Comparison of Measured and Simulated Phosphorus Losses with Indexed Site Vulnerability

T. L. Veith, A. N. Sharpley, J. L. Weld, W. J. Gburek

Abstract. *Nonpoint-source losses of agricultural phosphorus (P) at field and watershed scales must be quantified to facilitate selection and placement of P control measures. Quantification of P loss has been pursued through field monitoring, simulation models, and risk assessment indices. However, the intended users of these methods differ, impacting each method's functional design and ease-of-use. For example, the Pennsylvania P Index, a risk assessment tool for planners, requires less discipline-specific knowledge and more readily available data than the Soil and Water Assessment Tool (SWAT), a complex, watershed-level, research-based simulation model. This study compared measured losses of P from the outlet of a 39.5 ha mixed land use watershed (FD-36) in south-central Pennsylvania with watershed-level losses predicted by SWAT. Measured watershed exports of dissolved P (0.06 kg ha^{-1}) and total P (0.24 kg ha^{-1}) during the 7-month sampling period were similar in magnitude to SWAT-predicted losses (0.05 and 0.73 kg ha^{-1}, respectively). Additionally, the study compared field-level P losses predicted by SWAT with field-level vulnerabilities to P loss derived by the P Index. The P Index and SWAT categorized 73% of the 22 fields similarly in terms of vulnerability to P loss, with Pearson correlation significant at p = 0.07; all except one of the remaining six fields were over- or underpredicted by a single risk category. Results indicate that while actual P loss from FD-36 was small, three fields contributed a major proportion of this loss. Additionally, this study suggests that the P Index can provide land managers with a reliable assessment of where P loss occurs within a watershed, thus allowing more effective placement and selection of conservation practices, which lead toward improved downstream water quality.*

Keywords. *Field-scale modeling, Nonpoint source, Pennsylvania Phosphorus Index, Risk, SWAT.*

Phosphorus (P), an essential nutrient for crop and animal production, can accelerate freshwater eutrophication (Carpenter et al., 1998; Sharpley, 2000). Recently, the U.S. Geological Survey (1999) identified eutrophication as the most ubiquitous water quality impairment in the U.S. Water quality concerns such as these have forced states to recommend P-based nutrient management plans and best management practices designed to reduce P losses from agricultural fields (U.S. EPA, 2004). Formulating such recommendations requires information attainable through direct measurement or estimated through simulation models and risk assessment indices (Johnes and Heathwaite, 1997; Sharpley et al., 2002).

Direct measurement of P loadings from field to stream is often limited by site-specific watershed hydrology and land management. Field studies are typically expensive, labor intensive, and require several years in situ to adequately account for climatic fluctuations. Use of simulation models can circumvent most limitations associated with field studies and provide performance-based determinations of best management practices under given watershed location and management scenarios (Gitau et al., 2004; Veith et al., 2004). One such model, SWAT (Soil and Water Assessment Tool), was developed to assess long-term impacts of climate and land management on water quality in watersheds and large river basins (Arnold et al., 1998). Through daily time-step simulations, SWAT predicts water, sediment, and nutrient losses at a watershed outlet and from hydrologic response units within a watershed. Utility of the model has been tested in a variety of large-scale studies (Arnold et al., 1999; Santhi et al., 2001). Simulation models, such as SWAT, however, typically require a substantial amount of detailed spatial and temporal data, as well as expertise in running the model and correctly interpreting the results. Often, farmers and conservation agents require a simpler tool than a simulation model to assess a field's vulnerability to P loss.

In response, the P Index was developed as a practical tool to identify and rank the vulnerability of a site to P loss so that farmers could target remedial best management practices (Lemunyon and Gilbert, 1993). This index, in its current, most general form, is based on the delineation of critical source areas, which are specific, identifiable areas within a watershed that are most vulnerable to P loss in surface runoff (Gburek and Sharpley, 1998). Critical source areas depend on the coincidence of source (functions of soil, crop, and management) and transport factors (runoff, erosion, subsurface, and channel processes) (Sharpley et al., 2001). Source factors relate to fields or watershed areas that have a high potential to contribute to P export. Transport factors translate potential P sources into loss vulnerability from a field or watershed.

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Many studies have evaluated the use of simulation models (e.g., Rosenthal and Hoffman, 1999; Santhi et al., 2001) and P indices (e.g., Weld et al., 2002; Leytem et al., 2003) separately, but none have compared results of field studies and simulations in context of a simpler index-based risk assessment of P loss vulnerability. The objective of this research is to show, by comparing the P Index's portrayal of a watershed with that of SWAT and observed data, that the P Index can provide a simple assessment with a few, easily obtained inputs. Two steps are involved in addressing this objective:

- Compare SWAT estimates of surface hydrology, erosion, and P loss with measured data in a mixed land use watershed.
- Assess the reliability of using the P Index to categorize the potential risk of P loss from fields within a watershed by comparing with SWAT predictions.

