



Resilience and positive feedbacks: Water quality management and eelgrass health in Great Bay Estuary, NH/ME

“So What” Report

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***MAAM refers to the Municipal Alliance for Adaptive Management**

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Executive Summary

A three-year project was conducted to examine eelgrass health and potential stressors to guide management given significant eelgrass loss in the Great Bay Estuary since 1996. Questions and answers below summarize the findings:

Significant wastewater treatment facility improvements have reduced nitrogen loading but communities are being urged to further reduce nitrogen by better managing stormwater and septic systems. Has this project changed our thinking on this general approach?

No. During part of this period, plankton levels fueled by nitrogen were high enough to cause problems for eelgrass. However, in 2023, with record rainfall during the growing season, evidence suggests that stormwater reduced light so that even plankton levels were quite low. This indicates that strategies to conserve land and control stormwater, which will reduce nitrogen, sediments and organic matter, may have the greatest benefit for eelgrass. Restoration of rivers, salt marshes, eelgrass, and shellfish beds will also provide benefit.

So we don't know whether it's more important to reduce sediments versus nitrogen?

Correct. Strategies to reduce both nitrogen and sediments should be prioritized.

With regard to nitrogen, we've already reduced point-source nitrogen significantly. Should we reduce point sources more?

This project didn't answer that question but provided data for a model to address it. Nitrogen wasn't the only stressor on eelgrass during this period, so further point source reductions alone may not resolve the issues eelgrass beds face. Significant reductions have already occurred.

Communities are being asked to further reduce nitrogen from non-point sources, especially stormwater. Do we know how much more nitrogen we have to reduce?

We don't, but new insights bring us closer to developing models to help answer that.

With all the nitrogen reduction that has occurred, why aren't we seeing eelgrass increase? In fact, during this project period, eelgrass significantly decreased. Why?

It's complicated. First, let's focus on nitrogen, even though it's not the only stressor of concern. Yes, we have reduced nitrogen from point sources, but that only accounts for 22% of the nitrogen currently going into the estuary. Also, lots of nitrogen from past decades probably accumulated in the sediments and could slowly come out over time. Systems frequently take over 10 years to fully respond to reductions in nitrogen! We have to be patient and we have to better assess how long it might take to process all the nitrogen that was likely stored from previous years. For example, in our case, a 10-year delay would take us to approximately 2030 before we would see a notable change in eelgrass health. Second, as noted, nitrogen isn't the only stressor. Total suspended solids (TSS) and colored dissolved organic matter (CDOM) have also increased, and these constituents also reduce light and negatively impact eelgrass. A clear lesson from this project is the danger to eelgrass presented by the trend of increasing rainfall, which adds more nitrogen, TSS and CDOM to our system. Addressing stormwater issues, conserving open space and restoring habitats will help with these issues.

This project looked at how stressors impact eelgrass, but it also studied how eelgrass can impact its environment. What were the major results and management implications?

We found that when eelgrass is struggling as it did during this project period, it does not seem to perform the same functions of processing sediments and nitrogen that we'd expect based on research from other areas. This speaks to a negative feedback cycle that can happen in ecosystems. The worse things get, the harder it can be to bring the habitat back to earlier health. As with human health, prevention is far easier than restoration! Because prevention is no longer an option, we may need a more aggressive approach restoring habitat and water quality.

I'm told that hydrodynamics are important to understand for eelgrass health, and that this project advanced our understanding of how water moves in Great Bay Estuary. What is the main story in that regard?

It is often said that “well-mixed” or “well-flushed” estuaries can withstand higher levels of nitrogen loading than lagoons or estuaries that are less well mixed. This project illuminated how complicated our system is. Yes, the water moves quickly through the dredged navigation channels that extend all the way from Portsmouth Harbor to the mouth of the Lamprey River in Great Bay. However, the eelgrass doesn't grow in the channels; it grows in the shallower areas in Portsmouth and on the mudflats in Great Bay. This project showed that water can “reside” in these shallow areas far longer than previously thought, meaning that Great Bay actually functions more like a lagoon than a well-mixed system. In other words, it is more sensitive to nitrogen loading than previously thought.

What is “shear stress” and what did we learn about it through this project?

