

THE DISTRIBUTION OF PHOSPHORUS IN POPES CREEK, VA, AND IN THE POCOMOKE RIVER, MD: TWO WATERSHEDS WITH DIFFERENT LAND MANAGEMENT PRACTICES IN THE CHESAPEAKE BAY BASIN

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Abstract. This paper compares phosphorus (P) concentrations in sediments from two watersheds, one with, and one without, intensive animal agriculture. The watersheds are in the coastal plain of the Chesapeake Bay and have similar physiographic characteristics. Agriculture in the Pocomoke River, MD, watershed supplied 2.7 percent of all broiler chickens produced in the USA in 1997. Poultry litter is an abundant, local source of manure for crops. Broiler chickens are not produced in the Popes Creek, VA, watershed and poultry manure is, therefore, not a major source of fertilizer. The largest concentrations of P in sediment samples are found in floodplain and main-stem bottom sediment in both watersheds. Concentrations of total P and P extracted with 1N HCl are significantly larger in main-stem bottom sediments from the Pocomoke River than in main-stem bottom sediments from Popes Creek. Larger concentrations of P are associated with what are potentially redox sensitive iron oxyhydroxides in sediment samples from the Pocomoke River watershed than are associated with what are potentially redox sensitive iron oxyhydroxides in sediment samples from the Popes Creek watershed. Data for P and iron (Fe) concentrations in sediments from the Popes Creek watershed provide a numerical framework (baseline) with which to compare P and Fe concentrations in sediment from the Pocomoke River watershed.

Keywords: estuary, iron, land-use, phosphorus, sediment, watershed

1. Introduction

The Chesapeake Bay is the largest and most productive estuary in the United States. Over enrichment of the nutrients phosphorus (P) and nitrogen (N), has contributed to eutrophication of the Bay. During the last 30 years, concern has been increasing over the contribution of agricultural runoff to P concentrations in the Bay (Sims *et al.*, 1998). There is limited information about nutrient and sediment storage and transport, in particular for P, in coastal plain watersheds such as those on the eastern shore of the Bay. For example, data for total P concentrations in water samples used to evaluate trends in delivery of P to the Bay in the years 1985 to 1996 were collected in ten watersheds of which only one was located on the eastern

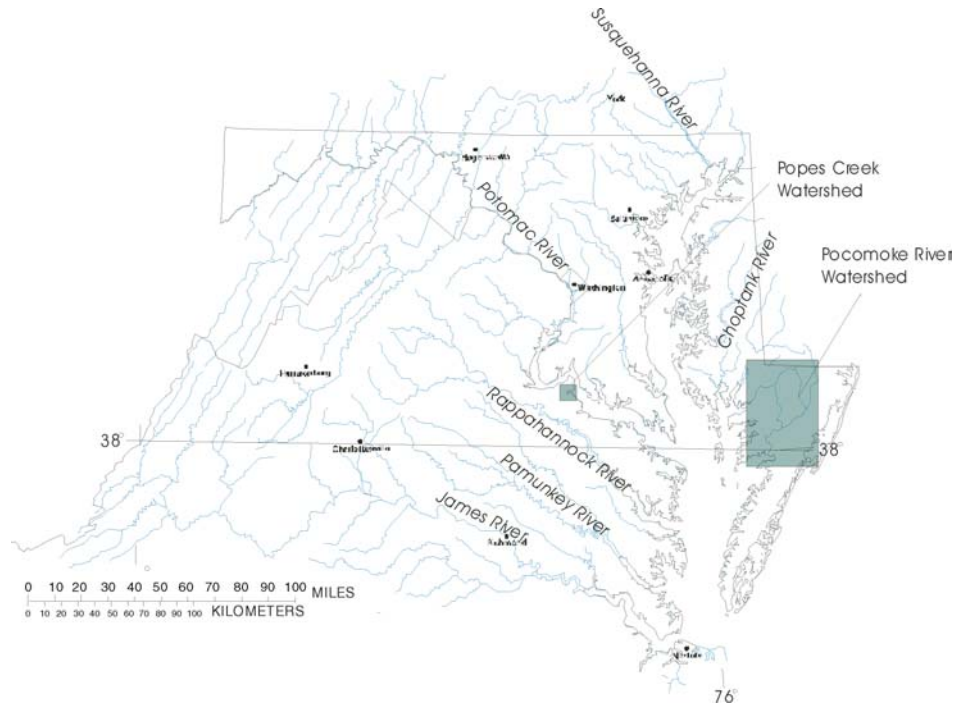


Figure 1. Chesapeake Bay Estuary showing the watersheds of Popes Creek, VA, and the Pocomoke River, MD.

shore of the Bay where the effects of the poultry industry are greatest (Langland, 1998).

To expand our knowledge of P fate and transport in the Chesapeake Bay watershed, sediments data were collected from November 1997 through December 1998 in the watersheds of Popes Creek, VA, and the Pocomoke River, MD, to evaluate the effects of land management practices on the distribution of P in sediments (Figure 1). Both watersheds are in the Atlantic Coastal Plain physiographic province. Popes Creek, in Westmoreland County, VA, is a tributary to the Potomac River, which discharges into the Chesapeake Bay. The Pocomoke River flows directly into the Bay through Pocomoke Sound; its watershed is more than 15 times larger than the watershed of Popes Creek. Annual rainfall is approximately 110 cm in both watersheds. Both streams flow through swamps, then marshes, as they move toward the receiving body of water. These two coastal plain rivers have an upland source with moderate relief and lowland flats with terraces. Tertiary Age sediments from the Chesapeake Group which is known for its abundance of marine fossils underlie the two rivers.

