8 Transfer of Phosphorus from the Farm to the Bay

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CONTENTS

ABSTRACT

Phosphorus is a key element related to the eutrophication of Chesapeake Bay. Farm fields are a major source of phosphorus in land discharges. Most of the phosphorus is transported from fields to the receiving waters via overland flows during storm events, particularly in wet seasons of the years. The flux of total phosphorus from Rhode River cropland was 58, 1350, and 10,800 g P ha^{-1} in very dry, average precipitation, and very wet years, respectively. Almost all of the phosphorus transported in storm events is particulate organic phosphorus and particulate inorganic phosphorus. Some of this phosphorus is released as dissolved inorganic phosphate after entering the Chesapeake. The integrated mean particulate phosphorus concentrations during storm events were directly correlated with peak water discharge during the storms. Increased fluxes of phosphorus in wet periods were due to both higher water discharges and higher phosphorus concentrations, especially in the spring. Rhode River watershed fluxes of phosphorus were higher in general than those we measured in other parts of the Coastal Plain and Piedmont. Riparian buffers

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will only intercept large amounts of phosphorus from overland storm flows if they are managed to prevent concentrated flows during storms. Reservoirs have a major impact on the transport of both particulate and dissolved forms of phosphorus.

INTRODUCTION

The transfer of phosphorus from agricultural lands to receiving waters is a function of weather, geology, soils, land use, and land use practices. In most settings, phosphorus is transported primarily in overland storm flows as a constituent of suspended particulates. These particulates derive both from soil erosion and the scouring of particulate organic matter from the soil surface. To prevent or alleviate the transport of too much phosphorus from agricultural lands, the first line of defense is good management of the fields. Practices such as the use of constructed wetlands in low areas of the fields and well-managed riparian vegetation buffers to trap eroded soil particles before they reach a stream channel also help to minimize the effects of storm events (Correll, 1997). Once these phosphorus-containing particulates enter receiving waters, their phosphorus contents begin re-equilibrating with the surrounding dissolved forms of phosphorus (Froelich, 1988). Often this results in the release into solution of some of this particulate phosphorus. When storm waters reach a site where water currents are slow, such as the Chesapeake, much of the particulates settle to the bottom where conditions are often anaerobic and more of their phosphorus contents are released to the overlying water column (e.g., Boynton and Kemp, 1985; Jordan et al., 1991). Once high levels of phosphorus and nitrogen reach receiving waters such as Chesapeake Bay, eutrophication will result in excessive growths of primary producers, depletion of dissolved oxygen, and the death of many aquatic organisms (Correll, 1998).

BACKGROUND

Our research group has been conducting a study of phosphorus transport from the watershed of the Chesapeake to the Bay for about 25 years. The goal is to understand the effects of geology and soils, land use, and variations in weather on the transport of phosphorus and other nutrients and sediments to the Chesapeake Bay. The study was initiated on the watershed of the Rhode River, a small tributary of the Bay where the Smithsonian has its facilities and carries out long-term ecological research. The Rhode River, located on the inner Coastal Plain near Annapolis, MD, has highly erodible soils rich in parent phosphorus and nitrogen and has average slopes of 5%. The drainage basin is fan shaped with a series of small streams draining subwatersheds that have shallow aquifers perched on an impervious clay layer, so that the stormwater and groundwater discharges of each subwatershed can be measured at V-notch weirs equipped to take continuous, volume-integrated water samples for laboratory analysis (Correll, 1977, 1981). For about the last 10 years, this program has been expanded to look at 16 other regions within the Chesapeake Bay watershed.

