Seasonal Transformation and Fluxes of Nitrogen, Carbon and Phosphorus in a Tidal Freshwater Marsh

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Abstract

In 1995 a study was conducted in a tidal freshwater wetland on the Anacostia River (Washington, DC), to assess nutrient interactions between the wetland and tidal river. The study site was the 32 acre Kenilworth Marsh which was restored one year prior to this study in 1993-4. From March to October of 1995 water samples and current velocities were obtained from the only inlet to the marsh over a 25 to 30 hr period (i.e., 2 tidal cycles) during a 10 month period. These data were then used to calculate the flux (mass per area per hour) of dissolved and particulate forms of nitrogen, carbon and phosphorus to and from the marsh. Levels of total dissolved nitrogen and phosphorus were high in the river as would be expected from a urban-suburban watershed. Total dissolved nitrogen concentrations generally ranged from 60 to 180 μM N and total dissolved phosphorus concentrations ranged from 0.5 to 1.8 μM P over the course of this study. Concentrations of some forms of nitrogen, phosphorus and carbon such as dissolved nitrate+nitrite and dissolved organic carbon exhibited strong seasonal changes during the study period. For example, dissolved nitrate+nitrite concentrations decreased from approximately 100 μM N in March to 40 μM N in June and August suggesting strong sediment microbial processing via denitrification. Nutrient fluxes were low in the late winter/spring time period, increasing to the summer and fall. In general, there was a substantial flux of total nitrogen and total phosphorus from the river to the marsh over the year with loads of 4,900 kg N and 1,100 kg P per year, respectively. While there was marked changes in specific forms of nitrogen and phosphorus in the tidal marsh system during the study, these fluxes were small compared to the input of nutrients estimated from the watershed. In addition, it appears that the one year post-restored Kenilworth Marsh acted in a similar fashion as other tidal freshwater wetland systems, however further studies after the marsh is allowed to "age" would be needed to assess the function of the marsh. Extensive restoration efforts, along with nutrient reduction, would need to be undertaken in order for tidal wetlands in the Anacostia to play a substantial role in both short and long term nutrient removal and retention.

Introduction

In eutrophic estuaries of the United States, tidal freshwater wetlands often receive significant loadings of dissolved inorganic and organic nutrients from both terrestrial and aquatic systems. They can potentially act as sinks, sources, or transformers of nutrients for adjacent or linked water bodies. The role of wetlands in the cycling of dissolved nutrients is dependent upon the age and ecological maturity of the wetland, the amounts of upland runoff and effluent input (Mitch and Gosselink, 1993). It has been suggested that tidal freshwater wetlands may serve as sinks for (i.e., remove) certain nutrients, at least during part of the year (Good et al., 1975; Grant and Patrick, 1970; Simpson et al., 1978; 1983a,b). Without question, wetlands serve an increasingly important role in estuarine nutrient modification and management.

In freshwater tidal wetlands different topographical and vegetational regions affect the fate of nutrients by various biogeochemical processes. For instance, plant debris in the low and high marshes degrades at different rates, and consequently influences the flux of nitrogen out of the marsh sediments (Odum et al., 1984; Whigham et al., 1989). The lower more recently developed marsh, inundated by tidal waters for the majority of the tidal cycle, tends to store very little nutrients because of the reduced amount of plant litter. The higher more mature areas of marsh typically have a greater capacity for temporary storage of nutrients due to more abundant plant litter (Mitsch and Gosselink 1993). Freshwater tidal wetlands contain a complex variety of micro- environments that differ in terms of vegetational structure and composition, litter accumulation, and soil conditions (Simpson et al. 1983a,b; Odum et al. 1984).

Information regarding the exchange and transformation of nutrients in freshwater tidal marshes is limited. Importantly, the role of marshes as either a source or sink of nitrogen, phosphorus or carbon can be seasonally dependent. Tidal marshes often retain inorganic nutrients during the spring and summer months (Valiela and Teal, 1974; Simpson et al.,1978). As an example, seasonal nutrient retention has been demonstrated by Heinle and Flemer (1976) in Gotts' marsh, located on the central portion of the Patuxent River in Maryland. They reported that large amounts of dissolved organic nitrogen (DON) were transported from the marsh into the adjacent estuary, while dissolved inorganic nitrogen (DIN) was “consumed” by the marsh. The estuarine sediment interface acted as a source of nutrients during summer when microbial remineralization rates were high, and as a sink during winter when the water column demand was usually low. Their study demonstrated that freshwater tidal marshes can function as "buffers" for inorganic nutrients (Valiela and Teal, 1974). Studies in salt marshes have also compared nutrient fluxes in high and low marsh areas. For example, a study conducted on the Rhode River estuary in Maryland by Jordan et al. (1983) revealed that the high marsh acts as a sink for ammonium, whereas the low marsh is either a source or exporter of ammonium.

The concept of marsh-estuary outwelling and exchange of nutrients and carbon has been the topic for much debate (Nixon, 1980; Childers et al., 2000). This paradigm suggests that tidal marshes can supply organic matter (and energy) to fuel coastal productivity. As Childers et al. (2000) noted, it is important, however, to define the spatial and temporal boundaries to test whether a marsh is a source or sink of material from the adjacent coastal area or, in this study, adjacent tidal river. In addition, the method of assessment is key to testing a tidal exchange process. Marsh flume studies that include plants and sediments (Chalmers and Wiegert, 1985), and sediment core incubations (Scudlark and Church, 1989), while used to address the same question, could provide different results and direction of fluxes due to the synergistic interactions of many processes within a specific marsh. Tidal channel studies between marshes and adjacent water bodies can be more accurate in estimating the net flux between the two, but provide little information concerning the specific biogeochemical process that is altering the nutrient concentration and form (Anderson et al., 1997; Childers et al., 2000). Processes such as particle (nutrient) deposition and resuspension, nitrification, denitrification, and plant uptake can affect the distribution and concentration of the various nitrogen and phosphorus chemical forms. These processes can take place in the sediments, plants or water column, Therefore, it is important for any testing of the nutrient outwelling paradigm to understand the bounds and constraints in the study plan and what information the specific study can provide.

Lastly, natural wetlands and aquatic systems have been used to help treat wastewater discharges since at least the beginning of this century (Kadlec and Knight, 1996). Due to a growing interest in the use of wetlands (tidal and non-tidal) as systems to treat nutrient inputs from various municipal and industrial sources, a better understanding and quantification of the actual benefits is developing. Because wetlands and their sediments have a higher rate of biological and microbial activity than most systems and there is a near constant innundation and mixing of water, they can transform or sequester many pollutants, including nitrogen and phosphorus, over specific time scales. While many studies indicate improvements of water quality in relatively small systems and wetlands, it is an objective of this study to provide an estimate of the potential impact that Kenilworth Marsh can have on nutrient transformations in the tidal Anacostia River.

In this study, we determined the exchange of various forms of nitrogen, phosphorus and carbon between a newly restored tidal freshwater wetland and its adjacent tidal river. We attempted to address the hypothesis that *substantial areas of wetlands need to be restored in the tidal Anacostia River so that sufficient processing and filtering capacity can be obtained*. The restoration of wetlands, both tidal and non tidal, is important so that a fully functioning ecosystem can be made. However, in many cases, it is often touted that these wetlands will act as filtering areas for nutrient levels in the adjacent waterway. Tidal wetlands can act at different times as a sink, source, or transformer of nitrogen and phosphorus to the adjacent tidal river. To better understand how well restored Kenilworth Marsh functions within the Anacostia River ecosystem, we undertook an almost year-long study of the nutrient dynamics and fluxes between the wetland and tidal river. The objective of this study was to determine if the newly created Kenilworth Marsh is a net source or sink of nitrogen and phosphorus to the Anacostia River.

Experimental Design

Study Area

The Anacostia is a complex urbanized watershed that has attracted considerable regional and national attention because it is classified among the most polluted waterways in the country and is listed as a Region of Concern by the Chesapeake Bay Program (CBP, 1994). Historically, the tidal river consisted of extensive freshwater tidal wetlands (> 2,500 acres or 1.0×10^7 m^2), however most of these wetlands were destroyed by dredge and fill operations by the Army Corps of Engineers (ACOE) during the first half of this century (ICPRB, 1988). This represents an overall loss of more than 90% of the originally-occurring tidal wetlands from the river.

In 1993, a project to restore a representative wetland component took place at the 32-acre (1.3×10^5-m^2) Kenilworth Marsh (Figure 1). For this project, the ACOE dredged a portion of the adjacent tidal Anacostia River, and carefully placed the material in the marsh. After contouring, consolidation and leveling of the sediment, nursery stock were planted and resident species (i.e., seed bank within sediments) became established. The species consisted of cattail, arrow-arum, rice cutgrass, and duck potato (arrowhead) covering most of the marsh surface (high, mid and low marsh). Presently, the marsh has extensive mid and high marsh zones, with smaller areas of low-marsh, relative to the 1-m tide cycle. There is only one opening or outlet for this system located on the tidal Anacostia River as well as one small urbanized stream that drains into the upper areas of the marsh (Nash Run; Figure 1). The newly restored marsh has been an active site for the ecosystem of the river attracting many species of birds, fish, beaver, and other organisms that were not present previously in the area (Syphax and Hammerschlag 1995).

Field Sampling

Monthly sampling was conducted from March to October of 1995, excluding May in which a storm prevented access to the sampling site. All sampling was conducted at the only inlet-outlet for the marsh using the District of Columbia's or National Park Service's 18 ft. whaler (Figure 1). Standard surveying techniques were employed to determine the cross-sectional area of the inlet feeding Kenilworth Marsh. Two sample transects 6.6 m apart were surveyed just following low tide. Readings were generally taken at 0.5-m or 1.0-m intervals across the 21.9-m inlet depending upon variations in bottom topography and grade. A Nikon (AE) Automatic Level was used in conjunction with a metric stadia rod to take elevation readings. Benchmarks were set for one of the transects that was use in the monthly sampling.

For each sampling period, a 3/4 inch rope was placed across the inlet from the benchmarks and divided into thirds. During the sampling period, water samples and velocity measurements across the inlet were collected along the rope transect every two hours over an approximately 30-hr period (i.e., two tidal cycles per month). Velocities were measured with a factory calibrated and verified Marsh-McBirney Flowmate 2000. The probe was connected to a 1.5-m stainless steel rod and orientated into the current at each sampling point. The sampling transect in the inlet was divided in thirds, and at the mid-point of each interval a velocity profile of three depths was obtained. At each depth at least 10 separate readings were taken at each depth over a two minute time period. The resultant relative standard deviation (%RSD = σ/mean X 100) was generally less than 20%, depending on the absolute velocity (i.e., lower velocities were more variable). Care was taken to ensure that values obtained were as precise as possible, and additional measurements were obtained if needed. The manufacturer's specification for the threshold velocity is approximately 0.5 cm/sec.

After the velocity measurement were made, a 3-L water sample was obtained using a pre-cleaned vertical polycarbonate tube and superball bottom stopper. The water sample was taken at the mid-point of the inlet and represents the entire water column at that point. During the study, depth-integrated samples were also obtained where the velocity measurements were taken to assess cross-channel variation. Variations of most parameters were less than 10% RSD, with slightly higher variability in particulate phase material than dissolved phase species.

On the boat, each water sample was placed into a pre-cleaned 3-L HDPE bottle and immediately taken to the field laboratory for filtration and preservation. Samples were filtered through Whatman GFF (0.7-µm nominal pore size) filters for dissolved and particulate separation. For particulate carbon and nitrogen (PC/PN), filters were pre-heated to 420˚C for 2 hr to remove background carbon and nitrogen. Filters for PC/PN were wrapped in pre-heated Al foil and placed on dry ice (-78˚C). Water samples for dissolved organic carbon (DOC) and DON were placed into pre-cleaned Teflon bottles, while inorganic nutrient samples were placed into pre-cleaned auto-analyzer vials. All water and particulate samples were immediately frozen with dry ice and transferred to a refrigerator (-20˚C). All sampling and field laboratory equipment was cleaned prior to and during each trip with dilute soap, double deionized water (DDW), soaked for a least 2 days in 0.5N HCL and rinsed with copious amounts of DDW. All equipment was dried in a dust free area and stored in plastic bags or Al foil.

All chemical analyses were accomplished at the Nutrient Analytical Services Laboratory, Chesapeake Biological Laboratory (University of Maryland) using standard methodologies (D'Elia et al. 1997; Parsons et al. 1984; U.S. EPA 1992). Samples were analyzed for the various forms of inorganic nitrogen and phosphorus (i.e., dissolved NH_4^++NH_3; NO_2^-+NO_3^-, o-PO_4^{3-}); dissolved forms of organic carbon (DOC), phosphorus (DOP), and nitrogen (DON); particulate forms of organic carbon (POC), nitrogen (PN), and phosphorus (PP). A Hydrolab Surveyor II was used to measure dissolved oxygen, temperature, conductivity and pH in the middle of the channel at approximately 1.5 m depth. The multiprobe meter was calibrated before each sampling program and checked after each day. Data did not need to be corrected for meter drift.

Data Reduction/Calculations

Fluxes (i.e., g/sec) were determined every 2 hr from the average water velocity, water level (i.e., tidal height in the inlet) and cross-sectional area, and the ambient concentration value. At each time point, in the mid-point of each of three cells across the inlet, the average vertical current velocity was calculated using the data taken at 0.2, 0.6, and 0.8 of the total depth (from the surface). The cross-sectional area was determined using a fitting calculation for the dimensions of the inlet and tidal height at each time point. The flux of water (L/sec) was determined using the average vertical velocity and the cross-sectional area. The flux of water into or out of the marsh was multiplied by the concentration value (e.g, ammonium+ammonia) at that time point in µmole/L to obtain the flux into or out of the marsh with units of µmol/sec or µg/sec. Fluxes could be either flood-directed (i.e., indicated by +; into the marsh from the tidal river) or ebb-directed (i.e., indicated by −; out of the marsh to the tidal river) depending on the direction of the water flow during the tidal cycle. The net flux for each parameter (e.g., µmol/m^2-hr or µmol/hr) over each sampling period (i.e., approximately 30 hr) was determined as the result of the integration of the area of the + or - fluxes over the ebb and flood tides for the approximately 30-hr period. Fluxes were corrected for any water imbalance over the time period due to tidal inhomogentity over the 30-hr tidal period.

Concentration and flux data presented below are given in molar units or moles per volume (e.g., µM = µmoles/L). These units allow a comparison of the nutrient resource ratios and limitation to autotrophic growth. However, for many water quality studies units are given in mass per volume (e.g., µg/L). As an example, to convert from molar units to mass units the following conversion factors are needed: 1 µM N X 14 µg N/µmole = 14 µg N/L, 1 µM P X 31 µg P/µmole = 31 µg P/L and 1 µM C X 12 µg N/µmole = 12 µg N/L.

Uncertainty Analysis

Estimates of nutrient fluxes in the Kenilworth Marsh system are dependent on accurate and precise nutrient concentrations and water velocities during sampling period. In addition, it is assumed that exchange of water to the marsh system is from the Anacostia River at the inlet with no other sources. By not accounting for all nutrient sources (or sinks) an inaccurate budget would result. While a rigorous uncertainty analysis has not be determined, an attempt to understand the potential errors is qualitatively described below.

Water sampling for dissolved and particulate nutrients entailed a single depth-integrated sample from the middle of the channel. This was done to get a instantaneous, fully-integrated sample of the water entering or leaving the marsh. During the June sampling period, samples were collected at three locations across the inlet to assess inchannel variability. For dissolved concentrations, samples (except for SRP) agreed to better than 5% RSD (relative standard deviation = σ/mean X 100), while particulate concentrations were more variable at approximately 8% RSD. In addition, during each time period one set of duplicate samples were obtained and the relative percent difference (RPD) was always better than 5.

Estimates of the water flow were more variable. This variability was largely dependent on the magnitude of the current velocity and any floating material in the water. Using the July data set as an example, the %RSDs were between 30 to 100% at velocities below approximately 5 cm/sec and decreased to less than 12% RSD at velocities above approximately 25 cm/sec. To help obtain accurate velocities at least 10 measurements were obtained at each depth and time point for assessing current velocity (except for March). Current velocity measurements were probably the largest source of systematic error in estimating the flux of material into or out of the marsh (i.e., cross sectional areas for multiple profiles were similar). However, since most of the volume that is transported between the marsh and river is at higher velocities, the amount of error may not be large. A more detailed analysis is needed to refine these estimates.

Other sources of error in the flux estimate are the estimate of the effective area of the marsh that can interact with the water column and on what time scales and addition sources to the marsh. To obtain areal rates of nutrient uptake or output, it was necessary to use the area of the marsh. This provided areal fluxes with units of mole/m^2-hr and these values can be compared to other tidal freshwater marsh sites along the East Coast of the United States. While we recognize that the effective area of the marsh is probably less than 32 acres (1.3 X 10^5 m^2), it would be difficult to determine a more accurate area unless a survey of the sediment level was available. In addition, areas that are mudflat versus vegetated would be needed to help in this study. As described below, a comparison of areal rates from this study to other sites indicate that the rates are in reasonable agreement.

Lastly, other inputs to the marsh need to be considered. This includes the small tributary on the south side of the marsh (Nash Run), overland flow during rain events, and potentially groundwater exchange. Estimates of overland flow and groundwater were beyond the scope of this project and would be difficult to determine. We did estimate the instantaneous flux of nitrogen, phosphorus and carbon from Nash Run during each time period. While these estimates were done at base flow therefore a minium, the flux into the marsh was minimal compared to the flux through the inlet. However, visual inspection of Nash Run after various rainfall events suggest that the water and nutrient input from the surrounding watershed could be substantial in the longer term, overall nutrient budget.

The discussion above outlines areas of uncertainty in the assessment of nutrient fluxes in the Kenilworth Marsh system. The uncertainties can be addressed with specific sampling and analysis and should be evaluated if a more accurate assessment is warranted.

Results and Discussion

The data for this study include concentrations of various forms of nitrogen, phosphorus and carbon taken every 2 hr over 2 tidal cycles over a 10-month period (see Appendix I). Water velocities were measured so that fluxes can be calculated. In addition, ancillary information (e.g., dissolved oxygen, temperature, pH, and conductivity) was obtained to help augment data interpretation, if needed. The focus of this study is the nutrient changes over the study period, summarized monthly and during each period. The fluxes were then calculated and data compared to fluxes from the watershed so that one perspective of the marsh interactions to the river can be assessed.

Monthly Nutrient Levels

The various forms of nitrogen, phosphorus and carbon (NPC) varied substantially over the course of this study. This variation is a result of various autotrophic and sediment microbial processes and variations in the sources of NPC. It was anticipated that dissolved inorganic forms of N and P would decrease during the late spring and summer and increase in concentration during the fall/winter time period. The decrease in concentrations could be due to both plant update and flux of nutrients into the sediment. For example the flux of dissolved NO_3^-+NO_2^-

would be used to support sediment denitrification. In addition, the input of organic forms (i.e., DON or DOP) were expected to increase during the summer and fall as microbial processes remineralize newly formed plant material in the sediments. In many studies, the remineralization of organic matter in the sediments, allow a buildup of porewater NH_4^++NH_3 in the sediments which can then move via advection+diffusion and seepage into the overlying waters. Therefore the interactions between the water-plants-sediments are important in understanding the monthly and seasonal changes in nutrient forms and concentrations.

Dissolved NH_4^++NH_3 concentrations at the inlet, while variable, generally decreased from approximately 30 in the late winter to 10 µM N in August, while dissolved NO_3^-+NO_2^- concentrations decreased substantially during the growing season from 100 µM N in late winter to approximately 35 µM N after June or July (Table 1; Figure 2). Dissolved organic nitrogen concentrations were variable, averaging 23 to 36 µM N during the study. Higher concentrations were observed in the late winter and mid-summer time periods (Figure 3). As a result of the large proportion (average of 48%) of the total dissolved nitrogen (TDN) being comprised of the oxidized forms (i.e., NO_3^-+NO_2^-), TDN concentrations decreased on average from 160 to 73 µM N from March to mid-summer (Table 2; Figure 2.) Particulate N concentrations increased from March to August with peak average concentrations of 54 µM N (Figure 4). As a result of the changes in the various species of N, total N (i.e., the sum of the all the species; TN) exhibited substantial changes during the year (Figure 4). Concentrations of TN were high in the late winter time period and decreased substantially until June, after which there was a mid-summer peak of approximately 140 µM N; concentrations were somewhat variable thereafter.

Soluble reactive phosphorus (SRP) concentrations were low during this study and averaged 0.31 to 0.68 µM P, with average concentrations generally highest in June and July (Tables 1 and 2; Figure 5). Similarly, concentrations of DOP were extremely variable during the study period (Figure 5) with concentrations as high as 0.78 µM P. On average, concentrations were generally around 0.4 µM P with slightly higher values in June and July. Soluble reactive P was generally around 65% of the total dissolved P (TDP = SRP + DOP) during this study (Table 2). Average TDP concentrations were also highest (i.e., 1.2 µM P) in June and July, while PP concentrations reached a mid-summer maximum of 4.3 µM P (Figure 6). Particulate P was the dominant form of phosphorus accounting for < 70% of the total P (TP) on average (Table 2). Total P average concentrations ranged from 3.0 to 5.0 µM P, and as with PP, peaked in during August (Figure 7).

Dissolved organic carbon exhibited a general increase in concentration from the late winter to mid summer with average peak concentrations of 604 µM C (Tables 1 and 2; Figure 8). In addition, while POC concentrations were variable each month, average concentrations increased to maximum levels in August. Total organic carbon (TOC) concentrations, which is the sum of DOC and POC, also increased during the summer with peak values in August of 946 µM C (Figure 7).

Many of the changes in particulate forms of N, P and C would be driven by variations in the total suspended matter (TSM) in the inlet during the study (Table 1; Figure 9). On average, TSM concentrations peaked during August at > 200 mg/L. This is a result of a thunderstorm in the Anacostia watershed during the sampling period. However, the storm occurred during the later part of the sampling period, and excluding these data, a similar trend is evident in that concentrations increase through the summer period.

