0.94	0.55	0.60	1.19	2.49	0.64	2.49	1.09
Sediment PO_4-P (kg/ha)	0.18	0.32	0.37	0.19	0.88	0.40	0.63	0.88	0.30	0.11	0.43
Sediment Organic P (kg/ha)	2.44	1.94	12.39	1.39	17.04	2.45	8.35	4.00	4.52	1.11	5.56
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	53.71	34.85	54.63	50.25	59.72	29.07	60.71	38.97	57.10	47.58

FOP is 20 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.24	0.63	0.94	0.55	0.60	1.19	2.49	0.64	2.49	1.09
Sediment PO_4-P (kg/ha)	0.18	0.32	0.37	0.19	0.88	0.40	0.62	0.88	0.30	0.11	0.43
Sediment Organic P (kg/ha)	2.44	1.94	12.40	1.39	17.06	2.45	8.36	4.00	4.53	1.11	5.57
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	53.71	35.23	54.63	50.25	59.72	29.55	60.71	38.97	57.10	47.66

FOP is 50 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.11	1.24	0.82	0.99	0.44	0.60	1.21	2.51	0.64	2.49	1.11
Sediment PO_4-P (kg/ha)	0.18	0.32	0.56	0.20	0.70	0.38	0.64	0.88	0.30	0.11	0.43
Sediment Organic P (kg/ha)	2.41	1.93	12.66	1.42	16.98	2.41	8.34	4.00	4.52	1.11	5.58
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	53.70	35.23	54.49	50.19	59.75	29.32	60.71	38.97	57.10	47.62

FOP is 100 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.11	1.25	0.83	0.99	0.43	0.60	1.21	2.51	0.64	2.49	1.11
Sediment PO_4-P (kg/ha)	0.19	0.32	0.56	0.20	0.69	0.38	0.64	0.88	0.30	0.11	0.43
Sediment Organic P (kg/ha)	2.38	1.93	12.64	1.42	16.98	2.41	8.34	4.00	4.52	1.11	5.57
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.83	53.70	35.23	54.49	50.71	59.75	29.55	60.71	38.97	57.10	47.70

Table C.2 GLEAMS 3.0 average annual output for Belle Mina PL9 data set with changes to fresh organic N (FON)

Annual Output

FON is 0 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.24	0.65	0.94	0.54	0.60	1.18	2.49	0.64	2.49	1.09
Sediment PO_4-P (kg/ha)	0.18	0.32	0.38	0.19	0.87	0.40	0.62	0.88	0.30	0.11	0.43
Sediment Organic P (kg/ha)	2.43	1.94	12.38	1.38	17.02	2.44	8.34	3.99	4.52	1.11	5.55
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	52.45	35.23	54.62	50.71	59.72	29.30	60.71	38.95	57.10	47.55

FON is 20 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.23	0.64	0.94	0.44	0.60	1.22	2.51	0.64	2.50	1.08
Sediment PO_4-P (kg/ha)	0.176085	0.32112	0.3795	0.1932	0.87589	0.40293	0.62457	0.87679	0.29827	0.11315	0.43
Sediment Organic P (kg/ha)	2.435439	1.93732	12.3898	1.38487	17.036	2.4472	8.34598	3.99563	4.52244	1.10711	5.56
PO_4-P Leached (kg/ha)	0.140948	0.10843	0.11011	0.10233	0.0741	0.07539	0.10571	0.12354	0.07066	0.13121	0.10
Plant Uptake of P (kg/ha)	36.7427	53.6763	35.2285	54.6259	50.1899	59.7244	29.3222	60.7119	38.9693	57.0996	47.63

FON is 40 kg/ha (Baseline)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.24	0.64	0.94	0.55	0.60	1.19	2.49	0.64	2.49	1.09
Sediment PO_4-P (kg/ha)	0.18	0.32	0.37	0.19	0.88	0.40	0.63	0.88	0.30	0.11	0.43
Sediment Organic P (kg/ha)	2.44	1.94	12.39	1.39	17.04	2.45	8.35	4.00	4.52	1.11	5.56
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	53.71	34.85	54.63	50.25	59.72	29.07	60.71	38.97	57.10	47.58

FON is 80 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.23	0.64	0.94	0.44	0.60	1.22	2.51	0.64	2.50	1.08
Sediment PO_4-P (kg/ha)	0.18	0.32	0.37	0.19	0.70	0.38	0.64	0.88	0.30	0.11	0.41
Sediment Organic P (kg/ha)	2.44	1.94	12.39	1.39	16.77	2.39	8.28	3.98	4.49	1.10	5.52
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	54.90	35.23	54.64	50.71	59.75	29.30	60.71	38.95	57.10	47.80

FON is 160 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.23	0.82	1.00	0.43	0.60	1.21	2.51	0.64	2.49	1.10
Sediment PO_4-P (kg/ha)	0.18	0.32	0.56	0.20	0.69	0.37	0.64	0.88	0.30	0.11	0.43
Sediment Organic P (kg/ha)	2.44	1.94	12.61	1.42	16.95	2.39	8.32	3.99	4.51	1.10	5.57
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	55.99	35.23	54.52	50.71	59.70	29.30	60.71	38.97	57.10	47.90

Table C.3 GLEAMS 3.0 average annual output for Belle Mina PL9 data set with changes to the P mineralization constant (CMN)

Annual Output

CMN is 0.0000 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.24	0.63	0.94	0.55	0.60	1.18	2.49	0.64	2.49	1.09
Sediment PO_4-P (kg/ha)	0.18	0.32	0.37	0.19	0.87	0.40	0.62	0.88	0.30	0.11	0.42
Sediment Organic P (kg/ha)	2.44	1.94	12.38	1.39	17.04	2.45	8.35	4.00	4.52	1.11	5.56
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	53.70	35.23	54.62	50.71	59.72	29.30	60.71	38.95	57.10	47.68

