Integrating Contributing Areas and Indexing Phosphorus Loss from Agricultural Watersheds

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Most states in the USA have adopted P Indexing to guide P-based management of agricultural fields by identifying the relative risk of P loss at farm and watershed scales. To a large extent, this risk is based on hydrologic principles that frequently occurring storms can initiate surface runoff from fields. Once initiated, this hydrological pathway has a high potential to transport P to the stream. In regions where hydrologically active areas of watersheds vary in time and space, surface runoff generation by "saturation excess" has been linked to distance from stream, with larger events resulting in larger contributing distances. Thus, storm-return period and P loss from a 39.5-ha mixed-land-use watershed in Pennsylvania was evaluated to relate return-period thresholds and distances contributing P to streams. Of 248 storm flows between 1997 and 2006, 93% had a return period of 1 yr, contributing 47% of total P (TP) export, while the largest two storms (10-yr return period) accounted for 23% of TP export. Contributing distance thresholds for the watershed were determined (50–150 m) for a range of storm-return periods (1−10 yr) from hydrograph analysis. By modifying storm-return period thresholds in the P Index and thereby contributing distance, it is possible to account for greater risk of P loss during large storms. For instance, increasing return period threshold from 1 (current P indices) to 5 yr, which accounted for 67% of TP export, increased the P-management restricted area from 20 to 58% of the watershed. An increase in impacted area relative to a decreased risk of P loss creates a management-policy dilemma that cannot be ignored.

In response to water quality concerns, each state in the USA has had to develop guidelines for managing the land application of phosphorus (P) at farm and watershed scales based on the potential for P loss in agricultural runoff (USDA and USEPA, 1999). This response was prompted by a federal initiative in which the U.S. Department of Agriculture and U.S. Environmental Protection Agency created a joint strategy to implement Comprehensive Nutrient Management Plans on Animal Feeding Operations, with a national implementation deadline of 2008. A survey of 50 states enacting Comprehensive Nutrient Management Plan strategies shows that 47 have adopted P Indexing for P-based nutrient management planning (Sharpley et al., 2003).

Reasons for this general acceptance of P Indexing include the fact that alternative P management options (agronomic and environmental soil test P) are inflexible and often overly restrictive. For instance, agronomic and soil test P thresholds are based on crop response to P applications required to meet expected crop yield goals and to estimate soil P levels at which no crop response to added P is expected. They were not designed to reflect the potential for P loss from a given soil. Environmental soil P thresholds have been developed from surface runoff studies and reflect the release of P from soil to runoff water as a function of soil P at a plot (approximately 2 m^2) or small field scale (<0.5 ha) (Pote et al., 1996; Sharpley et al., 1996). However, soil test P thresholds alone do not account for the critical role of transport mechanisms in determining a site's P loss potential. For example, a watershed-based comparison of the three assessment options showed that in the mixed land use watershed discussed in this paper, 90% of the managed area was above an agronomic threshold of 50 mg kg^{-1} Mehlich-3–extractable soil P (Mehlich-3 P), whereas 82% was above an environmental threshold of 190 mg kg^{-1} Mehlich-3 P,

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Abbreviations: DRP, dissolved reactive P; Mehlich-3 P, Mehlich-3–extractable soil P; TP, total P; VSA, variable source area.

Table 1. Phosphorus Index used to determine the risk of P loss within the FD-36 watershed (Weld et al., 2007).

Part A: Source factors					
Soil test			**Soil test P (mg P kg^{-1})**		
Soil test P rating = 0.20 × soil test P (mg P kg^{-1})					
Fertilizer P rate	fertilizer P (kg P ha^{-1})				
Manure P rate	manure P (kg P ha^{-1})				
P source application method	0.2 (placed or injected 2″ or more deep)	0.4 (incorporated <1 wk)	0.6 (incorporated >1 wk or not incorporated Apr.–Oct.)	0.8 (incorporated >1 wk or not incorporated Nov.–Mar.)	1.0 (surface-applied to frozen or snow covered soil)
Fertilizer rating = rate × method					
Manure P availability	0.5 (treated manure/biosolids)		0.8 (dairy)	1.0 (poultry/swine)	
	manure rating = rate × method × availability				
	source factor = soil test P rating + fertilizer rating + manure rating				
Part B: Transport factors					
Erosion			**Soil loss (t ha^{-1} yr^{-1})**		
Runoff potential	0 (very low)	2 (low)	4 (medium)	6 (high)	8 (very high)
Subsurface drainage	0 (none)		1 (some)		2 (patterned or rapid permeability soil near a stream)
Return period/ contrib. distance†	0 (>10 yr; >150 m)	2 (6–10 yr; 100–150 m)	4 (3–5 yr; 75–100 m)	6 (1–2 yr; 50–75 m)	8 (<1 yr; <50 m)
Transport sum = erosion + runoff potential + subsurface drainage + contributing distance					
Modified connectivity	0.7 (riparian buffer; applies to distance <30 m)		1.0 (grassed waterway or none)	1.1 (direct connection; applies to distance >30 m)	
Transport factor = modified connectivity × (transport sum/22)					
Phosphorus Index value = 2 × source factor × transport factor					
Part C: Risk of P loss as represented by P Index values					
P Index value	<60		60–79	80–100	>100
P loss rating	low		medium	high	very high

† Contributing distances are rounded to the nearest 5.

which would invoke P-restricted management (McDowell et al., 2001). Using the Pennsylvania P Index, where all factor contributing to P loss were considered, 23% of the managed area of the watershed would be P restrictive.

