Bloede Dam Biogeochemical Impacts – An Analysis Based on Patapsco River Nutrient Balances

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Introduction

The release of fine-grained sediment after removal of the Bloede Dam will release a substantial amount of sediment to flowing waters, and ultimately to the estuarine segments of the Patapsco River. Of particular interest are the ~87,000 cubic yards of fine grained material found at the base of the sediment profile. The phosphorus inputs from these sediments could be substantial, but need to be put in perspective with overall phosphorus loading to the ecosystem. Here, we provide background on how particulate phosphorus would interact with the estuary and provide what we believe to be reasonable bounds to potential deleterious effects. The most basic distinction is between inputs of total particulate phosphorus and inputs of particulate phosphorus forms that may be converted into forms that could grow algae. In the Chesapeake Bay, even in the deep anoxic mid-bay region where release of phosphorus from sediment is at its maximum, substantial amounts of sediment phosphorus remain permanently buried.

The analysis that follows here is based on information provided to us from the geological/chemical assessment of deposits behind the Bloede Dam, our data from the Patapsco Estuary and the Chesapeake, and reasonable assignment of controlling processes. Where there are data gaps and assumptions made, we have attempted to be explicit in our description of this analysis.

Estuarine Phosphorus Biogeochemistry – Fundamental Concepts

Although the cycling of phosphorus can vary significantly between different estuaries, and within estuaries, there are well known processes that control the release of phosphorus from estuarine sediments. The riverine delivery of phosphorus to Chesapeake Bay mainstem and tributary environments is dominated by inorganic particulate forms of phosphorus, rather than dissolved or inorganic dissolved phosphorus. Regionally, the most common association of inorganic phosphorus with fluvial particulates is the adsorption/co-precipitation of inorganic phosphorus with iron oxy-hydroxides (Jordan et al. 2008). Thus, the fate of particulate phosphorus is controlled by processes that reduce iron oxides to dissolved ferrous iron or convert iron oxides to iron sulfide minerals which poorly adsorb inorganic phosphorus (Lehtoranta et al. 2009). The reduction of iron oxides occurs most efficiently when overlying water is low in oxygen, and especially when low oxygen conditions in estuarine or marine sediments lead to the formation of iron monosulfide (FeS) or pyrite (FeS_2) minerals (Cornwell and Sampou 1995). The chief other mechanism of phosphorus release occurs when cyanobacterial blooms result in pH's > 9.2 (Gao et al. 2012).

In the estuarine environment, sediment habitats with salinity < 1 generally do not release appreciable phosphorus from sediments (Caraco et al. 1990). At the other extreme, release of phosphorus from saline sediments with low oxygen, such as the Chesapeake Bay mainstem, is highly efficient (Cowan and Boynton 1996, Boynton 2000). Thus, estimation of estuarine phosphorus releases depends on location relative to phosphorus inputs, the rate of organic matter inputs which along with temperature controls sediment metabolic activity, water column oxygen, and salinity. In the estuarine environment of the Patapsco River, all of these controlling factors matter. Fortunately, past measurements of sediment processes provide some important clues as to which of these are likely the most important in the Patapsco.

With rapid settling of suspended sediments during inflow events, we believe that the primary effect of these phosphorus inputs would be after sediment deposition. In our experience with dredging releases of nutrients, upon mixing aerobic surface water with sediment deposits rich in iron, especially pore water ferrous iron, any dissolved inorganic phosphorus would be rapidly bound to the sediments; this is likely to occur as well with release of fine grained deposits into the Patapsco River.

Some Chesapeake Bay P Cycling Examples

We investigated the chemistry of particulate phosphorus in the Potomac River in the mid-2000's to help modelers explain an apparent excess of dissolved inorganic phosphorus (Limnotech and UMCES 2007). Our approach examined the forms of suspended P in the river, from upstream sources, and eroding shorelines (Figure 1). We concluded that iron indeed was a key controlling factor in the cycling of inorganic phosphorus in the estuary. The key finding of this work was that there was not an important release of dissolved inorganic phosphorus to the water column from desorption from suspended particulates as salinity was encountered; this is consistent with more recent physio-chemical observations (Spiteri et al. 2008) that salinity effects on adsorption were not a key driving force. However, examination of earlier sediment-water exchange rates of dissolved inorganic phosphorus showed that bottom sediments could indeed explain the excess dissolved inorganic phosphorus (Figure 2). Observations of the effects of salinity on bottom sediment phosphorus cycling (e.g. (Caraco et al. 1990) suggest that with increasing salinity, the release of phosphorus is enhanced. In estuaries, it appears that conversion of iron oxides to iron sulfides drives high rates of phosphorus release (Roden and Edmonds 1997, Lehtoranta et al. 2009). In the Patapsco estuary, iron sulfide minerals are observed in most near-surface sediments (Baker et al. 1997), and we would expect high rates of conversion of iron oxides to iron sulfides. We have shown that low oxygen promotes the release of dissolved inorganic phosphorus in the upper Chesapeake Bay; experiments with added iron oxide-rich bottom sediment did not show a large increase in phosphorus release however (Figure 3).

