Nitrogen Loading to the South Shore, Eastern Bays, NY:

Sources, Impacts, and Management Options

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Abstract of the Thesis

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The excessive delivery of nitrogen from land into coastal waters can lead to a host of environmental problems including algal blooms, hypoxic zones, habitat loss, and acidification. While many of these environmental problems have manifested themselves within Long Island's coastal bays, the quantity and sources of nitrogen are largely unknown in much of this region, making the development of effective management plans to ameliorate these problems exceedingly difficult. This study was designed to quantify nitrogen loads and sources to Moriches, Quantuck and Shinnecock Bays within the eastern extent of Long Island's South Shore Estuary Reserve. Further this study assessed water quality within the bays as well as nitrogen mitigation scenarios tailored to the adjacent land on a subwatershed level. Two established nitrogen loading models were used to quantify nitrogen loads to each subwatershed as well as the relative contribution of each source (fertilizer, wastewater, and atmosphere) and transport mechanism (ground water, streams and runoff). Marine water quality data was compared to nitrogen loading rates and water residence times. Finally, the effectiveness of various nitrogen mitigation scenarios including changes in land use and wastewater handling was assessed within the models.

Nitrogen loads per hectare of waterbody to these three bays were moderate compared to other estuaries but were in the high range when loads were assessed on the basis of volume of waterbody. Over the entire study site, the relative contributions of wastewater, fertilizer, and atmospheric deposition to the total N loads from land were 65%, 20%, and 15%, respectively. Groundwater was responsible for the transport of > 90% of the nitrogen load in all but one of the subwatersheds, while stream and runoff delivery of N was small. The western portion of Moriches Bay including the Forge River estuary and Quantuck Bay were two of the areas of the bay with the largest N loads on a per volume basis, the longest residence times, and poorest water quality with regard to algal blooms, dissolved oxygen, and water clarity. As such, this thesis identified slow residence times as a key factor that, coupled with elevated N loads, drives poor water quality in coastal ecosystems. As wastewater was the major source of N to the estuaries studied here, connecting homes to a sewage treatment plant, upgrading septic systems and controlling future build-out were identified as managerial efforts that could reduce nitrogen loads to these vulnerable areas of the bay by up to 70%.

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Introduction

Excessive anthropogenic nutrient loading is one of the most pressing environmental concerns in coastal areas. Eutrophication occurs when coastal waterbodies are overloaded with nitrogen (N) and phosphorus, and phytoplankton populations, normally controlled by periodic nutrient limitation and grazing, become dense and pervasive (Nixon 1995). Such algal blooms can attenuate light penetration through the water column, decreasing the depth at which benthic phototrophs, such as seagrasses, can survive (Waycott et al. 2009). Additionally, oxygen concentrations can decrease sharply beneath the surface of the water due to the respiration and decomposition of the excessive organic matter from decaying algal blooms. In this way eutrophication often leads to hypoxia (very low levels of oxygen) or anoxia (zero oxygen), which can be deleterious to fish and benthic communities (Diaz and Rosenberg 2008).

Harmful algal blooms (HABs) are an additional environmental problem that can be initiated by nutrient overload. HABs have increased in their geographic extent, intensity, duration, and diversity in recent decades (Hallegraeff 1993; Heisler et al. 2008). There are clear linkages between increased loading of N in coastal waters and the presence and prevalence of HABs in many ecosystems (Anderson et al. 2008; Heisler et al. 2008). In some regions such as Long Island, HABs promoted by N have become annual occurrences. The phytoplankton that compose these HABs are diverse and can affect fisheries, humans, and/or ecosystems. For example, wastewater-derived N has been shown to support the proliferation of saxitoxin-producing blooms of *Alexandrium fundyense* that can cause paralytic shellfish poisoning (Hattenrath et al. 2010). Brown tides, caused by *Aureococcus anophagefferens* flourish when there are high levels of organic N and turbidity (Gobler et al. 2011) and negatively impact shellfish and eelgrass (Gobler and Sunda 2012). Nitrogen also promotes toxic dinoflagellate blooms of *Cochlodinium polykrikoides* that cause fish kills (Gobler et al. 2008; Kudela and Gobler 2012; Gobler et al. 2012).

Since N limits primary production in many coastal marine environments (Nixon 1995, Borum 1996), it is often the delivery rate of N that influences the prevalence of algal blooms, intensity of hypoxia, and the loss of seagrass beds (Bricker et al. 2008). Nitrogen found in coastal environments can be derived from natural as well as anthropogenic sources. As the human population of a watershed grows so too does the magnitude and proportion of anthropogenic N to coastal waters (Valiela et al. 1992). On Long Island, the major sources of N to Long Island Sound and the Peconic Estuary are waste water, fertilizer, and the atmosphere (LISS 1994, PEP 2001). However, the relative importance of a N source can vary even over small geographic distances (LISS 1994, PEP 2001). As a result, N loading models are required to determine the precise magnitude of multiple N sources to estuaries and how those spatial differences in N load relate to coastal land use (Kinney and Valiela 2011).

Long Island’s South Shore Estuary Reserve (SSER) is made up of a series of lagoons stretching over 70 miles from Long Beach to Southampton. Lagoons are common coastal features where barrier islands separate a marine water body from the ocean. Tidal exchange in these systems is often minimal and occurs through inlets in barrier islands. Lagoons are typically shallow, well-mixed, and have longer residence times than other coastal embayments (Kjerfve 1994). Because of this, organic material from the watershed tends to accumulate in lagoons making them productive marine environments but also very susceptible to eutrophication (Nixon 1982; Boynton et al. 1996). The SSER watershed is populated (>1 million people), heavily utilized, and economically important, particularly to the 30,000 residents employed in water-dependent businesses (Suffolk Co. Comprehensive Plan 2035, 2011). The entirety of the reserve was declared an impaired waterbody by the New York State Department of Environmental Conservation's 303d list in 2010 due to on-site waste water disposal and algal blooms (NYS DEC 2010).

Although the western extent of the SSER is heavily populated, regions to the east in Suffolk County, such as Moriches, Quantuck, and Shinnecock Bays, are less so but have still displayed signs of eutrophication. For example, prior to 1985 HABs had not been observed in Shinnecock Bay, but blooms of *A. anophagefferens* have become near annual occurrences since then (Gobler and Sunda 2012). *C. polykrikoides*, a dinoflagellate, was first observed in Shinnecock Bay in 2004 (Gobler et al. 2008) and has subsequently occurred every year since (Kudela and Gobler 2012). A third toxic species, *A. fundyense*, which causes paralytic shellfish poisoning in humans, was first observed in Shinnecock Bay in 2008 (C. Gobler, pers. comm.) and has since led to periodic closing of the Shinnecock Bay shellfish beds due to paralytic shellfish poison toxins (NYS DEC, 2011, 2012). In the past three years all three harmful algal blooms have occurred in succession. Concurrently, shellfish populations have declined in Shinnecock Bay (Weiss et al. 2007) and eelgrass coverage has decreased (Carroll et al. 2008).

While HABs have only been noted in the Eastern Bays since 1985, eutrophication due to excess N has been a problem in the region since the 1950's (Ryther 1954, Swanson et al. 2009). Historically, the Forge River area, in western Moriches Bay was a center for duck farming. With over 80 farms, the entirety of Suffolk County was a popular place to produce ducks for human consumption, but the Forge River watershed alone had 8 farms at its peak in the 1960's. Millions of ducks were produced annually, with approximately 10 ducks releasing the same amount of nitrogenous waste as one human (Swanson et al. 2009). While the last of these duck farms closed in 2011 (there is still a working pigeon ranch in the area), the sludge from their waste is still present in the sediments of the tributaries entering western Moriches Bay and thus continues to contribute to eutrophication in the region (Swanson et al. 2009).

As duck ranching in the area has subsided the human population within the watershed has grown. Since the 1980s the population growth of Suffolk County has outpaced Nassau County and it is projected that this trend will continue in the coming decades (Suffolk Co. Comprehensive Plan 2035, 2011). Between the years of 1990 and 2010 there was a 12% increase in the population of Suffolk County and the projected increase for the next 15 years is 16% (Suffolk Co. Comprehensive Plan 2035, 2011). This population increase and the corresponding increase in anthropogenic N supply suggest that environmental conditions in these watersheds could worsen in the coming decades. Additionally, the influx of summer residents and visitors is more than double the permanent population in eastern townships such as Southampton (Lambert 2010). Finally, in Southampton and Brookhaven Towns, there is a significant amount of open space that may still be developed.

Despite the prevalence of environmental problems within the Eastern Bays of the SSER, the rates and sources of N loads to Moriches, Quantuck and Shinnecock Bays have not been quantified. This knowledge gap prohibits the formulation and evaluation of management plans to effectively ameliorate N loads to these systems. Given the very large costs associated with such efforts, it is important to precisely quantify the relative contribution of all of the major sources of N to the Bays to ensure that expenditures made for these efforts are cost-effective. Quantifying the current N loads entering the eastern SSER as well as quantifying how those loads would change under differing N mitigation and land-development scenarios would be a vital tool for the proper management of these systems.

