Assessing Site Vulnerability to Phosphorus Loss in an Agricultural Watershed

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ABSTRACT

A P index was developed as a tool to rank agricultural fields on the basis of P loss vulnerability, helping to target remedial P management options within watersheds. We evaluated two approaches, a soil P threshold and components of a P index, by comparing site vulnerability estimates derived from these two approaches with measured runoff P losses in an agricultural watershed in Pennsylvania. Rainfall–surface runoff simulations (70 mm h^{-1} for 30 min) were conducted on 57 sites representing the full range of soil P concentrations and management conditions found in the watershed. Each site was comprised of two, abutting 2-m^2 runoff plots, serving as duplicate observations. For sites that had not received P additions for at least six months prior to the study, Mehlich-3 P concentration was strongly associated with dissolved P concentrations ($r^2 = 0.86$) and losses ($r^2 = 0.83$) in surface runoff, as well as with total P concentration ($r^2 = 0.80$) and loss ($r^2 = 0.74$). However, Mehlich-3 P alone was poorly correlated with runoff P from sites receiving manure within three weeks prior to rainfall. The P index effectively described 88 and 83% of the variability in dissolved P concentrations and losses from all sites in the watershed, and P index ratings exhibited strong associations with total P concentrations ($r^2 = 0.81$) and losses ($r^2 = 0.79$). When site-specific observations were extrapolated to all fields in the watershed, management recommendations derived from a P index approach were less restrictive than those derived from the soil P threshold approach, better reflecting the low P loads exported from the watershed.

Although P inputs are essential to crop and livestock production, P export in runoff can accelerate the eutrophication of receiving fresh waters (Carpenter et al., 1998; Sharpley, 2000). The concentration of crop and livestock production in separate areas of the country has led to accumulations of P in excess of local crop needs (Lander et al., 1998; Lanyon, 2000). Increases in surface soil P concentrations exacerbate P losses in surface runoff and subsurface flow (Hesketh and Brookes, 2000; Pote et al., 1999; Sims et al., 1998). In response to these trends as well as to frequent outbreaks of harmful algal blooms (e.g., *Pfiesteria* and *cyanobacteria*), the USDA and USEPA have developed a joint strategy for sustainable nutrient management (USDA and USEPA, 1999).

Three management options for land application of P are proposed in the new strategy: (i) managing P based upon agronomic soil P thresholds, so that P applications are based on crop needs; (ii) managing P based upon environmental soil P thresholds, by identifying a critical soil P concentration above which runoff P enrichment is unacceptable; and (iii) using a P index to limit P applications on fields at greatest risk for P loss (USDA and USEPA, 1999). Both agronomic and environmental soil P threshold approaches provide narrow, often incomplete, assessments of the risk of P loss, as variables other than soil P concentration control losses from fields and landscapes (Sharpley et al., 1996; Sims, 2000). Illustrating this point, Sharpley and Tunney (2000) found that the dissolved P concentration of surface runoff from 2-m^2 plots using simulated rainfall (50 mm h^{-1} for 30 min; 5-yr return period) varied from 0.20 to 0.49 mg L^{-1} over a 2-ha field. Elsewhere, Pote et al. (1996) measured total P losses of 0.05, 0.16, 0.35 kg P ha^{-1} from three sites with a Mehlich-3 soil test P ranging from only 285 to 295 mg kg^{-1}, due to varying erosion susceptibilities among sites. Thus, the USDA Natural Resources Conservation Service is recommending at a national level that the P index be used in development of P-based nutrient management plans (USDA and USEPA, 1999).

The P index accounts for transport and source factors controlling P loss (Lemunyon and Gilbert, 1993; Gburek et al., 2000). Transport factors include erosion, surface runoff, and subsurface flow, and whether the field is connected and flow contributes to stream discharge. Source factors are soil test P concentration and the form, rate, method, and timing of applied P. Overall, a field is ranked as highly vulnerable to P loss when high P availability due to soil test P concentrations and/or P application in fertilizer or manure coincides with high surface runoff or erosion potential. In some cases, where subsurface P transport is important, preferential flow through soil macropores is also considered as a factor (Leytem et al., 1999).

The P index is intended to serve as a practical screening tool for use by extension agents, watershed planners, and farmers to identify agricultural areas or management practices that have the greatest potential to accelerate eutrophication. As such, the P index identifies alternative management options available to land users, providing flexibility in developing remedial strategies.

The P index was not originally developed as a quantitative predictor of P loss from a watershed. Rather, it was designed to serve as a qualitative assessment tool that ranks site vulnerability to P loss, helping to identify and prioritize P management options. Ultimately, the P index serves as an educational tool that facilitates interaction between planners and farmers, helping to elucidate the water quality implications of management decisions.

Although there is a great deal of research that justifies the transport and source factors included in the P index, there has been little site evaluation of the index ratings. The P index has been used to assess the potential for P loss in several regions including the Delmarva Peninsula (Leytem et al., 1999; Sims, 1996), Oklahoma (Sharpley, 1995), Texas (McFarland et al., 1998), Vermont (Jokela et al., 1997), and Canada (Bolinder et al., 1998). How-

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Abbreviations: RUSLE, Revised Universal Soil Loss Equation.

ever, few comparisons of P index ratings and measured P loss have been made. In Nebraska, Eghball and Gilley (1999) found correlation coefficients between total P loss from simulated rainfall–runoff plots and P index ratings as high as 0.84, when erosion factor weighting was increased from 1.5 to 7.5.

This paper describes a quantitative evaluation of soil P and components of a P index approach to assess site vulnerability to P loss. For each approach, estimates of site vulnerability to P loss were compared with measured losses of P in surface runoff within a mixed–land use watershed in south central Pennsylvania (the FD-36 watershed). In addition, site-specific observations were extrapolated to all fields in the watershed, enabling a watershed-scale comparison of the management implications of both approaches.

MATERIALS AND METHODS

Site Description

The study was conducted on a 39.5-ha subwatershed of Mahantango Creek (FD-36), a tributary of the Susquehanna River and ultimately the Chesapeake Bay (Fig. 1). The watershed is typical of upland agricultural watersheds within the nonglaciated, folded and faulted, Appalachian Valley and Ridge Physiographic Province. Soils of the watershed are classified as Alvira (Aeric Fragiudults), Berks (Typic Dystrudepts), Calvin (Typic Dystrudepts), Hartleton (Typic Hapludults), and Watson (Typic Fragiudults) channery silt loams (Fig. 1 and Table 1). Slopes within the watershed range from 1 to 20%. The climate is temperate and humid: average rainfall is 1100 mm yr^{-1} and stream flow is about 450 mm yr^{-1}.

The watershed is characterized by mixed land use typical of that found in the northeast USA (60% soybean [*Glycine max* (L.) Merr.], wheat [*Triticum aestivum* L.], or corn [*Zea mays* L.]; 10% pasture; 30% woodland). Management of individual fields was obtained from annual farmer surveys (Table 1 and Fig. 2). Fertilizer application ranged from 17 to 77 kg P $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$, as a function of crop type. Manured fields received differing rates, ranging from 25 to 50 Mg $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$ as swine slurry (approximately 67 kg P and 150 kg N $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$ and 112 kg P and 300 kg N $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$, respectively) and 4 Mg $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$ as poultry manure (approximately 150 kg P $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$ and 300 kg N $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$) (Sharpley and Moyer, 2000).

A total of 57 sites in 11 fields were selected for rainfall–surface runoff simulation in FD-36 to represent a range of soil P concentrations (15 to 725 mg kg^{-1} as Mehlich-3 P) and manure applications (Table 1).