Tidal Changes in Nutrient Concentrations

Nutrient and related parameters, in many cases, changed substantially over the course of each monthly sampling. Figures 10 through 23 provide the tidal changes in the concentrations of the various forms of NPC and total suspended matter. As mentioned above, these tidally-related changes are in addition to seasonal changes in nutrient concentrations. The changes in concentrations between flood and ebb tide would be related to processes within the marsh that either produce, consume or transform the various forms of NPC. These processes could occur via the biogeochemical interactions of water-plant-sediment in the marsh. At times however, there was substantial variability in the concentration of many parameters suggesting little effect by the area of the marsh.

Dissolved NH_4^++NH_3 concentrations were generally lower just after low tide than at high tide in most months (Figures 10-23). This was evident during March and April; however during the June time period concentrations were higher in the inlet as the water ebbed out of the marsh. The higher concentrations during ebb tide in June suggest an export of NH_4^++NH_3 from the marsh. The concentrations of dissolved NO_3^-+NO_2^- were higher than dissolved NH_4^++NH_3 over the course of the study. Overall, dissolved NO_3^-+NO_2^- concentrations were lower at ebb tide as water left the marsh than at high tide (Figures 10-23). In the spring-summer months the difference between low and high tide concentrations was approximately 11 to 15 μM N, while in the late summer-fall the difference in dissolved NO_3^-+NO_2^- concentrations was much less, between 5 to 10 μM N. Dissolved organic nitrogen and PN concentrations were overall similar to dissolved NH_4^++NH_3 and were variable over the tidal cycle. In some months, DON concentrations were slightly higher at low tide than high tide (Figures 10-23). Total nitrogen, which is the sum of all the separate forms of nitrogen, exhibited tidal patterns that changed throughout the year. For example, in March and October concentrations of TN were lower at low tide, while in June concentrations were slightly higher at low tide.

The concentration and distribution of phosphorus were variable over each monthly tidal period (Figures 10-23). As stated earlier, PP was the dominant fraction of phosphorus. Soluble reactive phosphorus concentrations were generally less than 0.1 μM P and there is some indication that concentrations were higher at ebb tide. This is best illustrated with the October sampling period in which concentrations were approximately 0.3 μM P at high tide increasing to about 0.9 and 0.6 μM P just prior to low tide (Figure 22-23). Dissolved organic phosphorus concentrations were low (< 0.5 μM P) and did not exhibit any changes related to tidal height. Total phosphorus, which is dominated by the PP fraction (i.e., 70 to 85% of TP), was generally variable, but it appeared that concentrations were higher during the ebb tide (Figures 10-23). In June for example, concentrations of TP increased from approximately 3.5 μM P at high tide, to between 5.5 and 4.8 μM P at low tide (Figure 14-15); however, not all months exhibited this trend.

Carbon, both dissolved and particulate organic forms, changed substantially over the course of each tidal cycle. Dissolved organic carbon concentrations ranged from an average of 425 to 600 μM C throughout the study period and there was no substantial change during each tidal study (Figure 10-23). Particulate organic carbon concentrations appeared to be highest during mid-tide when water velocities were highest. This could be due to resuspension of bottom material in the marsh and within the inlet system. Total organic carbon concentrations, which were dominated by the dissolved fraction, were variable and indicated a distinct tidal trend during the study period (Figures 10-25). Some months suggested that there were higher concentrations at low tide (e.g., April, June and July), while other time periods were variable.

Fluxes of NPC Between the Tidal River and Kenilworth Marsh

Qualitatively, when concentrations are higher during the ebb tide as compared to flood tide, addition of the constituent within the marsh is suggested. For example, if dissolved NH_4^++NH_3 concentrations are higher during ebb flow, it is possible that NH_4^++NH_3 is being added to the water column. This would result from the organic matter remineralization (i.e., ammonification) in the marsh sediments and release of porewater NH_4^++NH_3 either by advection/diffusion or subsurface flow (i.e., seepage) from tidal creek banks. Conversely, if concentrations were lower during ebb flow than flood flow, it suggests that processes such as sediment nitrification or plant uptake are removing NH_4^++NH_3 within the marsh complex.

To illustrate the method of analysis, the flux of total dissolved nitrogen (TDN) data for the March and October time periods are presented in Figure 24. The flux values are presented in gN/sec for each time point (every 2 hr) over each sampling period. Minimum fluxes occurred during the slack period, during either high and low tide, while maximum fluxes generally occurred during the time period when current velocities were greatest (i.e., mid-flood or mid-ebb). As stated above, to determine the total flux of material into (+) or out (-) of the marsh complex, the area under each curve was determined using a spline-fitting routine and the areas summed during the approximate 25-hr time period. Table 3 presents the summary fluxes for each time period in units of μmol/m^2-hr (for N, P or C), where the area of the marsh was 1.3 X 10^5 m^2 (32 acres). The area of the marsh used for these calculation is assumed to be the effective area that is inundated by the tides on a daily basis. However, this is not totally accurate as most areas of the marsh are only inundated during the highest of tides, generally those exceeding approximately 0.9 m. Therefore, the fluxes in Table 3 should be considered maximal fluxes between the river and the marsh. It would be informative to have an areal coverage during different stages of the tide.

<u>Nitrogen</u>: Nitrogen fluxes are dominated by changes in the dissolved forms (i.e., TDN) compared to PN (Table 3). Dissolved nitrogen was low and directed out of the marsh in March and April with values of -144 and -17 μmol N/m^2 hr^{-1}, respectively. Fluxes from June to October

were directed into the marsh complex and increased in magnitude to a high of 1,014 µmol N/m^2 hr^{-1} in August. There was substantial variability between the dissolved forms of TDN with both dissolved NH_4^++NH_3 and NO_3^-+NO_2^- generally directed into the marsh system. Dissolved organic nitrogen was generally directed into the marsh in the early part of the year and out of the marsh from August to October (Table 3). Particulate nitrogen fluxes ranged from -261 to 408 µmol N/m^2 hr^{-1} and other than April and June were directed into the marsh. Using the sum of TDN and PN, total nitrogen fluxes were low (-70 to -170 µmol N/m^2 hr^{-1}) and directed out of the marsh in March and April, increasing to 1,080 µmol N/m^2 hr^{-1} in August and decreasing through October (Table 3).

These results indicate that in the early part of the year, marsh plant productivity or microbial processes were not substantial enough to result in a net flux into the marsh of dissolved, available nitrogen (i.e., various forms of dissolved nitrogen). From June to October, a mixture of plant growth and sediment microbial processes (i.e., nitrification or denitrification) resulted in a substantial input of dissolved nitrogen into the marsh from the river. Within the marsh, interconversion of nitrogen resulted in a net flux of organic forms to the river. These forms are directly available to microbial uptake and can also be converted to inorganic forms that are available to plant productivity (Seitzinger and Sanders 1997).

The nitrogen fluxes determined in this study were compared to other studies of tidal freshwater in the mid-Atlantic region (Table 4). For this analysis, only dissolved NH_4^++NH_3 and NO_3^-+NO_2^- data were available as DON studies were not found. Table 4 presents the average inorganic nitrogen fluxes from marshes in the Hudson River to Chesapeake Bay using a variety of methods. Most of the studies obtained for this project used core incubations to measure fluxes between wetland sediments and overlying water. The core studies are both batch and continuous incubations. In some studies a marsh flume was used to estimate water/marsh exchange rates. Physical manipulations of the sediment can alter the natural conditions of in-place sediments and modify the “real” flux of many elements. Also, rates are generally given as mass per area per unit time (i.e., g of an element/m^2-day) and do not take into account the time that the wetland area is inundated by tidal water. Dissolved NH_4^++NH_3 fluxes ranged from -95 to 200 µmol N/m^2 hr^{-1} with variable direction relative to the marsh and on average the dissolved NH_4^++NH_3 was 40 µmol N/m^2 hr^{-1}. For dissolved NO_3^-+NO_2^-, the fluxes ranged from -124 to 34 µmol N/m^2 hr^{-1}

with and overall average of -33 μmol N/m^2 hr^{-1}. The NH_4^++NH_3 fluxes determined during this study (Table 3) were in good agreement with other systems, while dissolved NO_3^-+NO_2^- fluxes were considerably higher (i.e., more positive) for Kenilworth Marsh. It is possible that the eutrophic nature of the tidal Anacostia affected the flux of NO_3^-+NO_2^- into the marsh. In this regard, plant uptake or possibly denitrification (i.e., NO_3^-+NO_2^- converted to N_{2gas}) is more dominant in the marsh (Seitzinger 1988; Bartlett et al., 1979). Overall, the data suggest that the fluxes obtained in this whole marsh flux study provide realistic fluxes for tidal freshwater wetlands.

Over the sampling period, there was a net input of nitrogen (as TN) into the marsh system (Table 3). Using a simple interpolation of data for the months that were not sampled, given the distribution from March to October, a total of 4,900 kg of N was removed by the marsh system over the year, and on average this results in a daily flux of 13 kg/day. In comparison, loads of nitrogen from the Northwest and Northeast Branches of the Anacostia River were estimated by Warner et al. (1997). Loads of nitrogen were dominated by non-point sources and were higher in the Northwest Branch. Total nitrogen loads were estimated at approximately 114,000 kg/yr using various water quality and runoff models. This accounts for approximately 40% of the 290,000 kg/yr load to the upper tidal Anacostia River (Warner et al., 1997). More recent data indicates that loads of nitrogen to the tidal river is approximately 50% higher at 400,000 kg/yr (Mandel, personal communication). While there is a large uncertainty with these estimates, just the loads from the NE and NW Branches of the Anacostia are approximately 20 times higher than the calculated removal of nitrogen by the marsh. In other words, while the marsh is acting as a sink and transformer of nitrogen, due to its relatively small area, the marsh does not currently appear to be able to impact the nitrogen inputs to the tidal river. As upstream loads are reduced with time, the wetlands influence will become more pronounced.

Phosphorus: Fluxes of phosphorus into or out of the marsh were largely controlled by particulate phosphorus movements (Table 3). Total dissolved phosphorus fluxes, which were composed of SRP and DOP, ranged from -12.4 μmol P/m^2 hr^{-1} in March to 3.2 μmol P/m^2 hr^{-1} in June. The flux of SRP was generally out of the marsh system except in April and June when the fluxes were low (0.8 to 2.5 μmol P/m^2 hr^{-1}, respectively) and into the marsh system. The movement of

DOP was always directed into the marsh and ranged from 0.5 μmol P/m^2 hr^{-1} in March to 16.1 μmol P/m^2 hr^{-1} in July. Particulate phosphorus fluxes were low (-24 to 0.7 μmol P/m^2 hr^{-1}) and generally directed out of the marsh in the early part of the year, but increased to 113 μmol P/m^2 hr^{-1} by July and September (Table 3). Total phosphorus fluxes ranged from approximately -22 μmol P/m^2 hr^{-1} in March and June to 120 μmol P/m^2 hr^{-1} in August, with the net flux over the year directed into the marsh. While the marsh is a net sink for P from the river, it does serve as a source of inorganic phosphorus (SRP) during the summer/fall time period (Table 3).

As with the flux of the inorganic forms of nitrogen, the inorganic forms of phosphorus (i.e., SRP) were compared to other flux studies (Table 5). Average fluxes of SRP ranged from -2 to 73 μmol P/m^2 hr^{-1} using a variety of sampling methods from benthic chambers to batch core incubations. The fluxes in these studies were generally directed into the marsh area or sediments, while in this study fluxes were directed out of the marsh system (Tables 3 and 5). It is possible that the flux of particulate P into the marsh and sediment microbial remineralization could account for the small SRP fluxes out of the marsh. Grant and Patrick (1970) reported a summer import of SRP to a tidal freshwater marsh near Philadelphia, PA, while Simpson et al. (1978) observed a release of SRP in a tidal freshwater marsh in New Jersey. In a study of tidal freshwater marsh in Louisiana by Stern et al. (1991), the flux of SRP was low (0.001 g P/sec) and directed out of the marsh. Evidently, there are conflicting data pertaining to the movement of SRP which warrants further investigation of the controlling factors that influence SRP fluxes between tidal freshwater marshes and adjacent waterways.

Data for the input of total phosphorus were obtained from Warner et al. (1997) and compared to the net flux of TP into the marsh. Using the same interpolation method as used for TN for missing months, a net flux of approximately 1,140 kg of P was removed by the marsh system in 1995. In comparison, approximately 16,000 kg/yr of P is introduced into the tidal Anacostia from the Northwest and Northeast Branches (Warner et al. 1997) and this accounts for 34% of the total load to the upper tidal Anacostia River of 46,200 kg/yr. Recent data suggests that inputs to the tidal river are approximately 50% higher at 71,000 kg/yr (Mandel, personal communication). Using the Warner et al. (1997) estimates, the data suggests that approximately 7% of the input from the NW and NE Branches is removed from the tidal river by the Kenilworth Marsh. However, the Northwest and Northeast Branches do not account for the total load of P from the watershed. Compared to the total input to the tidal river < 3% of the total load may be removed in the marsh.

Carbon: The forms of carbon that were determined in this study included only DOC and POC. Dissolved inorganic carbon was not determined as part of this study so that a total carbon budget or flux cannot be determined. Fluxes were largely controlled by changes in POC into or out of the marsh system. Dissolved organic carbon flux ranged from -1,250 μmol C/m^2 hr^{-1} in September to 1,460 μmol C/m^2 hr^{-1} in the following month. Particulate organic carbon fluxes were low and variable in March and April (Table 3), but increased substantially from July to September. The flux ranged from 2,000 to 7,100 μmol C/m^2 hr^{-1} and was directed into the marsh. The net POC flux was directed from the river to the Kenilworth Marsh. The resultant TOC flux ranged from -3,750 μmol C/m^2 hr^{-1} in June to 8,570 μmol C/m^2 hr^{-1} in October with lower fluxes in the spring/early summer period. On a yearly basis, there was a net flux of 3,760 kg of DOC moving out of the marsh while approximately 29,000 kg of POC was moving into the marsh. The overall net yearly flux was approximately 26,000 kg of TOC into the Kenilworth Marsh. Unfortunately there are no data for the input of carbon from the Anacostia watershed to compare with these data.

Summary and Future Directions

Plant nutrients, such as nitrogen and phosphorus, are introduced into the tidal Anacostia River from many sources. Sources to the tidal river include point sources (e.g., municipal and industrial wastewater), non-point inputs (e.g., urban and agricultural runoff, atmospheric deposition), and upstream runoff (Warner et al., 1997). Once these nutrients are in the tidal freshwater river they can be removed from the water column by processes such as plant uptake of nitrogen and phosphorus (e.g., emergent plants and others), sediment-water exchange of nutrients, denitrification, downstream transport to the Potomac, and sedimentation. Background information into the mechanisms and biogeochemical processes that control the interactions of nitrogen and phosphorus between wetland sediments and the water column are beyond the scope of this study. However, Mitsch and Gosselink (1993) provide some information regarding the microbial and physical reactions affecting these elements in wetlands (see also Klump and Martens, 1983; Bowden, 1987; Bowden et al., 1991).

One of the major removal processes for nitrogen from the Kenilworth system is the microbial reduction of nitrate (i.e., denitrification). Sediment denitrification is a microbial process that occurs under anoxic conditions in which dissolved nitrate is reduced to nitrogen gas (Grant and Long, 1981; Seitzinger, 1988). The nitrate for this process is supplied from the overlying water column (i.e., tidal flux of nitrate) or decomposition reactions within the sediments. This process can be a major removal mechanism for nitrogen from aquatic systems. Controlling factors for denitrification include ample supply of labile organic matter, dissolved nitrate, temperature, and anoxic conditions (Seitzinger, 1988). The source of nitrate for denitrification can be from the water column (i.e., flux of nitrate into the sediments) or from nitrification of porewater ammonium (i.e., coupled nitrification-denitrification).

Phosphorus, mainly as soluble reactive phosphorus (i.e., ortho-phosphate), can be adsorbed onto sediment particles such as iron-manganese oxides (Berner, 1980; Seitzinger, 1987). Soluble reactive phosphorus that is introduced into the Kenilworth Marsh could adsorb to sediment particles and deposit in the marsh. For example, Huanxin et al. (1997) found substantial quantities of bound phosphorus in sediments of the lower tidal Anacostia River. The bound phosphorus could be released to the water and be more available at different times of the year due to productivity and changes in pH of the overlying water (Seitzinger, 1987).

Seasonal removal of both nitrogen and phosphorus from the water is via plant uptake and incorporation into organic biomass (Simpson et al., 1978; Velinsky et al., 1998). These plants include aquatic macrophytes such as *Nuphar luteum* and *N. advena* (spatterdock, yellow water lily), *Peltandra virginica* (arrow arum); *Polygonum punctatum* (smartweed)*, and Typha* sp. (cattail) with many of these plants found in the Kenilworth Marsh (Syphax and Hammerschlag 1995). In addition, epiphytic algae, benthic microalgae and cyanobacteria have been shown to be a significant factor in nutrient dynamics (Kreeger, 2000). In the Kenilworth Marsh, the removal of nitrogen and phosphorus can be due to both plant biomass as well as microbial processes. In a detailed study of the tidal freshwater marshes in the Delaware estuary, Velinsky et al. (1998) showed that plant uptake can incorporate a substantial amount of nitrogen and phosphorus into organic biomass, however this was a small amount compared to the input of these nutrients to the Delaware river from upstream sources.

The processes outlined above reveal that nutrient cycling within the Kenilworth Marsh can be dynamic with a strong seasonal component. At the time of this study, the marsh complex was only a few years old and the aging process (i.e., build up of organic matter, changing plant community, etc) just starting. This study revealed that substantial amounts of nitrogen and phosphorus were sequestered in the marsh over the course of the study. There was some indication that the input of nutrients was smaller and out of the marsh during the late fall/winter time period and a more detailed study would be needed to confirm this seasonal component. The amount of nutrients taken up by the marsh however is small compared to the inputs from the surrounding watershed. It appears that a substantial amount of wetland area would need to be restored before a significant fraction of the "new" nutrients be removed, both permanently through burial and seasonal through plant uptake or denitrification. It appears that the one year post-restored Kenilworth Marsh acted in a similar fashion as other tidal freshwater wetland systems.

It would be of interest to repeat this study at Kenilworth Marsh to assess the potential changes with the aging process in the marsh (Zelder and Callaway, 1999). The increases of sediment organic matter and plant community changes for example, would alter the type and magnitude of specific processes and may help to effect nutrient levels within the marsh waters and adjacent tidal Anacostia. In addition, other studies that should be integrated include: 1) improved measures of tidal freshwater emergent aquatic vegetation biomass and production; 2) direct measures of nutrient cycling (i.e., core studies and denitrification); 3) investigate the role of microphytobenthos on nutrient cycling; and 4) investigate the role of secondary producers on nutrient cycles.

Lastly, integrated assessments of all of the tidal Anacostia marshes needs to be accomplished. To quantify the net import/export of nutrients (and dissolved oxygen) fluxes in/out of experimental marshes an integrated approach is needed. The most comprehensive way to examine the role of these tidal wetlands in removing nutrients is to summarily measure the flux of nutrient entering and leaving the wetland with each tide and modeling the net exchange. To be robust, this measure would need to be completed *in situ* at replicate sites having similar hydrology, but being characteristic for tidal marshes in general. Furthermore, it will be critical to repeat measurements seasonally since rates of primary and secondary production in the marshes vary greatly through the year. The approach should also be repeated over multiple lunar cycles to determine whether the net flux depends on tidal height. With this study, specific short-term process measurements within the wetland during this study such as plant uptake rates and oxygen production/consumption, nitrification/denitrification rates, and benthic algal productivity would be needed to assess the results from the tidal inlet study. Previous studies, while yielding important information, were done over a short period of time. Long-term measurements over a number of years and seasons can be made to assess nutrient, oxygen and contaminant fluxes, emergent plant productivity, benthic edaphic and epiphytic algal production and impacts, and overall material balances. Information from these studies can then be applied to the entire TFW area to determine how these systems filter and modify the flux of material down the tidal Anacostia River.