CMN is 0.0001 kg/ha/d (Baseline)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.24	0.64	0.94	0.55	0.60	1.19	2.49	0.64	2.49	1.09
Sediment PO_4-P (kg/ha)	0.18	0.32	0.37	0.19	0.88	0.40	0.63	0.88	0.30	0.11	0.43
Sediment Organic P (kg/ha)	2.44	1.94	12.39	1.39	17.04	2.45	8.35	4.00	4.52	1.11	5.56
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	53.71	34.85	54.63	50.25	59.72	29.07	60.71	38.97	57.10	47.58

CMN is 0.0005 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.24	0.64	0.94	0.55	0.60	1.19	2.49	0.64	2.50	1.09
Sediment PO_4-P (kg/ha)	0.18	0.32	0.37	0.19	0.87	0.40	0.63	0.88	0.30	0.11	0.43
Sediment Organic P (kg/ha)	2.44	1.94	12.39	1.39	17.04	2.45	8.34	4.00	4.52	1.11	5.56
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	54.87	35.23	54.71	50.71	60.35	29.30	60.71	38.95	57.31	47.89

CMN is 0.0010 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.24	0.64	0.94	0.55	0.60	1.19	2.49	0.64	2.50	1.09
Sediment PO_4-P (kg/ha)	0.18	0.32	0.37	0.19	0.88	0.40	0.63	0.88	0.30	0.11	0.43
Sediment Organic P (kg/ha)	2.44	1.94	12.38	1.39	17.05	2.45	8.34	3.99	4.52	1.11	5.56
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	54.90	35.23	55.22	50.71	60.44	29.30	60.71	39.09	57.97	48.03

CMN is 0.0050 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.23	0.65	0.94	0.56	0.61	1.20	2.63	0.61	2.39	1.09
Sediment PO_4-P (kg/ha)	0.18	0.32	0.38	0.19	0.89	0.40	0.63	0.88	0.29	0.11	0.43
Sediment Organic P (kg/ha)	2.44	1.94	12.39	1.39	17.07	2.44	8.31	3.99	4.49	1.09	5.55
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.11	0.08	0.08	0.11	0.13	0.07	0.14	0.11
Plant Uptake of P (kg/ha)	36.83	58.75	35.24	57.49	50.71	61.64	29.30	60.71	39.09	58.92	48.87

CMN is 0.0075 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.23	0.85	1.00	0.45	0.61	1.28	3.04	0.43	2.38	1.14
Sediment PO_4-P (kg/ha)	0.18	0.32	0.57	0.20	0.71	0.39	0.65	0.89	0.22	0.11	0.42
Sediment Organic P (kg/ha)	2.44	1.94	12.71	1.43	17.04	2.40	8.32	4.01	4.40	1.08	5.58
PO_4-P Leached (kg/ha)	0.14	0.11	0.12	0.11	0.08	0.08	0.11	0.13	0.07	0.14	0.11
Plant Uptake of P (kg/ha)	36.83	60.26	35.24	58.92	50.71	61.64	29.30	61.53	39.09	60.48	49.40

CMN is 0.0100 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.23	0.83	1.00	0.45	0.61	1.28	3.05	0.44	2.39	1.14
Sediment PO_4-P (kg/ha)	0.18	0.32	0.57	0.20	0.72	0.39	0.66	0.89	0.22	0.11	0.42
Sediment Organic P (kg/ha)	2.44	1.94	12.71	1.43	17.03	2.40	8.30	4.00	4.39	1.08	5.57
PO_4-P Leached (kg/ha)	0.14	0.11	0.12	0.11	0.08	0.08	0.11	0.13	0.08	0.14	0.11
Plant Uptake of P (kg/ha)	36.83	61.37	35.24	58.92	50.71	61.64	29.34	61.53	39.09	60.48	49.51

Table C.4 GLEAMS 3.0 average annual output for Belle Mina PL9 data set with changes to the P partitioning coefficient (CPKD)

Annual Output

CPKD = 1, β_p = 0.50	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.03	0.07	0.05	0.18	0.02	0.12	0.03	0.46	0.09	0.28	0.13
Sediment PO_4-P (kg/ha)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sediment Organic P (kg/ha)	2.25	1.55	10.91	1.12	14.77	1.87	6.07	2.65	3.66	0.86	4.57
PO_4-P Leached (kg/ha)	26.03	20.55	24.92	24.36	16.08	16.51	27.86	32.44	17.98	38.25	24.50
Plant Uptake of P (kg/ha)	36.45	52.36	33.46	53.18	49.81	58.93	27.42	58.96	38.09	55.69	46.44

CPKD = 3, β_p= 0.35	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.13	0.53	0.41	0.69	0.16	0.51	0.16	2.12	0.55	1.26	0.65
Sediment PO_4-P (kg/ha)	0.02	0.01	0.01	0.00	0.00	0.02	0.00	0.01	0.01	0.00	0.01
Sediment Organic P (kg/ha)	2.26	1.56	11.01	1.13	14.87	1.90	6.19	2.70	3.72	0.87	4.62
PO_4-P Leached (kg/ha)	10.39	7.99	8.34	8.03	5.64	5.76	8.24	9.83	5.49	10.61	8.03
Plant Uptake of P (kg/ha)	36.45	53.22	34.34	54.64	50.25	59.72	29.36	60.15	38.95	57.10	47.42

CPKD = 5, β_p= 0.24	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.18	0.89	0.70	0.92	0.32	0.66	0.24	2.76	0.80	2.00	0.95
Sediment PO_4-P (kg/ha)	0.03	0.02	0.03	0.01	0.02	0.04	0.01	0.02	0.03	0.00	0.02
Sediment Organic P (kg/ha)	2.28	1.58	11.10	1.14	14.94	1.93	6.28	2.74	3.75	0.88	4.66
PO_4-P Leached (kg/ha)	6.49	4.99	5.12	4.86	3.46	3.54	4.95	5.83	3.31	6.21	4.88
Plant Uptake of P (kg/ha)	36.65	53.66	35.23	54.64	50.25	59.72	29.55	60.71	38.97	57.10	47.65

