Phosphorus Management at the Watershed Scale: A Modification of the Phosphorus Index

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ABSTRACT

We considered hydrologic and chemical factors controlling P export from a 39.5-ha mixed land use watershed in east-central Pennsylvania, focusing our evaluation on watershed vulnerability to P loss. The spatial variations of P source factors, soil P, and P inputs from fertilizer and manure were evaluated. Distribution of Mehlich-3 soil P on a 30-m grid over the watershed showed that soil P varied with land use. Soils in wooded areas had low Mehlich-3 P (<30 mg kg^{-1}); grazed pasture had Mehlich-3 P values between 100 and 200 mg kg^{-1}; and cropped fields receiving manure and fertilizer applications were mostly >200 mg kg^{-1}. Phosphorus sources and transport controls on P loss were evaluated by examining in-stream P concentrations during storm hydrographs. Phosphorus concentrations decreased 50% downstream from headwaters to watershed outlet, and were more closely related to near-stream (within 60 m) distribution of high-P soils than to that of the whole watershed. This suggests that near-stream surface runoff and soil P are controlling P export from the watershed. Based on these findings, we modified the Phosphorus Index (PI), a user-oriented tool developed by the NRCS–USDA to identify critical source areas controlling P export from agricultural watersheds. The modification separately evaluates P source and transport factors, and incorporates the hydrologic return period to describe contributing areas. The modified PI was applied to the watershed to illustrate interactions between P source and transport processes controlling P export, and approaches for managing P loss.

THE RAPID growth and intensification of the livestock industry in certain areas of the USA and Europe have created imbalances between P input in feed and fertilizer and its output in produce (Isermann, 1991; Sharpley et al., 1998). On a national basis, an annual P surplus of 26 kg ha^{-1} exists in the USA (National Research Council, 1993), while the surplus for the UK is around 10 kg ha^{-1} (Sharpley and Withers, 1994). Actual surpluses are more dramatic regionally because the areas where feed is produced have become fragmented from those where livestock are raised (Lanyon and Thompson, 1996). Aggravating the situation even further, manure applications within the livestock production areas are typically based on crop N requirements, the desire to minimize the purchase of commercial fertilizer N, and the risk of NO_3 leaching into ground water. The N/P ratio of manure (2:1 to 6:1) is lower than that in crop uptake (7:1 to 11:1), so N-based manure management results in more P being added to the soil than the crop requires. In total, these factors contribute to an increased risk of P transport from agricultural land to surface waters (Sharpley et al., 1996, 1998; Sims and Sharpley, 1998).

Agricultural-management practices developed to

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Abbreviations: DP, dissolved P; AAP, algal available P; TP, total P; PP, particulate P; TN, total N; CSA, critical source area; VSA, variable source area; PI, Phosphorus Index; NRCS, Natural Resources Conservation Service; BMP, best management practice; GIS, geographic information system; SCS, Soil Conservation Service; CN, Curve Number; USLE, Universal Soil Loss Equation.

minimize P input to surface waters have addressed source and transport factors separately (Sharpley et al., 1994; Bottcher et al., 1995). We suggest an approach is needed that integrates both. It should incorporate the interactions between soil P and surface runoff at the point or plot scale, which are relatively well understood (e.g., Ryden et al., 1973; Sharpley et al., 1994; Pote et al., 1996), with P transport processes applicable to the multifield or watershed scale, where impacts of P loss are evaluated. This latter scale is difficult to quantify because of the need to integrate spatially variable P sources, sinks, and transport processes that are linked by the watershed-scale flow system (Pionke et al., 1997; Gburek and Sharpley, 1998).

To be most effective, P-management efforts must be targeted to critical source areas (CSA), which are specific, identifiable areas within a watershed that are most vulnerable to P loss, either in surface runoff or in subsurface flow, where it is an important part of the local hydrology (Heatwole et al., 1987; Prato and Wu, 1991; Heathwaite and Johnes, 1996; Gburek et al., 1996; Gburek and Sharpley, 1998). CSAs depend on the coincidence of two sets of factors, referred to here as source factors (functions of soil, crop, and management) and transport factors (surface runoff, erosion, subsurface flow where important, and channel processes). Source factors relate to fields or watershed areas that have a high *potential* to contribute to P export. These are typically well defined and reflect land use patterns related to soil P status, and fertilizer and manure P inputs (Pionke et al., 1997; Gburek and Sharpley, 1998). Transport factors are what transform potential P sources into actual P losses from a field or watershed.

Phosphorus transport shows a strongly skewed distribution in time (Johnes, 1997); the skewed distribution is the result of a large proportion of the total P load being delivered in a few major storm hydrographs (Dils and Heathwaite, 1996; Haygarth et al., 1998; Heathwaite et al., 1989; Johnes, 1997). Phosphorus transport generally occurs from hydrologically active areas of a watershed where surface runoff contributing to streamflow is coincident with areas of high soil P (Gburek et al., 1996; Gburek and Sharpley, 1998). Similarly, 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. Schoumans and Breeuwsma (1997) found that soils with high P saturation contributed only 40% of the total phosphorus (TP) load, but an additional 40% came from areas where the soils had only moderate P saturation but some degree of hydrological connectivity with the drainage network.

The NRCS–USDA developed the Phosphorus Index (PI) as a concept for a field-scale assessment tool to be used by field staff, watershed planners, and farmers to rank the vulnerability of fields as sources of P loss in runoff (Lemunyon and Gilbert, 1993). NRCS is encouraging all states within the Chesapeake Bay Basin to use the PI by 2002 to develop waste-management and nutrient-utilization plans for farms with confined animal feeding operations. The intent is to identify sources of P into the Chesapeake Bay and target effective remedial strategies while maintaining the viability of animal agriculture. Applying the original PI to 30 unit-source watersheds of about 2 ha each in Texas and Oklahoma showed that its rankings were closely related to total P loss from the watersheds (r = 0.79) (Sharpley, 1995). Sharpley (1995) also showed that when actual runoff and erosion data were used to calculate the PI, the relationship between PI and total P loss from the watershed was strengthened (r = 0.89), further emphasizing the importance of transport.

The PI is essentially an edge-of-field screening tool, but edge-of-field P losses, while important, must be evaluated with respect to their proximity, or connectivity, to a stream or receiving water body, such as the Chesapeake Bay. It is at this latter scale that the effects of excess P application are manifested and the results of P-management efforts will ultimately be evaluated. When the original PI was applied to a larger watershed in Pennsylvania having dynamic and variable source areas of runoff, its field rankings did not reflect watershed areas having combinations of high soil P and high runoff probability, which had a documented impact on the stream (Gburek et al., 1996). Consequently, we have incorporated findings from studies of the hydrologic and chemical processes defining source areas and transport of P from upland agricultural watersheds in east-central Pennsylvania, to develop a modified PI that reflects P transport from hydrologically active CSAs under humid-climate northeastern U.S. conditions. The modified PI incorporates field-scale interactions between transport and source factors that control P loss, and a watershed-scale probability-based description of the connectivity of fields to the stream, while maintaining the simplicity and user-oriented nature of the original PI.

BACKGROUND

Pionke et al. (1996) examined generalized controls on P export at the upland watershed scale. Dissolved P (DP) values in streamflow for 9 yr were collected at the outlet of watershed WE-38, a 7.3-km^2 upland agricultural subwatershed of Mahantango Creek in east-central PA, which is a tributary to the Susquehanna River and ultimately the Chesapeake Bay. The P concentrations were grouped into baseflow, elevated baseflow, and stormflow categories, depending on where within the continuous stream hydrograph the samples were collected. Long-term outflow from the watershed was found to be approximately 70% baseflow, 20% elevated baseflow and 10% stormflow. However, flow-weighted DP export was distributed about 70% in stormflow, 20% in elevated baseflow, and 10% in baseflow. On average, 90% of algal-available P (AAP) was exported in the seven largest storms per year. Similar findings have been reported by others. For example, more than 75% of annual streamflow from watersheds in Ohio (Edwards and Owens, 1991) and Oklahoma (Smith et al., 1991) was found to occur in one or two severe storms that were also found to contribute more than 90% of annual TP export.