Acknowledgments

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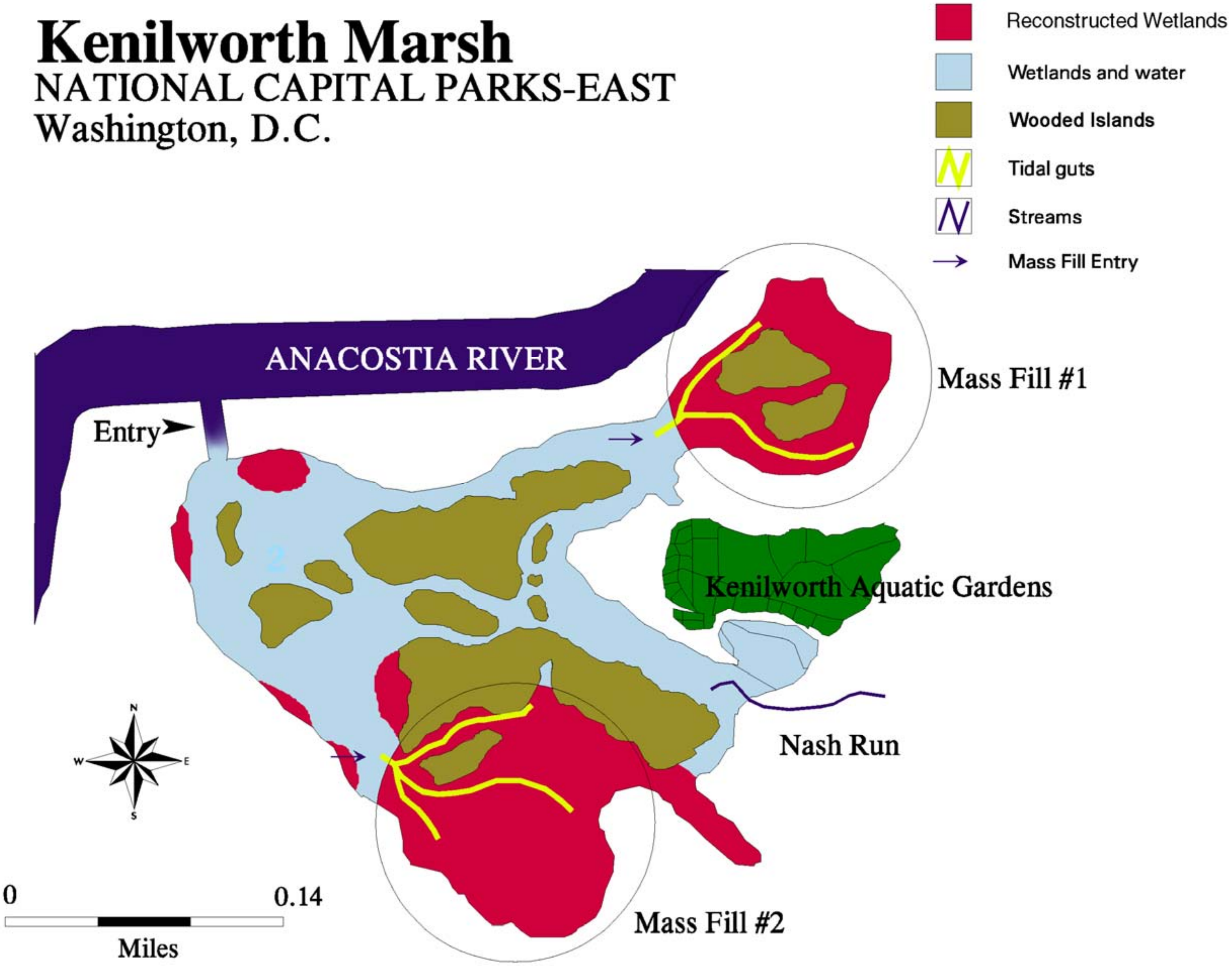
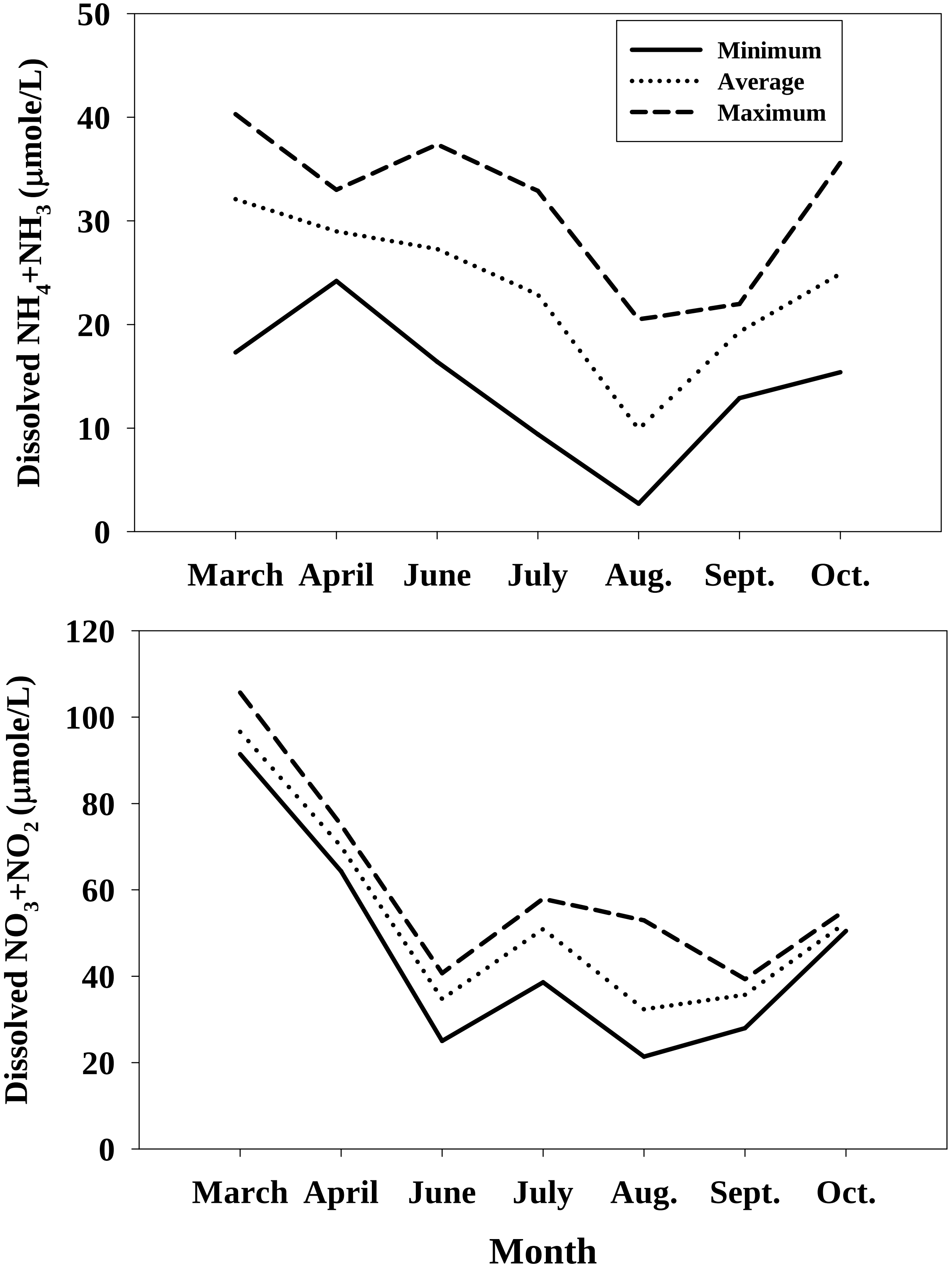
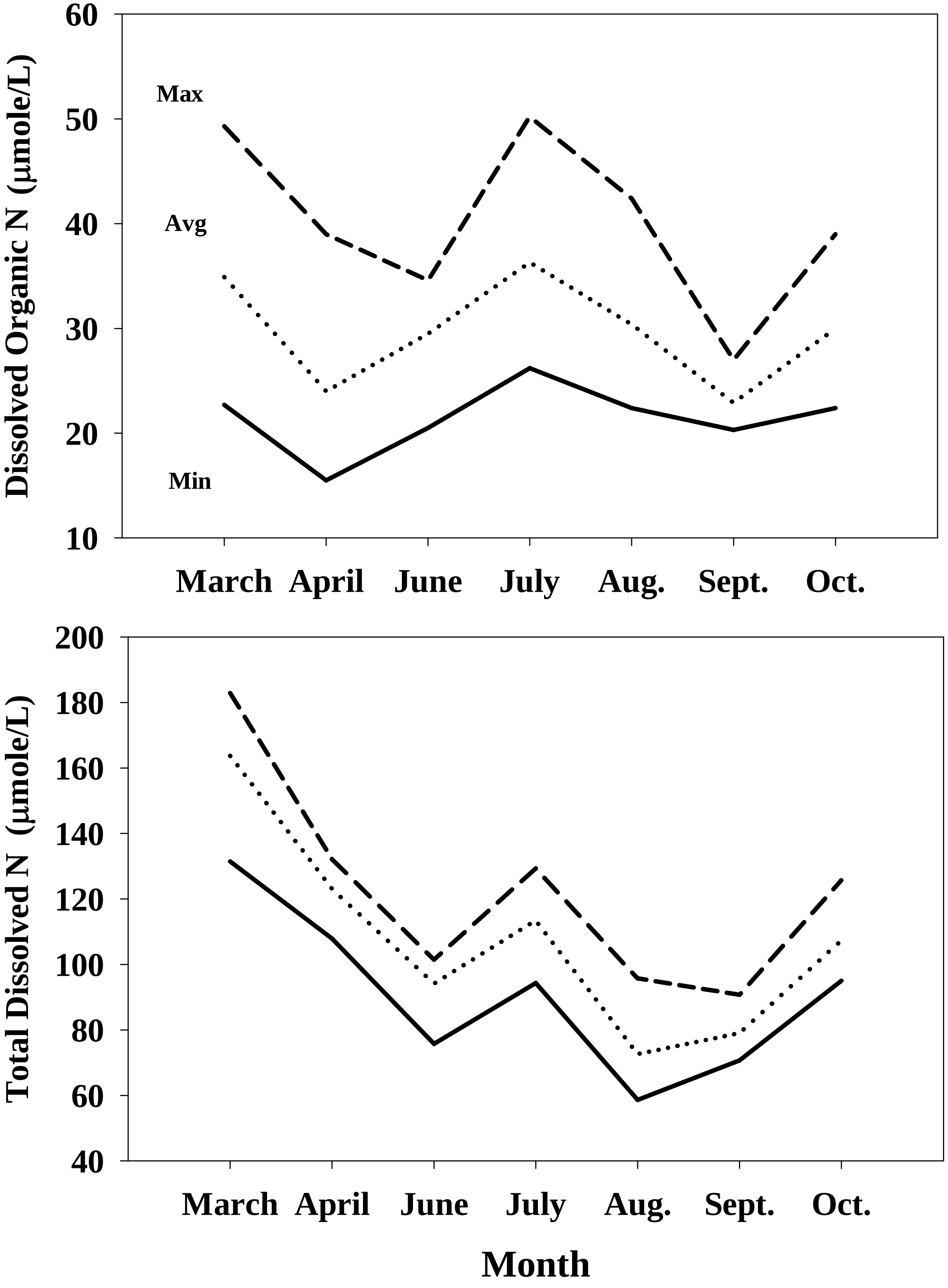
Figure 24. Fluxes of total dissolved nitrogen from the March and October time periods to illustrate the movement of nitrogen at the inlet. The areas under the curve were determined and summed over the total time period.

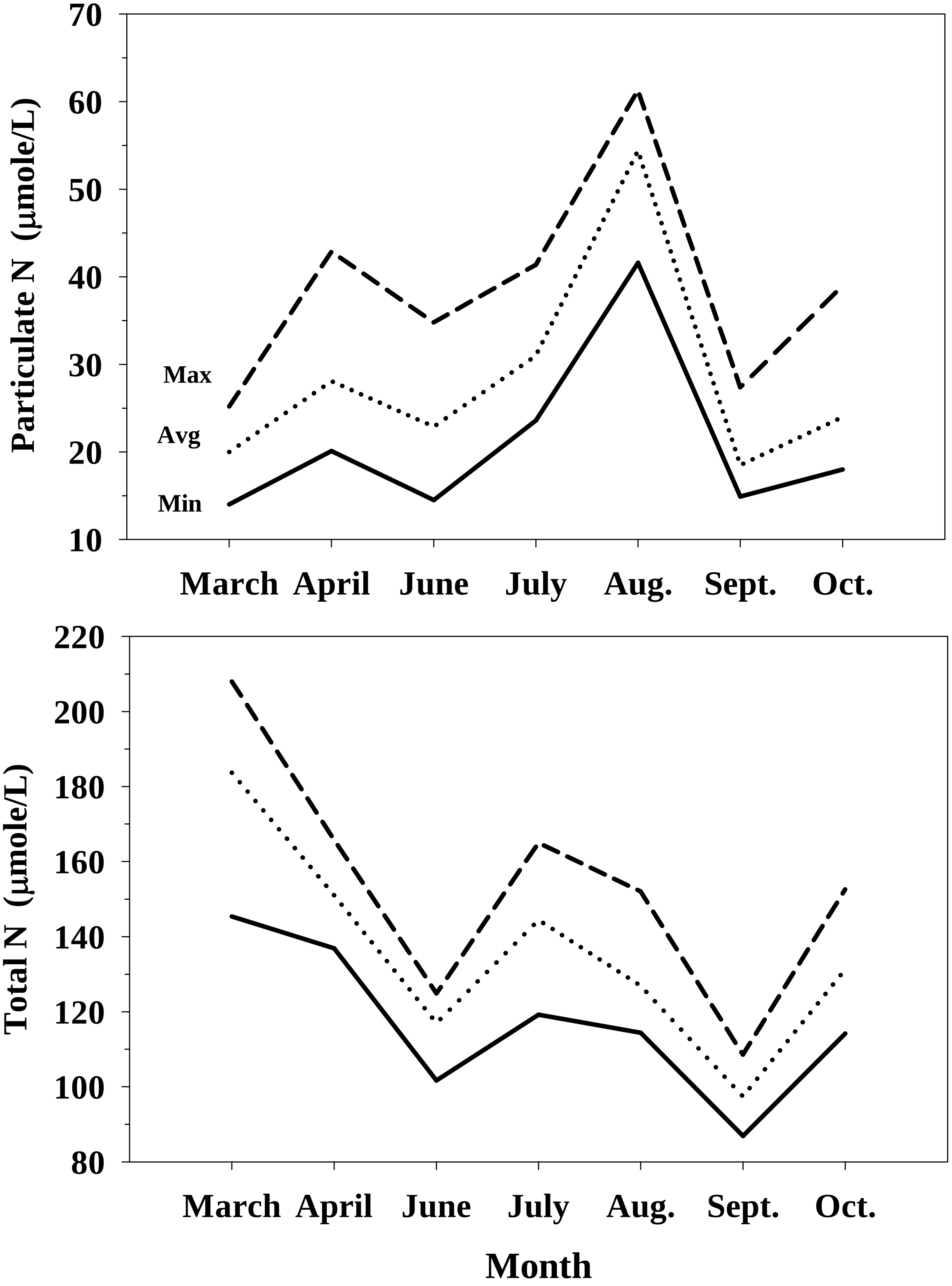
Kenilworth Marsh
NATIONAL CAPITAL PARKS-EAST
Washington, D.C.

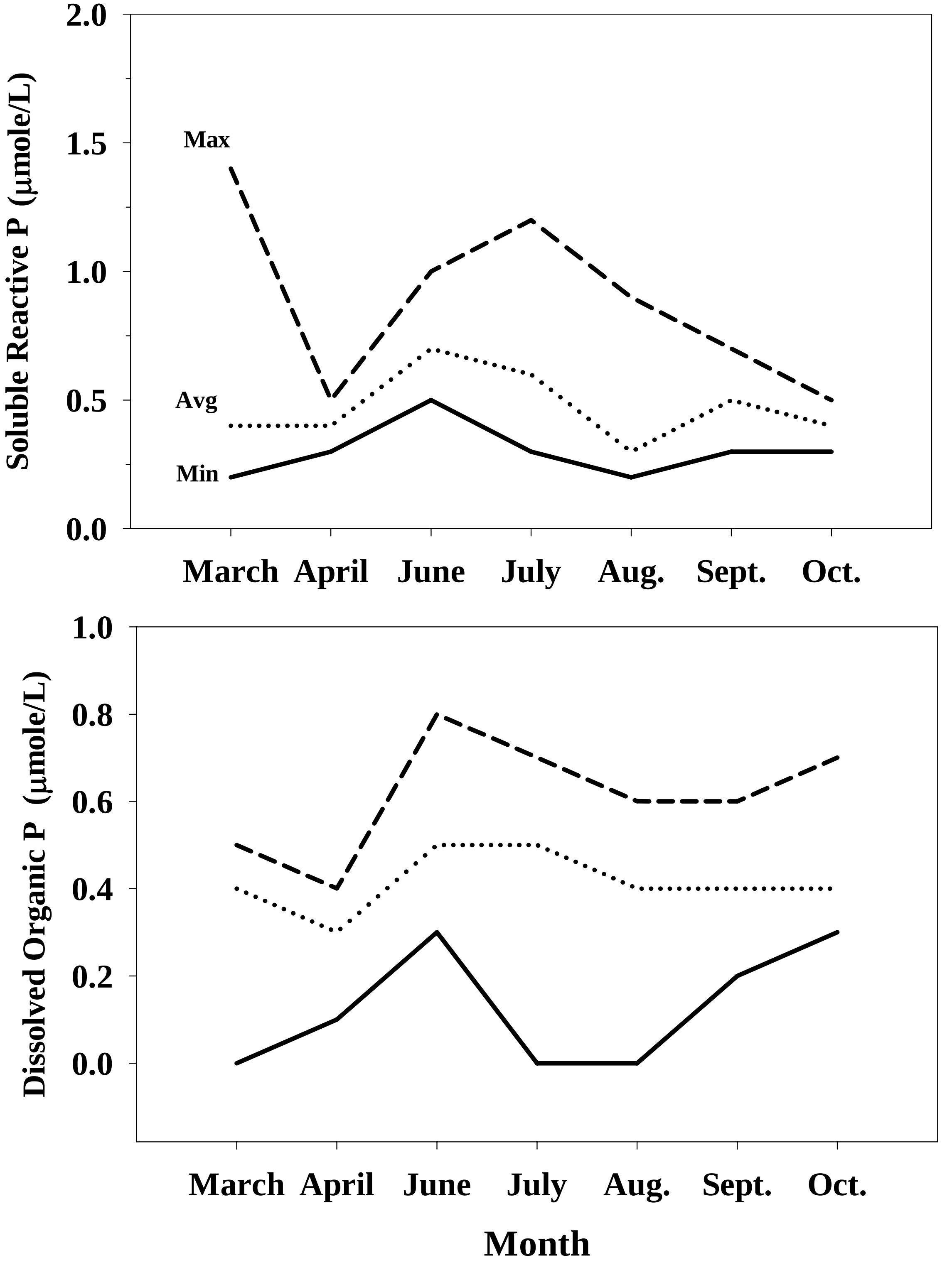


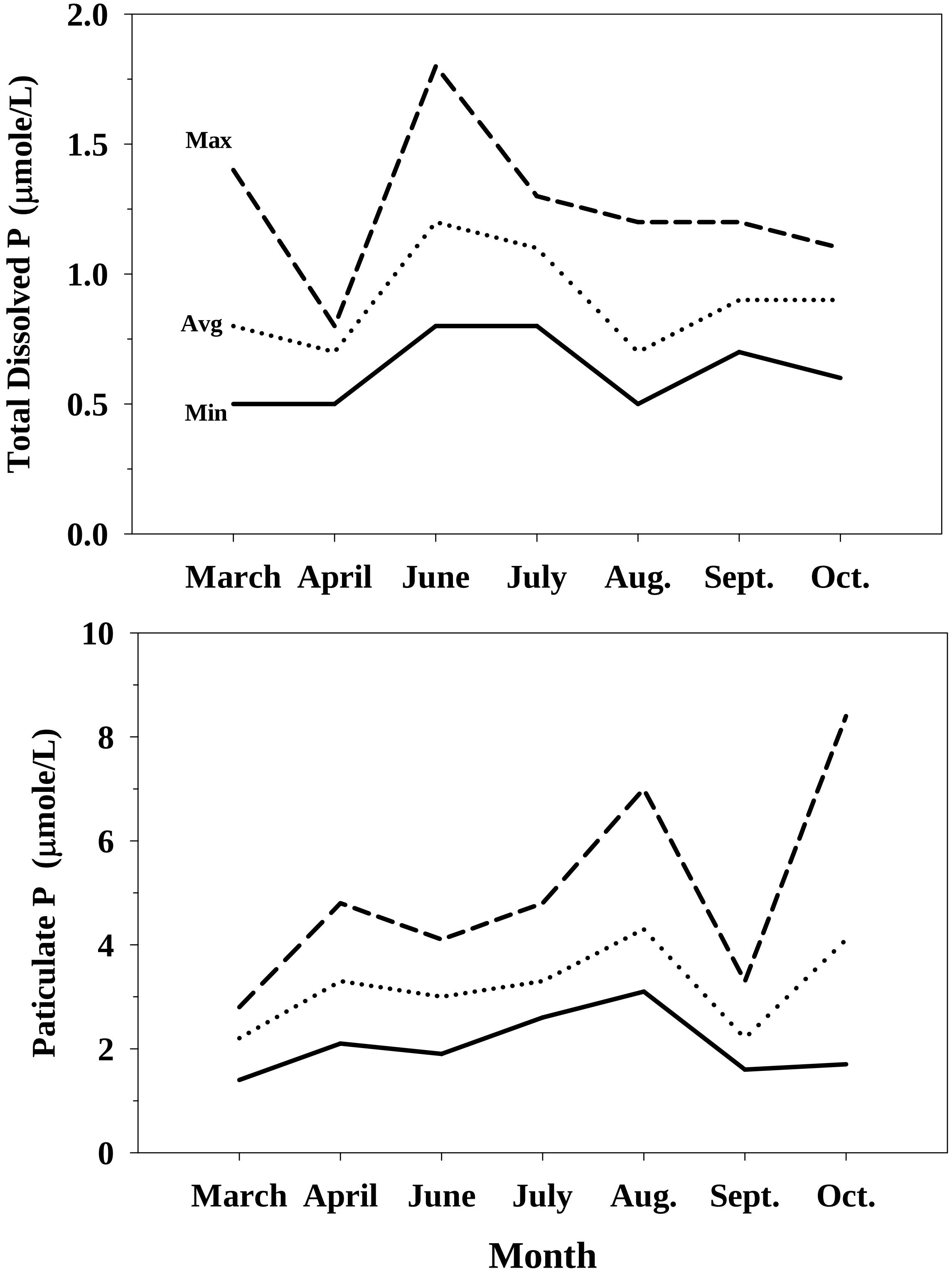


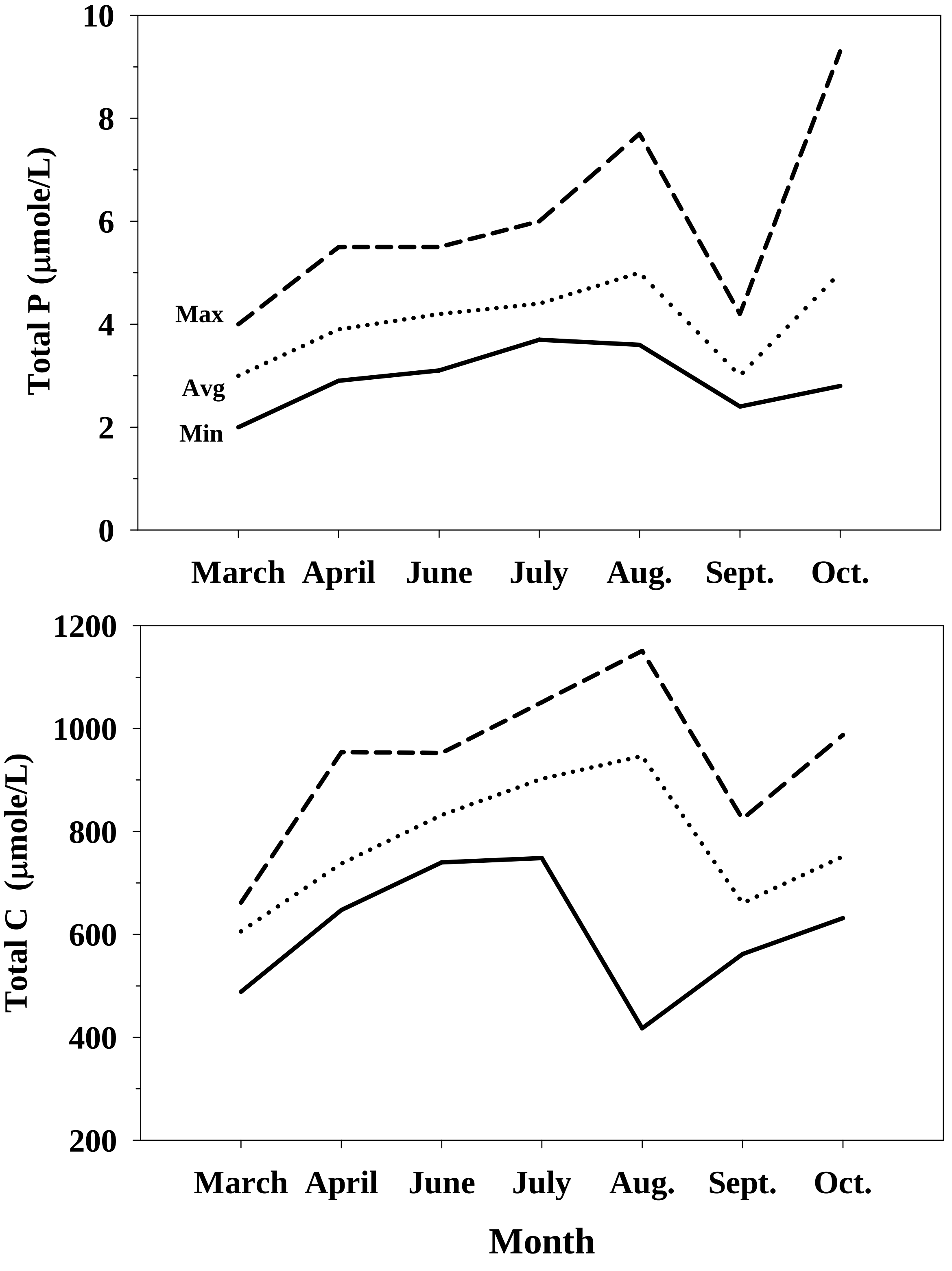
Minimum
Average
Maximum
Dissolved NH_4+NH_3 (μmole/L)
0
10
20
30
40
50
March
April
June
July
Aug.
Sept.
Oct.
Dissolved NO_3+NO_2 (μmole/L)
0
20
40
60
80
100
120
March
April
June
July
Aug.
Sept.
Oct.
Month