Popes Creek (Figure 2) and the Pocomoke River (Figure 3) watersheds were both settled in the 1600's. Poorly-drained parcels of land in both watersheds were artificially drained by ditches because wetness of the soils is a limitation to farming.

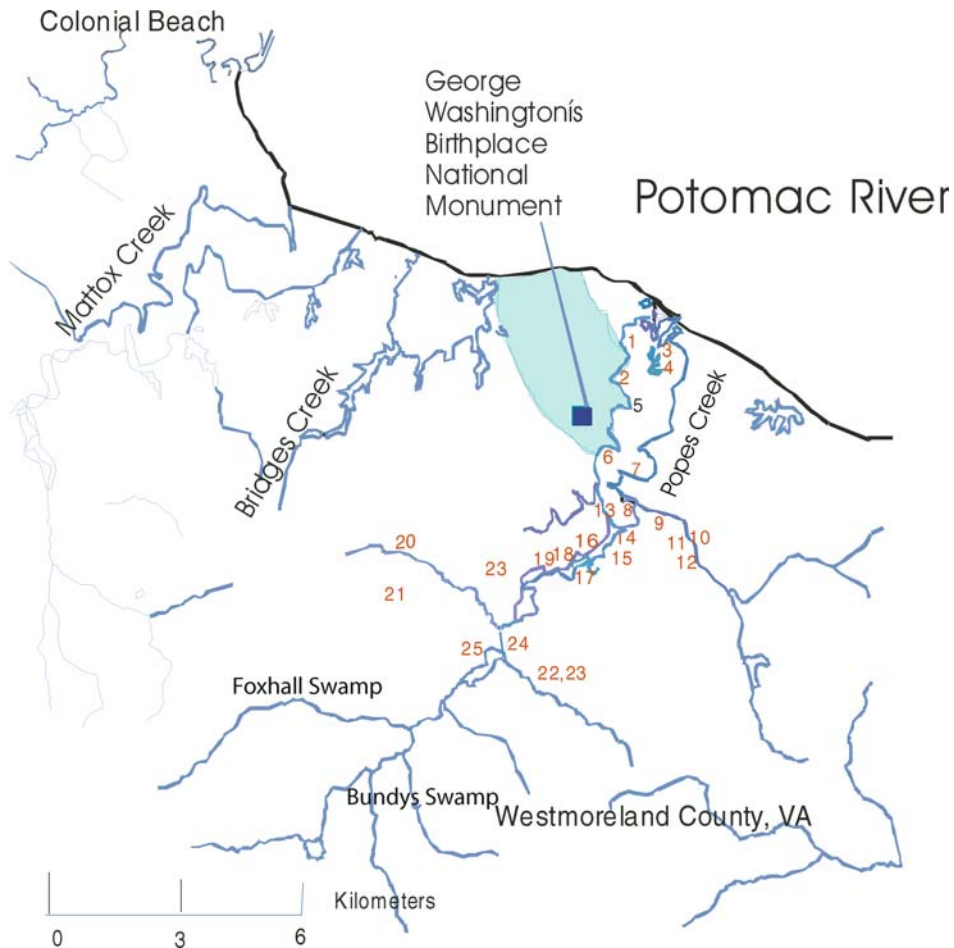


Figure 2. The watershed of Popes Creek, VA, showing sites sampled in 1998.

The soils in the upper watershed of Popes Creek are classified as well drained; soils classified as poorly drained are located in the area of the transition zone and mouth of the stream (Nicholson, 1981). The soils of the upper Pocomoke River watershed are classified as poorly drained. The classification of soils in the transition zone (midsection) and in the estuarine portion of the Pocomoke River range from poorly drained to well drained (Snyder and Gillett, 1925; Perkins and Bacon, 1928). Currently, poorly drained soils in the Pocomoke River watershed are tilled and ditched to permit cultivation. Many of these ditches extend into agricultural fields. In addition, the Pocomoke River is canalized north of Whitons Crossing, which is approximately 12 km upstream from Nassawango Creek.

Most of the tributaries to the Chesapeake Bay have major nutrient sources. These sources include intensive crop agriculture, poultry production, sewage treatment plants and/or a high density of private dwellings. None of these sources of nutrients