We have investigated surface runoff generation processes at a study site within WE-38 to better identify areas contributing surface runoff, a major component of stormflow and the flow component most associated with P transport (Gburek and Zollweg, in press). The study combined traditional hydrologic instrumentation, such as recording rain gages, flumes, and shallow wells, with a newly designed saturation sensor (Zollweg, 1996), to document small-scale variabilities of runoff-producing zones between and during storms. Surface runoff volumes measured from lateral runoff plots were found to be similar to volumes estimated by multiplying rainfall depth by average upslope saturated area during the storm. When the same storms were examined from the perspective of total streamflow from the watershed, calculated and observed surface runoff volumes followed the same pattern, supporting the assumption that surface runoff is generated primarily by near-stream surface-saturated areas. Most importantly from the perspective of the P export problem, the maximum extent of the surface runoff-producing areas for most storms was within approximately 30 m of the channel.

We have also performed simulations of rainfall-runoff P-loss dynamics on a 26-ha subwatershed of WE-38 to develop a modeling base for integration of the previously described studies (Zollweg et al., 1995; Gburek and Sharpley, 1998). The simulations accounted for interactions between source areas of surface runoff and distribution of soil P over a watershed, emphasizing the hydrologic controls on P export and illustrating potential for managing P loss. A variable-source-area (VSA)-based rainfall-runoff model (Zollweg et al., 1996) was combined with simple P generation and transport algorithms (Daniel et al., 1994) and applied to the watershed. Typically, nearly all surface runoff was found to be generated from less than 15% of the total watershed area, and the contributing areas were limited and identifiable zones that occurred primarily near the stream. Within the area contributing surface runoff, most DP loss was from cropland where soil P values were highest. In contrast, lower soil P values within a permanently grassed area around the lower reaches of the channel counteracted the transport potential of the large surface runoff volumes. In terms of area, DP loss was from about 10% of the watershed area, as compared with the 15% of the watershed area contributing surface runoff.

In total, these background studies show that limited, identifiable, and predictable portions of a watershed are

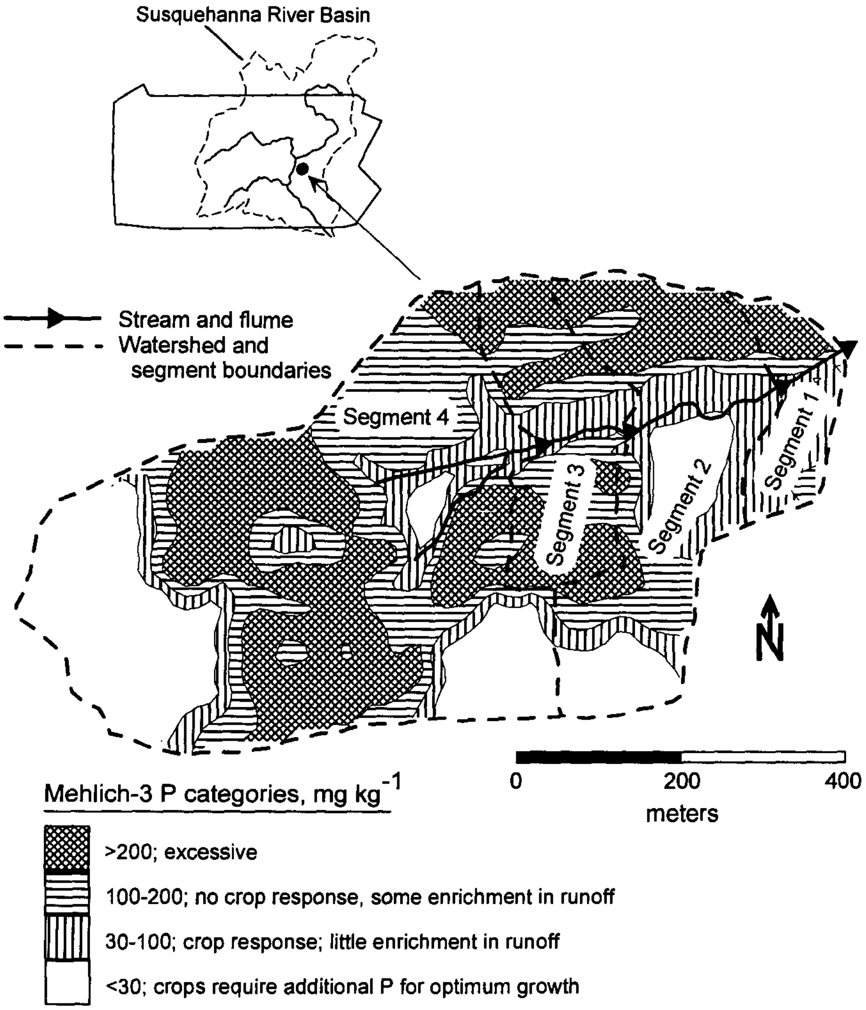


Fig. 1. Watershed FD-36; sampling segments, soil P distribution, and location within the Susquehanna River Basin.

sources of most P export. Such findings are at odds with management based on high soil P values within fields and point out the necessity to incorporate watershed dynamics into P-management schemes.

MATERIALS AND METHODS

The Study Area

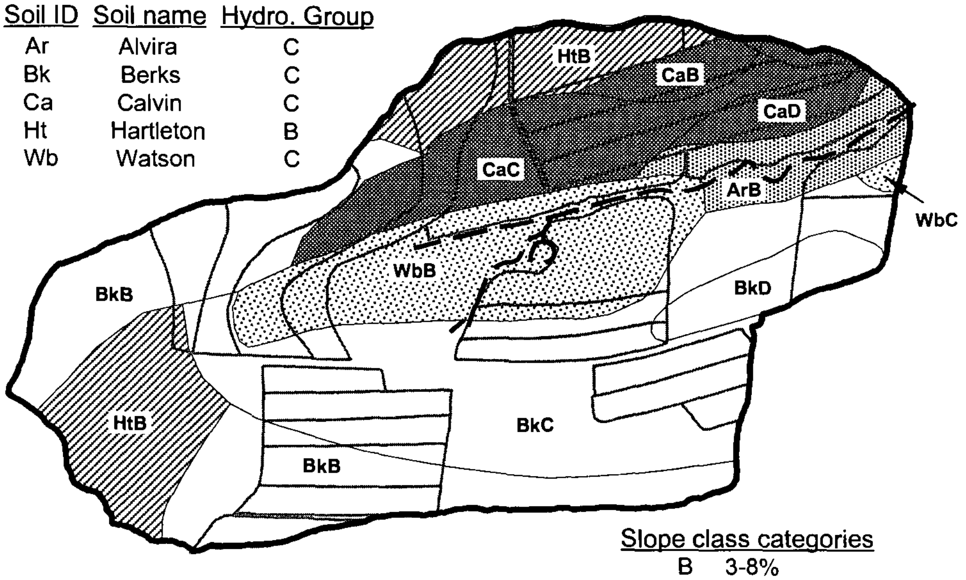
The study area is within the Susquehanna River Basin (Fig. 1), the primary source of fresh water to the Chesapeake Bay. Agriculture accounts for 33% of the land area within the Bay Basin; forest is 59% and urban is 8%. In general, the more intensive agricultural land uses tend to be located near streams and larger water bodies, while forests generally occupy the areas farther from the water. As a result, agriculture contributes 81% of P and 58% of N nonpoint source inputs, and 52% of P and 43% of N inputs to the Bay (Chesapeake Bay Program, 1995).

The study was conducted on the 39.5-ha watershed FD-36 (Fig. 1), a subarea of WE-38. FD-36 is typical of first-order upland agricultural watersheds within the nonglaciated, folded and faulted, Appalachian Valley and Ridge Physiographic Province of the northeastern USA. The climate is temperate and humid and average rainfall is ≈ 1100 mm yr^{-1}; streamflow is about 450 mm yr^{-1}. 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. 2). The watershed has mixed land use (50% soybean [*Glycine max*], wheat [*Triticum aestivum*], or corn [*Zea mays* L.]; 20% pasture; 30% woodland). In the last 5 yr, selected fields north of the stream received ≈ 60 $\text{m}^3\ \text{ha}^{-1}\ \text{yr}^{-1}$ pig slurry in spring and no fertilizer P. This amounts to ≈ 100 kg P $\text{ha}^{-1}\ \text{yr}^{-1}$, assuming a slurry P content of 1.6 g L^{-1} (Eck and Stewart, 1995; Sharpley et al., 1998). South of the stream, ≈ 5 Mg $\text{ha}^{-1}\ \text{yr}^{-1}$ of poultry manure was applied to cropland in the spring. This amounts to ≈ 85 kg P $\text{ha}^{-1}\ \text{yr}^{-1}$, assuming a manure P content of 16.9 g kg^{-1} (Eck and Stewart, 1995; Sharpley et al., 1998). Details of the FD-36 study can be found in Gburek and Sharpley (1998), but because the watershed was used to illustrate our modifications to the PI, we briefly describe its characterization and initial findings.