Dissolved Organic N (μmole/L)
60
50
40
30
20
10
Max
Avg
Min
March
April
June
July
Aug.
Sept.
Oct.
Total Dissolved N (μmole/L)
200
180
160
140
120
100
80
60
40
March
April
June
July
Aug.
Sept.
Oct.
Month

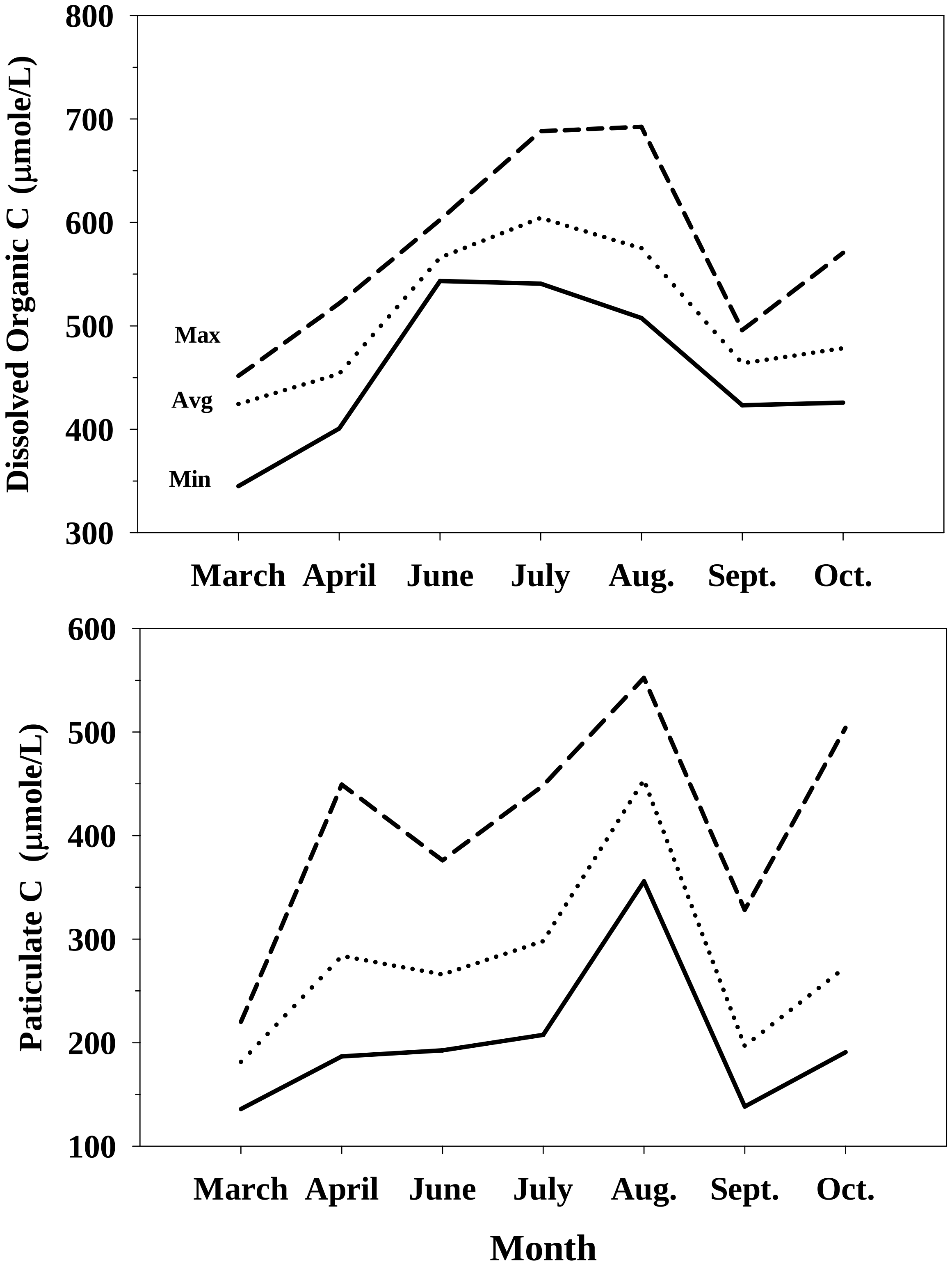

70
60
50
40
30
20
10
Particulate N (µmole/L)
Max
Avg
Min
March
April
June
July
Aug.
Sept.
Oct.
220
200
180
160
140
120
100
80
Total N (µmole/L)
March
April
June
July
Aug.
Sept.
Oct.
Month

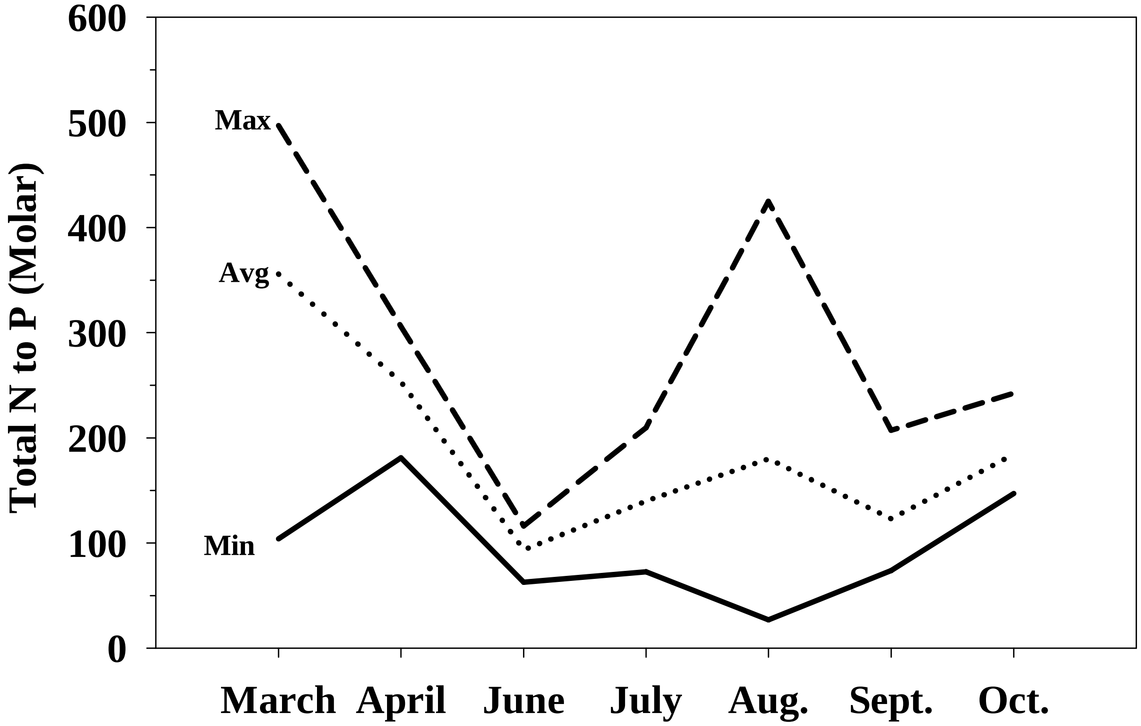

2.0
1.5
1.0
0.5
0.0
Soluble Reactive P (µmole/L)
Max
Avg
Min
March
April
June
July
Aug.
Sept.
Oct.
1.0
0.8
0.6
0.4
0.2
0.0
Dissolved Organic P (µmole/L)
March
April
June
July
Aug.
Sept.
Oct.
Month

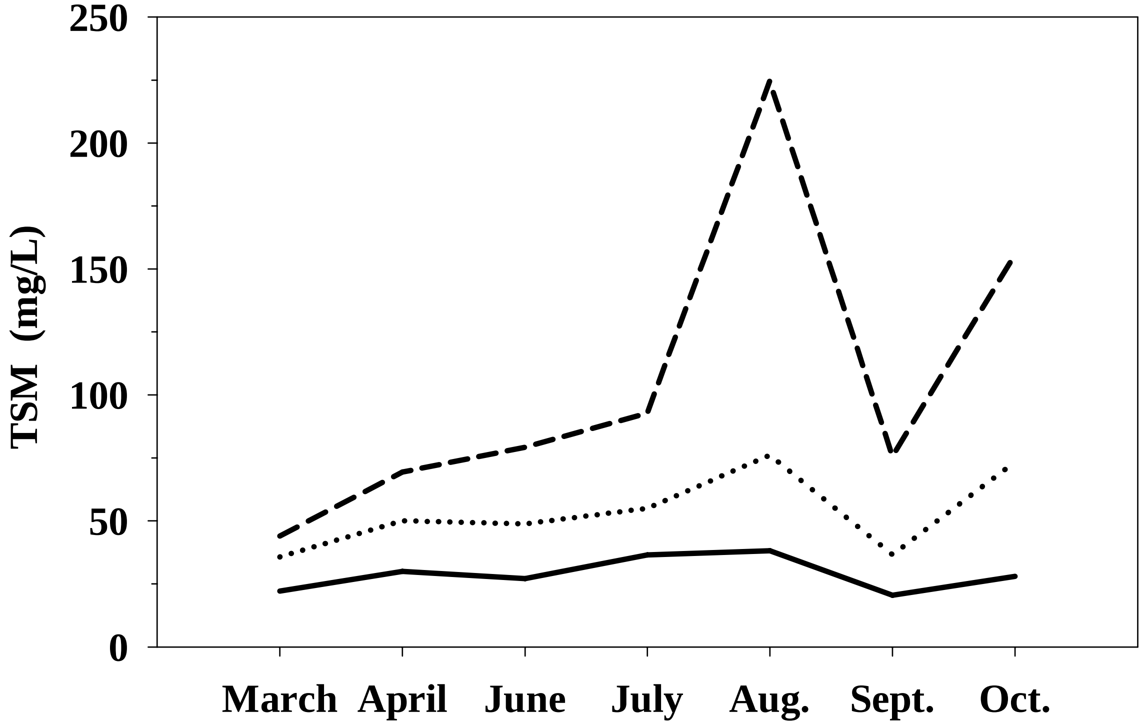

Total Dissolved P (µmole/L)
2.0
1.5
1.0
0.5
0.0
Max
Avg
Min
March
April
June
July
Aug.
Sept.
Oct.
Paticulate P (µmole/L)
10
8
6
4
2
0
March
April
June
July
Aug.
Sept.
Oct.
Month



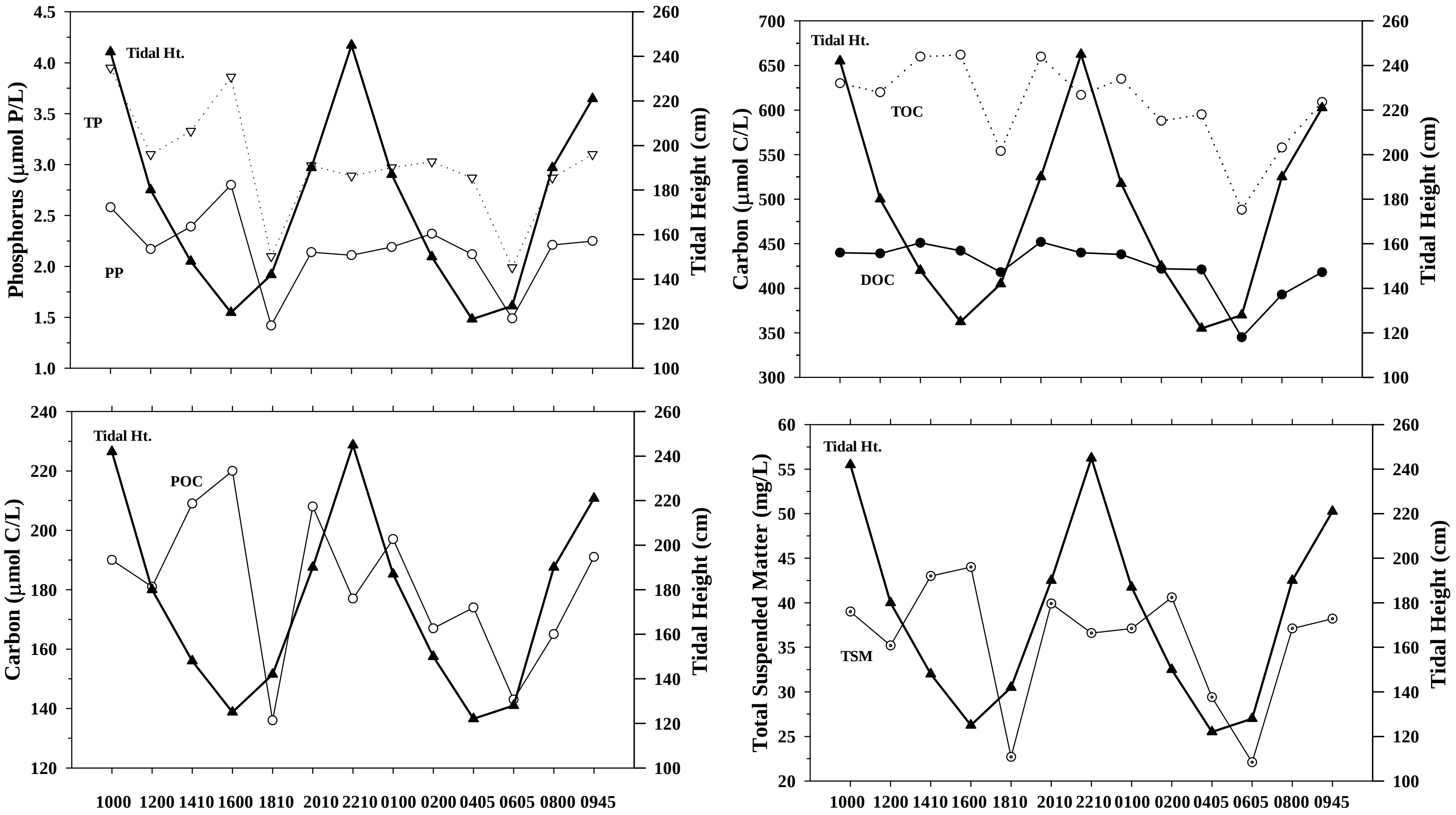
10
8
6
4
2
0
Total P (µmole/L)
Max
Avg
Min
March
April
June
July
Aug.
Sept.
Oct.
1200
1000
800
600
400
200
Total C (µmole/L)
March
April
June
July
Aug.
Sept.
Oct.
Month


800
700
600
500
400
300
Dissolved Organic C (µmole/L)
Max
Avg
Min
March
April
June
July
Aug.
Sept.
Oct.
600
500
400
300
200
100
Paticulate C (µmole/L)
March
April
June
July
Aug.
Sept.
Oct.
Month


Total N to P (Molar)
600
500
400
300
200
100
0
Max
Avg
Min
March
April
June
July
Aug.
Sept.
Oct.


TSM (mg/L)
250
200
150
100
50
0
March
April
June
July
Aug.
Sept.
Oct.

Kenilworth Marsh: March 1995



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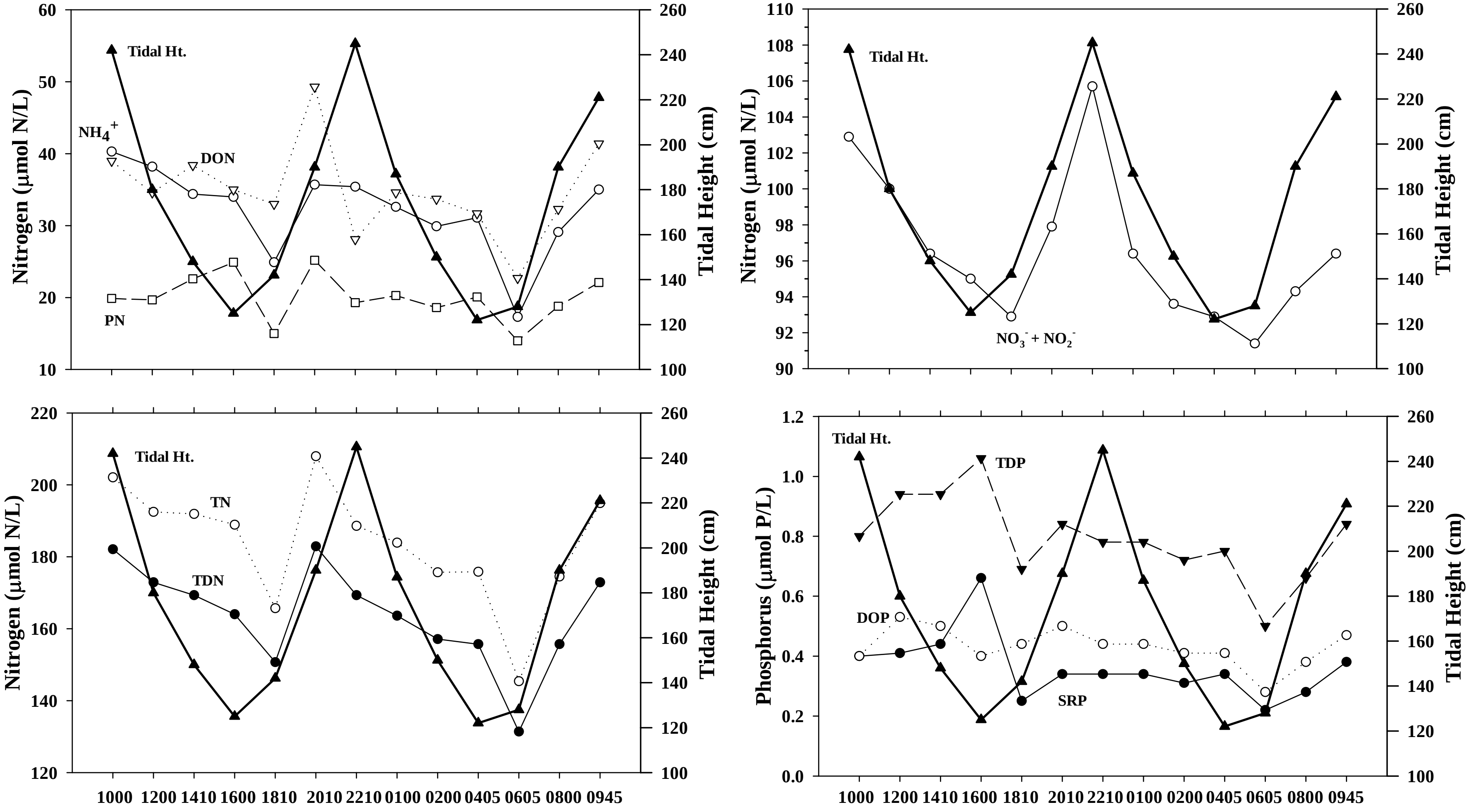