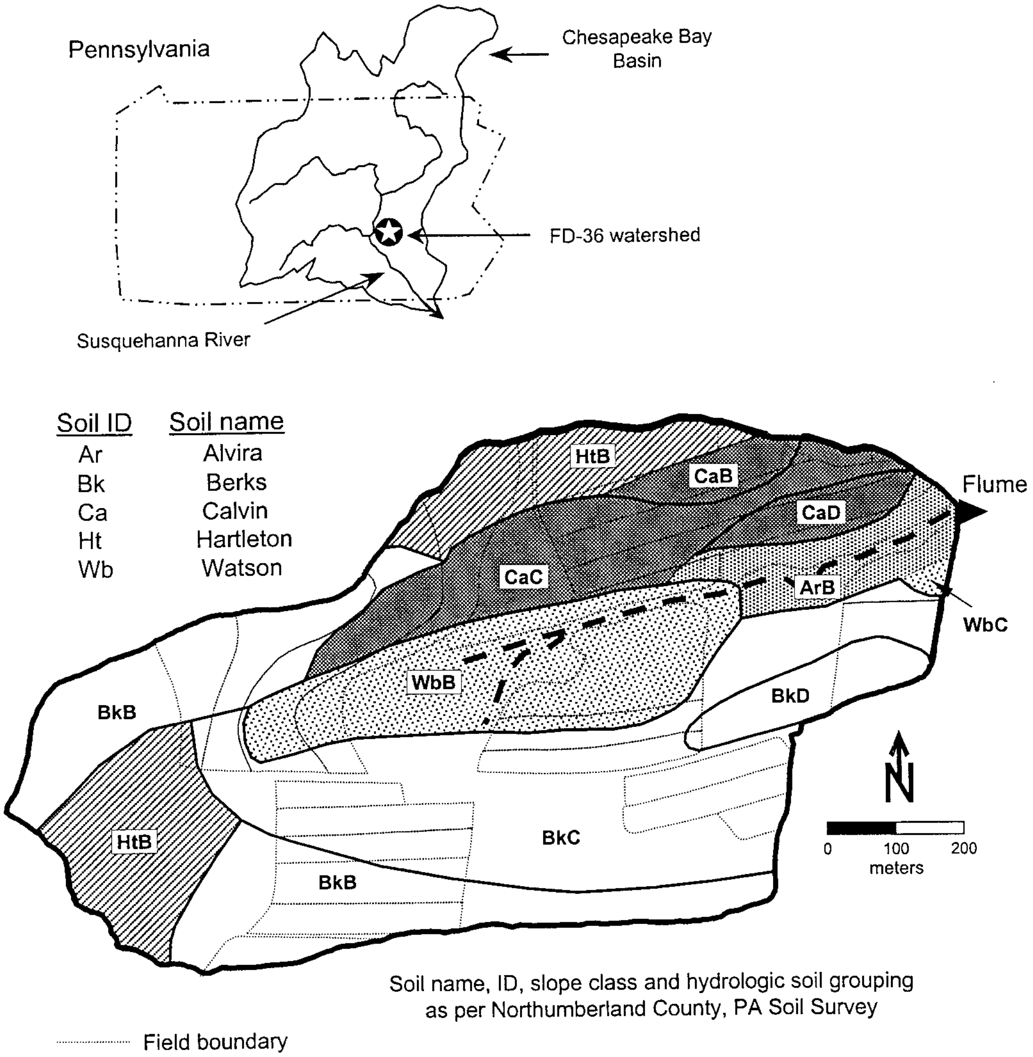

Fig. 1. The FD-36 watershed, soil type distribution, and field boundaries.

Table 1. Land use and P management of the fields in watershed FD-36 for 1999.

Field number†	Crop	Field area	Fertilizer P applied	Fertilizer application method, date	Manure P applied	Manure application method, date	Mehlich-3 soil P‡
		ha	kg ha^{-1}		kg ha^{-1}		mg kg^{-1}
9	*pasture*	*2.41*	*0*		*0*		*25*
10	corn	0.42	56	broadcast, April	0		400
11	barley	0.70	17	broadcast, March	0		220
12	pasture	0.93	0		0		225
13	barley	0.62	17	broadcast, March	0		210
14	corn	0.62	56	broadcast, April	0		210
15	barley	0.36	17	broadcast, March	0		195
16	*corn*	*0.22*	*0*		*150*	*broadcast, April§*	*310*
17	*soybean*	*0.55*	*56*	*broadcast, April*	*0*		*260*
18	*corn*	*0.53*	*0*		*150*	*broadcast, April§*	*305*
19	corn	0.62	73	broadcast, April	0		290
20	*wheat*	*0.77*	*77*	*broadcast, October*	*0*		*220*
21	*corn*	*1.63*	*73*	*broadcast, April*	*0*		*70*
22	*corn*	*1.00*	*0*		*112*	*broadcast, May¶*	*215*
23	*corn*	*0.61*	*0*		*112*	*broadcast, May¶*	*65*
24	corn	0.79	73	broadcast, October	0		200
25	wheat	1.06	73	broadcast, April	0		295
26	*corn*	*2.00*	*77*	*broadcast, October*	*0*		*290*
27	corn	1.83	73	broadcast, April	0		235
28	wheat	1.65	77	broadcast, October	0		92
29	corn	0.80	0		112	broadcast, May¶	225
30	*wheat*	*1.26*	*0*		*112*	*broadcast, May¶*	*180*
31	*corn*	*1.24*	*0*		*67*	*broadcast, April¶*	*370*
32	corn	1.06	0		112	broadcast, May¶	190
33	soybean	1.07	0		67	broadcast, April¶	350

† Refer to Figure 1. Fields in italic type are those in which rainfall–surface runoff simulations were conducted.
‡ Mehlich-3 extractable soil P measured on a 0- to 5-cm sample obtained from a 30-m grid sampling (Gburek et al., 2000).
§ Poultry manure applied.
¶ Swine slurry applied.

Surface Runoff Sites and Rainfall Simulation

Surface runoff sites were comprised of two abutting plots, each 1 by 2 m, with the long axis orientated down the slope (Fig. 3). At each site, the abutting plots were considered replicate observations and data from the two plots were averaged to give a single site value. Soil slope was measured at each plot location and used in the calculation of erosion and surface runoff factors of the P index (Table 2). Metal borders were installed 5 cm above and below ground level to isolate surface runoff, which was diverted by a downslope gutter to a collection vessel. A representative surface soil sample (0–5 cm depth) was obtained after rainfall simulation by collecting 10 cores (2.5-cm diameter) from within each plot. Soil cores were air-dried and sieved (2 mm), and equal amounts were combined and thoroughly mixed to give a representative bulk soil sample for each plot.

Simulated rainfall was applied to each plot with one TeeJet 1/2HH-SS50WSQ[1] nozzle (Spraying Systems Co., Wheaton, IL) approximately 245 cm above the soil to achieve terminal velocity (Miller, 1987; Sharpley et al., 1999a) (Fig. 3). The nozzle, associated plumbing, in-line filter, pressure gauge, and electrical wiring were mounted on a 305- × 305- × 305-cm aluminum frame, fitted with canvas walls to provide a windscreen. Local ground water was used as the water source for the simulator, having a dissolved reactive P concentration of <0.01 mg L^{-1}, nitrate N of 3.1 mg L^{-1}, and pH of 5.7.

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[1] Mention of trade names does not imply endorsement by the USDA.

