Patapsco and Back River Responses to Wastewater Treatment Successes and Failures

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Summary: The University of Maryland Center for Environmental Science has been studying how the Patapsco and Back River estuaries have responded to long-term improvements in wastewater treatment and also short-term failures of those facilities. The studies have examined changes over time in water chemistry, biological indicators, sediment nutrient recycling, and external inputs. The studies have concluded that estuaries respond rapidly to both increases and decreases in wastewater inputs, and that long-term investments in improved wastewater treatment have yielded substantial improvements in water quality. A summary of our major findings are listed below:

(1) **Wastewater nutrient contributions to the Patapsco and Back River estuaries have declined substantially over the last 40 years**. There have been clear reductions in industrial + wastewater nutrient loads to both the Patapsco and Back River estuaries since the mid-1980's. Some of this decline is due to changes in industrial activity, but wastewater improvements have led to substantial reductions in nitrogen and phosphorus loads over time.

(2) **Nutrient and algal density in the Patapsco and Back River estuaries have declined substantially over time**. There have been clear reductions in the concentration of nutrients and indices of algal abundance in both the Patapsco and Back River estuaries since the mid-1980's. These reductions are clear evidence that reduced wastewater nutrient inputs lead to improved water quality.

(3) **Recycling of nutrients from the 'soils of the estuary' has primarily declined over the past three decades**. The soils of estuaries, which marine scientists call sediments, often release nutrients to the water that can support water quality degradation. Many have speculated that they are a reservoir of historical pollution and can continue to release nutrients into the water even as watershed nutrient contributions are in decline. Our studies in the Patapsco and Back River estuaries have - in contrast to these speculations - clearly shown declines in the release of nitrogen from sediments and the consumption of oxygen by sediments as nutrient loads and algal biomass declines. Changes in phosphorus release from sediments have been less clear.

(4) **Wastewater Treatment Failures in the Patapsco and Back River facilities lead to a clear, but temporary degradation in water quality.** Long-term reductions in wastewater loads to both the Back and Patapsco Rivers were temporarily reversed during 2021-2022, where both N and P loads increased. The temporary WWTP load increases did not measurably increase nutrient concentrations in either estuary at long-term monitoring stations, but phosphate did increase in the Back River. There was a temporary increase in algae in the Back River during the WWTP load increase associated with the failures (during 2021 and 2022), but not in the Patapsco estuary. Both loading rates and water quality conditions returned to pre-failure levels by 2023.

(5) **Remaining water quality challenges in the Patapsco Estuary.** Despite the water quality improvements in the Patapsco River estuary, there remains a consistent low-oxygen problem in several regions of the Patapsco estuary, and there is evidence that the Patapsco imports relatively fresh oxygen-consuming material from the mainstem of Chesapeake Bay. Additionally, there may be areas of the estuary with other localized, nutrient related issues.

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Introduction

Background

Eutrophication, or the enhanced input of organic matter to aquatic ecosystems, remains a pressing social problem that is associated with declines in oxygen availability, the loss of submerged macrophyte habitats, and the proliferation of harmful phytoplankton blooms. Recognition of this problem has led to expensive and expansive socio-economic commitments to reduce the inputs of bioavailable nutrients that commonly support elevated phytoplankton biomass and associated bottom water and sediment degradation. Although initial efforts to mitigate eutrophication were difficult to associate with clear improvements in tidal waters (e.g., Duarte et al. 2009), sustained nutrient reductions and investments in improved wastewater treatment technologies have led to substantial declines in eutrophication in a growing number of estuaries (e.g., Boynton et al. 2014, Taylor et al. 2011, Stæhr et al. 2017, Testa et al. 2022a).

Substantial investments made to upgrade Maryland wastewater treatment plants (WWTPs) during the past several decades have significantly reduced the amount of nitrogen and phosphorus being discharged into Chesapeake Bay tidal waters. Several case studies (Boynton et al. 2014, Fisher et al. 2021, Testa et al. 2022a) have documented how these upgrades have ultimately led to the expected improvements in some aspects of water quality (e.g., reduced chlorophyll-a, turbidity). Statistical modeling of mainstem Chesapeake Bay hypoxia has also incorporated wastewater nutrient inputs to tidal waters, where model predictions of hypoxic volume improved when wastewater loads were included (Scavia et al. 2021). Given that wastewater nutrient load reductions in Bay tributaries have led to reduced nutrient flux to the mainstem Chesapeake Bay (Testa et al. 2022a), tributary sewage treatment upgrades should have an impact on mainstem water quality. In the Patapsco and Back River estuaries, both urban, highly degraded tributaries of Chesapeake Bay, large reductions in point-source nitrogen and phosphorus loading have led to large reductions in nutrient concentrations in the estuary (Testa et al. 2022a,b). However, in the wake of the COVID-19 pandemic, operational failures of the Back and Patapsco Wastewater treatment facilities led to reports of a temporary increase in wastewater loadings to both estuaries, potentially reversing the positive impacts of the recent WWTP upgrades for nutrient removal.

The purpose of this report is to quantify both the ecosystem and water quality response of the Patapsco and Back River estuaries to short-term increase in nutrient loads resulting from the 2021-2022 WWTP failures, in the context of long-term WWTP load reductions. These estuaries are ideal locations for this type of analysis, given the substantial magnitude of WWTP nutrient load reduction historically, the dominance of WWTP loads in the overall nutrient input budget, and a wealth of available data that can be used to examine (1) nutrient, chlorophyll-a, and oxygen concentration changes during multiple decades, (2) rates of nutrient recycling in sediments and the water-column, (3) physical transport and nutrient input-output budgets for the estuary, and (4) rates of organic matter production (i.e., ecosystem metabolism).

Data Sources and Methods

In this report, we combined analysis of historical data, numerical modeling, and diagnostic mass balance computations to comprehensively assess estuarine water quality changes in response to WWTP load reductions and temporary increases in 2021-2022 (Table 1). Specifically, we collated model estimates of nutrient input from the watershed, WWTP nutrient loads, and water-column nutrient and chlorophyll-a data collected by the Maryland Department of the Environment, the Department of Natural Resources, and the Chesapeake Bay Program. We also simulated sediment-water fluxes of nitrogen and phosphorus, nutrient burial, and denitrification rates. Finally, we made estimates of N and P exchange between each tributary and the mainstem of Chesapeake Bay. This evaluation provides information necessary to diagnose the past, current, and future water quality conditions of an estuary, an exercise that typically involves developing, testing and using, in a forecasting mode, various water quality models.

Non-Point and Point Source Nutrient Loads and Flow

We assembled freshwater and nutrient loading rates from the Patapsco and Back River WWTPs and other relevant point source inputs, as well as loads estimated for the PATMH and BACOH segments of the Phase 6 Chesapeake Bay Program watershed model to compute the magnitude and temporal pattern of change in loadings to the estuary since 1985. We used these data to make estimates of point source nitrogen (NH_4, NO_{23} and Total Nitrogen (TN)) and phosphorus (PO_4 and Total Phosphorus (TP)) inputs to the Patapsco and Back River estuaries during the 1985-2024 time period. Annual WWTP inputs directly to the Patapsco River from the Patapsco River WWTP and Back River WWTP were sourced from The National Pollutant Discharge Elimination System (NPDES) data and the Chesapeake Bay Program (Table 1).

Tidal Water Quality

We analyzed tidal water-quality monitoring data from long-term Maryland Department of Natural Resources stations WT5.1, CB3.2, and WT4.1 (1985-2024; Fig. 1) to assess temporal trends in water-quality. These data are collected at bi-weekly or monthly intervals at multiple depths. We focused on concentrations of nitrogen (NH_4, NO_{23} and Total Nitrogen (TN)), phosphorus (PO_4 and Total Phosphorus (TP)), dissolved oxygen, salinity, and chlorophyll-a.

Ecosystem Metabolism

We estimated ecosystem gross primary production, respiration, and net ecosystem metabolism (NEM) from observed continuous (15-minute) time-series of O_2 at continuous monitoring stations within the Patapsco River (Masonville Cove; Fig. 1) and the Back River (Riverside; Fig. 1). The original concept and method for computing gross GPP and respiration (and NEM) was developed in the 1950s (Odum and Hoskin 1958) and has subsequently been modified for a variety of aquatic ecosystems (Caffrey 2004). The approach derives ecosystem rates of gross primary production (P_g = GPP) and respiration (R_t) from increases in O_2 concentrations during daylight hours and declines during nighttime hours, respectively. The sum of these two processes over 24 hours, after correcting for air-sea exchange, provides an estimate of NEM. We used continuous O_2 concentration measurements at continuous monitoring stations in the Patapsco River estuary from times covering 2004 through 2023 (Figure 1) and the Back River (1997, 2014-2023 to apply a modified approach (Beck et al. 2015), which uses a weighted regression to remove tidal effects on O_2 time-series since the tide can advect higher or lower O_2 past the sensor thereby influencing the calculation of NEM. The changes in O_2 used to compute metabolic rates were corrected for air-water gas exchange using the equation $D = K_a (C_s\text{-}C)$, where D is the rate of air-water O_2 exchange (mg O_2 L^{-1} h^{-1}), K_a is the volumetric aeration coefficient (h^{-1}), and C_s and C are the O_2 saturation concentration and observed O_2 concentration (mg O_2 L^{-1}), respectively. K_a was computed as a function of wind speed derived from the North American Land Data Assimilation System (NLDAS) and details of the air-water gas calculation are incorporated into the R package WtRegDO (Beck et al. 2015) and described in detail elsewhere (Thébaultet al. 2008). The calculations utilized salinity, temperature, and O_2 times-series from the sensors at each platform. Tidal height, atmospheric pressure, and air temperature data were obtained from a nearby NOAA station at Baltimore, Maryland (https://tidesandcurrents.noaa.gov/stationhome.html?id=8574680). Any gaps in data were filled in the tides and meteorological data from Tolchester Beach, Maryland (https://tidesandcurrents.noaa.gov/stationhome.html?id=8573364). The O_2 data used to make metabolic computations were obtained from sensors deployed near-bottom in relatively shallow waters that were well-mixed, which is necessary for the air-water flux correction to be valid and for the O_2 time-series to be representative of the combined water-column and sediments (Murrell et al. 2018).