The concept of the P Index is to identify and rank the risk of P loss from fields within a watershed. Areas or fields most vulnerable to P loss occur where areas contributing surface runoff or erosion to stream flow (i.e., transport factors) coincide with high soil P or recent P applications (i.e., source factors) (Gburek and Sharpley, 1998; Gburek et al., 2000; Pionke et al., 2000) (Table 1). Even in regions where subsurface transport of P dominates watershed P loss (e.g., some areas of the Coastal Plain), areas contributing P to drainage waters are localized to soils with high soil P saturation and hydrologic connectivity to the surface drainage network (Schoumans and Breeuwsma, 1997). However, subsurface export of P via soil macropores and in drainflow may continue to operate over broad timeframes outside the storm event itself, whereas the timeframe of surface runoff incidence is much more discrete (Heathwaite and Dils, 2000). Additionally, different P fractions may be more or less susceptible to mobilization in surface runoff or subsurface pathways. Although relatively large soil particles may be important for P transfers in surface runoff, colloid-sized particles may represent an important vehicle for subsurface P transfers via macropores and drains (Heathwaite et al., 2005; 2006).

Source (soil, fertilizer, and manure P) and transport (erosion, surface runoff, and subsurface flow) factors in P Indices are scientifically supported and quantified by plot-, field-, and watershed-scale research. For instance, accumulation of P in the surface 5 cm of soil has been shown to enrich surface and subsurface runoff with P (Andraski and Bundy, 2003; Daverede et al., 2003; Torbert et al., 2002); the rate, method, and timing of P added as fertilizer or manure affects P loss (Andraski et al., 2003; Tarkalson and Mikkelsen, 2004); and greater runoff and erosion results in a direct increase in total P loss (Sharpley and Smith, 1994). One important factor recently addressed in the transport component of many P Indices is the proximity of a field to receiving water, expressed as contributing distance (Gburek et al., 2000). Sharpley et al. (2003) reported that 32 of 42 P Indices surveyed used some type of "connectivity" factor to account for the relative potential for connected runoff from field to stream and/or the presence of a buffer that could potentially filter runoff.

To a large extent, expression of the risk of P loss associated with contributing distance is based on the variable source area (VSA) hydrologic paradigm. Variable source area hydrology assumes that there are spatially and temporally dynamic areas within a watershed that generate surface runoff (Beven and Wood, 1983; Hewlett and Hibbert, 1967). Within watersheds characterized by VSA hydrology, areas producing surface runoff typically expand during a storm. Variable source areas can vary in their location within the watershed and in their size in response to interactions between rainfall, soil properties, topography, ground water levels, bedrock stratigraphy, and antecedent watershed moisture status (Freer et al., 2002; Gburek and Sharpley, 1998). Thus, although the VSA concept holds across watersheds, the location and extent of contributing areas varies with the previously mentioned factors.

Surface runoff from VSAs can be triggered where the soil becomes saturated via lateral percolation above an impeding horizon. Saturation-excess surface runoff can also occur where the water table rises to the ground surface through convergent flow into hillslope hollows or when rising groundwater levels result in

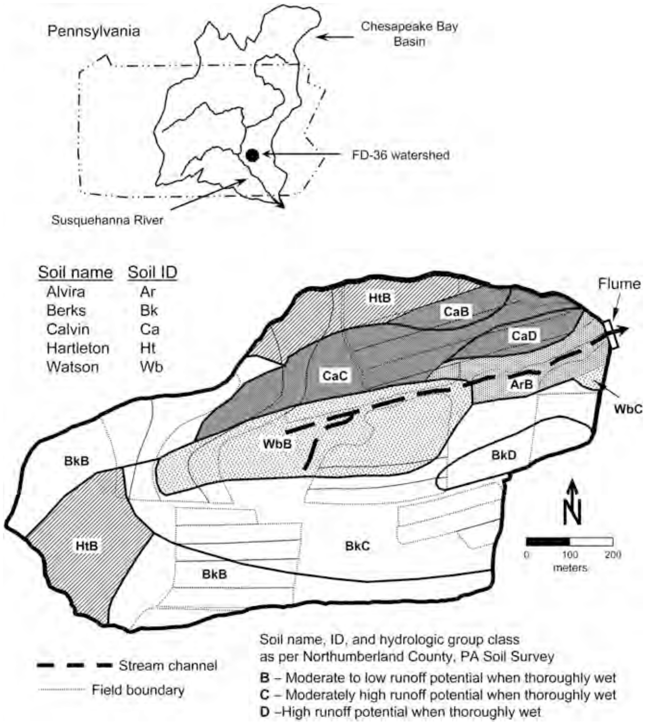

Fig. 1. The FD-36 watershed, soil series and drainage class distribution, field boundaries, and location within Pennsylvania and the Chesapeake Bay Watershed (USDA-NRCS, 1993).

saturation of near-stream zones. Under steady rainfall, saturation-excess flow (i.e., soil becomes saturated from below and rainfall runs off) requires much lower rainfall intensities to occur, constrasting with infiltration-excess flow (i.e., rainfall rate exceeds infiltration rate of soil and rainfall runs off). A growing body of research indicates that saturation-excess flow may be a more important mechanism of surface runoff generation than infiltration-excess flow in temperate, humid systems characterized by shallow soils or soils with pronounced discontinuities (e.g., Needleman et al., 2004). As a consequence, frequently occurring storm flow events have the potential to initiate runoff from near-stream critical source-areas (fields) and transport P from these locations to the stream (Gburek and Sharpley, 1998).

