Nutrient and Carbon Fluxes to Barnegat Bay from Marginal Saline Wetlands

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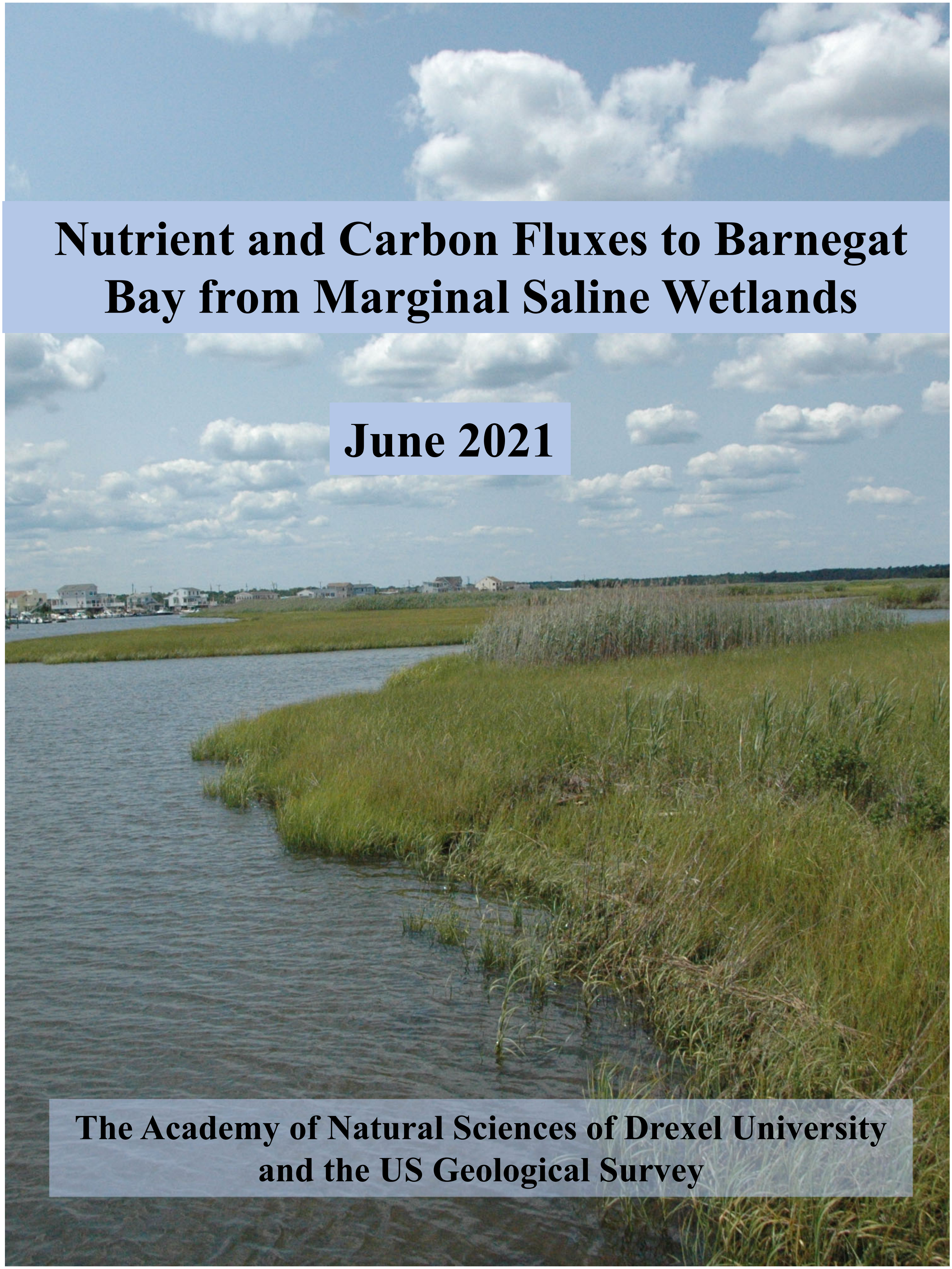

The Academy of Natural Sciences of Drexel University
and the US Geological Survey

Final Report

To
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Nutrient and Carbon Fluxes to Barnegat Bay from Marginal Saline Wetlands
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Executive Summary

Salt marshes play a large role in removing pollutants and nutrients from aquatic ecosystems, such as Barnegat Bay, and serve as a vital link between terrestrial watersheds and coastal waters. Biogeochemical processes transform nutrients during transport through the marsh complex, altering the form, concentration and fate of carbon, nitrogen, and phosphorus entering the bay. In some cases, water quality models do not account for marsh habitats in the assessment of the watershed flux of nutrients to coastal waters and with increasing coastal development pressures, marshes areas are shrinking, and their benefits will be greatly reduced.

This research measured nutrient and carbon exchange/transformations between the Westecunk Creek watershed, through the tidal river, flowing downstream towards Barnegat Bay. The creek flows through an extensive marsh complex to the open bay. *We hypothesize that the input of nitrogen, phosphorus and carbon from the watershed will be modified, and in some seasons reduced, as water flows through the surrounding marginal wetlands into the Bay.*

Water samples were collected along a salinity gradient monthly, from April to November 2018, at multiple locations from the non-tidal section of Westecunk Creek to the entrance with the bay proper. In addition, water samples were collected along a cross-section of the lower tidal river over multiple tidal cycles (~30hrs) in the spring, summer, and fall. All water samples were filtered and analyzed for various forms of carbon, nitrogen, and phosphorus. In addition, basic water quality parameters (e.g., salinity, temperature, and dissolved oxygen) were measured at each station or time point.

The results are presented in sections, highlighting monthly changes and import/export of nutrient constituents:

1) Monthly Changes in Dissolved Nutrients and Organic Carbon
   Nitrogen, specifically concentrations of dissolved nitrate and ammonium, were substantially altered during transport from the watershed to the open bay. During the late spring/early summer, concentrations of dissolved nitrate were near the detection limit in the tidal river, returning to higher levels by late summer/fall. In the fall, for both N forms, the bay appeared to be a source of inorganic nitrogen to the tidal river, as concentrations were higher in the mainstem bay. In addition, dissolved organic nitrogen was the

dominant form of dissolved nitrogen and the surrounding marshes were a source of nitrogen to tidal river. Dissolved forms of phosphorus (inorganic and organic) exhibited near conservative mixing with a small source from the marshes in the summer months. Dissolved organic carbon concentrations were higher in waters from the watershed than open bay, with an input from the marshes during the early to mid-summer months. These data indicate there was substantial nutrient processing in the surrounding wetlands, as the water moved from the watershed to the open bay.

2) Westecunk Creek Nutrient Import-Export

   These data show that TDN and TP were higher in the ebb tide, compared to the flood tide, on all three sampling dates. This resulted in a net mass loss of N and P from the watershed to the Bay. The magnitude of the losses varied over the three months, with the highest loss in May (i.e., when chlorophyll *a* levels were high), and corresponded to both hydrologic/tidal influences in water transfer and changes in concentrations in the endmember waters. These results indicate that the watershed and tidal marsh are net sources for these nutrients to the Bay, at least over a short time period. The magnitude of the gains and losses changed in relation to the magnitude of the water volume leaving the watershed and from the tidal and weather influences that affected the Bay during the study. These three dates, however, provided a relative picture of the mass transfer of nutrients, carbon, and sediment exchange between the watershed and the Bay.

Overall, some key findings include:

- Nutrients from the watershed are transformed during transport through the tidal wetlands during the year.
- The tidal wetlands can remove or add to the nutrient levels in the creek depending on season.
- Organic forms of nitrogen and phosphorus are a major component of the total dissolved burden in the creek, and
- Tidal channel studies can be an important tool in understanding the changes in nutrient concentrations and forms in waters that travel from the watershed to the mainstem bay.

This study, along with previous Barnegat Bay research, illustrates that the remaining marsh systems within the bay are important “bio-reactors” that can modify and supply or remove nitrogen and phosphorus to the open bay. The results of the current study support our hypothesis and show how the various forms of nitrogen and phosphorus change forms during transport from the watershed to the bay and that dissolved organic forms are a major component of the dissolved material cycling through the lower section of Westecunk Creek. Many of these changes are seasonally variable due to marsh, algal and microbial processes. The threats from coastal development and sea level rise will most likely result in further loss of the remaining wetlands, mainly in the southern sections of the bay. These losses will further amplify the potential changes that may be seen within adjacent wetlands. It is imperative that this information, along with previous research conducted in the bay, be used for the protection of the remaining wetlands in the bay, as they are a major component that helps to maintain a healthy bay ecosystem and serves to protect valuable near-shore infrastructure during extreme weather events.

Recommendations for Future Research and Monitoring

One area that needs to be considered, that was outside the scope of this project, is the level and mode of transport of nutrients through groundwater. These nutrients could be transported under the marsh complex into the bay directly. Research/monitoring has found substantial levels of groundwater nitrate originating from the unconfined Kirkwood-Cohansey aquifer system. Importantly, through stable isotope analysis, most of the nitrate was derived from fertilizers. How the nitrate is transformed through the subsurface marsh complex is a question that has implications to the total nutrient input to the bay.

For a better understanding of the areal extent of creek/bay water interactions with the tidal marsh, subsurface wells with dataloggers should be installed, along with precise GIS elevation analyses of the marsh structure. This would serve to obtain areal rates of nutrient change and would serve to balance past studies of nutrient removal (e.g., denitrification). This information could be then applied to other bay wetland areas to help provide more accurate models of nutrient transformation and transport.

A. General Introduction

Barnegat Bay is a large tidal lagoon located along the eastern margin of central New Jersey (**Figure 1**). It is fed by seawater entering Little Egg Inlet from the south, Barnegat Inlet from the east, and Pt. Pleasant Canal from the north. Toms River and the Metedeconk River, as well as numerous smaller creeks (Forked River, Oyster Creek, Cedar Creek and others) supply the Bay with freshwater.

Located along the western margin of the Bay are remnants of saline wetlands (**Figure 1**) that, in the past, likely extended along the entire coastal shoreline. These saline marshes represent areas where freshwater (groundwater and precipitation) mixes with seawater supplied by daily tidal flooding. While the marshes trap sediment providing a substrate for aquatic plants to thrive, the plants and related microbial community help recycle and remove nutrients and carbon. These wetlands also act as a barrier to storm flood surges, protecting the landward margin of the Bay. The ecology and biota of these wetlands have evolved in response to the flux of nutrients and sediment delivered by the various water sources and is an integral part of the Bay's bio-geochemical system.

Nutrient cycling through the marginal wetlands may affect the water quality in Barnegat Bay. Dissolved nutrients and nutrient-rich solid debris (inorganic and organic matter) are washed into and out of the wetlands by the daily tidal cycles and by storm surge. High-water events, associated with storms and hurricanes, cause more extensive flooding of the wetlands and would likely transfer large amounts of nutrient-rich, organic and inorganic debris. Processes such as plant uptake, microbial remineralization, volatilization, denitrification, and burial can alter the form and concentration of nutrients entering the Bay. In many cases, these processes can act on seasonal time frames.

The mixing process that occurs in a tidal estuary creates a very complex biogeochemical exchange between the salt water, the freshwater, and the surrounding marshland (see Childers et al. 2000 for example). The most prominent attribute of estuaries is the formation of a salinity gradient that can span great distances depending on freshwater flow and geomorphology. At the source of the freshwater input, ahead of the point of tidal excursion, salinity should be extremely low. Along the seawater boundary, the salinity will be much higher, near 25 to 30 ppt. When the water mixes, it does not do so at a single point between them, but instead, over the entire distance between the two sources, thus forming a salinity gradient. Salinity is a conservative trait, meaning that concentration of salts can only be changed by dilution and evaporation, while the quantity of the salts in the water does not change. This trait is often utilized in studies focusing on biogeochemical processes in marshland as the concentrations of reactants and products can be tracked over the extent of the gradient.

The use of the salinity gradient to study chemical constituents has shown to be incredibly useful in understanding processes, sources and sinks in estuarine environments (**Figure 2;** Boyle et al. 1974; Kaul and Froelich, 1984; McGurik Flynn, 2008; Fagherazzi et al. 2013; Lebo and Sharp, 1993). Given that salinity will increase somewhat steadily over the length of the estuary from the freshwater source to the saline seawater, it can be used as a unit for comparison. Boyle et al (1974) and Loder and Reichard (1981) showed that by plotting the concentration of a given water constituent, which may fluctuate, against a salinity concentration, it can be determined whether the marsh interacts with the constituent (Cifuentes et al. 1990; Loder and Reichard 1981). If the graph appears as a straight line, then the given component is said to act conservatively along the gradient, in the same fashion that the salinity does. If a curved line appears above the conservative baseline, the marsh is expected to be a source of the component, increasing its concentration in the water over the extent of the estuary. If the line appears curved below the conservative baseline, the marsh is expected to be a sink to the component, decreasing its concentration over the extent of the estuary, and locking the nutrients away (Loder and Reichard 1981; Cifuentes et al. 1990).

A principal factor in determining the mixing curves is determining the initial concentrations of both salinity and the concentration of the constituent under study at the water source, as well as the final concentrations once it enters the seawater. The concentrations in between the start and end points will show the gradient, but the end members themselves can be highly variable (Loder and Reichard, 1981). Boyle et al. (1974) addressed this issue and compared several studies, all of which failed to determine the variability in the end members, resulting in findings that were less precise and that negated similar studies (Boyle et al. 1974). They produced a model for determining whether a compound mixed conservatively but stressed the importance of determining the end member concentrations and their variabilities for their model to be valid.

For this study, the salinity gradient of a small creek in Barnegat Bay was determined from the source to the bay, and several constituents were tracked over the extent of the creek. The optimal time for collecting our samples was shortly after the end of high tide, giving the water constituents time to interact with the marsh surface and cycle between the marsh and the water. Salinity measurements and water samples were collected from the source of the freshwater to the end of the creek, bordering the open water of the Bay. This procedure helped determine internal marsh processes that impact nutrient concentrations and fluxes over time. In addition, nutrient fluxes can be determined using tidal channel studies in which water and nutrients are measured going into and out of the marsh complex (**Figure 3**). 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 (and 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, by plants, or within the water column, Therefore, it is important when testing the nutrient outwelling paradigm to understand the bounds and constraints in the study plan and what information the specific study can provide. The use of both axial surveys and flux measurements are invaluable in determining whole system processes.

A1 - Goal and Objective: This research measured nutrient and carbon exchange between the tidal streams that flow through marginal saline wetlands within Barnegat Bay. *We hypothesize that the input of nitrogen, phosphorus and carbon from the watershed will be modified, and in some seasons reduced, as water flow through the surrounding marginal wetlands into the Bay.* The results provide information needed to integrate exchange with wetlands into the Barnegat Bay geochemical model (i.e., current Water Quality Analysis Simulation Program (WASP) model framework).

A2 - Study Area

The Barnegat Bay-Little Egg Harbor estuary (BB; Barnegat Bay) is located along the central New Jersey coastline in the Atlantic Coastal Plain province (**Figure 1**). Barnegat Bay is a back-barrier lagoon-type estuary that extends from Point Pleasant south to Little Egg Inlet. The variety of highly productive shallow water and adjacent upland habitats found in this system include barrier beach and dune, submerged aquatic vegetation (SAV) beds, intertidal sand and mudflats, salt marsh islands, fringing tidal salt marshes, freshwater tidal marsh, and palustrine swamps. The bay and water quality concerns have been studied extensively over the past twenty years (e.g., Kennish, 2007; Buchanan et al., 2017 and many others).

The Barnegat Bay system, composed of three shallow bays (Barnegat Bay, Manahawkin Bay and Little Egg Harbor), is approximately 70 km in length, 2-6 km wide, and up to 7 m deep. The Bay watershed covers an area of approximately 1700 km^2 and has been extensively developed over the past 70 years. The tidal waters cover approximately 280 km^2 with a ratio of watershed area to water area of 6:1. The current land use (2015) of the watershed is agriculture (~1%), wooded/forest (~27%), tidal and non-tidal wetlands (~17%), urban areas (~22%) and open water (31%) (NJDEP, 2019). Importantly, watershed development (percent urban area) has increased over time. From 1986 to 2006 the amount of urban land cover increased from 15% to 21% of the land area, while forested land cover has decreased (NJ DEP, see https://rucore.libraries.rutgers.edu/rutgers-lib/42277/; Lathrop 2004). The population of the watershed has increased substantially from the 1940s (40,000) to over 600,000 year-round residents currently (US Census Reports; worldpopulationreview.com/us-counties/nj/ocean-county-population). During the height of the summer season the population can rise to approximately 1,000,000.

The specific area/creek we are investigating is Westecunk Creek (**Figure 4**) on the western shore south of the bay bridge. Westecunk Creek is a 17 km long tributary of Little Egg Harbor, with a watershed area of 41 km^2 with an additional area down to the mouth of 24 km^2. The tidal portion of the creek starts at approximately the Route 9 Bridge downstream ~4.9 km to the mainstem bay. Westecunk Creek originates in the NJ Pinelands, flows southeastward through Stafford Forge, continues through Eagleswood Township, and enters the Barnegat Bay estuary through a large mid/low marsh complex. Tributaries to Westecunk Creek include Swamp Branch, Governor's Branch, and Rail Branch (**Figure 4**). Approximately, 65% of the entire watershed is considered forest land, with less than 6% as developed land area (NJ DEP, 2019). Regional growth areas and rural development areas account for 16.1% and 14.9% of the study basin, respectively (BBNEP, 2005). For this study, we recognized the approximate head of tide as the Route 9 Bridge (RR Avenue Bridge), subject to changing runoff conditions. Data from the USGS gaging station at Stafford Forge, NJ (01409280), reflected flows varying from approximately 20 to 50 cfs over the study period. As part of their bay-wide study, Wieben et al (2013) characterized the flow and nutrient levels during base and stormflows in the Westecunk Creek. The tidal area of the creek, as it drains into the bay, is surrounded by a mixture of tidal freshwater wetlands near the head of tide, and to a much larger extent, low and mid-level salt marshes. We roughly estimate the area of the tidal marsh that could be impacted by the creek to be 800 acres (3.2×10^6 m^2).

B –Laboratory Methods: Longitudinal and Fixed Station Studies

B1. Laboratory Methods

Analyses of water samples collected from Barnegat Bay were conducted for organic and inorganic forms of nitrogen, phosphorus, carbon, and silica **(Tables 1 and 2)**. All samples were filtered for chlorophyll and nutrients through pre-rinsed, pre-combusted GF/F filters for organic carbon, chlorophyll-a and TSS analyses, and polycarbonate filters for nutrient analyses. Specific parameters included soluble reactive phosphorus (SRP), nitrite+nitrate (NO2+NO3-N), dissolved organic phosphorus (DOP), dissolved organic nitrogen (DON), total phosphorus (TP), total nitrogen (TN), dissolved organic carbon (DOC), and dissolved silicate. In addition, water samples were analyzed for total suspended matter, suspended chlorophyll *a*, total alkalinity, dissolved chloride and sulfate. All methods followed EPA and NOAA guidelines and are described in Velinsky et al (2006) and Fairchild and Velinsky (2006). Specifically, nitrate-nitrite and ammonium concentrations were determined using an Alpkem 300 Segmented Flow autoanalyzer with a detection limit of 6 and 5 ug/L for NOx and NH_4, respectively, while SRP had a detection limit of 2 µg P/L. Phosphorus samples were analyzed by an ascorbic acid and molybdate colorimetric method using an Alpkem Segmented Flow analyzer and Westco Smartchem 200. Chlorophyll-a was analyzed by a fluorometric detection method using acetone as the extract solution. While only a subset of the parameters are discussed in this report, it should be noted that all results are list in **Appendix J** (available in electronic format).