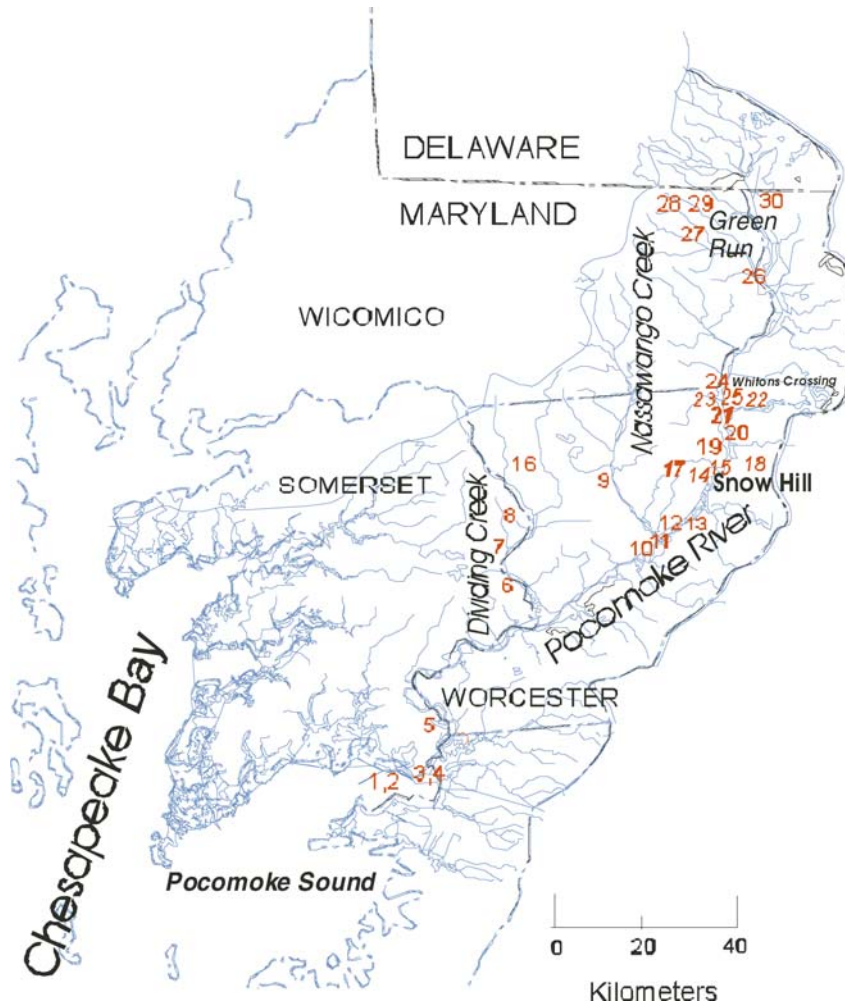


Figure 3. The watershed of Pocomoke River, MD, showing sites sampled in 1998.

are present in the Popes Creek watershed. Soybeans, corn, and grain crops are raised on 29 percent of the land in Westmoreland County, VA, (U.S. Department of Agriculture, 2003a) where Popes Creek watershed is located. The type and extent of crop agriculture is similar in both Popes Creek and the Pocomoke River watersheds. Soybeans, corn, and grain crops are raised on 31 percent of the combined areas of Somerset, Wicomico, and Somerset, the three Maryland counties through which the Pocomoke River flows (U.S. Department of Agriculture, 2003b).

Crop agriculture is important in the Pocomoke River watershed, and poultry farming is the dominant industry. In 1997, more than 175 million broiler chickens were produced in the three Maryland counties through which the Pocomoke River flows (U.S. Department of Agriculture, 2003c). This represents more than

2.7 percent of all of the broilers produced in the USA (U.S. Department of Agriculture, 2003c). In its lifetime each chicken generates approximately 1 kilogram of litter waste (Patterson *et al.*, 1998). This means that more than 175 million kilograms (approximately 385 million pounds) of litter were produced in the Pocomoke River watershed in 1997. The highest value for chicken litter produced on the Delmarva Peninsula is application as fertilizer to nearby cropland (Lichtenberg *et al.*, 2002). Most of the manure produced by the chickens grown in the Pocomoke basin is applied to agricultural fields close to the river. Poultry litter contains large concentrations of P. Patterson *et al.* (1998), reported an average concentrations of approximately 430 $\mu\text{mol/g}$ of P in 45 samples of poultry litter.

Run-off from agricultural fields is a major source of nutrients to the surface waters of the Chesapeake Bay Basin (Sims *et al.*, 1998; Goodman, 1999; Blankenship, 2003). The current practice of no-till farming contributes to nutrient runoff problems because with no-till manure and inorganic fertilizer are applied to fields without plowing to turn the soil. In the Pocomoke River watershed not only are inorganic fertilizer and poultry manure applied as fertilizer to crop fields, but poultry waste has been historically spread on fields solely as a means of disposal. Traditionally, rates of manure application for fertilization are based on the nitrogen content of the manure. Two to 3 times more P than required by crops is applied when poultry manure is used as a fertilizer because poultry manure ratios of N: P are 2 to 3 times larger than most crop requirements (Eghball, 1996). Phosphorus in the runoff can be attached to soil particles (Correll, 1998; Daniel *et al.*, 1998; Sims *et al.*, 1998) Transport processes can result in accumulation of P in downstream sediments. For this study, it is assumed that Popes Creek, a watershed with similar geomorphology, but not subject to intensive animal agricultural practices, will provide a data set of sediment P concentrations with which to compare sediment data from the Pocomoke River watershed where concentrated feeding operations are present.

This study is part of an ongoing U.S. Geological Survey (USGS) investigation to determine if geochemical processes in bottom sediments of streams reflect differences in land-use practices in watersheds of the Chesapeake Bay Basin. The main purposes of this paper are to present data documenting the distribution of P in mobile sediments from two watersheds, one with, and one without, intensive animal agricultural practices, and to evaluate the distributions of P concentrations with respect to distributions of Fe in sediment samples collected for this study.