Addressing the detrimental consequences of excess N loading to coastal waterbodies represents a daunting challenge for Suffolk County and for New York State. However, the quality of surface waters and the health of these Bays have a very large impact on the economy and quality of life in Suffolk County (Suffolk Co. Comprehensive Plan 2035,2011). It is widely recognized that the future of smart economic development in Suffolk County will require upgrades to the County's wastewater treatment infrastructure and local land-use policies. As a consequence the County is already exploring options such as new and expanded sewer districts and health department approval of alternative N reducing septic systems. However, the type of quantitative data generated by this study will assist in forecasting the value of any of these proposed projects in terms of how they will influence the N loads to coastal waters and the quality of surface waters in the SSER Eastern Bays.

Therefore, the main objectives of this project were to quantify the N loads to Moriches Bay, Quantuck Bay, and Shinnecock Bay and determine the major sources and transport mechanisms for this N. Additionally, I assessed the spatial variability in water quality (HABs, dissolved oxygen, water clarity) across these estuaries and compared them to N loading rates from land and flushing rates for each water body. Finally, I assessed how various watershed management strategies would alter N loads to these estuaries.

Methods

Watersheds

The area of the Moriches, Quantuck and Shinnecock Bay watersheds were determined from Suffolk County's LiDAR elevation data, topographical maps demarking the surface watersheds, groundwater flow patterns in the region, and GIS data. I assumed that the groundwater flow generally follows hydraulic gradients established by surface topography (Schubert 1998). The watersheds were separated into subwatersheds in the same manner. Moriches and Shinnecock Bays are each divided into three subwatersheds and Quantuck Bay, given its small size, was its own subwatershed. The resulting subwatersheds are finer than the Hydrologic Unit Code (HUC) 12 delineation (Fig 1).

Monti and Scorca (2003) determined that a certain portion of Long Island groundwater flow bypasses the south shore Bays and release directly into the ocean. This ground water comes from the furthest upgradient portion of the watershed. Kinney and Valiela (2011) used 20% as their underflow portion in their study of Great South Bay. The Moriches Bay watershed abuts their study area, however, its watersheds are smaller latitudinally, indicating less land area upgradient, and the Moriches Bay shoreline is much more irregular than that of Great South Bay. Because of this I used 10% underflow for the Moriches and Quantuck Bay watersheds. I assumed no underflow for the Shinnecock Bay watershed as there is significantly less upgradient area and little elevation gain in the watershed.

<u>Nitrogen Loading Model (NLM)</u>

The first model used to predict the total dissolved N input into the Eastern Bays was the Nitrogen Loading Model (NLM; Valiela et al. 1997) available through the N load web-based modeling tool (nload.mbl.edu) described in Bowen et al. (2007) and used in Bowen and Valiela (2004) and recently Kinney and Valiela (2011), among others. The NLM uses information about land use in a defined watershed to predict both the amount of N that is released into the watershed from various sources and how much of it ends up in a corresponding water body. This model requires accurate land-use information, such as area of agriculture, residential areas and impervious surfaces as well as other environmental data gathered from scientific literature, GIS data, US Geological Service (USGS) reports, the Town of Southampton, and Suffolk County.

The NLM is a good fit for watersheds such as the Eastern Bays that are a mix of residential, forested and agricultural lands (Valiela et al. 2000). NLM assumes that the primary transport mechanism for N entering the bay from the watershed is groundwater flow. This is a good assumption for this study site because there is little inflow to the bay from streams and geologically, Long Island is composed of unconsolidated sands that allow for relatively easy transport of ground water to coastal lagoons (Kinney and Valiela 2011). The NLM assumes that all new sources of N to the bay can be composed of atmospheric deposition to the watershed, waste water, and fertilizer. This study also included atmospheric deposition directly to the surface water of the Bays. Valiela et al. (2000) validated this model by comparing its N load prediction to empirically measured N levels. They found the NLM's results to be statistically indistinguishable from measured concentrations and also found a linear relationship between the percent contribution from waste water that NLM predicted and the stable isotope signature for waste water expected from known values of $\delta^{15}N$ of nitrate in ground water. The NLM is one of the most inclusive N loading models in regard to the transformation and transport of N as it travels from watershed to estuary (Bowen and Valiela 2001).

The NLM utilizes multiple features, which were obtained from the Town of Southampton and Suffolk County for Moriches, Quantuck, and Shinnecock Bays: number of buildings, buildings within 200m of shore, surface area of the watershed, area of freshwater wetlands, agriculture, golf courses, parks and athletic fields, freshwater ponds and impervious surfaces. The model also includes a list of inputs assigned default values based on an extensive metadata analysis (Valiela et al. 1997). These defaults were altered when local and site-specific information was available. For example, following a recent study by Young et al. (2013) of denitrification in Long Island's aquifer, the percent denitrification in ground water was assumed to be 15%. All NLM inputs and sources used for this study are listed in Table 1. NLM has a 12% bootstrap derived standard error coefficient (Valiela et al. 1997).

Atmospheric Deposition

Nitrogen that arrives in the watershed through wet and dry deposition may have more or less of a contribution to the bay depending upon the use of land where it falls.

Nitrogen that lands on natural vegetation has time to be assimilated by plants and organisms in the soils and/or denitrify in the aquifer. Nitrogen that falls on impervious surfaces may runoff directly into a stream, the bay, the municipal separate stormwater sewer system (MS4), or eventually seeps into sandy soils closer to an estuary than it would otherwise. Therefore, significantly less N is removed from atmospheric deposition that lands on impervious surfaces.

The land-use information used within NLM was ascertained through the Suffolk County land-use GIS maps as well as the Southampton GIS Department for the Shinnecock and Quantuck watersheds. The total area of impervious cover was determined by using these maps to provide the area for a given use-category (for example, low-density residential). The parcel areas were then multiplied by a percentage of imperviousness as determined averaging values from several sources (USDA 1986, Mass GIS 2003, Hoffman and Canace 2002, Kellogg et al. 1997, Center for Watershed Protection 2002, Arnold and Gibbons 1996, New York State Department of State 1999, see Table 2). Roof area per building was determined by calculating the average area of the footprint of buildings within the watershed. The area of road as a percent of total watershed was calculated by using the length of actual roads in the watershed and a standard road width of 25 feet. I then divided road area by watershed area to determine percent. Annual precipitation on Long Island was ascertained by calculating the average amount of precipitation at the Islip airport weather station, managed by the National Oceanic and Atmospheric Administration, over the past decade.

Nitrogen inputs from wet and dry deposition were determined using the National Atmospheric Deposition Program (NADP; wet) and the EPA's Clean Air Status and

Trends Network (CASTNET; dry). The closest NADP monitoring station to our study site is only 10 miles away in Southold, NY. Since CASTNET's three closest monitoring stations are located in Washington Crossing, NJ, Claryville, NY, and Abington, CT, I averaged the measurements from those three locales. Only the two most recent years (2010-2011) of data were used to obtain an average number for this model input as the atmospheric deposition of N is decreasing on Long Island (Fig 2) and the Northeast US in general, a trend expected to continue due to changes in industrial atmospheric discharge in the Midwest. Atmospheric deposition of organic N is often overlooked, though its contribution can be considerable (Cornell et al. 1995). While direct measurements are not available, a 1:1 ratio or inorganic to organic deposition of N has been suggested by Cornell et al. (1995). Hence, I doubled the value of wet and dry deposition to account for this ratio. I then conducted a literature review to determine that the atmospheric deposition value was comparable to prior studies (Table 3).

Waste water

The contribution of N load to the bays from waste water was calculated in NLM by multiplying the N released per person by the housing occupancy rate and number of homes. More or less N was removed from this source depending upon the type of sewer system (septic or cesspool) and the distance from shore.

The average occupancy rate per house was determined from the 2010 Towns of Southampton and Brookhaven census results. The occupancy rates of the owner-occupied homes and renter occupied homes were averaged. The seasonal influx of visitors is substantial in the Town of Southampton but minimal in the Town of Brookhaven. I accounted for the seasonal population influx by taking the estimated number of seasonal guests per year as determined by the Suffolk County Planning Department (Lambert 2010), dividing that number by six assuming that they visit for an average of two months, and further dividing by the number of houses to determine the additional occupancy rate.

Nearly all homes within the study area have individual septic tanks or cesspools, which differ in the fraction of N released to the underlying aquifer with cesspools releasing more. In 1973 in Suffolk County, a law was passed requiring all newly constructed buildings to include a septic system instead of a cesspool. Therefore, houses built before 1973 were assumed to have cesspools. There are currently no municipal wastewater treatment facilities in this study area. There are several small, privately owned treatment facilities that were accounted for by removing the homes attached to the facility from the number of buildings within the NLM calculation and adding their State Pollutant Discharge Elimination System (SPDES) permitted N discharge amount as a "point source" (Table 4).

Fertilizer

The NLM considers fertilizer input from agriculture (farms), golf courses, parks and athletic fields and lawns. The area of each was calculated using ArcGIS, except for lawns, where an average lawn area was used for each building. Suffolk County passed a law that went into effect in 2009 limiting fertilizer use and banning use on County owned property. Because of this I have removed all county parks from the area of parks and athletic fields. Fertilizer application rates were obtained from three Long Island-based studies: Hughes and Porter 1983, Trautmann et al. 1983, Hughes et al. 1985. The fertilizer application rate used for golf courses was the maximum allowed under the 2009 Suffolk County legislation.

