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Sources of phosphorus exported from an agricultural watershed in Pennsylvania

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Abstract

Freshwater eutrophication is usually controlled by inputs of phosphorus (P). As point source controls have decreased P inputs, the relative contributions of nonpoint inputs from agriculture have increased. Thus, remedial strategies are now being directed towards minimizing P export from agriculture. To identify critical sources of P, we investigated chemical and hydrologic factors controlling P export from a mixed land use (30% wooded, 40% cultivated, 30% pasture) 39.5 ha watershed in east-central Pennsylvania. The watershed was divided into four hydrologically distinct segments and streamflow and P concentration from each segment measured since June 1996. Mehlich-3 extractable soil P, determined on a 30-m grid over the watershed, ranged from 7 to 788 mg kg^{-1}. Generally, 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 in most cases above 200 mg kg^{-1}. Average flow-weighted P concentrations for ten storms during August–November 1996 decreased 60% downstream from segments 4–1 (watershed outlet). Streamflow P concentrations were more closely related to the near-stream (within 60 m) than whole watershed distribution of high-P soils in each watershed segment. This suggests that near-stream surface runoff and soil P, control P export form the watershed. Thus, managing P application in the primary surface runoff-producing areas near the stream has a greater potential to decrease P export in streamflow than for areas further from the channel. Clearly, the integration of areas of high soil P with areas of surface runoff production must be considered when guidelines are developed for P applications. Considering the distribution of high P soils alone may unnecessarily restrict farm management options without providing the desired reduction in P export from watersheds.

Keywords: Agricultural runoff; Eutrophication; Fertilizer; Manure; Nonpoint source pollution; Soil phosphorus

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1. Introduction

Since the late 1960s, point sources of water pollution have been reduced due to their relative ease of identification and control. Even so, water quality problems remain. As further point source control becomes less cost-effective, attention is now being directed towards the contribution of agricultural non-point sources to water quality impairment. In fact, reports to the US Congress by the Environmental Protection Agency have identified agricultural non-point source pollution as the major source of stream and lake contamination that prevents attainment of the water quality goals identified in the Clean Water Act (USEPA, 1988). Specifically, eutrophication has been identified as the most critical problem impairing the quality of surface waters in the US, with agriculture being the major source of nutrients (USEPA, 1996; Carpenter et al., 1998). Freshwater eutrophication is controlled in most cases by P inputs. Thus, regional authorities have mandated reductions in P inputs to P-sensitive waters such as the Chesapeake Bay, Florida Everglades, and Lake Champlain.

Research and implementation have identified agricultural management practices that minimize P losses in surface runoff by separately addressing source (soil P, crop, fertilizer, and manure management) or transport factors (surface runoff and erosion) (Sharpley et al., 1994; Bottcher et al., 1995). These practices include basing the application of P on soil test P recommendations and reducing surface runoff and erosion by the use of cover crops, contour plowing, conservation tillage, and riparian zones. However, implementation of these measures over broad areas of a watershed has not resulted in expected reductions in P export (Meals, 1993; Sharpley and Rekolainen, 1997). Typically, in humid climates and often during wet seasons in semi-arid climates, surface runoff is generated during limited times and from limited source areas within an upland watershed. These sources areas can expand and contract rapidly during a storm as a function of rainfall (intensity and duration) and site characteristics (soil moisture, topography, ground water level) over a watershed (Gburek et al., 1996). For example, more than 75% of annual flow from watersheds in Ohio (Edwards and Owens, 1991) and Oklahoma (Smith et al., 1991) occurred in one or two severe storms events. These same events contributed over 90% of annual total P export (0.2 and 5.0 kg ha^{-1} per year, respectively). Also, about 90% of annual algal-available P loss from watersheds in east-central Pennsylvania occurred from only 10% of the land area during a few large storms (Pionke et al., 1996, 1997). Thus, overall P management strategies will reduce P export most effectively when targeted to critical source-areas in a watershed that are most vulnerable to P loss, i.e., areas within the watershed where high soil P levels coincide with high surface runoff and erosion potentials (Heatwole et al., 1987; Prato and Wu, 1991; Heathwaite and Johnes, 1996). However, information is needed on the hydrologic controls linking spatially variable sources and transport processes that determine P loss from a watershed.