Shear stress describes how the sediment is eroded and resuspended when water velocities at the seafloor exceed a certain level. Within the Great Bay—but not in Portsmouth—we saw that eelgrass decreased as shear stress increased. This could provide part of the explanation of why eelgrass biomass in Great Bay is lower than in Portsmouth Harbor. We know that seeds are more important in Great Bay, and it is possible that shear stress erodes the seed bank and affects the survival of seedlings. In the Great Bay, where the sediment is extremely fine and holds more organic matter, quickly moving water and high shear stress can cause problems; in Portsmouth, with large/coarse sediment and less organic matter, the eelgrass may be more tolerant of high shear stresses.

The “So What” Report

Overview: This 3-year project tested a group of hypotheses meant to fill gaps in our understanding of how eelgrass responds to changes in water quality so that we could better manage human impact on the Great Bay Estuary. The stated management goal is to protect eelgrass habitat, which is often the first habitat to suffer under changes brought about through a combination of development and climate change. In the Great Bay Estuary, by 2022 eelgrass coverage (by acres) had declined in Great Bay by 41% since its recent peak in 1996, while eelgrass in Portsmouth Harbor had declined by 48% since its peak in 2002. 2023 was an especially bad year for eelgrass and those losses increased to 66% and 57%, respectively.

The fundamental hypothesis guiding our research objectives was that recent reductions in nitrogen from wastewater treatment facilities (WWTF) would have some demonstrably beneficial impact on eelgrass. Most of the reductions began in 2014 with improvements from Dover and Rochester; more significant reductions occurred with major facility upgrades from Newmarket in 2017, Portsmouth in 2019, and Exeter in 2020. Given the expectation of beneficial impact on eelgrass, we asked: *How will we judge whether additional nitrogen reductions would be beneficial to eelgrass?* To help with that question, we wanted to document how eelgrass health affected its environment, especially with regard to nitrogen and sediments, along a gradient. By doing this, we might be able to better predict future scenarios with regard to eelgrass, nitrogen and sediments.

For this project, eelgrass health is assessed by measuring eelgrass “coverage” (i.e., how many acres of the estuary have eelgrass habitat?) and “biomass,” which is the mass of eelgrass material above and below the ground. We recognize that these metrics are imperfect and do not capture important aspects of eelgrass health (e.g. genetic diversity).

Unfortunately for the ecosystem and for our project, eelgrass coverage and biomass took a significant downturn during the project period, which was characterized by much higher than normal precipitation rates. We have observed in the past that eelgrass is negatively impacted by high levels of precipitation and this project underscored that observation. The question remains: what can managers do to mitigate the effects of precipitation?

More broadly, the significant loss of eelgrass changed this work from a study of how a recovering eelgrass habitat filters nitrogen and sediment and transformed the project into a study of how—indeed, if—an eelgrass habitat with relatively low biomass and coverage can provide some of its core ecosystem functions.

Scientists working in other estuaries have stressed the importance of having realistic notions of if, how and when pollution reduction will have an impact. False expectations of rapid recovery can mask the long-term effectiveness of management actions. The literature indicates that, often, a system will have difficulty fully recovering from nitrogen pollution, for example, due to other ecosystem shifts that occur due to excessive nutrients. In addition, a significant recovery can take from 8 years to more than 20 in some cases. This study has underscored the importance of understanding those mechanisms that impact the connection between pollution reduction (i.e., decreases in nitrogen loading) and observable changes in ecosystem health. Perhaps the most important of these is time lags. Only when any lagged effects have propagated through the estuary will we have an accurate understanding of how eelgrass will react to pollution reduction.

This report is management focused. Therefore, we begin with the implications of the data. This is followed by a review of the project questions, answers and additional insights.

Project Implications

Please note that this “So What” report is an extended high-level summary. It does not include detailed context, background information, methods and results, which are found in the “Eelgrass Resilience Technical Report,” a companion document. In addition, the related work of analyzing historical trends—led by the Piscataqua Region Estuaries Partnership (PREP)—is not part of this report; rather, that analysis will be combined with this work, focusing on the years 2021 through 2023, and will result in a separate report in 2025.

This section is organized around four prompts that were developed in consultation with the Project Advisory Committee. 1) What did we learn about stressors on eelgrass, and which should we be concerned about? 2) What are the implications for the types of management activities that would be more or less effective under longer-term conditions? 3) What does this science mean for our collective work more broadly (e.g., water quality management, restoration, communication)? 4) What are the implications for approaches to setting nutrient and sediment targets? (Note: Prompt 4 will be addressed as part of the “PREP Eelgrass Report,” due out in 2025.)