For VSAs some distance from the stream, continuous hydrological connectivity along the flowpath is necessary to link fields to stream. Work by Lane et al. (2006) has demonstrated the value of the network index in predicting the likelihood of this pathway being connected. Unlike many of the other P Index factors, especially those dealing with P source, the weighting of contributing distance has been more based on educated conjecture than on field-based experimental findings. Contributing distances can be determined from watershed data relating storm-return period and peak stream flow (Stedinger et al., 1992; Gburek and Sharpley, 1998). For the Pennsylvania P Index, return periods of <1 to >10 yr are associated with distances of <30 to >150 m (rounded to the nearest 5), respectively, and assigned a decreasing risk of P input to the stream (Table 1). The shorter the storm-return period, the smaller the area that contributes runoff to a stream will be. Larger storms contribute P from a greater distance from the stream but occur less frequently (i.e., long return period). However, these large storms can contribute a large portion of P exported annually from watersheds assuming they remain hydrologically connected so that the initial P mobilized in surface runoff is not redeposited before it reaches the stream. For instance, Pionke et al. (1999) generalized that about 90% of annual P export from mixed land use watersheds (30% forest, 20% pasture, and 50% crops) occurs during only one or two of the largest storms. Also, more than 75% of annual runoff from catchments in Ohio (Edwards and Owens, 1991) and Oklahoma (Smith et al., 1991) occurred in one or two severe storms, which contributed over 90% of annual P export (0.2 and 5.0 kg ha^{-1} yr^{-1}, respectively).

The rationale for including contributing distances in P Indices is that fields close to or adjacent to a stream are more likely to contribute P than fields that are further away (Gburek and Sharpley, 1998). However, by assigning greater P loss risks (range from 0 to 8; Table 1) to decreasing storm-return periods (>10 to <1 yr), the P Indexing approach infers that the greatest P loss potential is from storms of short-return periods. This assumption allows a nutrient management planner to set a minimum contributing distance, and corresponding watershed area, at greatest risk of P loss that should be earmarked for conservation management to minimize the potential for P loss. Unlike the other P Index factors, there is little information defining the relationship between contributing distance as represented by storm-return period and P export from a watershed.

This paper reports an evaluation of the delineation of land area contributing surface runoff to stream flow as a function of storm size, risk of P loss, and P Indices for an agricultural watershed in Pennsylvania (FD-36). The risk thresholds are calibrated using data for the export of P as a function of storm-return period collected from the watershed during 1997 to 2006.

Materials and Methods

Watershed Description

The study watershed, FD-36 (39.5 ha), drains to the Susquehanna River, the largest contributor of fresh water to the Chesapeake Bay (Fig. 1). The watershed has mixed-land use, with 50% soybean [*Glycine max* (L.) Merr.], wheat (*Triticum aestivum* L.), or corn (*Zea mays* L.); 30% woodland; 18% pasture; 1% farm buildings and about 1% stream channel, typical of upland agriculture in the Northeast USA. Soils are classified as Alvira (fine-loamy, mixed, mesic Aeric Fragiaquults), Berks (loamy-skeletal, mixed, active, mesic Typic Dystrudepts), Calvin (loamy-skeletal, mixed, active, mesic Typic Dystrudepts), Hartleton (loamy-skeletal, mixed, active, mesic Typic Hapludults), and Watson (fine-loamy, mixed, active, mesic Typic Fragiudults). These soils are subject to variable source area hydrology due to seasonally perched water tables found at lower landscape positions in coluvial soils with fragipans (e.g., Alvira, Berks). The importance of saturation excess runoff generation in this watershed to the expansion/contraction of runoff generating areas within FD-36 was previously described by Needleman et al. (2004). Slopes within the watershed range from 1 to 20%, and management of individual fields was obtained from annual farmer surveys (Table 2 and Fig. 2).

Table 2. Land use and P management of the fields in the FD-36 watershed for 2000.