Sediment Flux Model

We synthesized previously measured rates of sediment-water exchanges (Boynton et al. 2017, Testa et al. 2022a) of dissolved nutrients and oxygen combined with the implementation of a sediment flux model (SFM) during a three decade period (1985-2023) to estimate sediment impacts on water quality and denitrification rates. Measured rates of Patapsco and Back River sediment-water fluxes of nutrients (NH_4, NO_{23}, PO_4) and oxygen have been made at several times and locations over the last several decades (Fig. 1). We used these measurements to constrain a 2-layer sediment biogeochemical model (SFM) that has been widely applied and validated in Chesapeake Bay (Brady et al. 2013, Testa et al. 2013) to examine the biogeochemical response of the sediments altered organic matter availability. The model structure for SFM involves 4 general processes: (1) the sediment receives depositional fluxes of POM (particulate organic matter), as well as biogenic and inorganic phosphorus and silica from the overlying water, (2) the decomposition of POM produces soluble intermediates that are quantified as diagenesis fluxes, (3) solutes react, transfer between solid and dissolved phases, are transported between the aerobic and anaerobic layers of the sediment, or are released as gases (CH_4, N_2), and (4) solutes are returned to the overlying water as sediment-water fluxes (NH_4, NO_{23}, PO_4, O_2). SFM numerically integrates mass-balance equations for chemical constituents in 2 functional layers: an aerobic layer near the sediment–water interface of variable depth (H1) and an anaerobic layer below that is equal to the total modeled sediment depth (0.1 m) minus the depth of H1. The model includes an algorithm that continually updates the thickness of the aerobic layer (H1) at a simulation time-step of 1 h, where output is aggregated at 1 day intervals. The diagenesis of POM is modeled by partitioning the settling POM into 3 reactivity classes, termed the G model, where each class represents a fixed portion of the organic material that reacts at a specific rate. Further details on the model and it implementation can be found elsewhere (Testa et al. 2013). To develop a time-series of organic carbon, nitrogen, and phosphorus (POM) deposition associated with reductions in phytoplankton biomass and reduced organic matter input from the Patapsco and Back River WWTPs, we developed a series of simulations during the 1985-2023 period. We estimated POM deposition from the overlying water chlorophyll-a concentration by converting chlorophyll-a to carbon (assuming C:CHL = 60) and assuming a sinking rate of algal biomass of 0.5 m d^{-1}. We ran simulations calibrated to data at stations in the middle region of the Patapsco estuary near WT5.1 and in the inner harbor, and also near WT4.1 in the Back River.

Nutrient Budget

We synthesized the loading, concentration, standing stock and model simulation rate data collated and generated during this analysis to generate whole-system nitrogen (N) and phosphorus (P) budgets for the Patapsco and Back River estuaries. We used this approach to identify the impacts of the WWTP failures on (1) how much of the WWTP input is retained in the Patapsco estuary/exported to Chesapeake Bay, (2) the magnitude of sediment recycling on water quality changes, and (4) how much of the internal load is lost to denitrification. We chose four time periods to develop these budgets, including a period during intense point-source nutrient loading (1985-1990), a period following large reductions in industrial nutrient loading (2010-2014), a period following the implementation of enhanced nitrogen removal at the Patapsco River WWTP (2019, 2023) and the failure period (2021-2022). The diffuse and point source N and P loads were obtained from the Phase 6 watershed model loads to the mesohaline Patapsco and Back River estuary water quality segments. Atmospheric nitrogen deposition was estimated from the Wye River station in the National Atmospheric Deposition Program (NADP). Total nitrogen and phosphorus concentrations in the water-column were computed by multiplying the depth-averaged concentrations at WT5.1 and WT4.1 by the volume of the estuary. While this single station does not represent every region of the estuary, comparisons of the WT5.1 and WT4.1 station with data measured by MDE between 2016 to 2019 (nutrients, chlorophyll-a) suggest that this is a reasonable representation of the system. We also estimated four properties of the sediment from a combination of observed sediment-water fluxes and modeled estimates of sediment-water NH_4 and PO_4 fluxes, nutrient burial, denitrification, and sediment N and P content. Finally, we made estimates of net exchange of N and P across the mouth of the Patapsco and Back River estuaries with the box model described below. All units are in kilograms or kilograms per year.

Salt and Water Balance Budget

We constructed a simple salt-and water-balance ‘box model’ to estimate water and nutrient exchange and export from the Patapsco River estuary to/with Chesapeake Bay and changes in the ecosystem-scale net retention of nitrogen and phosphorus by the Patapsco estuary. This approach involves estimating the net exchange of nitrogen and phosphorus from the Patapsco River to the upper Chesapeake Bay during the 1985-2024 period. Quantification of this exchange allows for an assessment of (1) whether the upper Chesapeake Bay is an additional source of nutrients to drive long-term change in the Patapsco and Back Rivers, or (2) if WWTP reductions in the Rivers led to a substantial reduction in overall nutrient export to Chesapeake Bay. The latter feature is important for understanding how nutrient processing within tributary estuaries may modulate the effect of nutrient reductions on the biogeochemistry of Chesapeake Bay overall. To do this, we computed both the Patapsco and Back River's time-dependent, seasonal mean circulation using salinity and freshwater input data. This box modeling approach computes advective and diffusive exchanges of water and salt between adjacent control volumes (which are assumed to be well mixed) and across end-member boundaries using the solution to non-steady state equations balancing salt and water inputs, outputs, and storage changes (Officer 1980, Hagy et al. 2000). Despite prior research that reveals that the Patapsco estuary has both 2-layer and 3-layer circulation, we decided to treat the Patapsco River as a single volume and characterize the salinity (and nutrients) within the estuary from the long-term monitoring station at WT5.1 (Fig. 1). The Back River estuary is shallow and well mixed, so there are fewer assumptions required for this model. Total watershed inputs of freshwater and nutrients were obtained from the Phase 6 model inputs. The seaward boundary concentrations were derived from a long-term monitoring station in the upper Chesapeake Bay (CB3.2). Estuarine area and volume were obtained from Cronin and Pritchard (1975) and through GIS analysis using digital elevation model (DEM) output. Details of the salt and water balance computation and nutrient export are included in many prior publications where we have successfully applied this approach to answer questions regarding water quality responses to WWTP upgrades (Testa et al. 2008, Stæhr et al. 2017, Testa et al. 2022a).

Results

Here we present the primary results of our study of nutrient and water quality responses of the Back and Patapsco Rivers to large and long-term nutrient load reductions as well as temporary wastewater treatment failures in both the Patapsco and Back River estuaries.

Wastewater Nitrogen and Phosphorus Loading Rates

Wastewater nitrogen loading to the Back River declined over the 1985-2024 period (Fig.2; Testa et al. 2022a), especially after enhanced nutrient removal was implemented in 2017. Nitrogen loading increased abruptly in 2021 to levels comparable to the pre-2017 period, but declined to the lowest levels reported by 2023 (Fig. 2). Phosphorus loading to the Back River followed a similar pattern, but the abrupt increases in TP load in 2021-2022 approached levels not reported since the 1980s (Fig. 2). Loading rates did decline back to 2017 levels by 2023, and those low loading levels persisted until 2024. Nitrogen loading to the Patapsco River also declined over the 1985-2024 period (Fig. 3), especially after enhanced nutrient removal was implemented in 2019. Nitrogen loading increased in 2021 to levels comparable to the pre-2019 period (Fig. 3). Phosphorus loading to the Patapsco River followed a similar pattern to nitrogen, but the increase in TP load in 2021-2022 only approached levels comparable to the 2000-2010 period (Fig. 3), after which loading rates declined to the lowest levels reported in the record by 2023.

Water-Column Concentrations

Temporal patterns of water-column nitrate+nitrite (NO_{23}) and phosphate (PO_4) concentrations at long-term monitoring stations in both estuaries reflect changes due to wastewater treatment failures (Figs. 4 & 5). For the Back River, NO_{23} concentrations declined during the record as reported previously, and did not seem to increase annually, or during summer in either surface or bottom water (Fig. 4). In contrast, PO_4 concentrations declined during the record as reported previously, but did increase to among the top-5 highest concentrations in 2021 before returning to recent levels (Fig. 4). Similar patterns occurred in the Patapsco River. For the Patapsco River, NO_{23} concentrations declined during the 2018-2024 period and did not seem to increase annually, or during summer in either surface or bottom water (Fig. 5). Surface layer PO_4 concentrations declined during the record as reported previously and the only increase in PO_4 concentrations occurred in 2021 but only in bottom waters, which is more likely due to low oxygen conditions (Fig. 5).

Ecosystem Metabolism, Primary Production, and Respiration

Estimates of net ecosystem metabolism (NEM), primary production (P_g), and water-column respiration (R_t) in the Patapsco and Back Rivers were highly variable over time, but revealed some indications of responses to high nutrient loading rates as well as WWTP failures (Fig. 6). Metabolic rates computed for both sites indicated enhanced rates relative to those often measured in less enriched systems. For example, P_g in both systems often was in excess of 2 g C m^{-2} day^{-1} (after converting oxygen to carbon units) and rates of P_g peaked in the Back River site during 2021 at about 5 g C m^{-2} day^{-1}, an exceptionally high rate.

There did not appear to be any strong temporal signal in metabolic variables (NEM, P_g, R_t) at the Masonville Cove site in the Patapsco in response to WWTP failures during 2020-2021. However, rates of P_g and R_t were both clearly enhanced in the Back River during 2021. In fact, average rates of P_g and R_t were the highest on record during 2021. Both metabolic variables decreased by 2023.

Surface Water Chlorophyll-a Concentrations

Water-column chlorophyll-a (Chl-a) in the Patapsco and Back Rivers were variable throughout the summer season (June-September) time series (Figs. 7 and 8). Surface water Chl-a concentrations were high at both sites during the summer period with occasional values in excess of 100 μg l^{-1} but values from the Back River site were clearly higher. At both sites Chl-a concentrations were correlated with metabolic variables (P_g and R_t) but the relationship was most evident in the Back River where P_g and R_t and Chl-a were all elevated during 2021. Summer average Chl-a concentrations averaged greater than 100 μg l^{-1} during 2021; concentrations subsided to levels seen prior to the WWTP failures by 2023.

Modeled Sediment-Water Fluxes

Estimates of sediment-water fluxes on ammonium, NO_{23}, and PO_4 were made from 1985-2023 and did not indicate a signal of influence from wastewater treatment failures (Fig. 9). For the Back River estuary, ammonium fluxes declined over the 1985-2024 period, and fluxes were comparable in the years since the Back River WWTP reached enhanced nutrient removal (ENR; Fig. 9). Modeled PO_4 fluxes did not decline in the long-term simulation for the Back River, but the observations at a more limited range of times would have suggested a decline (Fig. 9). Testa et al. (2022a) concluded that sediment-water PO_4 fluxes did not change appreciably after ENR, which is consistent with these results. However, in the Patapsco River estuary, both ammonium and PO_4 fluxes declined in the model simulations for the Inner Harbor (Fig. 9) and the fluxes did not appear to change in the recent years of WWTP failure.