Estimates of Potential Phosphorus Loading – Impact on Patapsco River Phosphorus Balances

Data Summary

In this section we provide background data relative to phosphorus issues related to dam removal and these include: 1) a time series of P loading rates to the Patapsco River system; 2) a comparison of phosphorus loading rates for 19 Chesapeake Bay tributaries, including the Patapsco and; 3) a summary of sediment P release rates measured in low salinity environments in Chesapeake Bay and specifically in the Patapsco River system. We also have included here a series of computations that provide some guidance as to the relative magnitude of potential phosphorus releases from the fine-gjrained sediments expected to be released to the estuary from the proposed dam removal.

In Figure 4 we have organized total phosphorus (TP) and dissolved inorganic phosphorus (DIP) loading rates to the full Patapsco River system. These data include both point and diffuse sources that we organized from the EPA Chesapeake Bay Program land-use model output (G. Shenk, *personal communication*). These phosphorus loads have been prorated over the surface area of the Patapsco

River system to yield areal loads in units of g phosphorus m^{-2} day^{-1}. If these daily loads are expanded to annual estimates (multiply daily loads by 365 day $year^{-1}$) TP and DIP loads are about 2.2 and 1.1 g phosphorus m^{-2} $year^{-1}$. Note also that there has been a general decrease in TP and DIP loads to this system between 1986 and 2005. Model generated TP and DIP loads are not available for more recent time periods.

In Figure 5 we have organized the same sort of loading data (just TP) for 19 Chesapeake Bay tributary systems, including the Patapsco River. Clearly, the Patapsco has one of the highest P loading rates among Chesapeake Bay tributaries, exceeded only by Piscataway Creek (upper Potomac tidal water creek) and the adjacent Back River system. Additionally, in the Patapsco, point sources of phosphorus are especially important sources of phosphorus and the vast majority of phosphorus from point sources is in a form (DIP) readily available to the phytoplankton community.

In Figure 6 we have organized sediment phosphorus release rates from selected regions of Chesapeake Bay, including data available from the Patapsco River system (only tidal portions of the Patapsco). These data are presented as box and whisker plots with the average flux (i.e., phosphorus release rate) shown as a solid line in each box, the median as a dashed line and the 5^{th} and 95^{th} percentiles as the bottom and top edges of the boxes. Extreme values are shown as single black dots. These data were from a large synthesis of Chesapeake Bay Sediment flux data and these data are available at a web site (www. gonzo. cbl.umces.edu). The left hand bar summarizes all sediment P flux data collected at Chesapeake Bay sites with water temperature greater than 20°C and no measurable salinity and has a mean rate of about 10 umoles phosphorus m^{-2} $hour^{-1}$. The next bar summarizes all data collected at temperatures greater than 20°C and salinities of 5 or less. The third bar summarizes flux data also collected at temperatures of greater than 20°C, any salinity but very low dissolved oxygen (DO) concentrations. The final two bars contain sediment flux data from just the Patapsco system, the first including all data available and the second data collected at sites where DO was very low (<1 mg l^{-1}). There were very few measurements available under low DO conditions (final bar; n=3) and these few measurements should be viewed with caution. It is clear that both median and average sediment phosphorus fluxes in the Patapsco are higher than those measured in roughly comparable sites in Chesapeake Bay and this is consistent with the high phosphorus loading rates estimated for this system (Fig. 5).

Computations

Based on the data presented above and data supplied to us by American Rivers and associated organizations, we can make some estimates of phosphorus impact related to dam removal and place these impacts into the context of P dynamics of the Patapsco estuary. Included in these computations are the following: 1) maximum potential sediment phosphorus release from sediments released from dam removal; 2) measured sediment P fluxes from the Patapsco and other similar Chesapeake Bay tributaries; 3) the amount of phytoplankton primary production that could be supported by sediment phosphorus fluxes and; 4) the magnitude of phosphorus loading rates to the Patapsco system. The estimates provided here tend to be "worse-case" scenarios.