Volumetric Flux Model (VFM)

The Volumetric Flux Model (VFM) predicts N loads to the bays based on the volume of water that discharges from the watershed into the bay and the N concentrations in ground water, streams, and runoff within the watershed. The VFM has been used successfully to predict N loads to several Long Island estuaries, bays, and harbors (Gobler and Sañudo-Wilhelmy, 2001, Gobler and Boneillo 2003, Koch and Gobler 2009). This model relies on the assumption that groundwater discharge to the bay is equal to the recharge of the aquifer (Valiela et al. 1992). In contrast to the NLM, the VFM further differentiates N inputs from stream flow and surface runoff from the groundwater flow. The VFM does not, however, break down the N loads into sources (i.e. waste water v. fertilizer) but direct atmospheric deposition to the bay was included. Variance of the VFM was determined to be 14% based on the mean relative standard deviation of the two primary factors used within the VFM, precipitation (19.7%) and N concentration (9%).

Ground water

To determine the volume of ground water that discharges into the Eastern Bays, watershed areas were multiplied by the annual average precipitation to obtain the volume of rain, which was corrected for the volume of rainfall that composes the stream flow, volume of runoff, and the fraction that does not recharge the aquifer (evapotranspiration percent). The recharge percent is the precipitation corrected for the evapotranspiration percent. The value used was the default provided by the meta-analysis by Valiela et al. (1997). However, to confirm that percentage, I compared it to the results of Steenhuis et al. (1985), an eastern Long Island-based study that highlighted the strong seasonal nature of groundwater recharge in this region determining that the best measure of annual recharge percent is 75-90% of the precipitation from between 15 October and 15 May only. In some years the value determined by Valiela et al. (1997) was slightly lower than the range given by Steenhuis et al. (1985) and in some it was higher but the decadal averages were extremely similar (Fig 3).

The resulting value for volume of ground water was multiplied by groundwater N concentrations to determine N load to the bays. The Suffolk County Department of Health Services (SCDHS) regularly measures the nitrate, nitrite and ammonium concentrations in hundreds of groundwater wells in this study area and has provided these measurements dating form 1990-2013. In wells that showed an increasing trend in N concentration, only the data from 2006 - 2013 was used. Additional groundwater well data was compiled from USGS wells measurements from 1970-2006 and Suffolk County monitoring wells near the Forge River. All groundwater wells were shallow (< 30 m) and less than 4 miles from the shore and thus are assumed to contribute aquifer discharge to coastal waters. The groundwater N concentrations across all sub-watersheds were interpolated and contoured using an inverse distance weighting (IDW) algorithm in ArcGIS permitting visual representation of the areas of the watershed that likely contribute the most N to the bays.

The following equation summarizes the groundwater N load determined via the VFM: Ground water N load (kg N yr^{--1}) = [(Watershed area (m^2) x precipitation (m yr^{-1})

x recharge %) – stream flow volume (m^3 yr^{-1}) – runoff volume (m^3 yr^{-1})] * ground water [N] (kg N m^{-3}).

Runoff

Most of the land use nearest to the shore on southeast Long Island consists of older, larger homes that have little impervious cover, therefore I assumed that most of the volume of runoff comes directly from the roads adjacent to the bays or through MS4 (Municipal Separate Storm Sewer Systems) systems. The MS4 system is important because it brings stormwater that might otherwise drain off roads and seep into the ground water, through storm drains, pipes, and outfalls, directly into the coastal waters. In this study area, both of the Townships and Suffolk County have constructed MS4 structures. However, based on GIS files from the County and Town of Southampton showing locations of pipes and outfalls, the MS4 system in these watersheds is minimal. The average distance from a pipe to its outfall is 172 m so I have assumed that all runoff from roads within 172 m from shore could end up in the bay. As in the groundwater determination, the area of road in the runoff zone can be multiplied by the precipitation rate to determine the volume of the runoff. The volume of runoff was then multiplied by a N concentration of 0.00126 kg m^3 (measured stormwater N concentration, Gobler 2009) to obtain the total nitrogen load contribution from runoff.

Streams

With the exception of the Forge River, which flows into western Moriches Bay, the streams that run into the Eastern Bays are small. The volume of precipitation that is captured in stream flow is not recharging groundwater, and thus was removed from the volume of ground water discharging into the Bays. Stream flow discharge was ascertained by field measurements, using a General Oceanics Mechanical Flowmeter to record velocity multiplied by the stream's measured width and depth. Water samples were collected from all freshwater creeks entering Moriches, Quantuck and Shinnecock Bays (Table 8). At each stream, salinity was measured using a YSI85 sonde (Yellow Springs Inc®) to determine whether the stream was fresh water or tidal creek. The latitude and longitude of each sampling location were recorded with a Garmin® GPS device. Water samples were collected by hand in 100 ml acid-and-distilled water-washed, polyethylene bottles that were rinsed and then filled with stream water. The samples were filtered with a 60ml polyethylene syringe coupled with a Swinnex filter holder holding a pre-combusted (2h at 450ºC) glass fiber filter (GFF, Pall®), then stored frozen until analysis. Filtered samples were colorimetrically analyzed for nitrate, nitrite, ammonium and total N (TN) standard wet chemistry and spectrophotometer methods (Parsons 1984). TN was used in the calculation of N load except in samples where the sum of the inorganic nutrients was greater than the TN. To enhance the representativeness of values, tributary volumes and N concentrations as reported within from the Forge River Nutrient Report (Swanson et al. 2009) and the SCDHS Forge River water-quality monitoring program were also included to determine a mean N load for this tributary. Multiplying streamflow discharge by empirically measured N concentrations produced the annual N load from streams.

Further Modeling and Analyses

Nitrogen Load Comparisons

Once the N load was calculated for each subwatershed from both models (NLM and VFM) the values were compared. The resultant N load yields (N load divided by area of watershed), N loads per volume of estuary, sources of N from the NLM, and transport mechanisms from the VFM were compared on a subwatershed level. Finally, the N load to Moriches, Quantuck, and Shinnecock Bays were compared to other studies that have quantified the N load per area of estuary for different water bodies, including using the NLM model: Great South Bay, NY (Kinney and Valiela 2011); Barnegat Bay, NJ (Bowen et al. 2007); Chincoteague Bay, VA (Boynton et al. 1996); West Falmouth Harbor and Pleasant Bay, MA (Carmichael et al. 2004), among others.

Estuarine Loading Model (ELM)

Following the quantification of N load to the Bays from the watershed, I employed an estuarine loading model to determine the eutrophication vulnerability of various estuarine regions. The Estuarine Loading Model (ELM; Valiela et al. 2004) as described in Bowen and Valiela (2004) and Bowen et al. (2007), is also available through the N-load modeling tool. The Estuarine Loading Model (ELM) calculates mean annual concentration of dissolved inorganic nitrogen (DIN) available to primary producers in shallow estuaries by considering how different processes modify pools of N provided by inputs and losses within components of the estuarine system (Valiela et al. 2004). The ELM, run on a subwatershed level helped determine the sections of the bays with the highest predicted DIN concentrations. The ELM results were compared with empirically measured DIN concentrations provided by the SCDHS (1976-2010).

ELM is organized similarly to the NLM in that it is a web-based program requiring site-specific data for the estuary. Some of the fields had default values (Valiela et al. 2004) that were changed when more relevant or applicable data was available (Table 5). Salt marsh area was calculated from the NY Department of State (NYDOS) GIS file available on the NY state GIS clearinghouse. Eelgrass bed area was also determined from a NYDOS GIS file on Submerged Aquatic Vegetation (SAV). In this file SAV coverage was broken down into patches that were continuous and discontinuous. The discontinuous patches were calculated at 50% of their area.

The depth of the Eastern Bays varies as ocean inlets in Moriches and Shinnecock Bays can be more than 10 m deep, while much of the southern extent of the bays are < 1 m. The average depth for Quantuck Bay is 1.25 m (Heerbrandt and Franson, unpublished 2003) and nearly all of Moriches and Shinnecock Bays are less than a 2 m deep. A mean depth of 1.25 m was used for all three Bays during this study. Tidal range was available in most subwatersheds from NOAA (http://tidesandcurrents.noaa.gov/). Multiple tidal monitoring stations were averaged per subwatershed. In two the subwatersheds with no NOAA stations, the tidal ranges were estimated based on the adjacent stations and the distance to the nearest ocean inlet.

Evaluating trends in marine water quality data

The Suffolk County Department of Health Services (SCDHS) has monitored numerous marine water quality parameters at various locations within the three Bays since 1976. These data include total N, dissolved inorganic N (DIN), salinity, chlorophyll *a*, *A. anophagefferens*, secchi depth (April-October), and bottom dissolved oxygen (DO; April-October). In addition, data regarding densities of *A. fundyense* were provided by Theresa Hattenrath-Lehmann who has quantified this toxic dinoflagellate in these Bays since 2008 using a molecular probe (Hattenrath et al. 2010). When averaging TN and DIN values for a station, all data points below their detection limit were used at half of the detection limit value. In evaluating secchi depth data, when the secchi depth was greater than the depth of the sampling site, I used the depth of the site as the secchi depth. Marine water quality data was not available for the Heady/Taylor Creek section of the Bay but was estimated with data from adjacent sections of the Bay and Old Fort Pond, a similarly sized tidal tributary located 1 km northwest of Heady/Taylor Creek. The marine data sets were interpolated in ArcGIS using a standard Kriging algorithm to produce colored contour maps. DIN concentrations across all locations showed very little spatial variation and, thus, contouring this data set was not attempted.