METHODS

SITE DESCRIPTION AND MANAGEMENT

The study site, FD-36, is a 39.5 ha subwatershed of Mahantango Creek, a tributary of the Susquehanna River and ultimately the Chesapeake Bay (fig. 1). Soils of FD-36 are classified as Alvira (fine-loamy, mixed, mesic Aeric Fragiaquults), Berks / Calvin (loamy-skeletal, mixed, active, mesic Typic Dystrudepts), Hartleton (loamy-skeletal, mixed, active, mesic Typic Hapludults), and Watson (fine-loamy, mixed, active, mesic Typic Fragiudults). Slopes within FD-36 range from 1% to 25%. Climate is temperate and humid, with average rainfall of 1100 mm year^{-1} and streamflow of 450 mm year^{-1}, based on data collected by USDA-ARS from 1966 to 2004. The encompassing Mahantango Creek watershed is a long-term study site of the USDA-ARS Pasture Systems and Watershed Management Research Unit, with 30 years of climatic and hydrologic data and a progression of research in runoff generation and nutrient movement for this region (Pionke et al., 1999).

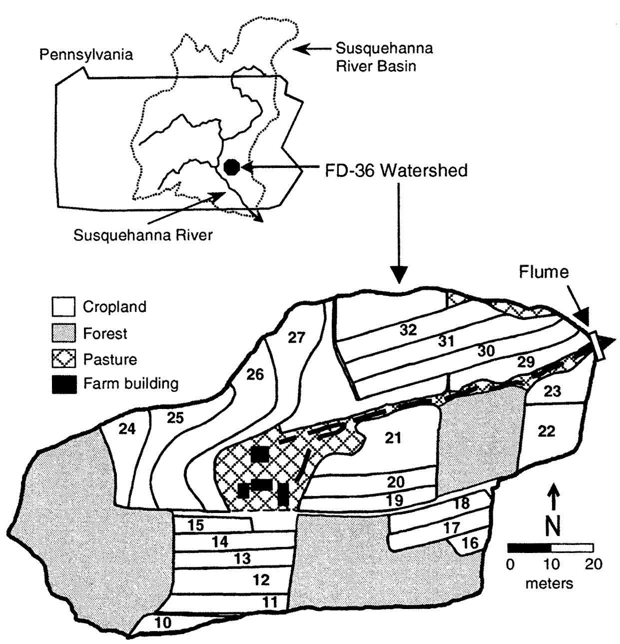

Figure 1. Watershed FD-36, with field boundaries and identification numbers.

Watershed FD-36 is characterized by mixed land use typical of that found in the northeast U.S. (50% soybean, small grain, or corn; 30% forest; 19% pasture; 1% farm buildings) (fig. 1). Information on the management of individual fields was obtained from annual farmer surveys (tables 1 and 2). Fertilizer application ranged from 7 to 66 kg P ha^{-1} year^{-1}, as a function of crop type, while manured fields received swine slurry at 51 or 86 kg P ha^{-1} year^{-1} (table 2).

SAMPLE COLLECTION AND ANALYSES

In July 1996, the watershed was surveyed and topographic elevations were digitized on a 5 m grid. Soil samples (0 to 5 cm depth) were collected in March 1998 and 2000 on a 30 m grid over the watershed. Samples were air dried, sieved (2 mm), and using the standard Pennsylvania soil test method, Mehlich-3 extractable soil P concentration was determined (Mehlich, 1984) (table 2).

Beginning in 1996, streamflow at the watershed outlet was continuously monitored from April 1 to October 31, using a recording H-flume, and storm flow samples for P analysis were taken automatically using a programmable stage activated ISCO sampler. Each year, ISCO samplers were removed from November through March to avoid damage by periodic freezing during these months. For each storm, a 1 L water sample was collected from every 2000 L passing through the flume, and samples were composited to give a single flow-weighted water sample. Baseflow samples were taken at the flume at two-week intervals for subsequent P analysis. All samples were refrigerated at 4°C from collection until analysis.

For all stream samples, a subsample was immediately filtered (0.45 μm) and analyzed within 24 h, and unfiltered

Table 1. Land use and tillage management of fields in FD-36.

Field	Area (ha)	Crop 1998	Crop 1999	Crop 2000	Tillage[a]
10	0.42	Soybean	Corn	Wheat	MTM
11	0.70	Barley	Corn	Barley	MP/DH
12	0.93	Corn	Barley	Corn	MP/DH
13	0.62	Corn	Barley	Corn	MP/DH
14	0.62	Oats	Barley	Hay	MP/DH
15	0.36	Corn	Corn	Corn	MP/DH
16	0.22	Corn	Barley	Corn	MP/DH
17	0.55	Oats	Corn	Corn	MP/DH
18	0.53	Corn	Corn	Barley	MP/DH
19	0.62	Corn	Barley	Corn	MTM
20	0.77	Corn	Corn	Corn	MP/DH
21	1.63	Wheat	Corn	Corn	MP/DH
22	1.00	Corn	Corn	Soybean	C/DH
23	0.61	Corn	Corn	Soybean	C/DH
24	0.79	Corn	Wheat	Corn	MTM
25	1.06	Wheat	Corn	Wheat	MTM
26	2.00	Corn	Corn	Wheat	MTM
27	1.83	Corn	Soybean	Soybean	MTM
29	0.80	Soybean	Corn	Corn	C/DH
30	1.26	Corn	Corn	Wheat	C/DH
31	1.24	Soybean	Wheat	Corn	C/DH
32	1.06	Corn	Soybean	Soybean	C/DH

[a] MTM = minimum tillage mulchmaster.
MP/DH = moldboard plow / disc harrow.
C/DH = chisel / disc harrow.