C – Westecunk Longitudinal Transects Study

In this portion of the study, tidal river transects were sampled on a monthly basis to understand some of the processes that modify nutrient flow from the watershed, through the marsh complex, and into the open waters of the bay. The flows from the watershed during each sampling period impact the water chemistry profiles that are measured from the head of tide to the bay. In general, there was slightly higher discharge in the spring and fall, with lower flows in the summer months (**Figure 5**). Loder and Reichard (1981) and others showed that variations in the endmembers' discharges, both upstream and downstream, can modify the shape of a property-property plot. For this study, flows in the upstream stations were fairly uniform prior to each event (**Table 2**) with most variations less than 7% (relative standard deviation). In the May and August time frame, there was slightly larger flow variations prior to sampling **(Figure 5**).

C1- Field Sampling and Methods

The approach for this portion of the project was to collect water samples from the head of tide out to the mainstem bay at salinity intervals. Water samples were collected from the head of tide (near RR Avenue Bridge) to the confluence with the mainstem bay at locations along the length of Westecunk Creek (WC) based on observed salinities (e.g., ~5psu intervals downstream). The actual location of each station varied according to the salinities at the time of collection but were generally in similar locations along the creek. There were seven monthly surveys conducted from April to November 2018 (**Table 1)**. At the RR Avenue Bridge location, multiple samples were collected before and after each survey to determine any short-term changes in water chemistry. Samples were obtained by hand-dipping a sampler (i.e., pre-cleaned water pitcher) into the water. Subsurface samples, approximately 0.5m from the bottom, were also collected, if possible, at selected stations using a pre-cleaned Van Dorn sampler. At each location, basic water quality parameters (dissolved oxygen, salinity, temperature, and pH) were measured using a YSI EXO2 multi-probe datasonde.

C2: Results: Monthly Changes in Dissolved Nutrients and Organic Carbon

The focus of this section is on the primary nutrients: dissolved nitrate+nitrite (nitrate), ammonium (NH4), soluble reactive phosphorus (SRP) and silicate (Si). Other parameters will be used as part of the discussion, as needed. While during this study, surface and, at times, near bottom water samples were collected, for this analysis below, only surface concentrations are presented. All data are presented in **Appendix J**. In each graph for nutrients, the dotted line is the conservative mixing line between the upper and lower salinity endmembers. As noted in **Figure 2**, concentrations that fall above the conservative mixing line suggest a source of the nutrient or element to the tidal creek from the marsh complex, while concentrations that fall below the mixing line suggest a sink or removal process (e.g., algal uptake, microbial transformation) during the water's transport out to the bay.

Nitrate+Nitrite (nitrate)

Dissolved nitrate exhibited substantial changes in both concentration and downstream distribution during the year (**Figure 6**). Overall, concentrations ranged from 0.4 to 84 µg N/L, with generally higher concentrations found at, or just downstream of, the approximate head of tide near the RR Avenue Bridge (in the spring), although higher concentrations were evident in the open bay in the late fall (i.e., October and November). Concentrations were highest in April, decreased to near undetectable levels in June and July, and increased in the late summer and fall. In April/May, concentrations fell above the theoretical-conservative mixing line (see above and **Figure 2**), suggesting that processes within the marsh system (ammonification/nitrification) were adding nitrate to the creek during transport. In June/July and August, while input concentrations were approximately 55 µg N/L, downstream concentrations were below the mixing line, indicating that algae, and possibly denitrification, (Velinsky et al., 2017) were reducing the levels of nitrate in the creek water. In this summertime period, concentrations were as low as 0.4 to 0.7 µg N/L. In the fall, the profiles shifted, with higher concentrations of dissolved nitrate in the bay than in the tidal creek moving through the marsh complex. It is possible that net biological processes (i.e., uptake and remineralization) were slowing down, resulting in no major changes in the creek's water chemistry. During October and November, while concentrations were higher in the bay there appeared to be a net conservative mixing down the creek.

Dissolved Ammonium+Ammonia (ammonium)

As with dissolved nitrate, dissolved ammonium showed substantial changes in concentrations and downstream distribution during the year (**Figure 7**). Concentrations at the approximate head of tide (RR Avenue Bridge, while overall concentrations ranged from 5.4 to 172 µg N/L.

In April, concentrations were variable in the upper creek, decreasing slightly downstream, with small increases in the bay water samples (**Figure 7**). In May, there appeared to be a substantial increase to 95 µg N/L down creek before a marked decrease in the bay samples. This distribution indicates there was a source of ammonium within the marsh complex to the tidal creek, such as organic matter remineralization to ammonium (i.e., ammonification). For the profiles in June and July, concentrations decreased, and were fairly constant, from the freshwater to bay endmember. The latter part of the year showed higher concentrations in the bay relative to the input to the bay, with a source of ammonium from the marsh in August and October (i.e., data fall above the conservative mixing line), while in November, there appeared to be linear increase from the tidal fresh to bay endmember (**Figure 7**).

These profiles illustrate the dynamic processes impacting dissolved ammonium during the year. In May, higher concentrations were noted due to the release of ammonium from remineralization of organic matter, while in the summer, lower levels were recorded presumably due to biological activity (i.e., uptake and nitrification, $NH_4 >> NO_{2,3}$). These processes changed during the year, with bay water eventually containing more dissolved ammonium, mixing with lower concentrations of tidal creek water.

Dissolved Organic and Total Dissolved Nitrogen

Total dissolved nitrogen (TDN) is the sum of nitrate and ammonium, along with dissolved organic nitrogen (DON). DON is a mixture of proteins, amino acids, and amino-sugars, along with humic-N compounds (McCarthy et al., 1997; Seitzinger and Sanders, 1997; Berman and Bronk, 2003; Sipler and Bronk, 2015). In many cases, it is a dominant form of dissolved nitrogen in marine and freshwater systems. DON is an important intermediary in the nitrogen cycle and has also been shown to be a direct source of nitrogen to some algal species (Seitzinger and Sanders, 1997; Seitzinger et al., 2002; Sipler and Bronk, 2015).

In this study, dissolved organic nitrogen comprised a substantial, and at times, a major component of TDN, with concentrations ranging from 81 to 380 μg N/L, accounting for between 45 and 98% of TDN (**Figure 8**). The highest percentages of DON were measured in May, June and July, ranging from 80 to 90% of the TDN, while in the other sampling periods, the fractions were lower, at approximately 70%. These distributions illustrate that DON is a major part of TDN, with substantial variability in its concentrations during the year.

Interestingly, the DON-salinity distributions are similar during the year. In all months, the bay endmember exhibited higher concentrations (277 ± 64 μg N/L) than the riverine input from the watershed (144 ± 55 μg N/L). In all distributions, some months more than others, the data falls above the conservative mixing line (**Figure 8**), with the largest increase in June and July. This suggests that drainage from the organic-rich marsh complex contained a substantial source of DON, most likely from the remineralization of plant organic matter. As DON is a dominant component of TDN, the salinity-TDN seasonal distribution is somewhat similar (**Figure 9**). The downstream endmember mean concentration of TDN was higher (363 ±120 μg N/L) than the upstream mean concentration (206 ± 50 μg N/L). Other than in the June and August sampling periods, there appeared to be a source of TDN from within the marsh complex, as water moved down the creek, i.e., there is a slight convex distribution between endmembers. This is especially notable in the May, July and October sampling periods.

Soluble Reactive and Total Dissolved Phosphorus

Total dissolved phosphorus (TDP) is comprised of soluble reactive phosphorus (SRP) and dissolved organic phosphorus. Organic phosphorus is an important fraction of bioavailable P and impacts nutrient budgets in many aquatic systems (Bentzen et al., 1992; Monaghan and Ruttenberg, 1999; Karl and Björkman, 2015; Thompson and Cotner, 2018) and is a largely overlooked source of phosphorus. Marine DOP contains mostly three major classes of compounds: P-esters, P-anhydrides and phosphonates that can vary over space and time (Young and Ingall, 2010). Exclusion of DOP may lead to erroneous estimates of the bioavailable P reservoir, affecting assessments of nutrient limitation and available nutrient budgets.

Soluble reactive phosphorus (SRP) concentrations ranged from < 0.50 μg P/L at the riverine endmember to approximately 45 μg P/L at the mainstem bay endmember (**Figure 10**). In most months, the distribution appeared to show conservative mixing from the RR Avenue Bridge to the bay, with the exception of the May and October profiles, in which there appeared to be a small source in the upper/middle portion of the tidal creek. Dissolved organic phosphorus ranged in concentrations from <0.5 to 25 μg P/L, and accounted on average, between 18 and 64% of the total dissolved phosphorus for each survey (overall range of 0 to 88%). As with other studies, the values in the Westecunk Creek indicated that the dissolved organic forms of phosphorus are important in considering fluxes and potential biological impacts.

Monthly longitudinal distributions of total dissolved phosphorus (TDP) and salinity are shown in **Figure 11**. Concentrations of TDP were higher in the open bay (average of 36 μg P/L) than in waters entering the tidal creek (average of 1 μg P/L). In most surveys, there was only a slight deviation from a linear salinity distribution. The May, August and October surveys showed a slight to moderate positive deviation relative to a conservative mixing line, indicating a small net source from the creek/marsh complex to the tidal waters. The positive deviation can be the result of many processes including adsorption/desorption reactions along the salinity gradient (Fox, 1989; Sundareshwar and Morris, 1999; Weston et al., 2006), marsh/benthic flux processes (Paudel et al, 2017), as well as algal degradation (Diaz et al., 2018 and other).

Dissolved Silica

Silica is considered a limiting nutrient as it is critical for the growth of diatoms, both planktonic and benthic, and is also used by many other forms of aquatic and terrestrial vegetation. The primary source of silica is the chemical weathering of silicate minerals and transport via rivers, a strictly geochemical process. However, it has been shown by Bartoli (1983) that vegetation can sequester a substantial amount of silica in their structural parts and when broken down, be part of the silica biogeochemical cycle in estuaries (Struyf and Conley 2010; 2012; Fagherazzi et al., 2013). Even with these biological processes, the watershed is still a major source of silica to coastal and marine waters (Tregur and De La Rocha, 2013). Salt marshes accumulate large amounts of biogenic silica present in plants (i.e., *Spartina sp*), sponges, and diatoms in sediments and vegetation (Struyf and Conley 2012; Fagerazzi et al. 2013). The biologically-incorporated silica can be recycled to create dissolved forms, mainly in pore water and surface puddles on the marsh. During ebb tide, this dissolved silica can be exported again to the tidal creek and bay, where it can be an important source of Si for planktonic diatoms.

In Westecunk Creek, the concentrations of dissolved silica at the RR Bridge site were similar from April to August, with an average of 2400 ± 203 µg Si/L **(Figure 12**). In the fall surveys (October and November), concentrations decreased dramatically at the RR Avenue Bridge site to an average of ~76 µg Si/L. This large decrease is not easily understood at this time; especially with regards to the other nutrients like nitrate, ammonium and SRP. One possibility is related to the large, constructed ponds just upstream of the Garden State Parkway (**Figure 13**). At the gauge in Stafford Forge (USGS 1409280) there is a small dam on the creek and water can form large shallow ponds. There have been numerous studies showing impounded systems (i.e., reservoirs or small ponds) as effective sinks for silica that can impact the algal ecology downstream (Humborg et al. 1997; 2000; Friedl et al. 2004; Fairchild and Velinsky, 2006; Wang et al. 2018; Winton et al. 2019). It is possible that in the late summer/fall there was a substantial bloom of diatoms that lowered the concentrations going past the gauge at Stafford Forge. The other nutrients should also be impacted but might be harder to detect. For example, dissolved ammonium and SRP are both very low in concentration at the upstream location, so harder to detect any changes, while dissolved nitrate is more consistent over time and does not show substantial seasonal change in concentrations.

The downstream salinity-silica distribution exhibits mostly conservative mixing from April to August, while in October and November, the distribution exhibits a convex shape that indicates a source of silica from the surrounding marsh complex. In the spring/summer the appearance of conservative mixing reflects lower biological uptake relative to the amount of silica present coming from the watershed through the marsh complex. With the reduction in upstream concentrations in October/November, along with the degradation of biogenic silica in the marsh in the fall, there is an observable efflux of silica from the marsh system to the adjacent creek that mixes with the bay. These distributions illustrate the importance of the solubilization of biogenic silica in a marsh system and how it can impact the levels in the adjacent creek water (Struyf and Conley, 2012; Fagherazzi et al., 2013).

Dissolved Organic Carbon (DOC)

The transport and alterations of organic carbon through estuaries and tidal wetlands has been a topic of many studies and can play a key role in the cycling of organic matter in the coastal system (Sholkovitz, 1976; Mantoura and Woodward, 1983; Fox, 1984; Spencer et al 2007, Clark et al. 2019 and others). Tidal marshes can export large quantities of dissolved organic carbon to an estuary and play a large role in the transport of many bio-active elements (Cai, 2011; Herrmann et al., 2014).

In Westecunk Creek, surface water dissolved organic carbon (DOC) concentrations ranged from 2 mg C/L to 13 mg C/L. Higher concentrations were generally seen in the upstream sections of the marsh complex at low salinities (5.9 ± 3.5 mg C/L), with lower concentrations in the open bay waters. (2.5 ± 0.6 mg C/L; **Figure 14**). The upstream input concentration was more variable, with higher concentrations observed in May, October and November and more similar concentrations measured during the other time periods (**Appendix I**). The highest upstream concentration in May (12.5 mg C/L) was associated with the highest discharge (47 CFS; over a three-day average) from the watershed.

The salinity-DOC profiles exhibited conservative behavior during most sampling periods (**Figure 14**). While in the June and July surveys, there was non-conservative behavior, with higher concentrations found in the mid-salinities between approximately 2 to 15 psu, suggesting a source from the marsh complex. During tidal changes, particularly ebbing tide, pore fluids enriched in DOC can seep from the marsh. This source could be from remineralization within the water column of particulate forms of OC (e.g., algal, plant debris) or the drainage through the creekbanks of marsh-derived organic carbon. Howes and Goehringer (1984) showed that creekbank export of DOC was not a significant export pathway from a salt marsh in Massachusetts to tidal waters. However, more recent studies show that marshes can export dissolved organic matter at ebbing tide (Tzortziou et al., 2008; Tobias and Neubauer, 2009). Osburn et al (2015) calculated that marsh habitats exported both DOC and POC in May, July, and August, but imported material in the fall.

C3- Summary: Biogeochemical Processing during Estuarine Mixing

The transport of nutrients from the watershed to the coastal region can be modified through biogeochemical mixing processes in adjacent marshes. Processes such as algal uptake, bacterial remineralization, adsorption-desorption reactions, photochemical reactions, as well as exchange with the marsh itself, can alter the transport of dissolved material to the open bay and coastal areas through marsh systems (Childer et al. 2000).

In this portion of the study, nitrate is the only primary nutrient that exhibited substantial non-conservative behavior during estuarine mixing within the marsh complex (**Figure 6**). In the spring, there are indications of a source of nitrate within the tidal creek/marsh complex, shifting towards an almost complete removal during the summer months, but changing to a more conservative mixing mode in the fall, with higher concentrations in the open bay, compared to inputs to the tidal creek.

There are multiple processes that may impact these changes over time. As the temperature increases (April-May) resulting in higher microbial activity, the remineralization of organic matter will be more active, releasing dissolved organic nitrogen and ammonium to the creek and pore fluids of the marsh. With the buildup of ammonium, nitrification, the oxidation of NH_4^+ to NO_3^- , occurs more readily in oxic environments, through the activity of nitrifying prokaryotes. In the summer months, there are two potential processes that can reduce the concentrations of dissolved nitrate in the water column: algal uptake and denitrification. An indicator of algal productivity is the buildup and standing stock of chlorophyll *a* in the water column. There were substantial changes in water column chlorophyll *a* concentrations during the sampling period (**Figure 15**). In summary, chlorophyll-*a* concentrations were very low in April/May, increasing in June-July, and decreasing in the fall. The high concentrations measured in the summer indicate that algal uptake reduced the levels of both nitrate and ammonium to lower levels during this period.

Phosphorus levels generally increased from the head of tide (near RR Avenue Bridge) to the mainstem bay in most months (except May; **Figure 10-11**). The increase in concentrations within the marsh complex was most likely due to the desorption reactions with increasing salinity, as well as the remineralization of particulate bound phosphorus. Low oxygen environments in bottom and marsh sediments result in the dissolution of iron/manganese solid phases and the release of inorganic phosphorus (Paudel et al., 2017 and others).

D: Westecunk Creek Nutrient Import – Export Studies

The goal of this study was to document and understand the changes in nutrient chemistry in the creek as it flows through the tidal portion of the Creek and mixes with estuarine waters entering from Barnegat Bay. As mentioned previously, two methods were utilized for this study, (1) documenting the relationship between nutrient concentrations and salinity longitudinally down the tidal creek, and (2) calculating the mass-loadings in nutrients entering and leaving the tidal creek during selected flood and ebb tidal cycles.

In this section the mass-loading study (2) is described, and data presented. The study involved sampling the tidal creek at the head-of-tide, near the junction of the creek and bay, and at the junction of a small tributary mid-way along the creek (See **Figure 4**). The main focus was at the junction of the creek with the bay. Water samples were collected, and water quality parameters recorded hourly over 24-hour periods during May, August, and November. These data show how the creek chemistry changed during flood and ebb tides.

To understand the longitudinal changes in water chemistry, and to calculate mass loadings during tide cycles, the volumes of water entering the creek from the watershed and from the Bay are required. Discharges entering the tidal creek have been measured by the USGS at the head-of-tide for many years, and the stage-discharge relationship is well calibrated. The tidal exchange of water from the Bay is more difficult to measure. As part of this work, automatic velocity measuring equipment was temporarily installed mid-way in the creek, and the velocity-stage-discharge relationship was established for both ebb and flood tides.

D1- Field Sampling and Methods

This phase of the sampling program was the collection of water at three fixed locations in the tidal creek over multiple tidal cycles (~30 hrs). These collections occurred three times during the program – May, August and early November. For each time period, samples were collected at the Railroad Avenue Bridge (RR), downstream of South Creek Drive (SCD) at entrance of South Creek and Westecunk Creek, and further downstream from D&S Marine Services (Leon's Dock) (460 Dock Road: **Figure 4**). Water-quality monitoring sondes and Acoustic Doppler Velocity meters (ADVMs) were used to measure flow and tidal stage in the channels and were attached to dock structures at these three locations.