FD-36 was divided into four monitoring and sampling segments (Fig. 1). Beginning in May 1996, streamflow from each segment was continuously monitored using H-flumes fitted with stage recorders, and stream samples for P analysis were taken automatically during storm hydrographs at 5- to 120-min intervals using programmable stage-activated samplers. Monthly baseflow samples were taken at each flume for P analysis. Sampling, handling, and analysis for DP, TP, and AAP were done using standard methods (Gburek and Sharpley, 1998). Soil samples (0- to 5-cm depth) collected on a 30-m grid over the watershed were analyzed for Mehlich-3 soil P concentration (Mehlich, 1984) after being air-dried and sieved (2 mm). This depth of soil sampling is environmentally based and represents the depth of soil interacting with rainfall and surface runoff that controls P release and transport in runoff (Sharpley et al., 1996).

Storm hydrographs from each of the four flumes were separated into baseflow and surface runoff components using techniques dependent on storm characteristics. For smaller storms with minimal change in baseflow, a straight-line separation from storm hydrograph beginning to end was used. For larger storms, a conventional semi-log separation was applied (Hall, 1968). Width of the near-stream zone producing surface runoff was estimated for all storms based on findings from the runoff-generation study site. Incremental surface runoff volumes within each segment were divided by rainfall depth to give runoff contributing areas, and then by stream length to approximate the widths contributing surface runoff (both sides of the stream). These areas are considered the minimum necessary to produce the increase in streamflow observed during the storm hydrograph.

Figure 3 shows watershed topography along with field boundaries and IDs. Topography was developed from a detailed survey of the entire watershed. Table 1 gives land use information related to Fig. 3 for 1996. This information comes from an annual farmer survey with information tabulated on a field-by-field basis. Other than rotating crops between fields,



Soil ID	Soil name	Hydro. Group
Ar	Alvira	C
Bk	Berks	C
Ca	Calvin	C
Ht	Hartleton	B
Wb	Watson	C

Slope class categories	
B	3-8%
C	8-15%
D	15-25%

Fig. 2. FD-36 soil map with field boundaries also shown; soil name, ID, slope class, and hydrologic soil grouping from Northumberland County, PA Soil Survey.

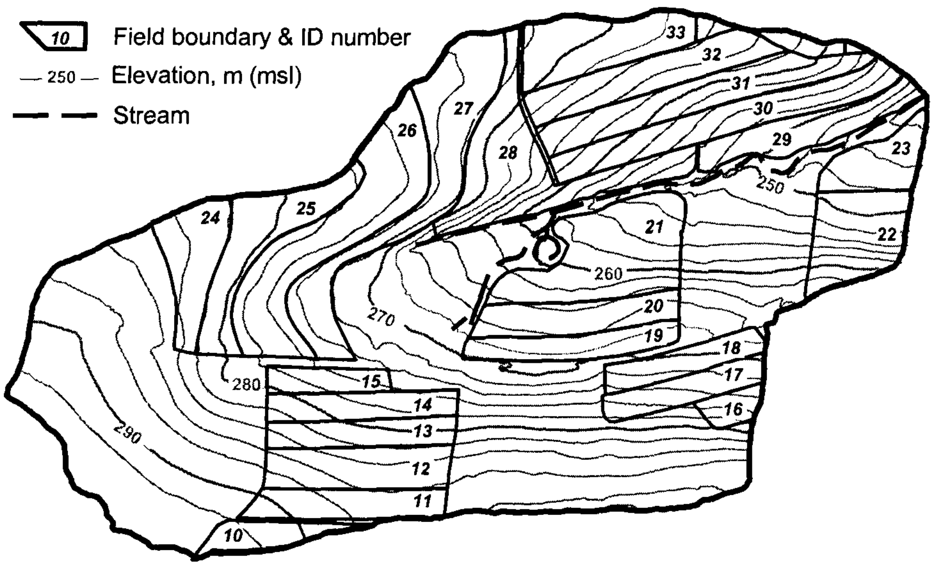


Fig. 3. FD-36 field boundaries, field IDs, and topography.

the overall breakdown of land use and management is currently constant from year to year.

Soil Phosphorus Distribution

Mehlich-3 soil test P values from the 30-m grid sampling were grouped into four categories based on agronomic and environmental factors (Fig. 1): <30 mg kg^{-1}, crops require additional P for optimum growth; between 30 and 100 mg kg^{-1}, crop response to P application but little enrichment of P in surface runoff; between 100 and 200 mg kg^{-1}, no crop response to applied P but some enrichment of P in surface runoff; >200 mg kg^{-1}, excessive in terms of crop requirements and enrichment of P in surface runoff is expected (Beegle, 1996; Sharpley et al., 1996). The pattern of Mehlich-3 soil P was generally related to land use and field boundaries within the watershed (compare Fig. 1 and 3). Soils in wooded areas had low Mehlich-3 P (<30 mg kg^{-1}); grazed pastures had values between 100 and 200 mg kg^{-1}; and cropped fields receiving manure and fertilizer applications were generally above 200 mg kg^{-1}. Mehlich-3 soil P concentrations in near-stream areas were typically <100 mg kg^{-1}. On a watershed basis, lower P soils tended to dominate downstream segments, and higher P soils upstream segments. For example, about 60% of segments 1 and 2 had Mehlich-3 P values <100 mg kg^{-1}, while about 80% of segment 3 and 50% of segment 4 had soils with Mehlich-3 P concentrations >100 mg kg^{-1}.

Streamflow Phosphorus

Flow-weighted DP, AAP, and TP concentrations in streamflow leaving each of the four watershed segments were determined for each storm event from August to the beginning of November 1996 (Gburek and Sharpley, 1998); averages are

Table 1. Land use and management data by field for watershed FD-36, 1996.

Field no.†	Field area	Crop	Chem. fert. P application rate	Chem. fert. P application method/date	Org. fert. P application rate	Org. fert. P application method/date	Mehlich-3 soil P	Runoff class	USLE soil loss
	ha		kg ha^{-1}		kg ha^{-1}		mg kg^{-1}		kg ha^{-1}
10	0.42	Soybean	65	Broadcast/Apr.	0		180	Low	450
11	0.70	Oat	40	Broadcast/Mar.	0		180	Medium	900
12	0.93	Corn	55	Broadcast/Apr.	0		240	Medium	3140
13	0.62	Alfalfa	0		0		210	Medium	0
14	0.62	Corn	55	Broadcast/Apr.	0		220	Medium	3360
15	0.36	Corn	55	Broadcast/Apr.	0		210	Medium	3590
16	0.22	Corn	0		515 poultry	Broadcast/Apr.	470	Medium	7620
17	0.55	Soybean	65	Broadcast/Apr.	0		400	Medium	2020
18	0.53	Corn	0		515 poultry	Broadcast/Apr.	420	Medium	5160
19	0.62	Soybean	65	Broadcast/Apr.	0		310	Medium	2240
20	0.77	Corn	0		515 poultry	Broadcast/Apr.	250	Medium	3140
21	1.63	Soybean	65	Broadcast/Apr.	0		190	High	2690
22	1.00	Soybean	0		170 swine	Broadcast/Apr.	70	Medium	4260
23	0.61	Soybean	0		170 swine	Broadcast/Apr.	40	Medium	900
24	0.79	Wheat	55	Broadcast/Oct. 1995	0		300	Medium	1120
25	1.06	Wheat	55	Broadcast/Oct. 1995	0		420	Medium	1340
26	2.00	Soybean	65	Broadcast/Apr.	0		370	Medium	1120
27	1.83	Soybean	65	Broadcast/Apr.	0		170	Medium	2020
28	1.65	Soybean	65	Broadcast/Apr.	0		100	Medium	5380
29	0.80	Soybean	9		170 swine	Broadcast/Apr.	110	Medium	4260
30	1.26	Corn	10	Banded/May	170 swine	Broadcast/May	180	Low	6280
31	1.24	Barley	0		170 swine	Broadcast/Apr.	280	Low	5160
32	1.06	Corn	10	Banded/May	170 swine	Broadcast/May	200	Low	3810
33	1.07	Barley	0		170 swine	Broadcast/Apr.	320	Medium	1340

† Refer to Fig. 3.