Table 2. Phosphorus management of fields in FD-36.

Field	Applied P[a] (kg ha^{-1})			Mehlich-3 soil test P[b] (mg kg^{-1})	
	1998	1999	2000	1998	2000
10	25	32	34	178	328
11	20	24	7	183	220
12	48	14	48	235	222
13	20	7	0	210	208
14	20	24	24	217	204
15	24	7	24	208	194
16	24	24	24	473	266
17	20	24	7	396	251
18	24	7	24	419	289
19	25	32	32	310	291
20	25	34	0	250	212
21	23	32	24	194	113
22	86[c]	51[c]	0	71	124
23	86[c]	51[c]	0	39	73
24	25	34	32	298	205
25	48	32	66	416	267
26	25	34	34	369	276
27	25	32	0	172	147
29	0	51[c]	86[c]	113	94
30	86[c]	51[c]	51[c]	178	181
31	0	51[c]	86[c]	276	330
32	86[c]	0	0	200	213

[a] Fertilizer, unless otherwise marked; applied in March or April at planting.
[b] Measured on 0 to 5 cm sample obtained from 30 m grid sampling in March 1998 and 2000.
[c] Manure; broadcast in May or June.

samples were analyzed within 7 d. The concentration of dissolved reactive P (DRP) in streamflow was determined on the filtered subsample. Concentrations of both total dissolved P (TDP) and total P (TP) were determined on filtered and unfiltered runoff samples, respectively, following digestion with a semimicro Kjeldahl procedure (Bremner, 1996). Particulate P (PP) was calculated as the difference between TP and TDP. Phosphorus in all soil extracts, filtrates, and neutralized digests was measured by the colorimetric method of Murphy and Riley (1962).

The suspended sediment concentration of each overland flow event was measured in duplicate as the difference in weight of 250 mL aliquots of unfiltered and filtered (0.45 μm) runoff samples after evaporation (105°C) to dryness.

SWAT Parameterization

Topography, soils, land use, and land management were represented in SWAT in as much detail as provided by measured data using a Geographic Information System (GIS) and the SWAT ArcView interface (AVSWAT2000; Di Luzio et al., 2002). Thus, land use at the field level was further subdivided by soil type to form spatial hydrologic response units in SWAT, which are homogenous in soils, land use, and management. Unique management of each field was maintained by simulating all management changes for each field. Because SWAT represents climatic data and stream output on a daily basis, the corresponding measured data were compiled from sub-hourly into daily values. Evapotranspiration was simulated by SWAT using the Penman-Monteith method (Singh, 1988), and the curve number (USDA-SCS, 1972) option for separating runoff and infiltration was employed.

SWAT predictions for watershed hydrology and sedimentation for 1997 to 2000 were matched as closely as possible to observed data by calibrating several non-measurable parameters of SWAT. In particular, adequately simulating the fragipan soils in FD-36 required calibration of parameters governing water movement between the root zone and aquifers to limit losses to the groundwater and increase soil moisture. Additionally, snowmelt, surface lag, and curve number parameters were adjusted to account for the highly responsive nature of FD-36 surface flow to snowmelt and storm events. The coefficient of determination (R^2) and Nash-Sutcliffe (Nash and Sutcliffe, 1970) statistics and visual comparison were used to compare both daily hydrographs and daily sediment concentrations at the watershed outlet. A validation period was not used, as meeting the study objective required configuring SWAT to the closest possible portrayal of the watershed system over the complete data set of detailed land management and water quality collection (1997 to 2000).

The P Index

The Pennsylvania P Index (Weld et al., 2003) was used in this study, as it encapsulates the major factors consistent among indices developed in the U.S. for determining agricultural P loss (tables 3, 4, and 5; Sharpley et al., 2003). Source factors of the P Index (table 3) include soil test P, fertilizer and manure type, rate, method, and timing of

Table 3. The Pennsylvania P Index: Source factors (Weld et al., 2003).