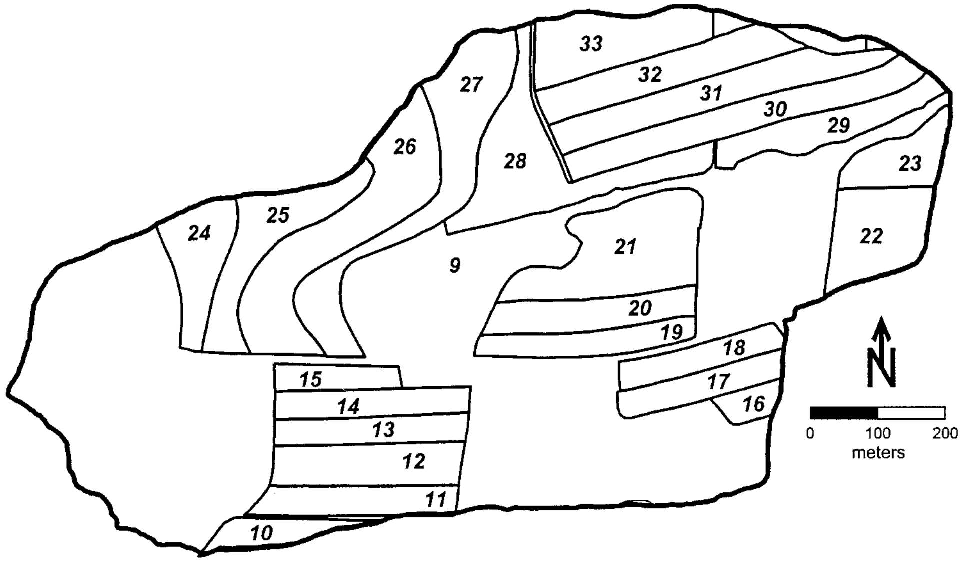

Fig. 2. The FD-36 field boundaries and identification numbers.

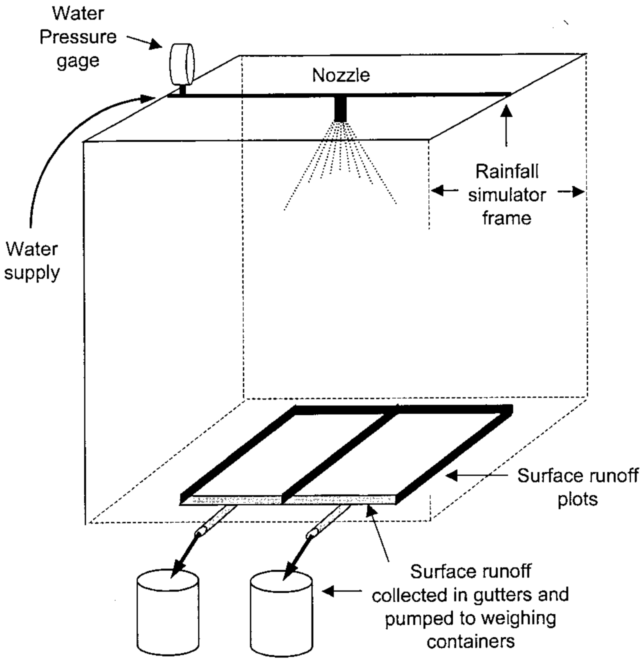

Fig. 3. Plan of the portable rainfall simulator, showing paired 1- by 2-m surface runoff plots, and water collection system. The nozzle is situated approximately 245 cm above the plots.

Water pressure at the nozzle was regulated to 28 kPa (4.1 psi) to establish a water flow rate of 126 mL s^{-1} through the nozzle. Shelton et al. (1985) found that this pressure gave the best coefficient of uniformity and produced drops with size, velocity, and impact energies approximating natural rainfall. For the simulator used in the present study, a coefficient of uniformity of 85% was obtained for rainfall over the 2-m^2 footprint of the abutting plots. A rainfall intensity of 70 mm h^{-1} for 30 min after runoff initiation was used. This rainfall intensity and duration has an approximate 10-yr return frequency in southcentral Pennsylvania. Three simulated rainfall events were applied, with data presented in this paper representing the average of flow-weighted concentrations for each of the three events.

Surface runoff was collected in metal gutters at the downslope edge of each plot and pumped to 200-L (50-gallon) plastic containers. Total surface runoff was measured by weighing the containers. A runoff sample was collected from each container after thorough mixing and agitation, and a subsample immediately filtered (0.45 μm) and stored at 4°C. Filtered samples were analyzed within 24 h of collection and unfiltered samples no more than 7 d after the completion of the rainfall simulation. All methods used in plot design and installation, rainfall simulation and runoff collection, and analysis follow protocols detailed in the National Phosphorus Research Project (2001).

Table 2. Soil properties used to calculate the P transport parameters.

Soil type	Map symbol	*K* factor†	Slope	Permeability
			%	cm h^{-1}
Alvira	**ArB**	**0.30**	**3–8**	**0.15–0.50**
Berks	**BkB**	**0.20**	**3–8**	**1.50–15.0**
	BkC	**0.20**	**8–15**	**1.50–15.0**
	BkD	**0.20**	**15–25**	**1.50–15.0**
Calvin	**CaB**	**0.20**	**3–8**	**5.0–15.0**
	CaC	**0.20**	**8–15**	**5.0–15.0**
	CaD	**0.20**	**15–25**	**5.0–15.0**
Hartelton	**HtB**	**0.20**	**3–8**	**1.5–15.0**
Watson	**WbB**	**0.27**	**3–8**	**0.15–0.5**
	WbC	**0.27**	**8–15**	**0.15–0.5**

† *K* factor for Revised Universal Soil Loss Equation (RUSLE).

Rainfall–surface runoff simulations were conducted between April and November 1999. For sites in fields where manure had been applied, simulations were conducted within three weeks of manure application. All other simulations were conducted in fields where no P had been applied in the last six months. The timing of the simulations was designed to distinguish between the effects of soil P and applied manure on runoff P, as well as the ability of the two site assessment approaches (soil P and P index) to represent these effects.

Chemical Analyses

Mehlich-3 soil P concentration was determined by extraction of 1 g soil with 10 mL of 0.2 *M* CH_3COOH, 0.25 *M* NH_4NO_3, 0.015 *M* NH_4F, 0.013 *M* HNO_3, and 0.001 *M* EDTA for 5 min (Mehlich, 1984). The concentration of dissolved reactive P (subsequently referred to dissolved P) in surface runoff was determined for a 0.45-μm filtered sample. The concentration of both total dissolved and total P was determined on filtered and unfiltered runoff samples, respectively, following digestion with a semimicro Kjeldahl procedure (Bremner and Mulvaney, 1982). Phosphorus in all filtrates and neutralized extracts and digests was measured by the colorimetric method of Murphy and Riley (1962). Particulate P was calculated as the difference between total P and total dissolved P. The suspended sediment concentration of each surface runoff event was measured in duplicate as the difference in weight of 250-mL aliquots of unfiltered and filtered runoff samples after evaporation (105°C) to dryness.

The Phosphorus Index

Site vulnerability to P loss in runoff is assessed by selecting rating values for a variety of transport (Table 3) and source factors (Table 4). We derived site vulnerability ratings by applying a P index developed for Pennsylvania to runoff plots in FD-36 based upon the following transport and source factors.

Transport Factors

The soil erosion factor for each site was calculated using the Revised Universal Soil Loss Equation (RUSLE) and published soil survey information (Table 2). The use of RUSLE, as opposed to observed erosion in runoff water, differs from the approach of Sharpley (1995) and Eghball and Gilley (1999), who employed actual erosion measurements to overcome error associated with RUSLE. As such, soil erosion estimates used for this study better reflect the estimates that would actually be derived by crop consultants, extension agents, and farmers applying a P index to agricultural fields.

Surface runoff class was assigned from the relationship between soil permeability class and slope detailed in the Soil Survey Manual (Soil Survey Staff, 1993) (Tables 2 and 5). Subsurface transport of P in FD-36 was assumed to be small relative to transport in surface runoff (Sharpley et al., 1999b), and index values for leaching potential were set at low (i.e., zero, Table 3). As the connectivity to the stream channel could not be assessed for surface runoff generated by the rainfall simulator, we assumed that all sites were connected to the channel and contributed equally to stream flow (i.e., connectivity factor was set at 8 for all sites, Table 3).