Potential maximum sediment releases from dam sediments:

a) Total phosphorus stored in muddy dam sediments 85,000 lbs; 38,590 kg phosphorus
b) Assume 50% of this TP could become available under appropriate environmental conditions; the remaining phosphorus is tightly bound to sediment particles and is only available for burial in accreting sediment column. In the Patuxent River estuary, about 81% of particulate phosphorus is retained in the upper estuary (Jordan et al. 2008) and for particles that were deposited in the saline lower estuary, about half of the original phosphorus was retained (on a mass basis).
c) Area of Middle Branch is 8.1 x 10^6 m^{-2}; assume all dam released sediments deposit in this area in one year following dam removal. It is more likely that sediments will be transported farther and during a period greater than one year.
d) With these assumptions the DIP release would amount to about 2.4 g P m^{-2} year $^{-1}$. This is a substantial rate and close to the current phosphorus loading rate from other external (point + non-point) sources for the full Patapsco system. Note that this relatively high loading rate applies just to the Middle Branch area and that represents only about 8% of the full Patapsco system
e) If we assume that the dam associated sediments were spread over a larger area (full Patapsco River estuarine system; 99 x 10^6 m^{-2}) the release rate (still assuming 50% of all phosphorus would be released from sediments during a single year) would be about 0.2 g phosphorus m^{-2} year $^{-1}$. This is a very modest phosphorus loading rate.

Measured sediment P releases:

a) Assume a measured in-situ DIP flux of 10 uMoles m^{-2} hr^{-1} for non-anoxic Patapsco sediments
b) Assume these fluxes persist for 50% of the year. Low temperatures restrict phosphorus and other fluxes. We assume net DIP flux to be close to zero for half the year.
c) With appropriate conversion factors, this flux converts to 1.3 g phosphorus m^{-2} yr $^{-1}$. This rate is about half of the external loading rate to the full Patapsco estuarine system.

Sediment P flux to support primary production

a) Assume molar-based Redfield ratio (106C: 16N:1P) for phytoplankton composition.
b) Convert sediment phosphorus flux (10 uMoles P m^{-2} hr $^{-1}$) to carbon units of g C m^{-2} day^{-1}

c) Sediment phosphorus flux would support phytoplankton production rates of about 0.3 g C m^{-2} day $^{-1}$. This is a relatively low rate of production. Phytoplankton production rates in the Patapsco are typically in the range of 2 – 3 g C m^{-2} day^{-1} during summer periods and such rates are typical of enriched estuarine systems.

Bay Program P loading rates to the Patapsco estuary

a) Based on Chesapeake Bay Program phosphorus loading rates to the Patapsco estuary (includes both point and non-point sources) we estimate current loading rates of about 2.2 g m^{-2} $year^{-1}$. This estimate is for the full Patapsco estuarine system. If we were to consider just portions of the system (e.g., Inner Harbor or Middle Branch) these loading rates would be much higher. We do not have data available to make sub-system loading rate estimates.

Summary

There is a reasonable expectation that release of Bloede Dam sediment could result in 1) the deposition of inorganic phosphorus in sediments of the tidal Patapsco River and that 2) under saline, and especially low oxygen conditions, a portion of that phosphorus could become bio-available for the growth of algae. The importance of these release rates is related to the area of deposition; if the area of deposition of fine-grained Bloede Dam material is amortized over the whole tidal Patapsco, these releases are aerially very moderate.

Mitigation of these modest P release rates is difficult because of unknown timing of when the particles reach the estuary. Under higher flow winter conditions, the particles will reach the estuary faster, but not have an important immediate effect because of low rates of sediment metabolism and high dissolved oxygen concentrations. Under lower flow summer conditions, one might expect lower immediate particulate inputs into the estuary; and inputs may be delayed until higher flow events occur in the fall/winter/spring. Either way, we do not expect significant phosphorus releases from deposited sediment except during summer.

We did not specifically consider nitrogen releases in this analysis because they are likely small because of the 1) terrestrial nature of particulate nitrogen stored in the sediment and 2) the long period over which they have degraded. Nitrogen is of importance though, because it tends to be the limiting nutrient for algal growth more of the time that does phosphorus. Bioassays (Fisher et al. 1999) have shown that stimulation of algal growth much more often is related to additions of nitrogen than phosphorus in the Patapsco River.