Each region was chosen to be representative of an important geological or physiographic unit or subunit, such as the Appalachian Plateau, the Ridge and Valley, the Great Valley, various types of Piedmont, and different parts of the Coastal Plain. For each geological unit, we have selected replicate regions for study. Within each region we select one or two medium-order streams, then select station sites that are either tributaries or reaches of those streams. Over 500 such stream sites have now been selected and studied. Some of these sites are then instrumented to continuously measure stream discharge and take volume-integrated samples for laboratory analysis. These stations are open-channel gauging stations, and we develop rating curves for water discharge vs. stage height. Those stream sites not instrumented are sampled synoptically at base flow for dissolved constituents released as groundwater flows into the stream. We use a Geographic Information System to spatially relate land use/land cover and geology to stream discharges. We also gather data on land management to use in relating discharges to watershed inputs. Selected data from these studies will be used in this article.

METHODS OF PHOSPHORUS ANALYSIS

Stream water samples were analyzed whole and after filtration through membrane filters with 0.45-μm effective pore size. Particulate phosphorus was calculated as the difference between whole and filtered samples, and phosphorus in filtered samples was termed dissolved phosphorus. Total phosphorus was determined by perchloric acid digestion (King, 1932), reaction with stannous chloride and ammonium molybdate, and colorimetric analysis (APHA, 1989). Phosphate was determined by reaction with stannous chloride and ammonium molybdate with no digestion (APHA, 1989). Organic phosphorus was calculated by subtracting phosphate concentration from total phosphorus concentration.

LAND USE AND WEATHER EFFECTS

Both land use and interannual variations in seasonal precipitation have large effects on the transport of phosphorus from uplands to receiving waters (Figure 1). The cropland watershed (#109) was in continuous corn production with no winter cover crop (Vaithiyanathan and Correll, 1992). The forested watershed (#110) was mature hardwood deciduous forest that was never clear-cut (Vaithiyanathan and Correll, 1992). The grazed watershed (#111) was used for low-intensity beef cattle production (Correll, 1996). The effects of precipitation volume are not linear. In very dry years (64 cm), total inorganic phosphorus (TIP) fluxes on the Rhode River watershed varied from 9 g P ha^{-1} for mature hardwood forest to about 27 g P ha^{-1} for either grazed land or cropland. In years of average rainfall (108 cm), TIP fluxes varied from about 100 to 130 to 790 g P ha^{-1} for forest, grazed land, and cropland, respectively. In very wet years (152 cm), TIP fluxes increased to 360, 480, and 7100 g P ha^{-1} for grazed land, forest, and cropland, respectively. These differences in phosphorus flux

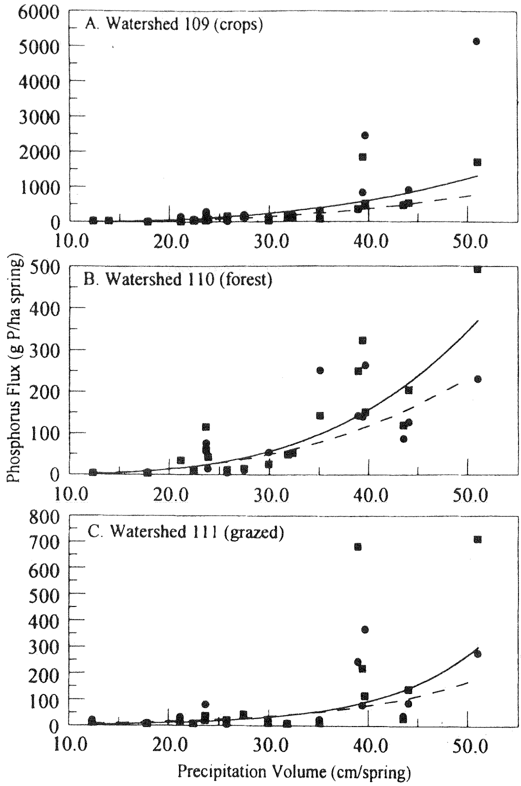

FIGURE 1 Variations in spring phosphorus flux from Rhode River subwatersheds with precipitation. Filled circles and the solid line are data for total inorganic phosphate (TPi) fluxes, and filled squares and the dashed line are data for total organic phosphorus (TOP) fluxes. For panel A, TPi flux = $0.00483X^{3.19}$ (R^2 = 0.69) and TOP flux = $0.00337X^{3.15}$ (R^2 = 0.69). For panel B, TPi flux = $0.00165X^{3.03}$ (R^2 = 0.65) and TOP flux = $0.00361X^{3.52}$ (R^2 = 0.73). For panel C, TPi flux = $3.67e^{0.0767X}$ (R^2 = 0.43) and TOP flux = $1.47e^{0.104X}$ (R^2 = 0.54).