To calculate transport potential for each site, erosion, surface runoff, leaching potential, and connectivity values were first summed (Table 3). Dividing this summed value by 23, the

Table 3. Phosphorus loss potential due to transport characteristics in the P index.

Transport factor	Relative ranking					Field value
Soil erosion	Soil loss (Mg ha^{-1} yr^{-1})					__________
Surface runoff class	0 Very Low	1 Low	2 Medium	4 High	8 Very High	__________
Leaching potential	0 Very Low	0 Low	1 Medium	2 High	4 Very High	__________
Connectivity	0 Not Connected†	1	2 Partially connected‡	4	8 Connected§	__________
	Total site value (sum of erosion, surface runoff, leaching, and connectivity values):					__________
	Transport potential for the site (total value/23)¶:					__________

† Field is far away from water body. Surface runoff from field does not enter water body.
‡ Field is near, but not next to water body. Surface runoff from the field sometimes enters water body (e.g., during large, intense storms).
§ Field is next to a body of water. Surface runoff from field always enters water body.
¶ The total site value is divided by a high value (23).

value corresponding to high transport potential (i.e., erosion is 7, surface runoff is 8, leaching potential is 0, and connectivity is 8), a relative transport potential was determined. Erosion of 7 Mg ha^{-1} is considered a high value for Pennsylvania (Natural Resources Conservation Service, 1994). This normalization process assumes that a site's full transport potential is realized when the value is 1. Transport factors <1 represent a fraction of the maximum potential (Table 3).

Source Factors

Calculation of source factors of the P index are based on the Mehlich-3 P concentration of surface soil samples collected at each site and P application as fertilizer or manure as determined from annual farmer surveys (Tables 1 and 4). The correction factor of 0.2 for soil test P is based on field data from the FD-36 watershed, which showed a fivefold greater concentration of dissolved P in surface runoff with an increase in fertilizer or manure addition compared with an equivalent increase in Mehlich-3 P (Sharpley and Tunney, 2000).

Phosphorus Index Value of a Site

A P index value, representing cumulative site vulnerability to P loss from each site, is obtained by multiplying summed transport and source factors (Table 6). Phosphorus index values are then normalized so that the division between high and very high categories is 100. This is done by calculating a site P index value, with all transport and source factors set as high. Specifically, erosion was set at 7 Mg ha^{-1}, considered a high value for Pennsylvania, and soil test P was set at 200 mg Mehlich-3 P kg^{-1}, proposed as a non–site specific threshold for Pennsylvania (Beegle, 1999; McDowell and Sharpley, 2001; also see Fig. 4).

The divisions between low to medium, and between medium to high, are calculated using the same method as for the high–very high break, with soil test P concentrations of 30 and 50 mg Mehlich-3 P kg^{-1}, respectively. These Mehlich-3 P levels correspond to crop response and fertilizer recommendations for Pennsylvania, with 65 mg kg^{-1} sufficient for production and no response to added P and 15 mg kg^{-1} the low value (Beegle, 1999).

Statistical Analyses

The relationship and change point between the dissolved P concentration of surface runoff and Mehlich-3 soil P concentration were determined using a split-line model that describes two linear relationships whose slopes are significantly different

Table 4. Phosphorus loss potential due to source and management practices in the P index.

Source factor	Relative ranking					Field value
Soil test P (STP)	Mehlich-3 extractable soil P (mg P kg^{-1} soil)					
STP rating value	Soil test P × 0.2					__________
Fertilizer P rate	Fertilizer rate (kg P ha^{-1})					
P fertilizer application method and timing	Placed with planter or injected >5 cm deep	Incorporated <1 week after application	Incorporated >1 week or not incorporated following application in late spring to early autumn	Incorporated >1 week or not incorporated following application in late autumn to early spring	Surface applied on frozen or snow covered soil	
Fertilizer rating value	0.2	0.4	0.6	0.8	1.0	
	Fertilizer P application rate × Loss rating for fertilizer P application method and timing					__________
Manure P rate	Manure application (kg P ha^{-1})					
P manure application method and timing	Placed with planter or injected >5 cm deep	Incorporated <1 week after application	Incorporated >1 week or not incorporated following application in late spring to early autumn	Incorporated >1 week or not incorporated following application in late autumn to early spring	Surface applied on frozen or snow covered soil	
Manure rating value	0.2	0.4	0.6	0.8	1.0	
	Manure P application rate × Loss rating for manure P application method and timing					__________
	Total source value (sum of soil, fertilizer, and manure P loss rating values):					__________

Table 5. The surface runoff class site characteristic determined from the relationship between soil permeability and field slope (data adapted from Soil Survey Manual, 1993).

	Soil permeability class, $cm\ h^{-1}$†				
	Very rapid	Moderately rapid and rapid	Moderately slow and moderate	Slow	Very slow
Slope, %	>50.0	50.0–15.1	15.0–0.51	0.5–0.15	<0.15
	Runoff class				
Concave	Negligible	Negligible	Negligible	Negligible	Negligible
<1	Negligible	Negligible	Negligible	Low	Moderate
1–5	Negligible	Very Low	Low	Moderate	High
5–10	Very Low	Low	Moderate	High	Very High
10–20	Very Low	Low	Moderate	High	Very High
>20	Low	Moderate	High	Very High	Very High

† Permeability class of the least permeable layer within the upper 1 m of the soil profile. Permeability classes were obtained form published soil surveys.

from each other (at $p < 0.05$) on either side of a threshold (McDowell et al., 2001; McDowell and Sharpley, 2001). Below the threshold:

$$\text{Dissolved P} = m_1(\text{Mehlich-3 P}) + c \qquad [1]$$

and above the threshold:

$$\text{Dissolved P} = m_1(\text{Mehlich-3 P}) + m_2(\text{Mehlich-3 P} - \text{Mehlich-3 P threshold}) + c \qquad [2]$$

where c is the intercept, m_1 is the slope of the linear relationship for values of Mehlich-3 extractable soil P less than the threshold, and m_2 is the difference in slopes after the threshold compared with m_1. The four parameters (m_1, m_2, Mehlich-3 P threshold, and c) were estimated by nonlinear regression, using the method of maximum likelihood in Genstat v5.0 (Genstat 5 Committee, 1995). In general, the standard error of the threshold was 10% or less. Hence, the estimates are reasonably precise. This can be attributed to the simple nature of the model to which all data points contribute toward the generation of the two slopes and where they meet to yield the threshold. A simple exponential regression was also used to describe the dissolved P − Mehlich-3 soil P concentration. In all cases, more variance (r^2) was accounted for by fitting the split-line model than by a simple linear regression. All additional analyses (e.g., mean and standard error) were calculated using SPSS v10.0 (SPSS, 1999).

RESULTS AND DISCUSSION

Relating Surface Runoff Phosphorus and Mehlich-3 Phosphorus

The concentration of dissolved and total P in surface runoff from plots located in fields that had not been fertilized or manured in the last six months was related to Mehlich-3 soil P concentration (Fig. 4). This curvilinear relationship (solid line of Fig. 4) could also be described by two linear relationships, which intersect at a Mehlich-3 soil P concentration of 202 mg kg^{-1} for dissolved P and 206 mg kg^{-1} for total P (dashed lines of Fig. 4). Although both models accurately describe the dependance of surface runoff P on soil P concentration, the split-line model does identify a threshold, above which the increase in P concentration of surface runoff is greater per unit increase in Mehlich-3 P than below the threshold (Fig. 4). Mehlich-3 P values for both thresholds are similar to the soil P threshold proposed for Pennsylvania (200 mg kg^{-1}; Beegle, 1999).

The similar relationship between dissolved and total P concentration of surface runoff and Mehlich-3 soil P concentration (Fig. 4) is due to the fact that dissolved P represented the major proportion of total P transported in surface runoff from most sites (an average

Table 6. Worksheet and generalized interpretation of the P index and manure management.