Table 2. Mean flow-weighted concentration of dissolved, algal-available, and total P in streamflow leaving each segment during 10 storm events on FD-36, 1966.

P component	Watershed segment† 1	2	3	4
	mg L^{-1}			
DP	0.084	0.110	0.138	0.163
AAP	0.140	0.192	0.227	0.270
TP	0.258	0.319	0.510	0.525

† Refer to Fig. 1.

given in Table 2. Distribution of all P forms (DP, AAP, and TP) changed little during transport through the channel. Dissolved P averaged about 30% of TP and AAP about 50% of TP at each flume. The decline in concentration between segments 4 and 1 was also similar for DP, AAP, and TP, i.e., approximately 50%. This suggests that during storms, channel processes in FD-36 may be relatively unimportant in modifying flow P concentration, compared with variations in source area P inputs along the channel.

Concentrations of P components in streamflow from FD-36 during 1996 and 1997 do not appear to reflect the fact that a large proportion of the cropped and pasture soils (78%) had high Mehlich-3 soil P (>100 mg kg^{-1}). From simulated rainfall studies on similar soils, Sharpley (1995) found DP concentrations of surface runoff to be >0.90 mg L^{-1} when Mehlich-3 was >100 mg kg^{-1}. Others have reported DP concentrations in runoff >0.65 mg L^{-1} (Pote et al., 1996) and 1.10 mg L^{-1} (Sharpley et al., 1986) at the same soil test P values. Clearly, there is a disparity between the areally extensive high soil P values and DP concentrations in streamflow lower than expected, suggesting that only some fraction of high-P soils over the watershed are controlling streamflow P concentrations.

Finally, over the entire watershed, there was little difference among the four watershed segments in the percent of soils >200 mg kg^{-1} Mehlich-3 P. This is the soil P category expected to result in enrichment of DP in runoff. However, on the near-stream basis, the areal distribution of these high P soils decreased from 50% in segment 4 to 8% in segment 1. The trend of decreasing stormflow DP concentration downstream (Table 2) is more closely related to the near-stream distribution of high P soils than to that of the whole watershed. This is consistent with findings from the runoff-generation study that the zone of surface runoff contributing to streamflow was typically within 30 m of the channel (Gburek and Zollweg, in press).

Considering the background studies and initial results from the FD-36 study in total, the point to emphasize is that it is not sufficient to consider only soil P, fertility, and land use characteristics of a watershed when developing P-management strategies. Rather, it is imperative that strategies also include the dominant hydrologic controls on P transport to better target monitoring and remediation programs, and more realistically evaluate the impact of P management.

The Phosphorus Index

In response to the need to reduce P export from agricultural land use, NRCS posed the Phosphorus Index (Lemunyon and Gilbert, 1993). The original PI (Table 3) incorporated transport characteristics (runoff and erosion) and source characteristics (soil test P and fertilizer and manure inputs) at the field scale in an additive and weighted format to assign a PI value. NRCS suggested that this value can be compared on a field-by-field basis to rank fields for their relative P-loss potential, and can also be categorized to express a site's absolute P-loss vulnerability.

All site characteristics in the PI are easily determined from field observations, farmer's records, and soil maps. A P-loss rating from None to Very High was assigned across the range of characteristic values, and each site characteristic was assigned a relative weighting based on the assumption that some characteristics have relatively greater effects on P loss than others. To determine the PI, the rating value for each characteristic is multiplied by the appropriate weighting factor, and the weighted ratings of all site characteristics are totaled. The PI values are also grouped into Site Vulnerability categories that can be used to guide application of BMPs to the site.

The ranking of PIs of individual fields was intended to identify where P-loss vulnerability is greatest. If one or more site characteristics appear to be influencing the PI disproportionately, the particular characteristic(s) may serve as the basis for implementing BMPs appropriate to the problem. Rather than use a general soil P-threshold approach applied categorically over the watershed, a proposal was made to apply the PI tool to allow greater flexibility and cost efficiencies in managing land use to protect water quality from degradation due to P loss (Lemunyon and Gilbert, 1993; Sharpley, 1995).

RESULTS AND DISCUSSION

The Original Phosphorus Index

Figure 4 shows the results of the original PI applied to FD-36, using information from Table 1. The PI methodology for determining surface runoff class for a field is adapted from the NRCS National Engineering Handbook (NRCS, 1985), where runoff is a function of curve number (CN) and field slope. Erosion-loss rate for each field was determined by applying the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and assigned a rating based on the values in Table 3. Table 1 shows that the field runoff ratings are typically in the low-to-medium categories because of the hydrologically similar well-drained soils over the watershed. Likewise, because of good management practices being applied to FD-36, the erosion characteristic ratings are always low, even though there are some soils with C and D slopes (Fig. 2). Mehlich-3 soil P values from the 30-m grid sampling (Fig. 1) were used to determine average soil P values for each field, and information on rates and methods of P application as fertilizer and manure was obtained directly from farmer surveys. Site Vulnerability groupings on Fig. 4 correspond to those in Table 3.

The PI shows a number of fields as having high vulnerability to P loss. These are fields that have high soil P values that are also receiving high applications of pig or chicken manure. Cropped fields having high soil P values, but receiving chemical fertilizer, tend to fall into the medium-vulnerability category. The low-vulnerability areas generally correspond to forest or near-stream marshy areas that were not in production and received no P as fertilizer or manure.

NRCS recognized that loss of P from the land surface to the stream is controlled by both source and transport factors, and included both in the original PI. However, they combined the two factors' effects in an additive format. On FD-36, the two transport characteristics of

Table 3. The Phosphorous Index, calculation methodology, and site vulnerability classification (adapted from Lemunyon and Gilbert, 1993).

		P loss rating (value)				
Site characteristic	**Weight**	**None (0)**	**Low (1)**	**Medium (2)**	**High (4)**	**Very High (8)**
Soil erosion	1.5	Not applicable	<10 Mg ha^{-1}	10–20 Mg ha^{-1}	20–30 Mg ha^{-1}	>30 Mg ha^{-1}
Runoff class	0.5	Negligible	Very low or low	Medium	High	Very high
Soil P test	1	Not applicable	Low	Medium	High	Excessive
P fertilizer application rate	0.75	None applied	1–15 kg P ha^{-1}	16–45 kg P ha^{-1}	46–75 kg P ha^{-1}	>76 kg P ha^{-1}
P fertilizer application method	0.5	None applied	Placed with planter deeper than 5 cm	Incorporated immediately before crop	Incorporated >3 mo before crop or surface-applied <3 mo before crop	Surface-applied >3 mo before crop
Organic P source application rate	1	None applied	1–15 kg P ha^{-1}	16–30 kg P ha^{-1}	31–45 kg P ha^{-1}	>46 kg P ha^{-1}
Organic P source application method	1	None	Injected deeper than 5 cm	Incorporated immediately before crop	Incorporated >3 mo before crop or surface-applied <3 mo before crop	Surface-applied to pasture, or >3 mo before crop

↓

PI = Σ (Characteristic rating value × Weight)

↓

PI	Site P loss vulnerability
<8	Low
8–14	Medium
15–32	High
>32	Very high

runoff and erosion typically contribute two to three points to the original PI value of each agricultural field. The additional points necessary to raise the PI values into the medium (PI > 8) or high (PI > 15) P loss vulnerability classifications come from source characteristics. Thus, the dominant control on P loss over FD-36 as indicated by the original PI is simply the pattern of land use.

Modifying the Phosphorus Index

The rationale behind formulating the original PI was that processes operating at the field scale indicate areas vulnerable to P loss, and PI values can be compared directly no matter where a field is located within the watershed-scale flow system. Our research into both runoff generation mechanisms and P transport patterns suggests that this assumption is incorrect. Areas ranked vulnerable to P loss by application of the PI to FD-36 (Fig. 4) also highlight the need for its modification. Fields along the northeastern boundary of the watershed (i.e., Fields 32 and 33) have well-drained permeable soils (runoff class, low to medium) and low rates of erosion, but high Mehlich-3 soil P and manure applications. Surface runoff rarely occurs on these fields but the PI ranks them as having high P-loss vulnerability.