At the Leon's Dock site, the bottom topography was recorded prior to the start of the sampling program so that the cross-sectional area could be calculated during each tidal period. This information was used to calculate water and solute movement up and down the tidal creek. Battery-powered automatic samplers (ISCO) were used to collect hourly water samples for 30 hrs., covering two plus tidal cycles (Jorden et al. 1983; Velinsky et al 2000). Samples were collected, stored on ice, and shipped back to the Academy for processing. During each collection, field duplicates were taken, along with equipment blanks (1 set per 15 samples). All gear was washed carefully, rinsed with dilute HCL, then rinsed with double deionized water (DDW) and stored in a dust free environment.

Figure 3 shows the locations of the fixed sampling stations used for the mass-loading study, and the locations of gaging stations used. Samples collected at the Railroad Avenue Bridge represent the freshwater (FW) endmember, while samples collected at the terminal station (Leon's Dock), represent the Barnegat Bay endmember. Leon's Dock is located approximately at station 15 of the longitudinal study. The hydrologic and chemical data described in this section include:

1. Hydrologic data (discharge, velocity, direction) measured by the USGS at the head-of-tide and the mid-creek station identified as "ADVM dock" in **Figure 16**.
2. The chemical analysis of creek water collected at three sites in the tidal stream and the mass exchange of nutrients calculated to enter and leave the tidal portion of the creek.

Field work was conducted in 2018, and involved the following activities:

1 Discharge of freshwater was measured at two USGS gauge stations, Station 01409280 on Westecunk Creek at Stafford Forge NJ that provides the discharge from the watershed and at RR Avenue Bridge (USGS Station 01409281), which represents the farthest upstream

point affected by the tidal influence of the Bay. Instrumentation at Stafford Forge includes a continuous "bubbler" type measurement system. The stage-discharge relation for this site was developed over many years and is verified, at least yearly, by making cross-channel discharge measurements. The site at RR Avenue Bridge was established for the New Jersey Barnegat Bay project. Discharge was measured manually periodically throughout 2018. Beginning in mid-summer of 2018, an automatic recording water level (pressure) sensor was deployed in the stream bottom at the bridge. The data from this sensor was used to verify the extent of tidal influence at this point.

2 Discharge, velocity, and direction in the tidal creek were measured at a station established on a dock (ADVM dock USGS 0140928320 Westecunk Creek 3700 ft upstream of the mouth West Creek NJ) mid-way between RR Avenue Bridge and the point where the tidal creek enters Barnegat Bay. Tidal currents were measured using a side looking ADVM unit installed on a dock pier. The stage-discharge-velocity relation for the ADVM was developed and checked three times shortly before each sampling event. Calibration involved making cross-channel measurements in a boat equipped with a downward facing Acoustic Doppler Current profiler (ADCP); cross-sections were measured approximately every 30 minutes over approximately 8 hours (1 full tidal cycle). The ADVM data were collected and processed by the Surface Water section of the USGS-NJ Water Science Center. The USGS published only the daily total discharge (the net sum of flood and ebb tides) for the period May through November 2018. The ADVM data, however, was measured continuously at 6-minute intervals; these data were obtained and used in this report.

3 As mentioned above, the tidal portion of Westecunk Creek was sampled during 7 field trips in 2018. This "longitudinal" sampling was conducted from a boat that slowly moved downstream from near RR Avenue Bridge to the Bay during ebb tide; ebb tide commonly occurred during the morning hours. The boat progressed downstream, stopping to sample and measure water quality parameters at multiple stations relative to space and salinity. The farthest downstream station was located downstream of the Leon's Dock station and was salinity dependent (approx. range 25-30 psu).

4 During three of the longitudinal sampling trips, the USGS deployed automatic samplers (ISCO) at 3 locations along the Creek to collect water samples. Autosamplers were deployed at the Railroad Avenue Bridge, at South Creek Drive (SCD) Bridge, and at the end of private dock (labeled Leon's Dock) near where the tidal creek joins the Bay. South Creek is a small wetland tidal creek that joins the Bay at a point south of Westecunk Creek. South Creek therefore represents a "short-cut" that supplies water from the Bay during flood tides and allows water to by-pass the ADVM measuring point. The contribution of this creek is unknown, but its tortuous path, small width, and shallow depth likely results in it having a minor influence on Westecunk Creek. The autosamplers had sampling intake tubes suspended on buoys that maintained the inlet (sampling point) 1 foot below the water surface. Samples were collected at 1-hour intervals for 24-hours; these samples were used for analyses of suspended sediment and nutrients. Water quality sondes were also deployed at these sites during the sampling events and were set at approximately 1 foot above the stream bed. These sondes continuously recorded water quality parameters including temperature, dissolved oxygen, specific conductance, and turbidity. The continuous data were verified by a USGS-NJ Water Quality Specialist and entered into the USGS NWIS Data Base.

5 In July 2018, an Aquatroll 200 recording pressure gauge was deployed at the ADVM dock, and the sensor set approximately 1 foot above the stream bed. This instrument measured pressure, specific conductance/salinity, and temperature. A second pressure transducer was installed on the dock to measure and correct for air pressure. These sensors were deployed by Dr. Wilson and the data produced are not official USGS-approved data.

6 All analytical methods were similar to those described above in Section B2.

D2 - Results

The principal hydrologic data include the discharge, velocity, and flow direction measured at the ADVM dock. These measurements allow the quantity of water passing the dock during each ebb and flood tide to be calculated. **Table 3** provides a summary of the available ADVM data. As planned, ADVM data were obtained for most of the sampling trips. However, gaps were found in the data, most likely due to equipment malfunctions or data that were removed during the USGS QA review process.

Two significant intervals were found to be missing data as they covered the April 11 and October 2 sampling trips. These intervals were:

April 11. The initial ADVM powerup occurred at 13:18 on April 11, while the sampling began earlier in the day. Volumes for the April 11 flood and ebb tides were calculated using data from the corresponding tide cycles on April 12.

October 2. No ADVM data were found for the period.

It is important to note that the USGS reported on "Approved" data for the average daily discharge. The calculations made herein used "provisional" discharge/velocity data measured at 6-minute intervals. These data were downloaded from the publicly accessible NWIS web page during 2018. Calculating the volume of water passing the ADVM dock required both the water velocity (in meters per second, m/s) and the cross-channel area (in square meters, m^2). The ADVM provides direct measurements of water velocity in the sonic beam that extends from the instrument outwards. In this project, the ADVM measurement area nearly extended across the stream, and as such, is a representative measure of the stream. The cross-sectional area is more difficult to ascertain because this dimension changes over each tidal cycle, and the tidal ranges in the Bay are typically around 1 meter. The boundaries of the tidal creek are, in many places, poorly defined because of the marsh located along the north shore of the creek. Along the south shore the bank is constrained by sheet pilings and the road levy.

To estimate cross-channel area, a method was devised to relate tidal stage to cross channel area using ADCP data collected during the cross-channel calibration effort. During calibration, the ADCP measured water depth (below the boat), the unit-cell discharge in multiple layers, and the cross-channel area represented by the boat course as it traversed the creek. The channel area reported for each traverse was plotted against the water pressure measured by the ADVM mounted on the dock. Although pressure could be converted to stage (using water density), water pressure was used due to the limited salinity/density data available. A least-squares linear regression was generated from the pressure-area data, which subsequently allowed the cross-sectional area to be estimated from the continuous ADVM record. Two equations based on date of calibration measurements were developed. **Figure 16** is a plot of the data set from the calibration measurements made over approximately 8 hours on May 23. The least-square relations were very good for both equations.

The equations used to relate pressure to cross-channel area used in this work are:

For 4/23 thru 7/31/18 sampling

$$\text{Area } (m^2) = (94.155 * P) + 65.152 \qquad r^2 = 0.96$$

For 8/23 thru 11/2/18 sampling:

$$\text{Area } (m^2) = (96.837 * P) + 67.743 \qquad r^2 = 0.91$$

Where P is water pressure in decibars measured by the ADVM.

It should be noted that the areas calculated using these equations slightly underrepresent the actual area because the boat could not traverse the entire width of the channel. However, the unmeasured area represents a very small portion of the stream cross section. It was also assumed that the effect of salinity on pressure was negligible over the range of salinities measured in the stream (10 to 24 psu).

For each ADVM data point, the cross-section area was estimated from the water pressure and combined with water velocity to estimate the instantaneous discharge across the channel. The compass heading of water travel was also measured. Because flow in Westecunk Creek is nearly east-west the sign of the discharge was provided by:

- For ebb tide, when measured directions were between 0-180 degrees (easterly), the velocity and discharge are reported as a positive value.

- For flood tide, when measured directions were between 180 and 360 degrees (westerly), the velocity and discharge are reported as a negative value.

Freshwater at the RR Avenue Bridge is always easterly and given a positive sign. Although the velocity of the water decreases and stage rises at the bridge as the tide rises, the freshwater is simply backing up and is returned downstream as tide stage falls. *Thus, discharge during flood tide is given as a – (negative) value, and during ebb tide it is reported as a + (positive) value; this convention is consistent with the USGS method for reporting discharge in tidal rivers.* Discharge was then summed for each tide cycle in the record. Flood tide started at the switch in direction from E to W, and ebb tide when the direction reversed. Inertial effects cause the times of high and low tide to differ slightly from the times when the tide reverses (as determined from flow direction measured by the ADVM).

Importantly, to determine the volumes of water, and subsequently the mass loadings of dissolved nutrients exchanged between the watershed and the Bay, the total discharge was calculated for the flood tide cycle preceding the sampling period, and then for the ebb cycle over which sampling occurred. Freshwater leaving the watershed was added to both the flood and ebb volumes to obtain the total water volume moving through the tidal creek. **Table 4** presents the volumes of water, water balance, and percent freshwater and Bay water in the volume. These volumes can be used to calculate the mass of sediment and nutrients entering and leaving the tidal Westecunk Creek. As a check on these calculations, the average discharge, average velocity, and average cross-channel areas were used to calculate the flood and ebb tide discharges for each sampling date.

The calculations show that, except for the July 27 sampling effort, less than a 20% difference was found between flood and ebb tide volumes, with most dates having differences of about -6%, indicating that more water left during ebb than entered during the preceding flood tide. Several phenomena may explain these differences and variation in the calculated volumes. For instance, excess water from early tide cycles may have been stored in the marsh and depending on the tides in the Bay, was released during later ebb tides. Also, strong onshore winds may inhibit easterly flow, causing water to “pile up” in the creek during ebb tide; this extra water is then released during subsequent tides. Finally, as mentioned earlier, a small bypass is provided by South Creek, allowing some water to enter and leave without passing the ADVM dock. The impact of this circuiting is unknown, and the effect may not be equal during flood and ebb cycles. However, the effect is assumed to be equal in both flood and ebb cycles and would have offsetting influence on the volumes presented in **Tables 2-4**.

<u>D3 - Nutrient mass-transfer during tide cycles</u>

The masses of nutrients, sediment, and carbon transferred between the Bay and the tidal Westecunk Creek were determined using the volumes of water and concentration data for the flood tides preceding sampling, and for the ebb tides over the time when samples were collected. The total mass load is the sum of the masses in the freshwater entering during each cycle, plus the mass in water passing the ADVM dock. Constituent mass is calculated using the average concentrations in multiple samples times the volumes of water and a conversion factor. Volumes of water in the flood and ebb tides passing the ADVM dock, and freshwater entering from the watershed, are used for mass transfers **(Table 4).** Loads are reported in units of grams for species reported in micrograms per liter, or kilograms for species reported in units of milligrams per liter.

$$\text{Mass load in grams} = ((\text{average concentration in } \mu g/L) *1000)/(m^3 \text{ of water}/10^6)$$

$$\text{Mass load in kilograms} = (\text{average concentration in mg/L}) *1000)/(m^3 \text{ of water }/10^6)$$

Concentrations of the various constituents were the averages of concentrations in the samples collected using the autosampler for the tide intervals determined from the flow direction. The automatic samplers were programmed to collect 1L of water each hour, so depending on the timing of the start of flood and ebb cycles, between 3 and 7 individual samples were available for each tide cycle.

Tables 3 and 4 present the sample identifiers, the times of collection and concentrations of constituents in the samples used to calculate the average concentrations for the May, August, and November sampling efforts, respectively. The mass loadings of each component are presented in **Tables 5-8.**

Total dissolved P, total dissolved N, total particulate C, and TSS were used as examples of the phosphorous, nitrogen, carbon, and sediment mass transfer during the May, August, and November sampling events. These data were from samples collected from Leon's Dock, located downstream in the tidal creek near where it empties into Barnegat Bay, and from samples collected at the Railroad Avenue Bridge. Differences in masses of constituents represent a net transfer either into the tidal creek or into the Bay.

The concentrations used and the calculated mass loadings are summarized in **Table 9**. These data show that TDN and TP were higher in the ebb tide compared with the flood tide on all three sampling dates. These concentrations result in a net mass loss of N and P from the watershed to the Bay. The magnitude of the losses varied over the three months, with the highest loss in May, and relate to both hydrologic/tidal influences in water transfer, and changes in concentrations in the endmember waters. These results indicate that the watershed and tidal marsh are net sources for these nutrients to the Bay, at least over a short time period. Particulate carbon concentrations are higher, or nearly equal, in the ebb tide compared with flood tide in May and November, and a net loss in mass from the watershed to the Bay is indicated. However, a gain in net particulate carbon mass within the tidal creek is found in August. This net increase may be the result of algae in the Bay, where high algal populations are typical throughout the summer months. The data for suspended sediment indicates the tidal creek gains sediment in May but loses sediment in August and November to the Bay. These transfers are expected to be mimicked by particulate nitrogen and phosphorous. The loss of sediment mass likely represents increased erosion in the marshlands during the spring and fall weather. The magnitude of the gains and losses changes in relation to the magnitude of the volume of water leaving the watershed and from the tidal and weather factors that affect the Bay. These three dates, however, provide a relative picture of the mass transfer of nutrients, carbon, and sediment exchange between the watershed and the Bay.

D4 - Summary of Import and Export

Table 10 presents a summary of material changes for primary nutrients (e.g., nitrate, ammonium, and soluble reactive phosphorus). These parameters were selected both due to their primary role in algal production within the bay and the observed changes along the longitudinal transects. Important to this discussion is a statistical analysis of the changes and how the tidal input/export results tie into the longitudinal sampling. The transects are a snapshot in time while the tidal exchange goes over multiple ebb and flood time periods. Overall, the water fluxes generally agree to within 5% of the total water flux, so this provides an idea of the level of comparability in the masses that were calculated.

The summary shows the amount of a nutrient coming into the creek, between RR Avenue Bridge and Leon's Dock during flood tide and the amount of a nutrient flowing out of that region from Leon's Dock (in grams) all in a similar time frame.

Dissolved nitrate (nitrate+nitrite) exhibits a substantial change during the year, with very low concentrations during the early to mid-summer months (**Figure 6**). In the May sampling, the distribution of nitrate reflects a source of nitrogen in the tidal creek, decreasing towards the open bay. The tidal flux study also suggests a source of nitrate within the tidal river creek (**Table 10**), with more nitrate ebbing out of the system compared to inputs. The source of nitrate could be related to ammonium release/diffusion from bottom/adjacent marsh sediments and nitrification within the creek waters. In August, the longitudinal transect indicated a net removal of nitrate from the creek. This was also indicated by the tidal flux study which showed a small, but negative, removal. The removal was most likely related to algal uptake (**Figure 15**), denitrification, and potentially plant uptake, within the marsh complex. In the early November transect, there was an indication of a small increase in the upper sections of the creek, while the tidal flux sampling also indicated a source of nitrate from within the tidal creek. Interestingly, the two methods appear to show a more complex result in November. The longitudinal work does suggest a more conservative mixing distribution (i.e., more linear) but the flux study suggests a source in the marsh creek.

Dissolved ammonium (ammonia+ammonium) also showed complex seasonal changes in the tidal creek (**Figure 7**). Notably, there was a large concentration increase in the tidal creek in May, with lower concentrations in early to mid-summer. In the late summer to fall, concentrations increased downriver towards the bay. By November, it appeared that there was a net conservative mixing from the RR Avenue Bridge location to the bay itself. The tidal flux studies indicate that watershed inputs are low throughout the year and more ammonium was leaving the tidal creek (i.e., the marsh was a net source of ammonium to the bay). This was especially evident in the May and November sampling periods (**Table 10**); but there is some complexity. For example, in May (**Figure 7**), the large non-conservative behavior reflected a source from the marsh complex (i.e., organic matter remineralization and ammonification) and the tidal flux study also indicated a source in the creek. This was not observed in the November period which indicated a conservative mixing from RR Avenue Bridge to the bay. While the differences will need to be reconciled, the flux data does show that the marsh can be a larger contributor of dissolved ammonium than the watershed.

Soluble reactive phosphorus (SRP), like the other primary nutrients, exhibited interesting changes over the year (**Figure 10**). In general, concentrations were lowest from the watershed, increasing towards the bay. Most longitudinal profiles exhibited conservative mixing, except in May and October, which reflect a potential source of SRP from the marsh complex to the tidal waters. The tidal flux study is more complex and does not compare closely, except in May. The May profile suggests a source of SRP from the marsh complex, and this is also evident from the tidal study that shows non-conservative behavior and an input from the marsh/tidal creek (**Table 10; Figure 10**). However, in the August and November time periods, the transects showed either a small source from the marsh complex or conservative mixing, respectively, while the tidal flux work indicated either a sink or large source within the creek/marsh complex. Sources of inorganic phosphorus could be from remineralization of organic matter and potentially increase reducing conditions within the sediments that could release bound phosphorus from iron/manganese solid phases. The complexity of the system at this point, with regards to these two methods, needs further analysis especially with teasing out the hydrodynamics of the tidal system.

E. Conclusions and Future Directions

Information regarding the exchange and transformation of nutrients in tidal marshes are complex, especially how they might modify the flow of nutrients from the watershed that flow to coastal areas. 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 (e.g., plant and algal uptake, denitrification); releasing material during the fall and winter. 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 low. 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; Tobias and Neubauer, 2009). 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, as in this study, the adjacent tidal creek.

In addition, the method of assessment is key to testing a tidal exchange process. Longitudinal studies using salinity-nutrient profiles (Kaul and Froliech, 1984, Lebo and Sharp,1993, McGuirk Flynn, 2008) show the complexity of source/sinks within the tidal system and can be quantified. Marsh flume studies that include plants and sediments (Chalmers and Wiegert, 1985), and sediment core incubations (Scudlark and Church, 1989; Tobais and Newbauer, 2009), while used to address the same question, could provide different results and directions of fluxes due to the synergistic interactions of many processes within a specific marsh. Tidal channel studies between marsh and adjacent waterbodies can be more accurate in estimating the net flux between the two, but provide little information concerning the specific biogeochemical processes that are altering nutrient concentrations and forms (Anderson et al., 1997; Childers et al., 2000; Velinsky et al., 2000). Processes such as particle (nutrient) deposition and resuspension, nitrification, denitrification, and plant uptake can affect the distributions and concentrations 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.