CPKD = 7, β_p= 0.17	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.21	1.10	0.84	0.98	0.47	0.68	0.29	2.93	0.88	2.39	1.08
Sediment PO_4-P (kg/ha)	0.04	0.04	0.05	0.01	0.03	0.05	0.01	0.05	0.04	0.01	0.03
Sediment Organic P (kg/ha)	2.29	1.60	11.19	1.15	15.00	1.95	6.36	2.79	3.79	0.89	4.70
PO_4-P Leached (kg/ha)	4.72	3.63	3.71	3.50	2.51	2.56	3.57	4.19	2.39	4.46	3.52
Plant Uptake of P (kg/ha)	36.65	53.71	35.23	54.64	50.25	59.72	29.55	60.71	38.97	57.10	47.65

CPKD = 15, β_p= 0.10	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.26	1.78	1.12	1.12	0.89	0.80	0.63	3.26	1.04	3.06	1.40
Sediment PO_4-P (kg/ha)	0.06	0.09	0.11	0.03	0.13	0.10	0.04	0.16	0.08	0.02	0.08
Sediment Organic P (kg/ha)	2.32	1.66	11.48	1.18	15.29	2.01	6.64	2.97	3.89	0.91	4.84
PO_4-P Leached (kg/ha)	2.26	1.74	1.77	1.66	1.19	1.22	1.70	1.99	1.13	2.11	1.68
Plant Uptake of P (kg/ha)	36.74	53.71	35.23	54.63	50.25	59.72	29.55	60.71	38.97	57.10	47.66

CPKD = 182.5, β_p= 0.10 (Baseline)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.24	0.64	0.94	0.55	0.60	1.19	2.49	0.64	2.49	1.09
Sediment PO_4-P (kg/ha)	0.18	0.32	0.37	0.19	0.88	0.40	0.63	0.88	0.30	0.11	0.43
Sediment Organic P (kg/ha)	2.44	1.94	12.39	1.39	17.04	2.45	8.35	4.00	4.52	1.11	5.56
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	53.71	34.85	54.63	50.25	59.72	29.07	60.71	38.97	57.10	47.58

Table C.5 GLEAMS 3.0 average annual output for Belle Mina PL9 data set with changes to the P extraction coefficient (β_p)

Annual Output

β_p is 0.10 (Baseline)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.10	1.24	0.64	0.94	0.55	0.60	1.19	2.49	0.64	2.49	1.09
Sediment PO_4-P (kg/ha)	0.18	0.32	0.37	0.19	0.88	0.40	0.63	0.88	0.30	0.11	0.43
Sediment Organic P (kg/ha)	2.44	1.94	12.39	1.39	17.04	2.45	8.35	4.00	4.52	1.11	5.56
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	53.71	34.85	54.63	50.25	59.72	29.07	60.71	38.97	57.10	47.58

β_p is 0.25	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.11	1.28	0.65	0.97	0.57	0.62	1.22	2.57	0.66	2.57	1.12
Sediment PO_4-P (kg/ha)	0.18	0.33	0.38	0.20	0.90	0.42	0.64	0.90	0.31	0.12	0.44
Sediment Organic P (kg/ha)	2.44	1.95	12.40	1.39	17.07	2.46	8.37	4.02	4.53	1.11	5.57
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	53.71	35.23	54.63	50.25	59.72	29.55	60.71	38.97	57.10	47.66

β_p is 0.50	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.11	1.29	0.66	0.98	0.57	0.63	1.24	2.59	0.66	2.60	1.13
Sediment PO_4-P (kg/ha)	0.18	0.34	0.39	0.20	0.91	0.42	0.65	0.91	0.31	0.12	0.44
Sediment Organic P (kg/ha)	2.44	1.95	12.40	1.39	17.08	2.46	8.37	4.03	4.54	1.11	5.58
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	53.71	35.23	54.63	50.25	59.72	29.55	60.71	38.97	57.10	47.66

β_p is 0.75	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.11	1.29	0.66	0.99	0.57	0.63	1.24	2.60	0.67	2.61	1.14
Sediment PO_4-P (kg/ha)	0.18	0.34	0.39	0.20	0.92	0.42	0.65	0.92	0.31	0.12	0.45
Sediment Organic P (kg/ha)	2.44	1.95	12.40	1.39	17.08	2.47	8.38	4.04	4.54	1.11	5.58
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	53.71	35.23	54.63	50.25	59.72	29.55	60.71	38.97	57.10	47.66

β_p is 1.00	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.11	1.30	0.67	0.99	0.57	0.63	1.24	2.61	0.67	2.61	1.14
Sediment PO_4-P (kg/ha)	0.18	0.34	0.39	0.20	0.92	0.42	0.65	0.92	0.31	0.12	0.45
Sediment Organic P (kg/ha)	2.44	1.95	12.40	1.39	17.08	2.47	8.38	4.04	4.54	1.11	5.58
PO_4-P Leached (kg/ha)	0.14	0.11	0.11	0.10	0.07	0.08	0.11	0.12	0.07	0.13	0.10
Plant Uptake of P (kg/ha)	36.74	53.71	35.23	54.63	50.25	59.72	29.55	60.71	38.97	57.10	47.66

Table C.6 GLEAMS 3.0 average annual output for Belle Mina PL18 data set with changes to fresh organic P (FOP)

Annual Output

FOP is 0 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.49	0.74	1.87	3.26	2.84	0.77	1.01	8.18	1.23	5.59	2.60
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.34	0.02	0.11	0.30	0.28	0.20	0.39
Sediment Organic P (kg/ha)	5.25	0.54	24.87	1.33	26.31	0.29	17.10	2.34	11.59	2.37	9.20
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.01	61.22	48.98	61.68	60.27	61.73	43.63	61.68	52.96	61.73	56.79