were partially due to increased volume of water discharged in wetter years, but they were also partially the result of increased concentrations of phosphorus in the watershed discharges in wetter years or seasons (Figure 2). In the spring, much of the variation in phosphorus fluxes and seasonal mean concentrations can be explained by variations in seasonal or annual precipitation (e.g., Figures 1 and 2).

STORM EVENTS

At the Rhode River site, we have taken discrete sequential samples from a large number of storm events on several subwatersheds. In almost all cases, there was a peak in particulate phosphorus, which preceded the hydrograph peak. In most cases,

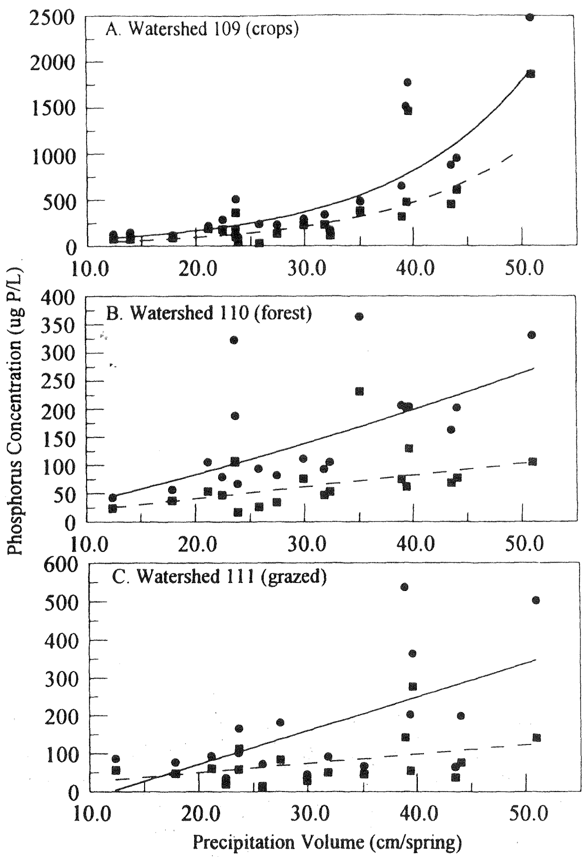

FIGURE 2 Variations in spring phosphorus concentrations from Rhode River subwatersheds with precipitation volume. Filled circles and solid lines are data for seasonal volume-weighted mean total phosphorus (TP) concentrations. Filled squares and dashed lines are data for seasonal volume-weighted mean total inorganic phosphate (TPi) concentrations. For panel A, TP concentration = $35.1e^{0.0784X}$ ($R^2 = 0.75$) and TPi concentration = $19.3e^{0.0798X}$ ($R^2 = 0.61$). For panel B, TP concentration = $1.98X^{1.25}$ ($R^2 = 0.52$) and TPi concentration = $2.08X^{0.998}$ ($R^2 = 0.31$). For panel C, TP concentration = $8.87X - 105$ ($R^2 = 0.37$) and TPi concentration = $2.43X + 1.61$ ($R^2 = 0.16$).

the majority of the particulate phosphorus was particulate organic phosphorus (POP; see Figures 3 and 4). In the storm shown in Figure 3, the stream draining the cropland watershed was dry prior to the storm, the hydrograph peaked at 32.9 L ha^{-1} sec^{-1} (a very intense July storm), and the watershed discharged 1.75 cm of water. The volume-weighted mean concentration of POP was 5500 µg P L^{-1}, and POP was 83% of the total phosphorus discharged during the storm event. Particulate inorganic phosphate (PPi) had a mean concentration of 1050 µg P L^{-1}, and PPi was 16% of the total phosphorus discharged. Even small initial peaks in the hydrograph were often