In the current study, it is apparent that the concentrations of the primary plant nutrients, nitrate, ammonium, and phosphate, were altered to some degree during transport through the tidal marsh creek and complex of Westecunk Creek. During the warmer spring months, both nitrate and ammonium were taken up and transformed to algal biomass, as evidenced by increase chlorophyll *a* concentration, and evidentially cycled back to the dissolved phase as inorganic and, as shown, dissolved organic nitrogen; similarly with inorganic phosphorus. It is vital to understand the fate and transport of the dissolved organic fractions as they are a major fraction of the total dissolved nitrogen and phosphorus and can be transformed back to inorganic forms or taken up directly (McGuirk Flynn, 2008; Wieben et al., 2013). As seen in Westecunk Creek, the nitrogen/phosphorus transformations during transport within the watershed-creek-marsh systems are important to understand the total export of nitrogen and phosphorus to the bay. This information can help to understand the overall productivity of coastal waters.

Some key findings include:

- Nutrients from the watershed are transformed during transport through tidal wetlands during the year.
- The tidal wetlands can remove or add to the nutrient levels in the creek.
- Organic forms of nitrogen and phosphorus are a major component of the total dissolved burden, and
- Tidal channel studies can be an important tool in understanding the changes in nutrient concentrations and forms in waters that travel from the watershed to the mainstem bay.

Future Directions

This study, along with previous Barnegat Bay research, illustrates that the remaining marsh systems within the bay are important "bio-reactors" that can modify and supply or remove nitrogen and phosphorus. The results from the current study show how the various forms of nitrogen and phosphorus change forms from the watershed to the bay and that dissolved organic forms are a major component of the dissolved transport.

One area that needs to be considered, that was outside the scope of this project for Westecunk Creek, is the level and mode of transport of groundwater nutrients that could be transported under the marsh complex into the bay directly. Wieben et al (2013) found substantial levels of groundwater nitrate and undetectable levels of dissolved phosphate originating from the unconfined Kirkwood-Cohansey aquifer system. They concluded, via stable isotope analysis, that most nitrate was fertilizer derived. How the nitrate is transformed through the subsurface marsh complex is a question that has implications to the nutrient input to the overall bay.

For a better understanding of the areal extent of creek/bay water interactions with the tidal marsh, subsurface wells with dataloggers should be installed, along with precise GIS elevation analysis of the marsh structure. This would serve to obtain areal rates of nutrient changes and would serve to balance past studies of nutrient removal (e.g., denitrification; Velinsky et al 2017). This information could be then applied to other bay wetlands areas to help provide more accurate transformations and eventual transport.

The threats from coastal development and sea level rise will most likely result in further loss of the remaining wetlands, mainly in the southern sections of the bay. It is imperative that this information, along with previous work in the bay (e.g., Kennish, 2007; Buchannan et al 2017 and others), be used for the protection of the remaining wetlands in the bay as they are a major component that helps to maintain a healthy bay and serves to protect valuable near-shore infrastructure during extreme weather events.

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G: Tables

Table 1. Sampling dates and flow ranges for various dates.

Month/Day 2018	Program	Flow CFS[1]	Avg ± 1SD
April 11	Survey	30-32	31.9 ± 0.8
May 23	Survey	42-50	47.0 ± 2.8
May 23-24	Time Series	42-50	“”
June 27	Survey	24-26	25.5 ± 1.3
July 31	Survey	23-28	25.0 ± 1.3
August 20	Survey	18-22	21.2 ± 1.1
August 20-22	Time Series	18-22	“”
October 2	Survey	24-27	25.7 ± 1.2
November 7	Survey	35-37	39.2 ± 2.6
November 6-7	Time Series	35-37	“”

1-USGS 01409280 Westecunk Creek at Stafford Forge, NJ; approx. range during three-day period prior to sampling.

Table 2. Measurements, Methods and Target Detection Limits for Water/Sediment Analyses.

Measurement	Reference Method	Detection Limit
Sediment Organic C and TN, TS	US EPA, 1997	<0.1%OC, TN and <0.5%TS
Sediment TP	Aspila et al. 1976	0.008 %P
Chlorophyll-*a*	ANSP SOP	<0.5 µg/L
Dissolved Si	EPA 366	<1 µg Si/L
Dissolved SO4	Dionex AS18/154	<0.1 mg SO4/L
Dissolved Cl	Dionex AS18/154	<0.2 mg Cl/L
Dissolved N and P (various forms)	US EPA (1983 and 1997); ANSP SOPs	generally, < 1 or 5 µg N or P/L

Table 3. Summary of ADVM data available for Westecunk Creek, April through November 2018.

Folder Date[1]	Start date	Finish date	Sampling dates and times	
2018-05-01	4/11/18 13:18	5/1/18 8:10	4/11 8:48-13:12	
2018-5-23	5/1/18 9:12	5/23 8:18		
	5/23 8:36	5/23 17:24	5/23 7:05-10:10	
2018-5-25	5/23 17:42	5/25 11:12		
2018-08-14.1	4/11 13:18	5/1 8:18		
	5/1 9:12	5/23 8:18		
	5/23 8:36	5/23 17:24		
	5/23 17:42	5/25 11:12		
	5/25 11:24	7/31 8:24	7/31 13:06-16:14	6/23 10:40-12:53
2018-08-14.2	8/14 11:48	8/14 16:47		
2018-10-26	8/14 11:48	8/14 16:47		
	8/14 17:00	8/24 11:54	8/20 12:19-13:42	
	8/24 12:30	9/9 22:12		
	10/26 10:00	10/26 13:07		
2018-11-02	10/26 13:18	10/27 11:24		
	10/27 11:47	10/27 12:59		
	11/2 10:04	11/2 11:04		
	10/26 13:18	10/27 11:24		
	10/27 11:47	10/27 12:59		
	11/2 10:04	11/2 10:04		
	11/2 10:18	11/19 13:18	11/7 10:10-13:05	
Missing Intervals				
	7/31 13:06-16:14			
	10/2 12:00-11:48			

Note: 1. Each computer file contains ADVM data recorded from the start date/time to the finish date/time. Multiple files exist in each folder. Missing intervals of data represent either instrument malfunction, the instrument was off for servicing, or sections removed from the file during quality assurance review by the USGS Surface Water Specialist. Data are removed for several reasons, usually very low signal/noise ratio.

Table 4. Summary of water volumes during single flood and ebb tides during the intervals when sampling was conducted in the tidal portion of Westecunk Creek, 2018. {min, minutes; m^3, cubic meters; FW, freshwater; %, percent].

	FLOOD TIDE						EBB TIDE						
Sampling date	**Time**	**Duration of tide min.**	**Freshwater entering[1] m^3**	**Bay water entering[2] m^3**	**Total volume of water entering m^3**	**% fresh water**	**Time**	**Duration min**	**Freshwater entering[1] m^3**	**Water leaving [2] m^3**	**Total water leaving m^3**	**% FW**	**Difference (In-Out) m^3 and (%)[5]**
April 23	2:06-8:18	372	19,300	-223,000	242,000	8.1	8:24-15:42	444	22,900	173,000	198,000	12	44,200 (20)
May 23	0:12-6:00	348	26,400	-303,000	329,000	7.9	6:06-13:24	438	32,600	315,000	348,000	9.6	-18,600 (-5.5)
June 27	5:24-10:30	306	12,500	-133,000	146,000	8.3	10:36-15:54	318	12,900	239,000	252,000	5.3	-106,000 (-53)
July 30[4]	8:06-12:11	252	10,400	-206,000	216,000	5.1	12:17-19:17	420	17,100	213,000	231,000	8.3	-14,700 (-6.6)
August 20	21:36 (8/19)-3:00 (8/20)	324	11,340	-195,000	207,000	5.4	3:06 (8/20)-9:12 (8/20)	360	12,400	209,000	221,000	5.8	-14,700 (-6.9)
October 2	No data found	--	--	--	--	--	--	--	--	--	--	--	--
November 7	5:30-10:54	324	20,500	-311,000	331,000	6.3	11:00-18:12	432	27,300	335,000	382,000	7.5	-51,200 (-14)

Notes: 1. Freshwater input calculated as average discharge at USGS gauge station 01409280 over period of tide * duration of tide

2. Water entering or leaving is the volume of water flowing easterly past the ADVM dock site. The sign assigned to the flood tide indicates direction of flow, (-) is flood water entering the tidal creek, (+) indicates water leaving the creek and entering the Bay during ebb tide.

3. ADVM data collection began on 4/11/18 at 13:18, so data were not available for the morning ebb tide. The discharge for April 11 was calculated using the data collected for the corresponding morning flood and ebb tides on April 12.

4. ADVM data ended on 7/31/18 at 8:24, so flood and ebb tide volumes were calculated from ADVM data collected on July 30, during morning flood and ebb tides. On 7/31, the flood tide ran from 8:06-12:11 and ebb ran from 12:17 – 19:17. The flood tide volumes measured on July 30, and July 31 19:23-1:24, and ebb tides from 1:24-7:00, differ by 774 m^3.

5. Sign associated with the difference and percent difference indicate gain (+) to the tidal creek or loss (-) from the creek.

Table 5a. Concentrations and mass-loadings of constituents in samples collected at Railroad Avenue Bridge and Leon's Dock, May 23, 2018.

Constituent headings are defined below (Table 10).

Date	Tide	Time	Salinity (psu)	TDN ug N/L	TDP ug P/l	SRP µg/L	NH4-N ug N/l	NO3-N ug N/L	Silica ug Si/L	Cl mg/L	SO4 mg/L	DOC mg C/L	PP µg/L	PC ug C/L	PN ug N/L	TSS mg/L	Chl-a µg/L	Phaeo µg/L
Railroad Ave																		
			0.030	307	4.1	3.1	13.9	35.4	2,200	12.1	2.56	11.5	ND	453	53	0.8	--	0.2
5/23	Fl	4:00	0.030	301	3.4	3.1	11.3	36.4	2,220	12.4	2.58	12.1	ND	592	69	1.6	--	0.2
5/23	Fl	5:00	0.030	286	2.7	3.6	13.9	35.9	2,210	12.2	2.62	12.1	ND	473	56	0.3	--	0.1
5/23	Fl	6:00	0.030	291	2.2	3.7	15.6	36.1	2,210	12.0	2.59	12.0	ND	353	24	0.2	--	0.6
Ave	**Fl**		**0.030**	**298**	**3.4**	**3.3**	**13.0**	**35.9**	**2,210**	**12.3**	**2.6**	**11.9**	**--**	**506**	**59.4**	**0.9**	**--**	**0.2**
Mass (g)	**Fl**		**0.791**	**7,860**	**90**	**87**	**344**	**947**	**58,300**	**324**	**69**	**315**	**--**	**13,300**	**1,570**	**23.7**	**--**	**4.5**
5/23	EB	7:00	0.030	291	2.2	3.7	15.6	36.1	2,210	12.0	2.59	12.0	ND	353	24	0.2	--	0.6
5/23	EB	8:00	0.030	309	3.1	3.4	14.2	42.4	2,170	13.3	2.92	12.1	21.2	652	63	2.5	--	0.2
5/23	EB	9:00	0.030	291	2.5	2.5	12.0	38.2	2,200	12.0	2.60	12.0	20.5	476	51	2.2	--	0.2
5/23	EB	10:00	0.030	301	2.6	2.3	13.5	38.1	2,190	11.9	2.64	12.0	20.4	425	49	1.2	--	0.2
5/23	EB	11:00	0.030	292	4.4	3.0	14.8	36.1	2,200	11.9	2.62	12.0	3.5	504	52	1.0	--	0.2
5/23	EB	12:00	0.030	282	2.0	2.7	14.9	35.5	2,160	12.8	2.75	11.7	ND	457	28	0.0	--	0.2
5/23	EB	13:00	0.030	298	3.8	3.2	12.0	37.4	2,220	12.0	2.62	11.6	15.6	481	28	0.0	--	0.2
Ave	**EB**		**0.030**	**295**	**2.9**	**3.0**	**13.9**	**37.7**	**2,190**	**12.3**	**2.7**	**11.9**	**16.2**	**478**	**42.1**	**1.0**	**--**	**0.3**
Mass	**EB**		**0.978**	**9,610**	**96**	**98**	**453**	**1,230**	**71,400**	**400**	**88**	**389**	**529**	**15,600**	**1,370**	**33**	**--**	**9.8**

Masses are in grams except TSS which are kilograms

Table 5b. Concentrations and mass-loadings of constituents in samples collected at Railroad Avenue Bridge and Leon's Dock, May 23, 2018 – continued

Leon's Dock																		
Date	Tide	Time	Salinity (psu)	**TDN ug N/L**	**TDP ug P/l**	**SRP µg/L**	**NH4-N ug N/l**	**NO3-N ug N/L**	**Silica ug Si/L**	**Cl mg/L**	**SO4 mg/L**	**DOC mg C/L**	**PP µg/L**	**PC ug C/L**	**PN ug N/L**	**TSS mg/L**	**Chl-a µg/L**	**Phaeo µg/L**
5/23	Fl	4:00	15.7	350	12.7	4.9	25.1	15.0	796	9,030	1,240	5.2	25.7	901	132	53.3	5.8	0.5
5/23	Fl	5:00	20.3	325	16.4	3.4	6.2	2.3	433	11,600	1,600	3.8	28.7	814	126	119	6.7	0.1
5/23	Fl	6:00	20.7	314	18.1	3.2	10.3	0.7	390	12,000	1,670	3.7	26.9	640	101	86.6	5.9	0.4
Ave	**Fl**		**18.9**	**330**	**15.7**	**3.8**	**13.9**	**6.0**	**539**	**10,900**	**1,500**	**4.2**	**27.1**	**785**	**119**	**86.4**	**6.1**	**0.3**
Mass	**Fl**		**5,730**	**99,900**	**4,760**	**1,150**	**4,210**	**1,820**	**163,000**	**3,300,000**	**454,000**	**1,270**	**8,210**	**238,000**	**36,100**	**26,200**	**1,850**	**90.9**
5/23	EB	7:00	17.4	336	15.7	2.7	24.7	9.4	644	10,000	1,380	4.7	19.7	842	118	91.0	4.9	0.2
5/23	EB	8:00	12.5	395	13.5	4.2	55.8	21.3	1,108	7,010	964	6.4	30.7	933	129	56.1	2.8	0.9
5/23	EB	9:00	11.1	394	13.5	4.5	67.1	23.6	1,206	6,320	868	7.0	32.1	1,090	149	83.5	2.8	0.9
5/23	EB	10:00	8.5	421	12.1	5.6	84.8	31.2	1,460	4,770	653	8.2	14.5	956	122	34.3	1.6	1.3
5/23	EB	11:00	7.3	498	38.5	14.8	76.9	32.8	1,540	4,090	561	8.7	59.9	2,930	290	73.3	2.3	2.9
5/23	EB	12:00	5.7	457	27.2	8.0	81.8	34.1	1,650	3,210	433	9.4	38.7	1,610	195	40.1	1.7	1.6
5/23	EB	13:00	5.0	410	11.9	5.2	61.9	34.1	1,710	2,810	375	9.7	31.7	1,430	174	35.3	2.2	1.6
Ave	**EB**		**9.6**	**416**	**18.9**	**6.4**	**64.7**	**26.6**	**1,330**	**5,460**	**748**	**7.7**	**32.5**	**1,400**	**168**	**59.1**	**2.6**	**1.3**
Mass	**EB**		**3,030**	**131,000**	**5,960**	**2,020**	**20,400**	**8,390**	**419,000**	**1,720,000**	**236,000**	**2,430**	**10,200**	**442,000**	**53,000**	**18,600**	**820**	**421**

Table 5c. Mass-loadings of constituents in samples collected at Railroad Avenue Bridge and Leon's Dock, May 23, 2018.

	FW m³	Bay Water m³	Min-utes	Salinity (psu)	TDN g	TDP g	SRP g	NH4-N g	NO3-N g	Silica g	Cl kg	SO4 kg	DOC kg	PP g	PC g	PN g	TSS kg	Chla g	Phaeo g
FLOOD																			
FW	26,370	--	--	0.0	7,860	90	87	343	947	58,300	324	69	314	nd	13,300	1,570	23.7	-	5.3
BW	--	303,000	348	5,730	99,900	4,76	1,150	4,210	1,820	163,000	3,300,000	455,000	1,270	8,210	238,000	36,100	26,200	1,850	91
Total IN (FL)		329,000		5,730	108,000	4,850	1,240	4,550	2,770	222,000	3,300,000	455,000	1,590	--	251,000	37,600	26,200	1,850	96
EBB																			
FW	32,594	--	--	0.98	9,620	95	98	453	1,230	71,400	400	88	388	528	15,600	1,370	33	-	9.8
BW		315,000	438	3,030	131,000	5,970	2,020	20,400	8,390	419,000	1,720,000	236,000	2,430	10,200	442,000	53,000	18,600	820	410
Total OUT (EB)		348,000		3,030	141,000	6,060	2,120	20,900	9,630	491,000	1,720,000	236,000	2,820	10,800	457,000	54,400	18,700	820	420
Delta IN-OUT		-18,600	-90	2,690	-33,100	-1,210	-878	-16,300	-6,860	-269,000	1,580,000	219,000	-1,230	--	-206,000	-16,700	7,540	1,030	-324
% difference		-5.5	-23	62	-27	-22	-52	-128	-111	-76	63	63	-56	--	-58	-36	34	77	-123

Negative delta indicates net loss from tidal Westecunk Creek to Barnegat Bay. FW – RR Avenue Bridge (from watershed), BW – Bay Water

Table 6a. Concentrations and mass-loadings of constituents in samples collected at Railroad Avenue Bridge and Leon's Dock, August 20, 2018.