Nutrient Budgets

Annual-scale, whole system nitrogen (N) and phosphorus (P) budgets were constructed for the Back and Patapsco River estuaries during a historic, early Bay Program period (1985-1990), a period pre-WWTP upgrades, the post-WWTP upgrade period (2019, 2023) and 2021-2022 when there were WWTP failures. Budget results are summarized in Figures 10 and 11 for N and P in the Back River and Figures 12 and 13 for N and P in the Patapsco River.

Budget results for the ***Back River*** (Figures 10 and 11) can be summarized as follows:

1. Inputs for both N and P from atmospheric deposition were small to negligible and did not change much during the four budget periods. However, point source N loads decreased by a factor of 3.5 between the 1985-1990 period and the 2019 period. There was close to a 60% increase in N loads associated with the WWTP failure during 2021 but those load increases were still about 2X below earlier load rates. Loads had returned to lower levels by 2023. Point sources of P also exhibited about a 4X reduction between the 1985-1990 and the 2019, 2023 time periods, similar in magnitude to the N reductions. There was a 2.7X increase in P loads associated with the WWTP failures during 2021-2022 but these input rates declined to previous lower levels by 2023. Overall, load changes were very substantial and almost entirely associated with point source reductions in N and P loads.

2. Water column and sediment stocks of N and P were responsive to load changes, as expected, with water column concentrations of N and P being more responsive than sediment stocks. Of particular note was the 2X decline in sediment P stocks during the period 1985-2023, a much sharper decline than observed for N sediment stocks. By far, most of the N and P in the Back River system is contained in the top 10 cm of sediments and represents the "nutrient memory" of the system.

3. Sediment recycling of N and P were important processes in the Back River and were responsive to nutrient load changes. In the case of sediment N recycling (mainly as NH_4) there was almost a 4X reduction in sediment N releases associated with decreased point source N inputs (as indicated in both observations and model estimates). In the case of sediment P release the decline was about 2X and the decline was continual, even during the 2021-2022 period of enhanced P inputs. The current scientific consensus is that recycling rates need to be decreased to a point where they no longer serve as the dominant N and P source for summer phytoplankton growth. The sharp declines observed in the Back River are consistent with this consensus.

4. Internal nutrient losses associated with long term burial in sediments and sediment denitrification were also related to nutrient input changes. In the case of N, N burial decreased over the longer-term period, but the decrease in burial rate was relatively small. However, the decrease in denitrification rate was significant and similar in magnitude to input declines. In the case of P, burial rates also declines and were large, amounting to almost a 3X decrease during the 1985-2023 period.

5. The net exchange of N and P at the Back River – Chesapeake Bay interface is perhaps the most difficult to estimate term in these budgets. Nitrogen was estimated to be exported from the Back River to the Bay during all four evaluation periods but there was not a clear relationship between loads and net river-Bay exchanges. In fact, the largest export

was associated with the lowest point source N loads. For P, export from the river to the Bay increased as point source loads decreased but reversed direction to import of P from the Bay to the river during the period of WWTP failure (2021-2022).

Budget results for the ***Patapsco River*** (Figures 12 and 13) can be summarized as follows:

1. Inputs for both N and P from atmospheric deposition were small to negligible and did not change much during the four budget periods. However, point source N loads decreased by a factor of 5 between the 1985-1990 period and the 2019 and 2023 period. There was a 50% increase in N loads associated with the WWTP failure during 2021-2022 but those load increases were still about 4X below earlier load rates. Point sources of P also exhibited about a 3.5X reduction between the 1985-1990 and the 2019 and 2023 time periods, similar in magnitude to the N reductions. There was a 2X increase in P loads associated with the WWTP failures during 2021-2022 but these input rates had declined to previous lower levels by 2023. Overall, load changes were very substantial and almost entirely associated with point source reductions in N and P loads.

2. Water column and sediment stocks of N and P were responsive to load changes, but not as much as the Back River estuary, where water-column TN declined by 20% and TP declined by 40%. There was also a 30% decline in sediment N stocks and 18% decline in sediment P stocks during the period 1985-2023. Like the Back River estuary, most of the N and P in the Patapsco River system is contained in the top 10 cm of sediments and represents the “nutrient memory” of the system.

3. Sediment recycling of N and P were important processes in the Patapsco River estuary and were responsive to nutrient load changes. In the case of sediment N recycling (mainly as NH_4) there was a 7X reduction in sediment N releases associated with decreased point source N inputs (as indicated in both observations and model estimates). In the case of sediment P release the decline was about 1.5X and the decline was continual, even despite a slight increase during the 2021-2022 failure period.

4. Internal nutrient losses associated with long term burial in sediments and sediment denitrification were also related to nutrient input changes. In the case of N, N burial decreased 35% over the longer-term period (1985-2023), while P burial decreased 20%. Denitrification declined by 34% over the 1985-2023 period, and remained similar in magnitude during the period of WWTP failures.

5. The net exchange of N and P at the Patapsco River – Chesapeake Bay interface did not give any clear responses to WWTP failures. Nitrogen was estimated to be exported from the Patapsco River to the Bay during all four evaluation periods, whereby the N export declined by 60% after the 1985-1990 period, and was fairly stable during the WWTP failure period. P exchange between the Patapsco and the Bay was low and did not change in a coherent way over the time series. Future studies should leverage additional methods to estimate this budget term, including deriving estimates from the Phase 7 Water quality models. Prior comparisons for the Patapsco River included an estimate of 0.083 and 0.05 kg P yr^{-1} from the Phase 6 WQSTM for the period 1985-1990 and 2010-2014, respectively, which were within range of the box-model derived values of -0.01 and 0.05 kg P yr^{-1} for the same respective periods (Fig. 13).

Discussion and Conclusions

To summarize the main implications of our study, we arrive at the following "Lessons Learned" from our analysis of the Back and Patapsco River estuaries response to WWTP failures:

1. Long-term reductions in WWTP loads in both the Back and Patapsco Rivers were temporarily reversed during 2021-2022, where both N and P loads increased for the Back River and only P loads for the Patapsco River.

2. The temporary WWTP load increases did not measurably increase dissolved inorganic N and P concentrations in either estuary at long-term monitoring stations, but phosphate did increase in the Back River.

3. There was a temporary increase in chlorophyll-a in the Back River during the WWTP load increase associated with the failures (during 2021 and 2022), but not in the Patapsco estuary.

4. There was a temporary increase in water-column primary production and respiration rates in the Back River during the WWTP load increase associated with the failures (during 2021 and 2022), but no similar increase at Masonville Cove in the Patapsco.

5. Sediment-water fluxes of N and P did not appear to increase in response to the WWTP-failures, suggesting that the impact would not have a longer-term effect on the estuaries.

6. Nutrient budgets reinforce the fact that sediments are both an important reservoir for nutrients, but also a responsive process with regard to nutrient loads. N recycling from sediments declined in both the Patapsco and Back Rivers over the entire record, while P fluxes responded weakly (Back River), but measurably (Patapsco River).

7. It appears that Back River water quality is more responsive to WWTP load changes than the Patapsco River. This conclusion is most likely associated with the fact that the Back River has a smaller volume, and thus its nutrient concentrations are more responsive to a given input of N or P from a wastewater treatment plant. For example, the Back River WWTP has a mean flow of 6 m^3/s and a volume of 24.26 x 10^6 m^3 whereas the Patapsco has a similar mean flow of 4.8 m^3/s but a volume of 381.69 x 10^6 m^3. Given these differences, the WWTP flow could replace the entire volume of the Back River estuary in 47 days, but the Patapsco WWTP would take 925 days. This does not discount the fact that WWTP failures could have local impacts on Patapsco River water quality, but it reflects the higher sensitivity to the WWTP loads from municipal WWTPs in the Back River.

8. The estimates of net N and P exchange between the estuaries and the Chesapeake Bay mainstem are likely the most unconstrained and uncertain values in our budgets. These estimates could be better constrained by comparing them to comparable estimates from other tools, such as the Phase 7 Main Bay Model and the Patapsco-Back Tributary models. Getting better estimates of these values is critical because they can inform (1) whether enrichment in a tributary is mainly a local problem or an imported problem, (2) how tributaries can contribute to mainstem Bay water quality, and (3) whether management actions can impact these fluxes.

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Tables

Table 1. Data sources used in the study.

Data Type	Source	Time Period	Reference
Nutrient Loads	Phase 6 Watershed Model	1985-2023	Q. Zhang, pers. Com.
Chlorophyll-a	CBP Monitoring Program	1985-2023	www.chesapakebay.net
Chlorophyll-a	DNR Eyes on the Bay	2009-2024	www.eyesonthebay.net
N and P conc.	CBP Monitoring Program	1985-2023	www.chesapakebay.net
SONE	UMCES Measurements	1995-2023	Boynton et al. 2017
N Deposition	National Atm. Dep. Program	1985-2023	https://nadp.slh.wisc.edu/
Denitrification	Sediment Flux Model	1985-2023	Testa et al.2022a,b
N, P Burial	Sediment Flux Model	1985-2023	Testa et al.2022a,b
Sediment N, P	Sediment Flux Model	1985-2023	Testa et al.2022a,b