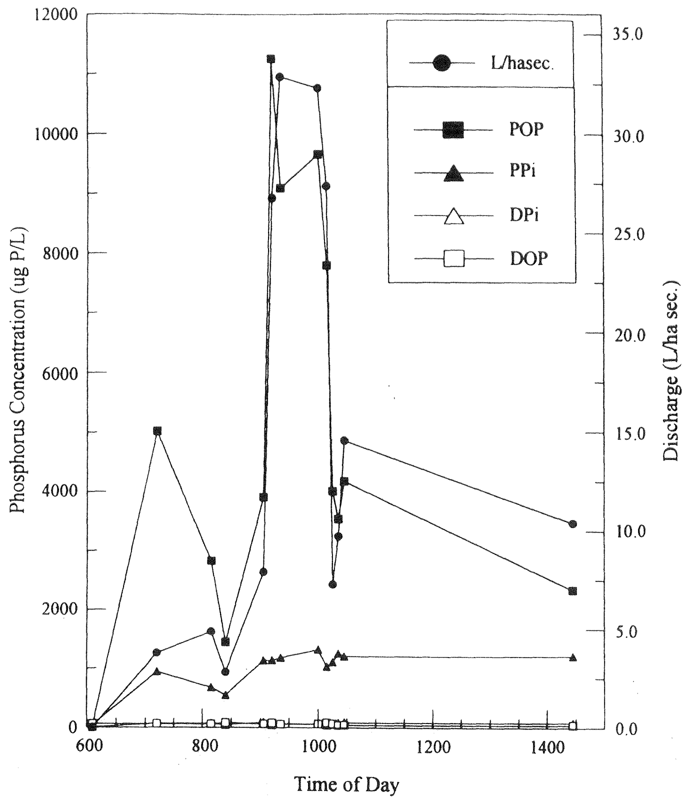

FIGURE 3 Phosphorus concentrations vs. time during a summer storm on the Rhode River cropland watershed (#109). Solid circles are water discharge, POP = particulate organic phosphorus, PPi = particulate inorganic phosphate, DPi = dissolved inorganic phosphate, DOP = dissolved organic phosphorus.

often associated with a peak in POP, as shown in Figure 3. Dissolved inorganic phosphate (DPi) and dissolved organic phosphorus (DOP) were always present during storms, but at very low concentrations, hardly elevated over those found in base flow. The storm events shown in Figure 4 were also on the cropland watershed, occurred in May, and consisted of three discrete hydrograph peaks of smaller magnitude. The first peaked at 2.02 L ha^{-1} sec^{-1}, and POP and PPi constituted 75% and 23% of the total phosphorus discharged, respectively. The second peak reached 4.29 L ha^{-1} sec^{-1}, and POP and PPi constituted 72% and 26% of the total phosphorus, respectively. The third peak also reached 4.29 L ha^{-1} sec^{-1}, and POP and PPi constituted 62% and 35% of the total phosphorus, respectively. The overall flux of total phosphorus in the July storm (Figure 3) was 1160 g P ha^{-1}, while in the sum of the three closely spaced events in May (Figure 4) the flux of total phosphorus was 550 g P ha^{-1}. The integrated mean concentration patterns from 22 storm events