This paper defines the critical source areas controlling P export from a small, upland agricultural watershed in east-central Pennsylvania. We determined flow and P concentrations in streamflow, relative to soil P distribution over the watershed and potential source areas of surface runoff.

2. Materials and methods

2.1. Study area

The study was conducted on a 39.5 ha subwatershed (FD-36) of Mahantango Creek, which is a tributary to the Susquehanna River and ultimately the Chesapeake Bay (Fig. 1). FD-36 is typical of upland agricultural watersheds within the nonglaciated, folded and faulted, Appalachian valley and Ridge Physiographic Province. Soils are mostly Berks (Typic Dystrochrepts), Calvin (Typic Dystrochrepts), Hartleton (Typic Hapudults), and Watson (Typic Fragiudults) channery silt loams, with slopes ranging from 1% to 20%. Climate is temperate and humid, average rainfall is approximately 1100 mm per year, and streamflow about 450 mm per year.

The watershed is of mixed land use, with 50% in soybean, wheat, or corn, 20% as pasture, and 30% wooded. In the last 5 years, cropped land north of the FD-36 stream channel received about 60 m^3 ha^{-1} per year pig slurry in spring and no fertilizer P. This

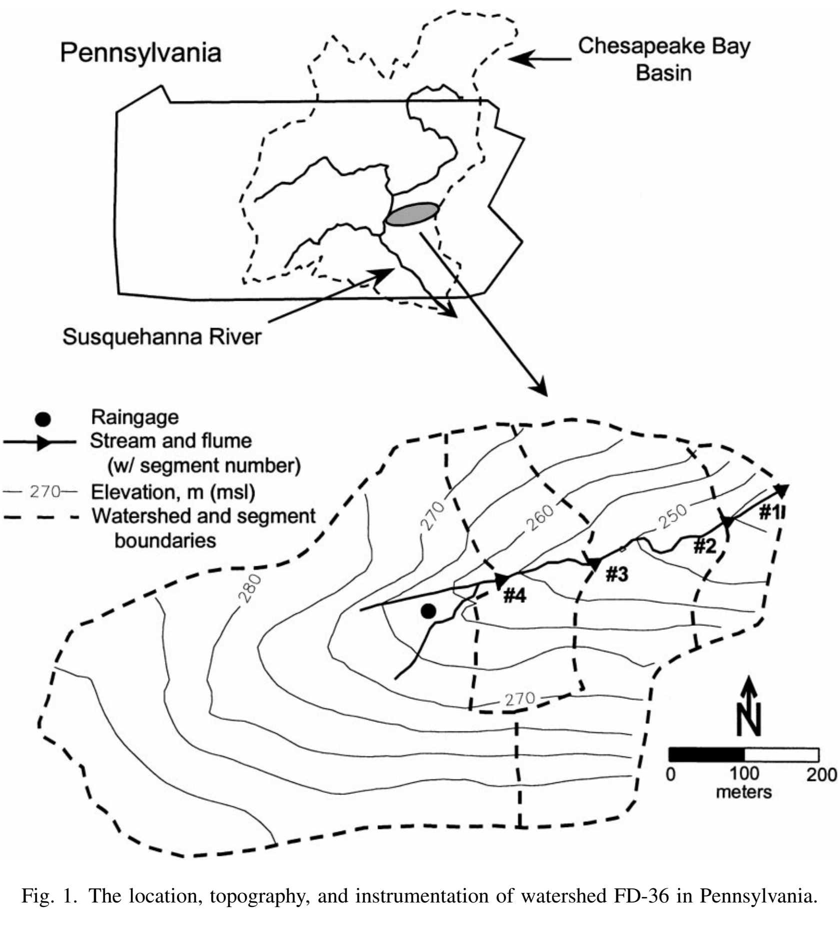

Fig. 1. The location, topography, and instrumentation of watershed FD-36 in Pennsylvania.

amounts to about 100 kg P ha^{-1} per year assuming a slurry P content of 1.6 g L^{-1} (Gilbertson et al., 1979). South of the stream channel, approximately 5 Mg ha^{-1} per year, poultry manure were applied to cropland in the spring. This amounts to about 85 kg P ha^{-1} per year, assuming a manure P content of 16.9 g kg^{-1} (Gilbertson et al., 1979). As application rates were obtained from annual farmer interviews and the P content of slurry and manure can be variable (Eck and Stewart, 1995), these estimated manurial inputs of P to FD-36 are approximate. However, the values provide relative comparison of inputs and streamflow export of P for FD-36.