Contributing Factors	Risk Levels				
	Very Low	Low	Medium	High	Very High
Soil test P risk	Risk value = Mehlich-3 soil test P (mg kg^{-1} P) × 0.20				
Loss rating for P application method and timing	Placed with planter or injected more than 2 in. deep	Incorporated <1 week after application	Incorporated >1 week or not incorporated following application in spring - summer	Incorporated >1 week or not incorporated following application in autumn - winter	Surface applied on frozen or snow-covered soil
	0.2	**0.4**	**0.6**	**0.8**	**1.0**
Fertilizer P risk	Risk value = Fertilizer P application rate (lbs P_2O_5 acre^{-1}) × Loss rating for P application				
Manure P availability	Based on organic P source availability coefficients[a]				
Manure P risk	Risk value = Manure P application rate (lbs P_2O_5 acre^{-1}) × Loss rating for P application × P availability coefficient				
Source factor = Soil test P risk + Fertilizer P risk + Manure P risk					

[a] The appropriate phosphorus availability coefficient to use in developing a nutrient management plan is determined based on the organic P source: 1.0 = swine slurry; 0.9 = layer, turkey, duck, liquid dairy; 0.8 = broiler, bedded pack dairy, beef, biological nutrient removal biosolids; 0.5 = alum-treated manure; 0.4 = alkaline-stabilized biosolids; 0.3 = conventionally stabilized and composted biosolids; and 0.2 = heat-dried and advanced-alkaline stabilized biosolids.

Table 4. The Pennsylvania P Index: Transport factors (Weld et al., 2003).

Characteristics	Risk Levels				
Soil Erosion	Risk value = Annual soil loss = ____________ tons $acre^{-1}$ $year^{-1}$				
Runoff Potential	Very Low **0**	Low **1**	Medium **2**	High **4**	Very High **8**
Subsurface Drainage	None **0**		Random **1**		Patterned[a] **2**
Contributing Distance	>500 ft. **0**	500 to 350 ft. **1**	350 to 250 ft. **2**	250 to 150 ft. **4**	<150 ft. **8**
Transport sum = Erosion + Runoff potential + Subsurface drainage + Contributing distance					
Modified Connectivity	Riparian buffer *Applies to distances <150 ft.* **0.7**		Grassed waterway or none **1.0**	Direct connection *Applies to distances >150 ft.* **1.1**	
Transport factor = Transport sum × Modified connectivity / 22[b]					
P Index = 2 × Source sum + Transport sum					

[a] Or a rapidly permeable soil near a stream.
[b] Transport value is divided by 22 (i.e., the highest value obtainable) in order to normalize transport to a value of 1, where full transport potential is realized

application and are obtained for FD-36 from farm information given in tables 1 and 2. As these factors do not all have the same quantitative effect on P loss, a coefficient of 0.2 is used in the P Index to convert soil test to a value that directly relates to P in manure and mineral fertilizers. This conversion is based on field data that show a five-fold greater concentration of dissolved P in surface runoff with an increase in mineral fertilizer or manure addition as compared to an equivalent increase in Mehlich-3 soil test P (Sharpley and Tunney, 2000).

Transport potential for each site is calculated in the P Index by first summing erosion, surface runoff, subsurface drainage, distance, and connectivity values by methods detailed by Weld et al. (2003) (table 4). The summed value is then divided by 22, the value corresponding to "high" transport potential (i.e., erosion = 6, surface runoff = 8, subsurface drainage = 0, and contributing distance = 8), to determine a relative transport potential. This normalization process assumes that when a site's full transport potential is realized, 100% transport occurs. Thus, transport factors <1 represent a fraction of the maximum potential. However, because erosion is open-ended, it is possible to have a transport factor >1 for extremely high erosion rates.

Table 5. Interpretation of the Pennsylvania P Index ratings with and without consideration of the contributing distance factor.

P Index Rating (Value) With Contributing Distance	P Index Rating (Value) Without Contributing Distance	Interpretation of the P Index
Low (<60)	Low (<22)	LOW potential for P loss. If current farming practices are maintained, there is a low probability of adverse impacts on surface waters. Manure applications are based on N content.
Medium (60 - 79)	Medium (23 - 30)	MEDIUM potential for P loss. The chance for adverse impacts on surface waters exists, and some remediation should be taken to minimize the probability of P loss. Manure applications are based on N content.
High (80 - 100)	High (31 - 39)	HIGH potential for P loss and adverse impacts on surface waters. Soil and water conservation measures and P management plans are needed to minimize the probability of P loss. Manure applications limited to P removed.
Very High (>100)	Very High (>40)	VERY HIGH potential for P loss and adverse impacts on surface waters. All necessary soil and water conservation measures and a P management plan must be implemented to minimize the P loss. No manure is applied.

A final P Index value, representing field vulnerability to P loss, is obtained by multiplying the summed transport and source factors (table 5). Pennsylvania P Index values are normalized so that the break between "high" and "very high" categories is 100, representing an initiative by northeastern and mid-Atlantic states to ensure that P Index guidelines and interpretations are consistent across state boundaries. Normalization is done by calculating the P Index value in which all transport and source factors are assumed to be "high." In the Pennsylvania P Index, erosion is set at 6 ton $acre^{-1}$ and soil test P is set at 200 mg kg^{-1} Mehlich-3 P for the "high" category. Breaks between "medium" and "high" and between "low" and "medium" are calculated with soil test P set at 50 and 30 mg kg^{-1} Mehlich-3 P, respectively. These Mehlich-3 P levels correspond to crop response and fertilizer recommendations for Pennsylvania, where >50 mg kg^{-1} is sufficient for production and no P addition is recommended, 30 to 50 mg kg^{-1} is sufficient where no crop response is expected but maintenance P is recommended, and <30 mg kg^{-1} is insufficient for maximum production and the crop will respond to added P (Beegle, 2004).