Date Sampled	Tide		Salinity (psu)	TDN ug N/L	TDP ug P/l	SRP µg/L	NH4-N ug N/l	NO3-N ug N/L	Silica ug Si/L	Cl mg/L	SO4 mg/L	DOC mg C/L	PP µg/L	PC ug C/L	PN ug N/L	TSS mg/L	Chl-a µg/L	Phaeo µg/L
Railroad Ave																		
8/20	Fl		0.030	215	4.6	3.9	23.7	51.6	nd	12.6	2.3	4.8	nd	599	66.8	-	-	--
Mass	**Fl**		**0.30**	**2,440**	**52**	**44**	**269**	**585**	**nd**	**143**	**26**	**54**	**0**	**6,790**	**758**	**--**	**-**	**--**
8/20	EB		0.030	274	1.5	4.0	25.6	51.9	2,700	12.9	2.3	4.0	nd	507	72.9	--	-	--
mass	**EB**		**0.37**	**3,400**	**19**	**50**	**318**	**644**	**33,500**	**160**	**28.6**	**49.7**	**nd**	**6,290**	**905**	**---**	**-**	**--**

Table 6b. Concentrations and mass-loadings of constituents in samples collected at Railroad Avenue Bridge and Leon's Dock, August 20, 2018. – continued

Leon's Dock																		
Date Sampled	Tide	Time	Salinity (psu)	TDN ug N/L	TDP ug P/l	SRP µg/L	NH4-N ug N/l	NO3-N ug N/L	Silica mg Si/L	Cl mg/L	SO4 mg/L	DOC mg C/L	PP µg/L	PC ug C/L	PN ug N/L	TSS mg/L	Chl-a µg/L	Phaeo µg/L
8/20/18	FL	13:34	12.0	387	32.1	19.7	61.3	28.0	13.1	7,647	1,113	4.7	47.3	1,532	258	10.8	29.1	16.6
8/20/18	FL	14:34	13.9	404	33.2	24.4	62.5	24.9	11.6	8,591	1,255	6.4	46.9	1,779	315	14.2	24.1	6.3
8/20/18	FL	15:34	16.0	406	33.2	25.4	79.6	25.2	11.8	9,937	1,462	7.0	42.2	1,869	330	17.8	20.2	7.9
8/20/18	FL	16:34	20.3	477	40.9	31.8	144	24.3	11.4	13,913	2,111	8.2	43.3	1,357	213	21.2	8.8	0.4
8/20/18	FL	17:34	24.6	522	51.5	41.8	160	27.9	13.0	16,659	2,570	8.7	42.1	1,340	215	19.4	7.9	1.2
8/20/18	FL	18:34	25.8	500	56.7	45.7	165	26.7	12.5	17,570	2,732	9.4	41.9	1,607	212	22.6	7.9	1.2
	FL	**Ave**	**18.8**	**450**	**41.3**	**31.5**	**112**	**26.2**	**12.2**	**12,400**	**1,873**	**7.4**	**44.0**	**1,580**	**257**	**17.7**	**16.3**	**5.6**
195,272 m^3		**Mass**	**3,670**	**87,900**	**8,064**	**6,150**	**21,900**	**5,110**	**2,380**	**2,420,000**	**366,000**	**1,450**	**8,590**	**308,000**	**50,200**	**3,460**	**3,180**	**1,090**
8/20/18	EB	10:34	13.2	455	37.6	27.7	143	30.4	14.2	9,163	1,345	5.2	34.7	1,412	201	10.4	10.9	0.3
8/20/18	EB	11:34	12.4	424	34.3	23.7	118	23.8	11.1	8,640	1,261	3.8	43.0	1,710	271	8.6	18.2	9.6
8/20/18	EB	12:34	10.8	469	38.7	24.2	86	33.3	15.6	7,729	1,122	3.7	53.9	2,003	335	9.7	32.6	9.3
	EB	**Ave**	**12.1**	**449**	**36.9**	**25.2**	**116**	**29.1**	**13.6**	**8,510**	**1,243**	**4.2**	**43.9**	**1,709**	**269**	**9.6**	**20.6**	**6.4**
208,926 m^3		**Mass**	**2,530**	**93,800**	**7,710**	**5,270**	**24,200**	**6,080**	**2,840**	**178,000**	**260,000**	**878**	**9,170**	**357,000**	**56,200**	**2,010**	**4,300**	**1,340**

Notes: Automatic sampling started at 8/20 10:34 during ebb tide, after the creek sampling had concluded; data from the preceding flood tide was not available at Leon's dock. Chemical data from the flood tide immediately following the ebb tide (beginning on 8/20 13:34) was substituted in place of the flood preceding the sampled ebb tide.

Table 6c. Mass-loadings of constituents in samples collected at Railroad Avenue Bridge and Leon's Dock, August 20, 2018.

	FW m^3	Bay Water m^3	Min-utes	Salinity (psu)	TDN g	TDP g	SRP g	NH4-N g	NO3-N g	Silica kg	Cl kg	SO4 kg	DOC kg	PP g	PC g	PN g	TSS kg	Chl-a g	Phaeo g
								FLOOD											
FW	11,340	--	--	0.34	2,440	52.2	44.2	269	585	nd	143	26.1	54.4	nd	6,790	758	--	--	--
BW	--	195,300	324	3,670	87,900	8,060	6,150	21,900	5,120	2,380	2,420,000	366,000	1,450	8,590	308,000	50,200	3,460	3,180	1,090
Total IN FL		207,000	--	3,670	90,300	8,120	6,200	22,100	5,700	2,380	2,420,000	366,000	1,500	8,590	315,000	50,900	3,460	3,180	1,090
								EBB											
FW	12,416			0.37	3,400	18.6	49.7	318	644	33,500	160	28.6	49.7	0	6,290	905	--	--	--
BW		208,926	360	2,530	93,900	7,710	5,270	24,200	6,080	2,840	1,780,000	260,000	878	9,170	357,000	56,200	2,010	4,300	1,340
Total out EB		221,000	--	2,530	97,200	7,730	5,320	24,600	6,720	36,400	1,780,000	260,000	927	9,170	363,000	57,100	2,010	4,300	1,340
Delta IN-OUT		-14,700	-36	1,140	-6,900	389	881	-2,410	-1,020	-34,000	643,000	106,000	572	-580	-48,000	-6,120	1,450	-1,120	-244
% diff		-6.9		37	-7.4	4.9	15	-10	-17	-175	31	34	47	-6.5	-14	-11	53	-30	-20

Negative delta indicates net loss from tidal Westecunk Creek to Barnegat Bay. FW – RR Avenue Bridge (from watershed), BW – Bay Water. nd – not determined

Table 7a. Concentrations and mass-loadings of constituents in samples collected at Railroad Avenue Bridge and Leon's Dock, November 6, 2018.

Date	Time	Tide	Salinity (psu)	TDN ug N/L	TDP ug P/l	SRP µg/L	NH4-N ug N/l	NO3-N ug N/L	Silica ug Si/L	Cl mg/L	SO4 mg/L	DOC mg C/L	PP µg/L	PC ug C/L	PN ug N/L	TSS mg/L	Chl-a µg/L	Phaeo µg/L
Railroad Ave																		
11/6	4:57	FL	0.040	242	3.6	2.8	17.1	65.4	2,790	16.1	2.98	7.7	N/A	N/A	N/A			
11/6	5:57	FL	0.030	231	3.6	3.2	17.5	54.1	2,850	15.2	2.77	8.1	4.3	496	39	0.6	--	0.1
11/6	6:57	FL	0.040	218	3.7	1.9	18.0	53.4	2,840	14.3	2.65	8.1	N/A	N/A	N/A			
11/6	7:57	FL	0.040	214	3.5	2.3	17.4	49.9	2,900	13.7	2.65	7.9	3.8	361	16	0.2	--	0.0
11/6	8:57	FL	0.030	222	3.3	1.8	21.5	54.9	2,850	13.6	2.66	8.0	N/A	N/A	N/A			
11/6	9:57	FL	0.030	210	2.3	1.5	19.9	42.7	2,810	13.5	2.63	7.8	0.6	303	0	--	--	--
11/6	11:00	FL	0.030	220	4.8	1.7	16.6	48.0	2,850	13.6	2.69	7.9	N/A	N/A	N/A			
Ave.		**FL**	**0.034**	**222**	**3.5**	**2.2**	**18.3**	**52.6**	**2,840**	**14.3**	**2.72**	**7.94**	**2.89**	**387**	**18.3**	**0.133**	**--**	**--**
Mass		**FL**	**0.70**	**4,560**	**72**	**45**	**376**	**1,080**	**58,300**	**294**	**55.8**	**163**	**59.3**	**7,950**	**376**	**2.74**	**--**	**--**
11/6	11:00	EB	0.030	220	4.8	1.7	16.6	48.0	2,850	13.6	2.69	7.9	N/A	N/A	N/A			
11/6	12:00	EB	0.030	211	3.1	1.2	20.8	56.1	2,850	13.9	2.65	7.7	0.6	306	--	0.4	--	--
11/6	13:00	EB	0.030	223	6.3	3.0	18.1	55.8	2,840	13.8	2.62	7.8	N/A	N/A	N/A			
11/6	14:00	EB	0.030	215	1.9	2.0	16.0	57.0	2,840	14.6	2.72	7.6	1.9	231	17	0.8	--	--
Ave		**EB**	**0.030**	**217**	**4.0**	**2.0**	**17.9**	**54.2**	**2,840**	**14**	**2.67**	**7.76**	**1.22**	**268**	**8.70**	**0.600**	**--**	**--**
Mass		**EB**	**0.820**	**5,920**	**110**	**55**	**488**	**1,480**	**77,500**	**382**	**72.9**	**212**	**33.3**	**7,320**	**238**	**16.4**	**--**	**--**

Table 7b. Concentrations and mass-loadings of constituents in samples collected at Railroad Avenue Bridge and Leon's Dock, November 6, 2018. Continued.

Leon's Dock																		
Date	Time	Tide	Salinity (psu)	**TDN ug N/L**	**TDP Ug P/l**	**SRP µg/L**	**NH4-N ug N/l**	**NO3-N ug N/L**	**Silica ug Si/L**	**Cl mg/L**	**SO4 mg/L**	**DOC mg C/L**	**PP µg/L**	**PC ug C/L**	**PN ug N/L**	**TSS mg/L**	**Chl-a µg/L**	**Phaeo µg/L**
11/7	5:01	FL	6.00	307	10.3	8.9	34.8	49.5	2,260	3,660	467	6.1	15.2	366	57	9.8	--	0.5
11/7	6:01	FL	11.34	354	17.4	10.0	57.9	57.3	1,770	6,950	927	4.7	18.2	476	79	19.6	0.4	0.7
Ave		**FL**	**8.67**	**330**	**13.9**	**9.45**	**46.4**	**53.4**	**2,010**	**5,300**	**697**	**5.4**	**16.7**	**421**	**68.4**	**14.7**	**0.1**	**0.58**
mass		**FL**	**2,690**	**103,000**	**4,320**	**2,940**	**14,400**	**16,600**	**624,400**	**1,650,000**	**217,000**	**1,680**	**5,200**	**131,000**	**21,200**	**4,570**	**31**	**180**
11/7	5:01	EB	6.00	307	10.3	8.9	34.8	49.5	2,260	3,660	467	6.1	15.2	366	57	9.8	--	0.5
11/7	6:01	EB	11.3	354	17.4	10.0	57.9	57.3	1,770	6,950	927	4.7	18.2	476	79	19.6	0.4	0.7
11/7	7:01	EB	24.6	391	35.9	23.9	119	63.2	838	15,100	2,110	1.7	39.2	781	125	45.2	1.4	1.6
11/7	8:01	EB	24.9	397	34.7	25.6	117	60.3	810	15,300	2,140	1.7	39.5	819	142	32.8	1.9	1.3
11/7	9:01	EB	24.9	368	33.7	22.2	111	65.7	779	15,300	2,130	1.6	23.5	439	52	25.2	1.4	0.5
11/7	10:01	EB	24.9	360	32.6	21.9	110	68.0	803	15,200	2,130	1.6	15.3	357	63	15.6	1.2	0.2
Ave		**EB**	**19.5**	**363**	**27.4**	**18.8**	**91.6**	**60.64**	**1,210**	**11,900**	**1,650**	**2.9**	**25.1**	**540**	**87**	**24.7**	**1.0**	**0.80**
mass		**EB**	**6,930**	**129,000**	**9,730**	**6,680**	**32,500**	**21,500**	**430,000**	**4,230,000**	**586,000**	**1,030**	**8,910**	**192,000**	**30,900**	**8,770**	**355**	**284**

Table 7c. Mass-loadings of constituents in samples collected at Railroad Avenue Bridge and Leon's Dock, November 6, 2018.

	FW m³	Bay Water m³	Min-utes	Salinity (psu)	TDN g	TDP g	SRP g	NH4-N g	NO3-N g	Silica g	Cl kg	SO4 kg	DOC kg	PP g	PC g	PN g	TSS kg
								Flood									
FW	20,533	--	--	0.70	4,560	71.9	45.2	376	1,080	58,300	294	55.9	163	59.3	7,950	376	2.73
BW	--	310,659	348	2,690	103,000	4,320	2,940	14,400	16,600	624,400	1,650	217	1,680	5,190	131,000	21,000	4,570
Total IN FL		331,000	--	2,690	107,000	4,390	2,980	14,800	17,700	683,000	1,650	217	1,840	5,250	139,000	21,600	4,570
								Ebb									
FW	27,304	--	--	0.82	5,920	109	54.6	489	1,480	77,500	382	0.073	212	33.3	7,320	238	16.4
BW		335,133	432	6,930	129,000	9,730	6,680	32,500	21,500	430,000	4,230	586	1,030	8,910	192,000	30,900	8,770
Total OUT EB		362,000	--	-6,930	135,000	9,840	6,730	33,000	23,000	507,000	4,230	586	1,240	8,950	199,000	31,100	8,790
Delta		-51,200	-84	-4,230	-27,800	-5,450	-3,750	-18,200	-5,350	175,000	-2,580	-369	599	-3,700	-60,400	-9,510	-4,220
% diff		-14	-22	-88	-23	-77	-77	-76	-26	29	-88	-92	39	-52	-36	-36	-63

Negative delta indicates net loss from tidal Westecunk Creek to Barnegat Bay. FW – RR Avenue Bridge (from watershed), BW – Bay Water

Table 8. Summary of average concentrations and mass loadings of total dissolved nitrogen, phosphorous, and sediment in the water collected from Leon's Dock, Westecunk Creek, in May, August and November 2018. [TDN, total dissolved nitrogen (µg-N/L); TDP, total dissolved phosphorous (µg-P/L); PC, particulate carbon (ug-C/L); TSS, total suspended sediment (mg/L); µg/L, micrograms per liter; g, grams; kg, kilograms]

Date	Flood Concentration or volume[1]	Ebb concentration or volume[1]	[2]Flood tide mass	[2]Ebb tide mass	3Net (flood-ebb)
May					
Water	329,000 m^3	348,000 m^3	--	--	-18,600 m^3
TDN	330 µg/L	416 µg/L	108,000 g	141,000 g	-33,100 g
Nitrate	6.0 µg/L	26.6 µg/L	2,770 g	9,630 g	-6,860 g
TDP	15.7 µg/L	18.9 µg/L	4,850 g	6,060 g	-1,210 g
PC	785 µg-C/L	1,400 µg-C/L	251,000 g	457,000 g	-206,000 g
TSS	86.4 mg/L	59.1 mg/L	26,200 kg	18,700 kg	7,540 kg
August					
Water	207,000 m^3	221,000 m^3	--	--	-14,700 m^3
TDN	450 µg/L	449 µg/L	90,300 g	97,200 g	- 6,900 g
Nitrate	26.2 µg/L	29.1 µg/L	5,700 g	6,720 g	- 1,020 g
TDP	41.3 µg/L	36.9 µg/L	8,120 g	7,730 g	389 g
PC	1,580 µg-C/L	1,710 µg-C/L	315,000 g	363,000 g	-48,000 g
TSS	17.7 mg/L	9.6 mg/L	3,460 kg	2,010 kg	1,450 kg
November					
Water	331,000 m^3	382,000 m^3	--	--	-44,000 m^3
TDN	330 µg/L	363 µg/L	107,000 g	135,000 g	-27,800 g
Nitrate	53.4 µg/L	60.6 µg/L	17,700 g	23,000 g	- 5,350 g
TDP	13.9 µg/L	27.4 µg/L	4,390 g	9,840 g	- 5,450 g
PC	421 µg-C/L	540 µg-C/L	139,000 g	199,000 g	- 60,400 g
TSS	14.7 mg/L	24.7 mg/L	4,570 kg	8,790 kg	- 4,220 kg

Notes.

1. Concentrations shown are averages for water collected at Leon's Dock
1. Mass of nutrients listed are the sum of masses in Bay water plus the sum of masses in FW collected at RR Avenue Bridge
2. Negative delta indicates net loss from tidal Westecunk Creek to Barnegat Bay

Table 9. Key to parameters and units.

Date	Date of sample		
Time	Time of sample		
Tide		E, ebb F, flood	
Salinity (psu)	Salinity	psu	practical salinity units
TDN	Total dissolved nitrogen	µg N/L	micrograms of nitrogen per liter
TDP µg P/l	Total dissolved phosphorous	µg P/L	micrograms of phosphorous per liter
SRP µg/L	Soluble reactive phosphorous	µg P /L	micrograms of phosphorus per liter
NH4-N ug N/l	Ammonia nitrogen	µg N/L	micrograms of nitrogen per liter
NO3-N ug N/L	Nitrate	µg N/L	micrograms of nitrogen per liter
Silica ug Si/L	Total dissolved silica	µg Si/L	Micrograms of silica per liter
Cl mg/L	Chloride	mg/L	milligrams per liter
SO4	Sulfate	mg/L	milligrams per liter
DOC	Dissolved organic carbon	mg C/L	milligrams of carbon per liter
PP	Particulate phosphorous	µg P /L	micrograms of phosphorous per liter
PC	Particulate carbon	µg C/L	micrograms of carbon per liter
PN	Particulate nitrogen	µg N/L	micrograms of nitrogen per liter
TSS	Total suspended solids	mg/L	milligrams per liter
Chloro-a	Chlorophyll-a	µg /L	micrograms per liter
Phaeo µg/L	Phaeo	µg /L	micrograms per liter

Table 10. Summary of Mass inputs and exports to Westecunk Creek during each sampling period.

	May	August	November		May	August	November
Nitrate	**Grams**	**Grams**	**Grams**	**Silica**	**Grams**	**Grams**	**Grams**
Watershed	2,177	1229	2,560	Watershed	129,700	91,500	135,800
Flood	1,820	5,120	16,600	Flood	163,000	2,380	624,400
Ebb	8,390	6,080	21,500	Ebb	419,000	2,840	430,000
NET: Sink/Source	4393	-269	2340	NET: Sink/Source	126,300	-91,040	-330,200
Marsh source of nitrate (+); sink (-)				Marsh source of Si (+); sink (-)			
Ammonium	**Grams**	**Grams**	**Grams**	**DOC**	**Grams**	**Grams**	**Grams**
Watershed	796	587	865	Watershed	702	104	375
Flood	4,210	21,900	14,400	Flood	1,270	1,450	1,680
Ebb	20,400	24,200	32,500	Ebb	2,430	878	1,030
NET: Sink/Source	15,394	1,713	17,235	NET: Sink/Source	458	-676	-1,025
Marsh source of ammonium (+); sink (-)				Marsh source of DOC (+); sink (-)			
SRP	**Grams**	**Grams**	**Grams**				
Watershed	185	93.9	100				
Flood	1,150	6,150	2,940				
Ebb	2,020	5,270	6,680				
NET: Sink/Source	685	-974	3,640				
Marsh source of SRP (+); sink (-)							

H: Figures

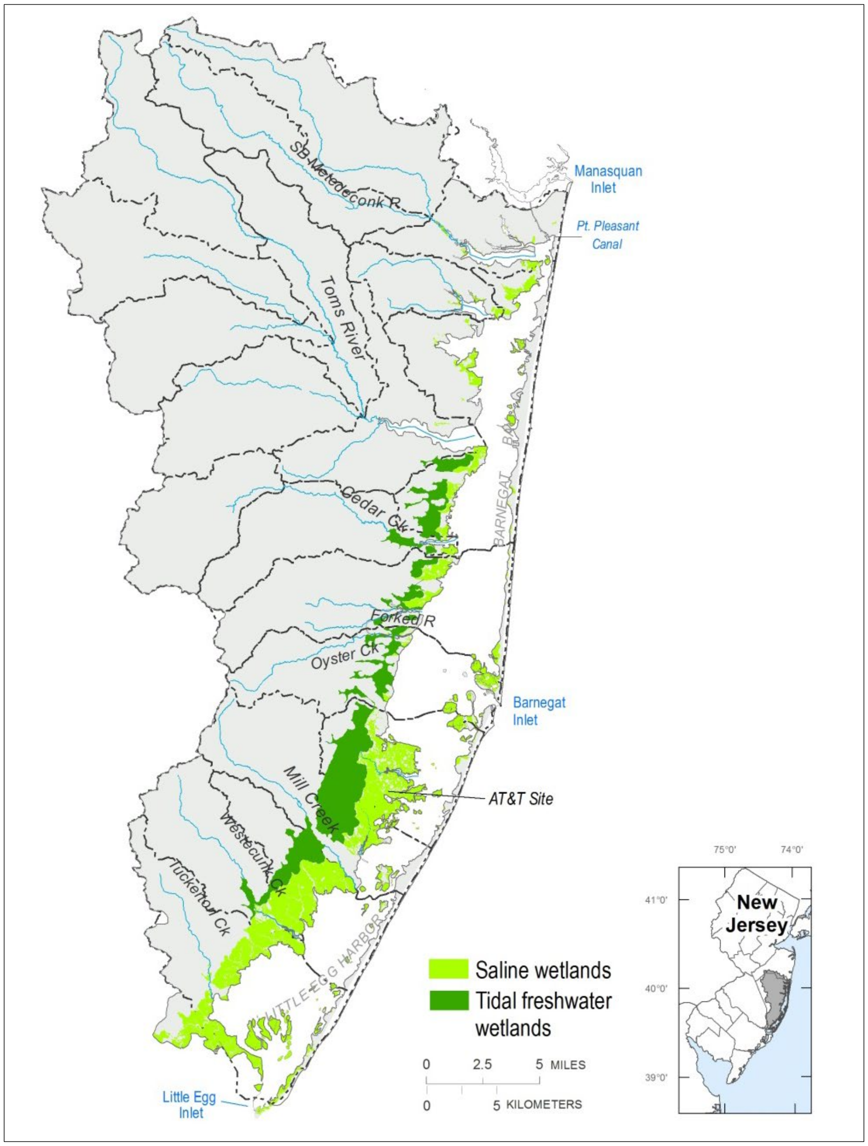


Figure 1. Barnegat Bay watershed and location of remaining tidal fresh and saline wetlands (from V. Depaul; USGS).