The watershed was divided into four distinct segments based on topography and drainage patterns derived from a detailed topographic survey and visual reconnaissance (Fig. 1). Beginning in May 1996, streamflow below each segment was continuously monitored using recording H-flumes, and water samples for P analysis were taken automatically during storm hydrographs at 5–120 min intervals using programmable stage-activated samplers. Baseflow samples were taken at each flume at monthly intervals for subsequent P analysis. All samples were refrigerated at 277 K from collection until analysis.

2.2. Phosphorus analyses

Dissolved ortho phosphorus (DP) was determined on filtered (0.45 μm) stream-water samples by the molybdenum-blue method of Murphy and Riley (1962). The same method was used for total phosphorus (TP) following digestion of unfiltered water samples with a semimicro Kjeldahl procedure (Bremner and Mulvaney, 1982). Algal-available phosphorus (AAP) was determined using Fe-oxide impregnated strips (Sharpley, 1993). Twenty-five ml of unfiltered water sample and one Fe-oxide strip were shaken end-over-end for 16 h at 4°C. The strip was removed, rinsed free of soil particles, and shaken end-over-end for 1 h in 1 M HCl to remove AAP.

In July 1996, individual soil samples (0–5 cm depth) were collected on a 30-m grid over the watershed. A 30-m grid sampling was chosen to give adequate coverage of each field, while minimizing the number of samples analyzed. Preliminary analysis of soils from a 10-m grid on one cropped field showed no difference ($p > 0.01$) in coefficient of variation with the 30 m grid. The samples were air dried, sieved (2 mm) and the Mehlich-3 soil P concentration determined by extraction of 1 g soil with 10 ml of 0.2 M CH_3COOH, 0.25 M NH_4NO_3, 0.015 M NH_4F, 0.013 M $HN0_3$, and 0.001 M EDTA for 5 min (Mehlich, 1984). Phosphorus in all filtered and neutralized extracts was determined by the method of Murphy and Riley (1962).

2.3. Hydrograph analysis

Storm hydrographs were separated into baseflow and stormflow components using techniques dependent on storm duration. For longer duration storms (rainfall lasting at least several hours), a semi-log separation technique was used (Hall, 1968). This approach assumes that where stormflow ends, the hydrograph is comprised solely of baseflow, and is the beginning of a straight line when the hydrograph is plotted in a semi-log scale. This straight line is then projected back to the time of the hydrograph peak.

Another straight line is then used to connect this point with the hydrograph at the time when streamflow begins to increase. The area below these lines is assumed to be baseflow. The area between the projected lines and streamflow hydrograph is assumed to be stormflow.

Baseflow was assumed not to increase during smaller storms of shorter duration. The shorter storms are defined where rainfall is typically less than a few hours and streamflow rates return to their pre-storm values within an hour or two after rainfall ends. Consequently, baseflow was assumed constant during the storm and was subtracted from the total streamflow to produce the stormflow volume.

The width of the near-stream zone producing surface runoff within each segment was estimated for all storms using the following procedure. Beginning with the downstream segment, stormflow volume for the next upstream segment was subtracted from that at the downstream flume to obtain stormflow volume produced within each watershed segment. Stormflow volumes from each segment were divided by rainfall depth to estimate surface runoff-contributing area, and then by stream length within each segment to approximate total surface runoff-producing width near the stream i.e., both sides of the channel. This calculation assumes that rainfall on the estimated saturated areas of each segment is converted to surface runoff, and that these saturated areas don't expand during the storm event (Gburek et al., 1996). These areas are the minimum needed to produce the observed streamflow. Note that this technique assumes all stormflow is surface runoff. Typically, some of this is subsurface return flow to the stream occurring at the storm time scale. Generally, the longer storms have a larger subsurface stormflow component. We did not correct for these subsurface contributions.

Mean flow-weighted concentrations of the various P components (DP, AAP, TP) in stormflow for each event were estimated by (1) calculating P loss of each P component in streamflow and baseflow as the product of the observed concentration and flow for each sampling time, (2) summing these values to obtain these P losses totaled over the hydrograph, (3) calculating these P losses in stormflow as the difference between stream and baseflow losses for each event, and (4) dividing these P losses in stormflow by stormflow volume to obtain the average P concentrations for each event. The average concentration of DP, AAP, and TP in monthly baseflow samples were 0.02, 0.03, and 0.04 mg L^{-1}, respectively. These concentrations were used to determine the P loss in baseflow and subsequent estimation of stormflow P losses.