P index rating for a site = (transport potential value × site management value) × 0.7†	
P index	Interpretation of the P index
Low <35	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 35–70	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 71–100	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 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.

† 0.7 (100/145) is the value to normalize the break between high and very high to 100. The value of 145 is derived as:
Transport value (23/23; i.e., 1.0)
  Erosion is 7 Mg ha^{-1} hr^{-1}: 7
  Surface runoff class is very high: 8
  Field is connected: 8
Site management (145)
  Soil test P is 200: 40
  Fertilizer P application is 30 kg P ha^{-1}: 30
  Manure P application is 75 kg P ha^{-1}: 75

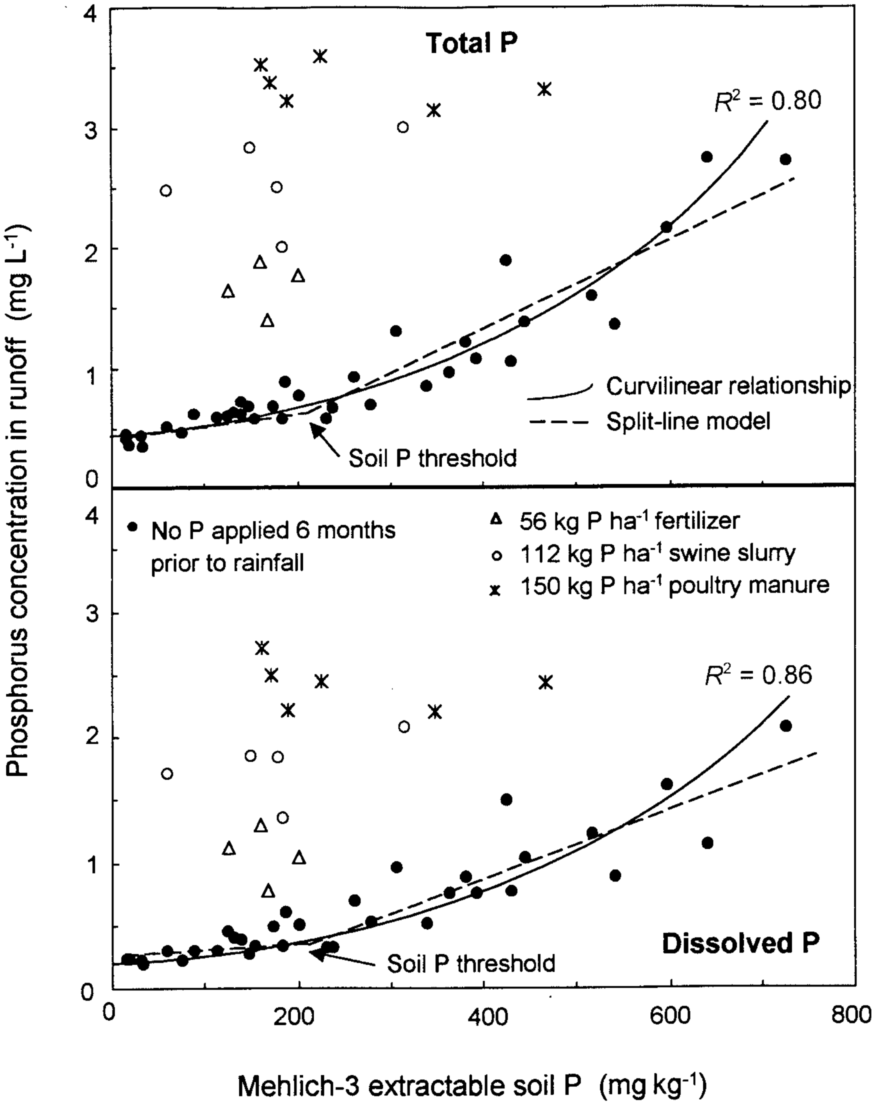

Fig. 4. Relationship between the concentration of dissolved and total P in surface runoff and Mehlich-3 extractable soil P concentration for sites in fields where no P had been applied within the last six months and where fertilizer or manure had been applied within three weeks of rainfall in FD-36 watershed. Regression equations and corresponding coefficients apply only to plots not having received P in the last six months.

64%). This was the case even though measured erosion ranged from 2 to 10 Mg ha^{-1} and RUSLE estimated that 20% of the sites were above the high P index value of 7 Mg ha^{-1}. The above differences in erosion among sites contributed to a lower correlation coefficient for Mehlich-3 P concentration and total P ($R^2 = 0.80$) than dissolved P ($R^2 = 0.86$) (curvilinear model of Fig. 4).

The concentration of dissolved and total P in surface runoff was not related to Mehlich-3 soil P for fields that had received P as fertilizer or manure within three weeks of rainfall simulation ($p > 0.05$; Fig. 4). As expected, both dissolved and total P concentrations in runoff increased with increasing rates of applied P. The average dissolved P concentration in runoff was 1.06 mg L^{-1} from sites receiving 56 kg P ha^{-1} (as triple superphosphate), 1.76 mg L^{-1} P from sites receiving 112 kg P ha^{-1} (as swine slurry), and 2.42 mg L^{-1} from sites receiving 150 kg P ha^{-1} (as poultry manure). Average total P concentrations from these sites were 1.67, 2.56, and 3.36 mg L^{-1}, respectively (Fig. 4).

As with P concentrations, the loss of dissolved and total P in surface runoff from sites not recently fertilized or manured was related to Mehlich-3 soil P concentration (data not presented). However, correlation coefficients were consistently lower for P loss than for concentration, due to the variability in surface runoff volume among sites (8–70 L event^{-1}). For example, correlation coefficients for Mehlich-3 P and dissolved and total P concentration were 0.86 ($y = 0.23e^{0.0031x}$) and 0.80 ($y = 0.42e^{0.0027x}$), respectively, while coefficients for dissolved and total P loss were 0.60 ($y = 29.78e^{0.0039x}$) and 0.55 ($y = 54.15e^{0.0031x}$), respectively (Fig. 4).

Ranking Site Vulnerability to Phosphorus Loss

Phosphorus index ratings for each site were closely related to both concentration and loss of dissolved and