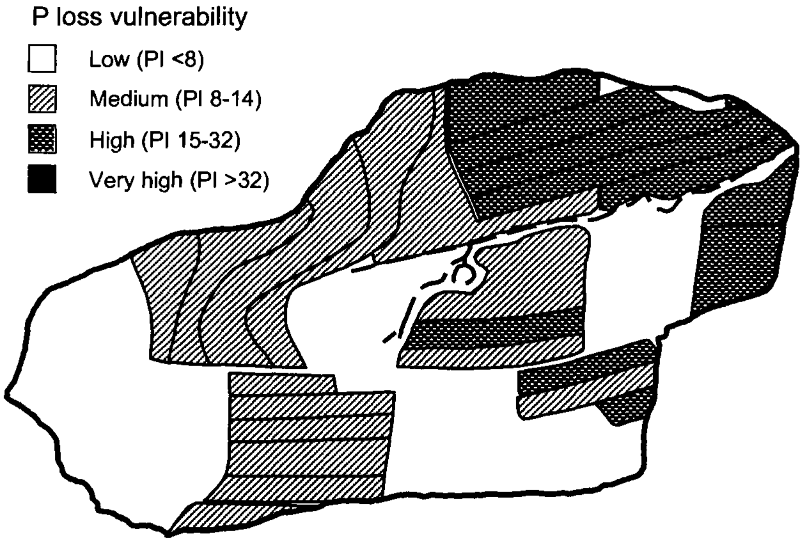


Fig. 4. Original Phosphorus Index applied to FD-36.

Table 4. The modified Phosphorous Index, calculation methodology, and site vulnerability classification; source and transport factors separated and return period incorporated.

		P loss rating (value)				
Site 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**	**<10 Mg ha^{-1}**	**10–20 Mg ha^{-1}**	**20–30 Mg ha^{-1}**	**>30 Mg ha^{-1}**
Runoff class	**1.0**	**Negligible**	**Very low or low**	**Medium**	**High**	**Very high**
		None (0.2)	**Low (0.4)**	**Medium (0.6)**	**High (0.8)**	**Very high (1.0)**
Return period/ distance	**1.0**	**>10 yr >170 m**	**6–10 yr 130–170 m**	**3–5 yr 80–130 m**	**1–2 yr 30–80 m**	**<1 yr <30 m**
Site source characteristics	**Weight**	**None (0)**	**Low (1)**	**Medium (2)**	**High (4)**	**Very high (8)**
Soil P test	**1**	**Not applicable**	**Low**	**Medium**	**High**	**Excessive**
P fertilizer application rate	**0.75**	**None applied**	**1–15 kg P ha^{-1}**	**16–45 kg P ha^{-1}**	**46–75 kg P ha^{-1}**	**>76 kg P ha^{-1}**
P fertilizer application method	**0.5**	**None applied**	**Placed with planter deeper than 5 cm**	**Incorporated immediately before crop**	**Incorporated >3 mo before crop or surface-applied <3 mo before crop**	**Surface-applied >3 mo before crop**
Organic P source application rate	**1**	**None applied**	**1–15 kg P ha^{-1}**	**16–30 kg P ha^{-1}**	**31–45 kg P ha^{-1}**	**>46 kg P ha^{-1}**
Organic P source applied method	**1**	**None**	**Injected deeper than 5 cm**	**Incorporated immediately before crop**	**Incorporated >3 mo before crop or surface-applied <3 mo before crop**	**Surface-applied to pasture, or >3 mo before crop**

↓

PI = (Erosion rating × Runoff rating × Return period rating*) × Σ (Source characteristic rating × Weight)

↓

PI	**Site P loss vulnerability**
<5	**Low**
5–9	**Medium**
9–22	**High**
>22	**Very high**

*** Note that rating for return period is different than that for Erosion and Runoff characteristics.**

Because of the additive nature of the PI calculation, the *lack of potential* for surface runoff to occur cannot impact the vulnerability classification. Further, the PI does not include provisions for characterizing whether or not surface runoff from a field impacts the stream, because proximity and potential for contribution to surface water via surface runoff was not considered. Clearly, based on our runoff-generation research and

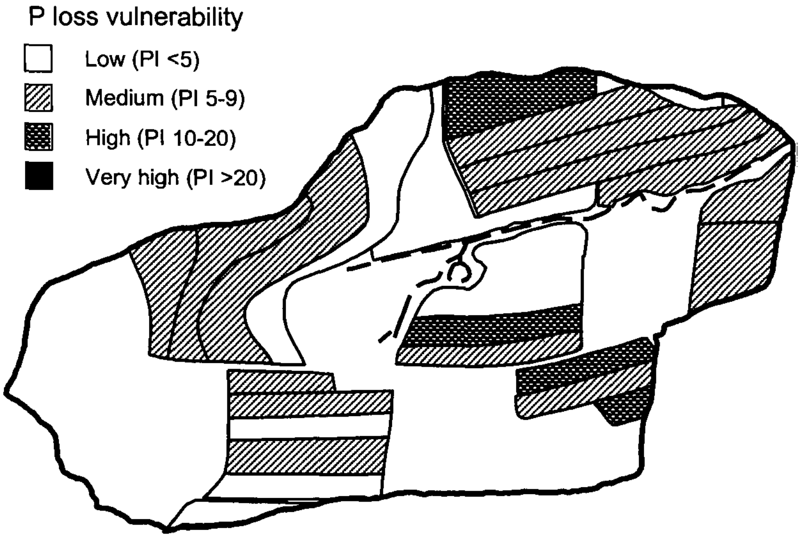


Fig. 5. Partially modified Phosphorus Index applied to FD-36; transport and source characteristics separated and multiplied, but return period not included.

initial research results from FD-36, proximity and potential for contributing to the stream via surface runoff must be considered in any tool for evaluation of P loss and management.

Based on these perceived shortcomings, we suggest two modifications to the original PI. One reformulates the PI to separately evaluate the P source and transport characteristics of a field and combine them in a multiplicative manner. This is referred to subsequently as the partially modified PI and is used to illustrate the effects of the multiplicative formulation only. The other modification incorporates the hydrologic return period concept to quantify the probability (or risk) of surface runoff from a field impacting the stream. The fully modified PI, incorporating separation and multiplication of source and transport factors, return period or surface runoff from contributing areas *applicable to FD-36* as an added transport factor, and methodology for the PI calculation and site ranking, is shown as Table 4. The modifications will be described in sequence, followed by application of the modified PI to FD-36.

Separation and Multiplication of Source and Transport Factors—The Partially Modified Phosphorus Index

High source characteristics alone can result in high P-loss vulnerability when applying the original PI. In reality though, if there is little or no possibility of transport from the site, high source factors simply indicate a potential source of P to the stream—in this situation, the site's P loss vulnerability should be low, regardless of amount of P available for transport. Conversely, a site may have high transport characteristics, i.e., higher soil erosion and runoff class values in Table 3, but correspondingly low source characteristics. Again, because of its additive nature, the original PI will rank the site as having high vulnerability to P loss even though there is little or no P available to lose. These two cases point out a basic flaw in the formulation of the PI and suggest making the two generalized controls on P loss from a field, source and transport, multiplicative in nature rather than additive. If ratings and weightings are reformulated in this manner, a low transport factor will counteract a high source factor, and vice versa, but the PI still maintains the capability to indicate a field with high P loss vulnerability when each factor is medium to high.

We began modifying the structure of the original PI (Table 3) by first separating site characteristics into P transport and source groups (see relevant parts of Table 4). The source characteristics (soil test, and fertilizer and manure rates and applications) ratings and weightings remain the same as in the original PI, and a total source factor is calculated as before. Each source characteristic's rating value is multiplied by its weight, and the five resulting values are totaled. Note that the source factor alone has a maximum value of 34.

The P transport characteristics of erosion and runoff class in the partial modification of the PI retain the same categorization as in the original PI, but their role in calculating the final site PI is different. Individual transport characteristics of erosion and runoff class (along with return period considered subsequently) are reformulated to give a composite transport factor. Weighting values for these characteristics in the second column of the table are set to 1.0, and the P-loss rating values across columns are used to account for each characteristic's weighting. In this section of the partially modified PI, loss rating values for the transport characteristics are assigned values between 0.0 and 1.0. We chose the rating values for runoff and erosion characteristics (0.6 to 1.0) specifically to represent the FD-36 situation because erosion and surface runoff have about the same importance related to P transport. However, where relative contributions of runoff and erosion to P loss are different, these rating values, as well as others in the PI, can be altered to reflect localized conditions. The transport characteristic rating values for runoff and erosion are then multiplied together to give the composite transport factor, and the partially modified PI is determined by multiplying the transport factor by the source factor.