3. Results and discussion

3.1. Soil P distribution

On a 30-m grid over the watershed, Mehlich-3 P ranged from 7 to 788 mg kg^{-1} (Table 1). Mehlich-3 soil P values were grouped into four categories based on agronomic and environmental factors: <30 mg kg^{-1}, crops require additional P for optimum growth; between 30 and 100 mg kg^{-1}, there will generally be a crop response to P application but little enrichment of P in surface runoff (probable crop response decreases as Mehlich-3 P increases from 50 to 100 mg kg^{-1}); between 100 and 200 mg kg^{-1}, there will be no

Table 1
Area of each watershed segment, number of soil samples collected on a 30 m grid and Mehlich-3 P contents for FD-36

Watershed segment	Area (ha)	Channel length (m)	No. of samples	Mehlich-3 P (mg kg^{-1})			Percent in each category (%)			
				Mean	Min	Max	<30	30–100	100–200	>200
1	2.34	86	26	118	14	404	16	44	9	30
2	8.92	222	99	166	7	788	43	13	6	38
3	4.70	106	52	199	21	449	6	16	39	39
4	23.58	332	262	141	10	775	41	9	21	29
Total	39.54	746	439	168	7	788	34	14	19	33

response to applied P while some enrichment of P in surface runoff may occur; >200 mg kg^{-1}, levels are considered excessive in terms of crop requirements and enrichment of P in surface runoff can be expected (Beegle, 1996; Sharpley et al., 1996a, b).

The pattern of Mehlich-3 P values over FD-36 is generally a function of land use and field boundaries within the watershed (Fig. 2). Soils in wooded areas have low values of Mehlich-3 P (<30 mg kg^{-1}), grazed pastures have values between 100 and 200 mg kg^{-1}, and cropped fields receiving manure and fertilizer applications are, in most cases, above 200 mg kg^{-1}. Also, near-stream areas were wet for much of year, which limited their productive value, and thereby amounts of P applied. Thus, Mehlich-3 P concentrations in

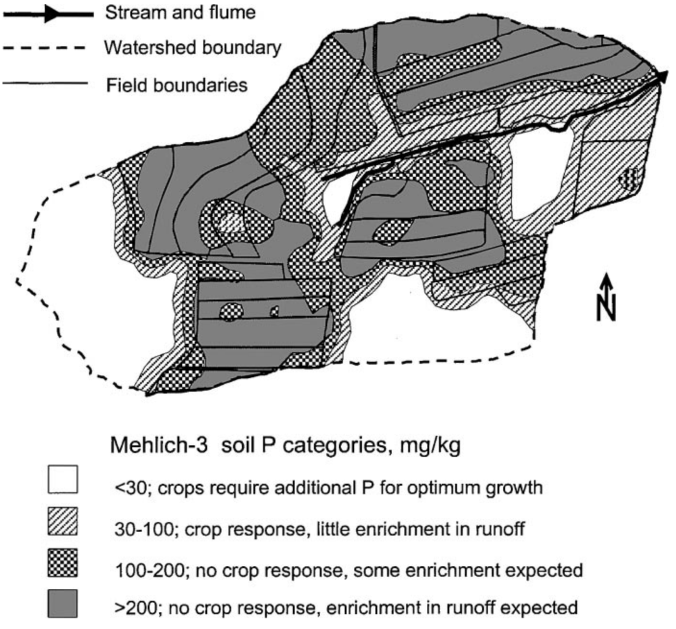

Fig. 2. Mehlich-3 soil P distribution over watershed FD-36; flume locations and segments are also shown.

near-stream areas were generally <100 mg kg^{-1}. Based on the grid sampling, 52% of the soils on FD-36 have Mehlich-3 P concentrations in excess of levels sufficient for optimum crop growth (>100 mg kg^{-1}) with 33% above 200 mg kg^{-1} (Table 1). Of the remaining 48% of soils, P application would be recommended on only 14% for optimum crop production (30–100 mg kg^{-1}), since the other 34% are mostly wooded (<30 mg kg^{-1}) (Table 1). On a watershed segment basis, low P soils tended to dominate downstream and high P soils upstream (Table 1). 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}.