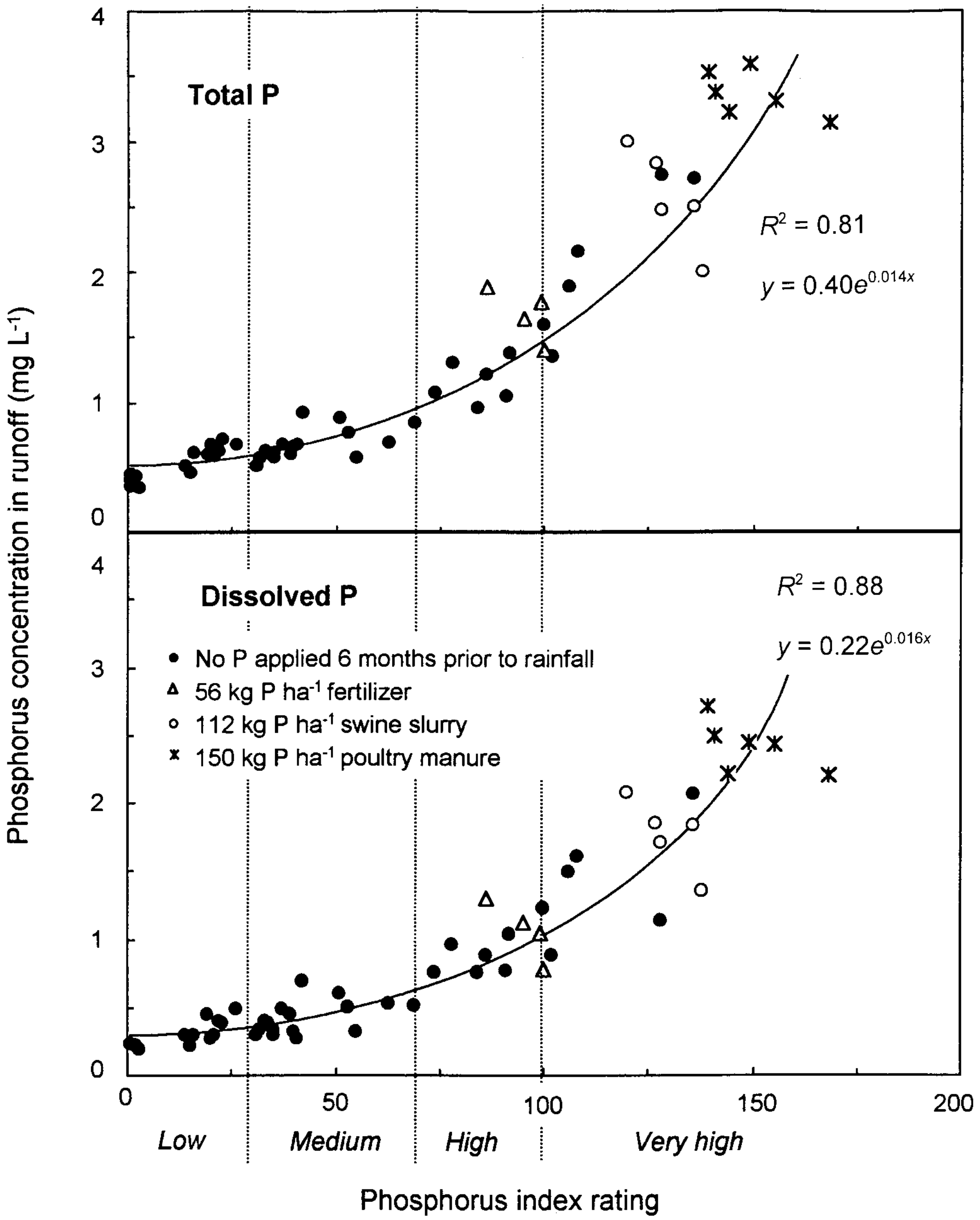

Fig. 5. Relationship between the concentration of dissolved and total P in surface runoff and the P index rating for sites in fields where no P had been applied within the last six months and where fertilizer or manure had been applied within three weeks of rainfall in FD-36 watershed.

total P in surface runoff from all sites (Fig. 5 and 6). Consideration of site potential for runoff and erosion, P application rate and method, and Mehlich-3 soil P concentration, effectively described surface runoff P concentration and loss from recently fertilized and manured fields, as well as from untreated fields. Clearly, the P index described P loss potential from a wider range of land management conditions than did Mehlich-3 soil P alone (Fig. 4).

The dissolved P concentration of surface runoff at which P index vulnerability ranking increased from low to medium was 0.43 mg L^{-1} and from high to very high was 1.07 mg L^{-1} (Fig. 5). Respective divisions in P index vulnerability rankings for total P were 0.65 and 1.62 mg L^{-1}. These concentrations reflect a shift from low through very high vulnerabilities for P loss for sites in FD-36. Similar relationships to those shown in Fig. 5 and 6 are expected to exist in other watersheds, with ranges in P concentration and loss reflecting local conditions.

Management Implications

Of the 57 surface runoff sites evaluated in FD-36, 32% were ranked as having a low vulnerability to P loss, 21% were medium, 18% were high, and 29% were very high. From these vulnerabilities, implications for nutrient management in FD-36 can be made considering the Animal Feeding Operations strategy established for Pennsylvania (Beegle and Sharpley, 1999). In this strategy, nutrient management recommendations are established from either P index or soil test P threshold options, as outlined in Table 7. In the case of the P index,

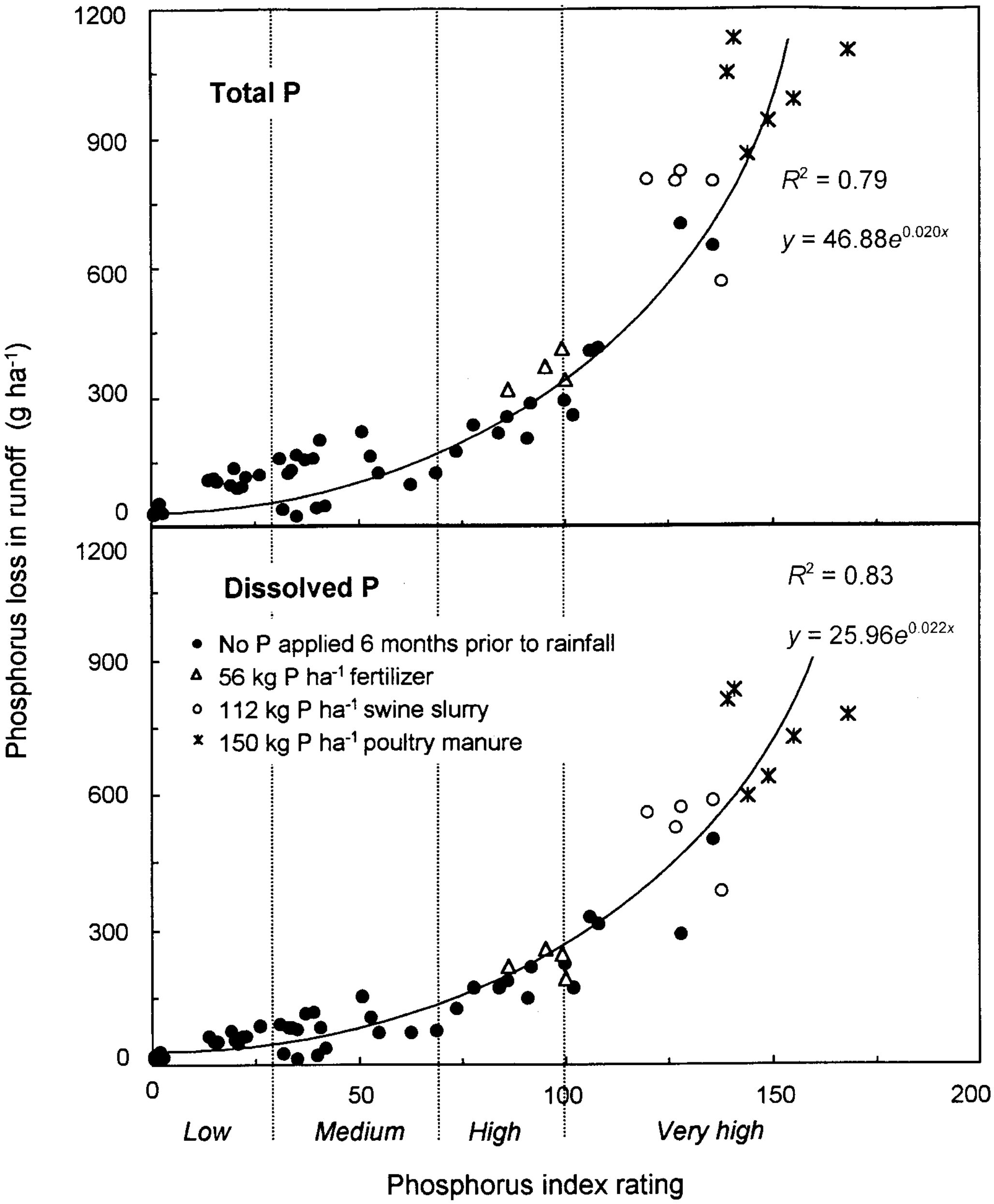

Fig. 6. Relationship between the loss of dissolved and total P in surface runoff and the P index rating for sites in fields where no P had been applied within the last six months and where fertilizer or manure had been applied within three weeks of rainfall in FD-36 watershed.

sites ranked at low and medium vulnerability to P loss could continue to receive manure applications based on crop N requirements. Sites ranked as high could receive manure applications, but on a crop P removal basis only, and sites ranked as very high would not be eligible to receive manure additions (Table 7). When using the soil P threshold option, manure application rates are based on crop removal of P above a Mehlich-3 soil P threshold of 200 mg kg^{-1} (see Fig. 4).