Flushing times of regions of the Bays adjacent to each subwatershed were determined using a salt balance approach that assessed the volumes of the estuarine regions, rates of freshwater flow, and the distribution of salinity across the estuarine region (Pickard and Emery 1990). The following two equations were used to determine flushing time in days: $fF = (f \times V) / R$ and $f = (SO - S) / SO$, where V equals the volume of the estuary (or section thereof), R equals the freshwater input, SO equals the salinity of the ocean and S equals the salinity of the section of estuary (Pickard and Emery 1990). The flushing time for eastern Shinnecock Bay East was modified to account for water flowing through the Shinnecock Canal from the Peconic Estuary. This influx (2×10^5 m^3

day^{-1}; Militello and Kraus 2001) was subtracted from the volume of the bay. Additionally the salinity within this basin was corrected for the salinity of the water entering from the Peconic Estuary using the long term mean salinity data from Suffolk County, canal flow rates (Militello and Kraus 2001), and known volumes of the basin. The extent to which marine data parameters were correlated to each other as well as with N loading rates and flushing times was evaluated via a Spearman's rank order correlation matrix using SigmaStat within SigmaPlot 11.0.

Nitrogen Management Options

Nitrogen mitigation scenarios were assessed by making changes to the NLM. For example, tertiary sewage treatment plant facilities remove 93% of the N entering the plant (Kinney and Valiela 2011b) hence models were run reducing the waste water contribution by this amount and the resultant change in total N loading was determined. In sewage treatment plants with an ocean outfall, 100% of the N contributions from homes in a watershed were removed and the resultant change in N loading was determined. The large proportion of homes in this study site with cesspools (nearly 50%) were upgraded in the model to conventional septic systems by changing the percentage of homes with cesspools or to alternative, denitrifying septic systems by changing the default value of N-removal percentage (35%; Valiela et al. 1997) to an average percent N-removal for alternative septic systems (68%; Maryland Department of the Environment 2012). Houses closest to the shore (200 m) are likely to release even more N into the bay as the sewage effluent does not have time to recharge the aquifer and go through the ensuing denitrification process, before it flows into the bay. Therefore, the N load effect of upgrading just cesspools closest to the shore was calculated. Finally, in regions with high density housing, upgrading to alternative septic systems can be highly efficient as several homes within a half mile radius can be connected to a single, central denitrifying system. Therefore, the model was run upgrading septic systems to alternative systems within high density residential areas. The amount of fertilizer applied to lawns, agriculture, golf courses or parks and athletic fields was reduced in NLM to assess how this might alter N loading to the bay. Finally, 'Build out' scenarios were assessed by adding homes of differing lot-sizes to undeveloped areas and the change in N load to the subwatersheds was determined. The amount of undeveloped land per subwatershed was provided by the Town of Southampton and a Suffolk County report for the Town of Brookhaven (Suffolk County Planning Department 2009). I also updated the area of imperviousness value, subtracting the area from naturally vegetated areas and adding it to medium or low density residential. I also proportionally decreased the percent of cesspools to reflect that the new homes would have septic systems not cesspools. To expedite the process of running the NLM, a spreadsheet version of the NLM was created that was capable of running these scenarios within all of the subwatersheds at once.

Results

<u>Nitrogen Loading Model</u>

Nitrogen loads varied greatly over the subwatersheds of Moriches, Quantuck, and Shinnecock Bays (Table 6). The largest N load came from the Moriches West (MW) subwatershed with 211,000 kg N yr^{-1} and the smallest N load was produced by the Heady-Taylor Creek (HTC) subwatershed with 17,500 kg N yr^{-1}. The total N loads to Moriches, Quantuck and Shinnecock Bays were 366,000, 20,600, and 132,000 kg N yr^{-1} respectively. Population density, land use and land area can all influence the N load. To best compare the N loading from the different subwatersheds, area-specific loading rates were quantified (kg N per ha of surface area). Moriches West had the largest yield with 36.7 kg N ha^{-1} yr^{-1}. Quantuck Bay (QB) had the smallest yield at 8.9 kg N ha^{-1} yr^{-1} (Fig 4).

Over the entire study site, the relative contributions of wastewater, fertilizer, and atmospheric deposition to the total N loads from land were 65%, 20%, and 15%, respectively. Adding atmospheric deposition directly to the Bays changed the percentages thusly: waste water contributed 51% of the N load, direct atmospheric deposition to the water contributed 24%, fertilizer contributed 14%, and atmospheric deposition to the land contributed 10%. The importance of waste water was further illustrated by the strong linear relationship between the population of the subwatersheds and the N load from that subwatershed (Fig 5).

The importance of each N source varied across the subwatersheds. Quantuck Bay had the highest percentage of atmospheric deposition to the land (32%), Moriches West had the highest percentage of waste water (76%), while the Middle Moriches subwatershed had the highest percentage of fertilizer (31%; Fig 6). The fertilizer N load was further broken down into agriculture, lawns, golf courses, and parks and athletic fields. The percent contribution by each constituent was variable by subwatershed but lawns and agriculture were the primary or secondary fertilizer contributor to all subwatersheds (Fig 7).

Volumetric Flux Model

The VFM was used to divide N sources between ground water, runoff and streams (Table 6). Mean groundwater N concentrations per sub-watershed ranged from 2.4 mg L^{-1} in SBE to 4.8 mg L^{-1} in MW and MM (Table 7). An interpolation of all groundwater N levels illustrated the widespread, high levels of N in groundwater in MW and MM, as well as regional 'hot spots' of high N levels in ground water underlying other subwatersheds (Figure 8). Ground water was responsible for over 90% of the N load contribution in all subwatersheds save MW where it contributed 76% and streams contributed 23% (Fig 9). The volume of runoff ranged from 343,000 m^3 yr^{-1} in SBE to 607,000 m^3 yr^{-1} in MW but overall contributed less than 3% of freshwater flow in all subwatersheds. Stream discharge rates ranged from 36,900 – 6,020,000 m^3 yr^{-1} and average stream N concentrations ranged from 0.139 – 6.09 mg L^{-1}. Many of the streams sampled had either low flow rates or N concentrations (Table 8) and streams were a substantial N source (>5%) to the MW subwatershed (23%) and ME subwatershed (7%) only.

Comparing Models

The two models produced similar N loading results for each watershed with differences between the models across the subwatersheds varying by 3 – 38% (Fig 10). There was a significant correlation between the amount of N predicted across the watersheds via the two models (p<0.001) and neither model was consistently lower or higher than the other (Fig 10). In the MM subwatershed the N load determined by NLM and VFM were nearly identical (103,000 v 111,000 kg N yr^{-1}; Fig 10). In contrast, the discrepancies were higher in the SBE and MW (38% and 37%) subwatersheds.

ELM

For most estuarine sites, the ELM produced results that were similar to the measured DIN concentrations. ELM's DIN concentrations ranged from 0.012 mg L^{-1} in SBE to 0.15 mg L^{-1} in MW with an average of 0.046 mg L^{-1}. With the exception of the MW subwatershed, the ELM prediction was within 0.01 mg L^{-1} of measured values and the correlation between the two data sets was statistically significant (p<0.05). However, the ELM predictions for marine water surrounding the MW subwatershed were > 80% greater than measured values (Fig 11), suggesting the ELM is likely not a good fit for estuaries experiencing N loads of the magnitude of this subwatershed.

Nitrogen Mitigation Scenarios

Nitrogen mitigation scenarios were assessed for all of Shinnecock and Moriches Bay as well as the Moriches West subwatershed and Quantuck Bay. Since waste water contributes the majority of the N load for this area, connecting homes to sewage treatment plants is an obvious N mitigation option. The decrease in N load via the construction of sewage treatment plants varied from 11 – 69% depending upon the watershed, percent of the area covered by the sewer system, and where the outfall for the plant was located (Fig 12). The smaller value (11%) was the connection of Shinnecock Bay with an estuarine outfall whereas the largest N removal (69%) was the connection of MW with an ocean outfall (Fig 12).

Because the lower population density within eastern regions of the study zone does not lend itself to sewage treatment plant construction, upgrading cesspools and septic systems (onsite waste water treatment systems) is another possible option. Upgrading all the cesspools in the study area had an effect of decreasing the N load by 10-18% (Fig 13). The N load effect of upgrading cesspools closest to the shore only produced an N load decrease of 2-4%. Quantuck Bay has the lowest percent of homes with cesspools therefore it showed less response to upgrading (Fig. 13).

Another promising solution to reducing wastewater N loads is alternative, denitrifying septic systems. Upgrading all homes within a watershed to alternative septic systems could decrease N loads by >40% in some regions (Fig 13). MW produced the best response (9% decrease) to upgrading systems in high-density residential areas whereas Shinnecock Bay produced a slightly larger response (10% decrease) to upgrading to alternative septic systems within 200 m of shore (Fig. 13).