3.2. P transport in streamflow

3.2.1. Hydrograph relationships

Ten storm events occurred on FD-36 in 1996. During each event, DP, AAP, and TP concentrations varied during the hydrograph. Although the magnitude of change in concentration varied among storms, the pattern of DP distribution with flow was similar and is represented by the 8 November storm shown in Fig. 3. Flow rate and volume at each flume increased downstream from segments 4–1 (watershed outlet). As expected,

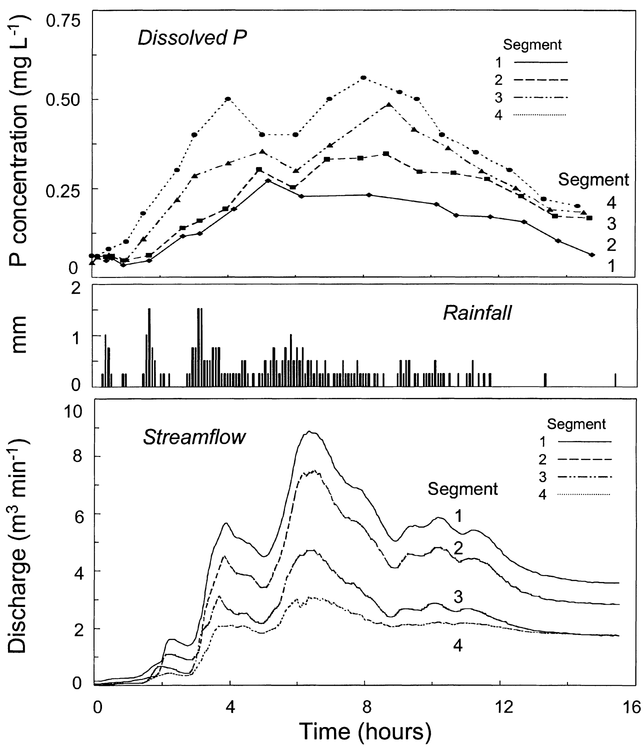

Fig. 3. Rainfall stream discharge, and concentration of dissolved P at each channel segment during a storm event at FD-36, starting on 8 November 1996.

storm flow tended to peak earlier moving upstream from segments 1–4 (Fig. 3). Dissolved P concentrations generally increased during the initial rise of the storm hydrograph where surface runoff occurred and contributed to stream flow (Fig. 3). In all storm events, DP, AAP, and TP concentrations during the hydrograph were consistently lower moving downstream from segments 4–1 (Fig. 3; only DP shown).

Average flow-weighted DP, AAP, and TP concentrations of total streamflow leaving each of the four watershed segments were determined for each storm event. For all events, DP concentration decreased downstream from segment 4 to the watershed outlet (Table 2). On average, DP concentration decreased by 60%, AAP 56%, and TP 59%. Dissolved P comprised 54% of AAP at segment 4 and 60% at segment 1. Although the concentration decrease and distribution of DP and AAP was similar from segment 4 to the watershed outlet, the relative importance of controlling hydrologic or chemical processes will vary in the stream channel. These processes may include dilution by input of subsurface flow to the stream channel, deposition and resuspension of particulate material and associated P, sorption of DP by suspended sediment and channel bank and bed material, and a differential contribution of P in surface runoff from spatially variable areas of surface runoff production and high soil P.

3.2.2. Hydrograph separation

Hydrograph analysis revealed that most streamflow (89%) from FD-36 during 1996 occurred during two major storm events (18 October and 8 November Table 2). The relative contribution of stormflow to total flow at the watershed outlet varied among flow events from 18% on 17 September to 57% on 18 October, due to differing antecedent soil moisture conditions and rainfall amounts, durations, and intensities. Overall, the contribution of stormflow to streamflow did not vary ($p < 0.5$) among segments, with an average of 43% of streamflow at each segment coming from stormflow (Table 2). For all events, stormflow DP concentrations decreased downstream from segments 4–1 (watershed outlet) (Table 2). As most of the stormflow originates as surface runoff, concentrations of P were greater (about 5 fold) than those in total streamflow (Table 2).

3.3. Streamflow and soil P relationships

Comparison of stormflow DP concentrations to soil P distribution patterns over the watershed may provide insight into the linkages between high P soils and surface runoff-producing areas. Estimated widths of areas adjacent to the stream channel that were saturated with water ranged from <1 to 62 m and showed a general increase downstream from segments 4–1 ($p < 0.5$; Table 3).