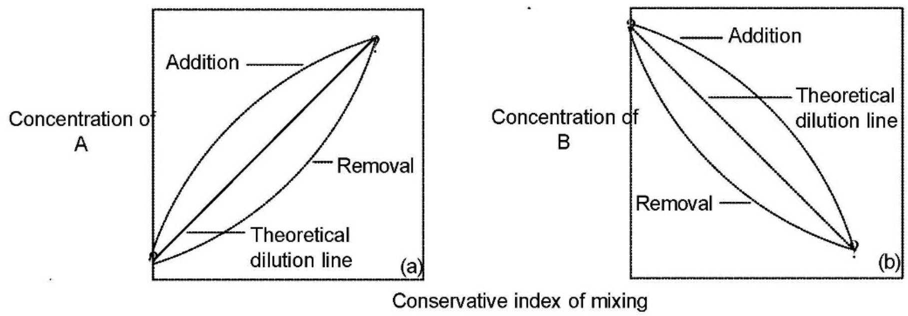


Figure 2. Simple model relationships between the concentration of a dissolved element and an index of conservative mixing (e.g., salinity) in an estuary under steady-state conditions. Graph (a) is when the element is higher in concentration than creek input while in graph (b) the seawater endmember is lower in concentration than riverine endmember. Curves above or below theoretical "non-reactive" line indicate either removal or addition within the system. Processes such as algal uptake, microbial process, adsorption/desorption, mineral formation, etc, can alter the flow of elements from riverine down the tidal creek (adapted from Liss, 1976).

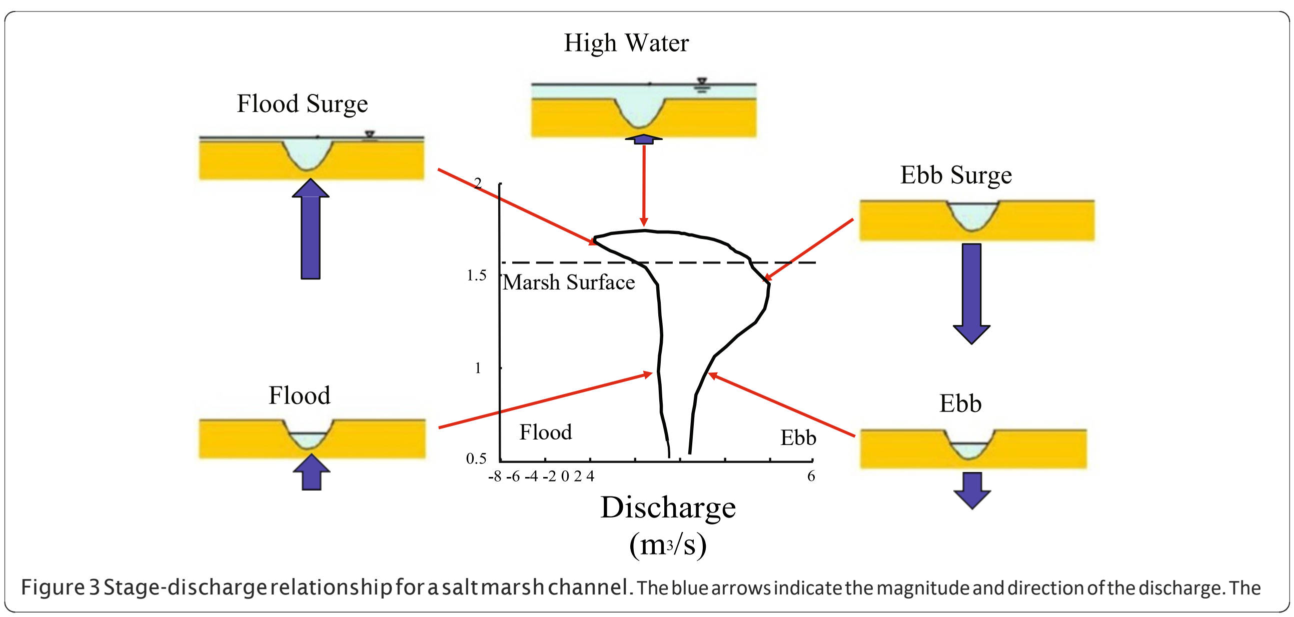
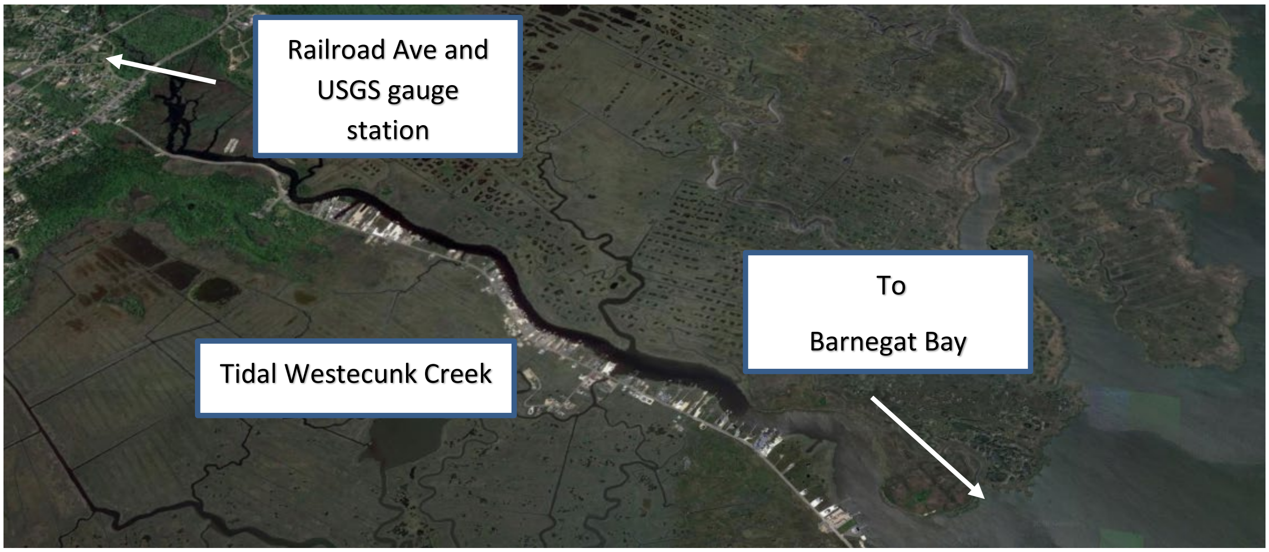


Figure 3. Conceptual view of the flux experiment at Leon's dock area over multiple tidal cycles



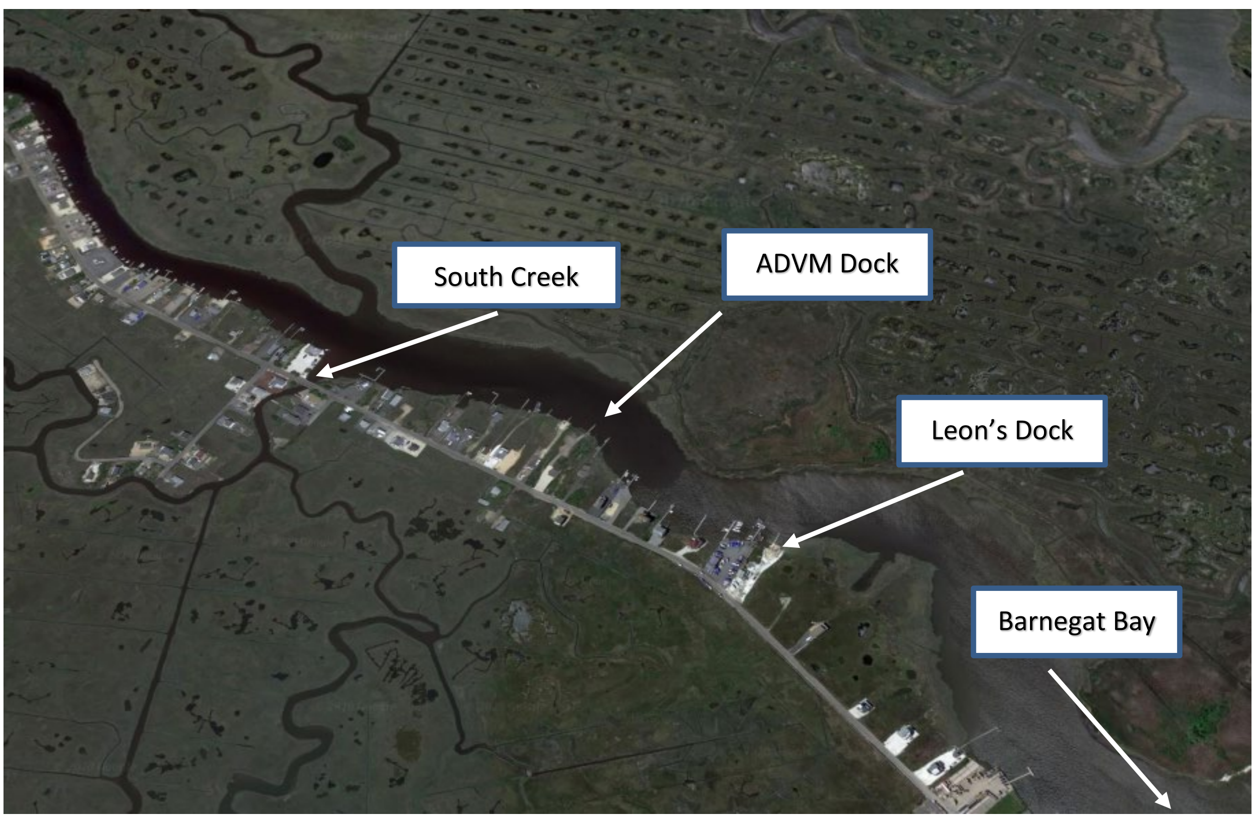


Figure 4. Location of sampling and measurement stations on the tidal Wesetcunk Creek.

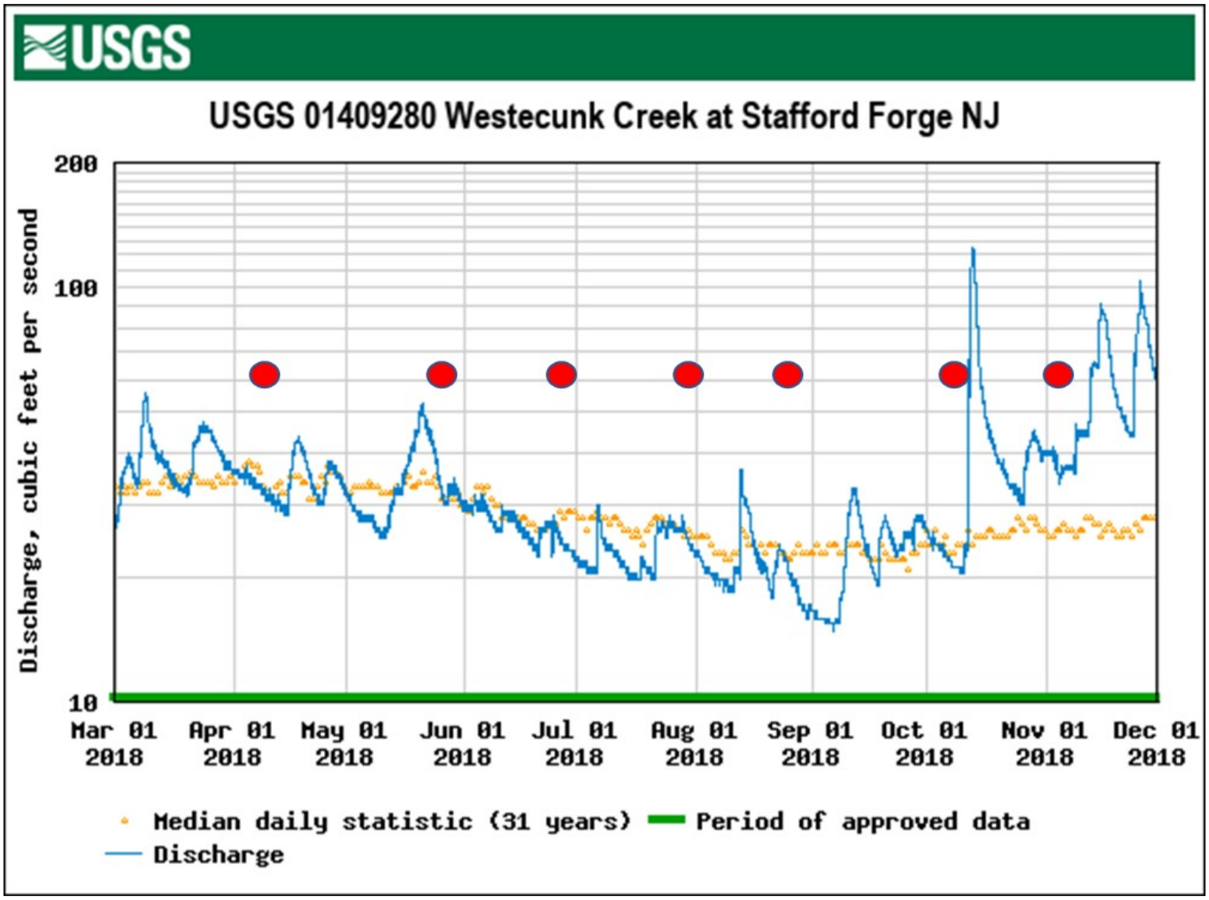


Figure 5. Discharge at USGS 1409280 monitoring gauge at Stafford Forge. Red dots indicate approximate time of sampling.

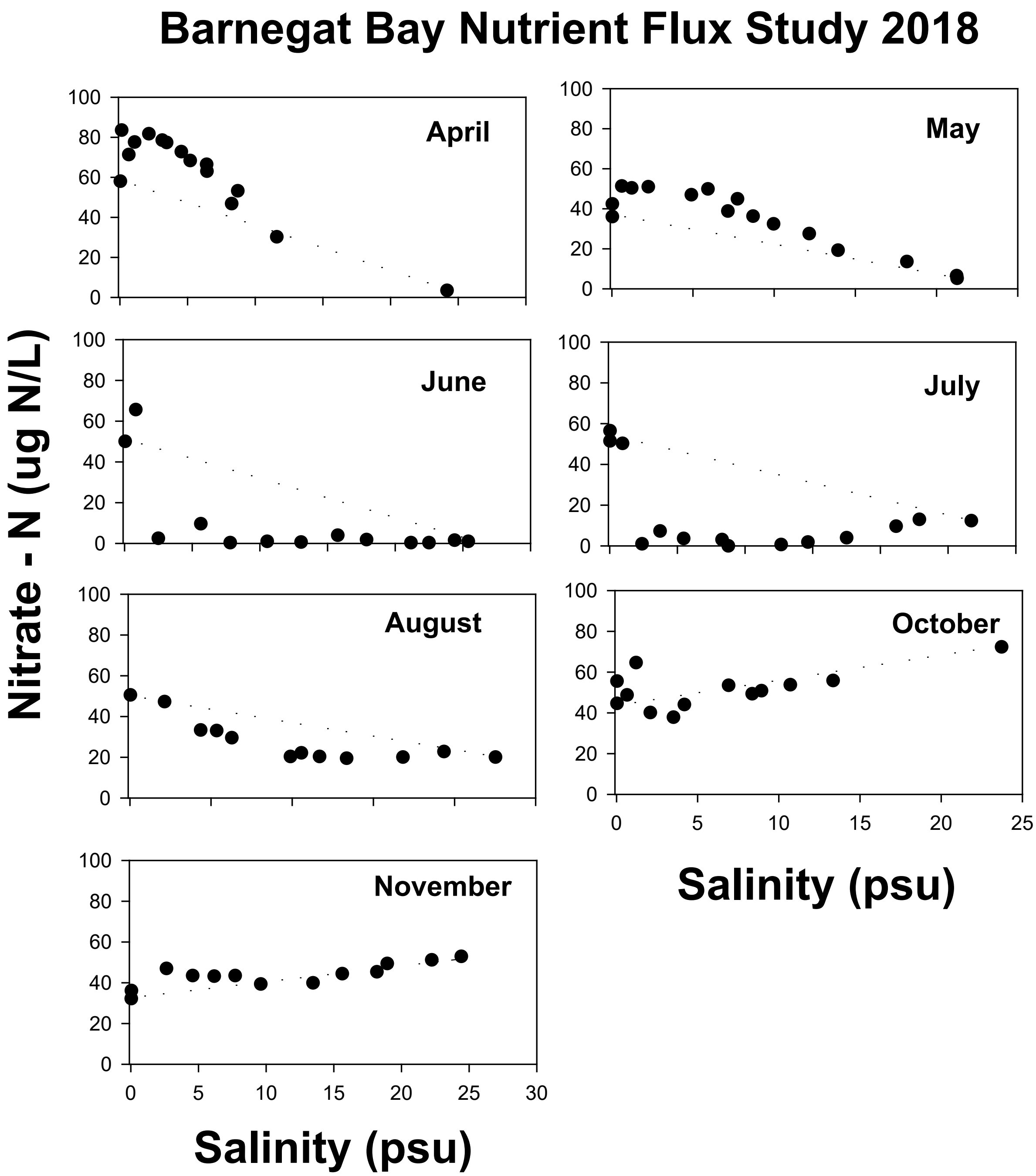


Figure 6. Dissolved nitrate (nitrate+nitrite) concentrations versus salinity during monthly surveys. Note: RR Avenue Bridge at 0 psu. The theoretical/conservative mixing line is indicated by the fine dotted line, running from 0 psu to the highest salinity during each month.