Figures

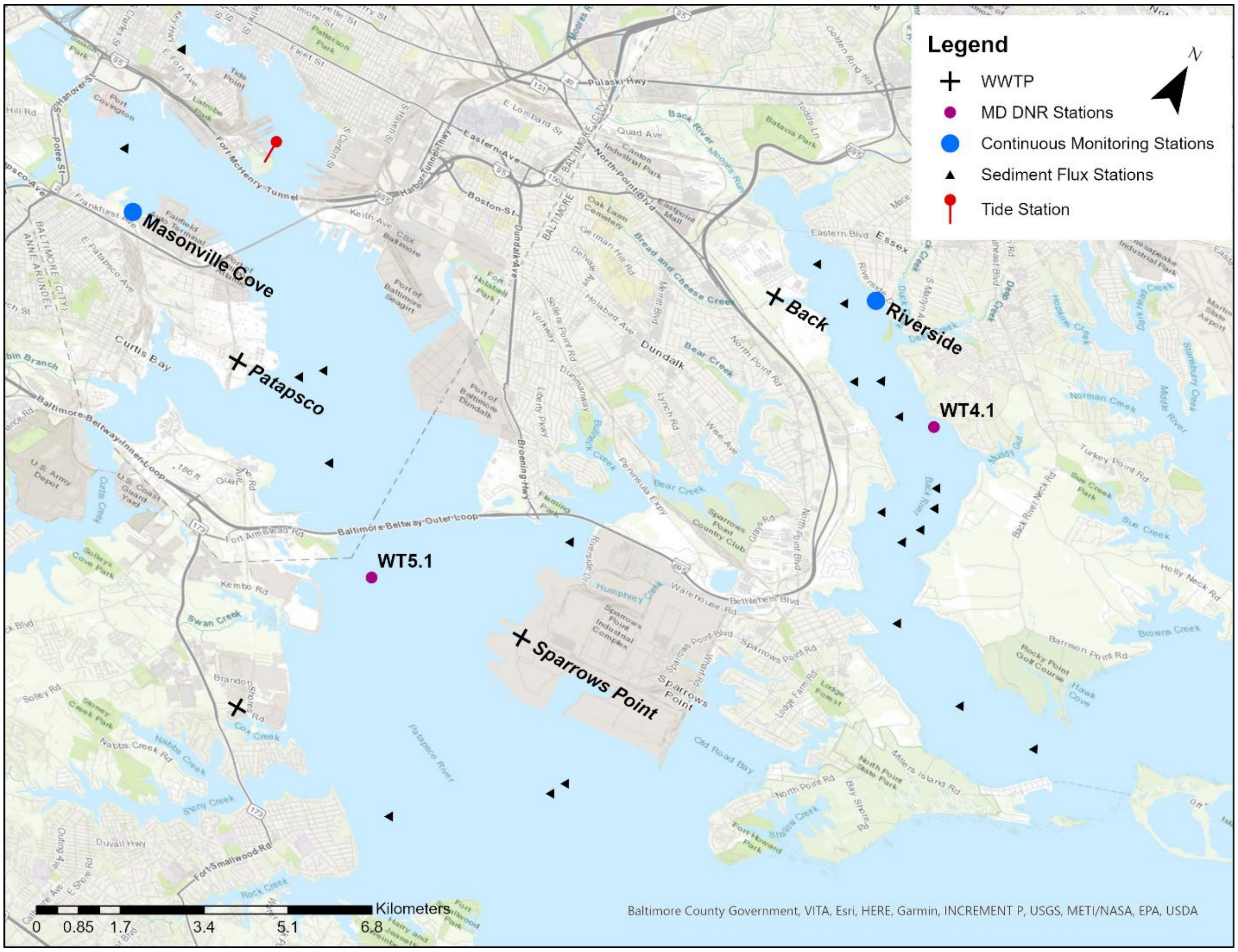


Figure 1: Map of the Back and Patapsco River estuaries with locations of relevant WWTPs (crosses) and stations used in this analysis for water quality (blue and maroon circles), estimates of metabolism (blue circles), and sediment-water fluxes (triangles).

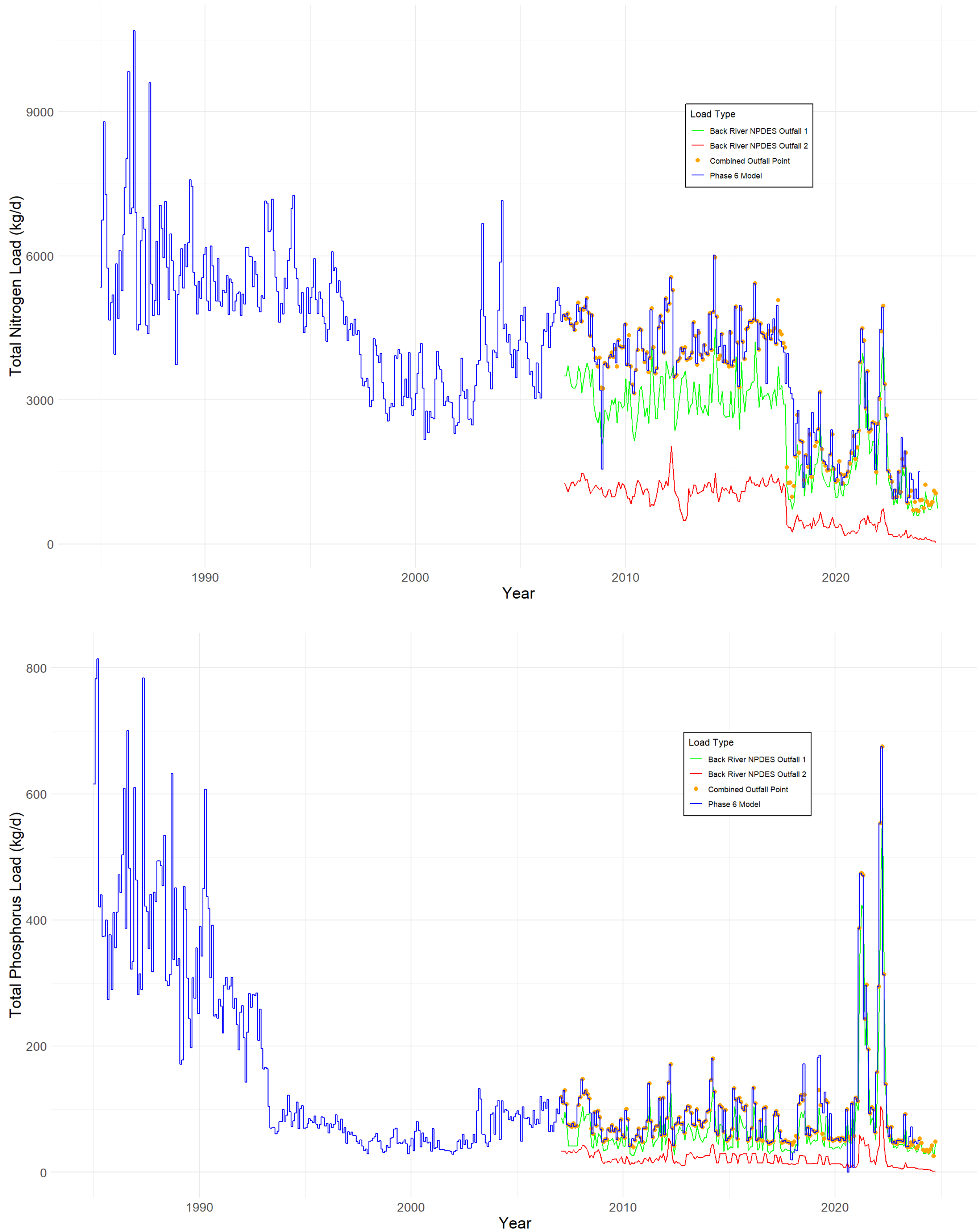


Figure 2: Time-series of point-source total nitrogen (top panel) and phosphorus (bottom panel) loading to the Back River estuary from the CBP Phase 6 watershed model (blue lines) and NPDES database for each Back River outfall.

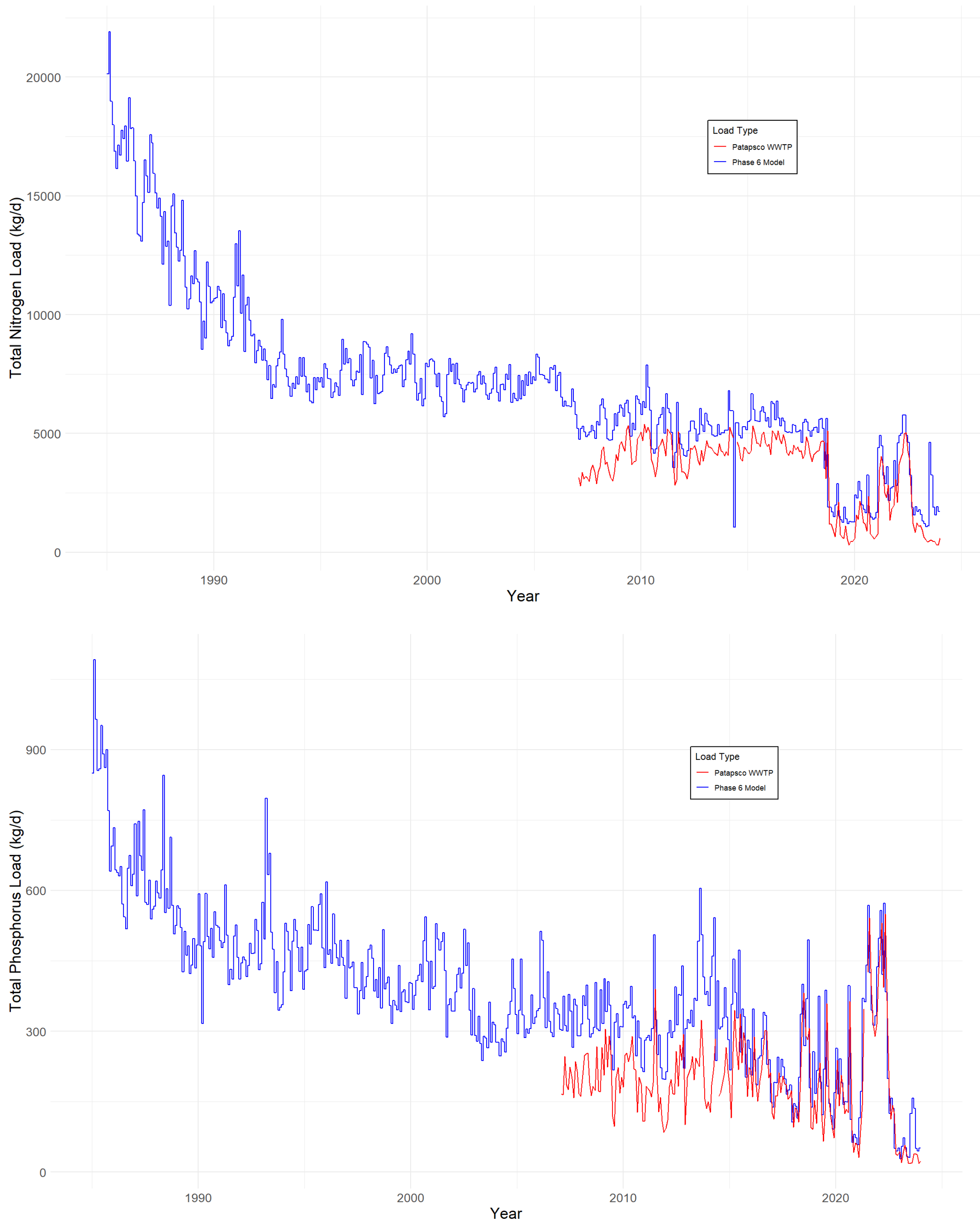
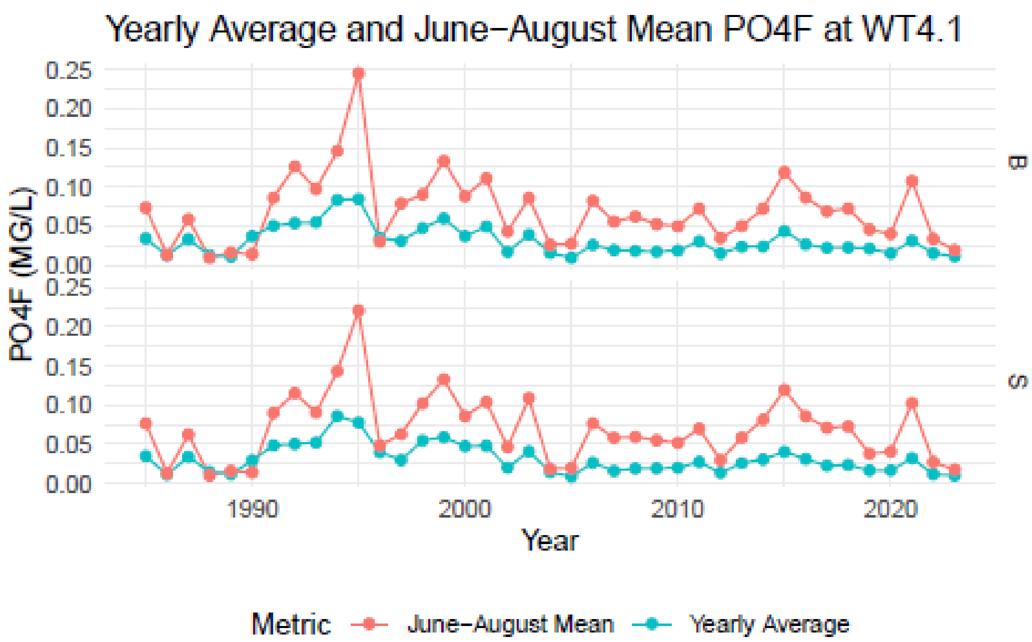