Because the transport characteristics' ratings range between 0.0 and 1.0 and are multiplied together, the composite transport factor will also be between 0.0 and 1.0. Thus, the transport factor provides a scaling of the P source factor. If all transport characteristics are categorized as very high, the composite transport factor will be 1.0 and the PI will equal the value of the source factor. We view this case as the full potential of the source being realized, i.e., it is not reduced by limited transport. Where any or all of the transport characteristic ratings are less than very high, they will reduce the composite transport factor to less than 1.0, and in turn reduce the effect of the P source, no matter what rating value it has.

Figure 5 shows the results of applying the partially modified PI to watershed FD-36; i.e., calculation of the PI using only the transport and source characteristics in Table 3, in the multiplicative format of Table 4 but not including the return period. Figure 5 illustrates the value of separating transport and source within the PI, and of using transport to scale the source factor. First note that the ranges of site vulnerability from the partially modified PI (see Table 4) are reduced in numeric value compared with Table 3. Only source characteristics contribute to the maximum possible value in the modified PI—34 (compared with 50 in the original PI). The site vulnerability categories in Table 4 and Fig. 5 are scaled by the ratio of 34:50 throughout their entire range. Secondly, note the effects of the new PI formulation in classifying fields originally designated high P-loss vulnerability based strictly on their high soil P and manure application rates. These fields (i.e., 22, 23, and 29–32) now are in the medium category—while they maintain a high source rating, medium-to-low transport factors reduce their overall vulnerability to P loss. Interestingly, Field 23 at the northern watershed boundary maintains its high rating because of a medium runoff rating combined with a high soil P. Nonetheless, simply separating source and transport factors and combining them in a multiplicative format provides a more realistic picture of P-loss vulnerability when comparing one field to another. However, this step is still related more to ranking of edge-of-field losses than it is to position of the field within the watershed and its relationship to the stream. Thus, no consideration is given to the potential for surface runoff, if it occurs, to actually reach the stream and contribute P to watershed discharge.

Incorporation of Return Period—The Modified Phosphorus Index

Both the CN runoff prediction method and the USLE were originally developed to apply to field-scale problems. Because of their success at this scale, they were extended to watershed-scale evaluations—the PI will certainly follow this same path. While P loss is a field-scale problem and will be managed at this same scale, the watershed is the scale of impact. This larger scale is where P loss will be documented and effects of P management will be evaluated. As importantly, the watershed is the control on formation of hydrologic source areas. Thus, the PI should have the capability to rank fields with respect to their relative vulnerability of P loss within the watershed-scale flow system.

Johnes and Heathwaite (1997) suggested a distance-decay function to model the impact of land use change on stream quality in the Slapton Watershed in southwest England. They argued that nutrient contributing areas in watershed highlands at some distance from the stream were less important than were near-stream zones due to attenuation and uptake of nutrients during downslope transit. In their model, different weighting was allocated to nutrient export from land located within 50 m of the stream relative to land more than 50 m from surface water. Magette (1998) considered distance to water bodies as a transport factor in a watershed-scale P Risk Index based on the PI. A number of other unpublished modifications to the PI currently being considered also include distance from the stream as a site characteristic, but these typically incorporate a single arbitrary distance and do not include it in a multiplicative format as is done here.

We suggest incorporating an additional transport characteristic reflecting potential for surface runoff from hydrologic source areas based on the return-period concept. The return period, a commonly accepted hydrologic design criterion, represents the probability (or risk) of a rainfall or a flood of a given magnitude. Return period is typically expressed in terms of years and is most simply understood to imply the particular event occurring once within that return period on the average. For instance, a flood having a 10-yr return period will occur, when averaged over the long term, once every 10 yr, but not necessarily once within every 10-yr period.

To incorporate return period into the partially modified PI as a transport characteristic, we developed a relationship between peak flow and contributing distance from the stream specifically for watershed FD-36 using data from each runoff event monitored in 1996 and 1997. The data and a best-fit relationship are shown in the upper part of the nomograph presented as Fig. 6. A relationship between peak flow and return period is needed to complete the nomograph. This latter relationship is commonly available in literature related to design hydrology. Stedinger et al. (1992) provide an excellent description of the return-period methodology and a comprehensive list of related references. Here, design equations for a watershed of the size of FD-36 within east-central Pennsylvania were presented by Flippo (1997). The necessary relationship is shown as the lower part of Fig. 6. The final steps when incorporating return period as an additional transport characteristic are to (i) choose a series of return periods (or probabilities of occurrence) representing acceptable levels of risk for impacting the stream by P loss corresponding to the none-to-very high ratings; (ii) use Fig. 6 to determine the associated contributing distances; and (iii) insert the return periods and distances into the partially modified PI with appropriate weightings.

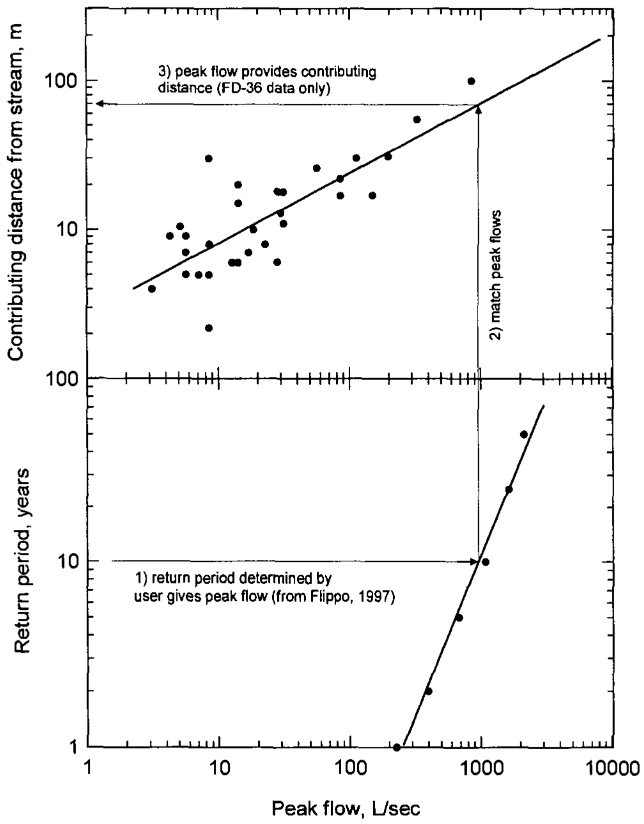


Fig. 6. Nomograph for determining contributing distance as a function of return period for FD-36.

We chose return periods of <1, 1 to 2, 3 to 5, 6 to 10, and >10 years as acceptable risks of P input to the stream to represent the loss rating categories from very high to none, respectively. The higher risk of surface runoff contributing P to the stream is associated with shorter return periods and smaller storms. These storms contribute surface runoff from more limited watershed areas but with a high frequency of occurrence. These areas *must* be managed to minimize P build-up in the soil and control P loss to the stream. Larger storms associated with longer return periods occur much less

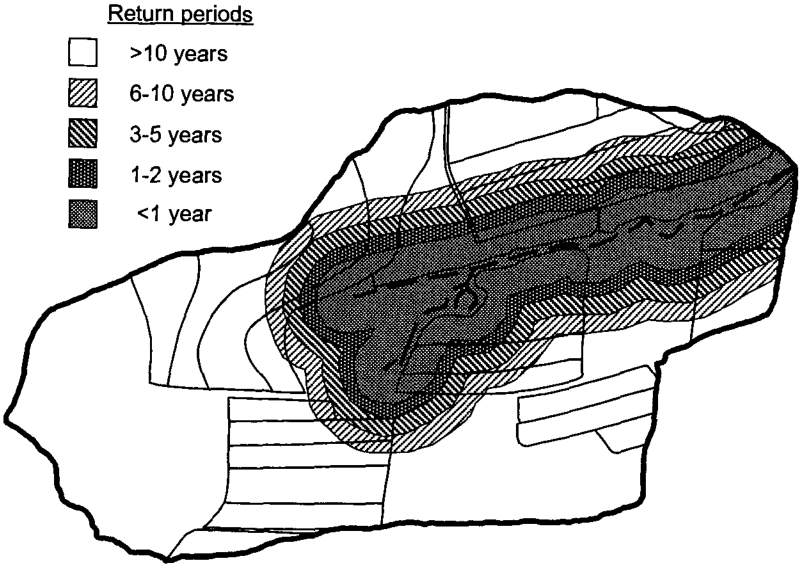


Fig. 7. Surface runoff contributing areas of FD-36 for modified Phosphorus Index return periods.

often. The contributing areas associated with these storms not already included with the smaller return period storms, pose a lower risk of P loss to the stream. Consequently, they require less intensive management for P loss via surface runoff. The return periods used here that correspond to the contributing distances determined from Fig. 6 are shown as part of Table 4. How these return periods are individually weighted may be a function of sensitivity of the receiving water and the degree to which planners and action or regulatory agencies want to protect or remediate a given water body. We consider this transport characteristic to be a critical part of the modified PI, so we assigned P loss rating values of 0.2 to 1.0 to the categories none to very high, respectively.