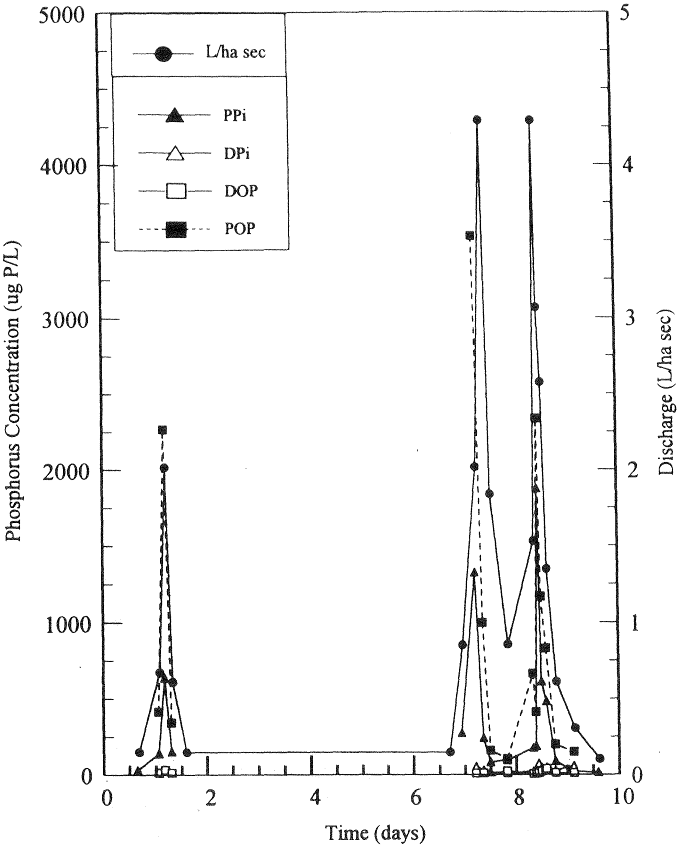

FIGURE 4 Phosphorus concentrations vs. time during a spring storm event on the Rhode River cropland watershed (#109). Solid circles are water discharge, POP = particulate organic phosphorus, PPi = particulate inorganic phosphate, DPi = dissolved inorganic phosphate, DOP = dissolved organic phosphorus.

shed (#109) are summarized seasonally in Figure 5. POP varied from 44% of the total in the summer to 70% in the winter. Only in the summer was average PPi larger than POP.

On average, the dissolved forms of phosphorus only constituted a few percent of the total. We have found that there is a highly significant relationship between peak water discharge during storms and the integrated mean concentrations of PPi and POP. Variation in peak water discharge explained 69% of the variation in integrated mean total phosphorus concentration during a storm event. For a mixed land use watershed, the relationship was TP concentration = $693X^{1.006}$, where X is peak discharge during the storm in L ha^{-1} sec^{-1}, and TP concentration is in μg P L^{-1}. The relationship between particulate phosphorus concentration and peak water discharge is fairly linear and does not show a lot of seasonality.

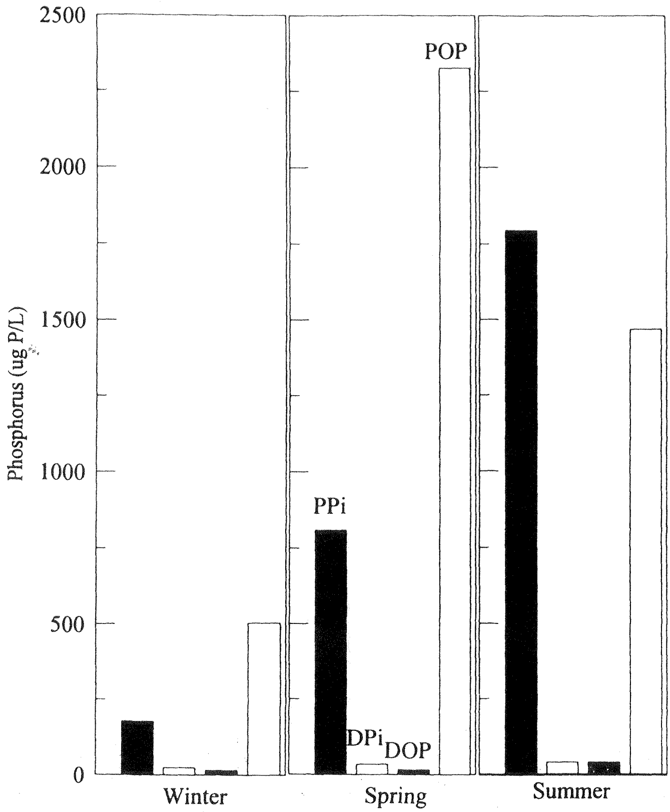

FIGURE 5 Seasonal mean distribution of forms of phosphorus in 22 storms studied on Rhode River cropland watershed (#109). Nine winter storms, eight spring storms, and five summer storms were measured. POP = particulate organic phosphorus, PPi = particulate inorganic phosphate, DPi = dissolved inorganic phosphate, DOP = dissolved organic phosphorus.