Comparison of SWAT Predictions And P Index Rankings

Predicted TP losses and vulnerability to P loss were compared on a field-by-field basis, using SWAT and the P Index. SWAT estimates field edge and in-stream losses but does not currently consider distance-to-stream effects. In contrast, the P Index typically includes distance-to-stream effects to assess vulnerability of field P losses reaching the stream but does not consider in-stream effects. Thus, to conduct a fair comparison at the field edge, Pennsylvania's P Index was modified by removing the contributing distance factor, and the P Index values were renormalized accordingly (table 5).

Phosphorus loss is simulated on a long-term, continuous basis by SWAT, whereas the P Index uses a combination of average annual estimates along with specific estimates corresponding to management within a given year. Thus, annual SWAT-predicted concentrations and yearly P Index rankings were each averaged over a three-year period (1998 to 2000). Fields were then numerically sorted by the SWAT-predicted averages and divided by visual inspection into four ranges: 0 to 1.0, 1.0 to 2.5, 2.5 to 7.0, and >7.0 mg L^{-1} TP. These ranges were used to assign the fields, with respect to each other, into SWAT-predicted groups of "low," "medium," "high," and "very high" risk. Had the TP concentration values suggested grouping into alternate ranges, the alternate ranges would have been used to assign fields to groups. Because the grouping is used simply as an aid for comparing results from the two tools, the group separations have no affect on the correlation between the tools' output values.

Results and Discussion

Watershed Export of P

During the sampling period (April to October) of 1997 to 2000, average rainfall was 639 mm and average measured runoff depth was 161 mm (table 6). The 1997 sampling period was drier than average (74 mm less), while the 1998 season was the wettest of the four (711 mm; 72 mm more than average). Higher rainfall in the 1998 sampling period is reflected in appreciably greater runoff (262 mm) than for the other years (109, 104, and 169 mm for 1997, 1999, and 2000, respectively). However, the greatest average concentration of TP was seen in 2000 (0.31 mg L^{-1}) compared to the other years (0.13, 0.18, and 0.15 mg L^{-1} for 1997, 1998, and 1999, respectively). Average losses of TP from FD-36 over the 7-month sampling period (0.24 kg ha^{-1}) are similar to average annual losses from several watersheds of similar land use (0.39 kg ha^{-1}) in the Piedmont region of the Chesapeake Bay watershed (southeastern Pennsylvania and northern Maryland), as reported by Jordan et al. (1997).

SWAT Predictions

SWAT overpredicted sampled flow at the FD-36 outlet by about 30 mm in both 1997 and 1998 and by 50 mm in 1999 and 2000 (table 6). Comparisons of monthly measured and predicted streamflow during the sampling period resulted in R^2 = 0.63 and Nash-Suttcliffe = 0.75. This is comparable to monthly Nash-Suttcliffe values of 0.71 and 0.75 for watersheds in southwestern Oklahoma (Van Liew and Garbrecht, 2003), 0.56 and 0.79 for a watershed in north-central Texas (Saleh et al., 2000; Santhi et al., 2001), and 0.44 for a watershed in south-central New York (Gitau et al., 2004).

In general for FD-36, because erosion is dependent on flow and SWAT overpredicted flow in the sampling periods of 1997 to 2000, overprediction of sediment during these years was expected. This is seen in 1998 and again in 1999 where mean sediment concentration was overpredicted by 102 mg L^{-1} (13.6 Mg) and 241 mg L^{-1} (16.6 Mg), respectively (table 6). However, sediment was underpredicted for 1997 and 2000. In June 1997, a storm resulted in 13 mm of flow and 5.1 Mg of sediment loss over a two-day period, whereas SWAT only simulated 7 mm of flow and a loss of 0.6 Mg. Similarly, two storms in May 2000, contributing a total of 5 mm of flow and 10.6 Mg of sediment, and a June 2000 storm of 6 mm flow and 4.1 Mg sediment loss were simulated by SWAT as producing 3 mm flow with 0.8 Mg sediment and 8 mm flow with 0.7 Mg sediment, respectively. These discrepancies may reflect erosion occurring during periods of high rainfall intensity, which are not well simulated since SWAT determines storm intensity from daily rain volume. Given the extremely large difference between measured and predicted value for several data points, as discussed above, sediment discharge was statistically not well predicted by SWAT (monthly R^2 = 0.04 and Nash-Sutcliffe = −0.75). In comparison, monthly Nash-Sutcliffe values for sediment reported by other studies include 0.81 and 0.80 for north-central Texas (Saleh et al., 2000; Santhi et al., 2001). The much higher values from these studies in Texas are likely due, in part, to having applied the SWAT model within the climatic region in which it was developed and tested.