Although fertilizer is a smaller source of N to these watersheds than waste water, reductions in fertilizer may be easier to implement than changes to septic systems. Therefore, I calculated the decrease in N load as fertilizer use was decreased by 25, 50, and 75% across the study site. I also calculated a reduction in the percentage of fertilized lawns from 50%, the current assumption, to both 25% and 0%, and a 100% reduction in fertilizer use in parks and athletic fields. Decreasing fertilizer use can lower the N load by as little as 1% if there is a 25% fertilizer reduction in QB, to as much as 16% if there is a 100% fertilizer reduction for all of Moriches Bay (Fig 14). The largest percent decrease in N load for an individual watershed with fertilizer reduction to lawns was found in MW (6%) whereas Shinnecock Bay showed the strongest response (4% decrease) to reduction in parks and athletic fields fertilizer.

Despite the rapid recent population growth in the study area there is still undeveloped land, particularly in the Middle Moriches subwatershed where 20% of the land area is undeveloped (Table 9). I used lot sizes of 0.25, 0.5 and 1 acre to calculate the additional buildings that would be added in a build out scenario. Complete build out (100%) would increase the N load by 6 - 9% for 1 acre lots, 10 - 13% for 0.5 acre lots, and 18 - 28% for 0.25 acre lots (Fig 15). However, these estimates may be slightly high as some of the undeveloped land may contain parcels too small to accommodate complete residential development.

Marine Data

Mean salinity in the Bays ranged from 26.4 - 31. Not surprisingly, the highest salinity was found near the inlets and the lowest was found in the Forge River (MW subwatershed) and QB. Total N (TN) ranged from 0.28 mg L^{-1} in the middle of SBE and SBW, to 0.58 mg L^{-1} in the Forge River and QB. Low bottom dissolved oxygen (DO) can be an indicator of eutrophication occurring within the waterbody. Seasonal (April – November) DO levels ranged from 6.5 mg L^{-1} in Moriches East (ME) to 8.5 mg L^{-1} near both inlets. Secchi depth is a measurement of clarity of the water; low secchi depths may indicate higher phytoplankton biomass (more chlorophyll *a*) in the water column (Canfield and Hodgeson 1983). Seasonal (April – November) secchi depths ranged from 1 m in QB to 3.1 m near the Shinnecock Bay Inlet. Chlorophyll *a* ranged from 3.2 µg L^{-1} near the Shinnecock Canal and in the middle of SBE to 16.5 µg L^{-1} in QB. Mean *A. anophagefferens* densities ranged from 6,800 cells mL^{-1} near the Shinnecock Canal to 200,000 cells mL^{-1} in Moriches East (ME). Bloom densities were also very high in QB (200,000 cells mL^{-1}). Maximum *A. fundyense* bloom densities were the lowest in the SBE and the highest in Weesuck Creek (SBW). Dissolved inorganic N (DIN) ranged from 0.013 mg L^{-1} near the Shinnecock Canal to 0.028 mg L^{-1} in the Forge River. Marine Data is summarized by subwatershed in Table 10.

Contouring the marine data produced recognizable spatial patterns across the study area (Fig 16). Quantuck Bay and the Forge River (MW subwatershed) stand out as the areas of the bays with the poorest water quality including signs of eutrophication (low DO and secchi depth, high TN and chlorophyll *a*) and harmful algal blooms (high *A. anophagefferens* and *A. fundyense* densities). In contrast, regions near the ocean inlets had water with high DO, salinity, and water clarity (deep secchi disc depth) and low TN, chlorophyll *a*, and harmful algae. Flushing times of the subwatersheds ranged from 9 days for the MM and SBE bay areas near the ocean inlets to 26 days in QB (Fig. 17). The mean flushing time was 15 days. The bay areas with the poorest water quality had the longest flushing times at 21 (MW) and 26 (QB) days.

A correlation matrix including all marine data, flushing times, and N loads showed that many of the parameters measured were significantly correlated (Fig.18).

First, many marine parameters were correlated or inversely correlated with each other. Specifically, total nitrogen, chlorophyll a, *A. anophagefferens*, and *A. fundyense* were all significantly correlated with each other and were all significantly, but inversely correlated with levels of DO, salinity, and secchi disc depth (Table 11). The next open question was the extent to which these trends were controlled by flushing rates or N loads. Flushing time was significantly correlated with TN, chlorophyll *a*, *A. anophagefferens*, and *A. fundyense* and inversely correlated with secchi depth, DO, and salinity. N load per area of waterbody (N load ha^{-1}) was significantly correlated with TN, chlorophyll *a*, and *A. fundyense* and inversely correlated with secchi depth, DO, and salinity although the correlation coefficients were generally lower than those with flushing times (Fig 18). DIN did not correlate with any other marine parameter save N load ha^{-1}.

Discussion

<u>Nitrogen Sources and transport mechanisms</u>

Waste water was the most important component to N load in each of the three bays studied. Because of this, there was a strong linear relationship between the population of a subwatershed and its N load. Given Great South Bay lies immediately to the west of Moriches Bay, Kinney and Valiela (2011) is a good comparative study. Both studies found waste water to be the largest N contributor and had similar overall percent contribution (50% and 51%). Not surprisingly given their proximity, direct atmospheric deposition to the bay was also similar (26% and 24%). Fertilizer was more important in

Eastern Bays however, (7% v. 14%) and atmospheric deposition was less important (16% v. 10%).

The VFM indicated that ground water is by far the most important transport mechanism for N loading to the Eastern Bays. Previous studies in the Forge River region (MW subwatershed) have determined that groundwater flow is twice as large as stream flow (Swanson et al. 2010). This study corroborates this, finding groundwater flow in MW was 1.75 times stream flow. In the other six subwatersheds ground water was more than three-fold greater than stream flow. Other recent studies in the same region have also found ground water to be the most important land-based transport mechanism for N and freshwater (Koch and Gobler 2009, Kinney and Valiela 2010). Temporal variations in N concentrations within a confined region are not common (Gobler and Boneillo 2003) but the variability in precipitation does create variable groundwater discharge rates and therefore controls the flux of inorganic N to these enclosed waterbodies on Long Island (LaRoche et al. 1997). This variability in inorganic N flux has been shown to influence the phytoplankton assemblages of the bays allowing for conditions amenable for HABs (LaRoche et al. 1997, Gobler and Sanudo-Wilhelmy, 2001, Gobler and Boneillo 2003).

Although it was not a part of either the NLM or VFM, water use does have an impact on N loading. Traditionally, N loading from septic systems had been calculated either by using N released per person (as in the NLM) or household water use (Kinney and Valiela 2010). Conventional septic systems become less effective when the flow through them increases with flow being a function of home water use (Kaplan 1991, Valiela et al. 1997). This is relevant to Suffolk County in that water use is very high at 623 m^3 per household per year (SCWA 2012). For comparison the value determined by

Valiela et al. (1997) in their metadata analysis was 110 m^3 per household per year. However, the SCWA assumes that 42% of its annual withdrawal from the aquifer goes towards outdoor water use (Suffolk County 2010), so 361 m^3 per household per year may be more accurate. Still the predicted N load from waste water in this study may be higher than predicted given that water use was not taken into account.

It is common to acknowledge a certain amount of uncertainty that occurs when making predictions using modeling studies. In this study I considered the standard percent errors for both N loading models (12% NLM and 14% VFM). However, with so many inputs to both models a true assessment of uncertainty is difficult to assess and a certain amount of error propagation may occur. However, having two models with such different approaches provides a level of robustness to my N load results; there was a highly significant correlation ($p<0.001$) between the two models.

Comparability

Nitrogen loads have been calculated for water bodies all over the world that range in size by orders of magnitude. To facilitate comparisons among waterbodies of differing sizes, N loading among waterbodies can be normalized to area of the receiving water body. Among a list of published N loads compiled by Bowen et al. (2007) and Kinney and Valiela (2011), the Bays in this study had a moderate N load per area of waterbody with several bays having much higher loading rates, and many others being lower (Fig 19a). Of the three bays, Quantuck Bay had the highest yield, followed by Moriches and Shinnecock Bay (Fig 19a). All three Bays had higher N load yields than Great South Bay. Importantly, a number of factors contribute to how N loading affects a waterbody, including depth, flushing, and aquatic vegetation (Valiela et al. 2004). For example, some of the other sites listed are deeper than the bays of the SSER. For example, the Wadden Sea has an average depth of 10 m and Moreton Bay, Australia, is 7 m deep, on average. Since the average depth of the Eastern Bays is only 1.25 m, the volume of water in these waterbodies is significantly smaller and thus the same areal N loading rate will have a much larger impact. The highest N load per volume of water was found in Bass Harbor Marsh, ME (0.045 kg N m^{-3} yr^{-1}), the waterbody with the lowest depth (0.5 m). The Eastern Bays have a larger N loading rate per volume of water than the Wadden Sea and Great Bay, NH has a comparable N load per volume despite having a much larger N load per area (Fig 19b). In fact, given the differences in depth, the Eastern Bays have some of the largest N loading rates per volume of water among the systems compared. Additionally, while it was not considered in this study, shallow lagoons, such as this study site, receive a regular benthic flux of regenerated N from the sediments to the water column that have a larger impact on shallow systems. As such benthic fluxes can be an important part of the N budget for shallow systems. For example, Gobler and Boneillo (2003) found benthic flux contributed 28% of the N load to the North Sea Harbor, NY. In contrast, deeper waterbodies are likely to have greater vertical stratification and benthic fluxes may have a smaller impact on the N concentration in the upper water column and phytoplankton in the euphotic zone.