Within any given field, P index ratings for individual sites did not vary greatly (Table 8). Field index ratings, calculated as the average of runoff sites within an individual field, varied widely among fields (Table 8). For example, Field 9 had an overall P index rating of 2, while Field 23 had a rating of 149. This difference reflects field or source management, with Field 9 in pasture having a low Mehlich-3 soil P (25 mg kg^{-1}) and receiving no P, while Field 23 was manured (112 kg P ha^{-1} as swine slurry) (Table 1). In contrast, different P index ratings between Fields 22 (53) and 23 (149) reflect variable transport potentials rather than source management (Table 8). Although both fields received similar amounts of swine slurry (112 kg P ha^{-1}) and Field 23 had a lower Mehlich-3 soil P than Field 22 (65 and 215 mg kg^{-1}, respectively), soil type and topographic differences result in runoff and erosion potentials being much greater from Field 23 than 22. In fact, the index transport potential calculated from soil permeability, slope, and RUSLE (Tables 2 and 4) was 1.0 for Field 23 and 0.7 for Field 22.

Nutrient management recommendations were derived from the P index and soil P threshold options for

Table 7. Summary of the soil P threshold and P index options outlined in the Animal Feeding Operations strategy for Pennsylvania.

P index option		Soil P threshold option	
P index rating	**Recommendation**	**Mehlich-3 soil P†**	**Recommendation**
Low <35	manure rates based on the N requirement of the crop	<0.75 threshold (<150 mg kg^{-1})	manure rates based on the N requirement of the crop
Medium 35–70	manure rates based on the N requirement of the crop	0.75 to 1.5 threshold (150–300 mg kg^{-1})	manure rates based on P crop removal
High 71–100	manure rates based on P crop removal	1.5 to 2 threshold (300–400 mg kg^{-1})	manure rates based on 0.5 × P crop removal
Very High >100	no manure P applied	>2 threshold (>400 mg kg^{-1})	no manure P applied

† Soil P threshold is the Mehlich-3 soil P concentration, established at 200 mg kg^{-1} for Pennsylvania.

Table 8. The mean and range in P index rating for sites in each field studied, overall vulnerability ranking, and Pennsylvania nutrient management recommendation using the P index rating and soil P threshold options (Beegle and Sharpley, 1999).

	Phosphorus index option					Soil phosphorus threshold option		
	P index rating							
Field	**Mean**	**Range**	**Vulnerability ranking**	**Management recommendation**	**Projected manure application†**	**Mehlich-3 soil P‡**	**Management recommendation**	**Projected manure application†**
					Mg field^{-1}	mg kg^{-1}		Mg field^{-1}
9	2	1–3	Low	crop N needs	9.6	25	crop N needs	9.6
16	105	84–136	Very High	no P added	0	310	0.5 × crop P removal	0.1
17	130	120–138	Very High	no P added	0	260	crop P removal	0.6
18	90	78–100	High	crop P removal	0.5	305	0.5 × crop P removal	0.3
20	28	21–37	Low	crop N needs	7.7	220	crop P removal	0.8
21	25	14–41	Low	crop N needs	16.3	70	crop N needs	16.3
22	53	51–55	Medium	crop N needs	10.0	215	crop P removal	1.0
23	149	139–168	Very High	no P added	0	65	crop N needs	6.1
26	95	86–100	High	crop P removal	2.0	290	crop P removal	2.0
30	69	63–74	High	crop N needs	12.6	180	crop P removal	1.3
31	37	32–42	Medium	crop N needs	12.4	370	0.5 × crop P removal	0.6

† Poultry manure application rate based on typical rates for a 3 Mg ha^{-1} corn crop for all fields except Field 9 in pasture.
‡ Average Mehlich-3 P concentration for each field obtained from the 30-m grid sampling (i.e., Table 1).

all fields in FD-36 (Table 8). Using the P index option, manure application would be N-based on Fields 9, 20, 21, 22, 30, and 31 (Table 8). No P would be added to Fields 16, 17, and 23, which were ranked very highly vulnerable to P loss. Using the soil P threshold option, N-based manure application would continue on only three fields (9, 21, and 23). Manure application to the remaining eight fields would be at either crop P removal (17, 20, 22, 26, and 30) or half crop removal rates (16, 18, and 31) (Table 8).

Differences in the implications of applying the two P management options are apparent. For example, Field 23 was ranked as very highly vulnerable to P loss due to high surface runoff and erosion potential and a recent history of P application (112 kg P ha^{-1} swine slurry). However, because Mehlich-3 soil P concentration was only 65 mg kg^{-1}, the soil P threshold option recommended N-based manure applications (Table 8). Indeed, mean dissolved P and total P runoff concentrations from sites in this field were 2.42 and 3.36 mg L^{-1}, respectively.

Overall, manure applications would be restricted on fewer fields using the P index (five fields totaling 3.96 ha) than the soil P threshold option (eight fields totaling 7.6 ha). For instance, manure applications to those fields that were part of this evaluation were projected based on the index and soil P threshold options of the Pennsylvania nutrient management strategy (Table 7). It was assumed that on a N basis, poultry manure would be applied to meet the N requirements of a 3 Mg ha^{-1} corn crop on all fields except 9. On Field 9 (pasture), a locally representative manure application rate of 9.6 Mg ha^{-1} (4 tons acre^{-1}) was assumed (Beegle, 1999). Overall, however, the total amount of poultry manure that was projected to be applied to the 11 fields studied was 71 Mg with the P index option and 39 Mg with the soil P threshold option (Table 8).

The smaller area of the watershed targeted for P management by the P index (23%) compared with soil P threshold option (51%) is consistent with measured P loss from FD-36. For example, the mean annual flow-weighted concentration of dissolved and total P in stream flow from FD-36 for 1996 to 1999 was 0.05 and 0.075 mg L^{-1}, respectively (Pionke et al., 1999; Sharpley et al., 1999b). These levels are below eutrophic criteria (0.1 mg L^{-1} as total P) established for streams or other flowing waters not discharging directly into lakes or impoundments (Dodds et al., 1998; USEPA, 1994). Based on the level of water quality impairment of FD-36, in terms of P loss criteria, there is little justification for major changes in P management at a watershed scale at the present time. Thus, a P index strategy may be the most prudent management approach, given the relatively low concentration of P in stream flow, as long as targeted conservation measures reduce the potential for P loss during high-risk periods (e.g., storm flow and after land application of manure or fertilizer).

CONCLUSIONS

This study described an evaluation of the P index on sites ranging in soil type, topography, and nutrient management. Mehlich-3 soil P concentration accounted for 86% of the variation in dissolved P concentration in surface runoff from sites that had not received P in the previous six months, but was not related to surface runoff P from recently manured sites. Using a P index, which considers transport and source effects on P loss potential, nearly 80% of the variability in surface runoff P concentration and loss was accounted for in both unmanured and manured sites.

Clearly, the P index recently adopted by the Natural Resources Conservation Service's P-based nutrient management strategy accurately described site vulnerability to P loss. Further, based on the relatively small export of P from the studied watershed, manure management projections using a P index were more defensible than the restrictive projections derived from a soil P threshold.

REFERENCES

Beegle, D.B. 1999. Soil fertility management. p. 19–46. *In* N. Serotkin and S. Tibbetts (ed.) The agronomy guide, 1999–2000. Publ. Distribution Center, Pennsylvania State Univ., University Park.