Field no.†	Crop	Field area	Distance to stream‡	Fertilizer P applied	Fertilizer application method/date	Manure P applied	Manure application method/date	Mehlich-3 P§
		ha	m	kg ha^{-1}		kg ha^{-1}		mg kg^{-1}
10	wheat	0.42	300	34	broadcast/Apr.	0		328
11	barley	0.70	265	7	broadcast/Mar.	0		220
12	corn	0.93	215	24	broadcast/Apr.	0		222
13	pasture	0.62	180	0		0		208
14	corn	0.62	150	24	broadcast/Apr.	0		204
15	corn	0.36	135	24	broadcast/Mar.	0		194
16	corn	0.22	225	24	broadcast/Apr.	0		266
17	barley	0.55	190	7	broadcast/Apr.	0		251
18	corn	0.53	160	24	broadcast/Apr.	0		289
19	corn	0.62	135	32	broadcast/Apr.	0		291
20	oats	0.77	105	0		0		212
21	corn	1.63	0	24	broadcast/Apr.	0		113
22	soybean	1.00	40	0		0		124
23	soybean	0.61	5	0		0		73
24	corn	0.79	200	32	broadcast/Oct.	0		205
25	wheat	1.06	85	66	broadcast/Apr.	0		267
26	wheat	2.00	30	34	broadcast/Oct.	0		276
27	soybean	1.83	10	34	broadcast/Apr.	0		147
28	corn	1.65	0	32	broadcast/Oct.	0		94
29	corn	0.80	0	0		112	broadcast/May	225
30	wheat	1.26	25	0		67	broadcast/Apr.	181
31	corn	1.24	60	0		112	broadcast/May	330
32	soybean	1.06	100	0		0		213
33	corn	1.07	135	0		67	broadcast/May	350

† Refer to Fig. 2.

‡ The distance from the lowest point in each field to the stream channel.

§ Field-averaged Mehlich-3 P measured on a 30-m grid.

Sample Collection and Analyses

Soil

In July 1996, the watershed was surveyed, and topographic elevation was digitized on a 5-m grid along with soil classification. Soil samples (0- to 5-cm depth) were collected in March 2000 on a 30-m grid over the watershed. The samples were air dried, sieved (2 mm), and kept in air-tight containers until analysis. Mehlich-3 P concentration was determined by extraction of duplicate 1 g soil with 10 mL of 0.2 mol L^{-1} CH_3COOH, 0.25 mol L^{-1} NH_4NO_3, 0.015 mol L^{-1} NH_4F, 0.013 mol L^{-1} HNO_3, and 0.001 mol L^{-1} EDTA for 5 min (Mehlich, 1984). The concentration of P in filtered (0.45 µm) and neutralized soil extracts was determined by the colorimetric method of Murphy and Riley (1962). Solutions were neutralized using *p*-nitrophenol indicator (color change at pH 7.0) and drop-wise addition of 0.5 mol L^{-1} H_2SO_4 or 1.0 mol L^{-1} NaOH.

Stream Flow

Beginning in 1997, stream flow at the watershed outlet was continuously monitored (at 5-min intervals) from 1 April to 31 October, using a recording H-flume with float and shaft encoder. Storm flow samples for P analysis were obtained automatically using a programmable stage-activated sampler (American Sigma, Loveland, CO). More detailed information on sample collection and analysis is given by Sharpley et al. (2008). Briefly, 200-mL samples were collected from every 5000 L passing over the flume during each storm and composited to give a single flow-weighted sample. A subsample was filtered (0.45 µm) within 24 h and stored at 4°C. The concentration of dissolved reactive P (DRP) was determined on a 0.45-µm filtered sample, and total P (TP) was determined on unfiltered runoff samples after acid persulfate digestion and filtration (Whatman No. 40 filter paper) (Patton and Kryskalla, 2003). Each of these P measurements was conducted in duplicate. Phosphorus in all stream water filtrates and neutralized digests was determined by the colorimetric molybdenum-blue method of Murphy and Riley (1962). Solutions were neutralized using a *p*-nitrophenol indicator (color change at pH 7.0) and drop-wise addition of 0.5 mol L^{-1} H_2SO_4 or 1.0 mol L^{-1} NaOH.

Stream flow at the watershed outlet was separated into storm and base flow using techniques dependent on storm characteristics (Hall, 1968). For smaller storms with minimal change in

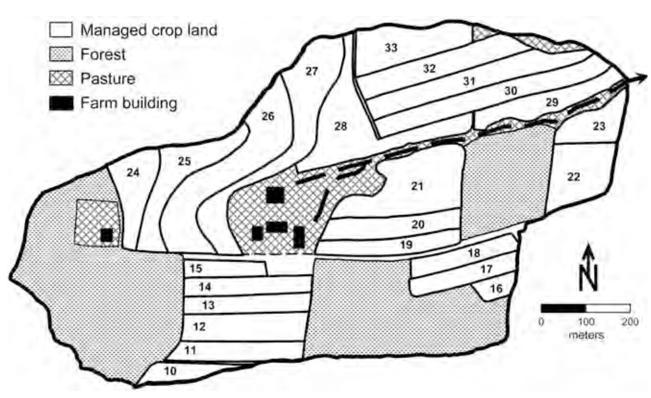

Fig. 2. Field boundaries, identification numbers, and land in crop, forest, pasture, and farm buildings in the FD-36 watershed.