Effects of Marine Nitrogen Loading

During the past three decades, the Eastern Bays have experienced multiple types of harmful algal blooms (Gobler et al., 2008, 2012; Gobler and Sunda 2012; Hattenrath-Lehmann and Gobler, 2011; Tang et al. 2013), the loss of eelgrass (Carrol et al. 2008), and declines in bivalve populations (Weiss et al. 2007); all occurrences with putative links to excessive N loading. While this study has assessed N loads in the Eastern Bays, N concentrations in the water column and the distribution of algal blooms in surface water bodies are controlled not only by N load but also by biological and physical processes. If TN is high in a given area of the bay, it may be due to an excessive N input, a small N loss, or a combination of these factors. TN was correlated with chlorophyll *a*, harmful algae (*A. anophagefferens, A. fundyense*) and inversely correlated with dissolved oxygen and water clarity and thus demonstrated that water quality impairments are associated with high nitrogen levels. These trends are partly driven by autocorrelation as the toxic phytoplankton are blooming in regions where there are high levels of algal biomass that contain chlorophyll *a* and high levels of N, and these algal blooms shade the water and their demise leads to oxygen consumption. Flushing time had a primary influence on TN and a host of other parameters during this study as it was strongly correlated with TN, chlorophyll *a*, harmful algae (*A. anophagefferens, A. fundyense*) and inversely correlated with dissolved oxygen and water clarity. This finding indicates that it is in the regions where algal biomass is retained that water quality impairments (algal blooms, shading, low DO) are most likely to manifest themselves. N load was also significantly correlated with the majority of the water quality parameters but the r values were smaller than the correlations amongst the marine data and between flushing time and the marine data. These findings suggest that the N loading rates in all regions are high enough to cause water quality problems and that extreme impairment is most likely when high N loads were combined with extended residence times.

Many studies have associated low dissolved oxygen (Valiela et al. 1992, Bricker et al. 2008, Diaz and Rosenberg 2008), declining water clarity (Valiela et al. 1992, Waycott et al. 2009), and harmful algal blooms (Anderson et al. 2008, Heisler et al. 2008) with excessive N loading. This study demonstrates that within the SSER and likely other shallow lagoons with moderate to higher N loading rates, water quality impairments are most likely to manifest themselves in regions with the longest flushing time. In practical terms, while N loading rates are high enough to stimulate algal growth in most regions, strong tidal flushing in zones near ocean inlets remove this algal biomass prior to it accumulating to high levels.

Regions Vulnerable to Eutrophication

An assessment of the marine data provided an indication of regions where the current rates of N loading are high enough and the flushing rates are long enough to result in the symptoms of eutrophication: low oxygen and water clarity coupled with HABs. Comparing water quality among estuarine regions allowed me to identify regions where management changes are most needed to deter eutrophication. Focusing mitigation efforts on the most vulnerable places may provide the most beneficial environmental outcome and ensure cost-effective management of the watershed.

The Forge River

Scientists and the Suffolk County government have been aware of the eutrophication and water quality problems in the Forge River (MW subwatershed) for over 60 years (Swanson et al. 2010). Redfield (1952) suggested that the only way to improve water quality in the Forge River was to reduce N at the source. The Forge River estuary, in fact, a two-fold problem: It has the highest N loading rates and the longest flushing times, leading to severe eutrophication. Consistent with these findings, measurements from the SCDHS indicate that TN concentrations average well above the 0.45 mg L^{-1} benchmark designated by the Peconic Estuary Program (PEP 2001) for optimal marine health and this system has been prone to low dissolved oxygen levels, fish kills, and HABs (Swanson et al. 2010; Tang et al. 2013; this study).

The Moriches West subwatershed is characterized by a high population density and degree of urbanization. The population density is approximately 11 people per hectare; almost double the next highest subwatershed. Despite having 400 ha of high-density residential and 1,600 ha of medium-density residential land, there is no public sewage treatment (Fig 20). Even if the septic systems and cesspools are working optimally, their density and the shallow depth to ground water may be prohibitive for optimal biological N removal (Hantzsche and Finnemore 1992, Kropf 2009). The groundwater well N concentration data demonstrated that water that percolates through the soil to the aquifer is still heavily laden with N (Fig 8). As such, it is likely that the best N mitigation scenario for the Moriches West subwatershed is sewer construction. Construction of sewerage is not economically viable for much of the study area because of low population density, but the high densities in MW make this a feasible option. Constructing sewerage with an ocean outfall for the MW subwatershed alone (at 100% of homes included) would lower the N load to the western part of the bay by 69% and to Moriches Bay as a whole by 32%. Further, the entirety of the watershed need not be connected to the sewer in order to make a large change to the N load. Kinney and Valiela (2011) found a sharp rise in the amount of N retained in the watershed after 75% of buildings were connected. While the location of the sewage outfall does not matter much in terms of the amount of N released (93% v. 100% removal), moving the outfall to the ocean may be preferable because of the N speciation in the effluent. Effluent released from sewage treatment plants tends to be high in dissolved organic nitrogen (DON), which has been linked to blooms of *A. anophagefferens* (LaRoche et al. 1997, Gobler et al. 2011), an increasing problem in the Eastern Bays.

Quantuck Bay

Quantuck Bay, site of severe eutrophication during this study, is a very different watershed then Moriches West. This subwatershed is latitudinally separated into three distinct sections. The northernmost portion consists of protected pine barrens that contribute no anthropogenic N and have the greatest chance of retaining N in the watershed (Valiela et al. 1997). South of the pine barrens lies the Francis Gabreski Airport, a largely impervious area, while the southern third of the watershed closest to the shore is primarily low and medium-density residential (Fig 21). Both models predicted that the total N load from the Quantuck Bay subwatershed is low. However, the N loading rate to Quantuck Bay on an areal and volumetric basis exceeds both Moriches and Shinnecock Bay. This system also has a very long flushing time. Accordingly, all of the marine data (toxic phytoplankton densities, N concentrations, secchi depth and DO) demonstrated this system has impaired water quality and is vulnerable to HABs.

Because of the low housing density across much of the Quantuck Bay watershed, N mitigation options are less likely to have the impact that they would in an area that is more heavily populated such as the Forge River. Excluding constructing sewerage because it is likely not economically feasible with homes that are spread apart like those in this area, the best N mitigation scenario for Quantuck Bay is upgrading cesspools and septic systems to denitrifying systems. Many varieties of alternative septic systems exist, all of which have the goal of decreasing the concentration of N in their effluent. Alternative septic systems have the added benefit of being able to cover multiple dwellings within a half-acre (Berry 2011), which is suitable for parts of the Quantuck Bay watershed. Given that a large percent of homes along Quantuck Bay have cesspools, upgrading to alternative septic systems can be preliminary step in N mitigation, reducing loads by more than 20%. A similar amount of N load increase can be prevented via the preservation of the remaining land within this watershed. Although only 8% of the QB subwatershed can be further developed, this subwatershed showed the greatest increase in N load with build-out and complete build-out in this watershed may have dire consequences for the already degraded Quantuck Bay. The ELM model predicted a 12-26% increase in DIN concentration in Quantuck Bay with 100% build out. This illustrates that in regions that are already stressed, flushing and other within-estuary processes cannot be counted on to naturally mitigate and attenuate increased N loading.

This study did not consider within-estuary N mitigation options. Because the problem in Quantuck Bay stems less from the magnitude of the land-based N load than from the physical and biological properties of the bay itself, within-estuary options, including protecting salt marshes, harvesting macroalgae, dredging channels, removing waterfowl, and enhancing the abundance of filter feeding bivalves, may be more beneficial. Among these within-estuary options, Bowen and Valiela (2004), in their Cape Cod based study, determined that protecting salt marshes was one of the highest priorities based on effectiveness and feasibility.

Conclusion

This study shows that portions of the Moriches, Quantuck and Shinnecock Bays are receiving very high N loads coming primarily from human-derived waste water traveling through ground water. In western Moriches Bay this N loading is compounded by poor flushing time to create an area of extremely poor water quality and large bloom densities of HABs. Construction of a sewage treatment plant in this region of the watershed would have the best effect on N load. In Quantuck Bay the N load is low compared to other areas of the watershed but quite high when considered per area or volume of water. Quantuck Bay had the longest flushing time of all the areas studied, the highest average for chlorophyll *a* and TN and the largest bloom density of *A. anophagefferens*. The most effective N mitigation options for Quantuck Bay are upgrading sewer systems and controlling any future development.

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Tables

Table 1. NLM inputs and sources. Default values were used for any input not listed here.