Figure 3: Time-series of point-source total nitrogen (top panel) and phosphorus (bottom panel) loading to the Patapsco River estuary from the CBP Phase 6 watershed model (blue lines) and NPDES database for the Patapsco municipal WWTP (red lines).



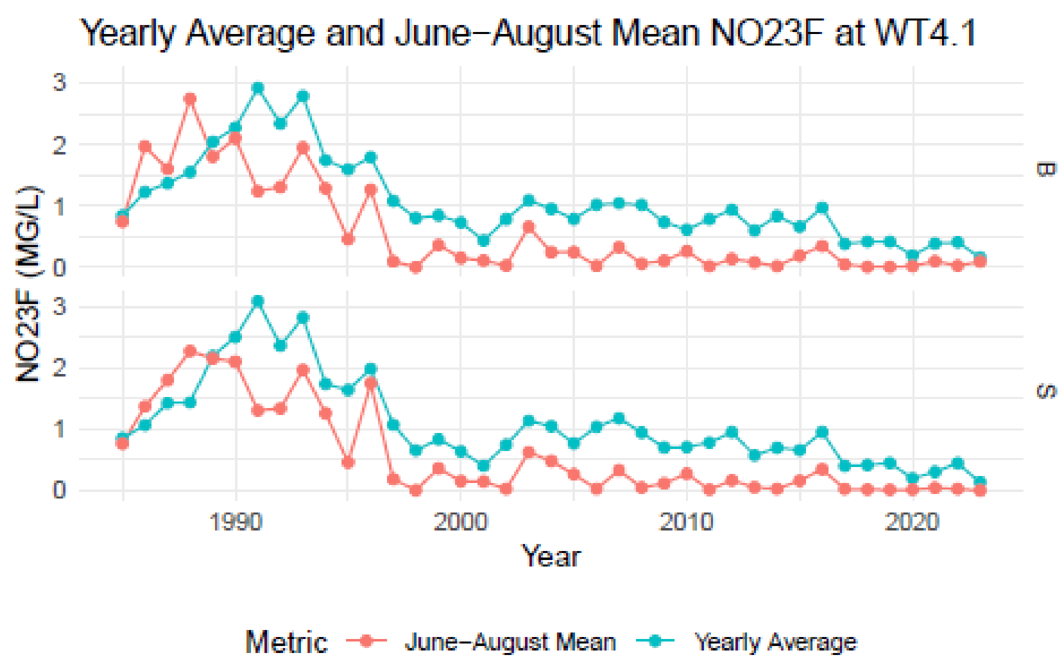
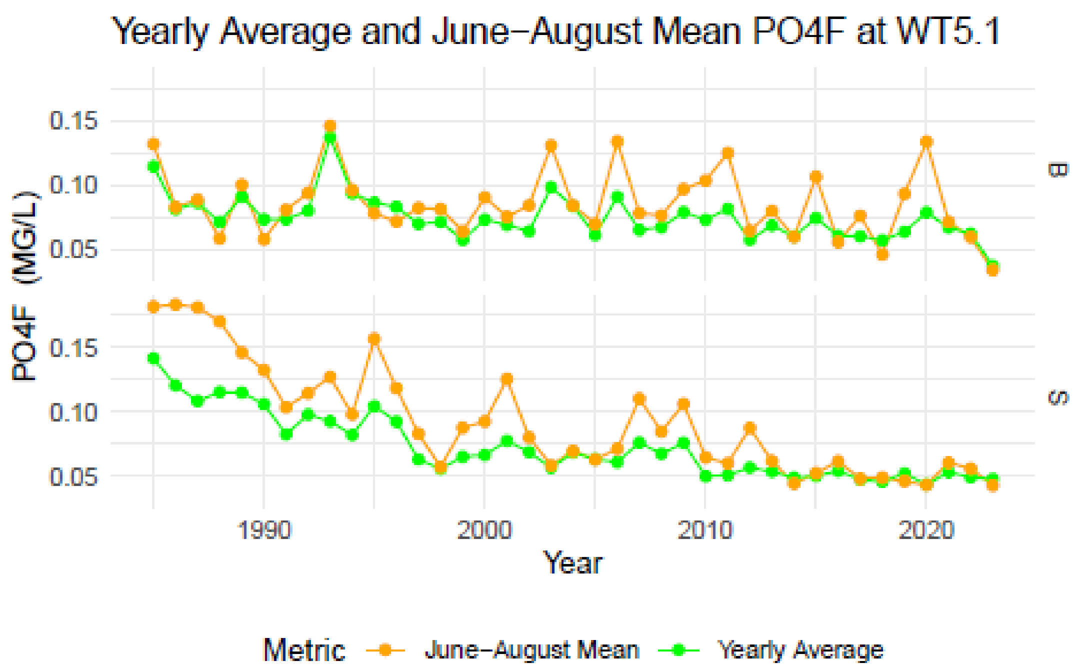


Figure 4: Surface and bottom water concentrations of dissolved inorganic phosphorus (top) and nitrate+nitrite (bottom) measured at long-term monitoring stations in the Back River estuary, averaged over the year (blue lines) and summer (June-August; red lines).



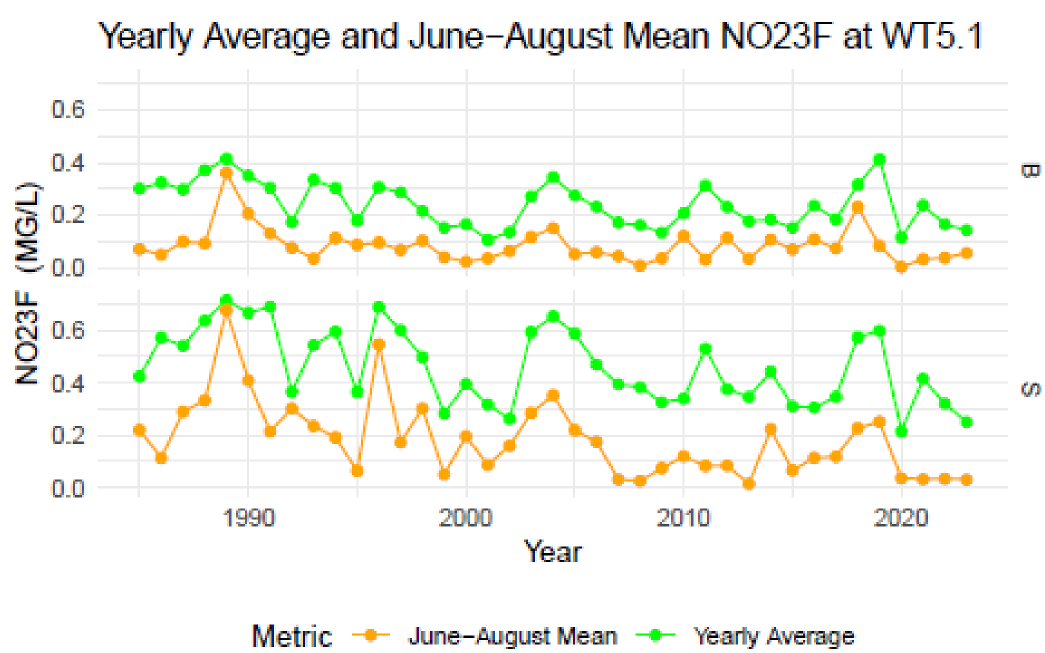


Figure 5: Surface and bottom water concentrations of dissolved inorganic phosphorus (top) and nitrate+nitrite (bottom) measured at long-term monitoring stations in the Patapsco River estuary, averaged over the year (green lines) and summer (June-August; orange lines).