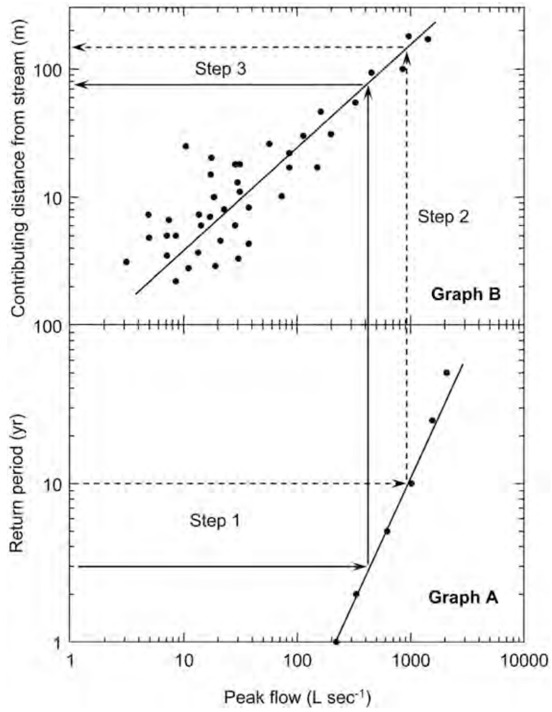

Fig. 3. Nomograph for determining contributing distance as a function of return period for the FD-36 watershed. In Step 1, peak stream flow is determined from the specified return period in graph A (adapted from Flippo, 1977); in Step 2, peak flow from graph A is matched to graph B; and in Step 3, graph B peak flow provides contributing distance from FD-36 data.

baseflow, a straight-line separation from storm hydrograph beginning to end was used to determine storm stop and start times. For larger storms, a conventional semi-log separation was applied to identify the beginning and end of storm flow. Near-stream areas assumed to produce surface runoff were estimated by dividing surface runoff volumes by rainfall depth for each storm, as proposed by Gburek and Sharpley (1998). This is the most conservative estimate of distance needed to produce the runoff measured for a given rainfall. Contributing area was then divided by stream length to approximate average widths contributing surface runoff (both sides of the stream). These contributing distances are considered the minimum necessary to produce the increase in stream flow observed during the storm hydrograph. Although the extent and location of contributing areas is watershed specific, the concept of defined yet limited areas holds across watersheds (Beven and Wood, 1983; Black, 1996).

Phosphorus loss in each storm was calculated as the product of flow and mean flow-weighted P concentration, with P loss in baseflow calculated as the product of flow between storms and baseflow P concentration. Annual export of P from the watershed was determined as the sum of all storm and baseflow loss for each year (April to October for 1997 to 2001). The return period for each storm during the study period was determined from peak flow of the stream during the storm (Flippo, 1977).

The Phosphorus Index

Site vulnerability to P loss in runoff is assessed with the P Index by selecting rating values for a variety of source and transport factors (Table 1). We derived site vulnerability ratings by applying a P Index developed for Pennsylvania (Weld et al., 2007) using the following source and transport factors.

Source Factors

The rate, method, and timing of fertilizer and manure application for each field were obtained from farm records (Table 1A and Table 2). The Mehlich-3 P concentration of surface soil samples collected in 2000 on a 30-m^2 grid was used to determine field-averaged values (Table 2). Because all source factors do not have the same quantitative effect on P loss, a coefficient of 0.2 was used to convert soil test P to a value that directly relates to P in manure and mineral fertilizers (Sharpley and Tunney, 2000).

Transport Factors

Values for each transport factor (Table 1B) were determined from soil information, widely used equations and soil-water relationships, and site-specific details. Erosion was estimated for each field based on current practices with the Revised Universal Soil Loss Equation (http://www.iwr.msu.edu/rusle/ and http://bioengr.ag.utk.edu/rusle2/), which accounts for soil tillage, slope length, and vegetative cover (Renard et al., 1997). Runoff potential was determined from soil permeability class and percent slope (USDA-NRCS, 1993). Subsurface drainage was determined from soil type, the presence of artificial drainage in the field, or whether the field was near a stream and had high permeability soils (USDA-NRCS, 1993). “Random” drainage is a single or a few tile lines in a field, and “Patterned” drainage is when most or the entire field is drained with a full patterned drainage system. Subsurface transport of P in FD-36 (25% of annual TP export) was small relative to transport in surface runoff (75% of annual TP export; Sharpley et al., 2008), and there was no known artificial drainage; consequently, Index values for subsurface drainage were set to “low” (i.e., zero; Table 1B).

Contributing distance as used in the P Index is defined as the distance from the lower edge or nearest part of a field to a stream or other water body (Table 2 and Fig. 2). Contributing distance was derived from storm-return period using the relationships shown in Fig. 3 (Gburek and Sharpley, 1998). For a watershed the size of FD-36 in east-central Pennsylvania and having a limited series of flow records with which to statistically derive a peak flow/return period relationship, design equations developed by Flippo (1977) and Stedinger et al. (1992) were used (Fig. 3A). A relationship between peak flow and contributing distance from the stream was developed for watershed FD-36 using data from each runoff event monitored in 1997 and 2000. The data and a best-fit relationship are shown in the upper part of the nomograph presented as Fig. 3B. Using this nomograph, peak flow was determined from a given storm-return period (or probability of occurrence) (Step 1, Fig. 3A). Contributing distance was then estimated from peak flow using FD-36 data (Step 3, Fig. 3B).