Because SWAT currently moves sediment directly from field to stream (Di Luzio et al., 2002) and in-channel stream processes were not modeled for this study, predictions reflect sediment yield from each hydrologic response unit, which is a sub-field area. Thus, discrepancies with measured data are at least partially due to not considering deposition or resuspension of eroded sediment during transport as well as streambed and bank erosion.

Annual predictions of PP and TP concentrations and losses were under- and overpredicted by SWAT following the same pattern as for sediment concentrations and losses; most DRP losses and all concentrations were consistently under−predicted (table 6). Currently, SWAT assumes that P added

Table 6. Measured and SWAT-predicted rainfall, flow, and water quality concentration and losses from FD-36 over the 7-month sampling period (April through October).

Year	Rainfall	Flow		Sediment		Dissolved P		Particulate P		Total P	
		Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.
	(mm)			Mean Concentrations (mg L^{-1}) [a]							
1997	565	109	140	300	45	0.03	0.01	0.10	0.06	0.13	0.07
1998	711	262	288	198	300	0.07	0.04	0.11	0.53	0.18	0.57
1999	609	104	154	102	343	0.07	0.03	0.08	0.51	0.15	0.54
2000	672	169	220	387	126	0.05	0.01	0.26	0.16	0.31	0.17
Average	639	129	160	197	163	0.04	0.02	0.11	0.25	0.15	0.27
				Losses (kg ha^{-1})							
1997				327	63	0.02	0.01	0.08	0.08	0.10	0.09
1998				520	864	0.13	0.12	0.24	1.51	0.37	1.63
1999				106	527	0.03	0.04	0.04	0.78	0.07	0.82
2000				653	277	0.07	0.03	0.36	0.35	0.42	0.38
Average				321	346	0.05	0.04	0.14	0.54	0.19	0.58

[a] Concentrations are flow-weighted using the "Flow" columns, which includes both storm and baseflow.

via fertilizer or manure is assimilated into labile and stable pools of P within one day of application (Arnold et al., 1998). However, land-applied fertilizer and manure can be a major source of DRP in runoff for several weeks after application (Pierson et al., 2001). Thus, the artificially rapid assimilation of applied nutrients into soil P pools in SWAT likely contributes to the underprediction of DRP concentrations and losses.

P Index Ratings

P Index ratings reflect the application of manure during a crop rotation and the proximity of a field to the stream channel. For example, application of swine manure in 1999 (51 kg P ha^{-1}) and 2000 (86 kg P ha^{-1}) to field 31 and consequent 54 mg kg^{-1} increase in soil test P (table 2) led to this field being ranked as "low," "high," and "very high" risk to P loss in 1998, 1999, and 2000, respectively (table 7), even though the field is not located next to the stream (fig. 1). Similarly, the fact that no manure was applied to field 23 in 2000 was reflected in this field's risk declining from "very high" and "high" in the years when manure was applied to "low" in 2000 (tables 2 and 7). However, the sensitivity of field 23's risk of loss by manure management is increased by its bordering the stream (fig. 1). In contrast, soil test P for field 16 declined (207 mg kg^{-1}) between the 1998 and 2000 samplings, despite constant levels of applied P (table 2). This decline is likely due to incorporation and dilution of fertilizer P within the soil profile by plowing (Sharpley, 2003), resulting in the assigned risk for field 16 being reduced from "high" to "low" (table 7).

Comparison of SWAT Predictions and P Index Rankings

Field-level comparisons between SWAT and the P Index, without contributing distance, are shown spatially in figure 2. The correlation between SWAT and the P Index was significant at p = 0.07 without distance consideration (Pearson correlation coefficient = 0.361). When the contributing distance component of the P Index is removed, other components, such as soil test P and erosion potential, have a greater impact on the final P Index value. In particular, field 16 had a very high soil test P value for 1998 (473 mg kg^{-1}) along with a high erosion potential. As a result, the 1998 to 2000 average P Index for this field was "very high" (fig. 2). In contrast, soil P values for a given year in SWAT are determined based on additional factors, such as simulated P pool balances and P inputs in fertilizer and manure for that year. SWAT predicted low losses of P from field 16 (0.27 kg ha^{-1}), thus heavily impacting the overall correlation between the two models. With field 16 removed, the correlation between SWAT and the P Index is significant at p = 0.002 (Pearson correlation coefficient = 0.640).

Figure 3 is a scatter plot of P Index numerical values, without contributing distance, and SWAT-predicted TP loss. Seventy-three percent of fields (16 of 22) were ranked similarly by the two tools, while only 14% (3 each) were either under- or overpredicted. Other than field 16, P Index and SWAT ratings differed by, at most, one ranking category. SWAT overpredicted the P Index "low" category for one field (13), and the P Index "medium" category for two fields (12 and 20). Fields ranked as "high" risk by the P Index were more consistently ranked "high" by SWAT, with SWAT underpredicting only field 25. The "very high" P Index category was underpredicted by SWAT for two of three fields, with field 16 ranked as "low" and field 29 as "high" by SWAT.