Number of buildings	Suffolk County building footprint dataset
Watershed area	ArcGIS®
Area of wetlands	Suffolk County NYS freshwater wetlands GIS map
Area of agriculture	Suffolk County land-use maps
Area of golf courses	Southampton GIS department (SB, QB) and Google Earth (MB)
Area of parks and athletic fields	Suffolk County land-use maps
Impervious surfaces (commercial, industry, etc.)	Suffolk County land-use maps with % imperviousness as determined by averaging values from Arnold and Gibbons 1996, Center for Watershed Protection 2002, Hoffman and Canace 2002, Kellogg et al. 1997, Mass GIS 2003, New York State Department of State 1999, and USDA 1986
Area of freshwater ponds	Southampton GIS department (SB, QB) and Google Earth (MB)
Buildings 200 m from shore	Suffolk County building footprint dataset
Average occupancy rate per house	2010 census + estimated seasonal population from Suffolk County (Lambert 2010)
Percent of buildings with cesspools	Southampton GIS department (houses built before 1973 have cesspools) (SB, QB), estimate MW, MM
Percent of buildings with fertilized lawns	The Nature Conservancy, Long Island Chapter
Area of roof per building	Suffolk County building footprint dataset
Area of road as a percent of total watershed	Length of all roads in the subwatershed multiplied by a standard road width
Annual precipitation	Weather underground Islip station, decadal average
Recharge from vegetated lands as % of precipitation	Meta-analysis by Valiela et al. 1997 consistent with Steenhuis 1985
N inputs from wet and dry deposition	National Atmospheric Deposition Program and the EPA's Clean Air Status and Trends Network
Fertilizer applied to lawns	Hughes and Porter 1983; Trautmann et al. 1983; Hughes et al. 1985
Fertilizer applied to golf courses	Maximum amount allowed by Suffolk County fertilizer law
Fertilizer applied to parks and athletic fields	Hughes and Porter 1983; Trautmann et al. 1983; Hughes et al. 1985
Fertilizer application to agriculture	Hughes and Porter 1983; Trautmann et al. 1983; Hughes, Pike and Porter 1985
Denitrification in aquifer	Young et al. 2013

Table 2. Impervious percentages from various sources by land-use category. Table adapted from Joubert et al. 2004.

Land-use Category	Percent Impervious							Average
LD Res (3-5 acre lot)		8		8				LD 14.8+
MLD Res (2 acre lot)	12	12		11	11			
MD Res (1 acre lot)	20	18	10	14	14	40		
MHD Res (1/2 acre lot)	25	27	13	25	21			MD 34.5+
MHD Res (1/3 acre lot)	30	34						
MHD Res (1/4 acre lot)	38	39	57	36	28	75		
HD Res (1/8 acre lot)	65	59		55	33	100		HD 62.3+
Multi family residential			80		44			
Institutional	50			34	34			39.3
Agriculture								0
Vacant								0
Commercial	85		90	72	72		85	80.8
Recreational and open space								0
Industrial	72		75	54	53		75	65.8
Transportation	72		75	72	80		100	79.8
Utilities								75*
Waste Handling and mgmt.								75*
Surface waters								0
Sources	a	b	c	d	e	f	g	

+ Only three residential categories are used by Suffolk County: Low Density (LD) is ≥ 1-acre lots, Medium Density (MD) is ¼ - ½ acre lots, and High Density (HD) is ≤ 1/8-acre lots.

* Estimated

Sources: a. USDA 1986 b. Hoffman and Canace 2002 c. Mass GIS d. Kellogg et al. 1997 e. Center For Watershed Protection 2002 f. New York State Department of State 1999 g. Arnold and Gibbons 1996.

Table 3. Literature review of atmospheric deposition rates including this study. Not all studies included organic atmospheric deposition.

Source	**Rate in kg^{-1} ha^{-1} yr**	**Location**
Paerl 1993	2.8 - 14	Worldwide
Hu et al. 1998	6.64	Long Island, NY
Kinney and Valiela 2011	10	NE-NY area
Luo et al. 2002	9 - 23	CT coast
Bowen and Valiela 2001	12.26	MA
Valiela et al. 1997	15	Metadata analysis
This study	17.55	NY, CT, NJ
Peconic Estuary Program 2001	22	Peconic, NY

Table 4. SPDES permitted N release amount from point sources in each subwatershed. Data from the private sewers Suffolk County GIS file.

Subwatershed	**Permitted N load (kg N yr^{-1})**
Moriches West	42,800 *
Middle Moriches	3,700
Moriches East	1,600
Quantuck Bay	2,800
Shinnecock Bay West	180
Shinnecock Bay East	0
Heady/Taylor Creek	1,100

*MW subwatershed includes 32,300 from Jurgielewicz duck farm (Cameron Engineering and Associates LLP 2012), which was closed in 2011 but was included because the N from the duck farm is likely still present in the watershed.

Table 5. Sources for the Estuarine Loading Model. For all inputs not listed below the model default value was used (meta-data analysis by Valiela et al. 2004).

Open Water area (ha)	ArcGIS
Salt marsh area (ha)	NYDOS GIS file
Eelgrass bed area (ha)	NYDOS Submerged aquatic vegetation GIS file
Average Depth (m)	Heerbrandt and Franson, unpublished 2003 and estimate
Freshwater discharge volume from ground and surface water (m^3/yr)	VFM
Total watershed area (land) (ha)	ArcGIS
Length of receiving shoreline subtended (m)	ArcGIS
Number of houses	Suffolk County building footprint dataset
Land derived TDN (kg N per yr)	NLM
Freshwater stream reaches TDN (kg N per year)	VFM
Tidal range (m)	Carroll et al. 2008
Tidal period (Hours/day)	NOAA tidal charts
Flushing time	Pickard and Emery 1990
Flushing time of the freshwater reach	Flushing time estimated at 0 because stream input is small
Occupancy rate	2010 census and estimated seasonal population from Suffolk County (Lambert 2010)
Atm. Dep. Of DIN (kg N per ha per yr)	National Atmospheric Deposition Program (NADP) and the EPA's Clean Air Status and Trends Network (CASTNET)
Atm. Dep. Of DON (kg N per ha per yr)	Cornell et al. 1995
N fixation estuarine sediments (kg N per ha per yr)	Carpenter et al. 1991
N fixation eelgrass (kg N per ha per yr)	Carpenter et al. 1991
N fixation marsh sediments (kg N per ha per yr)	Carpenter et al. 1991
N fixation planktonic (kg N per ha per yr)	Carpenter et al. 1991

Table 6. Nitrogen loading results in kg N yr^{-1} from the nitrogen loading model (NLM) and volumetric flux model (VFM). These values include point sources (NLM only) and subtracting for underflow but do not include direct atmospheric deposition to the bay.

Subwatershed	**NLM**	**VFM**
Moriches West	211,000	133,000
Middle Moriches	96,400	99,800
Moriches East	58,800	77,800
Quantuck Bay	20,600	27,400
Shinnecock Bay West	88,900	65,100
Shinnecock Bay East	26,500	16,400
Heady Taylor Creek	16,400	13,900

Table 7. Average ground water nitrogen concentrations by subwatershed.

Subwatershed	Average GW N (mg L^{-1})
MW	4.83
MM	4.83
ME	2.81
QB	2.78
SBW	3.07
SBE	2.35
HTC	2.96

Table 8. Average volume, nitrogen concentration and N loads from individual streams.

Stream Name	**Ave. Volume (m^3 yr^{-1})**	**Ave. N Concentration (kg m^{-3})**	**N load (kg N yr^{-1})**
Swift Creek	1,790,000	0.006	10,900
East Millpond	2,570,000	0.002	6,220
Forge River	3,800,000	0.001	4,260
Seatuck Creek	2,050,000	0.002	3,490
Lawrence River	1,870,000	0.002	2,970
East River	2,460,000	0.001	2,740
Terrell River	6,020,000	0.000	2,310
Pattersquash Creek	788,000	0.003	1,980
Poospatuck Creek	357,000	0.004	1,600
Old Neck Creek	1,741,000	0.001	1,550
Dave's Creek	488,000	0.003	1,460
Ely Creek	439,000	0.002	969
Speonk River	1,030,000	0.001	944
Philips Creek	1,160,000	0.001	823
Stone Creek	487,000	0.001	658
Weesuck Creek	282,000	0.002	501
Beaverdam Creek	201,000	0.002	497
Quantuck Creek	3,100,000	0.000	432
Aspatuck Creek	108,000	0.001	116
Little Seatuck	95,000	0.001	116
Wills Creek	13,000	0.004	46
Unnamed (MM2)	37,000	0.000	6

Table 9. Area of land available for development and the percent of the subwatershed that it represents. MW and MM data from 2009, all others from 2013.

Subwatershed	Area undeveloped (ha)	Percent of watershed
MW	907	16
MM	951	20
ME	807	14
QB	178	8
SBW	658	16
SBE	137	10
HTC	144	16

Table 10. Marine Data averages by subwatershed for salinity, Chlorophyll *A*, total nitrogen, dissolved inorganic nitrogen, *Aureococcus anophagefferens*, dissolved oxygen, secchi depth, and *Alexandrium fundyense*.