Site transport potential was calculated as summed transport factors multiplied by the modified connectivity factor, which for FD-36 was 1 because there were no riparian buffers in the watershed (Table 1B). The summed transport value was

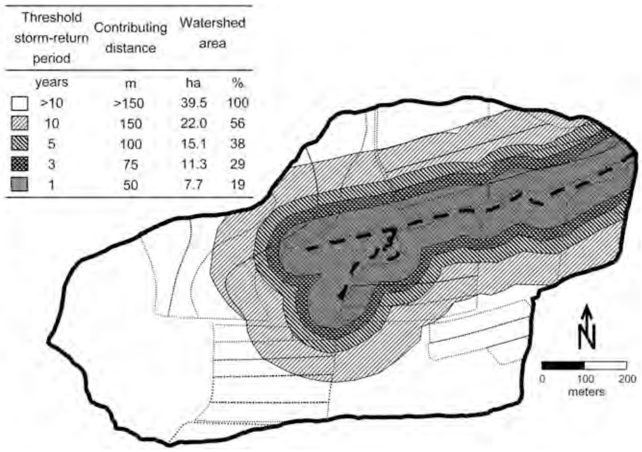

Fig. 4. Surface runoff contributing areas of the FD-36 watershed as a function of storm return period (adapted from Gburek and Sharpley, 1998).

divided by 22 to standardize the full transport potential to a value of 1 (Weld et al., 2007).

The P Index value for each site was calculated by multiplying summed source factors and transport potential. Phosphorus Index values are finally multiplied by 2 to normalize the upper limit of the high value to be 100 (Table 1C). This normalization is an attempt to ensure that Index categories and output are consistent across state boundaries (Sharpley et al., 2003).

Statistical Analysis

Statistical analyses (*t* tests, means, and standard errors) were performed with SPSS v10.0 (SPSS, 1999). The first order exponential and power equations were fitted using least squares regression and the fit assessed through a linear plot of observed versus predicted values giving a r^2 value. All r^2 values given are significant at the $P < 0.05$ level.

Results and Discussion

Contributing Distance and Storm Size

Using the nomograph relating storm-return period and contributing distance from the stream, distances for threshold storm-return periods can be determined. This approach assumes that runoff-generating areas within a watershed, particularly those connecting to a stream, begin at the stream and expand upslope as lower positions become saturated. Such conditions have been documented within FD-36 (Needleman et al., 2004) and at other sites in the region (Srinivasan et al., 2005). For threshold return periods of 1, 3, 5, and 10 yr, average contributing distances within FD-36 are approximately 50, 75, 100, and 150 m, respectively (Fig. 3). As distance from the stream increases with greater return-period thresholds, so does the area of the watershed-generating runoff that contributes to P export (Fig. 4). For example, the potential contributing area of a 1-yr storm return period is 7.7 ha, or 19% of FD-36. This area increases to 38% of the watershed (15.1 ha) for a 5-yr storm, and for storms with a return period >10 yr, all of FD-36 (39.6 ha) would be considered an actively contributing source area (Fig. 4).

Table 3. Contributing distances and associated risk factors used in the P Index as a function of storm-return period threshold.

Threshold return period	Contributing distance for P Index rankings†				
	0	2	4	6	8
	m				
Year 1	>150	101–150	76–100	50–75	<50
Year 3	>225	151–225	101–150	75–100	<75
Year 5	>300	226–300	151–225	100–150	<100
Year 10	>450	301–450	226–300	150–225	<150

† The contributing distances are rounded to the nearest 5.

Based on increasing threshold-storm return periods, contributing distances for inclusion in Part B of the P Index were developed along with relative rankings (Table 3). Phosphorus Index values were then calculated for each cultivated field in the watershed (i.e., forested area not included) with threshold-storm return periods set at 1, 3, 5, and 10 yr. The numbers of fields categorized as low, medium, high, and very high risk for P loss for each P Index evaluation are given in Table 4. As storm-return period threshold, and thus contributing distance, increased in each P Index evaluation, the number of fields classified as at low risk for P loss decreased, whereas those at very high risk increased (Table 4). This represents a greater proportion of the cultivated acreage in the watershed.

Phosphorus Loss and Storm Size

The majority of P Indices in the USA assign the highest weighting factor to fields within 50 m of either side of the stream channel (Sharpley et al., 2003), which implies that these fields have the greatest potential for P loss in surface runoff (rating of 8; Table 1B). Although the rationales for assigning the highest risk to near-stream areas can vary, for most areas, including FD-36, a 50-m distance from stream channel equates to a 1-yr storm return period. A similar approach was used by Johnes and Heathwaite (1997) to define high-risk areas for P and N loss using the export coefficient modeling approach. In fact, the 1-yr return period storms accounted for 54% of DRP and 47% of

Table 4. The number of fields and their area in the FD-36 watershed with the same P Index values as a function of storm-return period threshold.