The contributing distances associated with the return periods chosen are a function of hydrology and watershed geometry, not field boundaries and land use as are the PI source and transport characteristics. Thus, to apply the return period/contributing distance concept to a watershed, we must define watershed geometry in a spatial manner, not restricted to field boundaries. Here for example, we redefined the FD-36 watershed as a series of 5 by 5-m grid cells using the Idrisi GIS (Eastman, 1997), and represented the contributing distances in Table 4 as buffers around the stream (Fig. 7); some type of buffer subroutine is found in most GIS packages. Depending on the user's resources and precision desired though, there are alternative methods for mapping these distances, such as simple scaling on air photos used for soil interpretation. The desired precision depends, to a great extent, on the scale of the mapping. For smaller storms and detailed examination of the runoff generation process, we observe a high degree of irregularity in the outer boundary of the contributing distance. However, as storms get larger and the spatial scale of concern increases, this boundary becomes smoother, allowing the use of mapping techniques less sophisticated than GIS.

It is obvious from our mapping that larger return periods (i.e., >5 yr) impact sizable areas of the watershed and a relatively large number of fields. This observation alone suggests some degree of caution when attempting to manage P loss associated with storms of larger return periods. Figure 7 may also be used in a positive manner though, to illustrate frequencies at which we can expect the stream to be affected by P loss from specific areas of the watershed. This allows P-management decisions to be made that afford some level of protection to the stream, but do not impact existing agricultural operations in a significant way. In other words, it allows us to more easily evaluate the trade-offs between protecting the stream and allowing agricultural activities to continue.

Application of the Modified Phosphorus Index

Results of applying the modified PI to FD-36 are shown as Fig. 8. The PI for each 25-m^2 cell within the watershed was calculated directly from Table 4 as though each cell was an individual field, and the cell-based PI values were grouped according to the P Loss Vulnerability classifications in the table. Selected sites are numbered on the figure for subsequent discussion.

Only one relatively small area (Site 4, part of Field 20) remained in the high P-loss vulnerability category. Field 20 had high soil P and manure application, and the zone of high P loss vulnerability is within the 1-yr return period contributing distance. Two areas bordering the stream near the watershed outlet (Sites 1 and 2 on Fig. 8) that had medium P-loss vulnerability when considering only runoff and erosion transport characteristics (Fig. 5), remained in the medium category because they were within the 2-yr return period contributing distance. These areas were within the zones of the watershed that were observed to contribute surface runoff to the stream during a number of storms in 1996 and 1997. The remainder of the fields that were medium and high in Fig. 5 were ranked as low P-loss vulnerability after applying the modified PI, because they were within loca-

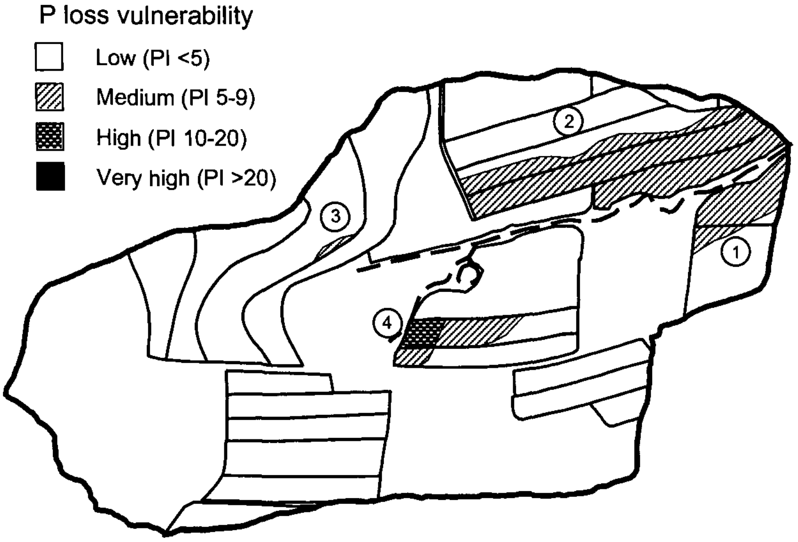


Fig. 8. Modified Phosphorus Index applied to FD-36; sites noted are keyed to discussion in text.

tions of the watershed corresponding to larger return periods for surface runoff impacting the stream. With the return periods and weightings we chose, all areas of the watershed outside the 5-yr return period boundary were ranked as having low P-loss vulnerability, even though many of them had high source characteristics (soil P and organic P applied, Table 1).

The pattern of P-loss vulnerability illustrated by Fig. 8 reflects hydrologic controls on P transport at the watershed scale, something not considered in the original PI. The modified PI accounts for the interaction between source and transport factors more realistically (multiplying rather than adding) and incorporates the probabilities of occurrence of the transport phenomenon expressed in a return period format. With this reformulation, the PI can provide flexibility in P management over a watershed based on choice of appropriate risk levels, delineation of CSAs controlling P loss, and application of appropriate BMPs for management. Specific return periods and the corresponding contributing distances and the relative weightings for all transport characteristics, as well as those of the source characteristics for that matter, can be adjusted to reflect regional differences in controlling processes and acceptable levels of risk. In a more general sense though, the modified PI we have developed represents the *form* of the interactions between P source and transport factors that create CSAs of P loss from a watershed perspective. It maintains much of the simplicity of the original PI, yet is more realistic when ranking fields on a whole-watershed basis.

MANAGEMENT IMPLICATIONS

A P management framework should begin by assessing spatial distribution in site vulnerability to P loss. In general, managing source factors involves reducing soil P levels and fertilizer and manure applications, while managing transport factors involves minimizing the incidence and extent of surface runoff. Which approach to emphasize depends on the status and management objectives of the watershed. In some eastern states in the USA for instance, legislation has been introduced to base manure inputs to land on P rather than N, and to apply these guidelines over the entire watershed (Sims and Sharpley, 1998). If enacted, such legislation will preclude consideration of hydrologic characteristics of the watershed that determine the dominant flow pathways, source areas, and likelihood of P loss. However, it is clear that a technically sound framework for P management from a watershed perspective should incorporate definition of CSAs of P export so that optimal strategies can be implemented and evaluated at both the farm and watershed scales to best manage P loss.

Source Management

Related to P source management, some recent nutrient management programs in the USA have sought to establish general threshold soil P concentrations to guide P application rates (Sharpley et al., 1996). With such programs in place, source management for P would be based solely on soil test P for all fields within the watershed. Without considering the hydrologic pathways that govern P transport, these blanket programs are likely to prove unnecessarily restrictive. For example, based on soil P testing alone, applying P to 63% of the cropped area within watershed FD-36 would be limited or restricted. In contrast, the modified PI suggests that P management should be focused on the specific, limited, CSAs where source and transport factors interact to produce P loss. For fields outside of these source areas where transport potential is minimal, P source management for P loss via surface runoff is of less immediate concern. As addressed in the next section though, there may be other concerns related to P management in these less-critical source areas.