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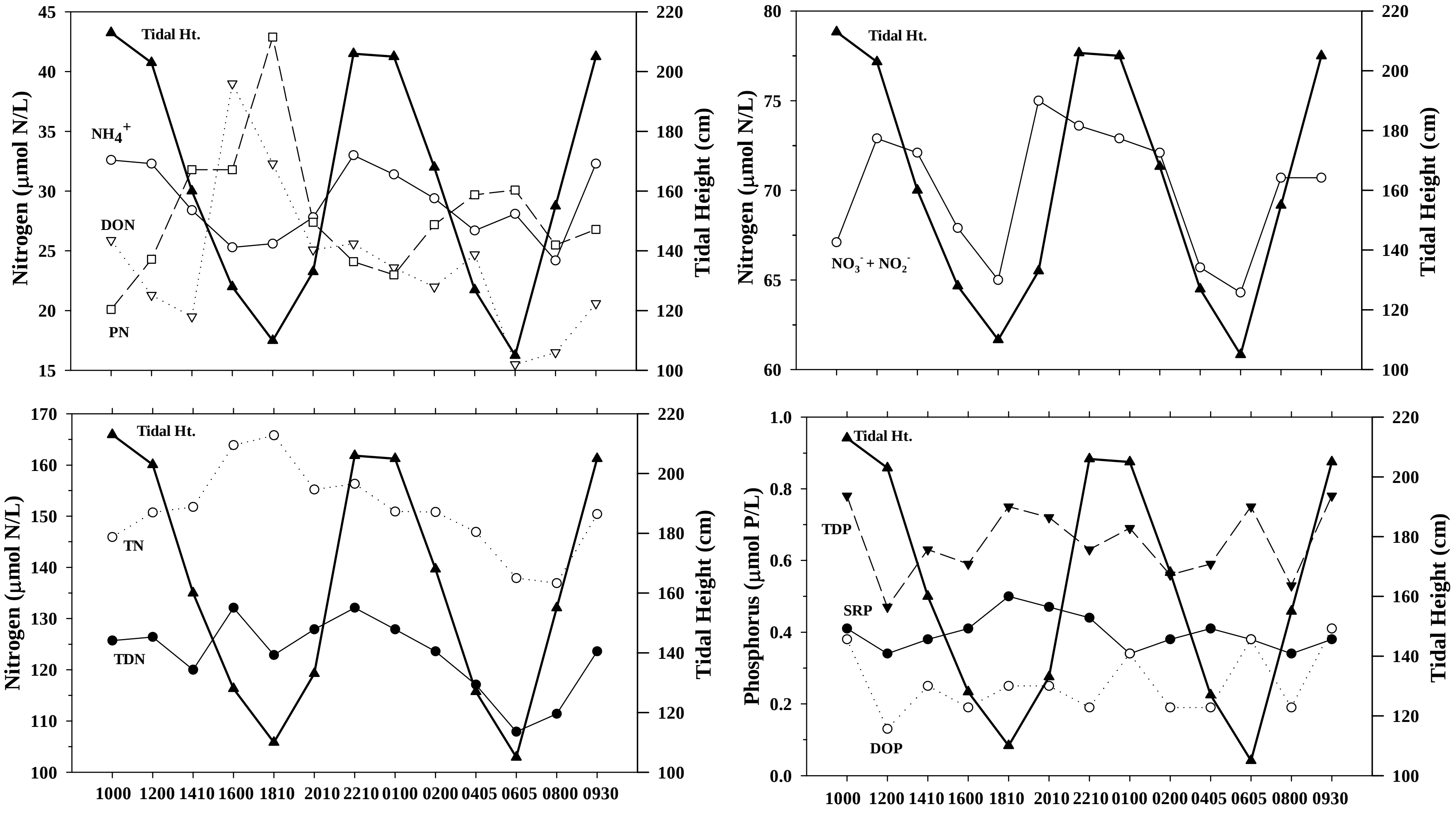

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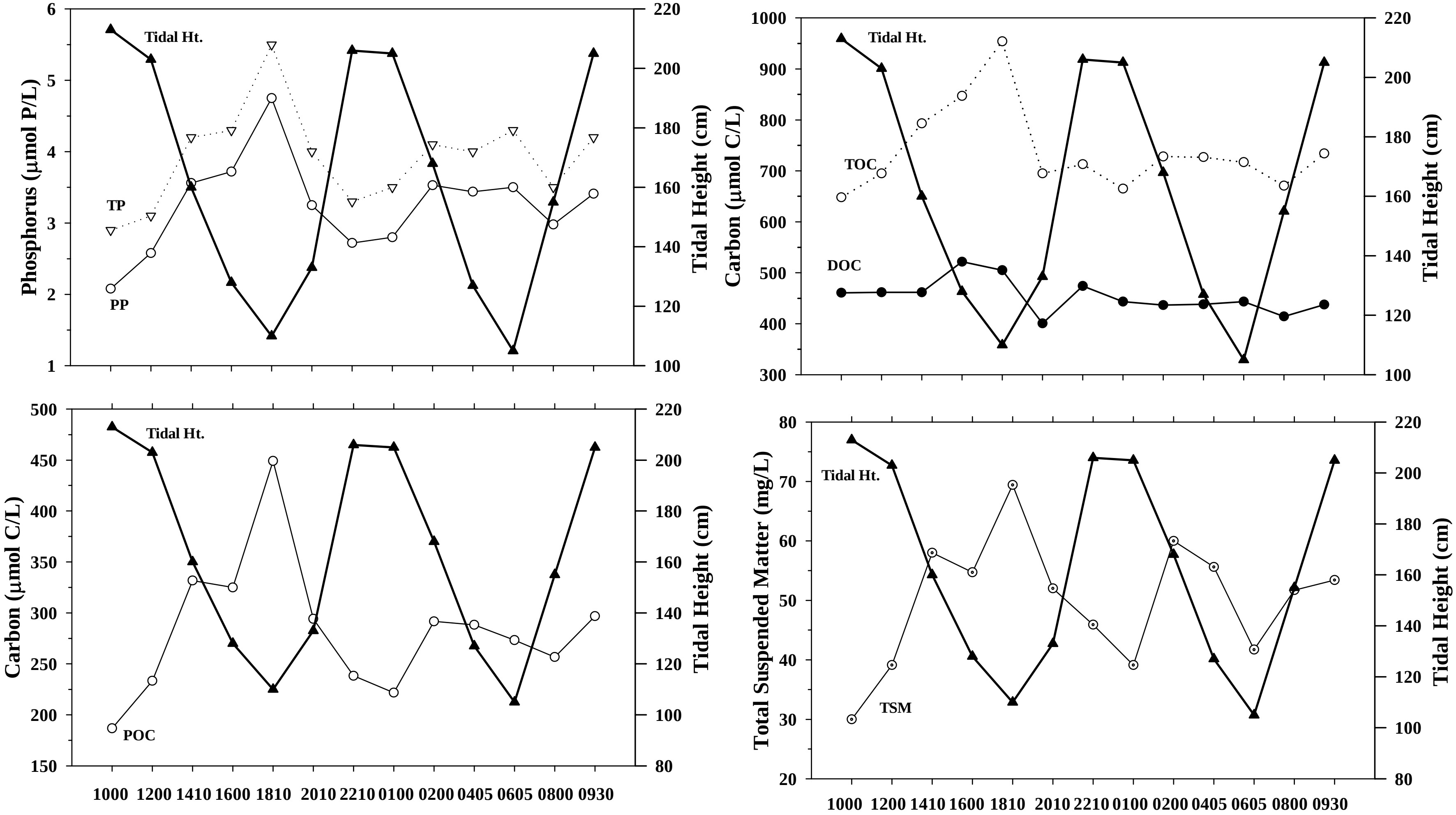

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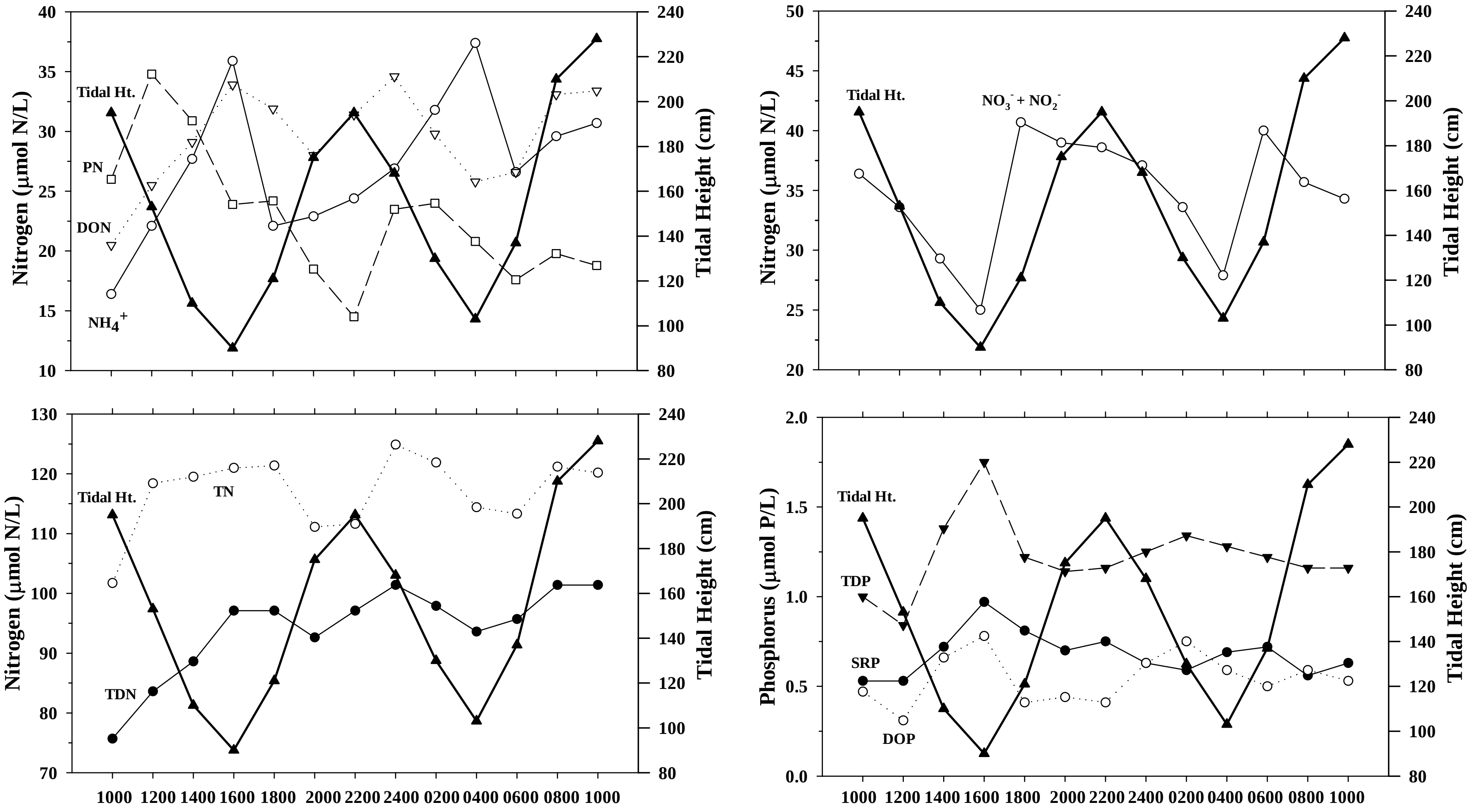

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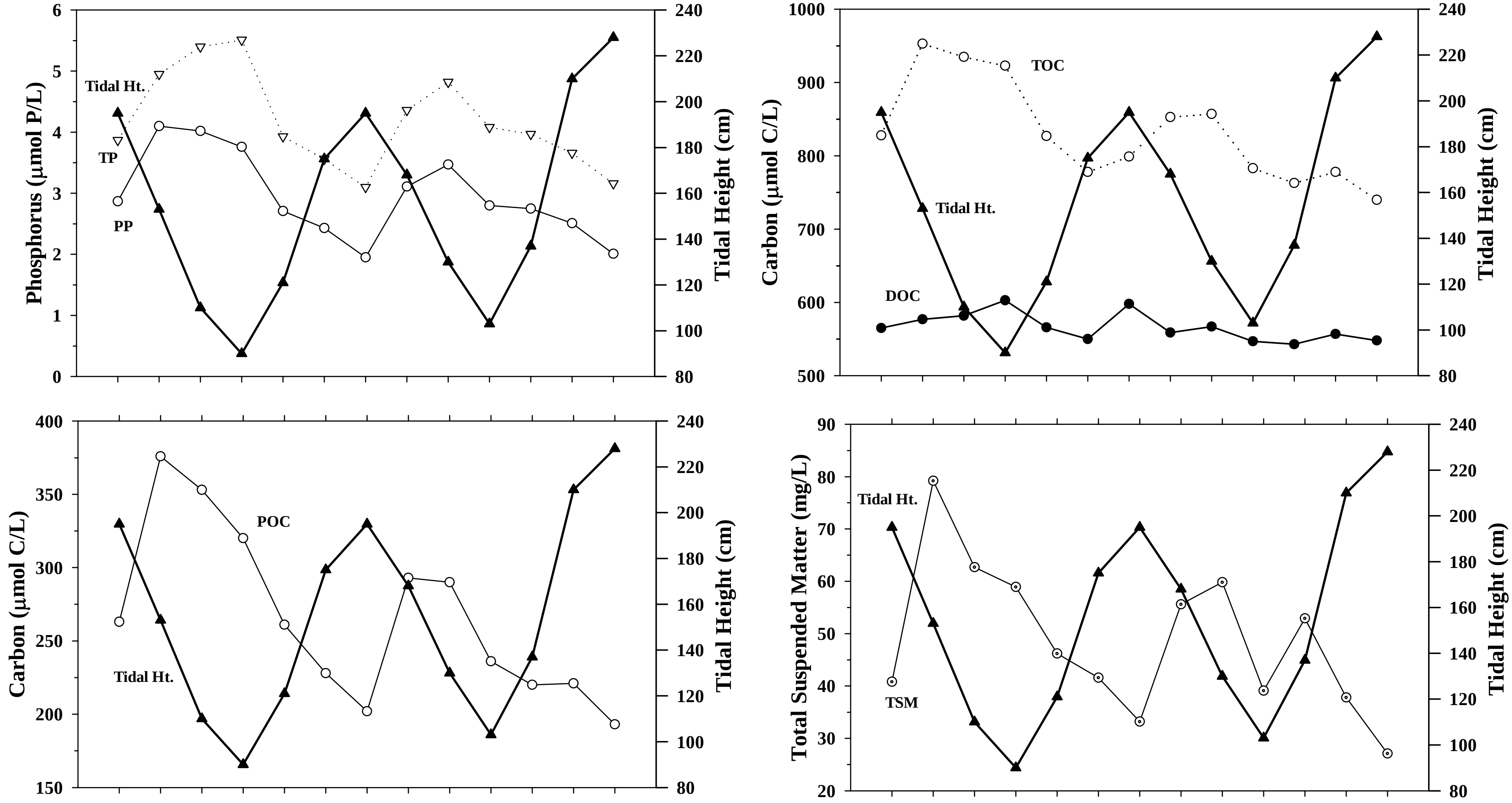

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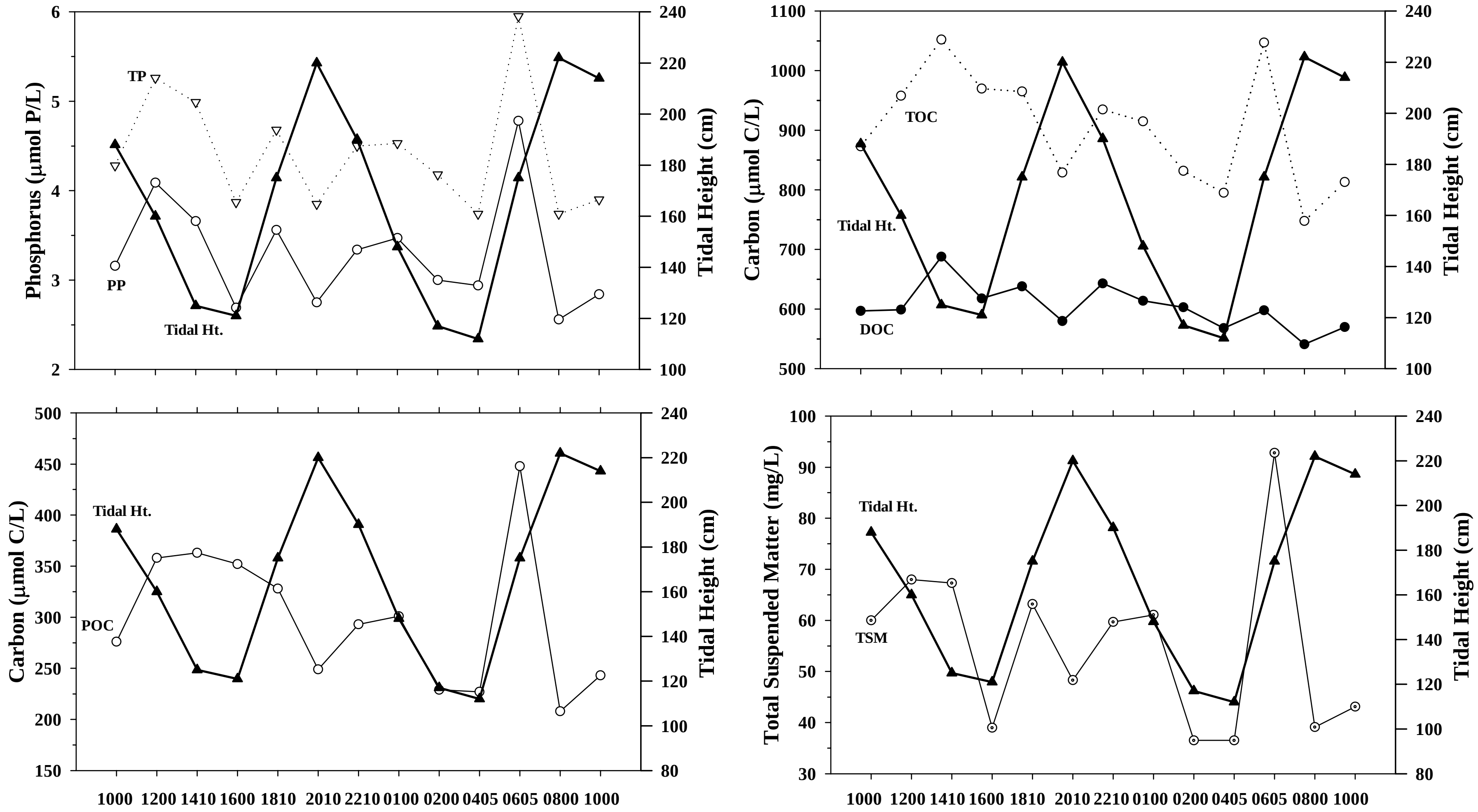

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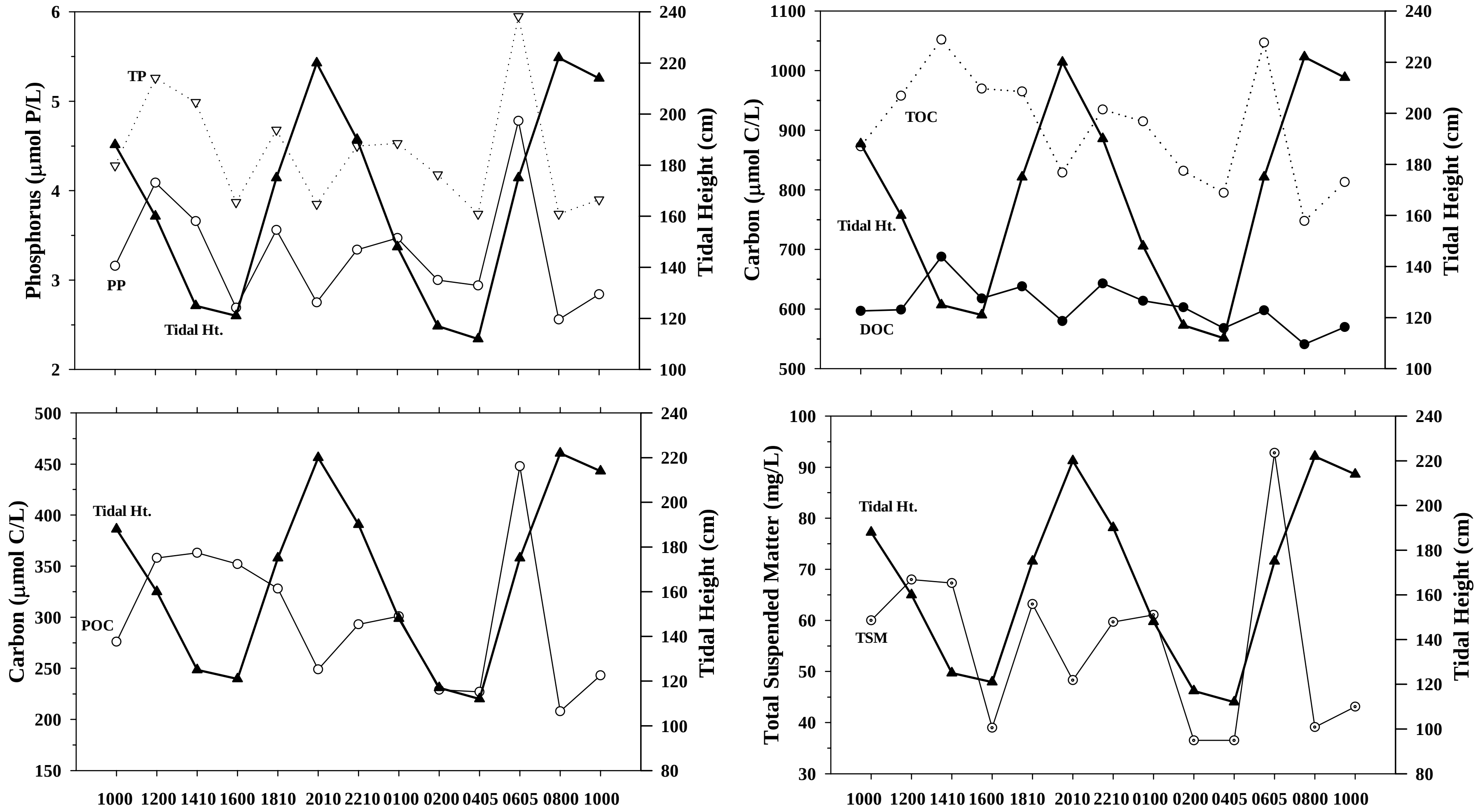

