IDENTIFYING CRITICAL SOURCES OF PHOSPHORUS EXPORT FROM AGRICULTURAL WATERSHEDS[1]

Jennifer L. Weld, Andrew N. Sharpley, William J. Gburek[2], and Douglas B. Beegle[3]

INTRODUCTION

Phosphorus (P) is an essential element for plant and animal growth, and its input to agriculture is necessary to maintain profitable crop and animal production. Eutrophication, the natural aging of lakes or streams brought on by nutrient enrichment, can be accelerated by P inputs to fresh waters from human activities (Carpenter et al., 1998; Schindler, 1977).

Eutrophication has been identified as the main problem in surface waters withimpaired water quality (USEPA, 1996). It restricts water use for fisheries, recreation, industry, and drinking due to the increased growth of undesirable algae and aquatic weeds, and oxygen shortages caused by their death and decomposition. Associated periodic surface blooms of cyanobacteria (blue-green algae) occur in drinking water supplies and may pose a serious health hazard to animals and humans. Recent outbreaks of the dinoflagellate *Pfiesteria piscicida* in the eastern U.S. have been linked to excess nutrients in affected waters (Burkholder et al., 1992). Neurological damage in people exposed to the toxic volatile chemicals produced by this dinoflagellate has dramatically increased public awareness of eutrophication and the need for solutions (Bever, 1998; Grattan et al., 1998; Matuszak et al., 1997).

Although nitrogen (N) and carbon (C) are essential to the growth of aquatic biota, most attention has focused on P inputs because of the difficulty in controlling the exchange of N and C between the atmosphere and water and fixation of atmospheric N by some blue-green algae. Thus. P is often the limiting element and its control is of prime importance in reducing the accelerated eutrophication of fresh waters.

Environmental concern has forced many states to consider developing recommendations for P applications and watershed management based on the potential for P loss in agricultural runoff. At the moment, these recommendations center on the identification of a threshold soil test P level above which there is an unacceptable enrichment of P in surface runoff. However, we must be careful how we interpret soil test results for environmental purposes. Interpretations given on soil test reports (i.e., low, medium, optimum, high) were established based on the expected response of a crop to P. It cannot be assumed that there is a direct relationship between the soil test calibration for crop response to P and runoff enrichment potential.

Threshold soil P levels are too limited to be used as the sole criterion to guide P applications and management. For example, adjacent fields having similar soil test P levels, but differing susceptibilities to surface runoff and erosion due to contrasting topography and management, should not have similar P management recommendations. Also, most of the P exported from

---

[1] Presented at 28th North Central Extension-Industry Soil Fertility Conference, Nov. 11-12, 1998, St. Louis, MO
[2] Pasture Systems and Watershed Management Research Laboratory, USDA-ARS, University Park, PA 16802
[3] Department of Agronomy, Penn State University, University Park, PA 16802

agricultural watersheds generally comes from only a small part of the landscape during a few relatively large storms (Pionke et al., 1997). Therefore, threshold soil P values will have little meaning unless they are used in conjunction with an estimate of a site's potential for surface runoff and erosion. Even in regions where subsurface flow pathways dominate, areas contributing P to drainage waters appear to be localized to soils with high soil P saturation and hydrologic connectivity to the drainage network.

In cooperation with research scientists, the Natural Resource Conservation Service has developed a Phosphorus Index (PI) as a screening tool for use by field staff, watershed planners, and farmers to rank the vulnerability of fields as sources of P loss in surface runoff (Lemunyon and Gilbert, 1993). The PI accounts for source and transport factors controlling P loss in surface runoff and ranks sites where the risk of P movement is expected to be higher than others. It is intended for use as a tool for field personnel to easily identify agricultural areas or practices that have the greatest vulnerability to P loss, allowing farmers more flexibility in developing remedial strategies.

Conventionally applied remediations may not produce the desired results and may prove to be an inefficient and a cost-ineffective approach to the problem if this source-area perspective to target application of P fertility, surface runoff and erosion control technology is not used. A technically sound framework must be developed that identifies the sources and transport pathways controlling P export from agricultural watersheds so that optimal remedial strategies can be targeted to critical areas of the farm or watershed.

This paper outlines research that quantifies the relationship between P in soil and surface runoff. This relationship is then incorporated into the PI to more accurately reflect P export potential from an upland agricultural watershed in Pennsylvania.

MATERIALS AND METHODS

Study Area

The study was conducted on a 98-acre subwatershed (FD-36) of Mahantango Creek, which is tributary to the Susquehanna River and ultimately the Chesapeake Bay (Fig. 1). FD-36 is typical of upland agricultural watersheds within the nonglaciated, folded and faulted, Appalachian Valley and Ridge Physiographic Province. Soils are mostly Alvira (Typic Dystrochrepts), Berks (Typic Dystrochrepts), Calvin (Typic Dystrochrepts), Hartleton (Typic Hapudults), and Watson (Typic Fragiudults) channery silt loams, with slopes ranging from 1 to 20% (Fig. 1). Climate is temperate and humid, average rainfall is approximately 43 in./yr and streamflow is about 18 in./yr.