Prompt 1: What did we learn about stressors on eelgrass? Which should we be concerned about?

Yes, Light Matters, But Other Things Matter, Too

Light is often the first thing to worry about when eelgrass is lost and this 3-year study hasn't changed that concern, although the lack of a statistical relationship between eelgrass health and light within Great Bay sites suggests that light may not be the sole issue limiting eelgrass within the Bay. Still, where light is consistently above established thresholds, eelgrass biomass tends to be higher. Eelgrass biomass tends to be lowest in Great Bay, where there is the most light attenuation, slightly higher with slightly better light in the Little Bay/Piscataqua Region and highest in Portsmouth Harbor, where the water is clearest. Of course, the water is colder and there is less organic matter in the sediments in Portsmouth Harbor, so the higher eelgrass biomass there cannot be solely attributed to light.

Which components of light should we be concerned about? In short, all of them. While only dissolved organic carbon—a proxy for colored dissolved organic matter (CDOM)—was statistically related to eelgrass biomass, the data clearly indicate that phytoplankton (chl a) and TSS (Total Suspended Solids) levels are high enough to warrant concern—higher than 15 µg/L and 15 mg/L, respectively. Specifically, in 2022, median TSS levels were higher than these levels of concern in Great Bay and Little Bay/Pisc River; in 2023, median TSS levels were of concern only in Great Bay, where the lowest eelgrass biomass was found. Throughout the estuary during this 3-year study, chlorophyll-a ranged from low to high. For example, in 2021, a very rainy year with fairly low eelgrass biomass, median chl-a levels were about 25 µg/L in Great Bay. In 2023, even rainier than 2021, chl-a levels were much lower. In 2023, even more eelgrass was lost, suggesting that TSS and/or CDOM made conditions challenging for both phytoplankton and eelgrass.

Both Sediments and Nutrients Matter

Therefore, we conclude that both TSS and nutrients continue to be the main manageable stressors of eelgrass health in Great Bay Estuary. This conclusion is underscored by the result that strong negative correlations—high nutrients correlate with low eelgrass—were observed between multiple types of nitrogen concentrations, including total nitrogen (TN), particulate nitrogen (PN), total dissolved nitrogen (TDN), and dissolved organic nitrogen (DON), and eelgrass biomass. While it is possible that these correlations were driven by high eelgrass biomass in Portsmouth, we still believe these findings point to the potential influence of nitrogen on eelgrass.

Both suspended sediments and nutrients are also of concern because of the unknowns surrounding them. For example, with sediments, there is still so much we do not understand about sediment origin and transport, and how much of the sediments we're seeing come from re-suspension of estuarine sediments as opposed to new sediments loaded from the rivers. Also, sea level rise has the potential to greatly increase suspended sediments as shorelines and river banks are eroded. These unknowns are incentives for prudence with regard to this stressor.

The same can be said for nutrients. Future weather patterns are uncertain, but if forecasts are correct, many more years like 2023 are in store for us, and this translates into increased loading of non-point source nutrients. In addition, this study underscored the potential importance of nutrient recycling from the sediment beds. When looking at the trends in nitrogen loading, it is natural to be optimistic since we now have the lowest amount of loading—especially in dry years—since our dataset began in 2003. However, this dataset does not include nutrients re-introduced to the water column from loading that occurred in past years. In many estuaries, the amount of nutrients recycled exceeds what comes in currently from the rivers.

CDOM, Temperature, Salinity: They Matter But Are Much Harder to Manage

Finally, while CDOM may be a stressor, it is very difficult to manage. CDOM levels have increased in the northern hemisphere in recent decades, and some scientific literature suggests that watershed scale mitigation measures are possible. However, given the uncertainties in the ability to reduce CDOM, we suggest that it not be the priority in terms of manageable stressors. Likewise, other stressors, such as temperature, salinity, and sea level rise, are also exerting an influence on eelgrass health, but are not amenable to local management.

Prompt 2: What are the implications for the types of management activities that would be more or less effective under longer-term conditions?