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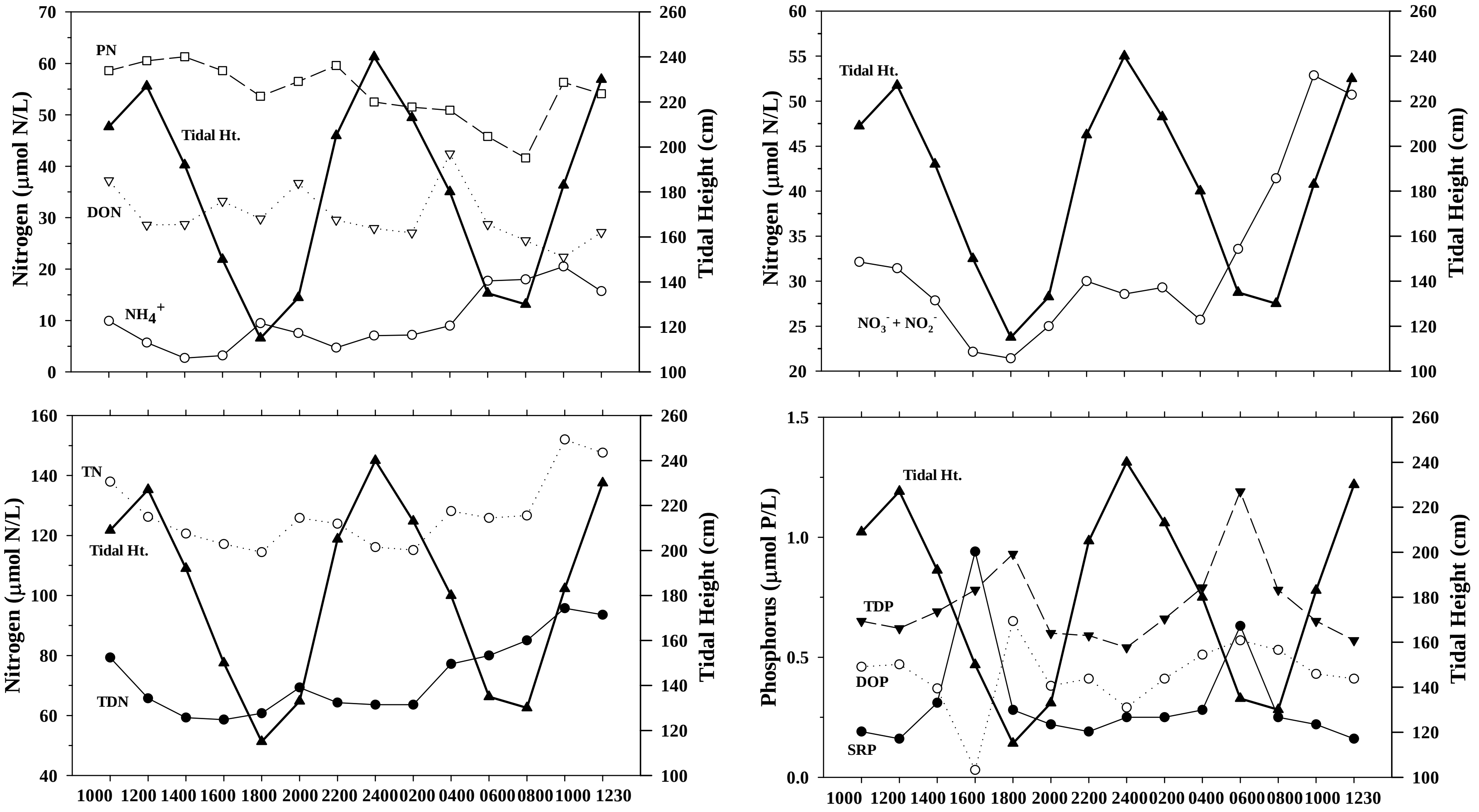

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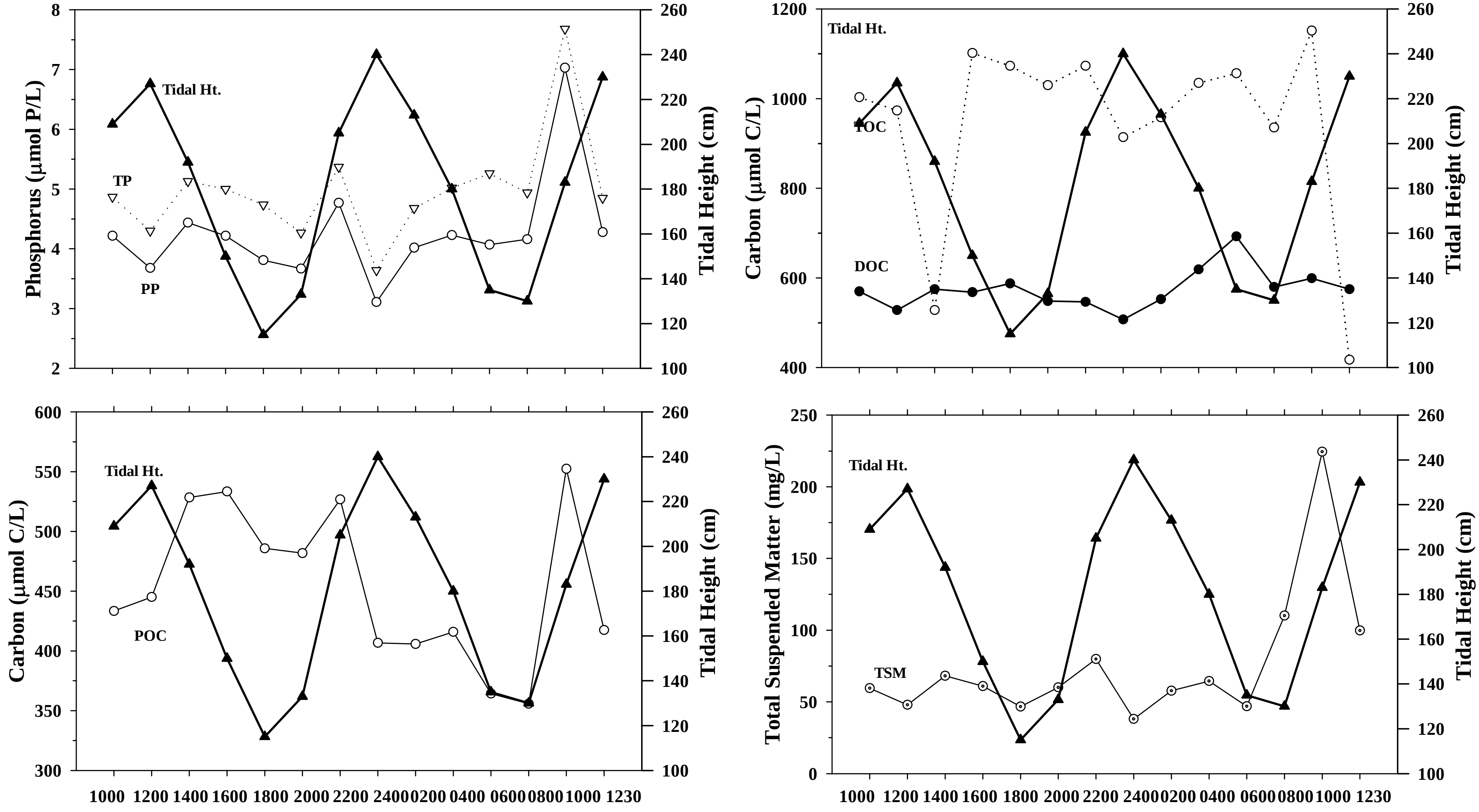

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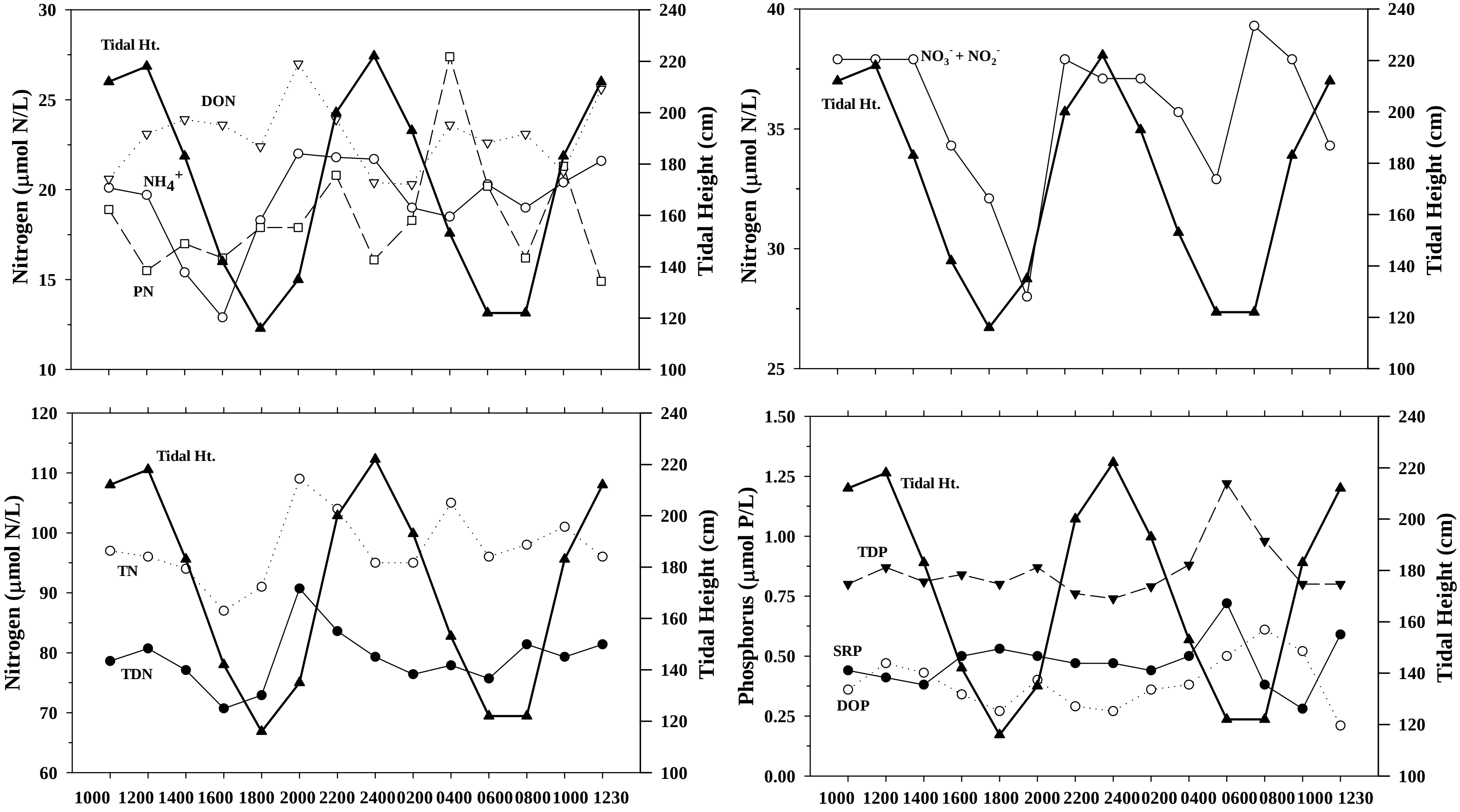

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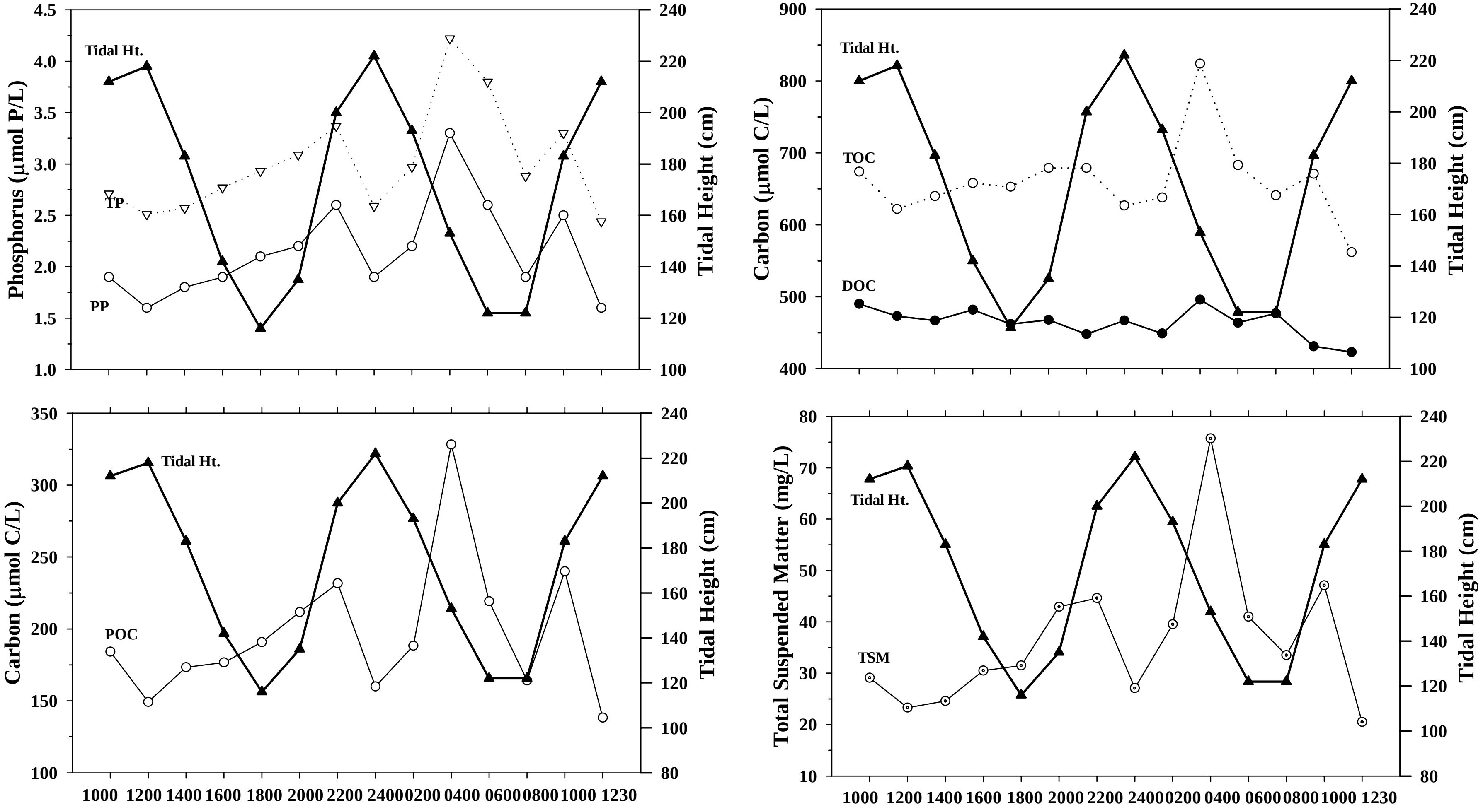

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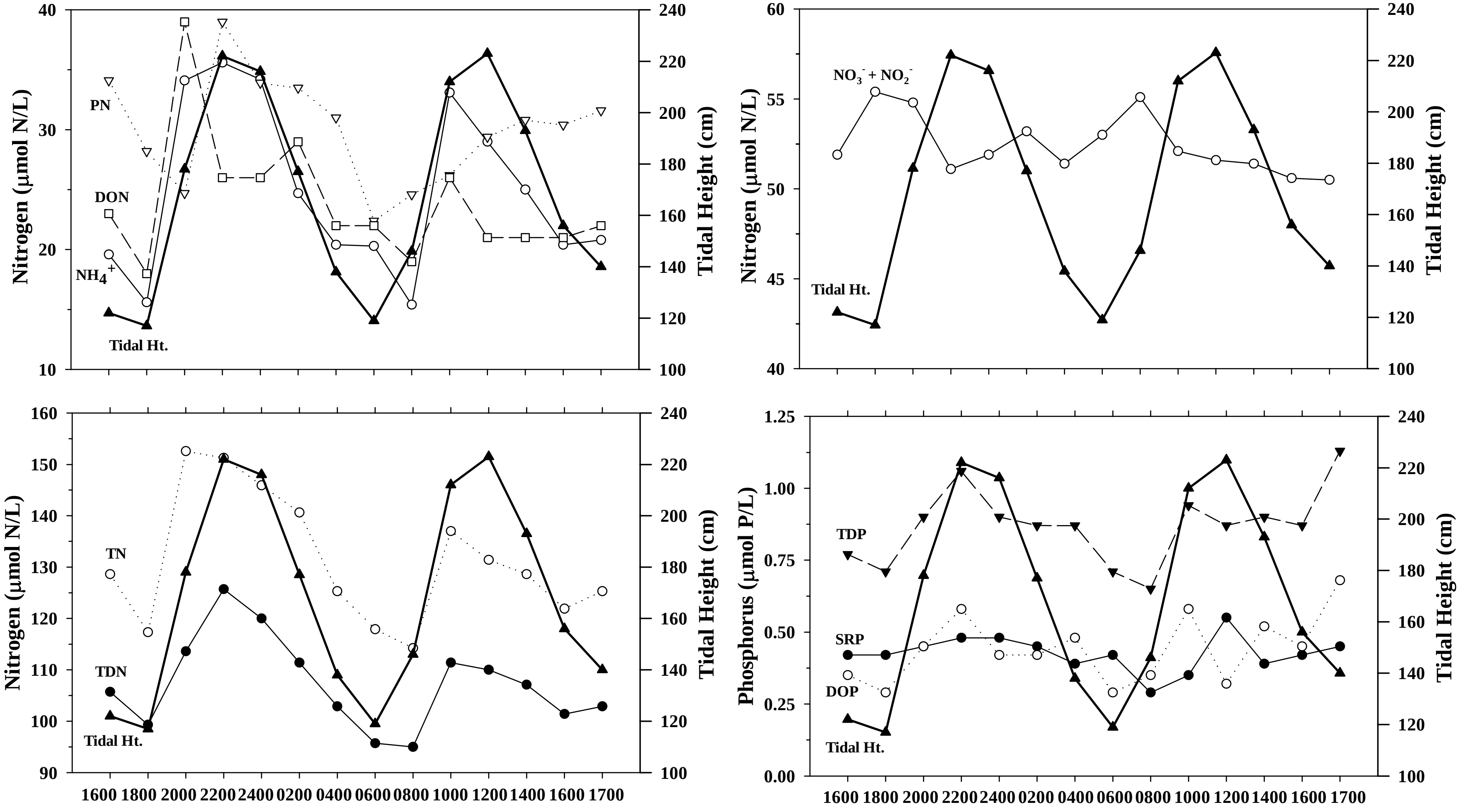

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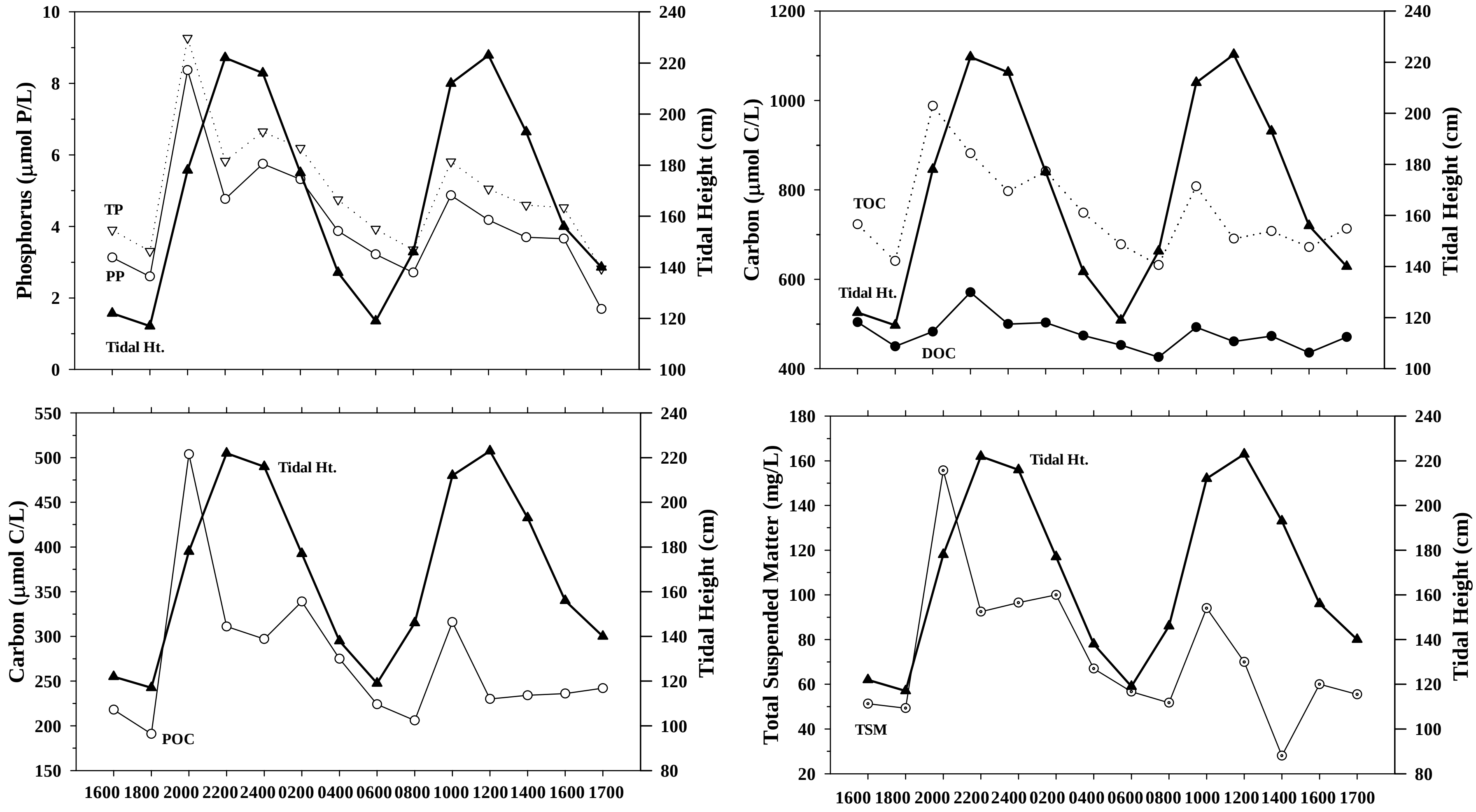