2. Materials and Methods

2.1. STUDY AREA

Sampling sites were selected to represent both well- and poorly-drained land types based on slope steepness and landscape position and areas where there are geomorphic indicators of sediment accumulation. Figures 2 and 3 show the

sampling sites in each watershed. Site numbers for sampling locations increase from the confluence of Popes Creek with the Potomac River to the upper Popes Creek watershed, and from the confluence of the Pocomoke River with the Chesapeake Bay to the upper Pocomoke River watershed. Areas of sediment accumulation included floodplains, channels and man-made impoundments. In each watershed, samples were collected along the main-stem of the stream and along major tributaries or sediment sources to the stream. The streams that run through Bundys and Fox Hall Swamps are sediment sources to Popes Creek. Dividing Creek, Nassawango Creek and Green Run are major tributaries to the Pocomoke River. Site locations are shown in Figures 2 and 3. Site descriptions are given in (Simon *et al.*, 1999).

2.2. SAMPLE COLLECTION AND PROCESSING

Samples were collected from November 1997 through November 1998 in the watersheds of Popes Creek, VA, and the Pocomoke River, MD. Because the intent of this study was to evaluate the P content of sediments subject to transport, surface sediments were collected. Sediment grab samples were collected using a stainless steel shovel in dry areas and in areas where water depth did not exceed 0.5 meter. Grab samples were transferred to 1-gallon zip-lock bags and transported to the laboratory in an ice chest. The upper 1–5 cm of sediment was prepared for analysis. In addition, box cores were collected from a boat where the water column depths were 2–5 m. The top 1–2 cm of sediment at the sediment-water interface was saved and analyzed for this study. All samples were air-dried. When dry, samples were ground to a particle size of not more than 250- μm , either with an agate mortar and pestle or a ball mill.

2.3. ANALYTICAL PROCEDURES

To prepare sediment for analyses of total P and trace metals, samples were digested with concentrated nitric and hydrofluoric acids using the Microwave Sample Preparation System, Model MDS-2100, manufactured by CEM Corporation. To protect the analytical instrumentation, hydrochloric acid was not added to the acid matrix. Details are given in Simon *et al.*, 1999. SRM material 1646a, Estuarine Sediment, was included in two-thirds of the microwave digestions and analytical results were compared with the certified concentration values for calcium (Ca), aluminum (Al), Fe, and P in order to insure that the digestion process had been efficient for each set of samples. Analyses for Ca, Al, and Fe were done using a Perkin-Elmer Corporation Model 5100 ICP-AES using the methods suggested by the manufacturer.

The microwave digestion procedure described above converts all forms of phosphorus in samples to orthophosphate. The molybdenum blue method of Murphy and Riley as described in Rand and others (1976) was used to determine orthophosphate concentrations in microwave digests of sediment samples. Boric acid was added to the samples before the addition of the color reagent to complex any fluoride that

was not completely removed by the addition of boric acid during the microwave digestion procedure.

Samples were extracted with 1N HCl as described by Ruttenberg (1992) to differentiate between organic P and P associated with carbonates, sulfides, and oxides of Fe and manganese (Mn). Iron oxide phases soluble in 1N HCl could include amorphous iron oxyhydroxides, lepidocrocite, ferrihydrite and hematite. Modification of the method (Anderson and Delaney, 1999) included scaling the sample size from 0.5 g sediment and 50 mL of extracting solution to 0.1 g sediment and 10 mL of 1N HCl. Fe and P concentrations in the acid extracts were determined as described above using standards made up in the sample matrix.

3. Results

Data are divided into groups based on land type including ditch (Ditch) sediments (not present in Popes Creek watershed), creek (Cr) sediments, floodplain (FP) sediments and main-stem bottom (Bottom) sediments. Floodplain sediments include over bank deposits that are derived from suspended sediment in water that has flowed over the riverbank during periods of high flow. Concentrations of total P, 1N HCl extractable P, total Fe, 1N HCl extractable Fe, total Al, total Ca and percent carbon (C) in sediment collected in 1998 from the Popes Creek, VA, watershed and the Pocomoke River, MD, watershed are presented in Table I.

TABLE I

Chemical data (averages \pm standard deviation) for samples collected from November 1997 through November 1998 from Popes Creek watershed, VA, and Pocomoke River watershed, MD.

	1N HCl		1N HCl		Total Al $\mu\text{mol g}^{-1}$	Total Ca $\mu\text{mol g}^{-1}$	%C
	Total P $\mu\text{mol g}^{-1}$	Extracted P $\mu\text{mol g}^{-1}$	Total Fe $\mu\text{mol g}^{-1}$	Extracted Fe $\mu\text{mol g}^{-1}$			
Ditch							
Popes Creek	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Pocomoke River	11 \pm 9	7 \pm 9	197 \pm 147	76 \pm 89	1058 \pm 463	45 \pm 21	1.3 \pm 1.0
Creek							
Popes Creek	7 \pm 0	1 \pm 0	179 \pm 74	30 \pm 11	450 \pm 88	33 \pm 28	3.5 \pm 4.5
Pocomoke River	23 \pm 6	10 \pm 7	206 \pm 52	76 \pm 37	1340 \pm 449	62 \pm 17	4.6 \pm 2.3
Floodplain							
Popes Creek	17 \pm 8	5 \pm 5	443 \pm 160	207 \pm 150	1301 \pm 330	11 \pm 2	2.2 \pm 2.3
Pocomoke River	45 \pm 27	30 \pm 29	382 \pm 203	230 \pm 192	1438 \pm 376	100 \pm 38	14.9 \pm 8.8
Main-Stem Bottom							
Popes Creek	27 \pm 8	16 \pm 6	471 \pm 230	230 \pm 134	1527 \pm 710	73 \pm 42	4.3 \pm 3.1
Pocomoke River	69 \pm 26	52 \pm 21	657 \pm 184	432 \pm 190	1679 \pm 325	98 \pm 33	6.8 \pm 3.5

n.a. = not available.