Focus on Measures that Address Both Nutrients and Sediments

Given that both nutrients and sediments are most likely impacting eelgrass health, strategies that address both stressors together should receive highest priority. In addition, the data indicate that the Estuary exhibits differences in eelgrass response dependent on spatial context. This is true even within one region, such as Great Bay; one side of Great Bay seems to have different stresses and responses than the other. This suggests that one very focused strategy—for example, focusing on just nutrients or just sediments—is likely too narrow of an approach. Some strategies to address both include focusing on land conservation; maintenance of buffers; stormwater management; and wastewater from treatment plants.

Improvements and upgrades of WWTFs have the potential to not only reduce nitrogen and phosphorus but also TSS. The 12 municipalities that preside over the 13 WWTFs in the Great Bay Estuary—Portsmouth presides over 2 facilities—have accomplished impressive pollution reduction over the past 10 years. Scientifically, it is unclear if further reductions at WWTFs are the most cost-effective way to improve eelgrass health. Moreover, this is not only a technical question but also a public policy issue, because 48 municipalities contribute nutrients to the Great Bay Estuary but the burden of upgrading WWTFs falls only on 12 communities in New Hampshire and 4 in Maine. (MS4 permits and/or waivers, which address stormwater issues, have been issued to many communities in the Piscataqua Watershed.)

Shoreline Management and Habitat Restoration

Shoreline management is another action that addresses both sediments and nutrients. When natural shorelines are converted into “hardened” shorelines, they increase wave energy and decrease opportunities for filtering nutrients as well as opportunities for creating habitat for fish and shellfish. Shoreline armoring can also reduce the supply of coarser sediments (e.g., sand) that eelgrass tend to prefer as a substrate over finer sediments.

Restoration of key habitats (salt marshes, eelgrass, oyster reefs, river habitat, etc.) is also a high priority. Successful restoration can help to jumpstart recovery or slow feedback cycles. Increased habitat availability can benefit fish populations, exerting top-down benefits for eelgrass, as higher numbers of fish lead to fewer green crabs and healthier grazer populations, which keep epiphytes on eelgrass blades in balance. Unfortunately, estuarine habitat restoration is not always successful and does not negate the need for adequate water quality to sustain a healthy ecosystem.

Septic Systems? Yes, But Other Actions First

Other management actions that focus only on nutrients are mentioned frequently, such as septic tank improvements and fertilizer control. Certainly, there is reason to believe that these actions will improve ecosystem health. However, unless such an action would result in large, wide-scale decreases in the nutrient inputs that are actually delivered to the Estuary, we consider them as slightly lower in priority only because they do not address sediments as well as nutrients.

Prompt 3: What does this science mean for our collective work more broadly (e.g., water quality management, restoration, communication)?

Yes, It’s Complicated, But More Communication Can Bring Common Understanding

First, communication. This project has been a success in terms of collaboration and communication in many ways. That success needs continued effort so that more than just a handful of people understand the importance of eelgrass and the importance of the entire Great Bay Estuary watershed ecosystem. The partners in this project are committed to continuing this communication. A key component of the communication effort needs to address the role of eelgrass as an important ecosystem health indicator, but to remind people that eelgrass is only one component of a well-functioning ecosystem. Yes, eelgrass is a key habitat, but it works collaterally with oysters, fish, salt marshes and upland habitats to keep the Piscataqua Watershed functioning in an ecologically sound manner.

Managing Expectations Is Critical

Effective communication is also important in terms of managing expectations. Many people are concerned that, after all the work that has gone into significant pollution reduction, 2023 represented a step backwards instead of forwards in terms of eelgrass health. Somehow, we need to be able to see the big picture and understand that it can take time for the ecosystem to respond to the many actions taken on the landscape to control both nutrients and sediments. In addition, it is important to understand that the path to ecosystem health will require an adaptive approach over time, so that new and improved information and changing conditions can be leveraged for the best management outcomes.