COMPARISONS WITH OTHER PARTS OF THE BAY WATERSHED

The Rhode River may not be typical of the Coastal Plain, let alone other physiographic provinces represented on the Chesapeake Bay watershed. Although we have not completed our overall study, we do have comparative data from other parts of the Coastal Plain and from the northern Piedmont (Table 1). The forested site on the Rhode River had higher phosphorus fluxes than the other Coastal Plain and Piedmont sites, but not much higher than the Piedmont site. The cropland site on the Rhode River also had higher phosphorus fluxes than the other Coastal Plain and Piedmont sites with similar land use composition.

TABLE 1
Comparison of Chesapeake Bay Watershed Phosphorus Discharge Fluxes

Watershed and Location	Total Phosphorus	Total Phosphate	Total Organic	Ref.
Forested				
Coastal Plain of Maryland and Delaware: #301 and #307 (native hardwoods/pine)	0.044	0.009	0.035	Jordan et al. (1997a)
Piedmont of Maryland: #401 (native hardwoods)	0.37	0.09	0.28	Jordan et al. (1997b)
Rhode River, Maryland: #110 (old growth deciduous hardwoods)	0.43	0.19	0.24	This chapter
Cropland				
Coastal Plain of Maryland and Delaware: mean of 6 watersheds (57.8% crops)	0.59	0.34	0.25	Jordan et al. (1997a)
Piedmont of Maryland: mean of 6 watersheds (62.4% crops)	0.47	0.16	0.31	Jordan et al. (1997b)
Rhode River, Maryland: #109 (64% crops)	2.54	1.40	1.14	This chapter

[a] All fluxes are in kg P ha^{-1} yr^{-1}

The high phosphorus fluxes from Rhode River subwatersheds (Table 1) are partially due to the high phosphorus content of the surface soils in this region of the Chesapeake watershed. The cropland watershed had 647 mg total P kg^{-1} of topsoil, and even a control mature forest watershed had 472 mg total P kg^{-1} of topsoil (Vaithiyanathan and Correll, 1992). This high soil phosphorus content combined with the steep slopes and highly erodible nature of the soils results in very high phosphorus fluxes, especially from cropland. Although cropland constituted only 24% of the Rhode River landscape, it was the source of 64% of the annual total phosphorus flux from the watershed, and the Rhode River subestuary of the Chesapeake was hypereutrophic (Correll et al., 1992).

RIVER CORRIDOR EFFECTS

We will address two types of corridor effects: riparian vegetation and reservoirs. Riparian forests are known to bring about a large reduction in the concentration of nitrate in shallow groundwater as it moves toward a stream channel, and this effect has been found at a number of sites (Correll, 1997); however, riparian forest effects on phosphorus fluxes are less documented. The Rhode River cropland site has a continuous riparian forest buffer. Where the flow during storms is not concentrated, about 85% of the particulate phosphorus in overland storm flows was trapped annually (Peterjohn and Correll, 1984). However, when concentrated overland flows occur, riparian forests are not very effective particulate phosphorus traps. In these situations, net erosion of riparian soils may result in the formation of gullies. An example was a site we studied on the Chester River watershed on the eastern shore of the Bay (Jordan et al., 1993). At this site, overland storm flows were concentrated and little if any net particulate trapping occurred. Another way in which riparian buffers remove particulate phosphorus is by trapping particles when the stream waters flood out onto the floodplain during storm events (Hupp et al., 1993). Vegetation on the flood plain slows the water, and substantial amounts of particulates are often trapped.