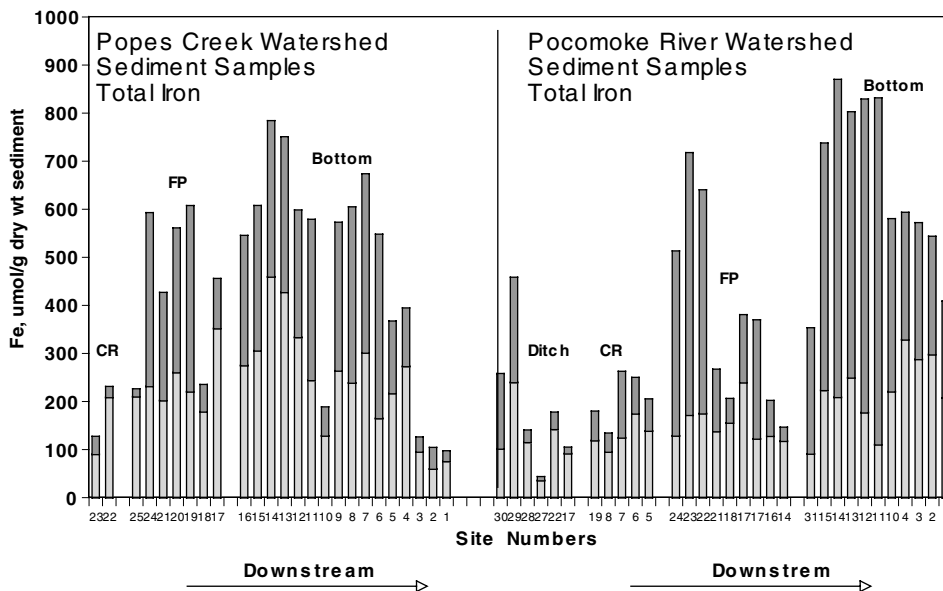


Figure 4. The distribution of Fe as $\mu\text{mol g}^{-1}$ dry wt in sediments from the watersheds of Popes Creek, VA, and the Pocomoke River, MD. Bar height represents the total concentration of Fe. The dark segment at the top of each bar represents the concentration of Fe that was extracted with 1N HCl. Samples are classified as ditch (Ditch, Pocomoke River only), stream (CR), floodplain (FP) and mainstem bottom sediment (Bottom).

Concentrations of total and 1N HCl extracted Fe for all samples from Popes Creek and the Pocomoke River watersheds are shown in Figure 4. Total Fe concentrations in all sediments are similar in both watersheds. The average values for concentrations of total Fe in all sediment from the Popes Creek watershed and the Pocomoke River watershed are 440 ± 214 ($n = 25$) and 417 ± 259 ($n = 30$) $\mu\text{mol g}^{-1}$, respectively. The concentrations of Fe that are extracted with 1N HCl appear larger in the Pocomoke River watershed sediments than in the Popes Creek watershed sediments. The average values for concentrations of Fe that are extracted with 1N HCl from all sediments are 207 ± 114 ($n = 25$) and 247 ± 216 ($n = 30$) $\mu\text{mol g}^{-1}$ for Popes Creek and Pocomoke River sediments, respectively.

Figure 5 shows the concentrations of total and 1N HCl extractable P for all samples from Popes Creek and the Pocomoke River watersheds. The average concentrations of total P in all sediments are 21 ± 10 ($n = 25$) and 38 ± 28 ($n = 30$) $\mu\text{mol g}^{-1}$ for Popes Creek and the Pocomoke River watersheds, respectively. The average values for concentrations of P that are extracted with 1N HCl from all sediments are 11 ± 8 ($n = 25$) and 26 ± 25 ($n = 30$) $\mu\text{mol g}^{-1}$ for Popes Creek and the Pocomoke River watersheds, respectively. Average values for the concentration of total P and 1N HCl extractable P tend to be larger for sediment samples from the Pocomoke River watershed than for sediment samples from Popes Creek watershed.

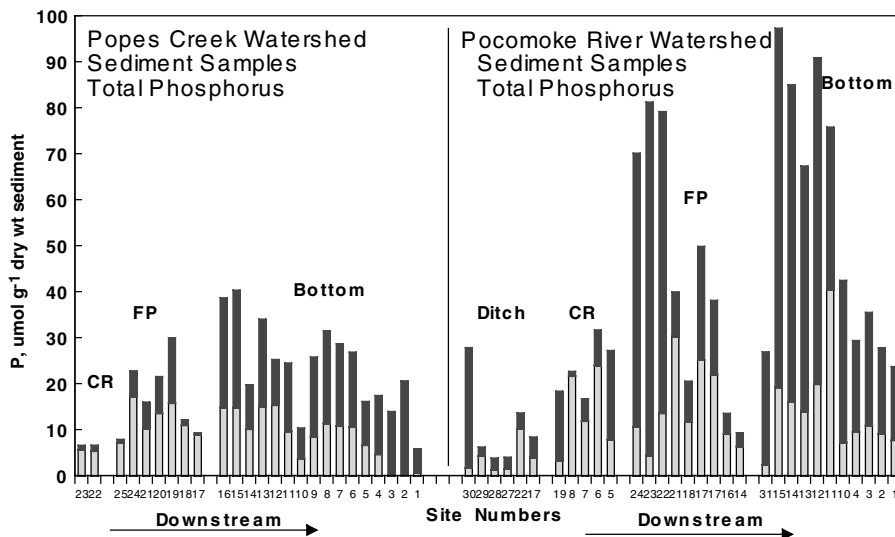


Figure 5. The distribution of P as $\mu\text{mol g}^{-1}$ dry wt in sediments from the watersheds of Popes Creek, VA, and the Pocomoke River, MD. Bar height represents the total concentration of P. The dark segment at the top of each bar represents the concentration of P that was extracted with 1N HCl. Samples are classified as ditch (Ditch, Pocomoke River only), stream (CR), floodplain (FP) and mainstem bottom sediment (Bottom).