Recycling of “Old” Nutrients from the Sediments: A Key Expectations Challenge

The issue of nutrient recycling from sediments is a key part of the “expectations” challenge. It is well known in estuarine ecology that there is often a time lag between pollution reduction and ecosystem response, primarily due to nutrients accumulated in the sediments slowly being recycled. Another issue is “legacy” nutrients, which refers to those nutrients that are slowly making their way to the estuary from the watershed. In the case of the Great Bay Estuary, this applies to nutrients in the groundwater. It has been estimated that the mean residence time of groundwater entering our estuary is 20 to 30 years; this means it can take between 20 and 30 years for groundwater surrounding Great Bay and Little Bay to make its way to the estuary. These time lags offer both a communications challenge and a science challenge: How do we assess these processes so that we can offer Piscataqua Watershed residents a more resolved picture of what they can expect? Addressing these communications and science challenges will be vital if we want municipalities to continue to do the hard work of reducing pollution and protecting the Piscataqua Watershed.

This concludes the “Implications” section. We now turn our attention to the specific questions posed by our project, along with results and additional insights.

Questions We Set Out to Answer and Additional Insights

Directly below, we present our overarching and more detailed research questions with short answers to our questions interspersed.

Our proposal posed this overarching question: Have recent nitrogen loading reductions improved eelgrass health or resulted in positive feedbacks that enhance the resilience of eelgrass in Great Bay Estuary?

Short Answer: No. Not that we could measure. The last year of this project saw a significant decrease in acreage of eelgrass habitat, hitting the lowest point since 1989. Logically, this means that one or more of the following explanations applies: 1) Any potential positive feedbacks from nitrogen reductions were overwhelmed by rain and the non-point source pollution (including nitrogen, sediments, and organic matter) that the rain delivered to the estuary over the project period; 2) Other stressors in addition to nitrogen loading are having an influence on eelgrass health that is equal to or greater than nitrogen levels; 3) Time lags: there are time lags between loading reductions and eelgrass response, due to the life history characteristics of the eelgrass plant, historical loading and the slow rate at which past nitrogen is processed. Therefore, it will take additional time to see the impact of recent reductions on eelgrass health.

Under our overarching question, two main research questions were posed, each having a set of sub-hypotheses:

Question 1: Does eelgrass health vary spatially in correspondence with water residence time, bed shear stress, algae, nitrogen concentrations, light attenuation and light attenuating components?

Residence Time Answer: Residence time, a measure of how long water remains in a given location, is relevant to water quality management. For example, we know that the tributaries have different levels of water discharge and nitrogen loading. If all the water in the estuary is instantly mixed, these differences between tributaries are unimportant. However, if residence time differs depending on where you are, as this project showed, then differences between sub-watersheds could be important. In this study, when looking at the whole Estuary, shorter residence time correlated with healthier eelgrass. Portsmouth Harbor, which has the shortest residence time, has the healthiest eelgrass. However, within Great Bay, the pattern was the opposite; longer residence time was associated with healthier eelgrass.

Additional Residence Time Insights: Empirical hydrodynamic data gathered as part of this project has significantly changed the way scientists view Great Bay. One of the project external advisors, after seeing the simulations, began referring to Great Bay as a “lagoonal estuary,” because “there’s this push and pull between clear inputs of new water through the deeper channels, but then the shallow banks of Great Bay act much more like an estuary with a very constricted outlet to the adjacent waterbody” (Lora Harris, June 26 Meeting, 2024). This project agreed with past assessments of the “average” residence time in Great Bay, but noted that certain areas of the bay, such as Eastern Great Bay, and areas close to the shore that often serve as eelgrass habitat, could have much longer residence times (far exceeding 20 days) than previously thought. This new understanding of hydrodynamics in Great Bay Estuary could have significant impacts on how we approach nutrient and sediment management.

Bed Shear Stress Answer: Shear stress, which can impact sediment resuspension and nitrogen and phosphorus recycling—that is, nutrients from past years being re-introduced into the water column—did not correlate with eelgrass health across the whole estuary; however, in Great Bay, eelgrass health did decrease as shear stress increased. This could be related to the effects of shear stress on the sediment seed bank—eelgrass seeds in the sediment—and the survival of seedlings. Increasing shear stress correlating with decreasing eelgrass could also be related to the finding that shorter residence times in Great Bay correlated with lower eelgrass health. In the Great Bay, where the sediment is extremely fine and holds more organic matter, quickly moving water and high shear stress can cause problems; in Portsmouth, with large cobble sediment and less organic matter, the eelgrass tolerates high shear stresses.

Additional Shear Stress Insights: This project agrees with past work noting that sediment resuspension can certainly be a mechanism by which more nutrients (loaded in previous years) are introduced into the water column. This may be an area where more science and monitoring are needed to guide our expectations regarding impacts from nutrient management.