FOP is 10 kg/ha (Baseline)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.49	0.74	1.87	3.26	2.84	0.77	1.01	8.18	1.23	5.59	2.60
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.34	0.02	0.11	0.30	0.28	0.20	0.39
Sediment Organic P (kg/ha)	5.25	0.54	24.89	1.33	26.33	0.29	17.11	2.35	11.59	2.37	9.20
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.01	61.22	48.98	61.68	60.27	61.73	43.63	61.68	52.97	61.73	56.79

FOP is 20 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.49	0.74	1.87	3.26	2.84	0.77	1.01	8.18	1.23	5.59	2.60
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.34	0.02	0.11	0.30	0.28	0.20	0.39
Sediment Organic P (kg/ha)	5.25	0.54	24.90	1.33	26.34	0.29	17.12	2.35	11.60	2.37	9.21
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.01	61.22	48.98	61.68	60.27	61.73	43.63	61.68	52.96	61.73	56.79

FOP is 50 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.50	0.74	1.88	3.26	3.03	0.81	1.01	8.12	1.22	5.59	2.61
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.39	0.02	0.11	0.29	0.28	0.20	0.39
Sediment Organic P (kg/ha)	5.21	0.54	24.86	1.33	26.39	0.30	17.10	2.34	11.55	2.36	9.20
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.11	61.22	48.98	61.68	60.30	61.73	43.63	61.68	52.96	61.73	56.80

FOP is 100 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.51	0.76	1.86	3.21	3.04	0.81	1.00	8.12	1.22	5.59	2.61
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.40	0.02	0.11	0.29	0.28	0.20	0.39
Sediment Organic P (kg/ha)	5.18	0.55	25.17	1.33	26.30	0.30	17.09	2.34	11.55	2.36	9.22
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.11	61.22	48.83	61.68	60.30	61.73	44.06	61.68	52.97	61.73	56.83

Table C.7 GLEAMS 3.0 average annual output for Belle Mina PL18 data set with changes to fresh organic N (FON)

Annual Output

FON is 0 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.49	0.74	1.87	3.26	2.84	0.77	1.01	8.18	1.23	5.59	2.60
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.34	0.02	0.11	0.30	0.28	0.20	0.39
Sediment Organic P (kg/ha)	5.25	0.54	24.87	1.33	26.32	0.29	17.11	2.34	11.59	2.37	9.20
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	53.49	61.22	48.98	61.68	60.27	61.73	43.63	61.68	52.96	61.73	56.74

FON is 20 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.49	0.74	1.87	3.26	2.84	0.77	1.01	8.18	1.23	5.59	2.60
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.34	0.02	0.11	0.30	0.28	0.20	0.39
Sediment Organic P (kg/ha)	5.25	0.54	24.88	1.33	26.33	0.29	17.11	2.35	11.59	2.37	9.20
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	53.96	61.22	48.98	61.68	60.27	61.73	43.63	61.68	52.96	61.73	56.78

FON is 40 kg/ha (Baseline)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.49	0.74	1.87	3.26	2.84	0.77	1.01	8.18	1.23	5.59	2.60
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.34	0.02	0.11	0.30	0.28	0.20	0.39
Sediment Organic P (kg/ha)	5.25	0.54	24.89	1.33	26.33	0.29	17.11	2.35	11.59	2.37	9.20
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.01	61.22	48.98	61.68	60.27	61.73	43.63	61.68	52.97	61.73	56.79

FON is 80 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.49	0.74	1.87	3.26	3.03	0.81	1.01	8.12	1.22	5.59	2.61
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.39	0.02	0.11	0.29	0.28	0.20	0.39
Sediment Organic P (kg/ha)	5.25	0.54	24.89	1.33	26.40	0.30	17.11	2.34	11.55	2.36	9.21
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.01	61.22	48.98	61.68	60.30	61.73	43.63	61.68	52.96	61.73	56.79

FON is 160 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.49	0.76	1.83	3.22	2.84	0.77	1.01	8.18	1.23	5.59	2.59
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.34	0.02	0.11	0.30	0.28	0.20	0.39
Sediment Organic P (kg/ha)	5.25	0.55	25.21	1.33	26.35	0.29	17.13	2.35	11.60	2.37	9.24
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.01	61.22	48.98	61.68	60.27	61.73	43.63	61.68	52.96	61.73	56.79

Table C.8 GLEAMS 3.0 average annual output for Belle Mina PL18 data set with changes to the mineralization constant (CMN)

Annual Output

CMN is 0.0000 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.49	0.74	1.87	3.26	2.84	0.77	1.01	8.17	1.23	5.60	2.60
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.34	0.02	0.11	0.30	0.28	0.20	0.39
Sediment Organic P (kg/ha)	5.25	0.54	24.89	1.33	26.33	0.29	17.12	2.35	11.59	2.37	9.20
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.01	61.22	48.98	61.68	60.27	61.73	43.63	61.68	52.96	61.73	56.79

CMN is 0.0001 kg/ha/d (Baseline)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.49	0.74	1.87	3.26	2.84	0.77	1.01	8.18	1.23	5.59	2.60
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.34	0.02	0.11	0.30	0.28	0.20	0.39
Sediment Organic P (kg/ha)	5.25	0.54	24.89	1.33	26.33	0.29	17.11	2.35	11.59	2.37	9.20
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.01	61.22	48.98	61.68	60.27	61.73	43.63	61.68	52.97	61.73	56.79

CMN is 0.0005 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.49	0.74	1.87	3.26	2.98	0.81	1.01	8.12	1.22	5.59	2.61
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.34	0.02	0.11	0.29	0.28	0.20	0.39
Sediment Organic P (kg/ha)	5.25	0.54	24.89	1.33	26.33	0.30	17.08	2.34	11.54	2.36	9.19
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.01	61.22	48.98	61.68	60.30	61.73	43.63	61.68	52.96	61.73	56.79

CMN is 0.0010 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.49	0.74	1.87	3.26	2.98	0.81	0.99	8.13	1.23	5.60	2.61
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.34	0.02	0.10	0.29	0.28	0.20	0.38
Sediment Organic P (kg/ha)	5.25	0.54	24.88	1.33	26.32	0.30	17.06	2.34	11.54	2.36	9.19
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.01	61.22	49.05	61.68	60.30	61.73	43.63	61.68	52.96	61.73	56.80