The watershed has mixed land use (50% soybean, wheat, or corn; 20% pasture; 30% woodland). Other than rotating the crops between fields, land management is relatively constant from year to year. In the last five years, several fields north of the stream received about 6,000 gal/A/yr of swine slurry in spring and no fertilizer P. This amounts to about 200 lb P_2O_5/A/yr. South of the stream, approximately 2.25 ton/A/yr of poultry manure was applied to cropland in the spring. This amounts to about 175 lb P_2O_5/A/yr.

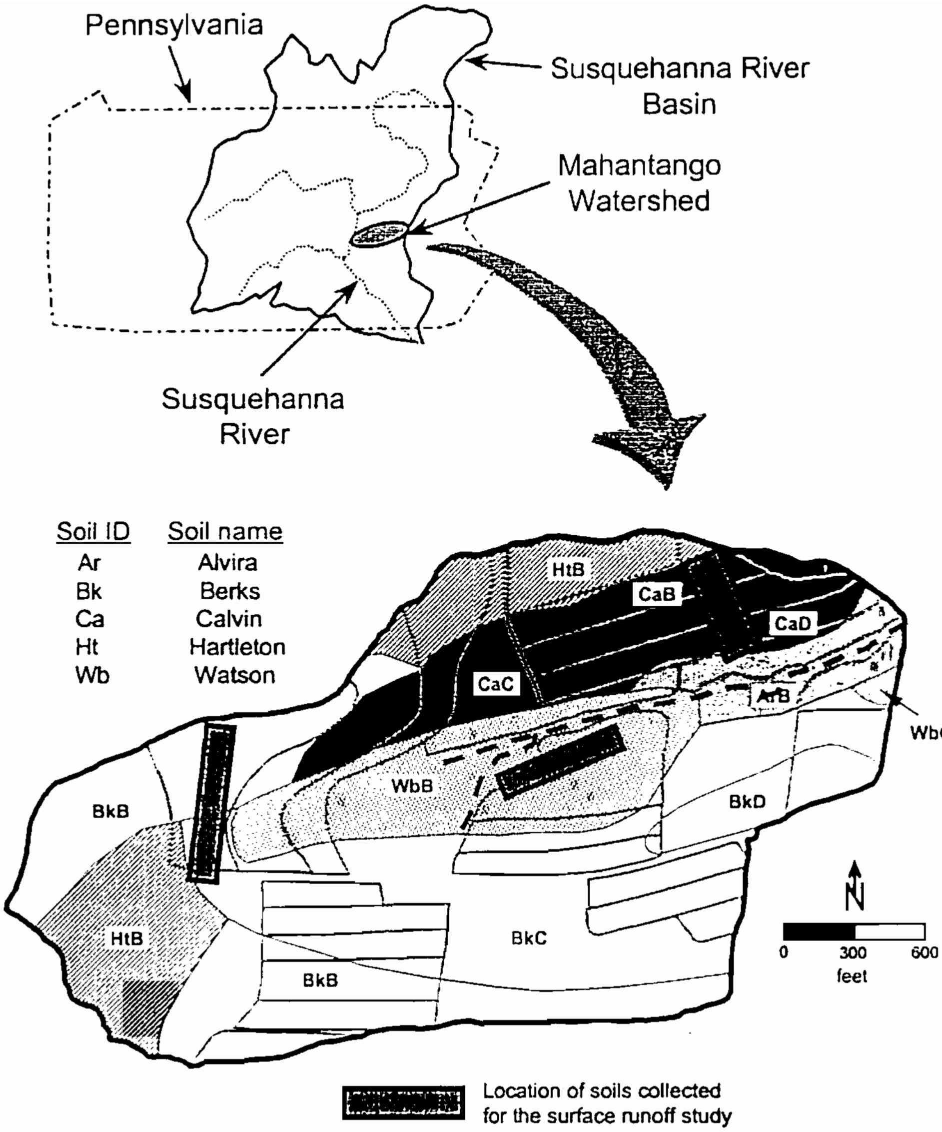

Figure 1. Location, soil type, field boundaries, and soil collection sites for the surface runoff study in watershed FD-36 (within Chesapeake Bay Basin).

Soil Analysis

In July 1996, soils samples (0 to 2 in. depth) were collected on a 100-ft grid over the watershed. The samples were air dried, sieved (0.08 in.), and the Mehlich-3 soil P concentration determined. (Mehlich, 1984).