Algae (phytoplankton, seaweed, and epiphytes) Answer: An increase in algae with corresponding decreases in eelgrass is the classic sign of excessive nutrients such as nitrogen and phosphorus. In this 3-year study, at both the Estuary-wide and Great Bay only scales, eelgrass biomass did not significantly correlate with any seaweed, epiphyte, or phytoplankton metric. If we use eelgrass percent cover instead of biomass, however, eelgrass was negatively correlated with seaweed percent cover. Also, for Little Bay/Piscataqua River, there was actually a significant positive relationship between eelgrass and seaweed biomass. This may be due to eelgrass providing a place for unattached (drift) seaweeds to become entangled, like tinsel on a Christmas tree. Without rooted eelgrass, drift algae would most likely be swept away by currents, either to nearby shores or out to the ocean.

Other algae (phytoplankton, seaweed, and epiphytes) Insights: It is certainly not clear that seaweeds are having a direct negative impact on eelgrass. In very wet years, such as 2023, light in Great Bay may be poor enough to even limit seaweed, not just eelgrass. In drier years with better light conditions, seaweed could be more detrimental if it continues to not be limited by nitrogen in the water column. More data are required to determine this. Similarly, for phytoplankton, in 2023, poor light most likely kept phytoplankton levels down. However, in 2021, median phytoplankton levels in Great Bay were higher than 20 µg/L as chlorophyll a, which is certainly high enough to warrant concern. Even in Portsmouth Harbor, median levels were above 10 µg/L; to be considered “low,” median phytoplankton levels should be below 5 µg/L.

Nitrogen Concentrations Answer: In this study, across the Estuary, strong negative correlations were observed between multiple types of nitrogen concentrations, including total nitrogen (TN), particulate nitrogen (PN), total dissolved nitrogen (TDN), and dissolved organic nitrogen (DON), and eelgrass biomass. Those correlations did not hold up when only Great Bay data were examined, suggesting that the Portsmouth sites were driving the estuary-wide correlations. Of additional note was the significant, negative correlation between DON and eelgrass biomass, which also is driven by the Portsmouth Harbor sites. The relationship between DON and eelgrass biomass, though weak, is another indicator that light may be a stressor in the system. Since DON is part of the larger dissolved organic matter (DOM) pool, DON concentrations in Great Bay Estuary could contribute to light attenuation.

Additional Nitrogen Concentrations Insights: Water quality monitoring in Massachusetts estuaries has shown that healthy eelgrass meadows typically have total nitrogen concentrations below 0.34 – 0.37 mg/L, with degraded meadows having twice that amount of TN. In Great Bay, total nitrogen concentrations often exceeded 0.40 mg/L in 2023.

Light Attenuation Answer: Light attenuation (or Kd) is inversely related to water clarity: it is a measure of how much light is extinguished as you proceed from the surface to deeper water. Within Great Bay, there was not a relationship between light attenuation and eelgrass biomass. This may not be surprising given that the majority of light attenuation data points were higher than the published threshold for eelgrass, which is 1.0. In other words, a range of Kd values between 1.5 and 3.0 will most likely result in very little eelgrass biomass, thereby quashing any statistical relationships. However, when looking estuary wide, eelgrass biomass is negatively correlated with light attenuation: meaning that as light attenuation increased (i.e., light availability decreased), there was less eelgrass biomass. Once again, this correlation is driven by sites in Portsmouth Harbor, which had the best water clarity and the healthiest eelgrass. As noted previously, there are other characteristics close to the ocean that also favor eelgrass, such as lower water temperature and less organic matter in the sediment.

Additional Light Attenuation Insights: In contrast with Portsmouth Harbor, Great Bay had the highest values of Kd and the lowest values for eelgrass biomass, suggesting poor water clarity may be reducing light availability to the eelgrass meadows. It is also important to note that most sites in Great Bay have Kd values over 1.0, the maximum threshold recommended for Great Bay eelgrass. For the 3-year period, the data indicate that only Great Bay is receiving less light than is required for eelgrass habitat maintenance, which agrees with the empirical relationship between Kd and eelgrass biomass in 2022 and 2023.