Transport Management

Phosphorus transport generally occurs in surface runoff pathways from well-defined areas of a watershed, so the primary transport management strategy is to minimize surface runoff and particulate transport. Surface runoff mobilizes sediment together with P originally applied as either fertilizer or manure. From the transport point of view, P loss can be reduced by any management practice that slows or reduces surface runoff and/or encourages infiltration or sediment trapping. Practices can be directed toward on-site prevention or transport interception and include such measures as terracing, contour tillage, cover crops, buffer strips, riparian zones, and impoundments or small reservoirs. These practices are generally more efficient at reducing particulate P as compared with DP. It may also be possible to reduce P loss by breaking the link between the source and the transport pathways. For instance, incorporating manure into the soil profile either by tillage or subsurface placement reduces its degree of exposure, and thus the potential for transfer into the transport process (Sharpley et al., 1998).

As a caveat, these transport-oriented approaches, as well as our particular emphasis on transport controls in the modified PI, tend to focus on P management in the potential contributing areas, while not directly addressing the need for management in the noncontributing zones. Such focus will only be effective in managing P export to streams under conditions where potential subsurface pathways of P loss are unimportant. However, where there are conditions conducive to subsurface transport (e.g., coarse-textured soils, artificial drainage, ditches, and shallow ground water tables), there is a risk that disposal of manure in typically noncontributing areas may transfer P loss from surface to subsurface delivery mechanisms (Heathwaite, 1997).

Phosphorus Management on FD-36—The Watershed Scale

The four sites noted on Fig. 8 illustrate specific approaches or limitations to P source and transport management at the upland watershed scale. Site 1 is a location where the management-related boundary between a medium and low P-loss vulnerability zone is at about the same distance from the stream as is a field boundary. However, the field and P-management boundaries are at different angles with respect to the stream. In this case, simply realigning the field boundary slightly to make it coincident with the contributing distance boundary would not change the pattern of land use substantially but, based on application of the modified PI, would reduce risk of P loss to the channel.

Site 2 illustrates two potential problems resulting from application of the revised PI. First, the boundary between low and medium P-loss vulnerability areas is parallel to the meandering path of the stream, but the field boundaries in the proximity of the P-management boundary are straight. Second, the P-management boundary falls in the middle of an existing field rather than along an established field boundary. The question raised is how do we resolve these two mismatches? There is one potential solution for both problems. Considering the uncertainties in our understanding of the natural watershed flow system and the assumptions made in development of the modified PI, the generalized contributing distance from the stream should be the main concern in P management, not the small-scale variabilities associated with detailed stream geometry or surface topography. The solution would be to combine Fields 30, 31 (containing the P-management boundary), and 32 into two fields, with the new field boundary being straight but generally coincident with the P-management boundary. Since field and P management boundaries are roughly parallel in this part of the watershed, conformance with every meander in the management boundary reflecting those of the stream is of secondary importance.

Site 3 illustrates the case of a very small P-sensitive area being delineated because of a local and unique combination of source and transport characteristics. Here we encounter a conflict between P-management recommendations and the practicalities of agricultural operations. It is highly unlikely that a watershed planner or action agency would request that a farmer manage this small piece of land having a medium P-loss vulnerability differently than the low-vulnerability areas surrounding it. Because of our limited understanding of the system, designation of this zone by the modified PI has a high degree of uncertainty. Yet this situation is worth noting because it illustrates that when the modified (or even the original) PI is applied to a watershed, there will always be variabilities in source or transport factors at unmanageably small scales that may disproportionally contribute to P loss from the watershed. If we attempt to define the PI incorporating return periods and contributing distances that transcend field boundaries, we will have to determine when these small contributing areas (like that at Site 3) are important and when they can be overlooked. Application of the modified PI, like the original, will still rely on judgement and common sense in defining areas of the watershed where P management will be recommended.

Finally, Site 4 illustrates what is the most important CSA for P loss from FD-36, based on application of the modified PI. Consequently, what is done at this site may be the most critical P-management decision made for FD-36. The particular area having a high P-loss vulnerability designation is only a small part of Field 20. But because of its P loss vulnerability, proper management of that small area must be stressed to the farmer and incorporated into farm management plans. Here it is most obvious that when attempting to manage P loss at the watershed scale, we will have to resolve the spatially variable aspects of the modified PI that are not always associated with established field boundaries. In this case, the farmer has only limited alternatives. Either the entirety of Field 20 must be managed to limit available P in the high P-loss vulnerability zone, or that particular portion of the field will have to be separated from routine management for production and instead managed to control P loss to the stream.

Because the return period transport characteristic of the modified PI is generally aligned with the stream (Fig. 7), encouraging contour farming may help in P management since field and row boundaries will generally parallel the P management boundaries, especially in the near-stream zones. Altering field management to meet P-management needs will be more easily implemented under these conditions. Farmers may not want to modify their overall field boundaries, but differential land management to accommodate P-management objectives within a field based on a number of rows away from the stream, for instance, may be acceptable.

The approach to farm and watershed management necessary to reduce P export suggested by application of the modified PI to FD-36 is that of a *precision agriculture* type of farming, even within the context of the relatively small fields characteristic of agriculture in the northeastern USA. Yet that appears to be the most effective approach to P management over the type of landscapes and hydrologic framework in which these small fields exist.

CONCLUSIONS

In the most simple sense, intersections of surface runoff source areas within a watershed with areas of high soil P and P application via manures and fertilizers are what create CSAs controlling P export. Thus, P export may be most efficiently managed by focusing on controlling soil P levels and fertilizer and manure applications in the watershed zones most likely to produce surface runoff. In the long term, the overall flow systems of humid-climate upland watersheds tend to be fixed in space—outside of major structural modifications, there is minimal opportunity to control or manipulate the hydrology of these flow systems at a scale large enough to alter the dominant flowpath patterns. Thus, management of the source terms in the PI will be easier and more effective than those associated with transport.

Strategies for P management have been developed and implemented at farm or watershed scales, but because of a lack of consideration of P transport characteristics, these narrowly targeted strategies may lead to conflicting or suboptimal advice. Rather, the prevention of P loss from agricultural watersheds must focus on defining, targeting, and remediating the CSAs of P loss. These CSAs are spatially variable over the watershed, even within individual fields, so differing management levels are appropriate for different areas of a watershed. The CSAs for P loss in our study area are primarily close to the stream, perhaps on the order of tens of meters wide. These specific zones and/or distances may be different depending on physiographic region, controlling hydrology, and varying methods for their delineation as discussed previously. But the *concept* of CSAs will apply in any setting—there will always be some areas of a watershed more conducive to producing surface runoff and associated P loss than others. The structure of these areas must be considered, along with patterns of land use, when evaluating or attempting to manage P loss from an agricultural watershed.

The suggested modifications to the Phosphorus Index represent these CSAs conceptually, accounting for the interactions between P source and transport factors and the probabilities with which the P sources over the watershed are translated to P loss in streamflow. The modified PI delineates where P-based management of fertilizers and manures should be targeted for most effective remediation, and accounts for the transport characteristics at the watershed scale. It provides a categorization of edge-of-field risk of P loss that is linked quantitatively to its impact on the stream by using hydrologic design criteria specific to the watershed. The impact is expressed quantitatively in terms of the hydrologic return-period concept, and the key is inclusion of a relationship between return period and contributing distance.

We report initial research results linking the spatial variation in watershed P-loss vulnerability to P concentrations in receiving waters during storms, but the extent to which edge-of-field risks of P loss are reflected by in-stream water quality remains under-researched. Understanding this relationship is essential to assess the impact of field-scale land management on receiving waters. Likewise, the factors and weightings we present are specific to conditions represented by the combination of land use and hydrology of watershed FD-36. These may be altered based on other conditions to which the modified PI is applied, but like CSAs, the *concept* of the modified PI should be able to be adapted to any conditions.

Further research is needed to apply and evaluate the modified PI on watersheds within the variety of Physiographic Provinces of the Chesapeake Bay Basin, preferably with the aid of trained nutrient-management planners. This will allow continued improvement and refinement of the PI so that it can become an effective tool for integration into the NRCS planning program for nutrient management.

Finally and perhaps most importantly, the modified PI proposed is still only an interim measure. It provides immediate direction for P management that accounts for the spatially variable source and transport properties of a watershed. However, we must remember the figures presented in the introductory portion of this paper: an annual excess of 26 kg P ha^{-1} in the USA and 10 kg ha^{-1} in the UK, a problem further complicated by uneven distribution typically tied to concentrated animal production. While we are developing tools to address immediate P management at the watershed scale, we should also be working to reduce these two excesses. Achieving an overall P balance is the ultimate answer to P management at the watershed scale.

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