Beegle, D.B., and A.N. Sharpley. 1999. Approaches to managing phosphorus to protect the environment. p. 42–46. *In* D. Linenfelter (ed.) 1999 Penn State Agronomic Field Diagnostic Clinic. Pennsylvania State Univ. College of Agric. Sci. Coop. Ext., University Park.

Bolinder, M.A., R.R. Simard, S. Beauchemin, and K.B. MacDonald. 1998. Indicator of risk of water contamination: Methodology for the phosphorus component. p. 11–21. *In* Agri-Environmental Indicator Project Report no. 24. Agriculture and Agri-Food Canada, Sainte Foy, QC, Canada.

Bremner, J.M., and C.S. Mulvaney. 1982. Nitrogen—Total. p. 595–624. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Applic. 8:559–568.

Dodds, W.K., J.R. Jones, and E.B. Welch. 1998. Suggested classification of stream trophic state: Distributions of temperate stream types by chlorophyll, total nitrogen, and phosphorus. Water Res. 32:1455–1462.

Eghball, B., and J.E. Gilley. 1999. Phosphorus risk assessment index and comparison with results of runoff studies. p. 30. *In* 1999 Agronomy abstracts. ASA, Madison, WI.

Gburek, W.J., A.N. Sharpley, A.L. Heathwaite, and G.J. Folmar. 2000. Phosphorus management at the watershed scale: A modification of the phosphorus index. J. Environ. Qual. 29:130–144.

Genstat 5 Committee. 1995. Genstat 5 Release 3 reference manual. Clarendon Press, Oxford.

Hesketh, N., and P.C. Brookes. 2000. Development of an indicator for risk of phosphorus leaching. J. Environ. Qual. 29:105–110.

Jokela, W., F. Magdoff, and R. Durieux. 1997. Soil testing for improved phosphorus management. Vermont Coop. Ext. Serv., Burlington.

Lander, C.H., D. Moffitt, and K. Alt. 1998. Nutrients available from livestock manure relative to crop growth requirements. Resource Assessment and Strategic Planning Working Paper 98-1. Available online with updates at http://www.nhq.nrcs.usda.gov/land/pubs/nlweb.html (verified 17 July 2001). USDA Natural Resour. Conserv. Serv., Washington, DC..

Lanyon, L.E. 2000. Nutrient management: Regional issues affecting the Chesapeake Bay. p. 145–158. *In* A.N. Sharpley (ed.) Agriculture and phosphorus management: The Chesapeake Bay. CRC Press, Boca Raton, FL.

Lemunyon, J.L., and R.G. Gilbert. 1993. The concept and need for a phosphorus assessment tool. J. Prod. Agric. 6:483–496.

Leytem, A.B., J.T. Sims, F.J. Coale, A.N. Sharpley, and W.J. Gburek. 1999. Implementing a phosphorus site index for the Delmarva Peninsula: Challenges and research needs. p. 336. *In* 1999 Agronomy abstracts. ASA, Madison, WI.

McDowell, R.W., and A.N. Sharpley. 2001. Approximating phosphorus release from soils to surface runoff and subsurface drainage. J. Environ. Qual. 30:508–520.

McDowell R.W., A.N. Sharpley, P.A. Brookes, and P. Poulton. 2001. Relationships between soil test phosphorus and phosphorus release to solution. Soil Sci. 166:137–149.

McFarland, A., L. Hauck, J. White, W. Donham, J. Lemunyon, and S. Jones. 1998. Nutrient management using a phosphorus risk index for manure application fields. p. 241–244. *In* Proc. of Manure Management in Harmony with the Environ. and Society. 10–12 Feb. 1998. Soil and Water Conserv. Soc., Ames, IA.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409–1416.

Miller, W.P. 1987. A solenoid-operated, variable intensity rainfall simulator. Soil Sci. Soc. Am. J. 51:832–834.

Murphy, J., and J.P. Riley. 1962. A modified single solution method for determination of phosphate in natural waters. Anal. Chim. Acta 27:31–36.

National Phosphorus Research Project. 2001. National research project for simulated rainfall–surface runoff studies. Available at http://www.soil.ncsu.edu/sera17/publications/National_P/National_P_Project.htm (verified 17 July 2001). Southern Ext. Res. Activity Information Exchange Group 17.

Natural Resources Conservation Service. 1994. National Map Unit Interpretation Record (MUIR) database. Available on-line at http://www.statlab.iastate.edu/soils/muir/ (verified 17 July 2001). USDA-NRCS, Fort Worth, TX.

Pionke, H.B., W.J. Gburek, R.R. Schnabel, A.N. Sharpley, and G. Elwinger. 1999. Seasonal flow and nutrient patterns for an agricultural hill-land watershed. J. Hydrol. 220:62–73.

Pote, D.H., T.C. Daniel, D.J. Nichols, A.N. Sharpley, P.A. Moore, Jr., D.M. Miller, and D.R. Edwards. 1999. Relationship between phosphorus levels in three Ultisols and phosphorus concentrations in runoff. J. Environ. Qual. 28:170–175.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, Jr., D.R. Edwards, and D.J. Nichols. 1996. Relating extractable phosphorus to phosphorus losses in runoff. Soil Sci. Soc. Am. J. 60:855–859.

Sharpley, A.N. 1995. Identifying sites vulnerable to phosphorus loss in agricultural runoff. J. Environ. Qual. 24:947–951.

Sharpley, A.N. (ed.) 2000. Agriculture and phosphorus management: The Chesapeake Bay. CRC Press, Boca Raton, FL.

Sharpley, A.N., T.C. Daniel, J.T. Sims, and D.H. Pote. 1996. Determining environmentally sound soil phosphorus levels. J. Soil Water Conserv. 51:160–166.

Sharpley, A.N., T.C. Daniel, B. Wright, P. Kleinman, T. Sobecki, R. Parry, and B. Joern. 1999a. National research project to identify sources of agricultural phosphorus loss. Better Crops 83:12–15.

Sharpley, A.N., W.J. Gburek, G.J. Folmar, and H.B. Pionke. 1999b. Sources of phosphorus exported from an agricultural watershed in Pennsylvania. Agric. Water Manage. 41:77–89.

Sharpley, A.N., and B. Moyer. 2000. Phosphorus forms in manure and compost and their release during simulated rainfall. J. Environ. Qual. 29:1462–1469.

Sharpley, A.N., and H. Tunney. 2000. Phosphorus research strategies to meet agricultural and environmental challenges of the 21st century. J. Environ. Qual. 29:176–181.

Shelton, C.H., R.D. von Bernuth, and S.P. Rajbhandari. 1985. A continuous-application rainfall simulator. Trans. ASAE 28:1115–1119.

Sims, J.T. 1996. The Phosphorus Index: A phosphorus management strategy for Delaware's agricultural soils. Fact Sheet ST-05. Delaware Coop. Ext. Serv., Newark, DE.

Sims, J.T. 2000. The role of soil testing in environmental risk assessment for phosphorus. p. 57–81. *In* A.N. Sharpley (ed.) Agriculture and phosphorus management: The Chesapeake Bay. CRC Press, Boca Raton, FL.

Sims, J.T., R.R. Simard, and B.C. Joern. 1998. P losses in agricultural drainage: Historical perspective and current research. J. Environ. Qual. 27:277–293.

Soil Survey Staff. 1993. Soil survey manual by the Soil Survey Division Staff, Natural Resources Conservation Service. USDA Handbook 18. U.S. Gov. Print. Office, Washington, DC.

SPSS. 1999. SPSS Version 10.0. SPSS, Chicago, IL.

USDA and USEPA. 1999. Unified national strategy for Animal Feeding Operations. 9 Mar. 1999. Available online with updates at http://www.epa.gov/owm/finafost.htm (verified 17 July 2001). USDA and USEPA, Washington, DC.

USEPA. 1994. Water quality standards handbook. 2nd ed. EPA 823-B-94-005a. USEPA Office of Water, Washington, DC.