CMN is 0.0050 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.49	0.74	1.88	3.27	2.98	0.81	0.99	8.17	1.40	5.62	2.63
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.35	0.02	0.10	0.30	0.37	0.20	0.39
Sediment Organic P (kg/ha)	5.25	0.54	24.87	1.33	26.28	0.29	17.01	2.33	11.58	2.35	9.18
PO_4-P Leached (kg/ha)	0.10	0.10	0.10	0.10	0.06	0.07	0.08	0.11	0.05	0.12	0.09
Plant Uptake of P (kg/ha)	54.11	61.68	49.19	61.68	60.90	61.73	43.63	61.68	52.97	61.73	56.93

CMN is 0.0075 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.49	0.80	1.88	3.27	3.04	0.81	0.99	8.18	1.40	5.64	2.65
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.39	0.02	0.10	0.30	0.37	0.20	0.40
Sediment Organic P (kg/ha)	5.25	0.54	24.85	1.33	26.32	0.29	16.99	2.33	11.55	2.35	9.18
PO_4-P Leached (kg/ha)	0.10	0.10	0.10	0.10	0.06	0.07	0.09	0.11	0.06	0.12	0.09
Plant Uptake of P (kg/ha)	54.16	61.68	49.19	61.68	60.90	61.73	44.06	61.68	52.96	61.73	56.98

CMN is 0.0100 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.49	0.81	1.88	3.28	3.05	0.81	1.00	8.21	1.40	5.66	2.66
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.40	0.02	0.10	0.30	0.37	0.21	0.40
Sediment Organic P (kg/ha)	5.25	0.54	24.84	1.33	26.30	0.29	16.96	2.33	11.53	2.34	9.17
PO_4-P Leached (kg/ha)	0.10	0.10	0.10	0.10	0.06	0.08	0.09	0.11	0.06	0.12	0.09
Plant Uptake of P (kg/ha)	54.18	61.68	49.19	61.68	60.90	61.73	44.06	61.68	53.52	61.73	57.03

Table C.9 GLEAMS 3.0 average annual output for Belle Mina PL18 data set with changes to the P partitioning coefficient (CPKD)

Annual Output

CPKD = 1, β_p = 0.50	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO$_4$-P (kg/ha)	0.01	0.42	0.20	0.91	0.35	0.91	0.11	1.60	0.22	1.47	0.62
Sediment PO$_4$-P (kg/ha)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sediment Organic P (kg/ha)	4.96	0.43	22.22	0.98	21.13	0.23	13.65	1.71	9.72	1.90	7.69
PO$_4$-P Leached (kg/ha)	18.73	19.36	23.03	25.35	13.77	16.81	27.87	36.27	16.90	44.10	24.22
Plant Uptake of P (kg/ha)	53.01	60.12	48.27	61.32	60.30	61.21	42.92	60.61	52.76	61.31	56.18

CPKD = 3, β_p= 0.35	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO$_4$-P (kg/ha)	0.01	1.91	1.11	3.10	1.31	3.92	0.49	6.67	1.24	5.39	2.52
Sediment PO$_4$-P (kg/ha)	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.01	0.00	0.01
Sediment Organic P (kg/ha)	4.96	0.44	22.64	1.00	21.39	0.24	13.98	1.75	9.91	1.94	7.83
PO$_4$-P Leached (kg/ha)	7.51	7.43	7.10	7.44	4.54	5.40	6.58	8.81	4.23	9.73	6.88
Plant Uptake of P (kg/ha)	53.01	60.12	49.17	61.68	60.30	61.73	43.63	61.68	52.96	61.73	56.60

CPKD = 5, β_p= 0.24	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO$_4$-P (kg/ha)	0.71	3.18	1.65	3.97	1.86	4.78	0.70	8.63	1.70	7.69	3.49
Sediment PO$_4$-P (kg/ha)	0.07	0.00	0.00	0.01	0.06	0.00	0.01	0.01	0.03	0.01	0.02
Sediment Organic P (kg/ha)	5.04	0.45	22.54	0.99	21.30	0.24	14.02	1.76	9.91	1.94	7.82
PO$_4$-P Leached (kg/ha)	4.70	4.62	4.36	4.49	2.78	3.29	3.87	5.04	2.48	5.48	4.11
Plant Uptake of P (kg/ha)	53.81	61.26	49.17	61.68	60.30	61.73	44.06	61.68	52.96	61.73	56.84

CPKD = 7, β_p= 0.17	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO$_4$-P (kg/ha)	0.77	3.84	2.35	4.20	2.20	4.78	0.93	9.08	1.75	8.62	3.85
Sediment PO$_4$-P (kg/ha)	0.08	0.01	0.02	0.01	0.11	0.01	0.02	0.01	0.05	0.01	0.03
Sediment Organic P (kg/ha)	5.05	0.45	22.58	0.99	21.40	0.24	14.23	1.78	9.98	1.96	7.87
PO$_4$-P Leached (kg/ha)	3.42	3.35	3.16	3.23	2.01	2.38	2.78	3.58	1.78	3.89	2.96
Plant Uptake of P (kg/ha)	53.81	61.26	49.32	61.68	60.30	61.73	43.63	61.68	52.96	61.73	56.81

CPKD = 15, β_p= 0.10	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO$_4$-P (kg/ha)	0.89	5.42	3.50	4.56	3.47	4.61	1.80	10.06	1.58	9.90	4.58
Sediment PO$_4$-P (kg/ha)	0.13	0.02	0.07	0.02	0.34	0.01	0.05	0.03	0.09	0.03	0.08
Sediment Organic P (kg/ha)	5.10	0.48	23.27	1.02	22.02	0.26	14.84	1.84	10.16	2.00	8.10
PO$_4$-P Leached (kg/ha)	1.64	1.59	1.50	1.53	0.96	1.13	1.31	1.67	0.84	1.82	1.40
Plant Uptake of P (kg/ha)	53.91	61.26	49.22	61.68	60.30	61.73	43.63	61.68	52.96	61.73	56.81