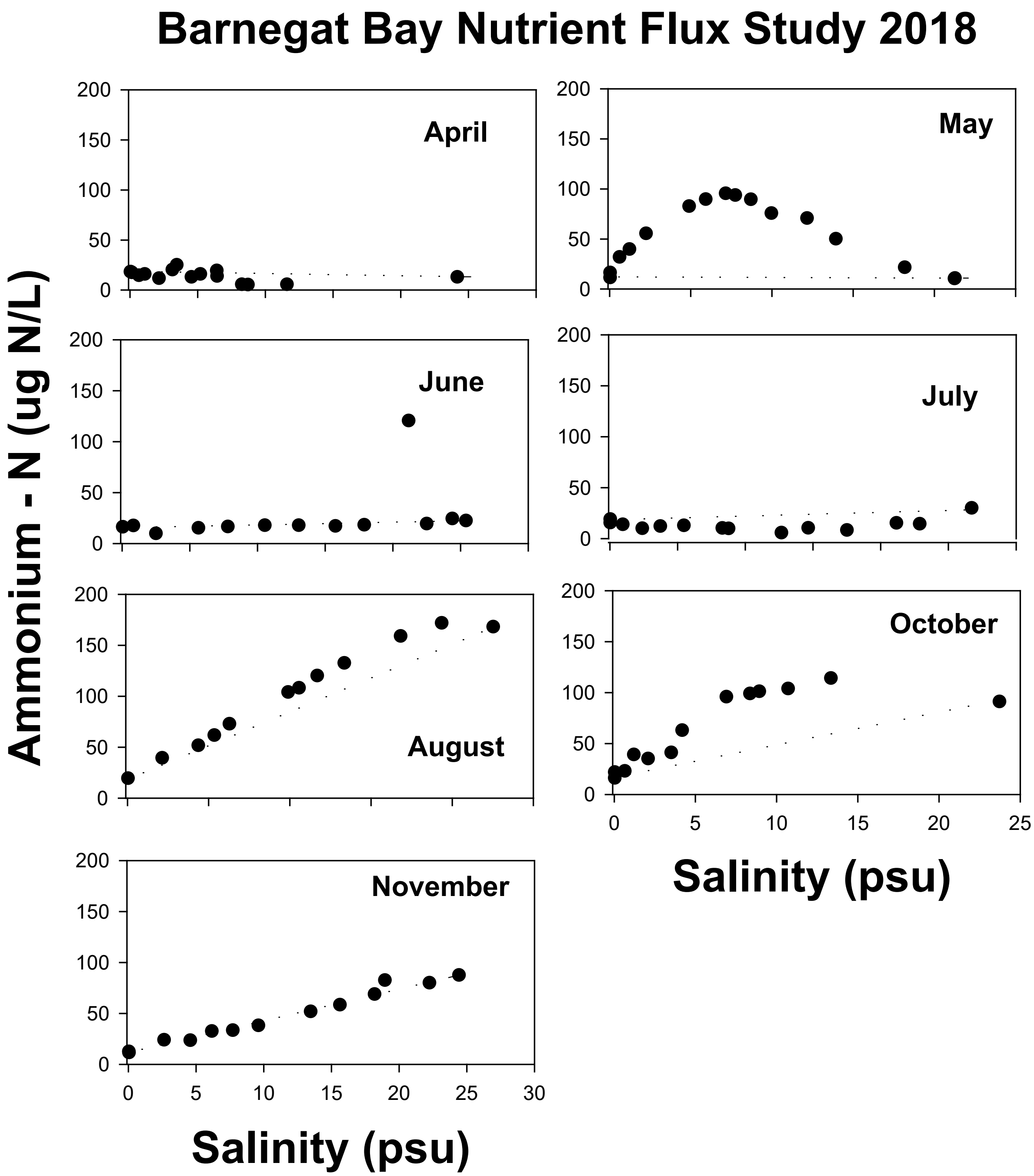


Figure 7. Dissolved ammonium (ammonia+ammonium) concentrations versus salinity during monthly surveys. Note: RR Avenue Bridge at 0 psu. The theoretical/conservative mixing line is indicated by the fine dotted line, running from 0 psu to the highest salinity during each month.

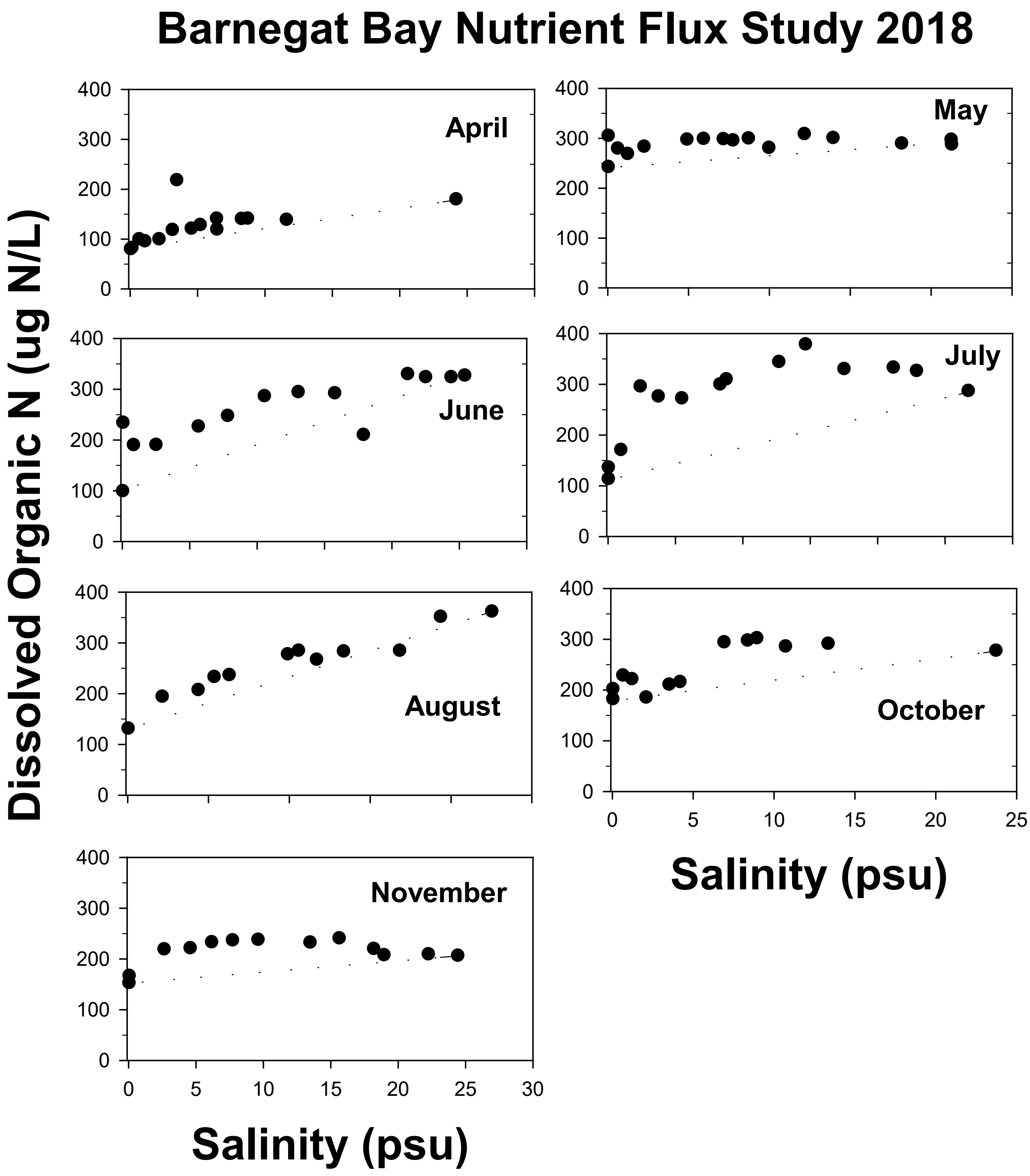


Figure 8. Dissolved organic nitrogen concentrations versus salinity during monthly surveys. Note: RR Avenue Bridge at 0 psu. The theoretical/conservative mixing line is indicated by the fine dotted line, running from 0 psu to the highest salinity during each month.

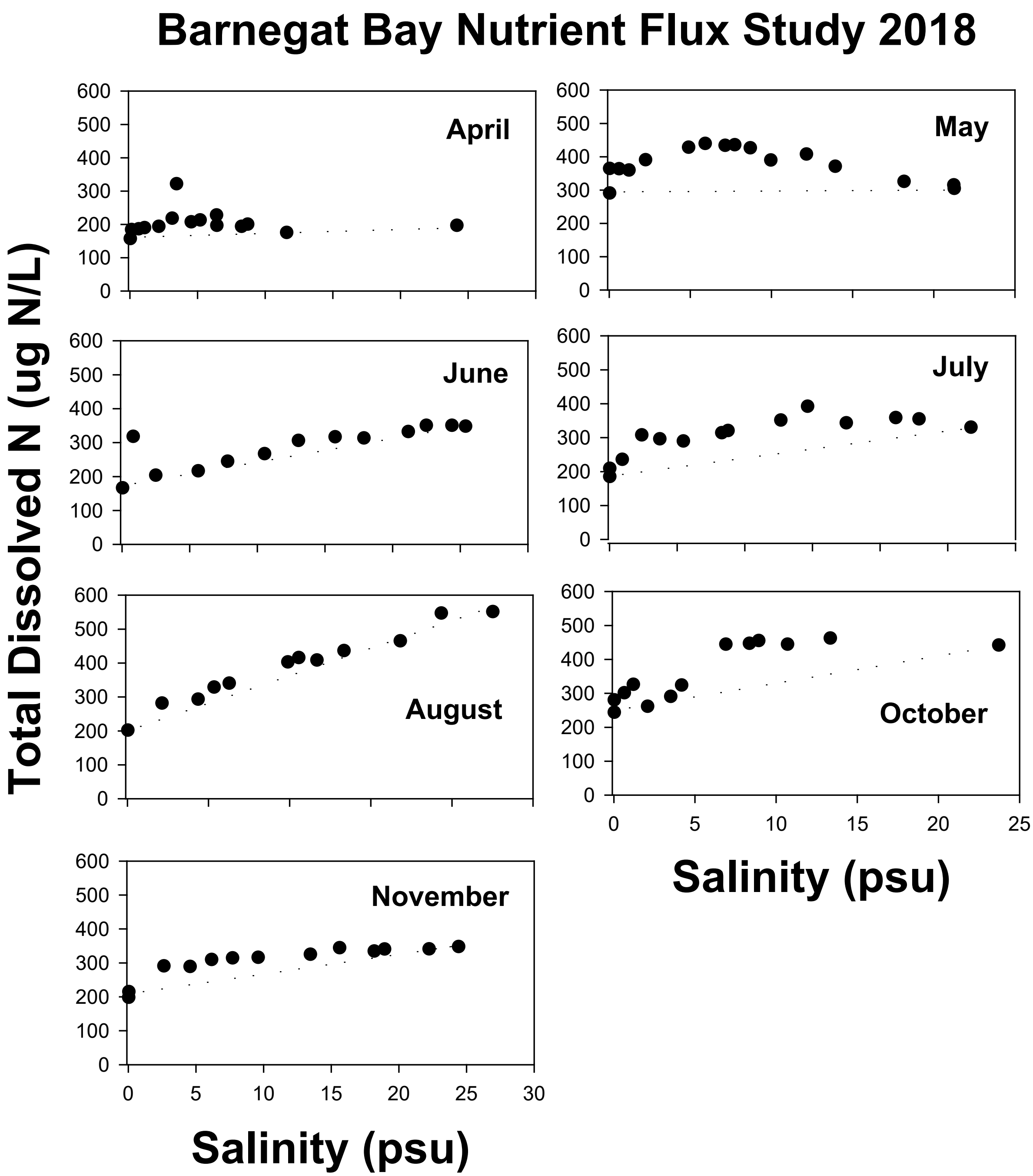


Figure 9. Total dissolved nitrogen concentrations versus salinity during monthly surveys. Note: RR Avenue Bridge at 0 psu. The theoretical/conservative mixing line is indicated by the fine dotted line, running from 0 psu to the highest salinity during each month.

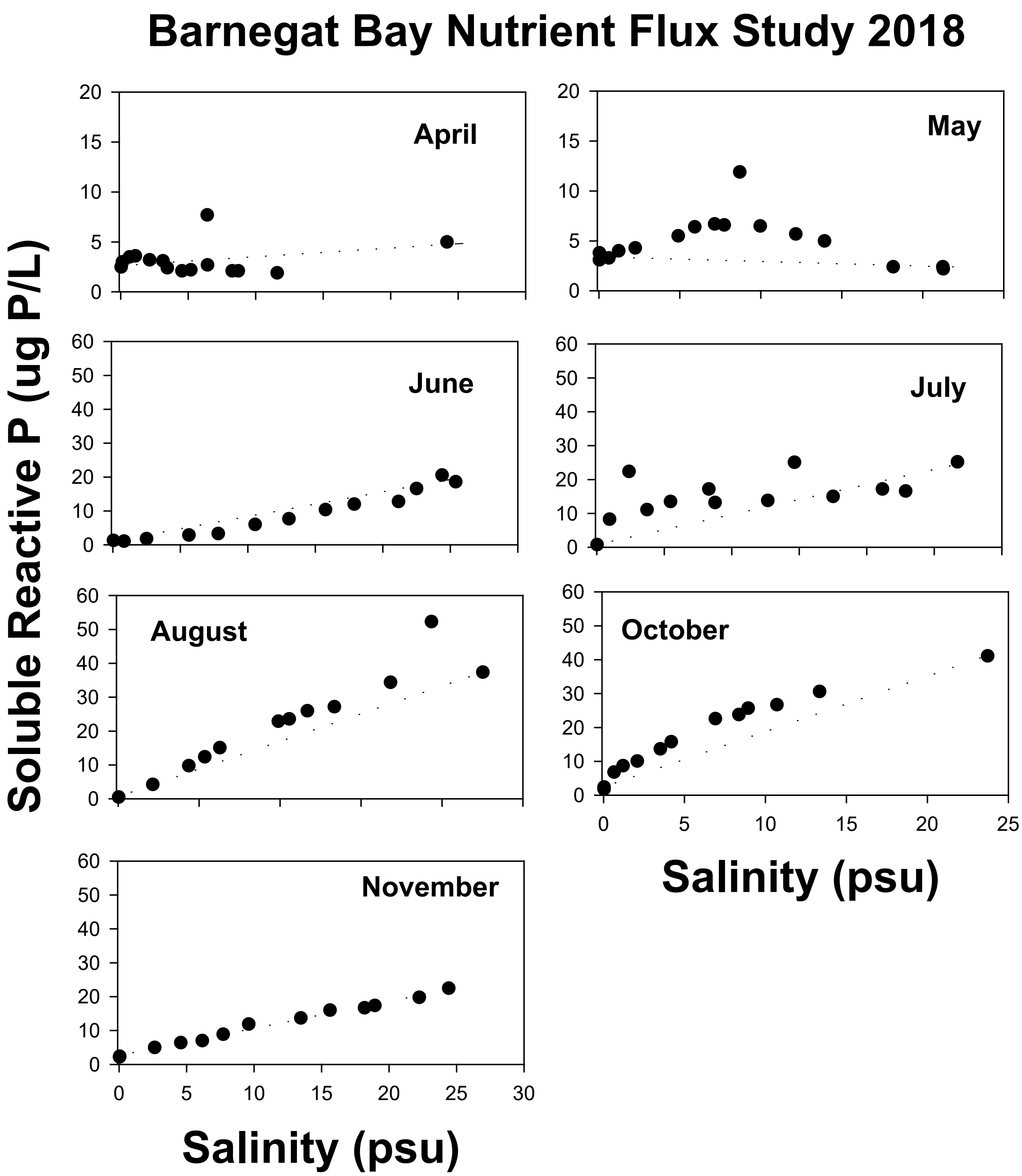


Figure 10. Soluble reactive phosphorus concentrations versus salinity during monthly surveys. Note: RR Avenue Bridge at 0 psu. The theoretical/conservative mixing line is indicated by the fine dotted line, running from 0 psu to the highest salinity during each month.

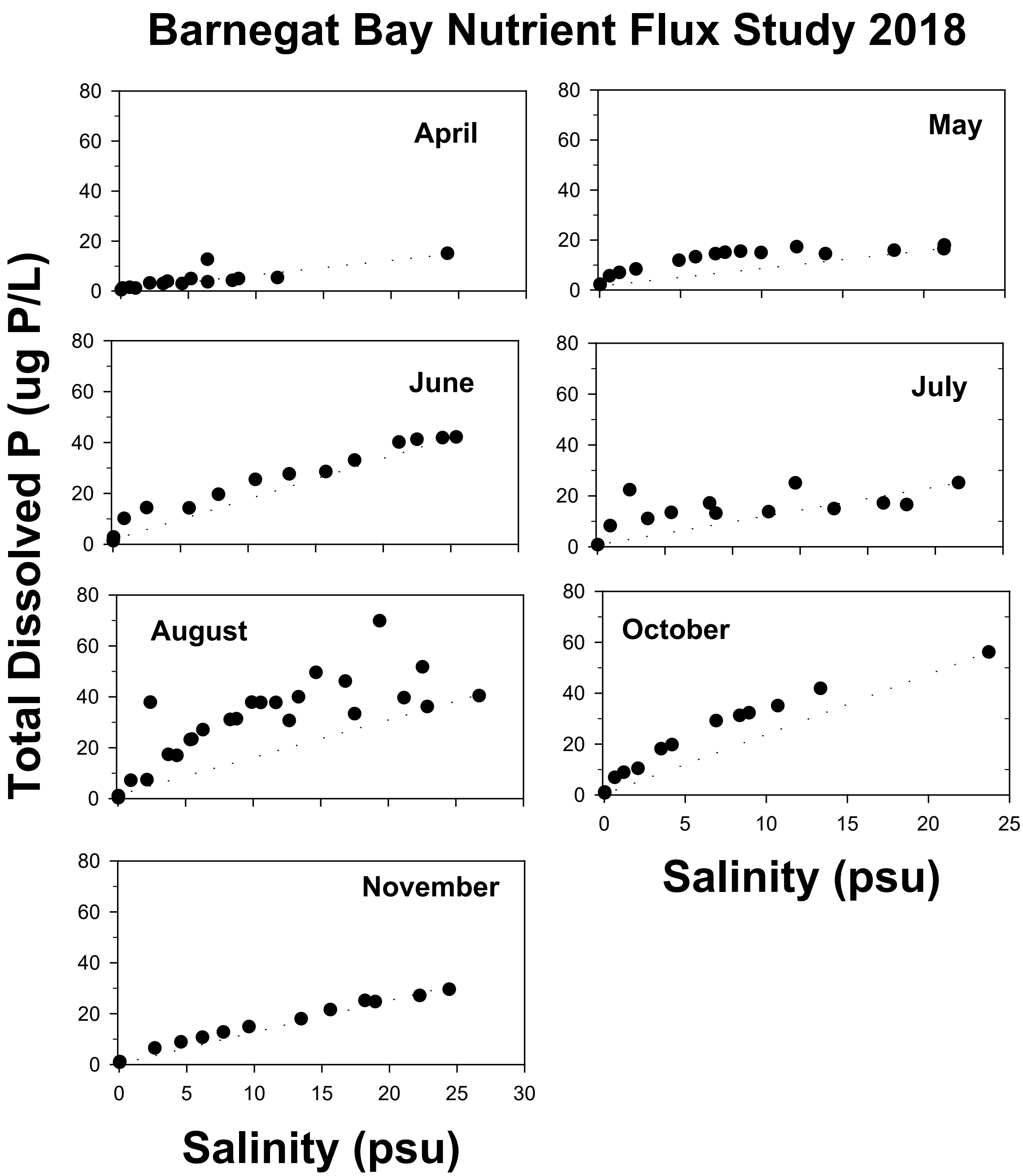


Figure 11. Total Dissolved phosphorus concentrations versus salinity during monthly surveys. Note: RR Avenue Bridge at 0 psu. The theoretical/conservative mixing line is indicated by the fine dotted line, running from 0 psu to the highest salinity during each month.