Assuming most of the stormflow increase between segments originates as surface runoff from the near-stream area (Table 2), the distribution of Mehlich-3 soil P within this area and the whole watershed were compared (Fig. 4). On a whole watershed basis, there was little difference among the four watershed segments in the percent of soils >200 mg kg^{-1} Mehlich-3 P (29–39%, Table 1, Fig. 4). This is the Mehlich-3 P category that is expected to result in the enrichment of DP in surface runoff. However, on a near-stream basis, the areal distribution of these high P soils decreased from 50% in segment 4 to 8% in segment 1. Thus, the trend of decreasing stormflow DP concentration

Table 2
Rainfall, stream flow and mean flow-weighted dissolved P concentration for each watershed segment for several storms during 1996

Flow event	Rainfall		Streamflow (m^3)				Stormflow (m^3)			
	Amount (mm)	Duration (h)	Watershed segment				Watershed segment			
			1	2	3	4	1	2	3	4
9 August	11	3.1	68	32	10	13	31	18	8	9
6 September	7	0.8	20	9	3	5	4	2	2	2
7 September 7	12	2.4	79	43	22	26	33	22	17	15
13 September	14	4.4	81	44	19	23	28	17	11	9
16 September	35	12.2	950	647	428	365	352	275	211	132
17 September	5	2.4	333	216	134	131	61	46	34	19
28 September	15	5.4	283	165	85	78	133	81	53	38
9 October	13	12.4	78	41	18	19	16	11	6	5
18 October	100	24.1	10978	9557	5802	4512	5605	4666	3040	1721
8 November	46	16.8	4111	3301	2051	1628	1896	1762	972	622
Total	258		16980	14054	8572	6801	8159	6899	4353	2570
Percent[a]							48	49	51	38
Dissolved P concentration, (mg l^{-1})										
9 August			0.019	0.036	0.050	0.097	0.029	0.041	0.055	0.125
6 September			0.027	0.038	0.070	0.088	0.053	0.091	0.104	0.191
7 September			0.020	0.024	0.039	0.046	0.020	0.024	0.042	0.050
13 September			0.060	0.073	0.119	0.148	0.134	0.151	0.188	0.328
16 September			0.104	0.137	0.163	0.202	0.247	0.290	0.301	0.490
17 September			0.074	0.080	0.099	0.111	0.270	0.283	0.301	0.542
28 September			0.066	0.082	0.103	0.119	0.117	0.141	0.146	0.203
9 October			0.065	0.123	0.172	0.206	0.270	0.337	0.441	0.709
18 October			0.448	0.511	0.743	0.731	0.867	1.005	1.391	1.853
8 November			0.195	0.253	0.322	0.392	0.410	0.435	0.647	0.962
Average			0.046	0.062	0.088	0.116	0.242	0.280	0.362	0.545

[a] Percent of total flow as storm flow.

Table 3
Saturated distance from the stream channel for watershed segments during each flow event in 1996

Flow event	Watershed segment (m)			
	1	2	3	4
9 August	10.4	3.2	0.6	1.9
6 September	1.4	0.2	0.1	0.3
7 September	5.4	0.9	0.5	1.9
13 September	5.0	1.0	0.6	1.0
16 September	12.9	4.1	10.7	5.7
17 September	17.6	5.4	14.6	5.6
28 September	20.1	4.2	4.7	3.8
9 October	2.2	0.9	0.6	0.5
18 October	54.6	36.6	62.2	25.9
8 November	17.0	38.7	35.9	20.4
Average	14.7	9.5	13.0	6.7

downstream was more closely related to the near-stream distribution of high P soils in each watershed segment than to that of the whole watershed (Fig. 4). This integration of hydrologic processes and chemical properties of watershed soils suggests that near-stream soil P concentration has a greater influence on P export from the watershed than does soil P concentration at the whole-watershed scale.