The distributions are similar for the concentrations of total Al and total Ca in sediments collected in the two watersheds; the distribution was not similar for the percent carbon (C) in sediment samples. Concentrations of C in sediment grouped by type from the Pocomoke River watershed tended to contain larger concentrations of C than in sediment grouped by type from the Popes Creek watershed. Table I presents average concentrations of total Al, total Ca and C for each sediment category in both watersheds.

4. Discussion

4.1. DISTRIBUTION OF PHOSPHORUS AND Fe PHASES IN SEDIMENT SAMPLES

Iron phases play an important role in sorption of phosphate in sediment samples collected for this study. Phosphate is strongly attracted to Fe containing minerals, especially oxyhydroxides (Sallade and Sims, 1997; Vadas and Sims, 1998). The P in Atlantic Coastal Plain soils is normally associated with Fe and Al minerals or sorbed to Al and Fe (hydroxy)oxides (Vadas and Sims, 1998). Clays are not expected to play a major role in phosphate sorption in these oxidized sediments because the most likely role of clays in oxidized sediments is that of a carrier for the substrates which bind metals (Jenne, 1977). Extraction of sediment samples with 1N HCl will remove

carbonates, sulfides, and oxides of Fe (Ruttenberg, 1992; Cooper and Morse, 1998). One N HCl extractable Fe is interpreted for this discussion to be non-crystalline Fe oxides and poorly crystalline Fe minerals; organic and refractory P are left in the residue after extraction with 1N HCl (Luoma and Bryan, 1981; Ruttenberg, 1992). The samples collected for this study are surface sediments. Sulfides are not expected in the samples and hydrogen sulfide was not emitted when dilute HCl was added in the extraction process. In the Pocomoke River watershed, Fe oxyhydroxides are formed when Fe-rich groundwater from the Beaverdam formation (Hamilton *et al.*, 1993; Ator *et al.*, 2004) reaches the sediment or soil surface. This process might explain the large percentage of 1N HCl extractable Fe concentrations in bottom sediments and in sediments from swampy areas adjacent to the Pocomoke River in the area of Nassawango Creek. Bricker *et al.* (2003) have reported ubiquitous seeps containing deposits of amorphous Fe oxides in the Nassawango Creek area of the Pocomoke River. There is limited information about the composition of groundwater in Popes Creek watershed; evidence for iron in the groundwater is anecdotal.

Ditching of agricultural fields aids in the transport of sediment, as well as water from the fields. The only ditches in Popes Creek watershed are remnants of colonial farming practices. However, there are 1200 miles of ditches that are currently draining cultivated fields in the Pocomoke River watershed (Bricker *et al.*, 2003). These ditches, and tile drains that feed them, short-circuit the natural vegetative buffer zones that would normally filter runoff from fields before the runoff enters the stream. They provide a potential conduit for the transport of nutrients and sediment from agricultural fields into larger ditches, tributary streams, or directly into the Pocomoke River. There is evidence that topsoil can enter stream flow via tile drainage (McDowell and Wilcock, 2004). Because phosphate binds to Fe oxides in sediment solids, the transport of phosphate is related to the transport of sediment in a watershed.

The mean concentration of total P in the upper 1–5 cm sediment collected from creeks in the Popes Creek watershed is $7 \mu\text{g g}^{-1}$ dry wt of sediment. There are no active ditches in the Popes Creek watershed. The mean concentration of total P in the upper 1–5 cm ditch and stream sediments from the Pocomoke River watershed is $16 \mu\text{g g}^{-1}$ dry wt of sediment. These values for total P concentrations in sediments are similar to the reported means of the concentrations of total P in soils and sediments from agricultural fields and ditches in other areas of the mid-Atlantic Coastal Plain physiographic province. Soil classified as Pocomoke sandy loam that was collected from a drained agricultural field in the Inlands Bays watershed, a coastal plain watershed adjacent to the Pocomoke River watershed, had a mean concentration of approximately $16 \mu\text{mol/g}$ dry wt total P in the 0–18 cm horizon (Vadas and Sims, 1998). Sallade and Sims (1997) reported a mean value for total P of approximately $12.6 \mu\text{mol g}^{-1}$ in samples from a depth of 1–5 cm in sediment from 17 ditches in Delaware's Inland Bays' watershed.

While the concentrations of total Fe are similar in sediment from both watersheds, the concentrations of total P are apparently different (Figures 4 and 5).