CPKD = 182.5, β_p= 0.10 (Baseline)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO$_4$-P (kg/ha)	0.49	0.74	1.87	3.26	2.84	0.77	1.01	8.18	1.23	5.59	2.60
Sediment PO$_4$-P (kg/ha)	0.28	0.03	0.09	0.21	2.34	0.02	0.11	0.30	0.28	0.20	0.39
Sediment Organic P (kg/ha)	5.25	0.54	24.89	1.33	26.33	0.29	17.11	2.35	11.59	2.37	9.20
PO$_4$-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.01	61.22	48.98	61.68	60.27	61.73	43.63	61.68	52.97	61.73	56.79

Table C.10 GLEAMS 3.0 average annual output for Belle Mina PL18 data set with changes to the P extraction coefficient (β_p)

Annual Output

β_p is 0.10 (Baseline)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.49	0.74	1.87	3.26	2.84	0.77	1.01	8.18	1.23	5.59	2.60
Sediment PO_4-P (kg/ha)	0.28	0.03	0.09	0.21	2.34	0.02	0.11	0.30	0.28	0.20	0.39
Sediment Organic P (kg/ha)	5.25	0.54	24.89	1.33	26.33	0.29	17.11	2.35	11.59	2.37	9.20
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.01	61.22	48.98	61.68	60.27	61.73	43.63	61.68	52.97	61.73	56.79

β_p is 0.25	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.50	0.76	1.93	3.36	2.93	0.79	1.05	8.43	1.27	5.77	2.68
Sediment PO_4-P (kg/ha)	0.29	0.03	0.09	0.22	2.41	0.02	0.11	0.31	0.29	0.21	0.40
Sediment Organic P (kg/ha)	5.26	0.54	24.89	1.34	26.40	0.30	17.12	2.35	11.60	2.38	9.22
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.01	61.22	48.98	61.68	60.27	61.73	43.63	61.68	52.96	61.73	56.79

β_p is 0.50	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.51	0.77	1.95	3.39	2.96	0.80	1.06	8.52	1.28	5.83	2.71
Sediment PO_4-P (kg/ha)	0.29	0.03	0.10	0.22	2.44	0.02	0.12	0.31	0.30	0.21	0.40
Sediment Organic P (kg/ha)	5.26	0.54	24.89	1.34	26.43	0.30	17.12	2.36	11.60	2.38	9.22
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.01	61.22	48.98	61.68	60.27	61.73	43.63	61.68	52.96	61.73	56.79

β_p is 0.75	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.51	0.77	1.96	3.41	2.97	0.81	1.06	8.55	1.28	5.85	2.72
Sediment PO_4-P (kg/ha)	0.29	0.03	0.10	0.22	2.45	0.02	0.12	0.31	0.30	0.21	0.40
Sediment Organic P (kg/ha)	5.26	0.54	24.89	1.34	26.44	0.30	17.12	2.36	11.60	2.38	9.22
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.01	61.22	48.98	61.68	60.27	61.73	43.63	61.68	52.96	61.73	56.79

β_p is 1.00	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Average
Runoff PO_4-P (kg/ha)	0.51	0.77	1.96	3.41	2.98	0.81	1.06	8.57	1.29	5.86	2.72
Sediment PO_4-P (kg/ha)	0.29	0.03	0.10	0.22	2.45	0.02	0.12	0.31	0.30	0.21	0.40
Sediment Organic P (kg/ha)	5.26	0.54	24.89	1.34	26.44	0.30	17.12	2.36	11.60	2.38	9.22
PO_4-P Leached (kg/ha)	0.10	0.10	0.09	0.09	0.06	0.07	0.08	0.10	0.05	0.11	0.09
Plant Uptake of P (kg/ha)	54.01	61.22	48.98	61.68	60.27	61.73	43.63	61.68	52.96	61.73	56.79

Table C.11 GLEAMS 3.0 average annual output for Gilbert Farm data set with changes to fresh organic P (FOP)

Annual Output

FOP is 0 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.18	0.04	0.88	1.76	1.64	1.46	1.00
Sediment PO_4-P (kg/ha)	0.04	0.01	0.13	0.20	0.33	0.43	0.19
Sediment Organic P (kg/ha)	0.61	0.49	0.59	0.91	1.45	1.76	0.97
PO_4-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	79.35	32.20	15.09	32.46	25.82	26.61	35.26

FOP is 10 kg/ha (Baseline)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.19	0.06	0.94	1.79	1.65	1.47	1.02
Sediment PO_4-P (kg/ha)	0.04	0.01	0.13	0.21	0.34	0.44	0.19
Sediment Organic P (kg/ha)	0.61	0.50	0.60	0.91	1.46	1.77	0.98
PO_4-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	81.44	32.42	15.22	32.35	25.69	26.50	35.60

FOP is 20 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	ERROR N2: Underflow in Phosphorus initialization						
Sediment PO_4-P (kg/ha)							
Sediment Organic P (kg/ha)							
PO_4-P Leached (kg/ha)							
Plant Uptake of P (kg/ha)							

FOP is 50 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	ERROR N2: Underflow in Phosphorus initialization						
Sediment PO_4-P (kg/ha)							
Sediment Organic P (kg/ha)							
PO_4-P Leached (kg/ha)							
Plant Uptake of P (kg/ha)							

FOP is 100 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	ERROR N2: Underflow in Phosphorus initialization						
Sediment PO_4-P (kg/ha)							
Sediment Organic P (kg/ha)							
PO_4-P Leached (kg/ha)							
Plant Uptake of P (kg/ha)							

Table C.12 GLEAMS 3.0 average annual output for Gilbert Farm data set with changes to fresh organic N (FON)