For fields with surface-applied nutrients, it was expected that SWAT would tend to predict a lower vulnerability to P loss than would the P Index. This is because of the way,

Table 7. Pennsylvania P Index values and ratings for fields in FD-36, calculated with the contributing distance factor.

Field	P Index Value 1998	P Index Value 1999	P Index Value 2000	P Index Rating 1998	P Index Rating 1999	P Index Rating 2000
10	13	15	25	Low	Low	Low
11	27	27	32	Low	Low	Low
12	38	29	37	Low	Low	Low
13	26	20	15	Low	Low	Low
14	51	50	48	Low	Low	Low
15	36	27	35	Low	Low	Low
16	84	84	55	High	High	Low
17	50	49	31	Low	Low	Low
18	65	55	49	Med.	Low	Low
19	76	83	89	Med.	High	High
20	69	78	35	Med.	Med.	Low
21	81	93	58	High	High	Low
22	107	69	22	V. High	Med.	Low
23	127	80	16	V. High	High	Low
24	37	41	34	Low	Low	Low
25	47	51	46	Low	Low	Low
26	62	67	68	Med.	Med.	Med.
27	41	22	18	Low	Low	Low
29	33	124	199	Low	V. High	V. High
30	138	97	90	V. High	High	High
31	42	89	141	Low	High	V. High
32	75	21	19	Med.	Low	Low

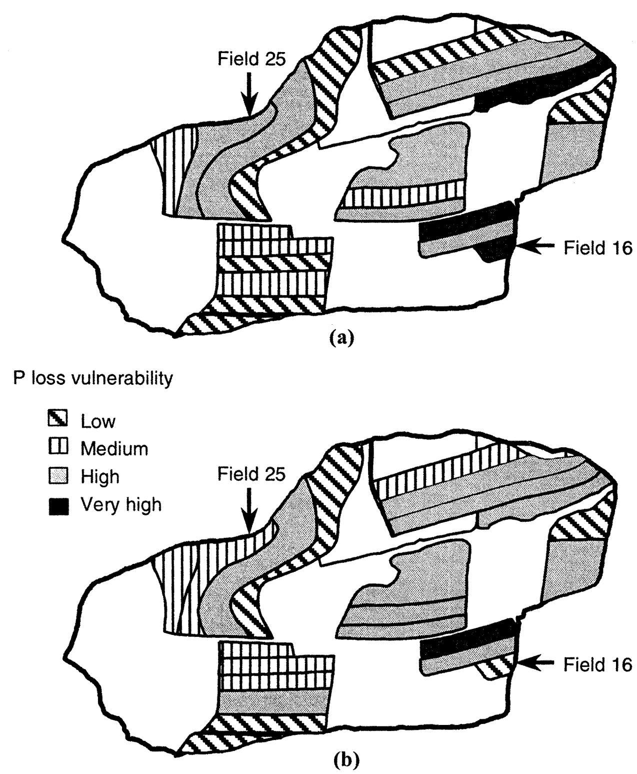

Figure 2. P Index and SWAT ratings for FD-36 reported on a field-by-field basis: (a) P Index ratings without the distance factor, and (b) SWAT ratings.

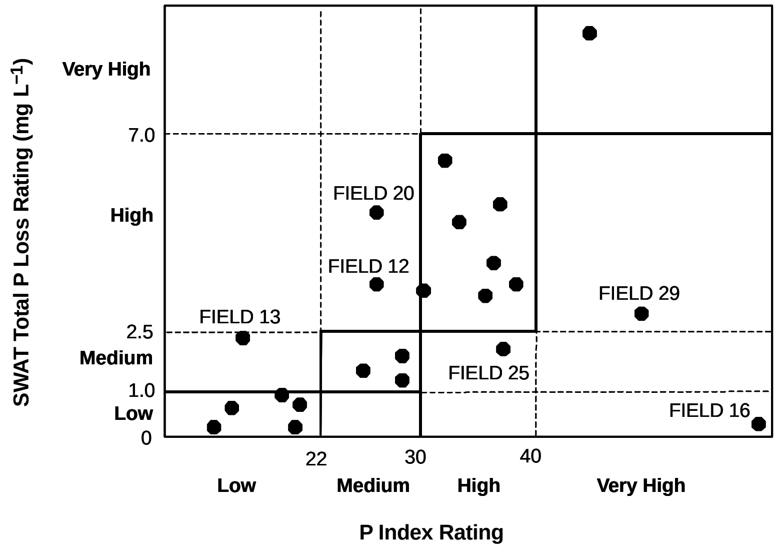

Figure 3. Correlation between P Index and SWAT vulnerability ratings.

previously discussed, in which SWAT currently simulates immediate incorporation of applied fertilizers and manures into the P pools. For example, field 29 (P Index = "very high," SWAT = "high") incurred a major increase in surface application of manure in years 1999 and 2000 as a result of unrelated experimental procedures. If this manure had been incorporated, the 3-year P Index rating, with or without contributing distance, would have been "high," matching the SWAT rating.