Light Attenuating Components Answer: Individual light attenuation components did not show strong relationships with eelgrass biomass across the Estuary nor in Great Bay specifically, except for dissolved organic carbon (DOC) estuary wide. Again, this relationship may be driven by the high biomass and low DOC in Portsmouth Harbor.

Additional Light Attenuating Components Insights: The lack of relationship between TSS and eelgrass biomass is surprising. However, while the data do not show a relationship between TSS and eelgrass health, the TSS levels in this time period were certainly high enough to be of concern. As already noted, the same can be said for phytoplankton. The available dataset probably underrepresents the effects of wet weather events on TSS loading and light attenuation in the Great Bay. Visual observations confirm that water clarity is lower in the Great Bay after wet weather events, and that the sediments in Great Bay are easily resuspended.

In summary, the data from this 3-year period indicate that all three light attenuating components are most likely factors in blocking light and negatively impacting eelgrass health. Given this work's focus on nutrients with respect to the EPA Permit, it should be noted that both CDOM and TSS contain nutrients. TSS contains not only inorganic particulate matter—mostly clays and other inorganic sediment—but also any organic matter, such as phytoplankton, that is retained by a 0.7 μm filter. CDOM also incorporates nitrogen since CDOM refers to dissolved organic matter; a portion of the “organic matter” is often comprised of nitrogen contained in these organic compounds.

Question 2: Does nitrogen and/or sediment filtration (i.e., ecosystem services) vary along transects that span unvegetated areas to areas vegetated with eelgrass?

Nitrogen/TSS concentrations Answer: In this study, concentrations of dissolved inorganic nitrogen (DIN) in the surface water did not consistently decrease with increasing distance into the eelgrass meadow flowpaths. Flowpaths varied between net uptake of DIN (negative flux) and net release of DIN (positive flux), with the median DIN fluxes centering around zero, indicating no change. Concentrations of total suspended solids (TSS) did not consistently decrease with increasing distance into the eelgrass meadows.

Additional Nitrogen/TSS concentrations Insights: Given low eelgrass biomass values during the project period, our results could be viewed as what happens when eelgrass habitats begin to lose their ability to perform ecosystem functions. For example, the striking difference in TSS behavior between 2022 and 2023 demonstrates the loss of an ecosystem service, with increasing TSS along those flowpaths with little to no eelgrass in 2023.

Nitrogen Filtering and Residence Time Answer: In this study, nitrogen uptake by eelgrass did not significantly vary with meadow residence time, although this result could be influenced by the small number of data points available. Based on these data, nutrient filtering is occurring in Great Bay, though at reduced rates, once again indicating a struggling eelgrass habitat.

Additional Nitrogen Filtering and Residence Time Insights: In this study, rates of denitrification were higher in Great Bay Estuary than in Atlantic coast eelgrass meadows (Virginia), a surprising finding given that the density of eelgrass in Great Bay was half that of the restored Virginia meadows. This could be partially explained by the fact that Great Bay sediments have greater carbon content across both habitat types, measured as both percent organic matter and percent carbon, than Virginia sediments. In addition, our sediments have much higher nitrogen levels in the porewater than in Virginia, which catalyzes denitrification.

Nitrogen Filtering and Water Parcel Origin Answer: In this study, eelgrass nitrogen uptake did not significantly vary as a function of river water source, a surprising result given that the tributaries have different levels of water discharge and nitrogen loading. Again, this could be due to the low eelgrass biomass, reflecting a struggling ecosystem.

Additional Nitrogen Filtering and Water Parcel Origin Insights: The previously noted caveats apply; both the low number of sample replicates and the poor health of eelgrass could have confounded results. In the future, given the better health of eelgrass in Portsmouth Harbor, a similar experiment could be done comparing Great Bay sites with sites closer to the ocean.

Eelgrass Health and Nitrogen Filter Processes Answer: In this study, eelgrass biomass did not exhibit a clear pattern with increasing eelgrass nitrogen uptake. Once again this is surprising, given that other studies typically show positive correlations between aboveground eelgrass biomass and DIN net uptake.

Additional Eelgrass Health and Nitrogen Filter Processes Insights: As noted throughout this report, the very low eelgrass biomass values were unanticipated and made it more difficult to discern relationships. For example, in previous years, we could very well have had eelgrass biomass as high as 100 g/m², rather than topping out at less than 15 g/m².