Annual Output

FON is 0 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.18	0.06	0.92	1.76	1.64	1.46	1.00
Sediment PO_4-P (kg/ha)	0.04	0.01	0.13	0.20	0.33	0.43	0.19
Sediment Organic P (kg/ha)	0.61	0.50	0.59	0.90	1.45	1.76	0.97
PO_4-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	79.13	31.97	14.90	31.86	25.73	26.26	34.98

FON is 20 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.19	0.06	0.94	1.79	1.68	1.48	1.02
Sediment PO_4-P (kg/ha)	0.04	0.01	0.13	0.21	0.34	0.44	0.19
Sediment Organic P (kg/ha)	0.61	0.50	0.60	0.92	1.47	1.78	0.98
PO_4-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	81.45	32.48	15.27	32.07	25.27	26.60	35.53

FON is 40 kg/ha (Baseline)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.19	0.06	0.94	1.79	1.65	1.47	1.02
Sediment PO_4-P (kg/ha)	0.04	0.01	0.13	0.21	0.34	0.44	0.19
Sediment Organic P (kg/ha)	0.61	0.50	0.60	0.91	1.46	1.77	0.98
PO_4-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	81.44	32.42	15.22	32.35	25.69	26.50	35.60

FON is 80 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.26	0.93	0.92	1.54	1.56	1.43	1.11
Sediment PO_4-P (kg/ha)	0.05	0.12	0.13	0.18	0.31	0.43	0.20
Sediment Organic P (kg/ha)	0.63	0.64	0.66	0.92	1.47	1.78	1.01
PO_4-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	81.21	33.37	15.29	32.27	25.33	26.78	35.71

FON is 160 kg/ha	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.27	0.96	0.88	1.56	1.62	1.46	1.12
Sediment PO_4-P (kg/ha)	0.05	0.12	0.13	0.19	0.33	0.43	0.21
Sediment Organic P (kg/ha)	0.63	0.64	0.63	0.86	1.40	1.70	0.98
PO_4-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	80.42	33.31	15.27	32.17	26.06	27.15	35.73

Table C.13 GLEAMS 3.0 average annual output for Gilbert Farm data set with changes to the mineralization constant (CMN)

Annual Output

CMN is 0.0000 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.19	0.06	0.94	1.84	1.69	1.49	1.04
Sediment PO_4-P (kg/ha)	0.04	0.01	0.13	0.21	0.34	0.44	0.20
Sediment Organic P (kg/ha)	0.61	0.50	0.60	0.92	1.47	1.79	0.98
PO_4-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	81.40	32.36	14.91	30.95	25.69	26.33	35.27

CMN is 0.0001 kg/ha/d (Baseline)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.19	0.06	0.94	1.79	1.65	1.47	1.02
Sediment PO_4-P (kg/ha)	0.04	0.01	0.13	0.21	0.34	0.44	0.19
Sediment Organic P (kg/ha)	0.61	0.50	0.60	0.91	1.46	1.77	0.98
PO_4-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	81.44	32.42	15.22	32.35	25.69	26.50	35.60

CMN is 0.0005 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.19	0.06	0.94	1.79	1.61	1.40	1.00
Sediment PO_4-P (kg/ha)	0.04	0.01	0.13	0.21	0.33	0.42	0.19
Sediment Organic P (kg/ha)	0.61	0.50	0.60	0.91	1.45	1.73	0.97
PO_4-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	81.62	32.98	15.77	33.04	27.23	27.22	36.31

CMN is 0.0010 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.27	0.97	0.94	1.54	1.47	1.28	1.08
Sediment PO_4-P (kg/ha)	0.05	0.12	0.14	0.18	0.30	0.39	0.20
Sediment Organic P (kg/ha)	0.63	0.64	0.66	0.91	1.44	1.70	1.00
PO_4-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	81.84	34.30	16.78	33.22	29.09	28.51	37.29

CMN is 0.0050 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.28	1.02	0.97	1.60	1.51	1.27	1.11
Sediment PO_4-P (kg/ha)	0.05	0.13	0.14	0.19	0.31	0.37	0.20
Sediment Organic P (kg/ha)	0.63	0.65	0.68	0.93	1.46	1.66	1.00
PO_4-P Leached (kg/ha)	0.03	0.02	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	83.58	37.47	21.22	34.59	35.89	34.01	41.13

CMN is 0.0075 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.28	1.07	1.00	1.65	1.55	1.30	1.14
Sediment PO_4-P (kg/ha)	0.05	0.13	0.15	0.20	0.31	0.38	0.20
Sediment Organic P (kg/ha)	0.63	0.66	0.69	0.95	1.48	1.69	1.01
PO_4-P Leached (kg/ha)	0.03	0.02	0.02	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	84.60	39.41	23.05	34.86	37.18	34.24	42.22

CMN is 0.0100 kg/ha/d	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.28	1.10	1.03	1.71	1.59	1.34	1.17
Sediment PO_4-P (kg/ha)	0.05	0.14	0.15	0.20	0.32	0.39	0.21
Sediment Organic P (kg/ha)	0.63	0.66	0.70	0.97	1.51	1.72	1.03
PO_4-P Leached (kg/ha)	0.03	0.02	0.02	0.02	0.00	0.00	0.02
Plant Uptake of P (kg/ha)	85.63	41.30	24.88	35.12	37.83	34.44	43.20

Table C.14 GLEAMS 3.0 average annual output for Gilbert Farm data set with changes to the P partitioning coefficient (CPKD)

Annual Output

CPKD = 1, β_p = 0.50	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO$_4$-P (kg/ha)	0.46	0.27	0.92	0.49	0.39	0.81	0.56
Sediment PO$_4$-P (kg/ha)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sediment Organic P (kg/ha)	0.56	0.45	0.38	0.45	0.65	0.67	0.53
PO$_4$-P Leached (kg/ha)	5.10	2.07	1.65	1.46	0.46	0.45	1.87
Plant Uptake of P (kg/ha)	80.88	32.00	17.43	31.55	26.45	27.05	35.89