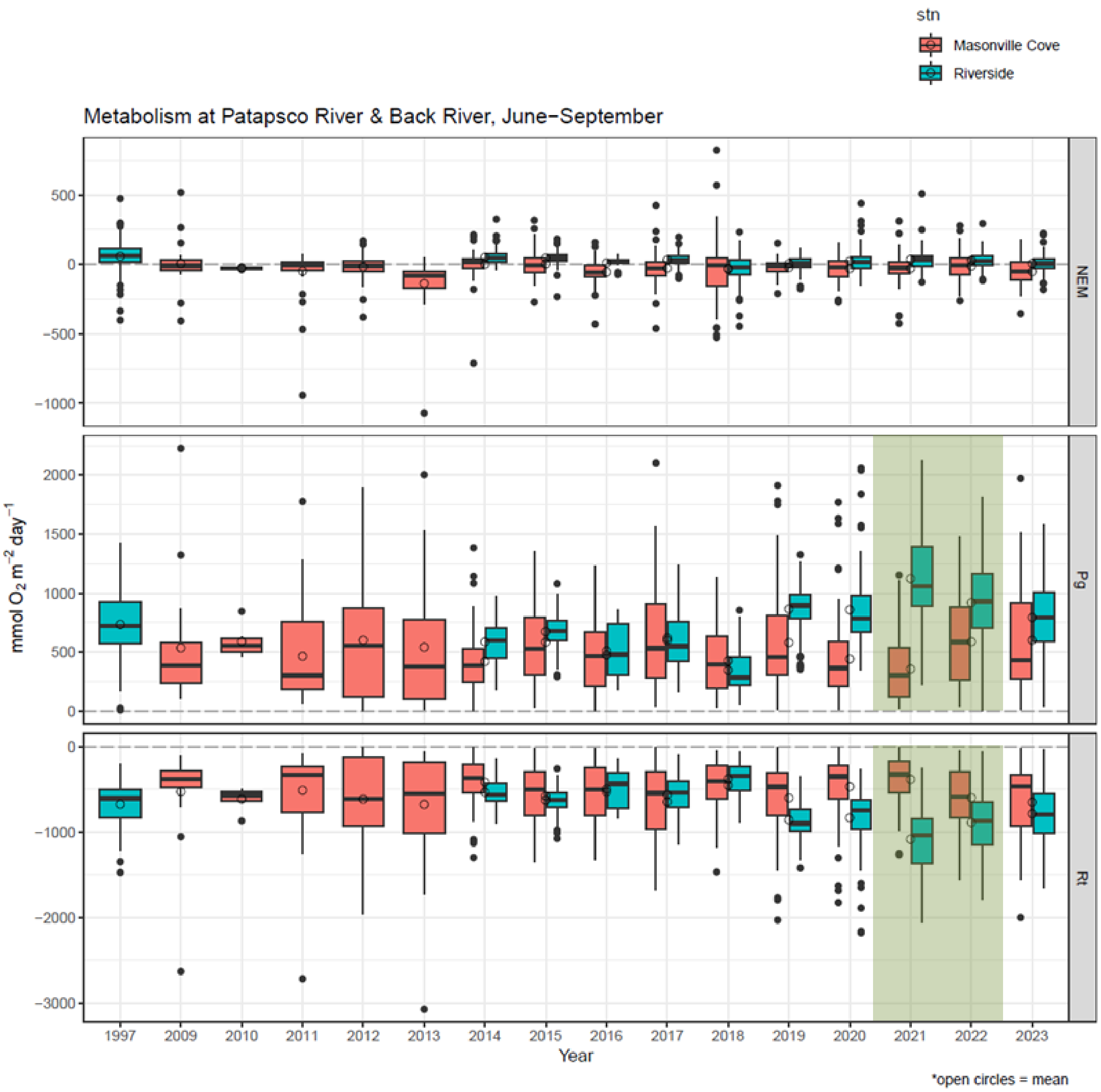


Figure 6: Estimates of June-September ecosystem metabolism (NEM, top), gross primary production (P_g, middle), and ecosystem respiration (R_t, bottom) at stations in the Back River estuary (Riverside; see Fig. 1) and the Patapsco River estuary (Masonville Cove; see Fig. 1). The shaded area highlights the period of WWTP failures.

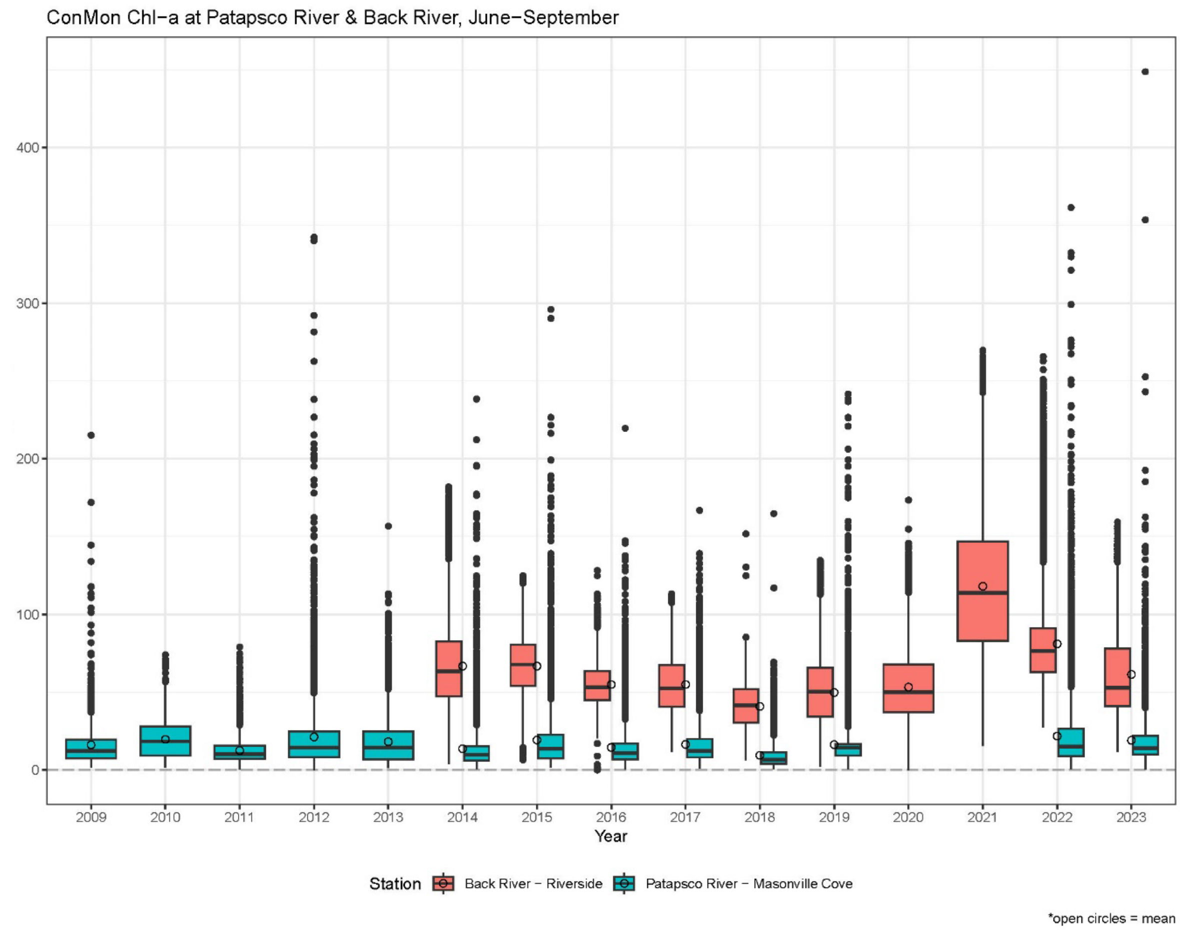


Figure 7. Measurements of June-September chlorophyll-a (μg/L) at stations in the Back River estuary (Riverside; see Fig. 1) and the Patapsco River estuary (Masonville Cove; see Fig. 1) from 2009 to 2023.

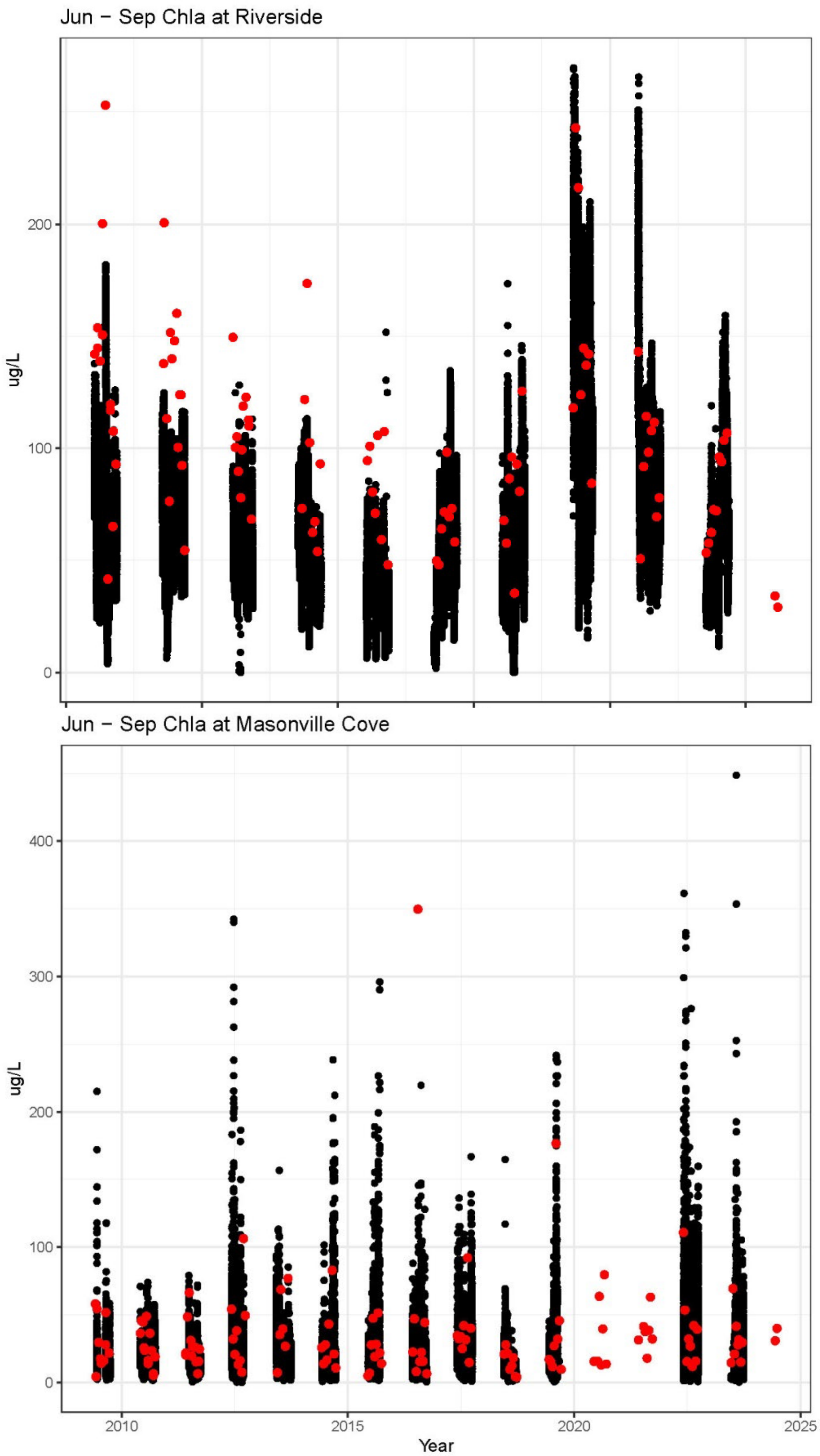


Figure 8: June-September chlorophyll-a at stations in the Back River estuary (Riverside; see Fig. 1) and the Patapsco River estuary (Masonville Cove; see Fig. 1) from 2009 to 2023, where black circles are sensor-based estimates and red circles are discrete, extracted measurements.