Appendix – Figures

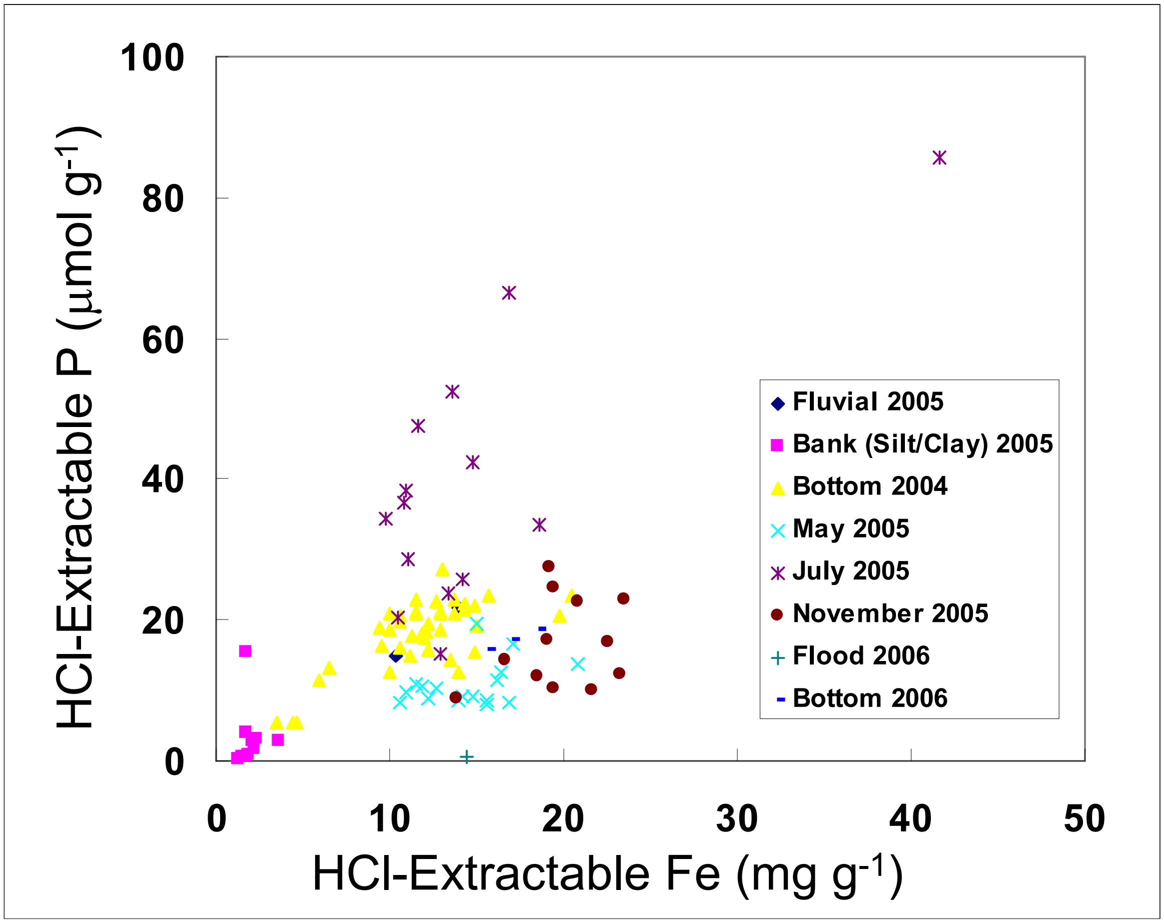

Figure 1. Plot of inorganic P versus HCl-Fe for samples from the Potomac River (Cornwell 2007, Limnotech and UMCES 2007). The bottom samples from 2004 are tidal freshwater samples (Bailey et al. 2006) and consisted of the top 2 cm of sediment. The May, July and November data are suspended sediment samples with salinities < 1. Fluvial samples are suspended sediments from Chain Bridge, and bank sediments are from eroding banks. For reference, 100 µmol g^{-1} is 3.1 mg g^{-1} P.

These data show that the iron content of suspended and bottom sediment is a reasonably good predictor of solid phase inorganic P concentrations. This study strongly suggested that particulate phosphorus suspended in the water column was not a large P source.