Surface Runoff Simulation

Forty soil blocks (3 ft x 6 in.) were collected from FD-36 in September 1997. The locations were on Berks, Calvin, and Watson soils, located in hydrologically active areas potentially contributing surface runoff to the stream channel, and covered a range in land management and

Mehlich-3 P content (10 to 800 ppm). The soil blocks were brought to the ARS Pasture Systems and Watershed Management Research Laboratory, University Park, PA and three simulated rainfall events (2 in./hr) were applied at one-day intervals. Soil samples taken prior to rainfall were analyzed for Mehlich-3 P as described above. Surface runoff from the boxes was collected, filtered (0.45µ), and dissolved P measured by the molybdenum-blue method of Murphy and Riley (1962). This data was used to determine the relationship between soil P and runoff dissolved P.

RESULTS AND DISCUSSION

Soil Test P Distribution

Over watershed FD-36, Mehlich-3 P ranged from 7 to 788 ppm. The pattern of Mehlich-3 P values over FD-36 is generally a function of land use and field boundaries within the watershed (Fig. 2). Soils in wooded areas have low values of Mehlich-3 P (<30 ppm), grazed pastures have values between 100 and 200 ppm, and cropped fields receiving manure and fertilizer applications are, in most cases, above 200 ppm. Also, near-stream areas are wet for much of the year which limits their productive value, and thereby amounts of P applied. Thus, Mehlich-3 P concentrations in near-stream areas were generally <100 ppm (Fig. 2). From the grid sampling, 52% of the soils on FD-36 have Mehlich-3 P concentrations in excess of levels sufficient for optimum crop growth (>100 ppm), with 33% above 200 ppm. Of the remaining 48% of soils, P

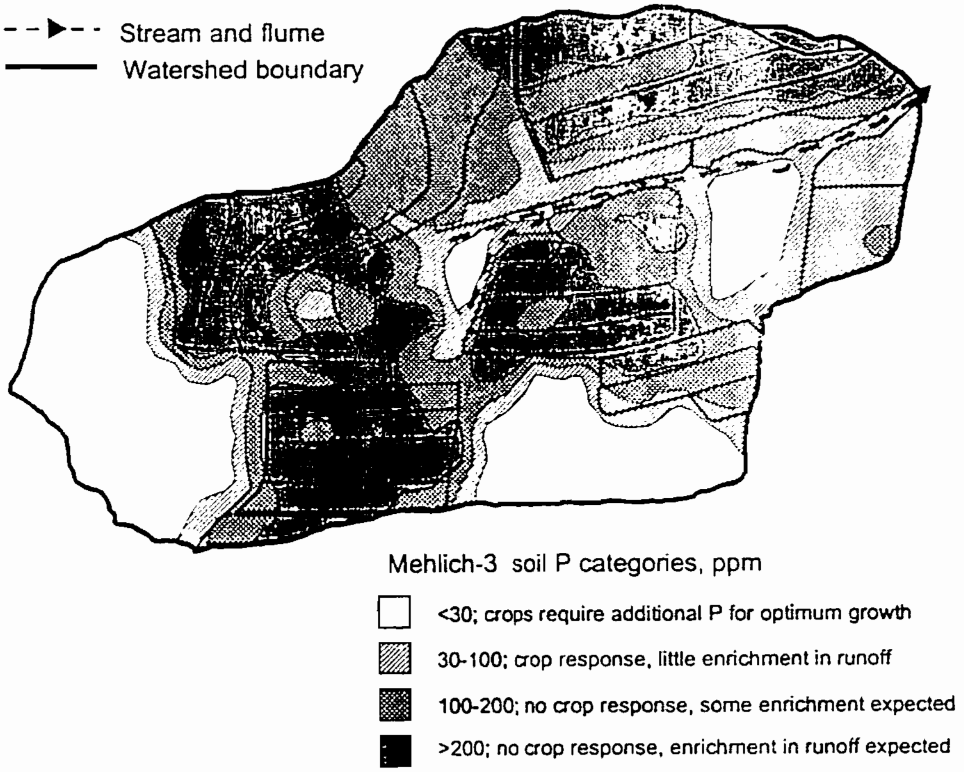

Figure 2. Distribution of Mehlich-3 soil P (0-2 in. soil depth) for FD-36.

application would be recommended on only 14% for optimum crop production (30-100 ppm), since the other 34% are mostly wooded (<30 ppm). Based on agronomic-based soil P testing alone, application of P to 63% of the cropped area of FD-36 would be limited or restricted based simply on soil test P levels.

Relating Surface Runoff and Soil Phosphorus

The soil test levels indicate only the magnitude of the source of P in the soil. The relationship between the soil P content and transport of P in surface runoff was evaluated using the 40 undisturbed soil blocks collected from FD-36. The average dissolved P concentration of three surface runoff events from each soil were related to Mehlich-3 P content (0 to 2 in. depth) prior to rainfall ($r^2 = 0.67$; Fig. 3). The relationship between surface runoff P and soil test P was similar for the three soils studied.