The concentrations of both total P and 1N HCl extracted P tend to be larger in the Pocomoke River watershed than in Popes Creek watershed. Data for creek and floodplain samples are not statistically significantly different, however, due to sample variation. (Ditch samples were only available in the Pocomoke River watershed.) The average concentrations of total P and 1N HCl extractable P in bottom sediments from the main-stem of the Pocomoke River are significantly larger (95 percent confidence level) than concentrations of total P and 1N HCl extractable P in main-stem bottom sediments of Popes Creek (Table I). Sedimentation of P containing particles in a river channel can an important P retention process (Venterink *et al.*, 2003). The watershed with the larger concentrations of P in main-stem bottom sediment samples is the watershed in which there is a large poultry industry. The watershed with similar physiographic characteristics and similar land-use practices but without a large poultry industry, has statistically smaller concentrations of total P in main-stem bottom sediment samples.

A comparison of these data indicate that variation of concentrations of total P and 1N HCl extractable P in sediment samples was related to total Fe and 1N HCl extractable Fe but not to concentrations of total Al, total Ca, or percent C in the sediment samples collected for this study. Data for the concentrations of Fe extracted with 1N HCl were a better indicator of the patterns of distribution of concentrations of total P in sediment samples than were concentrations of total Fe in sediments collected in this study. The r^2 values for a linear relationship between total P concentrations and 1N HCl extractable Fe concentrations in these samples are 0.7 and 0.8 for samples from the Popes Creek and from the Pocomoke River watersheds, respectively (Figure 6). This relationship could be explained by P sorption by the fractions of iron oxides in these samples that are poorly crystalline and readily extracted with 1N HCl.

Retention of P in main-stem bottom sediments is not necessarily a permanent loss of P from the water column. The release of phosphate from sediment to associated water is contingent on redox conditions, that is, on the dissolution of ferric oxides when reducing conditions develop in the water-column or sediment (Föllmi, 1996). Larger concentrations of P are associated with poorly crystalline iron oxides in the bottom sediments of the Pocomoke River than are associated with poorly crystalline iron oxides in the bottom sediments of Popes Creek. There is more P vulnerable to release when ferric iron is reduced to the more soluble ferrous iron in reducing environments in Pocomoke River main-stem bottom sediments than is available in Popes Creek main-stem bottom sediments.

4.2. RATIO OF 1N HCl EXTRACTABLE PHOSPHATE TO 1N HCl EXTRACTABLE Fe

The pattern of distribution of the ratios $\mu\text{mol g}^{-1}$ dry wt of 1N HCl extractable phosphate to $\mu\text{mol g}^{-1}$ dry wt of 1N HCl extractable Fe in sediment samples is uniform throughout the Popes Creek watershed (Figure 7). The calculated average

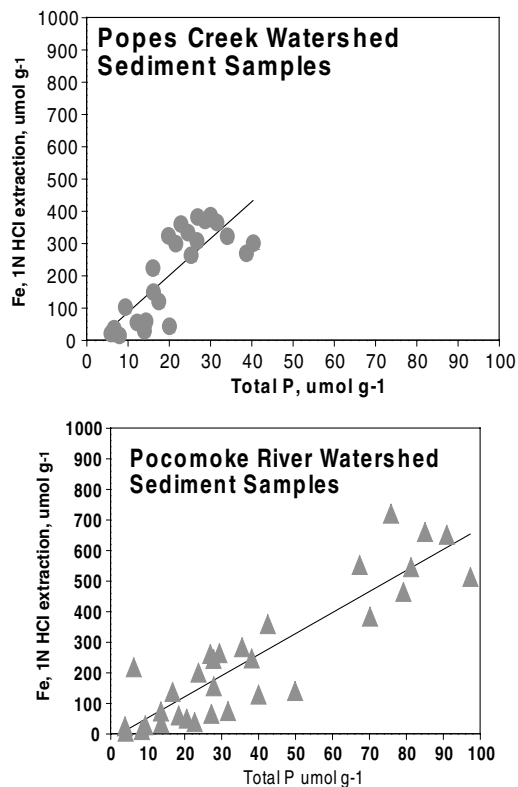


Figure 6. The concentration of total P as $\mu\text{mol g}^{-1}$ dry wt plotted against the concentration of Fe as $\mu\text{mol g}^{-1}$ dry wt extracted with 1N HCl from sediment samples collected in the Popes Creek watershed and the Pocomoke River watershed.

was 0.05 for the of ratio of $\mu\text{mol g}^{-1}$ dry wt of 1N HCl extractable phosphate to $\mu\text{mol g}^{-1}$ dry wt of 1N HCl extractable Fe in sediments from the Popes Creek watershed collected above the confluence of the Popes Creek and the Potomac River. This indicates that approximately 0.5 reactive units of phosphate are sorbed per 10 reactive units of poorly crystalline Fe minerals. If there were a source of P in the system, the ratio of $\mu\text{mol g}^{-1}$ of 1N HCl extractable phosphate to $\mu\text{mol g}^{-1}$ 1N HCl extractable Fe might show a localized increase. An increase was not observed.