Instantaneous P discharge during each stormflow event was calculated as the product of instantaneous flow and periodic measurement of P concentration (Fig. 3). Phosphorus export for each event was calculated as the sum of instantaneous P discharges. Events were summed to give total P export over the period of record. The major proportion

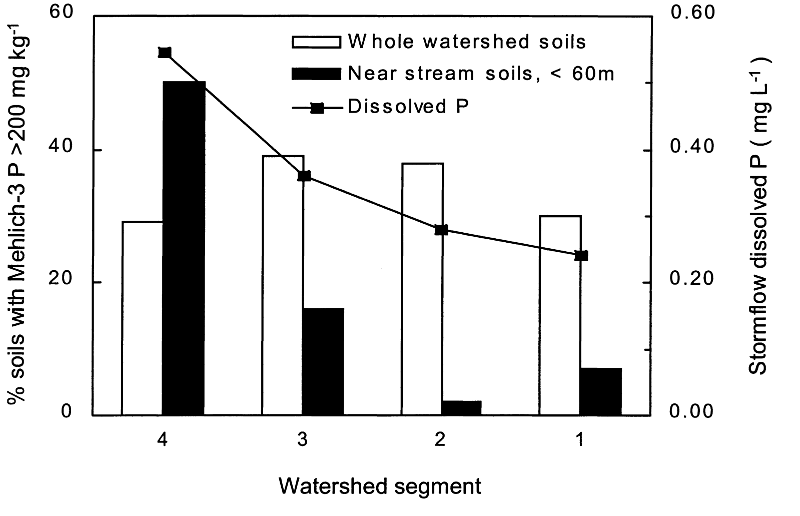

Fig. 4. Distribution of soils with Mehlich-3 $p > 200$ mg kg^{-1} on whole-watershed and near stream (<60 m) basis and mean flow-weighted dissolved P concentration in stormflow from each segment for August–November, 1996.

Table 4
Flow and P loss from the watershed for August–November 1996

Flow	Volume ($m^3 \times 10^3$)	P loss ($g\ ha^{-1}$)		
		Dissolved	Algal-available	Total
Stream flow	16.98	149	200	288
Storm flow	8.16	146	193	278
Base flow	8.82	3	7	10

(>96%) of P exported from FD-36 during the study period (288 $g\ ha^{-1}$) occurred as stormflow (Table 4). Of the 288 $g\ ha^{-1}$ exported, 52% was dissolved and 69% algal-available. Although P export was small compared to the amounts of P applied as fertilizer and manure to the cropped areas of FD-36 (from 85 to 100 kg P ha^{-1} per year), most of it was exported in forms readily available for algal uptake.

4. Conclusions

Results of this study show that 52% of the soils over FD-36 have soil P concentrations in excess of levels sufficient for optimum crop growth (100 mg kg^{-1}), with 33% above 200 mg kg^{-1}. Even so, P loss from FD-36 (0.29 kg P ha^{-1}) was appreciably less than that added annually as fertilizer or manure to the cropped areas (85–100 kg ha^{-1}). As 48% of the streamflow from FD-36 was estimated to be stormflow and this was assumed mostly surface runoff, not all areas of the watershed contributed equal amounts of P to the stream channel. Hydrograph analysis and soil P distribution implied that surface runoff and P loss in FD-36 occurred mainly from an area extending not much more than 60 m from the channel.

These findings have important implications for watershed management of P from fertilizer or manure applications. For instance, current thinking may set P management goals based solely on Mehlich-3 P concentrations for soils over the entire watershed (Sharpley et al., 1996a, b). In this case, nearly 80% of the cropped and pasture soils over FD-36 are sufficiently high in P (>100 mg kg^{-1}) that there would be no crop-yield response to further P applications.

An environmental soil test P level of 200 mg kg^{-1} Mehlich-3 P has been proposed by several states in the US as a threshold level above which P enrichment of surface runoff and increase in P export is likely, indicating P applications should be more carefully managed on soils having this level (Sharpley et al., 1996a, b). Based on this, application of P to 63% of the cropped area of FD-36 would be limited or restricted. Clearly, this would impact those farmers having confined swine and poultry operations on the watershed where produced manures are presently applied.

Alternatively, delineation of surface runoff-producing areas, and recognition of the similarity between patterns of P concentration in streamflow and P concentration of near-stream soils, suggests that P management goals should focus on the near-stream areas rather than the whole watershed. With this approach, where soil P, land use, and hydrologic characteristics of the watershed are considered, it becomes possible to better target remedial programs to the hydrologically controlled critical P source areas of the watershed. However, soils further from a stream channel, in non-surface runoff producing areas, should not be considered to be of no environmental concern, simply because they are further from the channel. Attempts should also be made to better balance P inputs and outputs on these areas.

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