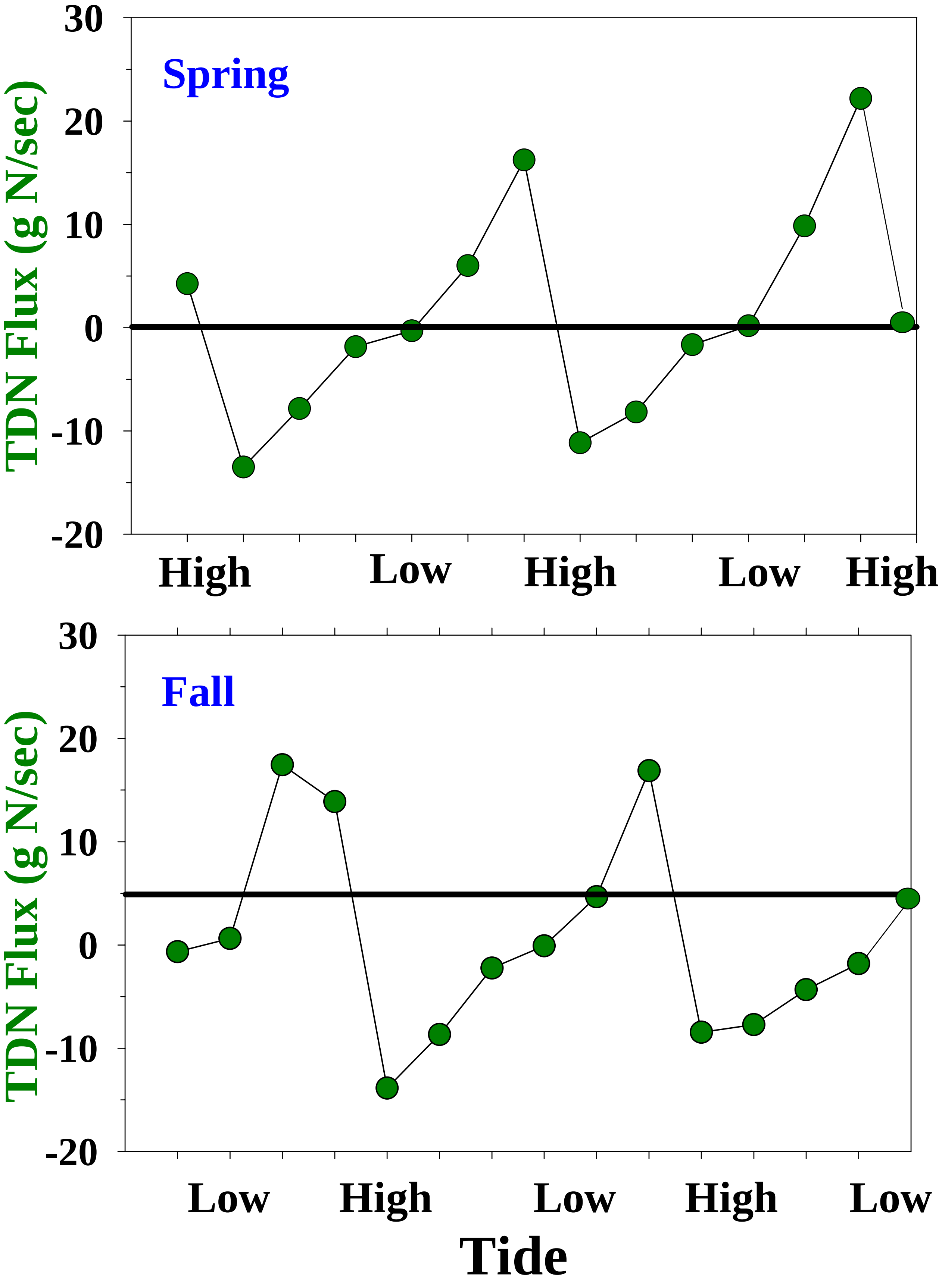

Spring
Fall
TDN Flux (g N/sec)
TDN Flux (g N/sec)
30
20
10
0
-10
-20
High
Low
High
Low
High
Low
High
Low
High
Low
Tide

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Table 1. Summary of seasonal nutrient and suspended solid concentrations at the Kenilworth Marsh in 1995.

	NH_4 µM N	NO_2+NO_3 µM N	NO_2 µM N	DON µM N	TDN µM N	SRP µM P	DOP µM P	TDP µM P	DOC µM C	TSM mg/L	PP µM P	PC µM C	PN µM N	TN[1] µM N	TP[1] µM P	TOC[1] µM C
March																
Min	17.3	91.4	1.0	0.0	131.4	0.2	0.0	0.5	345.0	22.1	1.4	135.8	14.0	145.4	2.0	488.3
Max	40.3	105.7	1.5	49.3	182.9	0.7	0.5	1.4	451.7	44.0	2.8	220.0	25.2	208.0	4.0	661.7
Avg	32.1	96.6	1.3	32.2	163.7	0.4	0.4	0.8	424.5	35.7	2.2	181.3	20.0	183.7	3.0	605.8
April																
Min	24.2	64.3	1.7	15.5	107.9	0.3	0.1	0.5	400.8	30.0	2.1	186.7	20.1	136.9	2.9	647.5
Max	33.0	75.0	2.4	39.0	132.1	0.5	0.4	0.8	521.7	69.4	4.8	449.2	42.9	165.8	5.5	954.2
Avg	29.0	70.0	2.1	24.0	123.0	0.4	0.3	0.7	453.8	50.0	3.3	283.6	28.1	151.0	3.9	737.4
June																
Min	16.4	25.0	2.4	20.5	75.7	0.5	0.3	0.8	543.3	27.1	1.9	192.5	14.5	101.7	3.1	740.0
Max	37.4	40.7	3.0	34.6	101.4	1.0	0.8	1.8	602.5	79.2	4.1	375.8	34.8	124.9	5.5	952.5
Avg	27.3	34.7	2.6	29.5	94.1	0.7	0.5	1.2	566.1	48.8	3.0	265.7	22.9	117.0	4.2	831.8
July																
Min	9.4	38.6	2.6	26.2	94.3	0.3	0.0	0.8	540.8	36.5	2.6	207.5	23.6	119.2	3.7	748.3
Max	32.9	57.9	3.7	50.2	129.3	1.2	0.7	1.3	688.3	92.8	4.8	448.3	41.4	165.0	6.0	1051.7
Avg	22.9	50.9	3.3	36.3	113.4	0.6	0.5	1.1	604.4	55.0	3.3	297.9	31.0	144.4	4.4	902.3
August																
Min	2.7	21.4	1.5	22.4	58.6	0.2	0.0	0.5	507.5	38.1	3.1	355.8	41.6	114.4	3.6	417.5
Max	20.5	52.9	3.2	42.4	95.7	0.9	0.6	1.2	692.5	224.5	7.0	552.5	61.3	152.0	7.7	1151.7
Avg	9.9	32.3	2.3	30.4	72.6	0.3	0.4	0.7	575.0	76.1	4.3	453.8	54.4	126.9	5.0	946.6
September																
Min	12.9	28.0	0.1	20.3	70.7	0.3	0.2	0.7	423.3	20.5	1.6	138.3	14.9	86.9	2.4	561.7
Max	22.0	39.3	2.0	27.0	90.7	0.7	0.6	1.2	495.8	75.7	3.3	328.3	27.4	108.6	4.2	824.2
Avg	19.3	35.7	1.6	22.9	79.0	0.5	0.4	0.9	463.9	36.5	2.2	196.8	18.5	97.4	3.0	660.8
October																
Min	15.4	50.5	1.1	22.4	95.0	0.3	0.3	0.6	425.8	28.0	1.7	190.8	18.0	114.2	2.8	631.7
Max	35.6	55.4	2.1	39.0	125.7	0.5	0.7	1.1	570.8	155.7	8.4	504.2	39.0	152.6	9.3	987.5
Avg	24.9	52.4	1.7	30.0	107.3	0.4	0.4	0.9	478.4	73.4	4.1	273.0	24.0	131.3	5.0	751.4

[1] TN, TP, and TOC are the sum of their respective forms.

Table 2. Summary percentages of various nutrient forms at Kenilworth Marsh in 1995.

	NH_4	NO_2+NO_3	NO_2	DON	TDN	SRP	DOP	TDP	DOC	PP	POC	PN
	(F_{TDN})	(F_{TDN})	(F_{TDN})	(F_{TDN})	(F_{TN})	(F_{TDP})	(F_{TDP})	(F_{TP})	(F_{Toc})	(F_{TP})	(F_{Toc})	(F_{TN})
March												
Min	0.13	0.54	0.01	0.17	0.87	0.36	0.00	0.23	0.67	0.65	0.25	0.09
Max	0.22	0.70	0.01	0.27	0.91	1.00	0.64	0.35	0.75	0.77	0.33	0.13
Avg	0.19	0.59	0.01	0.21	0.89	0.49	0.48	0.28	0.70	0.72	0.30	0.11
April												
Min	0.19	0.51	0.01	0.14	0.74	0.48	0.27	0.14	0.53	0.73	0.29	0.14
Max	0.26	0.63	0.02	0.30	0.86	0.73	0.52	0.27	0.71	0.86	0.47	0.26
Avg	0.24	0.57	0.02	0.19	0.81	0.62	0.38	0.17	0.62	0.83	0.38	0.19
June												
Min	0.22	0.26	0.02	0.27	0.71	0.44	0.33	0.17	0.61	0.63	0.25	0.13
Max	0.40	0.48	0.03	0.35	0.87	0.67	0.56	0.37	0.75	0.83	0.39	0.29
Avg	0.29	0.37	0.03	0.31	0.80	0.56	0.44	0.30	0.68	0.70	0.32	0.20
July												
Min	0.09	0.35	0.02	0.28	0.73	0.37	0.00	0.20	0.57	0.69	0.28	0.16
Max	0.27	0.58	0.03	0.43	0.84	1.00	0.63	0.31	0.72	0.80	0.43	0.27
Avg	0.20	0.45	0.03	0.32	0.79	0.51	0.49	0.26	0.67	0.74	0.33	0.21
August												
Min	0.05	0.33	0.02	0.23	0.49	0.25	0.04	0.08	0.51	0.77	0.34	0.33
Max	0.22	0.55	0.05	0.57	0.67	1.20	0.75	0.23	1.38	0.92	1.00	0.51
Avg	0.13	0.44	0.03	0.43	0.57	0.42	0.60	0.15	0.66	0.85	0.52	0.43
September												
Min	0.18	0.31	0.00	0.26	0.74	0.35	0.26	0.21	0.60	0.65	0.24	0.15
Max	0.27	0.49	0.02	0.33	0.85	0.74	0.65	0.35	0.76	0.79	0.40	0.26
Avg	0.24	0.45	0.02	0.29	0.81	0.55	0.45	0.29	0.71	0.71	0.29	0.19
October												
Min	0.16	0.41	0.01	0.22	0.74	0.38	0.37	0.10	0.49	0.60	0.30	0.15
Max	0.30	0.58	0.02	0.32	0.85	0.63	0.62	0.40	0.70	0.90	0.51	0.26
Avg	0.23	0.49	0.02	0.28	0.82	0.50	0.50	0.19	0.64	0.81	0.36	0.18

F_x is the fraction of that constituent from the total constituent x.

Table 3. Fluxes of nitrogen, phosphorus, and carbon between the tidal Anacostia River and Kenilworth Marsh.

Month	NH_4	NO_{23}	DON	TDN	PN	TN	SRP	DOP	TDP	PP	TP	DOC	PC	TOC
March[2]	-216	-84	194	-144	39	-107	-16.4	0.5	-12.4	-12.5	-25.9	-936	-485	-1,421
April[2]	14	9	-39	-17	-56	-70	2.5	4.4	6.8	0.7	7.4	-895	178	-720
May[2]	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
June[2]	194	84	150	439	-261	180	0.8	2.2	3.2	-23.6	-20.3	-951	-2,791	-3,753
July[2]	-150	139	321	299	156	458	-16.0	16.1	1.5	23.7	25.4	-1,102	2,595	1501
August[2]	441	791	-217	1,014	66	1,080	-9.6	1.9	-6.5	113	119	303	5,242	5,542
September[2]	200	-3	-2	263	124	385	-4.1	0.8	-2.6	21.9	19.4	-1,250	2,040	782
October[2]	370	96	-246	221	408	629	-3.2	5.8	2.6	101	104	1,460	7,093	8,571
Yearly[3]	1,480	137	139	3,248	1,644	4,898	-249	141	-66.3	1,157	1,113	-3,756	29,810	26,090
Avg Daily[3]	4.1	0.4	0.4	8.9	4.5	13.4	-0.7	0.4	-0.2	3.2	3.1	-10.3	81.7	71.5

[1] (+) fluxes are into the marsh, while (-) fluxes are out of the marsh to the river. [1] Fluxes are in µmol (N, P or C)/m^2-hr. [3] Yearly and Average daily fluxes are in kg/yr and kg/day, respectively using a marsh area of 32 acres (1.3×10^5 m^2)

Table 4. Summary information for inorganic nitrogen fluxes from tidal freshwater marshes.

Marsh Area	Location	Year	Ammonium Average	Nitrate+nitrite Average	Method	Reference
Phillips Creek Marsh	James River	1992	38.4	ND	Chamber method	Chambers, 1992
Rhodes River	Chesapeake Bay	1982	-2.7	-1.9	Hydrologic export model	Jordan et al. 1983
Gott's Marsh	Chesapeake Bay	1975	-1.4	-3.4	Core studies	Heinle and Flemner, 1976
Freshwater tidal marsh	Potomac River	1987	-76.8	1.4	Core Batch	Seitzinger, 1987
North River Marsh	Massachusectts	1985	-94.8	-124.6	Flume	Bowden, 1986
Tivoli Bay: North, LM	Hudson River	1997	69.1	34.4	Core Batch	Zelenke, 1997 (unpublished)
Tivoli Bay: North, LM	Hudson River	1997	1.3	ND	Core Batch	Zelenke, 1997 (unpublished)
Tivoli Bay: South, LM	Hudson River	1997	-4.8	ND	Core Batch	Zelenke, 1997 (unpublished)
Jug Bay Wetlands: HM	Patuxent River	1992	-54.2	34.1	Core Batch	Zeigler et al (1995)
Jug Bay Wetlands: LM	Patuxent River	1992	35.9	-17.3	Core Batch	Zeigler et al (1995)
Jug Bay Wetlands: Mudflat	Patuxent River	1992	44.0	-63.5	Core Batch	Zeigler et al (1995)
Jug Bay Wetlands: HM	Patuxent River	1995	51.0	-14.5	Core incubation: Batch	Groszkowski, 1995
Jug Bay Wetlands: LM	Patuxent River	1995	83.4	-12.5	Core incubation: Batch	Groszkowski, 1995
Jug Bay Wetlands: Mudflat	Patuxent River	1995	99.2	ND	Core incubation: Batch	Groszkowski, 1995
Jug Bay Wetlands: HM	Patuxent River	1995	201.4	-104.3	Core Continuous	Groszkowski, 1995
Jug Bay Wetlands: LM	Patuxent River	1995	126.0	-79.9	Core Continuous	Groszkowski, 1995
Jug Bay Wetlands: Mudflat	Patuxent River	1995	166.2	-87.2	Core Continuous	Groszkowski, 1995
Kenilworth Marsh	Anacostia River	1995	122.0	147.2	Seasonal: whole marsh	This Study

Notes: LM = low marsh, HM = high marsh, (+) into marsh, (-) out of marsh; units: μmol N/m^2-hr.

Table 5. Ranges for SRP fluxes from tidal freshwater marshes in Chesapeake Bay.

Marsh Area	Location	Year	SRP Low	SRP High	SRP Average	Method	Reference
Phillips Creek Marsh	James River	1992	-1.7	9.0	1.7	Chamber	Chambers, 1992
Jug Bay Wetlands: HM	Patuxent River	1995	-2.9	67.8	27.4	Core Batch	Groszkowski, 1995
Jug Bay Wetlands: LM	Patuxent River	1995	-2.7	0.0	-0.5	Core Batch	Groszkowski, 1995
Jug Bay Wetlands: Mudflat	Patuxent River	1995	0.0	2.4	1.2	Core Batch	Groszkowski, 1995
Jug Bay Wetlands: HM	Patuxent River	1995	-2.1	321.0	73.3	Core Continuous	Groszkowski, 1995
Jug Bay Wetlands: LM	Patuxent River	1995	-9.3	12.1	-2.0	Core Continuous	Groszkowski, 1995
Jug Bay Wetlands: Mudflat	Patuxent River	1995	-7.1	9.0	0.4	Core Continuous	Groszkowski, 1995
Kenilworth Marsh: Whole Marsh	Anacostia River	1995	-16.4	2.5	-6.6	Seasonal: whole	This Study

Notes: LM = low marsh, HM = high marsh, (+) into marsh, (-) out of marsh; units: µmol P/m^2-hr.

Appendix I: Concentrations of nitrogen, phosphorus, carbon and related parameters during each time period.

Conversion factors:

To convert from molar units to mass units the following conversion factors are needed:

1 μM N = 14 μg N/L

1 μM P = 31 μg P/L

1 μM C = 12 μg N/L

Table 2. Kenilworth Marsh Water Quality Data

Date: March 3-4, 1995

A) Nutrients

		Dissolved									Particulate					Totals		
	Tidal Ht.	NH4	NO2+NO3	NO2	DON	TDN	oPO4	DOP	TDP	DOC	TSM	Turb.	PP	PC	PN	TN	TP	TOC
Time Point (2400)	cm	uM N	uM N	uM N	uM N	uM N	uM P	uM P	uM P	uM C	mg/L	NTU	uM P	uM C	uM N	uM N	uM P	uM C
1000	242	40.3	102.9	1.40	39.0	182.1	1.38	ND	1.38	440	39.0	59.9	2.58	190	19.9	202.1	3.95	630
1200	180	38.2	100.0	1.37	34.6	172.9	0.41	0.53	0.94	439	35.2	52.9	2.17	181	19.7	192.5	3.10	620
1410	148	34.4	96.4	1.49	38.4	169.3	0.44	0.50	0.94	451	43.0	58.2	2.39	209	22.6	191.9	3.33	660
1600	125	34.0	95.0	1.37	(35.0)	164.0	0.66	(0.40)	1.06	442	44.0	58.5	2.80	220	24.9	188.9	3.86	662
1810	142	24.9	92.9	1.16	33.0	150.7	0.25	0.44	0.69	418	22.7	38.7	1.42	136	15.0	165.7	2.10	554
2010	190	35.7	97.9	1.35	49.3	182.9	0.34	0.50	0.84	452	39.9	54.9	2.14	208	25.2	208.0	2.99	660
2210	245	35.4	105.7	1.46	28.1	169.3	0.34	0.44	0.78	440	36.6	55.6	2.11	177	19.3	188.6	2.89	617
0010	187	32.6	96.4	1.36	34.6	163.6	0.34	0.44	0.78	438	37.1	54.5	2.19	197	20.3	183.9	2.97	635
0200	150	29.9	93.6	1.36	33.7	157.1	0.31	0.41	0.72	422	40.6	55.4	2.32	167	18.6	175.7	3.03	588
0405	122	31.1	92.9	1.54	31.7	155.7	0.34	0.41	0.75	421	29.4	45.3	2.12	174	20.1	175.8	2.87	595
0605	128	17.3	91.4	1.01	22.7	131.4	0.22	0.28	0.50	345	22.1	36.8	1.49	143	14.0	145.4	1.99	488
0800	190	29.1	94.3	1.20	32.3	155.7	0.28	0.38	0.66	393	37.1	53.6	2.21	165	18.8	174.5	2.87	558
0945	221	35.0	96.4	1.46	41.4	172.9	0.38	0.47	0.84	418	38.2	55.2	2.25	191	22.1	194.9	3.10	609
Nash Run	NA	1.1	161.4	0.71	18.9	181.4	0.31	ND	0.31	281	1.2	2.9	0.25	21	2.5	183.9	0.56	302

Note: Dissolved organic N and P sample at 1600 were lost. Data in ( ) are estimated from the average of all tidal data.