	Storm-return period threshold, yr			
	1	3	5	10
Number of fields in index category				
Low	18	10	6	4
Medium	2	8	5	6
High	0	2	8	5
Very high	4	4	5	9
Watershed area, ha				
Low	14.5	8.5	5.0	3.4
Medium	3.5	7.2	4.3	4.3
High	0.0	2.3	6.8	6.4
Very high	4.4	4.4	6.3	8.3
Watershed area, % of cultivated land†				
Low	65	38	22	15
Medium	16	32	19	19
High	0	10	30	29
Very high	20	20	28	37
P-management restricted area, % of cultivated land				
High + very high	20	30	58	66

† Cultivated area of watershed is 22.2 ha

Table 5. Amount of dissolved, particulate, and total P exported in storm flow and percent of total storm P export from the FD-36 watershed during 1997 to 2006 as a function of storm-return period.†

Storm return period	No. of storms	Percent of total	Amount exported			Percent of total exported		
			Flow	Dissolved P	Total P	Flow	Dissolved P	Total P
years			m^3 ha^{-1}	g ha^{-1}		%		
<1	230	93	6507 b	574 c	2423 c	63	54	47
1–3	8	3	1059 a	106 a	528 a	10	10	10
3–5	5	2	861 a	106 a	533 a	8	10	10
5–10	3	1	706 a	90 a	493 a	7	8	10
>10	2	1	1247 a	195 b	1177 b	12	18	23
Total	248		10,380	1071	5154			

† Phosphorus loss values within the same column followed by different letters are significantly different ($P < 0.05$) as determined by Tukey's studentized range test.

TP exported from FD-36 between 1997 and 2006 (Table 5). There was an increase in cumulative P loss in stream flow from FD-36, with an increase in storm size represented as storm-flow return period (Fig. 5). For instance, all storms with a return period of <1 yr contributed 0.68 kg DRP ha^{-1} and 2.95 kg TP ha^{-1}, whereas storms with a return period of <10 yr contributed 0.88 kg DRP ha^{-1} and 3.98 kg TP ha^{-1} (Fig. 5). The slope of the relationship between storm-flow return period and cumulative P loss was greater for TP (slope of 0.26) than DRP (slope of 0.21). The greater slope suggests that increasing storm size has a greater effect on TP than DRP (Fig. 5). This increase in difference between TP and DRP transport reflects a greater erosion potential and thereby PP transport with an increase in storm size.

The fact that the current P Index calibration using a 1-yr return period threshold designated 65% of the cultivated area of the watershed as low P loss risk is consistent with the low loss of P from FD-36 (Table 5). Over the 10-yr observation, the average annual DRP loss was 0.11 kg ha^{-1} yr^{-1} and for TP was 0.52 kg ha^{-1} yr^{-1}. These losses are relatively low, given the history of P application to fields and current Mehlich-3 soil test P concentrations (73–350 mg kg^{-1}; Table 2), which are above crop response thresholds (50 mg kg^{-1}) (Beegle, 2002). For instance, the loss of TP from FD-36 (0.52 kg ha^{-1} yr^{-1}) was lower than the average TP loss of 1.36 kg ha^{-1} yr^{-1} measured by Udawatta et al. (2004) for several Missouri watersheds (1.7–4.4 ha)

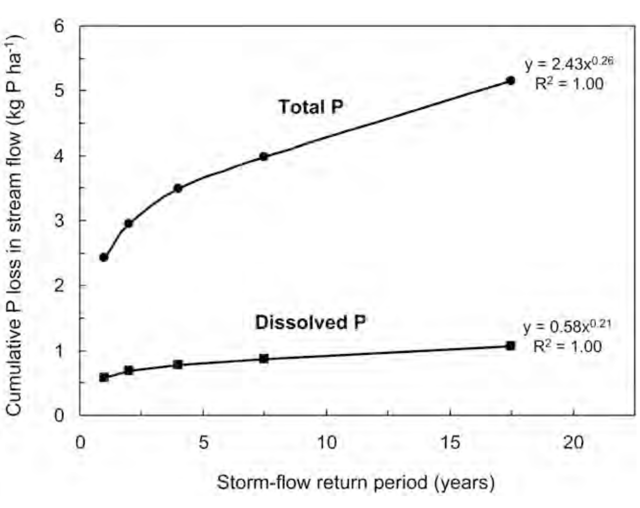

Fig. 5. Relationship between storm-flow return period and cumulative dissolved and total P loss in stream flow from the FD-36 watershed.

in no-till corn–soybean rotation from 1991 to 1997. Indeed, TP loss from forested or unfertilized pastures generally ranges from 0.02 to 0.68 kg ha^{-1} yr^{-1} (Alexander and Smith, 2006; Rekolainen, 1989; Ryden et al., 1973).

Thus, a decision can be made as to what relative risk of P loss is acceptable, such as in considering the sensitivity of receiving waters to P inputs. For instance, after assessing the greatest risk for P loss (rating of 8) to represent 100 m on either side of the stream channel or a storm-return period of 5 yr, 82% of DRP and 77% of TP exported from FD-36 would be accounted for (Table 5).

Indexing Phosphorus Loss and Field Management

The distribution of P Index ratings in FD-36 using 1- and 10-yr return period thresholds are shown in Fig. 6. Using a 1-yr threshold, only four fields (#29, 30, 31, and 33; Fig. 2) on the north side of the stream channel, each of which received additions of swine manure (51–86 kg P ha^{-1} yr^{-1}; Table 2), were rated at very high risk for P loss. With a 10-yr threshold, these same fields, plus fields 16, 17, 18, 19, and 26, which received fertilizer P applications (24–34 kg P ha^{-1} yr^{-1}) and had high Mehlich-3 P (251–291 mg kg^{-1}; Table 2), were categorized as having a very high risk for P loss (Fig. 6). Conversely, most fields were designated as being at low risk for P loss using a 1-yr return period threshold (18 of 24; Table 4). With a 10-yr threshold, only four fields remained classified at low risk. Field 32 was the only field in the block north of the channel (i.e., fields #29–32; Fig. 2) that received no manure, field 13 received no fertilizer, and fields 22 and 23 were close to the stream channel and therefore received no fertilizer or manure and had relatively low Mehlich-3 P concentrations (124 and 73 mg kg^{-1}; Table 2) (Fig. 6).