Investigation of the management practices on fields 12, 13, and 20 indicated that the overprediction by SWAT, or perhaps underprediction by the P Index, was largely due to a change in nutrient management in one of the three years; i.e., a major increase or decrease in manure application quantity as compared to the other two years. This again demonstrated the design difference between the two tools. Because SWAT is a continuous, event-driven model, predictions are influenced by daily fluctuations in climate and day-to-day management impacts. In contrast, the P Index addresses long-term risk by characterizing annual impacts of management combined with average annual runoff and erosion estimates. For instance, high losses of P that would occur during large, intense rainfall events soon after a tillage operation or P application are not accounted for by the annualized P Index. Similarly, short-term, lower-than-average rainfall and subsequent P loss in runoff would not be reflected in a P Index value or rating but would be captured by SWAT.

These differences do not indicate a failing in either SWAT or the P Index, as both tools clearly operate differently, have different objectives, and were designed to meet the needs of separate users (Sharpley et al., 2002). However, accepting the assumption that SWAT is a decent portrayal of the natural system for FD-36, the overall similarity between SWAT and P Index rankings of field vulnerability to P loss suggests that the P Index can identify and rank relative likelihoods of fields to contribute to P export from their encompassing watershed.

Ease-of-Use for SWAT and P Index

Because SWAT is a complex, daily time-step model and the P Index is a simple, annual risk screening tool, the two techniques differ in the types of input required and how they are obtained (table 8). Input data for SWAT are more detailed, both spatially and temporally, and not as readily available for the farmer or county extension agent as are the data needed for the P Index. When long-term, watershed-specific data are provided and input parameters are adjusted to suit the study area, SWAT is an effective tool for simulating watershed hydrology and studying alternative management scenarios (Santhi et al., 2001; Van Liew and Garbrecht, 2003; Gitau et al., 2004). However, such adjustment is time-consuming and requires modeling experience. The complexity of using a simulation model, such as SWAT, increases the utility of simpler alternatives, such as the P Index, when field assessments of potential vulnerability to P loss are needed. For example, the P Index is an easy-to-use tool for assessing field vulnerability to P loss as required by comprehensive nutrient management planning strategies (U.S. EPA, 2004).

Conclusions

Current methods for accurately measuring field-level nonpoint-source P losses are equipment and labor intensive and, thus limited to individual research fields. Measurements of losses at the watershed outlet are more feasible but remain limited in quantity. Complex watershed-level simulation models, such as SWAT, have been used and accepted by the research community for prediction of losses within and leaving the watershed, particularly when measured data exist for calibration and validation of model parameters. Unfortunately, complex simulation models are also time, data, and expertise intensive.

For many questions of nutrient management planning and risk assessment, the simplicity and accessibility of the P Index approach suggests its use over more complex models, such as SWAT. Categorical agreement between SWAT-predicted and Index-assigned vulnerabilities of P loss for fields in the study watershed suggests the P Index can provide land managers with a reliable assessment of where P loss occurs within a watershed. Consequently, application of the P Index can facilitate adoption and placement of appropriate conservation practices to effectively control

Table 8. Input requirements for SWAT and the Pennsylvania P Index.

Inputs	Source of Information	Determination Method	Reference
	SWAT		
Soil test (optional)	Measurement or farmer records	Mehlich-3 (ppm P)	Mehlich, 1984
Fertilizer/manure N-P-K application rate	Farmer records	Farm management	--
Fertilizer/manure application method	Farmer records	Farm management	--
Land use and management	Farmer records	Farm management	--
Soil properties	Soil survey	GIS	USDA-NRCS, 2003
Topography	Survey or existing databases	GIS	--
Climate	Measurement or existing databases	Data analysis	--
Empirical coefficients	Previous studies, observational knowledge of watershed characteristics	Manual or autocalibration	Van Griensven et al., 2002
	P Index		
Soil test	Measurement or farmer records	Mehlich-3 (ppm P)	Mehlich, 1984
Fertilizer/manure P application rate	Farmer records	Calculated from nitrogen based rate	Beegle, 2004
Fertilizer/manure application method	Farmer records	Farm management	--
Manure P availability	Manure species	Water extractable P	Kleinman et al., 2002
Estimated erosion	Farm conservation plan	RUSLE or USLE	Renard et al., 1997
Runoff potential	Index surface runoff class tables	Saturated conductivity and slope	USDA-NRCS, 2003
Subsurface drainage	Farm conservation plan or farmer records	Presence or absence of drains	--
Contributing distance (distance to water)	Measurement or farm maps	Distance from bottom edge of field	Weld et al., 2003
Connectivity to water	Farm conservation plan or farmer records	Presence or absence of specified management practices	Weld et al., 2003

undesirable sediment and P loss from agricultural watersheds to sensitive surface waters. P Index users can have increased confidence that diligent application of the P Index will ultimately improve downstream water quality.

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