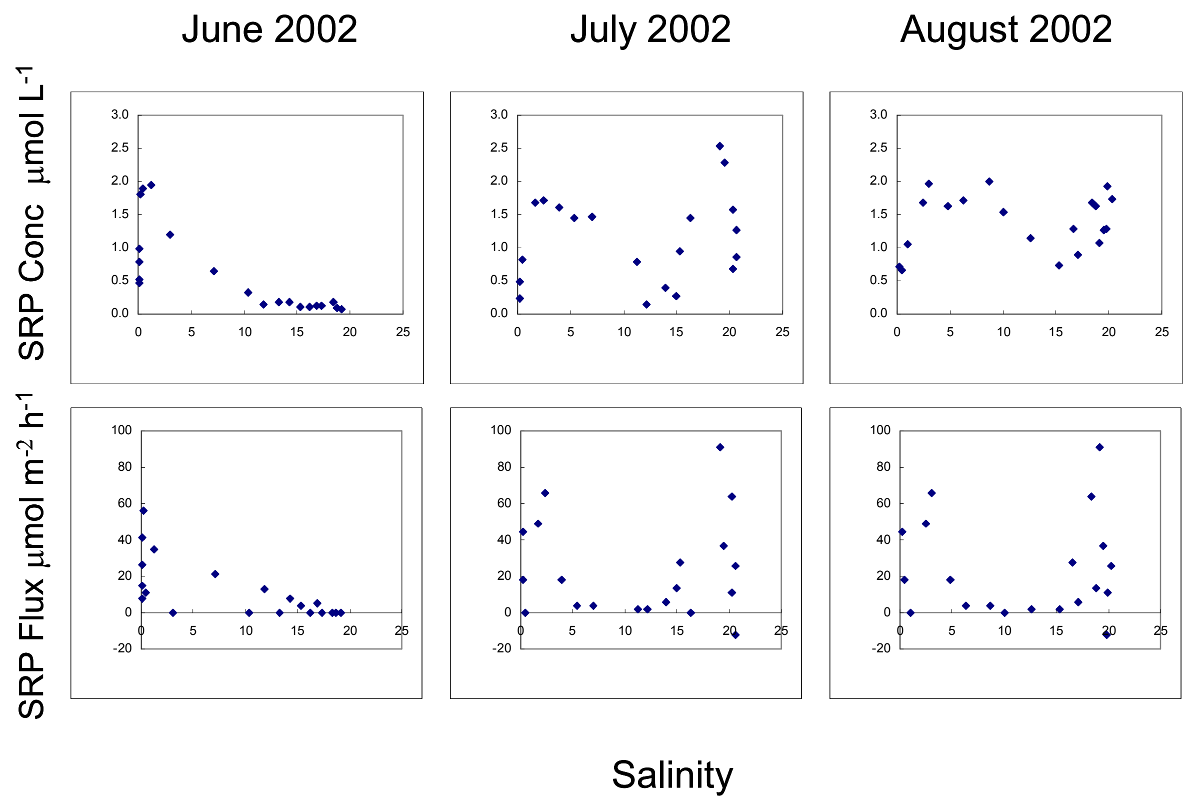

Figure 2. Bottom water SRP (soluble reactive P) and sediment SRP exchange rates in the Potomac River estuary as a function of salinity in 2002 (Bailey et al. 2003). There are two main mechanisms at play that release sediment P. At higher salinity, low oxygen leads to high P releases in July and August. We observed an increase in P fluxes as salinity moved up the river; similar effects have been noted on the Patuxent River. In contrast, in the Choptank River we did not observe very high salinity or oxygen-driven SRP releases (Cornwell, unpublished).

These data indicate that increases in available dissolved P in the Potomac River estuary most likely have a sediment source, rather than coming from desorption of P from suspended particulates. We believe that Bloede sediment in suspension would not have a large effect on the estuary; only after deposition would it potentially have an impact on ecological processes in the Patapsco subestuary.