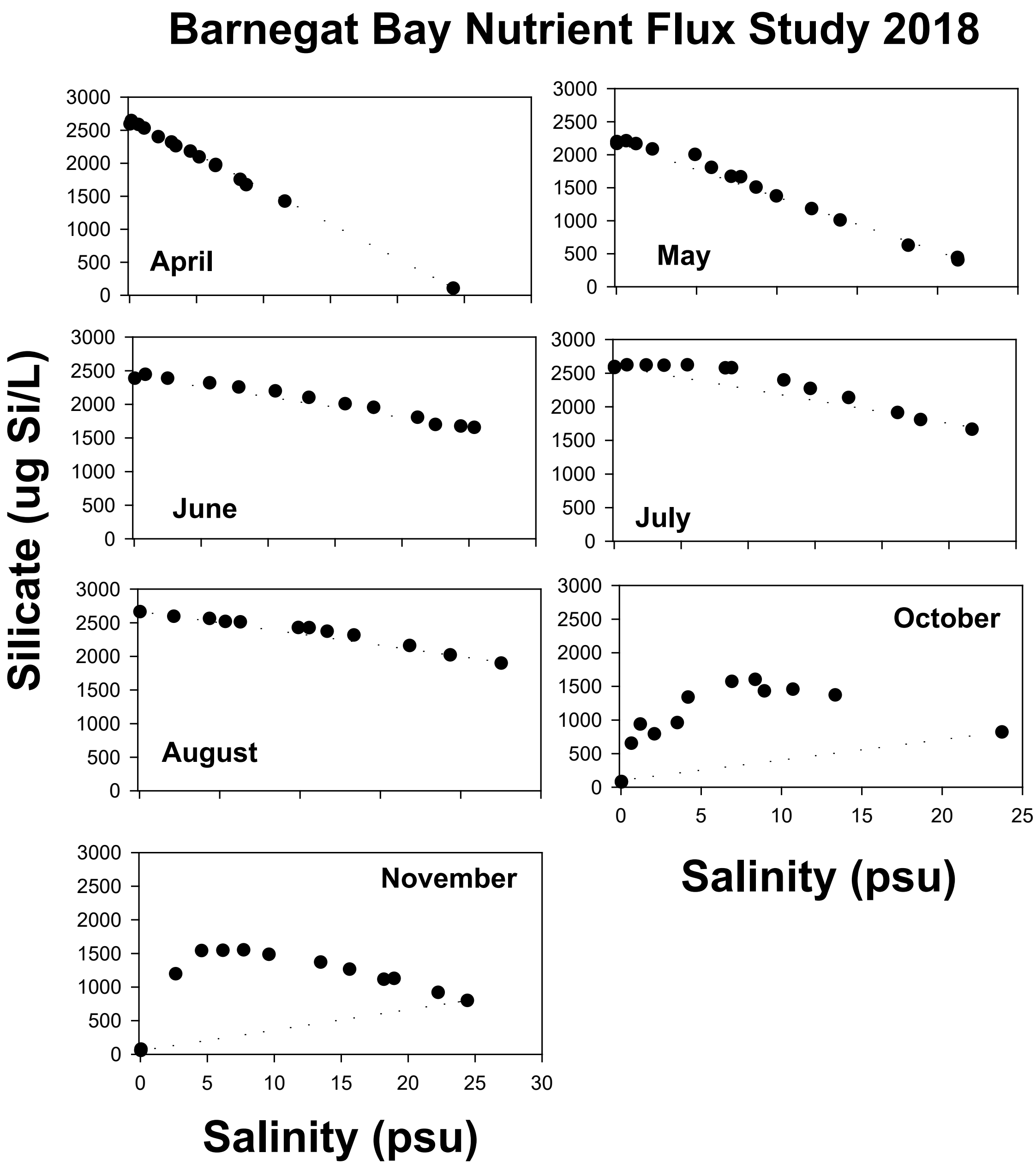


Figure 12. Dissolved silica concentrations versus salinity during monthly surveys. Note: RR Avenue Bridge at 0 psu. The theoretical/conservative mixing line is indicated by the fine dotted line, running from 0 psu to the highest salinity during each month.

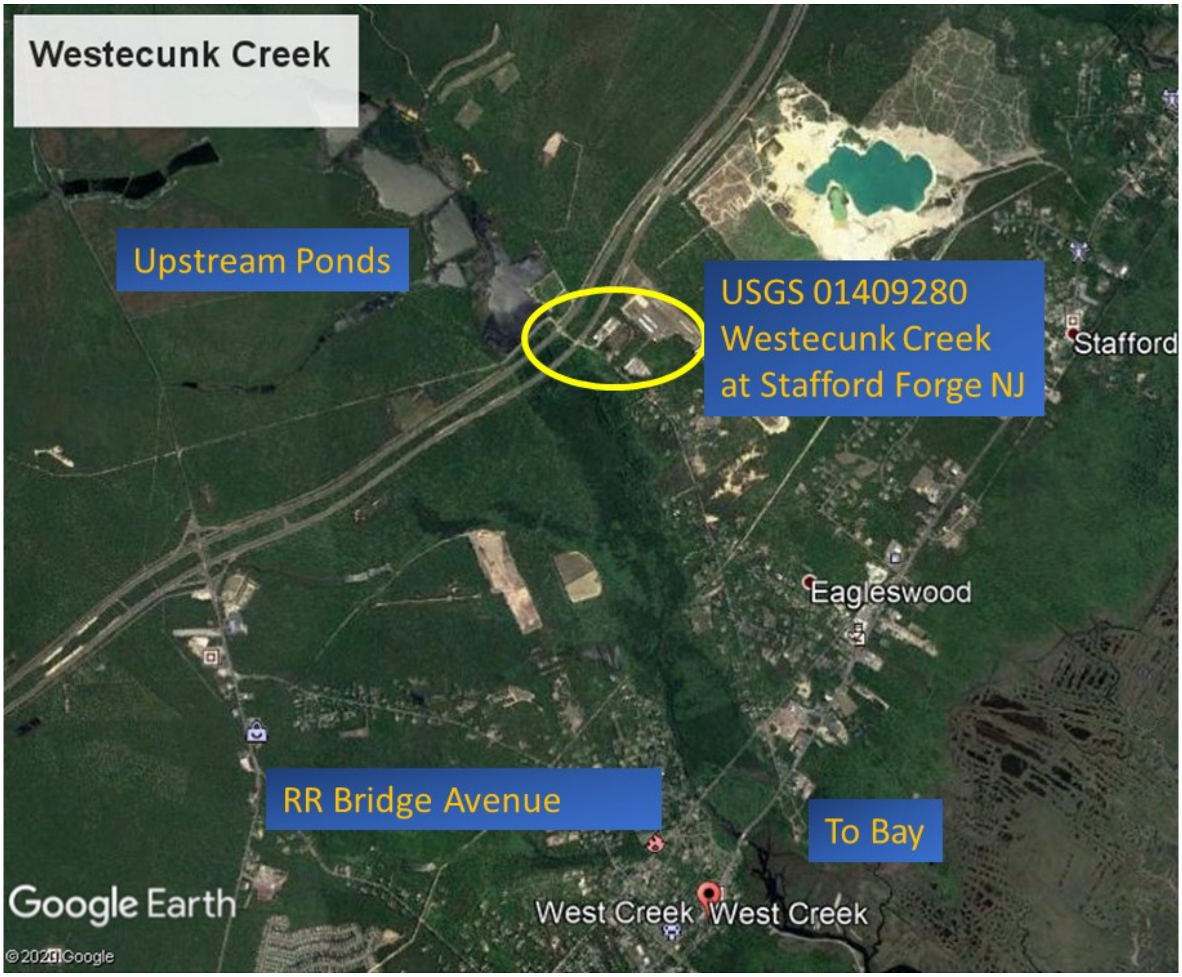


Figure 13. Image of watershed just upstream of creek and sampling locations. Notice the extensive ponds just upstream of the USGS Gauging station (140928).

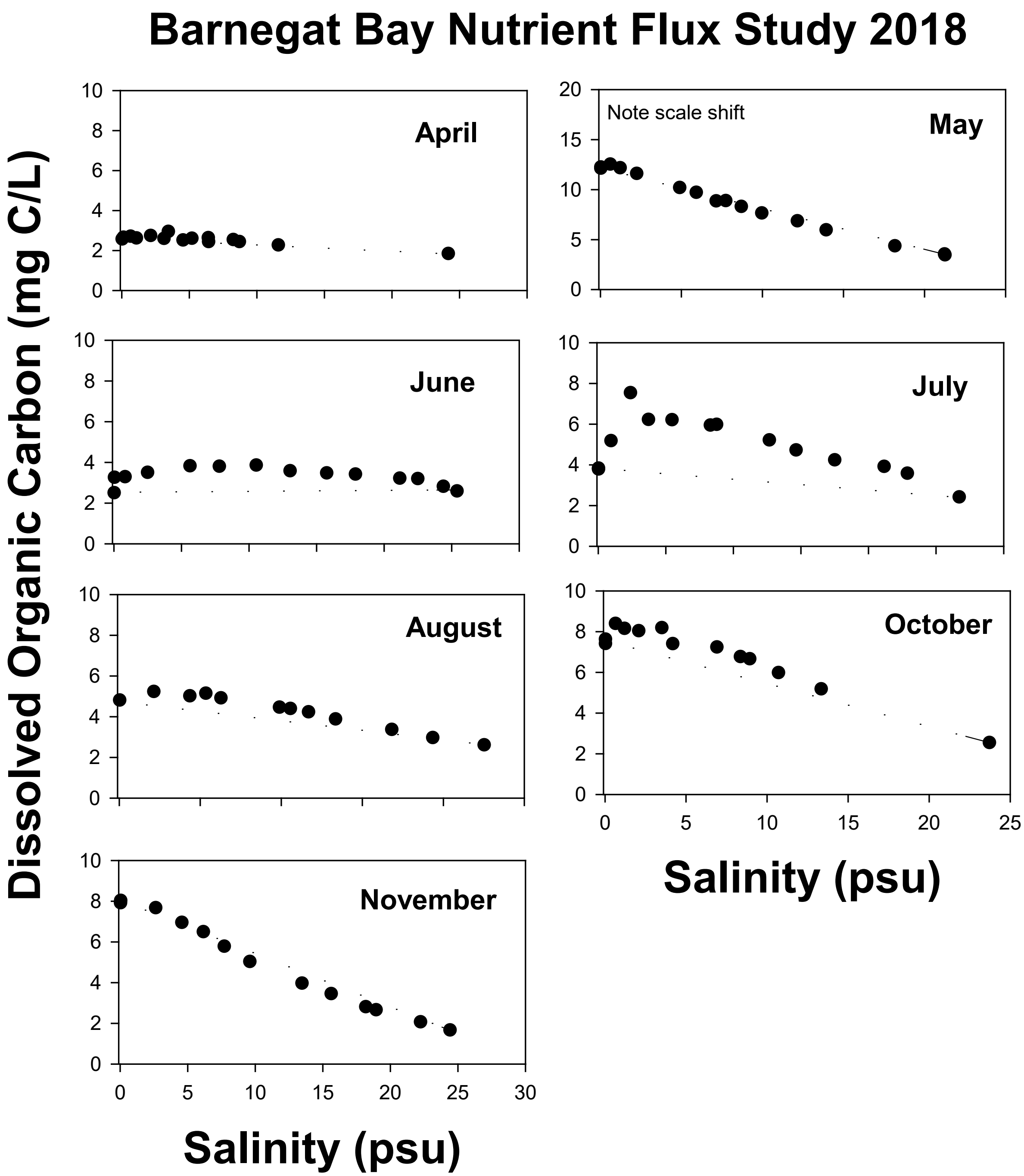


Figure 14. Dissolved organic carbon concentrations versus salinity during monthly surveys. Note: RR Avenue Bridge at 0 psu.

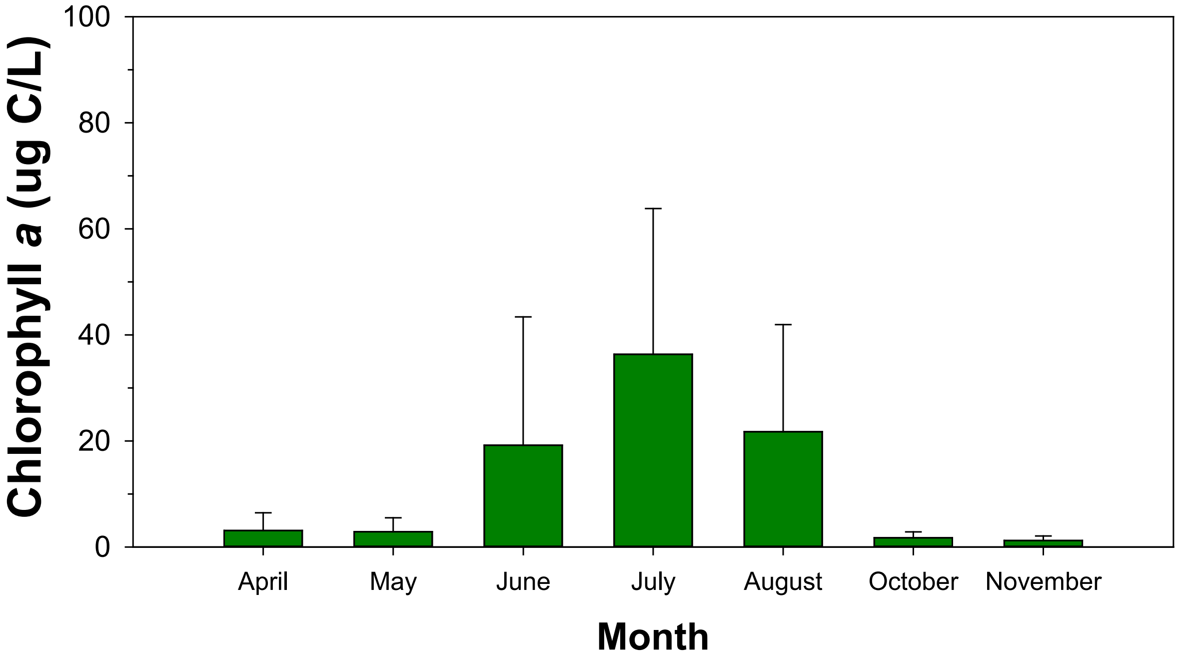


Figure 15. Monthly concentrations of chlorophyll *a* (mean±1sd). Collected from Westecunk Creek marsh creek. Each month is the mean for all stations from the RR Avenue Bridge to the downstream site.

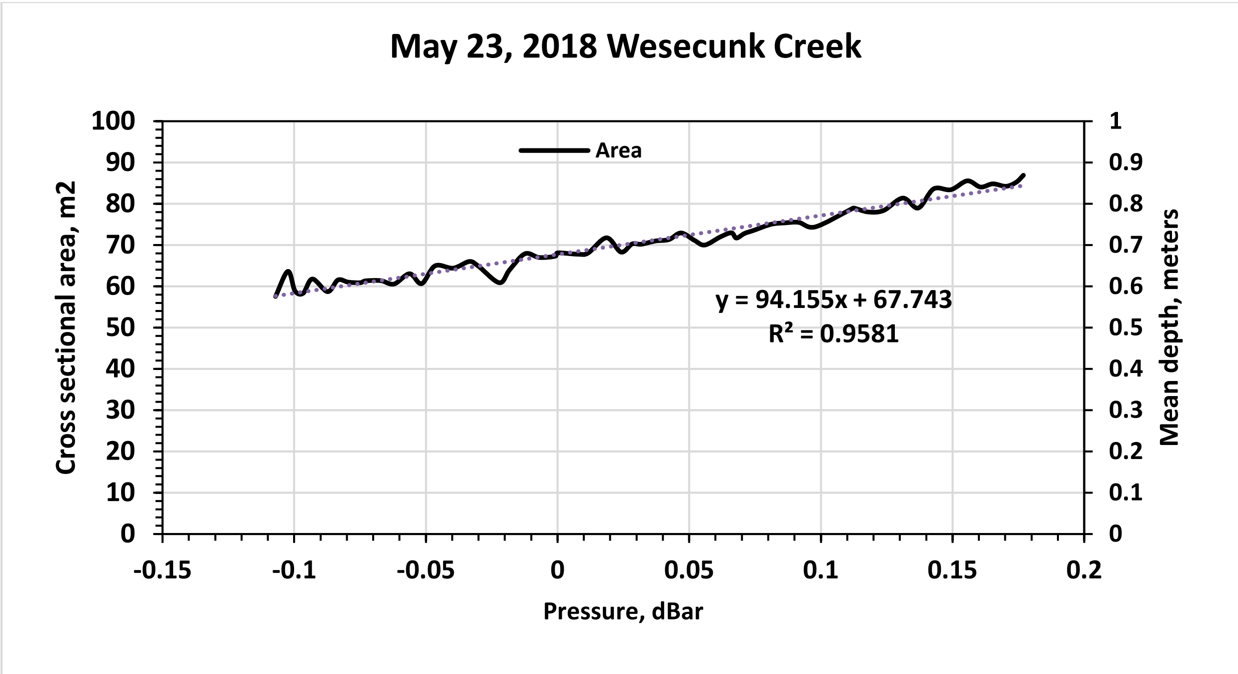


Figure 16. Plot of water pressure and cross-sectional area of the tidal Westecunk Creek measured during the May 23, 2018, calibration study from Leon's Dock site.

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J. Appendix I

Summary Data: Excel File