This relationship can be use to determine the critical soil test level where an unacceptable dissolved P concentration in surface runoff could occur if there is runoff. For example, an upper limit of 1 ppm P has been used for point-source discharge from sewage treatment plants (USEPA, 1996). This level of 1 ppm dissolved P concentration would be exceeded if Mehlich-3 soil P was greater than 450 ppm P (Fig. 3). Although we are not proposing a critical dissolved P concentration of 1 ppm in surface runoff, this scenario shows how our relationship may be used to establish environmentally based threshold soil test P levels. The current PI (Lemunyon and Gilbert, 1993) uses a soil test level of 200 ppm as the critical level. Based on the surface runoff-

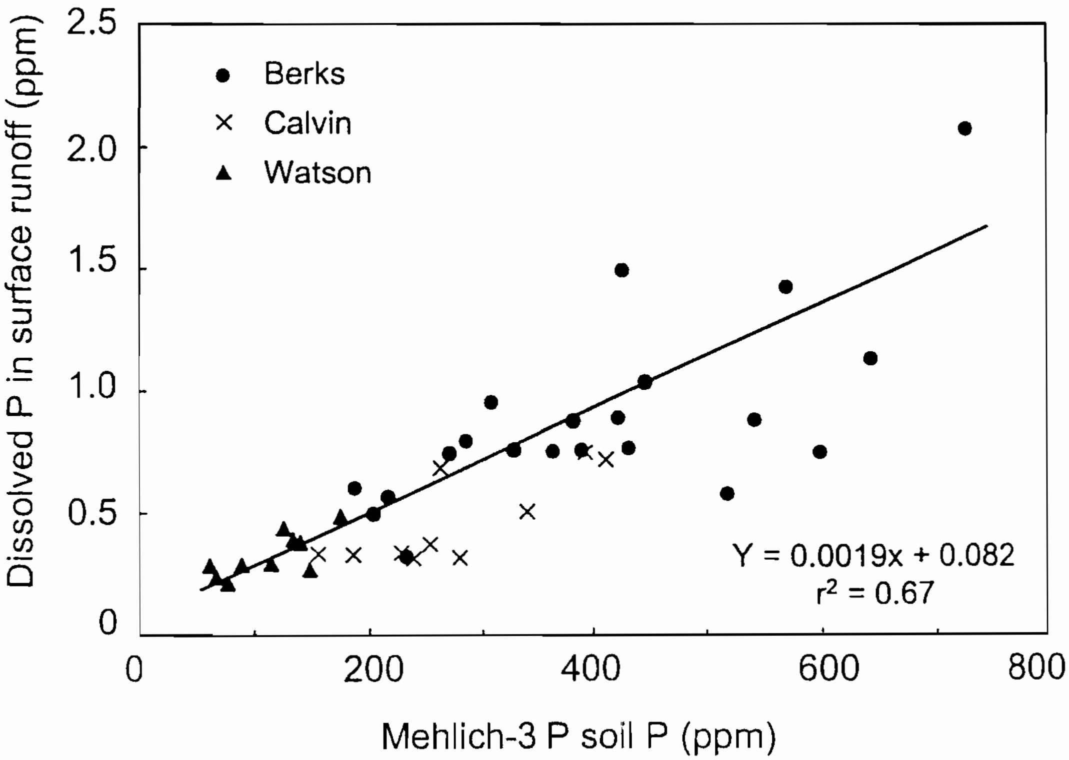

Figure 3. Relationship between dissolved P concentration in surface runoff and Mehlich-3 P content of soils from watershed FD-36.

soil P relationship we obtained for FD-36, this level would support a dissolved P concentration of about 0.5 ppm. The decision about the "safe level" of P in runoff from agricultural land is a complex question, the answer to which will have to involve many stakeholders. However, when society decides on a safe level, relationships such as that in Fig. 3 can be used to determine the acceptable soil test levels to be used in P management tools like the PI.

The Phosphorus Index

The Phosphorus Index as used in this study was modified from the original PI described by Lemunyon and Gilbert (1993) to more accurately represent P source and transport relationships and potential for surface runoff to contribute to streamflow (Table 1; Gburek et al., 1998). Two major changes were introduced. First, transport factors were made multiplicative rather than additive. We suggest that multiplicative transport factors better represent actual site vulnerability to P loss. For example, if surface runoff does not occur at a particular site, its vulnerability should be low regardless of the amount of soil P. In the original PI, a site could be ranked as very highly vulnerable based on high source factors alone, even though no surface runoff or erosion occurred.