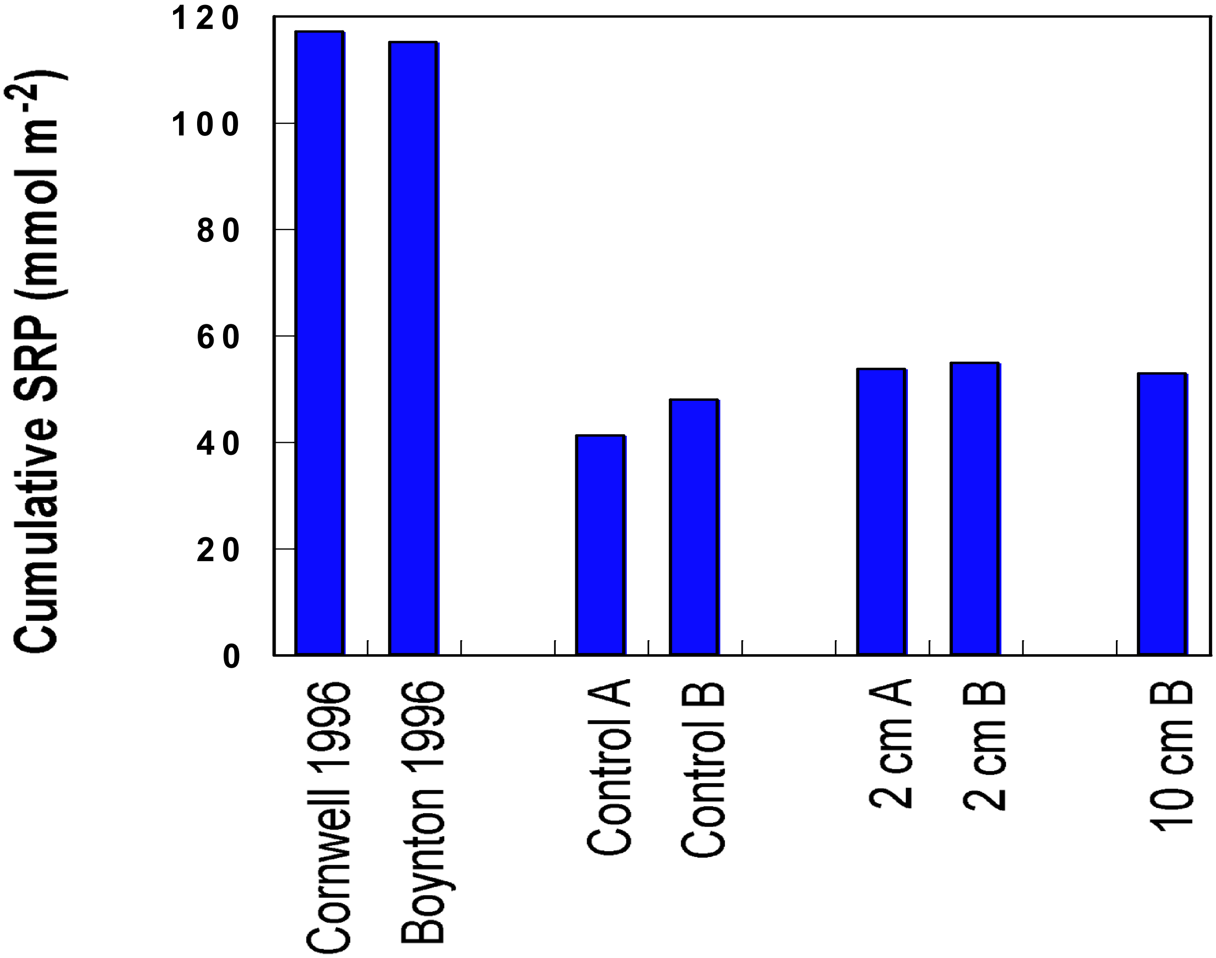

Figure 3. Fluxes of SRP from two 1996 field studies at Site 104, control cores with no added channel sediment, and experimental cores with 2 and 10 cm of homogenized, elutriated channel sediment (Cornwell et al. 2000). The experimental data are for 37 days of hypoxic/anoxic fluxes; one core was used for pore water from each treatment and one extra core was not included from the 10 cm site because of irregular flow. The Cornwell and Owens and Boynton data are from Site D1, the same site the experimental cores were collected from; the 1996 data is for summer fluxes while the experimental data are from cores collected in the fall. The Cornwell data is from changes in stored inorganic phosphorus (15 μmol g^{-1} change, 7,800 g m^{-2} solids) and the Boynton data is calculated from the mean Station D1 anoxia/hypoxic SRP flux rate (40 μmol m^{-2} h^{-1}) and a duration of 120 days.

These data show that the addition of P-rich sediments to anoxic sediments did not have an immediate, large effect on the release of SRP from sediments. We believe the release could still occur over the long-term, but Bloede Dam-derived sedimentation at low oxygen concentrations may not have an immediate, large increase in P releases.