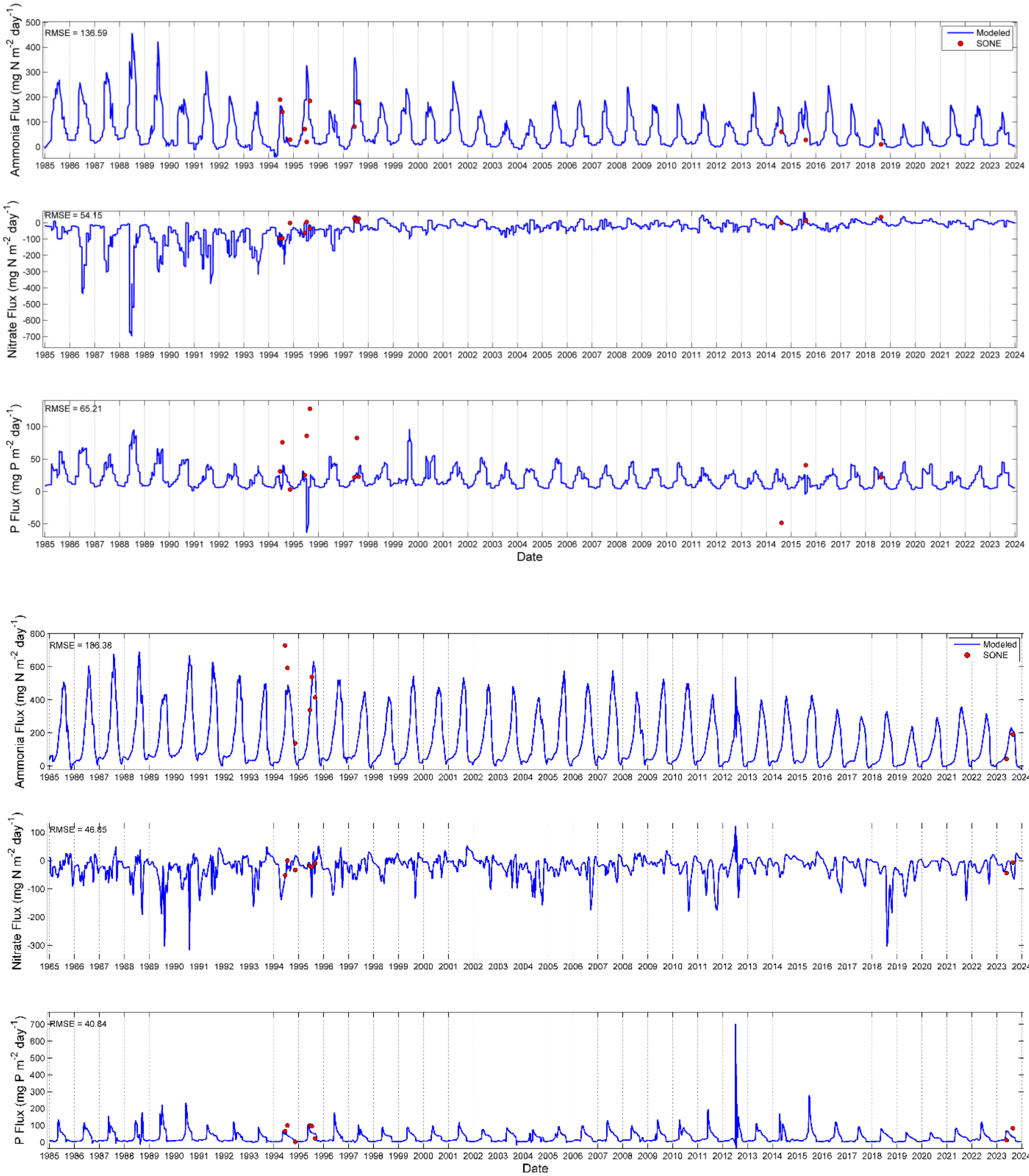


Figure 9: Modeled sediment-water fluxes of ammonium, nitrate+nitrite, and phosphate at a representative station in the Back River estuary (top panels) and the Inner Harbor of the Patapsco River estuary (bottom panels) from 1985-2023. Red circles are direct measurements and blue lines are model estimates. The RMSE for each variable are indicated on the figures.

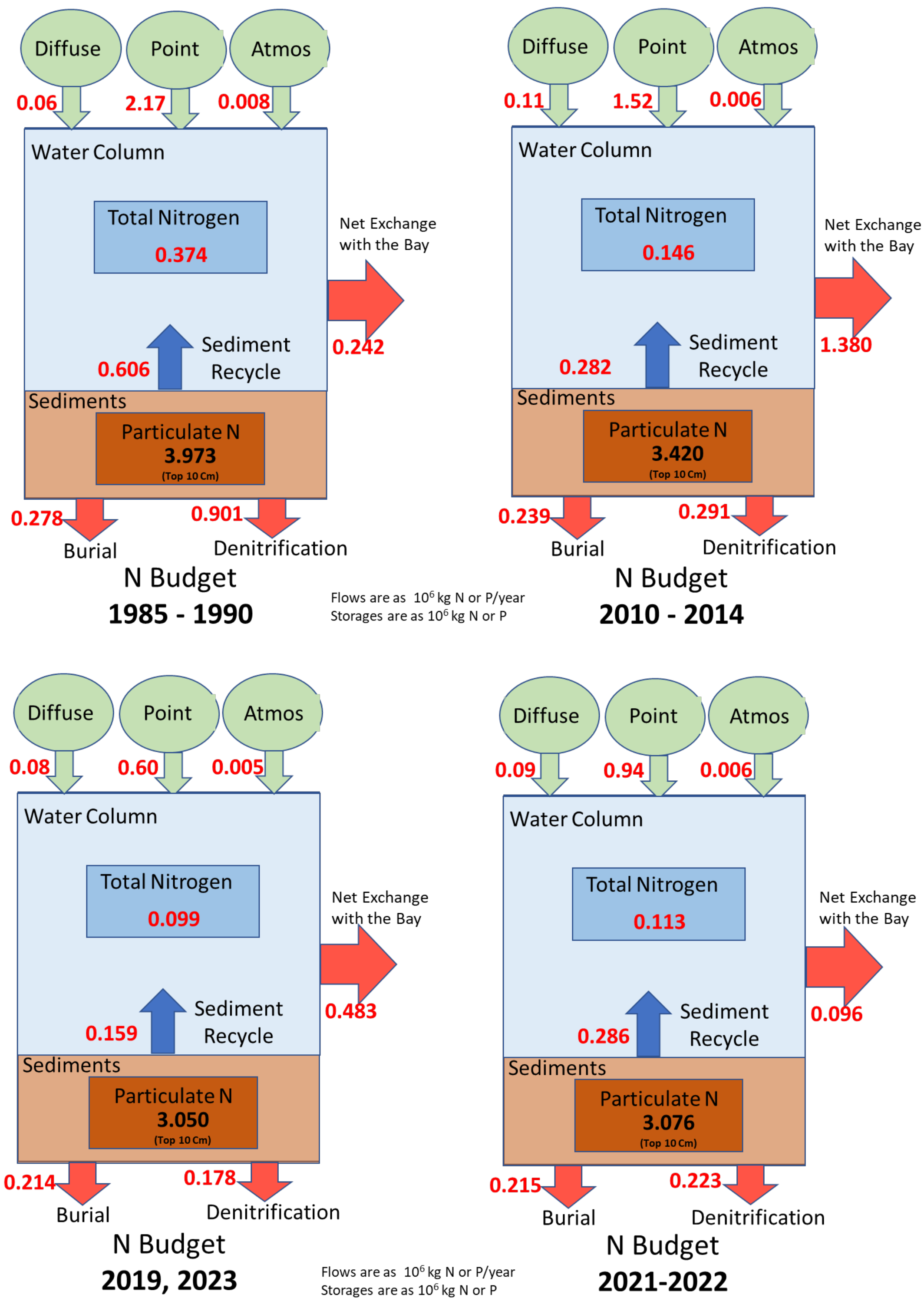


Figure 10: Comparison of nitrogen budgets for the Back River estuary during a historic period (1985-1990), a period pre-WWTP final upgrades (2010-2014), the post-WWTP upgrade period (2019, 2023), and the 2021-2022 period when there were WWTP failures.