The P Index can be tailored to address a specific risk of P loss by identifying a larger area of the watershed for P-based management. By increasing the storm-return period threshold in Part B of the Index from 1 to 10 yr (Tables 1 and 3), the area of FD-36 ranked at a high or very high risk for P loss increased from 20 to 66% of the cultivated acreage (Table 4). This is a dramatic increase in the proportion of the watershed that would require some form of P-based management. By increasing the return period threshold, however, one would expect to mitigate a greater loss of P over the long term. For example, 7% of the storms between 1997 and 2006 (i.e., >1-yr storm return period) accounted for 36% of DRP and 46% of TP loss from FD-36, whereas the largest two storms (>10-yr storm return period) accounted for 16% of DRP and 21% of TP loss (Table 4).

A further consideration is how the high-risk fields are topographically connected and how land management options may have accelerated or retarded the likelihood of P loss in surface runoff. The network index (Lane et al., 2006) can be used in this instance to identify where the pivot points are in a catchment in terms of where the lowest point of the network index is located because this controls whether the surface runoff pathway is continuous or becomes disconnected. Second, land management factors are important here because the location of roads and tracks and gateways and the characteristics of field boundaries (e.g., hedges and walls) can break or enhance the surface runoff pathway and hence the capacity to deliver P mobilized in surface runoff to the stream (Beven et al., 2005).

Conclusions

The 10-yr measurement of P transport from the FD-36 watershed as a function of storm size allows us to quantify the relative importance of near-stream areas in delivering P to the channel under differing storm conditions. By examining P concentrations in storm runoff from all events sampled in terms of return period and (assumed) variation in extent of the watershed area generating the runoff volumes observed, we demonstrate the varying importance of landscape position as one moves away from the channel in contributing to total P load to the channel. The findings, although still inferential, allow us to develop a data-based rationale for determining the importance of, and the weightings associated with, the "connectivity" factor in the P Index.

Large infrequent storm flow events have the potential to carry large amounts of P from a watershed. Modifying the P Index to account for these large storms is possible by adjusting the storm-return period threshold, which sets contributing distances in the Index. By increasing the storm-return period threshold, fields more distant from the stream channel contribute runoff and P. This reflects the variable source area hydrologic concept, which dominates flow pathways, spatial contributions, and P transport in many watersheds.

By increasing the storm-return period threshold from 1 yr (as in most current P Indices) to 10 yr, the cultivated area of FD-36 that would be P-management restricted increased from 20 to 66%. Thus, it is possible to formulate the P Index to forecast a predetermined risk of P loss. However, the increased watershed area affected relative to a reduced risk of P loss creates a management policy dilemma that must be faced. In other words, implementation of more conservative or restrictive watershed management strategies for P maximizes P loss reductions but may limit certain farm operations even further.

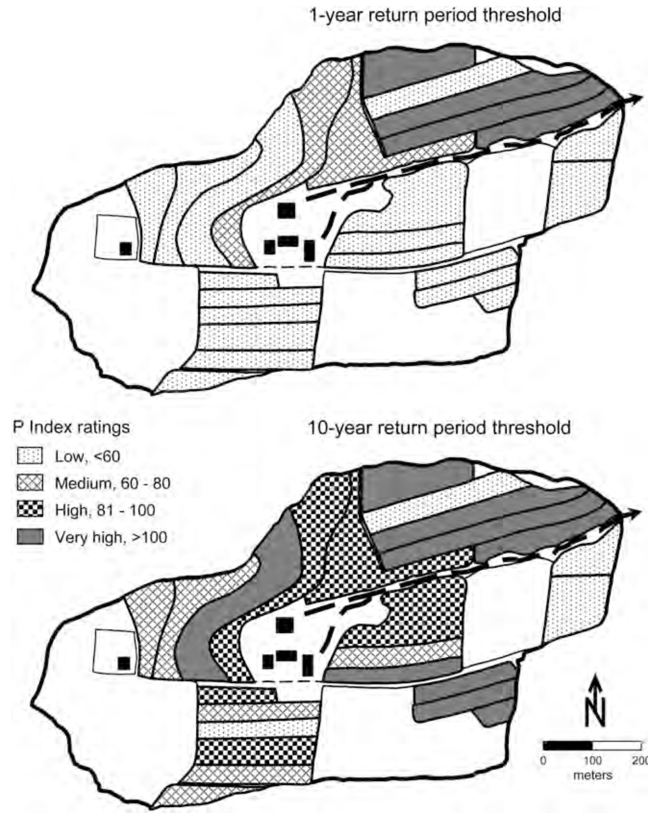

Fig. 6. Phosphorus Index ratings for managed fields in the FD-36 watershed as a function of 1- and 10-yr storm return period thresholds.

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