We incorporated an additional transport characteristic reflecting distance from the stream into the PI. The contributing distance categories in the revised PI are based on a hydrologic analysis of the probability (or risk) of occurrence of a rainfall event of a given magnitude which will result in surface runoff to the stream from soils at this distance (Gburek et al., 1998). A higher risk of surface runoff contributing P to the stream channel is associated with the shorter distances from the stream and small storms because of their high frequency of occurrence. Storms large enough to cause runoff to the stream from long distances from the stream occur much less often, and therefore, pose a lower risk of P loss to the stream. These categories for the FD-36 watershed are shown in Fig. 4 in terms of the frequency at which runoff is likely to occur. For example, on this basis, we would only expect runoff to occur to the stream from the white areas in Fig. 4 on the average of once every ten years.

The modified PI was applied on a 270-ft^2 cell scale over the FD-36 watershed. Erosion and surface runoff class was obtained from Soil Survey Descriptions of each soil type in the watershed (Fig. 1). Mehlich-3 soil P values from the 100-ft grid sampling were used to determine the soil test P for each cell (Fig. 2). Soil P categories were initially based roughly on expected crop yield response and perceived P enrichment of surface runoff: <30 ppm, crops require additional P for optimum growth; between 30 and 100 ppm, there will generally not be a crop response to P application but little enrichment of P in surface runoff (probable crop response decreases as Mehlich-3 P increases from 30 to 100 ppm); between 100 and 200 ppm, there will be no response to applied P while some enrichment of P in surface runoff may occur; >200 ppm, levels are considered excessive in terms of crop requirements and enrichment of P in surface runoff can be expected (Beegle, 1996; Sharpley et al., 1996). The upper threshold value of 200 ppm is about twice the maximum crop response value. A similar approach has been used by several states to develop environmental threshold soil P levels (Sharpley et al., 1996).

Management information required in the PI about the rate and method of P application as fertilizer or manure was obtained from annual surveys of farmers operating within the FD-36 watershed. The PI value for each "site" (270-ft^2 cell) is the sum of the weighted values of all

Table 1. The modified Phosphorous Index to rate potential P loss in runoff using site characteristics (adapted from Gburek et al., 1998).

		Phosphorous Loss Rating (value)				
Transport Characteristics	**Weight**	**None (0.6)**	**Low (0.7)**	**Medium (0.8)**	**High (0.9)**	**Very High (1.0)**
Soil erosion	1.0	Not applicable	< 5 tons/ac	5-10 tons/ac	10-15 tons/ac	> 15 tons/ac
Irrigation erosion	1.0	Negligible	Infrequent irrigation on well-drained soils	Moderate irrigation on soils with slopes < 5%	Frequent irrigation on soils with slopes of 2 to 5%	Frequent irrigation on soils with slopes > 5%
Runoff class	1.0	Negligible	Very low or low	Medium	High	Very high
Return period/ contrib. distance	1.0	None (0.2) > 10 yr > 500 ft	Low (0.4) 6-10 yr 500-400 ft	Medium (0.6) 3-5 yr 400-250 ft	High (0.8) 1-2 yr 250-100 ft	Very High (1.0) < 1 yr < 100 ft
Source Characteristics	**Weight**	**None (0)**	**Low (1)**	**Medium (2)**	**High (4)**	**Very High (8)**
Mehlich-3 soil test P	1.0	< 10 ppm	10-30 ppm	30-100 ppm	100-200 ppm	> 200 ppm
P fertilizer rate	0.75	None applied	< 15 lbs P/ac	16-40 lbs P/ac	41-65 lbs P/ac	> 65 lbs P/ac
Fertilizer application method	0.5	None applied	Placed with planter deeper than 2 in.	Incorporated immediately before crop	Incorporated >3 mos or surface applied <3 mos before crop	Surface applied >3 mos before crop
Organic P rate	1.0	None applied	< 15 lbs P/ac	16-40 lbs P/ac	41-65 lbs P/ac	> 65 lbs P/ac
Organic P application method	1.0	None	Injected deeper than 2 in.	Incorporated immediately before crop	Incorporated >3 mos or surface applied <3 mos before crop	Surface applied >3 mos before crop

PI = (erosion rating x runoff rating x return period rating†) x Σ (source characteristic rating x weight)

†Note that ratings for Return Period are different than those for Erosion and Runoff characteristics

PI	Site P Loss Vulnerability
<5	Low
5 - 9	Medium
9 - 22	High
>22	Very high

source factors multiplied by the transport factors (Table 1). The total PI rating values were categorized into four classes of site vulnerability to P loss, ranging from low to very high risk (Table 2).