CPKD = 3, β_p= 0.35	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO$_4$-P (kg/ha)	0.95	0.38	1.97	1.39	0.95	2.05	1.28
Sediment PO$_4$-P (kg/ha)	0.00	0.00	0.01	0.01	0.00	0.02	0.01
Sediment Organic P (kg/ha)	0.56	0.45	0.40	0.48	0.68	0.73	0.55
PO$_4$-P Leached (kg/ha)	1.95	0.80	0.63	0.51	0.16	0.16	0.70
Plant Uptake of P (kg/ha)	82.33	32.47	16.22	32.74	26.03	27.52	36.22

CPKD = 5, β_p= 0.24	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO$_4$-P (kg/ha)	1.01	0.34	2.25	1.53	1.17	2.34	1.44
Sediment PO$_4$-P (kg/ha)	0.01	0.00	0.01	0.01	0.01	0.03	0.01
Sediment Organic P (kg/ha)	0.57	0.45	0.41	0.50	0.72	0.78	0.57
PO$_4$-P Leached (kg/ha)	1.21	0.49	0.39	0.31	0.10	0.10	0.43
Plant Uptake of P (kg/ha)	82.50	32.56	15.81	32.79	25.97	27.94	36.26

CPKD = 7, β_p= 0.17	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO$_4$-P (kg/ha)	0.93	0.30	2.30	1.49	1.25	2.27	1.42
Sediment PO$_4$-P (kg/ha)	0.01	0.00	0.02	0.01	0.01	0.05	0.02
Sediment Organic P (kg/ha)	0.57	0.46	0.42	0.52	0.75	0.82	0.59
PO$_4$-P Leached (kg/ha)	0.88	0.36	0.28	0.23	0.07	0.07	0.31
Plant Uptake of P (kg/ha)	82.48	32.62	15.58	32.86	26.04	28.23	36.30

CPKD = 15, β_p= 0.10	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO$_4$-P (kg/ha)	0.73	0.20	2.35	1.67	1.51	2.01	1.41
Sediment PO$_4$-P (kg/ha)	0.01	0.00	0.04	0.02	0.03	0.08	0.03
Sediment Organic P (kg/ha)	0.58	0.47	0.46	0.58	0.86	0.96	0.65
PO$_4$-P Leached (kg/ha)	0.42	0.17	0.13	0.11	0.03	0.03	0.15
Plant Uptake of P (kg/ha)	82.23	32.65	15.32	32.81	26.53	27.82	36.23

CPKD = 155.0, β_p= 0.10 (Baseline)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO$_4$-P (kg/ha)	0.19	0.06	0.94	1.79	1.65	1.47	1.02
Sediment PO$_4$-P (kg/ha)	0.04	0.01	0.13	0.21	0.34	0.44	0.19
Sediment Organic P (kg/ha)	0.61	0.50	0.60	0.91	1.46	1.77	0.98
PO$_4$-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	81.44	32.42	15.22	32.35	25.69	26.50	35.60

Table C.15 GLEAMS 3.0 average annual output for Gilbert Farm data set with changes to the P extraction coefficient (β_p)

Annual Output

β_p is 0.10 (Baseline)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.19	0.06	0.94	1.79	1.65	1.47	1.02
Sediment PO_4-P (kg/ha)	0.04	0.01	0.13	0.21	0.34	0.44	0.19
Sediment Organic P (kg/ha)	0.61	0.50	0.60	0.91	1.46	1.77	0.98
PO_4-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	81.44	32.42	15.22	32.35	25.69	26.50	35.60

β_p is 0.25	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.19	0.07	0.97	1.85	1.71	1.52	1.05
Sediment PO_4-P (kg/ha)	0.04	0.01	0.13	0.21	0.35	0.45	0.20
Sediment Organic P (kg/ha)	0.61	0.50	0.60	0.92	1.47	1.78	0.98
PO_4-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	81.44	32.44	15.22	32.35	25.71	26.47	35.60

β_p is 0.50	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.20	0.07	0.99	1.87	1.73	1.53	1.06
Sediment PO_4-P (kg/ha)	0.04	0.01	0.14	0.22	0.35	0.46	0.20
Sediment Organic P (kg/ha)	0.61	0.50	0.60	0.92	1.48	1.79	0.98
PO_4-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	81.44	32.44	15.22	32.34	25.71	26.46	35.60

β_p is 0.75	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.20	0.07	0.99	1.88	1.74	1.54	1.07
Sediment PO_4-P (kg/ha)	0.04	0.01	0.14	0.22	0.35	0.46	0.20
Sediment Organic P (kg/ha)	0.61	0.50	0.61	0.92	1.48	1.79	0.98
PO_4-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	81.44	32.44	15.22	32.34	25.71	26.46	35.60

β_p is 1.00	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Average
Runoff PO_4-P (kg/ha)	0.20	0.07	0.99	1.89	1.74	1.54	1.07
Sediment PO_4-P (kg/ha)	0.04	0.01	0.14	0.22	0.35	0.46	0.20
Sediment Organic P (kg/ha)	0.61	0.50	0.61	0.92	1.48	1.79	0.98
PO_4-P Leached (kg/ha)	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Plant Uptake of P (kg/ha)	81.44	32.44	15.22	32.34	25.71	26.46	35.60

Vita

Amelia A. Vincent

Amelia Vincent was born in Baton Rouge, LA. As an undergraduate at Louisiana State University, she participated in the National Science Foundation Research Opportunity for Undergraduates at Virginia Tech during the summer of 1997. In 1998, she participated in the Summer Undergraduate Research Program at Texas A&M University. She graduated Cum Laude from Louisiana State University in the spring of 1999 with a Bachelor's degree in Biological Engineering with a minor in Environmental Engineering. She began work on her Master's Degree at Virginia Tech in the fall of 1999. As a Graduate Research Assistant, she was part of the team that developed the first Virginia Phosphorus Index. She left graduate school in 2002 to work with URS Corporation in Gaithersburg, MD. At URS, Ms. Vincent has worked on a variety of projects including hurricane evacuation and coastal planning, GIS, and terrain development for hydrological and hydraulics modeling.