Reservoirs with long retention times on the main stems of rivers are effective traps for particulate phosphorus. Reservoirs support populations of primary producers, which also remove much of the DIP inputs to the reservoir. An example is found on the Patuxent River in Maryland where there are two such reservoirs in series. Time series of data for DIP inputs from the two major watersheds above the reservoirs and the Patuxent River below the reservoirs show the reduction in concentration caused by the reservoirs (Figure 6). This reservoir effect is quite common, and a number of reservoirs are present on Chesapeake Bay tributary streams.

SUMMARY

It is important for land managers to understand that discharges of POP and PPi and DOP to receiving waters are detrimental. Most of the phosphorus is transported in particulate forms. These forms cannot be assimilated directly by primary producers in the receiving waters, but biological and physical processes in the receiving waters convert significant amounts of this phosphorus to DIP, which can be assimilated (Correll, 1998). Therefore, any land management practices that will reduce the loss of any of these forms of phosphorus are very desirable. The installation of constructed wetlands and the protection of natural wetlands will help intercept phosphorus after it leaves the fields. The protection and establishment of well-managed riparian buffers will help intercept phosphorus after it leaves the fields. The protection and establishment of floodplain forests will also reduce phosphorus transport to the Chesapeake Bay. Reservoirs are effective phosphorus traps, but we must remember that these reservoirs fill up with trapped sediments. When that happens, either the reservoir loses its function or the sediments must be removed. If they are removed, the sediments must be distributed in such a manner that they will be retained on the watershed.

Because phosphorus fluxes to the receiving waters are much higher in wet seasons and years and during major storm events, we can expect the Chesapeake to receive much higher phosphorus inputs during these time periods. Much of these

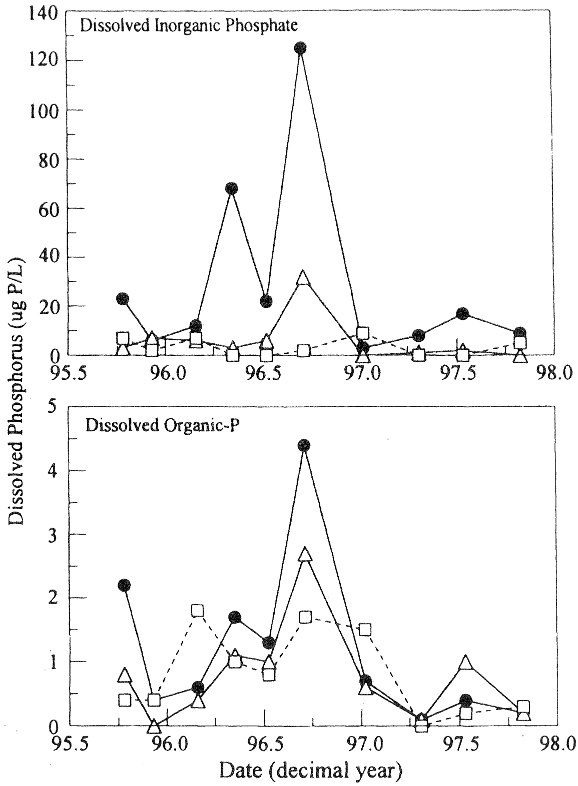

FIGURE 6 Effects of Tridelphia and Rocky Gorge reservoirs on dissolved phosphorus concentrations in the Patuxent River, MD. The main inputs were from two roughly equal sized streams, the Patuxent River (open triangles) and Cattail Creek (solid circles). The outputs to the Patuxent River below the reservoirs are shown as open squares and a dashed line.

phosphorus inputs are in the form of particulates, and much of these particulates settle to the bottom of the Bay, where they undergo diagenesis and release DIP to the overlying waters. Therefore, there is a "phosphorus memory" effect, and water-column phosphorus concentrations are higher for several years after these high flux time periods (Boynton and Kemp, 1985).

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