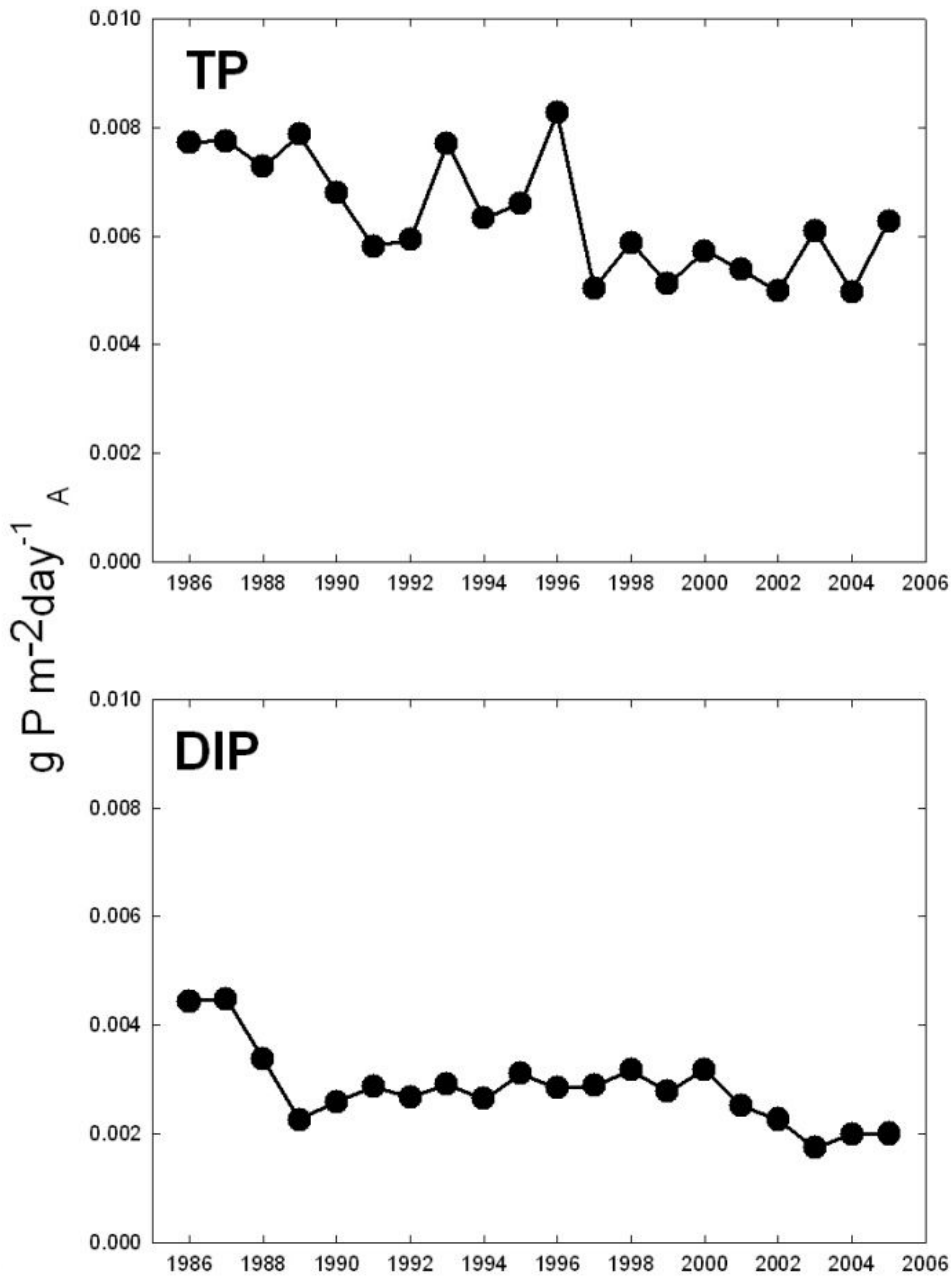

Figure 4. A time-series of Total Phosphorus (TP) and Dissolved Inorganic Phosphorus DIP) loading rates to the Patapsco River estuary. These areal rates were estimated by dividing the TP and DIP inputs by the surface area of the Patapsco River estuary. Data were from the EPA-Cheasapeake Bay Program (G. Shenk, pers. comm.).