Applying the Phosphorus Index

The PI values calculated for the FD-36 watershed are shown in Fig. 5. Areas close to the stream channel where there is a high probability of frequent runoff to the stream and which also had high Mehlich-3 soil test P values were ranked highly vulnerable. It was observed that these

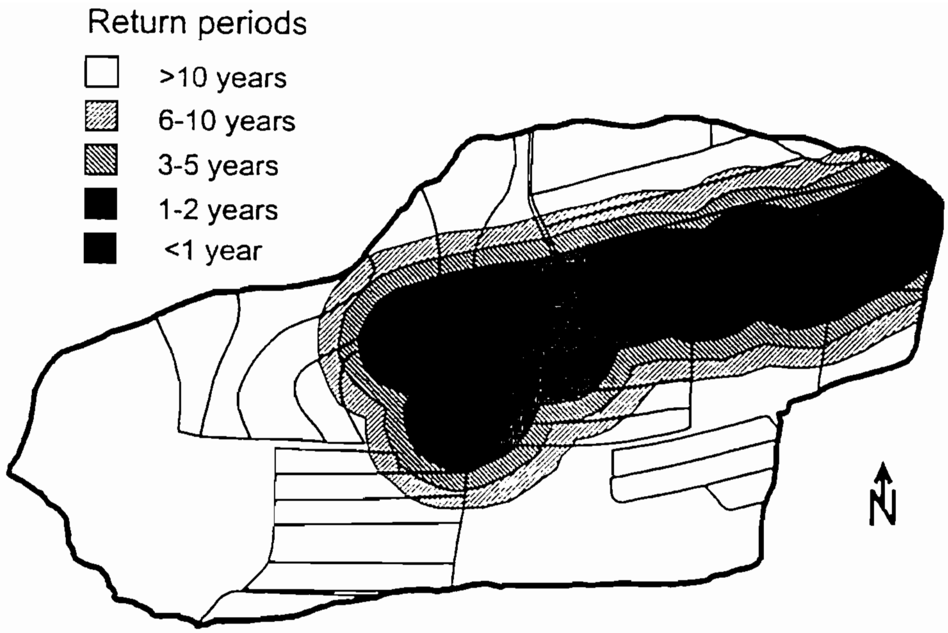

Figure 4. Surface runoff potential controlling P transport from FD-36.

areas did contribute surface runoff to the stream channel during most storm flow events in FD-36 during 1996 and 1997. Areas on the upper boundaries of the watershed not contributing surface runoff to the stream channel were ranked as having a low vulnerability (Fig. 5).

We then applied the PI to FD-36 using a Mehlich-3 soil P threshold value of 450 ppm for the very high category. This was based on the relationship shown in Fig. 3 and on a limit of 1 ppm dissolved P concentration in surface runoff (Fig. 6). The main difference in PI ranking between the two soil P criteria was the reduction of high to medium vulnerability areas (Fig. 6). Although a Mehlich-3 soil P concentration of 450 ppm is not proposed here as a general environmental threshold value, it is clear that the PI is sensitive to both source and transport factors.

Table 2. Phosphorus Index and generalized interpretations of the rankings.

PI rating	Generalized interpretation
< 5	LOW potential for P loss. If current farming practices are maintained, there is low probability of adverse impacts on surface waters.
5-8	MEDIUM potential for P loss. Chance for adverse impacts on surface waters exists, and some remediation should be taken to minimize probability of P loss.
9-22	HIGH potential for P loss and adverse impacts on surface waters. Soil and water conservation measures and a nutrient management plan are needed to minimize probability of P loss.
> 22	VERY HIGH potential for P loss and adverse impacts on surface waters. All necessary soil and water conservation measures and a nutrient management plan must be implemented to minimize P loss.