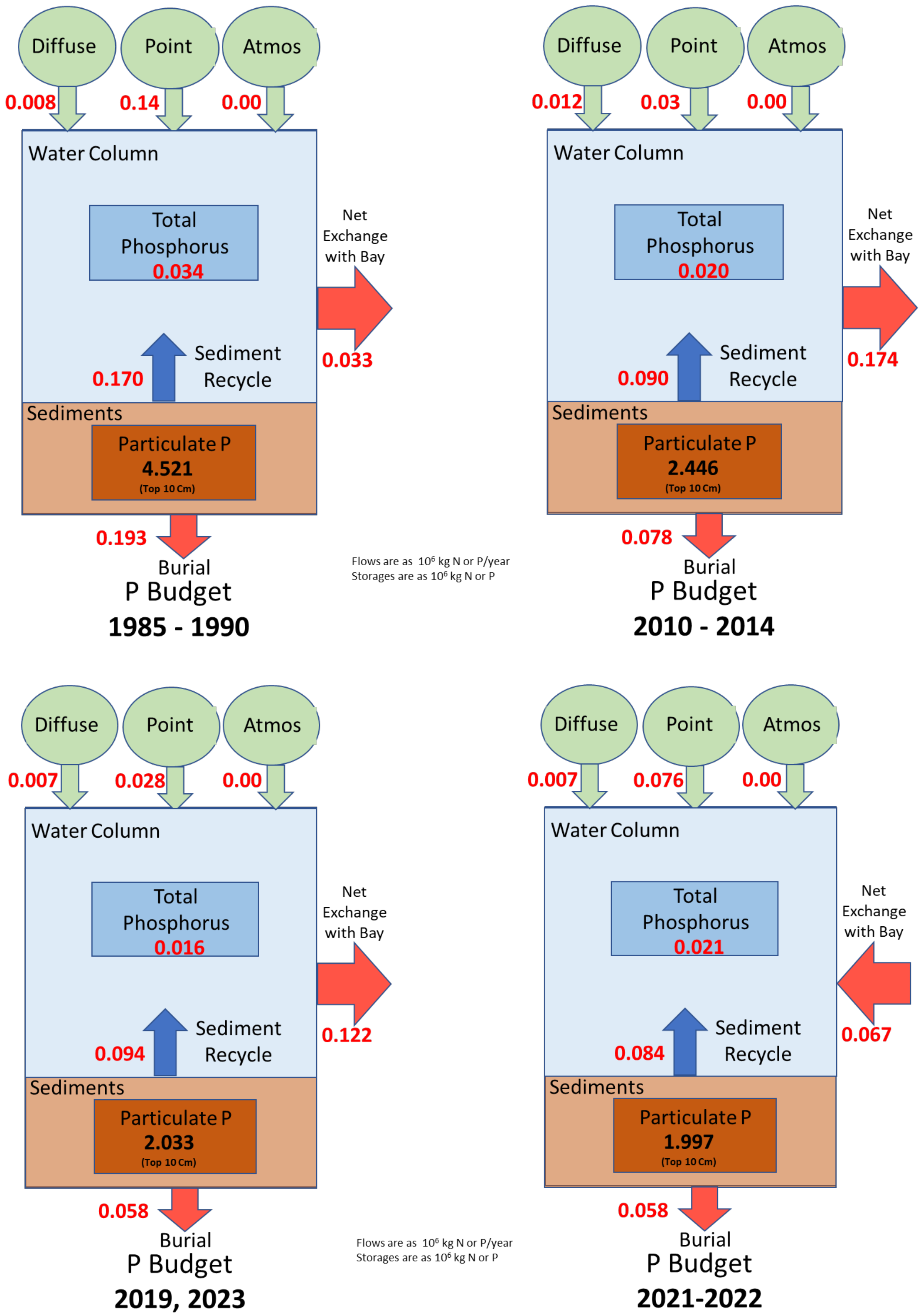


Figure 11: Comparison of phosphorus budgets for the Back River estuary during a historic period (1985-1990), a period pre-WWTP final upgrades (2010-2014), the post-WWTP upgrade period (2019, 2023), and the 2021-2022 period when there were WWTP failures.

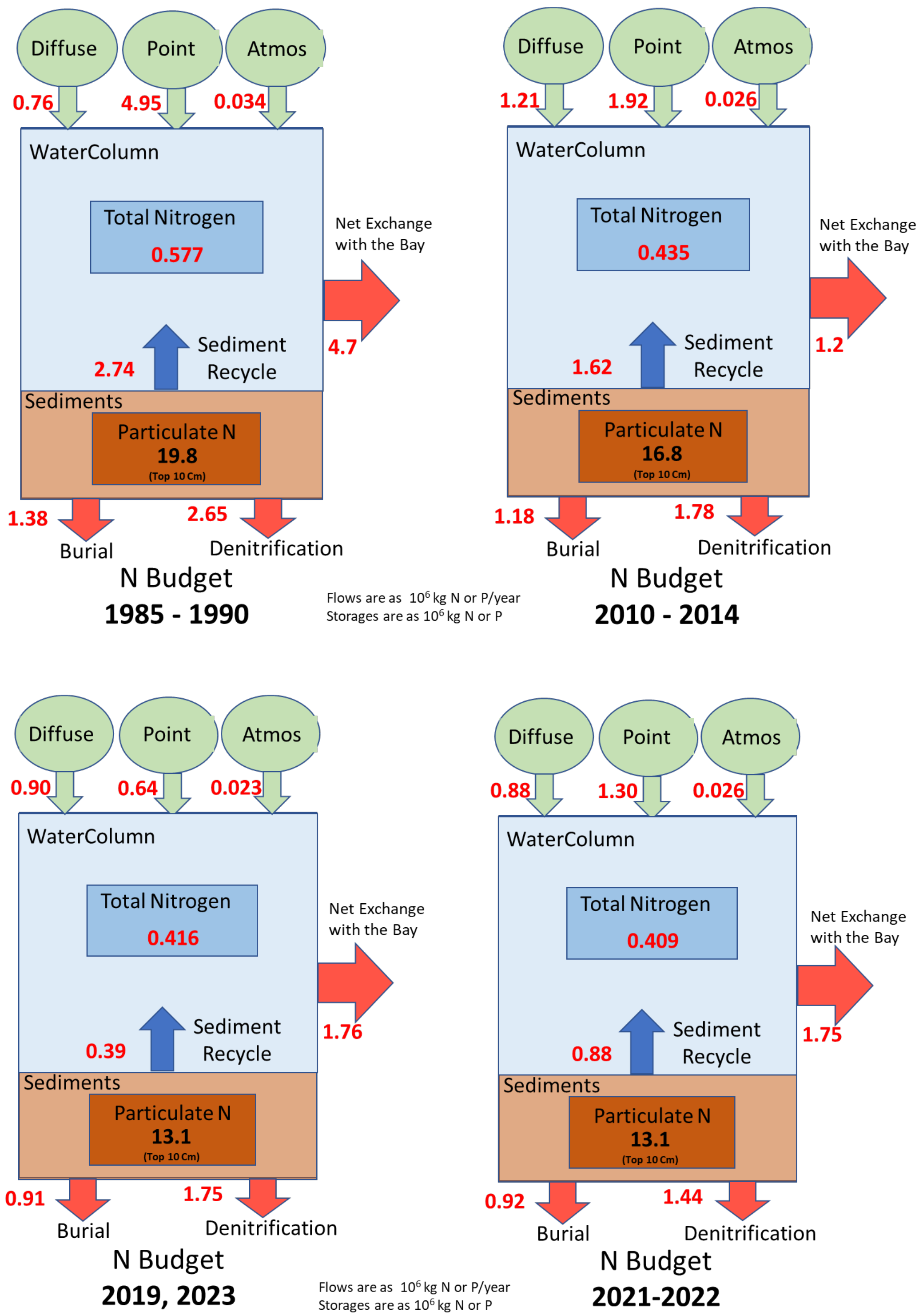


Figure 12: Comparison of nitrogen budgets for the Patapsco River estuary during a historic, period (1985-1990), a period pre-WWTP final upgrades (2010-2014), the post-WWTP upgrade period (2019, 2023), and the 2021-2022 period when there were WWTP failures.

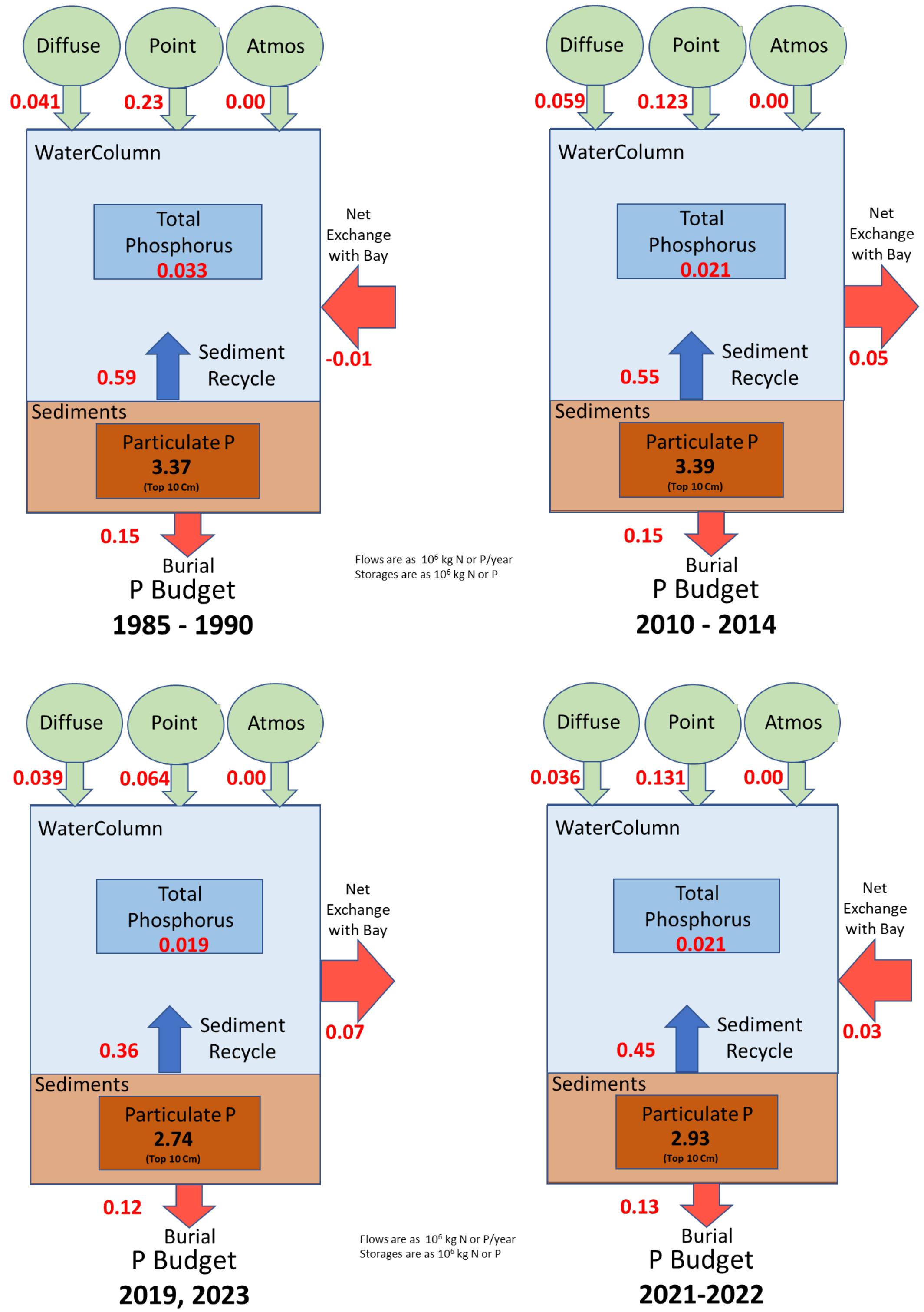


Figure 13: Comparison of phosphorus budgets for the Patapsco River estuary during a historic, period (1985-1990), a period pre-WWTP final upgrades (2010-2014), the post-WWTP upgrade period (2019, 2023), and the 2021-2022 period when there were WWTP failures.