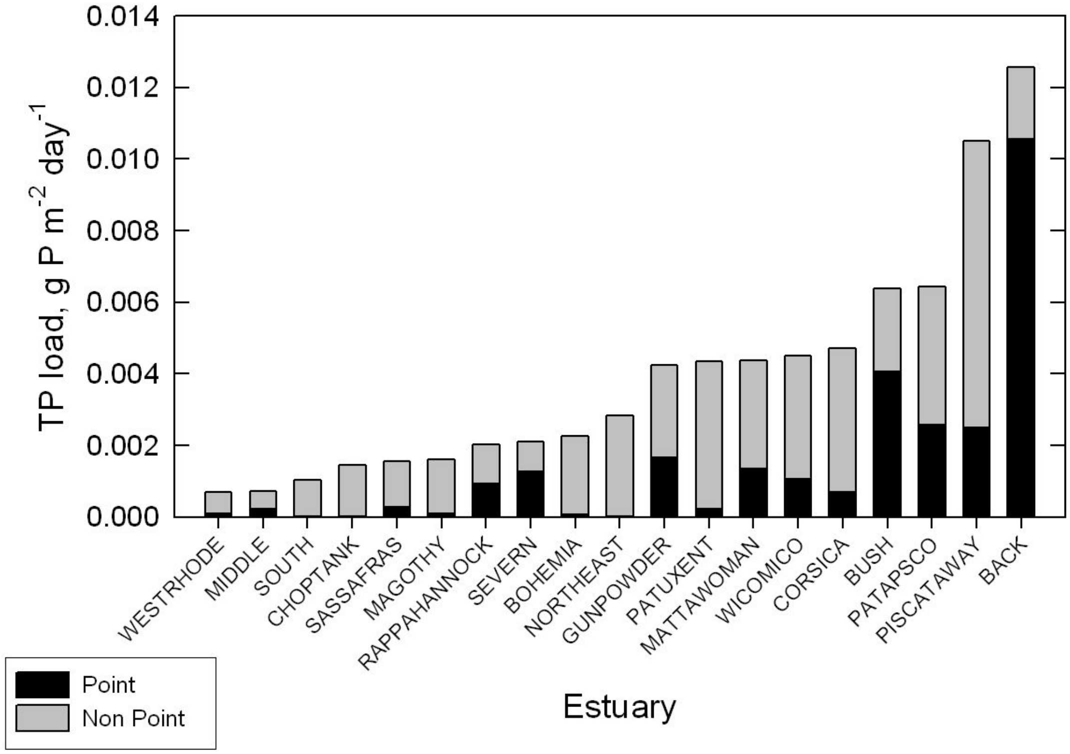

Figure 5. Estimated Total Phosphorus (TP) loading rates (areal basis) to 19 tributary rivers of the Chesapeake Bay system, including the Patapsco River estuary. All estimates are 20 year average rates. Areal loading rates were estimated by dividing the full TP load (point plus diffuse sources) to each estuary by the surface area of each estuary thus making it possible to make rough comparisons between these systems. Clearly, the Patapsco is a heavily loaded system and has significant point and diffuse sources. Loading data were from the EPA-Chesapeake Bay Program (G. Shenk, pers. comm.).

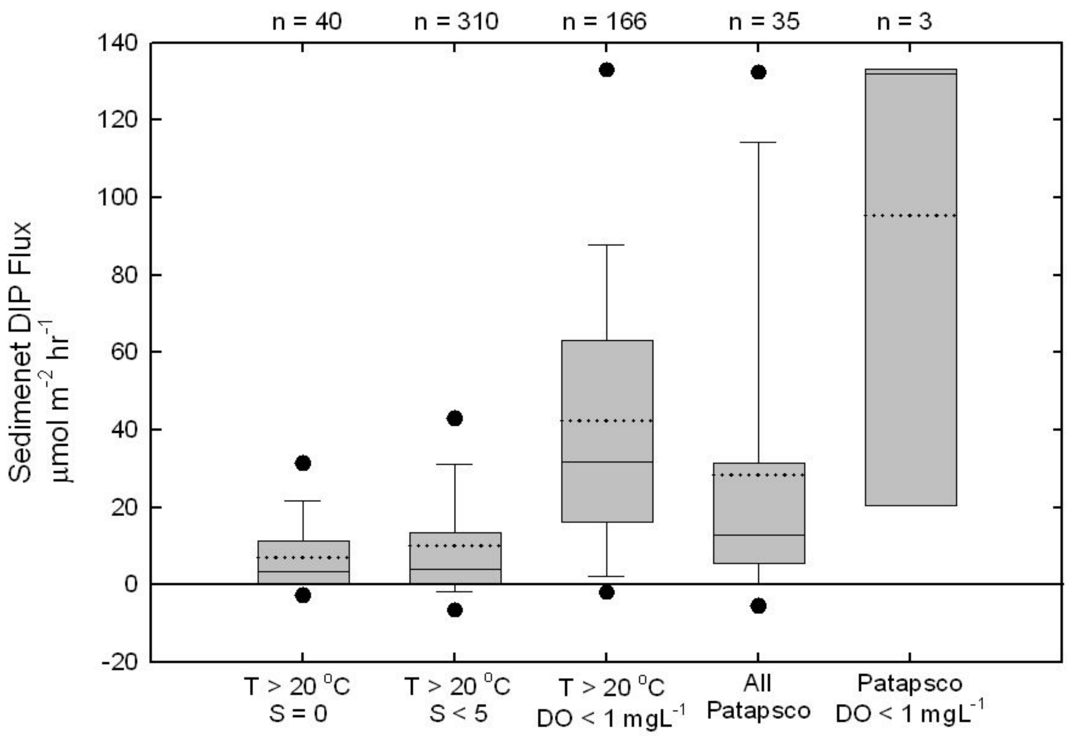

Figure 6. Box and whisker plots of net sediment-water exchange rates of DIP from a variety of Chesapeake Bay locations including the Patapsco River estuary. In each gray box the mean and median flux of DIP is indicated by dashed and solid lines, respectively. The gray boxes include the 25th to 75th percentiles of measurements. The thin vertical lines indicate the 5th and 95th percentiles of measurements. From left to right the boxes include the following data: a) All DIP flux data collected in Chesapeake Bay at temperature > 20 C and salinity of zero; b) same as in (a) but with salinity < 5; c) all fluxes measured in Chesapeake Bay with temperature > 20C and bottom water dissolved oxygen (DO) < 1 mg L^{-1}; d) all sediment flux data collected in the Patapsco River estuary; e) sediment DIP fluxes measured in the Patapsco River estuary with DO < 1 mg l^{-1}. In boxes a-c we chose flux data at temperatures greater than 20 C because this is the temperature range when sediment fluxes are most active. Boxes d-e have flux data that may have been measured at temperatures less than 20 C. The numbers at the top of the diagram indicate the number of flux measurements available for each flu x category. Data are from the public data set named Fluxzilla (www.gonzo.cbl.umces.edu).

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