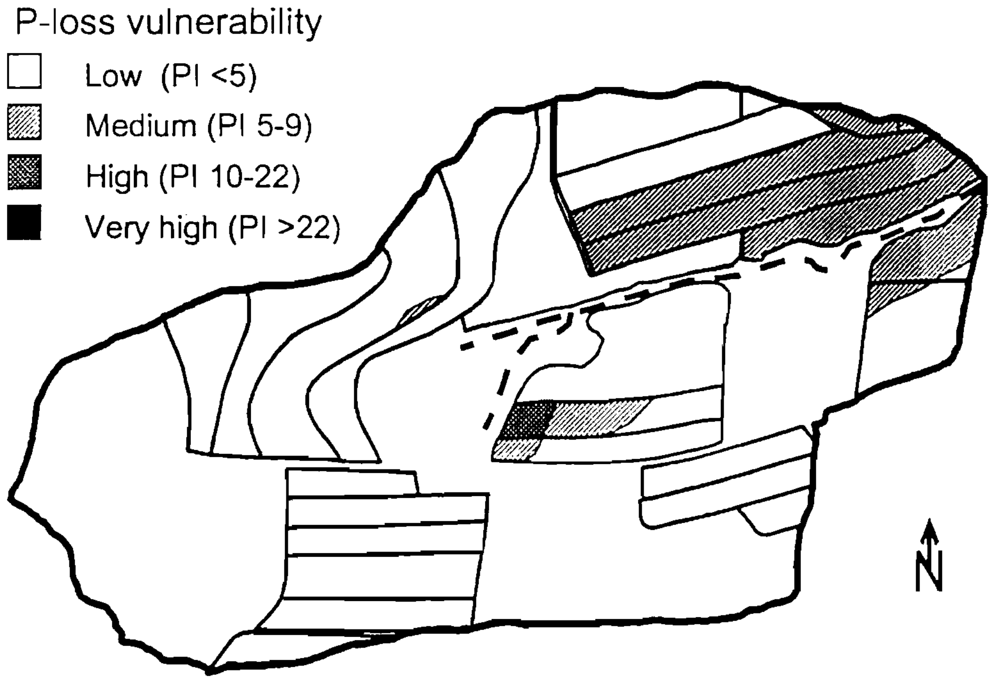

Figure 5. Modified Phosphorus Index using agronomic soil P thresholds for FD-36.

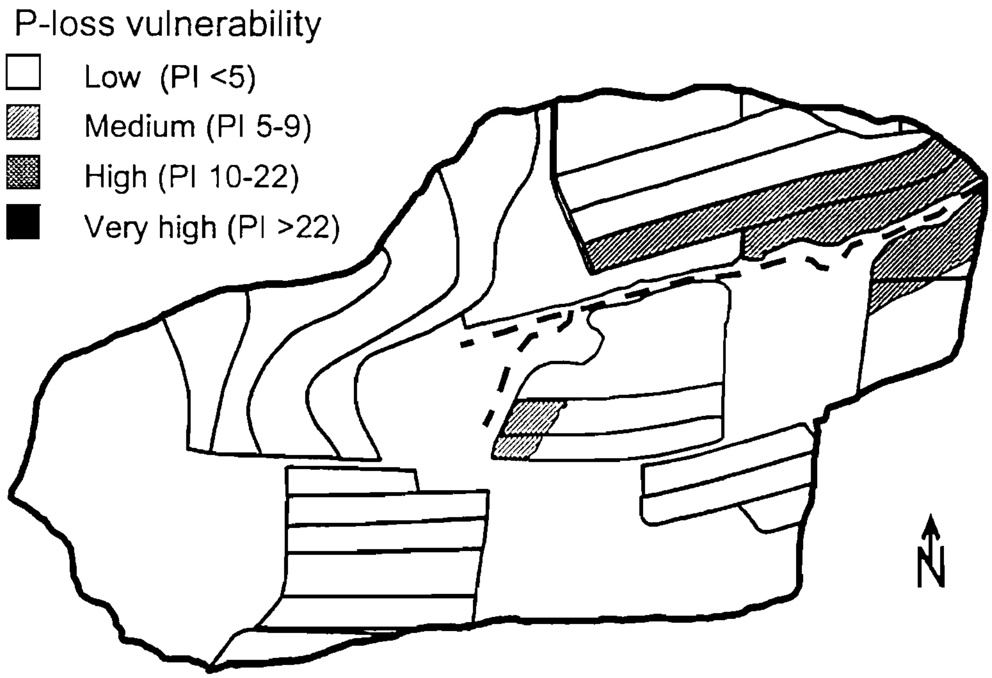

Figure 6. Modified Phosphorus Index using environmentally based soil P thresholds for FD-36.

CONCLUSIONS

In summary, this research shows that the concentration of dissolved P in surface runoff is related to the Mehlich-3 P concentration in surface soil. The relationship can be used to define environmentally based threshold soil P levels once a limit for P concentration in surface runoff is established. Further:

- This relationship can be used to quantify the soil P categories of the PI into high and very high vulnerabilities to P loss to surface runoff.
- Critical source areas or "hot spots" of P loss from the watershed were identified by the PI and were generally located near the stream channel where areas of surface runoff and high soil P coincided.
- The PI was modified to more accurately represent the surface runoff-soil P relationship and potential for surface runoff to contribute to streamflow. The modified PI indicated where P-based management of fertilizers and manures should be targeted for most effective remediation.

Much work is still needed to develop comprehensive management strategies that control P loss from fields and/or watersheds by incorporating all hydrologic implications, particularly source-area concepts of runoff generation. Modeling tools and field data are not currently available to integrate all aspects of hydrologic controls from the flow perspective alone, much less from that of their interactions with water quality. However, we can draw conclusions based on results from the studies presented.