The ratios phosphate extracted with 1N HCl to Fe extracted with 1N HCl were uniformly larger for samples collected in the Pocomoke River watershed than for samples collected in the Popes Creek watershed (Figure 7). The concentrations of total Fe and 1N HCl extractable Fe are similar in the two watersheds. In comparison, the concentrations of total P and 1N HCl extracted P tend to be larger in sediments from the Pocomoke River watershed than in sediments from the Popes Creek watershed. The calculated average for sediment samples from ditches and creeks in

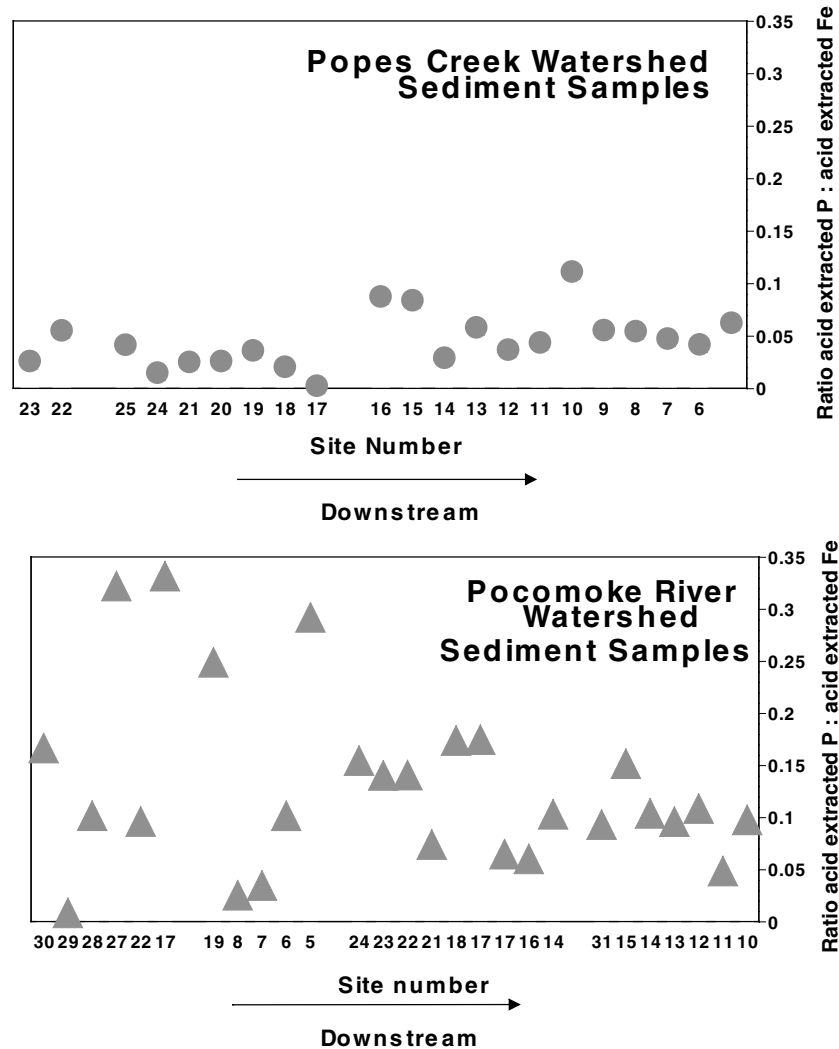


Figure 7. Ratios of $\mu\text{mol g}^{-1}$ dry wt of total P to $\mu\text{mol g}^{-1}$ dry wt of dilute acid-extractable Fe for sediment samples from Popes Creek, VA, and the Pocomoke River, MD.

the Pocomoke River watershed was 0.18 for the ratio of $\mu\text{mol g}^{-1}$ dry wt of 1N HCl extractable phosphate to $\mu\text{mol g}^{-1}$ dry wt of 1N HCl extractable Fe. This indicates that approximately 1.8 reactive units of phosphate are sorbed per 10 reactive units of poorly crystalline Fe minerals. A possible explanation for this is that there are sources of phosphate in the areas of the Pocomoke River watershed where ditches and creeks are located. The ratio of $\mu\text{mol g}^{-1}$ dry wt of 1N HCl extractable phosphate to $\mu\text{mol g}^{-1}$ dry wt of 1N HCl extractable Fe decreased to 0.12 for floodplain

sediments and 0.09 for main-stem bottom sediments from the Pocomoke River watershed. For bottom sediments from the main-stem of the Pocomoke River, the calculated ratio indicates that approximately 1 reactive unit of phosphate is sorbed per 10 reactive units of poorly crystalline Fe minerals. This compares with an average value of approximately 0.5 reactive units of phosphate sorbed per 10 reactive units of poorly crystalline Fe minerals for all sediment samples from the Popes Creek watershed.

5. Conclusions

This study contributes to an understanding P transport and fate in the Chesapeake Bay Basin by comparing P distributions in two coastal plain watersheds with similar physiographic characteristics and similar land-use practices but one with, and one without, intensive animal agriculture. In the Pocomoke River watershed there is a large poultry industry that provides abundant chicken litter for application to fields; there is no poultry industry in the Popes Creek watershed. Concentrations of total and 1N HCl extractable P in sediment samples from the Pocomoke River watershed were generally larger than concentrations of total and 1N HCl extractable P in sediment samples from Popes Creek watershed. The concentration of total P and 1N HCl extractable P in main-stem bottom sediments of the Pocomoke River were significantly larger than, and approximately twice the concentrations of, total P and 1N HCl extractable P in the main-stem bottom sediments of Popes Creek. Data obtained from the extraction of sediment with 1N HCl indicate that larger concentrations of P are associated with poorly crystalline iron oxides in the bottom sediments of the Pocomoke River than are associated with poorly crystalline iron oxides in the bottom sediments of Popes Creek. This implies that more P is vulnerable to release by reduction of ferric iron to the more soluble ferrous iron from Pocomoke River main-stem bottom sediments than from Popes Creek main-stem bottom sediments.

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