B) Hydrolab Scout Data

Time Point (2400)	Tidal Ht. cm	Temp (oC)	pH	Cond.	DO (mg/L)	DO Sat.
1000	242	5.85	7.23	0.386	11.7	92.2
1200	180	6.22	7.24	0.381	12.97	103
1410	148	7.37	7.31	0.387	15.03	121.2
1600	125	7.82	7.35	0.39	13.06	109.8
1810	142	6.22	7.27	0.361	13.23	103.7
2010	190	6.26	7.24	0.379	11.85	95.4
2210	245	6.12	7.25	0.364	11.59	92.9
10	187	5.99	7.24	0.376	11.39	91.1
200	150	5.59	7.23	0.376	11.16	88.1
405	122	5.22	7.21	0.386	11.13	86.5
605	128	5.74	7.25	0.354	11.76	93.4
800	190	5.59	7.25	0.375	12.53	96.8
945	221	5.74	7.21	0.387	11.96	95.1
	Min	5.22	7.21	0.354	11.13	86.5
	Max	7.82	7.35	0.39	15.03	121.2

Kenilworth Marsh Data Sheet

A) Nutrients

		Dissolved									Particulate		
	Tidal Ht.	NH4	NO2+NO3	NO2	DON	TDN	oPO4	DOP	TDP	DOC	TSM	Turb.	PP
Time Point (2400)	cm	uM N	uM N	uM N	uM N	uM N	uM P	uM P	uM P	uM C	mg/L	NTU	uM P
1000	213	32.6	67.1	2.4	25.9	125.7	0.41	0.38	0.78	460.8	30.0	41.8	2.08
1210	203	32.3	72.9	2.3	21.3	126.4	0.34	0.13	0.47	461.7	39.1	50.3	2.58
1410	160	28.4	72.1	2.1	19.5	120.0	0.38	0.25	0.63	461.7	58.0	72.3	3.56
1550	128	25.3	67.9	2.1	39.0	132.1	0.41	0.19	0.59	521.7	54.7	66.2	3.72
1805	110	25.6	65.0	2.0	32.3	122.9	0.50	0.25	0.75	505.0	69.4	76.4	4.75
2005	133	27.8	75.0	1.8	25.1	127.9	0.47	0.25	0.72	400.8	52.0	61.5	3.25
2205	206	33.0	73.6	2.2	25.6	132.1	0.44	0.19	0.63	474.2	45.9	51.1	2.72
0010	205	31.4	72.9	2.2	23.6	127.9	0.34	0.34	0.69	443.3	39.1	48.8	2.80
0205	168	29.4	72.1	2.0	22.0	123.6	0.38	0.19	0.56	436.7	60.0	68.5	3.53
0405	127	26.7	65.7	1.9	24.7	117.1	0.41	0.19	0.59	438.3	55.6	66.1	3.44
0605	105	28.1	64.3	2.0	15.5	107.9	0.38	0.38	0.75	443.3	41.7	56.3	3.50
0800	155	24.2	70.7	1.7	16.5	111.4	0.34	0.19	0.53	414.2	51.7	57.2	2.98
0925	205	32.3	70.7	2.3	20.6	123.6	0.38	0.41	0.78	437.5	53.4	65.0	3.41
Nash Run		3.1	199.3	1.7	0.0	201.4	0.28	0.00	0.22	325.0	1.23	3.1	0.25

B) Hydrolab Scout Data

	Tidal Ht.	Temp (oC)	pH	Cond.	DO (mg/L)	DO Sat.
Time Point (2400)	cm					
1000	213	13.9	6.9	0.268	7.2	69.1
1200	203	14.4	7.0	0.274	7.5	73.5
1400	160	14.5	7.1	0.280	8.9	87.1
1600	128	14.7	7.2	0.287	10.6	104.0
1800	110	15.0	7.3	0.294	10.4	102.8
2000	133	13.7	7.1	0.275	8.5	82.3
2200	206	14.1	7.0	0.276	7.5	72.5
2400	205	13.8	7.0	0.277	7.6	73.5
200	168	13.4	7.0	0.280	7.1	68.4
400	127	12.9	7.0	0.287	6.9	65.4
600	105	12.5	7.0	0.300	6.6	62.2
800	155	13.3	7.0	0.291	7.5	71.6
1000	205	13.5	7.0	0.281	7.7	73.5

Table 2. Kenilworth Marsh Water Quality Data; June 1995

A) Nutrients

		Dissolved									Particulate					Totals	
	Tidal Ht.	NH4	NO2+NO3	NO2	DON	TDN	oPO4	DOP	TDP	DOC	TSM	Turb.	PP	PC	PN	TN	TP
Time Point (2400)	cm	µM N	µM N	µM N	µM N	µM N	µM P	µM P	µM P	µM C	mg/L	NTU	µM P	µM C	µM N	µM N	µM
1000	195	16.4	36.4	2.4	20.5	75.7	0.53	0.47	1.00	565	40.8	62	2.87	263	26.0	101.7	3.87
1200	153	22.1	33.6	2.4	25.5	83.6	0.53	0.31	0.84	577	79.2	81	4.10	376	34.8	118.4	4.95
1400	110	27.7	29.3	2.5	29.1	88.6	0.72	0.66	1.38	582	62.7	80	4.02	353	30.9	119.5	5.40
1600	90	35.9	25.0	2.4	33.9	97.1	0.97	0.78	1.75	603	58.9	NR	3.76	320	23.9	121.0	5.51
1800	121	22.1	40.7	2.4	31.9	97.1	0.81	0.41	1.22	566	46.2	58	2.71	261	24.2	121.4	3.93
2000	175	22.9	39.0	2.7	28.0	92.6	0.70	0.44	1.14	550	41.6	55	2.43	228	18.5	111.1	3.56
2200	195	24.4	38.6	2.8	31.4	97.1	0.75	0.41	1.16	598	33.2	49	1.95	202	14.5	111.6	3.10
2400	168	26.9	37.1	2.7	34.6	101.4	0.63	0.63	1.25	559	55.6	67	3.11	293	23.5	124.9	4.36
200	130	31.8	33.6	2.7	29.8	97.9	0.59	0.75	1.34	567	59.8	70	3.47	290	24.0	121.9	4.82
400	103	37.4	27.9	2.5	25.8	93.6	0.69	0.59	1.28	547	39.1	55	2.80	236	20.8	114.4	4.08
600	137	26.6	40.0	2.5	26.6	95.7	0.72	0.50	1.22	543	52.9	58	2.75	220	17.6	113.3	3.97
800	210	29.6	35.7	3.0	33.1	101.4	0.56	0.59	1.16	557	37.8	48	2.51	221	19.8	121.2	3.66
1000	228	30.7	34.3	3.0	33.4	101.4	0.63	0.53	1.16	548	27.1	36	2.01	193	18.8	120.2	3.16
Nash Run	NA	1.14	117.1	1.7	14.3	134.3	0.56	0.38	0.94	482	30.6	12	0.71	55	5.4	139.7	1.65
Field Blank-2	NA	0.36	0.7	0.01	3.9	5.0	0.03	0.00	0.03	37	ND	ND	0.04	10	0.4	5.4	0.07

B) Hydrolab Scout Data

(+) into marsh, (-) out of marsh
Velocity (cm/sec)

Time Point (2400)	Tidal Ht.	Temp	pH	Cond.	DO	DO Sat.
	cm	(oC)	SI	µS/cm	mg O_2/L	%
1000	195	21.36	6.75	0.15	3.34	37.5
1200	153	21.44	6.75	0.161	3.68	41.3
1400	110	21.77	6.79	0.173	4.25	47.6
1600	90	21.9	6.77	0.184	3.25	37.2
1800	121	20.81	6.79	0.16	4.68	52.2
2000	175	21.43	6.75	0.157	3.76	42.3
2200	195	21.15	6.75	0.159	3.54	39.6
2400	168	20.85	6.73	0.16	3.09	34.4
200	130	20.21	6.73	0.171	1.91	20.7
400	103	19.79	6.74	0.183	2.11	22.9
600	137	20.00	6.75	0.167	3.52	38.5
800	210	21.22	6.71	0.179	1.94	21.6
1000	228	21.25	6.72	0.179	2.21	24.8

Table 2. Kenilworth Marsh Water Quality Data

A) Nutrients

		Dissolved									Particulate					Totals		
	Tidal Ht.	NH4	NO2+NO3	NO2	DON	TDN	oPO4	DOP	TDP	DOC	TSM	Turb.	PP	PC	PN	TN	TP	T
Time Point (2400)	cm	µM N	µM N	µM N	µM N	µM N	µM P	µM P	µM P	µM C	mg/L	NTU	µM P	µM C	µM N	µM N	µM P	µ
1000	188	30.7	54.3	3.7	34.1	122.9	0.44	0.68	1.12	597	60.0	80.5	3.16	276	28.6	151	4.28	8
1200	160	22.1	49.3	3.6	28.6	103.6	0.72	0.44	1.16	599	68.0	NR	4.09	358	36.7	140	5.26	9
1410	125	23.0	40.7	3.2	50.2	117.1	0.75	0.58	1.33	688	67.3	81	3.66	363	39.4	157	4.99	1
1600	121	9.4	55.7	2.6	38.0	105.7	0.53	0.65	1.18	618	39.0	48	2.69	352	38.1	144	3.87	9
1810	175	22.5	57.9	3.5	40.4	124.3	0.47	0.64	1.11	638	63.2	79	3.56	328	30.9	155	4.68	9
2010	220	24.1	54.3	3.5	35.2	117.1	0.59	0.50	1.10	580	48.3	63	2.75	249	26.6	144	3.85	8
2210	190	27.6	56.4	3.6	41.6	129.3	1.16	**0.31**	1.47	643	59.7	75	3.34	293	28.0	157	4.81	9
0010	148	23.1	45.0	3.2	29.3	100.7	0.53	0.53	1.07	614	61.1	76	3.47	301	31.1	132	4.53	9
0200	117	23.6	38.6	3.1	30.5	95.7	0.69	0.49	1.18	603	36.5	50	3.00	229	26.1	122	4.18	8
0405	112	10.6	55.0	2.6	26.2	94.3	0.31	0.49	0.80	568	36.5	43	2.94	227	24.9	119	3.74	7
0605	175	21.3	55.0	3.3	44.0	123.6	0.44	0.73	1.17	598	92.8	102	4.78	448	41.4	165	5.95	1
0800	222	32.9	49.3	3.6	37.1	122.9	0.50	0.68	1.18	541	39.1	55	2.56	208	23.6	146	3.74	7
1000	214	26.7	50.0	3.4	36.3	116.4	0.44	0.62	1.05	570	43.1	57	2.84	243	27.4	144	3.90	8
Nash Run		0.36	55.0	2.5	30.0	87.9	0.50	0.71	1.21	1142	5.86	NR	0.88	118	9.1	97	2.08	1
Field Blank-2		0.21	0.14	0.03	3.90	4.29	0.29	ND	0.20	36	NS	NS	NS	11	0.8			
							a problem											

B) Hydrolab Scout Data

Time Point (2400)	Tidal Ht.	Temp	pH	Cond.	DO	DO Sat.
	cm	(oC)	SI	µS/cm	mg O_2/L	%
1000	188	25.60	6.6	0.188	2.5	31.0
1200	160	26.60	6.6	0.196	3.4	42.0
1410	125	28.90	6.7	0.200	5.3	69.0
1600	121	28.20	7.0	0.209	6.2	79.0
1810	175	27.10	6.8	0.201	4.8	60.0
2010	220	27.60	6.7	0.181	3.2	40.0
2210	190	27.10	6.7	0.194	3.3	41.0
10	148	26.50	6.6	0.204	2.4	30.0
200	117	25.90	6.7	0.210	2.0	24.0
405	112	26.10	6.8	0.219	4.7	58.0
605	175	26.20	6.7	0.206	3.6	44.0
800	222	26.80	6.6	0.176	1.8	23.0
1000	214	26.60	6.7	0.188	2.4	29.0

Table 2. Kenilworth Marsh Water Quality Data

A) Nutrients

		Dissolved									Particulate					Totals		
	Tidal Ht.	NH4	NO2+NO3	NO2	DON	TDN	oPO4	DOP	TDP	DOC	TSM	Turb.	PP	PC	PN	TN	TP	TOC
Time Point (2400)	cm	µM N	µM N	µM N	µM N	µM N	µM P	µM P	µM P	µM C	mg/L	NTU	µM P	µM C	µM N	µM N	µM P	µM C
1000	209	9.93	32.14	3.15	37.21	79.29	0.19	0.46	0.65	570.0	59.5	60	4.22	433.3	58.6	137.9	4.87	1003.3
1200	227	5.71	31.43	3.01	28.57	65.71	0.16	0.47	0.62	528.3	47.9	52	3.68	445.0	60.5	126.2	4.30	973.3
1400	192	2.71	27.86	2.36	28.71	59.29	0.31	0.37	0.69		68.1	71	4.44	528.3	61.3	120.6	5.13	528.3
1600	150	3.21	22.14	1.73	33.21	58.57	0.94	0.03	0.78	568.3	61.0	63	4.22	533.3	58.6	117.1	5.00	1101.7
1800	115	9.50	21.43	1.50	29.79	60.71	0.28	0.65	0.93	587.5	46.7	56	3.81	485.8	53.6	114.4	4.74	1073.3
2000	133	7.57	25.00	1.48	36.71	69.29	0.22	0.38	0.60	548.3	60.1	70	3.67	481.7	56.5	125.8	4.27	1030.0
2200	205	4.71	30.00	2.77	29.57	64.29	0.19	0.41	0.59	546.7	79.9	81	4.77	526.7	59.6	123.9	5.37	1073.3
0	240	7.07	28.57	2.81	27.93	63.57	0.25	0.29	0.54	507.5	38.1	43	3.11	406.7	52.5	116.1	3.64	914.2
200	213	7.21	29.29	2.73	27.07	63.57	0.25	0.41	0.66	552.5	57.7	65	4.02	405.8	51.5	115.1	4.68	958.3
400	180	9.00	25.71	2.13	42.43	77.14	0.28	0.51	0.79	619.2	64.5	70	4.23	415.8	50.9	128.1	5.02	1035.0
600	135	17.71	33.57	2.17	28.71	80.00	0.63	0.57	1.19	692.5	46.9	63	4.07	364.2	45.8	125.8	5.26	1056.7
800	130	18.00	41.43	1.89	25.57	85.00	0.25	0.53	0.78	580.0	110.1	156	4.16	355.8	41.6	126.6	4.94	935.8
1000	183	20.50	52.86	2.32	22.36	95.71	0.22	0.43	0.65	599.2	224.5	270	7.03	552.5	56.3	152.0	7.68	1151.7
1240	230	15.71	50.71	2.36	27.14	93.57	0.16	0.41	0.57		99.8	152	4.28	417.5	54.1	147.6	4.85	417.5
Nash Run		17.93	173.57	4.42	-5.79	185.71	0.50	0.28	0.78	338.3	13.7	11	1.77	144.2	15.6	201.4	2.55	482.5
		6.452381	18.107143	171.91667														

B) Hydrolab Scout Data

Time Point (2400)	Tidal Ht.	Temp	pH	Cond.	DO	DO Sat.	
	(cm)	(oC)	SI	µS/cm	mg O_2/L	%	
1000	209	28.75	6.81	0.207	4.88	63.1	6-1
1200	227	29.13	6.90	0.208	6.10	76.2	6-2
1400	192	30.23	7.07	0.211	7.66	101.6	6-3
1600	150	31.16	7.18	0.217	8.74	118.1	6-4
1800	115	32.88	7.19	0.223	8.54	116.8	6-6
2000	133	29.30	6.80	0.226	5.83	73.0	6-7
2200	205	30.12	7.05	0.211	7.44	98.8	6-8
0	240	29.90	7.05	0.208	6.44	85.6	6-9
200	213	29.57	6.89	0.215	5.52	72.6	6-10
400	180	28.66	6.74	0.219	3.58	45.1	6-11
600	135	27.39	6.68	0.203	2.64	33.6	6-12
800	130	27.66	6.75	0.206	3.98	50.5	6-13
1000	183	27.50	6.72	0.178	4.17	52.9	6-14
1300	230	28.59	6.79	0.193	3.94	50.9	6-15
Nash Run	ND	ND	ND	0.443	ND	ND	

Table 2. Kenilworth Marsh Water Quality Data

NOTE::: Assume from graphs Conc for Nh4, NO23, to get DON and OP to get DOP

A) Nutrients

		Dissolved									Particulate			
	Tidal Ht.	NH4	NO2+NO3	NO2	DON	TDN	oPO4	DOP	TDP	DOC	TSM	Turb.	PP	PC
Time Point (2400)	cm	uM N	uM N	uM N	uM N	uM N	uM P	uM P	uM P	uM C	mg/L	NTU	uM P	uM C
1000	212	20.1	37.9	1.9	20.6	78.6	0.4	0.4	0.8	490	29.1	40	1.9	184.2
1200	218	19.7	37.9	1.8	23.1	80.7	0.4	0.5	0.9	473	23.3	33	1.6	149.2
1400	183	15.4	37.9	1.6	23.9	77.1	0.4	0.4	0.8	467	24.6	35	1.8	173.3
1600	142	12.9	34.3	1.5	23.6	70.7	0.5	0.3	0.8	482	30.5	40	1.9	176.7
1800	116	18.3	32.1	1.5	22.4	72.9	0.5	0.3	0.8	462	31.5	43	2.1	190.8
2000	135	22.0	28.0	2.0	27.0	90.7	0.5	0.4	0.9	468	42.9	49	2.2	211.7
2200	200	21.8	37.9	1.9	23.9	83.6	0.5	0.3	0.8	448	44.6	54	2.6	231.7
2400	222	21.7	37.1	2.0	20.4	79.3	0.5	0.3	0.7	467	27.1	36	1.9	160.0
200	193	19.0	37.1	1.8	20.3	76.4	0.4	0.4	0.8	449	39.5	46	2.2	188.3
400	153	18.5	35.7	1.8	23.6	77.9	0.5	0.4	0.9	496	75.7	73	3.3	328.3
600	122	20.3	32.9	1.8	22.6	75.7	0.7	0.5	1.2	464	41.0	53	2.6	219.2
800	122	19.0	39.3	1.4	23.1	81.4	0.4	0.6	1.0	477	33.5	45	1.9	164.2
1000	183	20.4	37.9	1.8	21.0	79.3	0.3	0.5	0.8	431	47.1	56	2.5	240.0
1230	212	21.6	34.3	0.1	25.6	81.4	0.6	0.2	0.8	423	20.5	32	1.6	138.3
Nash Run		3.1	105.7	2.3	25.5	134.3	0.7	0.4	1.1	453	0.9	2	0.4	28.7
Field Blank-3		0.21	0.71	0.06	<0.9	0.00	0.13	-0.1	0.00	170	ND	ND	ND	5.3

B) Hydrolab Scout Data

Time Point (2400)	Tidal Ht.	Temp	pH	Cond.	DO	DO Sat.
	cm	oC		uS	mg/L	%
1000	212	18.35	6.69	0.214	3.98	42.1
1200	218	18.85	6.71	0.216	5.55	56.8
1400	183	20.03	6.71	0.216	5.10	56.2
1600	142	21.23	6.74	0.218	5.56	62.7
1800	116	21.94	6.78	0.224	6.53	74.5
2000	135	19.31	6.73	0.219	5.55	60.2
2200	200	19.50	6.69	0.217	5.39	56.6
2400	222	19.73	6.71	0.220	4.20	45.0
200	193	18.96	6.68	0.217	4.30	47.0
400	153	17.93	6.62	0.220	3.57	37.6
600	122	17.31	6.64	0.227	3.60	37.5
800	122	17.99	6.67	0.229	3.91	41.3
1000	183	18.67	6.67	0.223	4.23	45.3
1230	212	19.68	6.71	0.223	4.58	50.1

Table 2. Kenilworth Marsh Water Quality Data

A) Nutrients

		Dissolved									Particulate					Totals		
	Tidal Ht.	NH4	NO2+NO3	NO2	DON	TDN	oPO4	DOP	TDP	DOC	TSM	Turb.	PP	PC	PN	TN	TP	TOC
Time Point (2400)	cm	uM N	uM N	uM N	uM N	uM N	uM P	uM P	uM P	uM C	mg/L	NTU	uM P	uM C	uM N	uM N	uM P	uM
1600	122	19.6	51.9	1.5	34.1	105.7	0.42	0.35	0.77	504	51.3	80	3.13	218	23	128.6	3.90	723
1800	117	15.6	55.4	1.4	28.2	99.3	0.42	0.29	0.71	450	49.3	68	2.60	191	18	117.3	3.31	641
2005	178	34.1	54.8	1.7	24.7	113.6	0.45	0.45	0.90	483	155.7	230	8.37	504	39	152.6	9.27	988
2200	222	35.6	51.1	2.1	39.0	125.7	0.48	0.58	1.06	571	92.5	149	4.77	311	26	151.3	5.83	882
2400	216	34.2	51.9	1.9	33.9	120.0	0.48	0.42	0.90	500	96.5	148	5.75	297	26	145.9	6.65	797
200	177	24.7	53.2	1.9	33.5	111.4	0.45	0.42	0.87	503	100.0	139	5.32	339	29	140.6	6.19	842
410	138	20.4	51.4	1.8	31.0	102.9	0.39	0.48	0.87	474	67.0	106	3.87	275	22	125.3	4.75	749
600	119	20.3	53.0	1.8	22.4	95.7	0.42	0.29	0.71	453	56.7	88	3.22	224	22	117.9	3.93	678
750	146	15.4	55.1	1.1	24.6	95.0	0.29	0.35	0.65	426	51.7	76	2.71	206	19	114.2	3.35	632
1000	212	33.1	52.1	1.8	26.2	111.4	0.35	0.58	0.94	493	94.0	135	4.87	316	26	137.0	5.81	808
1155	223	29.0	51.6	1.7	29.4	110.0	0.55	0.32	0.87	461	70.0	111	4.18	230	21	131.4	5.05	691
1400	193	25.0	51.4	1.8	30.8	107.1	0.39	0.52	0.90	473	28.0	96	3.70	234	21	128.6	4.60	708
1600	156	20.4	50.6	1.8	30.4	101.4	0.42	0.45	0.87	436	60.0	90	3.66	236	21	121.9	4.53	672
1710	140	20.8	50.5	2.0	31.6	102.9	0.45	0.68	1.13	471	55.5	88	1.69	242	22	125.3	2.82	713
Nash Run		2.8	222.1	1.4	0.8	225.7	0.39	0.13	0.52	298	1.3	2.6	0.32	63	3	229.0	0.84	361
Field Blank-8		0.2	0.0	0.0	17.6	17.9	0.35	-0.19	0.16	42	NA	NA	0.04	6	0	18.0	0.20	47

B) Hydrolab Scout Data

Time Point (2400)	Tidal Ht.	Temp	pH	Cond.	DO	DO Sat.
	cm	oC		uS	mg/L	%
1600	122	16.51	6.74	0.234	7.15	72.7
1800	117	15.29	6.71	0.239	6.26	61.8
2005	178	14.73	6.65	0.228	6.07	59.5
2200	222	14.84	6.59	0.196	5.09	49.4
2400	216	14.44	6.61	0.206	5.26	51.0
200	177	13.52	6.62	0.222	6.29	58.1
410	138	12.58	6.62	0.232	4.82	45.0
600	119	12.29	6.63	0.243	5.14	47.7
750	146	13.82	6.68	0.246	6.08	58.2
1000	212	13.95	6.61	0.215	5.43	52.3
1155	223	14.26	6.63	0.219	5.35	51.8
1400	193	14.74	6.65	0.226	5.53	54.1
1600	156	15.20	6.7	0.241	6.13	60.7
1710	140	15.53	6.52	0.241	5.81	57.8
Nash Run	NA	NA	7.44	0.523	NA	NA