In the most simple sense, the intersection of surface runoff source areas within a watershed with areas of high soil P generally creates the critical source areas controlling most P export. Thus, it appears that P export may be most efficiently managed by focusing primarily on control of soil P levels in the hydrologically active zones most likely to produce surface runoff. The corollary to this implication that soil P levels are critical in runoff-producing zones is that they are less important in other areas when it comes to controlling P export from a watershed. There are, of course, exceptions to this – in limited cases, the possibility of P transport by preferential subsurface flow in coarse-textured soils must also be considered. Nonetheless, the typical case suggests that differing levels of P management may be necessary for different areas of the watershed, an approach to land management that will have to be addressed by action agencies.

Based on these results, we have initiated further research to address:

- How the PI outlined in Table 1 can be applied to watersheds in other geographic, climatic, and hydrologic regions using readily available data.
- How the PI can account for P leaching when subsurface flow pathways contribute a major portion of P exported from a watershed.
- In practice, the PI will be applied on an individual field basis. We are working to make sure the PI is presented in a way that it is simple enough to be utilized in the field without the use of computers, sophisticated models, or GIS.
- Testing of the refined PI on farms in the upper Chesapeake Basin with the aid of a trained nutrient management planner for each farm, and improving the index where needed to facilitate its field application and integration into nutrient management systems.

The modified Phosphorus Index will go a long way toward providing reliable technology to identify and target critical source areas of P export from watersheds for more effective remediation. But we must keep in mind that while we are developing such tools to address the immediate problem of P management at the watershed scale, we must also be working to bring the overall farm systems into P balance. This is the long-term answer to P management at the watershed scale.

ACKNOWLEDGEMENTS

Contribution from the U.S. Department of Agriculture, Agricultural Research Service, in cooperation with the Pennsylvania Agricultural Experiment Station, the Pennsylvania State University, University Park, Pennsylvania.

REFERENCES

Beegle, D.B. 1996. Soil fertility management. p. 17-40. *In* N. Serotkin (ed.), The Agronomy Guide, 1997 - 1998. Publications Distribution Center, Pennsylvania State Univ., University Park, PA.

Bever, C.T. Jr., L. Grattan, and J.G. Morris. 1998 Neurologic symptoms following Pfiesteria exposure: case report and literature review. Maryland Medical Journal 47:120-123.

Burkholder, J.M., E.J. Noga, C.W. Hobbs, H.B. Glasgow, Jr., and S.A. Smith. 1992. New "phantom" dinoflagellate is the causative agent of major estuarine fish kills. Nature 358:407-410.

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. Ecological Applications 8:559-568.

Gburek, W.J., A.N. Sharpley, and G.J. Folmar. 1998. Critical areas of phosphorus export from agricultural watersheds. *In* A.N. Sharpley (ed.), Agricultural Phosphorus in the Chesapeake Bay Watershed: Current Status and Future Trends. Chesapeake Research Consortium, Annapolis, MD. (In press).

Grattan, L.M., D. Oldach, T.M. Perl, M.H. Lowitt, D.L. Matuszak, C. Dickson, C. Parrott, R.C. Shoemaker, C.L. Kauffman, M.P. Wasserman, J.R. Hebel, P. Charache, and J.G. Morris Jr. 1998. Learning and memory difficulties after environmental exposure to waterways containing toxin-producing Pfiesteria or Pfiesteria-like dinoflagellates. Lancet 352: 532-539.

Lemunyon, J.L., and R.G. Gilbert. 1993. Concept and need for a phosphorus assessment tool. J. Prod. Agric. 6: 483-486.

Matuszak, D.L., M. Sanders, J.L. Taylor, and M.P. Wasserman. 1997. Toxic Pfiesteria and human health. Maryland Medical Journal 46:515-520.

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

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

Pionke, H. B., W.J. Gburek, A.N. Sharpley, and J.A. Zollweg. 1997. Hydrologic and chemical controls on phosphorus losses from catchments. p225-242, In Tunney, H., Carton, 0. and Brookes, P. (eds.) Phosphorus Loss to Water from Agriculture. CAB International, Cambridge, England.

Schindler, D.W. 1977. Evolution of phosphorus limitation in lakes. Science 195:260-262.

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.

U.S. Environmental Protection Agency. 1996. Environmental indicators of water quality in the United States. EPA 841-R-96-002. USEPA, Office of Water (4503F), U.S. Govt. Printing Office, Washington, DC. 25 p.

PROCEEDINGS OF THE

TWENTY-EIGHTH NORTH CENTRAL EXTENSION-INDUSTRY SOIL FERTILITY CONFERENCE

Volume 14

November 11-12, 1998
St. Louis Westport Holiday Inn
St. Louis, Missouri

Program Chair:
Dr. David Franzen
North Dakota State University
229 Walster Hall, Box 5758
Fargo, ND 58105
701-231-8884

Published by:
Potash & Phosphate Institute
772 – 22nd Avenue South
Brookings, SD 57006
605/692-6280