	Salinity (PSU)	**Chl. *a* (µg L^{-1})**	**TN (mg L^{-1})**	**DIN (mg L^{-1})**	***A. anophagefferens* (cells mL^{-1})**	**DO (mg L^{-1})**	**Secchi Depth (m)**	***A. fundyense* (Log Max. cells)**
MW	27.3	8.93	0.525	0.023	26,000	7.67	1.44	4.04
MM	30.0	5.16	0.359	0.024	24,000	8.18	2.14	1.07
ME	28.4	12.33	0.490	0.022	129,000	7.10	1.32	1.77
QB	27.0	16.50	0.580	0.021	155,000	7.00	1.07	3.28
SBW	29.6	8.68	0.398	0.022	67,000	7.88	1.64	2.96
SBE	29.8	3.42	0.318	0.017	8,310	8.13	2.45	1.13
HTC	29.8	9.61	0.382	0.027	8,480	5.82	1.36	2.62

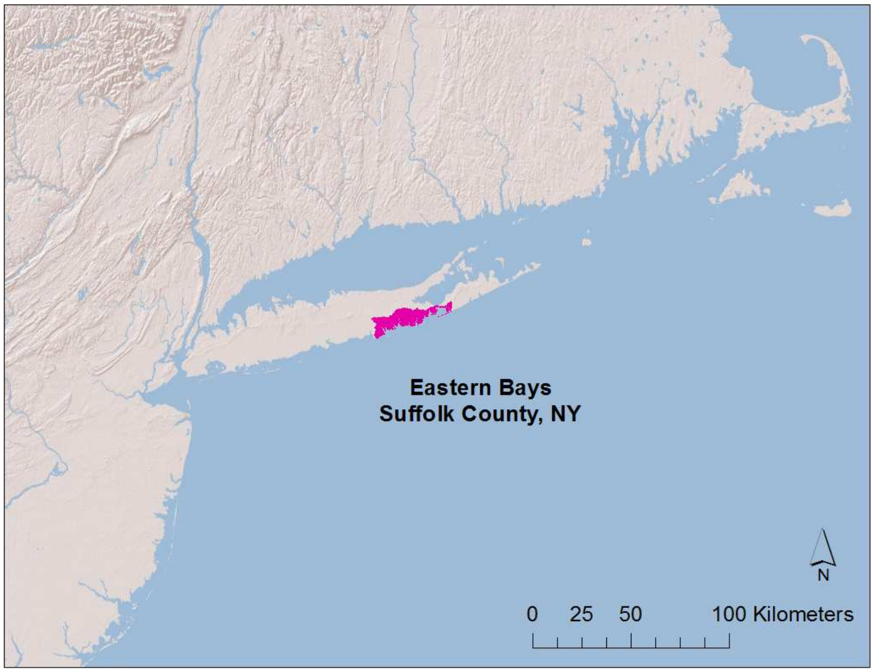
Table 11. Correlations between the marine data, flushing time and N load. Correlation coefficients are shown numerically. Any values with * are statistically significant. P-values are represented as such: * indicates < 0.05, ** indicates <0.01, *** indicates < 0.001, **** indicates < 0.0001. N=7 (# of subwatersheds) for N load and flushing time, N=13 (# of sampling locations) for *A. fundyense*, and N=23 (# of marine stations) for all other marine data.

	Salinity	**Chl. *a***	**TN**	**DIN**	**DO**	**Secchi Depth**	***A. anophagefferens***	***A. fundyense***	**N load ha^{-1}**
Flushing time	-0.631 ***	0.849 ****	0.742 ****	0.261	-0.648 ***	-0.684 ***	0.749 ****	0.612 *	0.491
Salinity		-0.659 ***	-0.897 ****	0.195	0.679 ***	0.729 ****	-0.564 **	-0.687 **	-0.543 **
Chl. *a*			0.851 ****	0.151	-0.767 ****	-0.873 ****	0.847 ****	0.713 **	0.445 *
TN				-0.071	-0.757 ****	-0.836 ****	0.708 ****	0.804 ****	0.545 **
DIN					0.143	0.0202	-0.031	0.0826	0.409 *
DO						0.778 ****	-0.609 **	-0.643 *	-0.474 *
Secchi Depth							-0.737 ****	-0.793 **	-0.582 **
A. anophag-efferens								0.521	0.039
A. fundy-ense									0.531 *

Figures

Figure 1. a. The study area in pink. b. The subwatersheds labeled: MW-Moriches West, MM-Middle Moriches, ME-Moriches East, QB-Quantuck Bay, SBW- Shinnecock Bay West, SBE-Shinnecock Bay East, HTC-Heady/Taylor Creek.

a.



b.

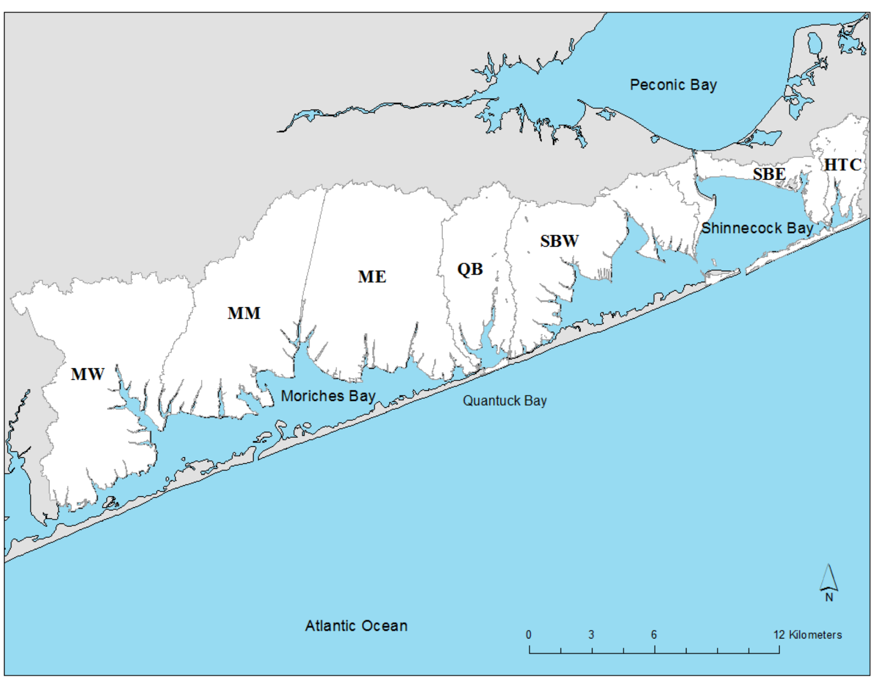


Figure 2. Wet atmospheric deposition measurements by year from the three nearest CASTNET stations: Washington Crossing NJ, Claryville NY and Abington CT.

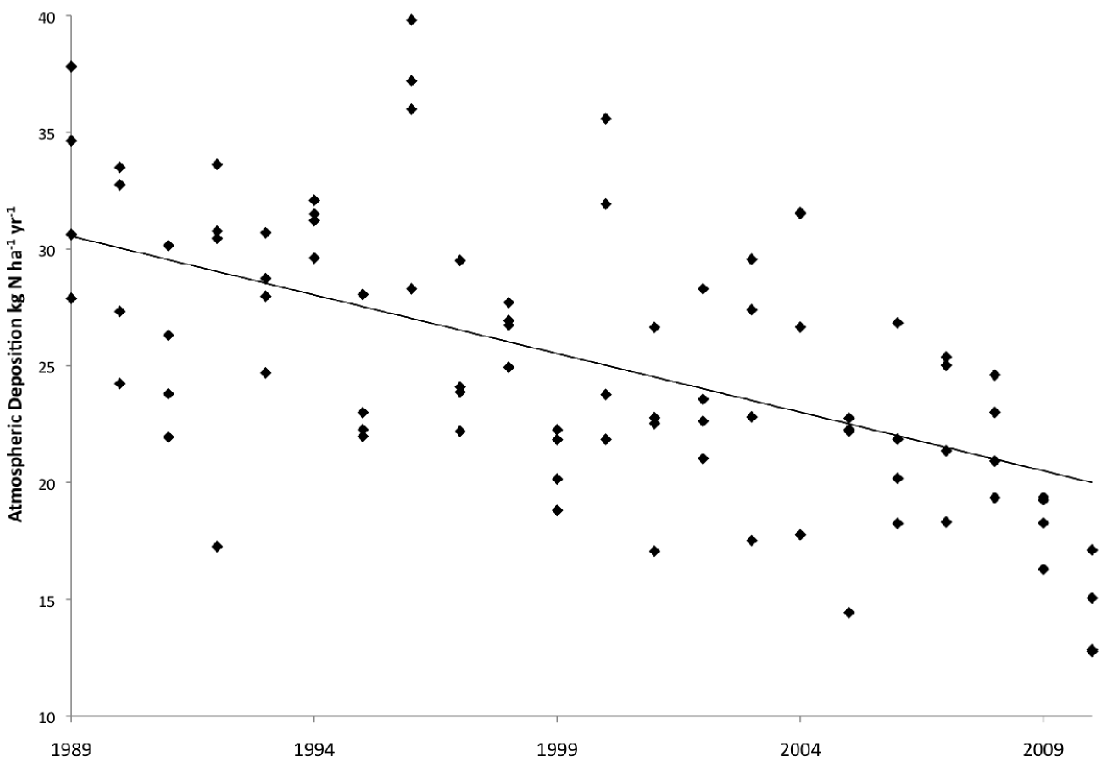


Figure 3. Estimates of groundwater discharge using the methods of Valiela et al. (1997) and Steenhuis et al. (1985).

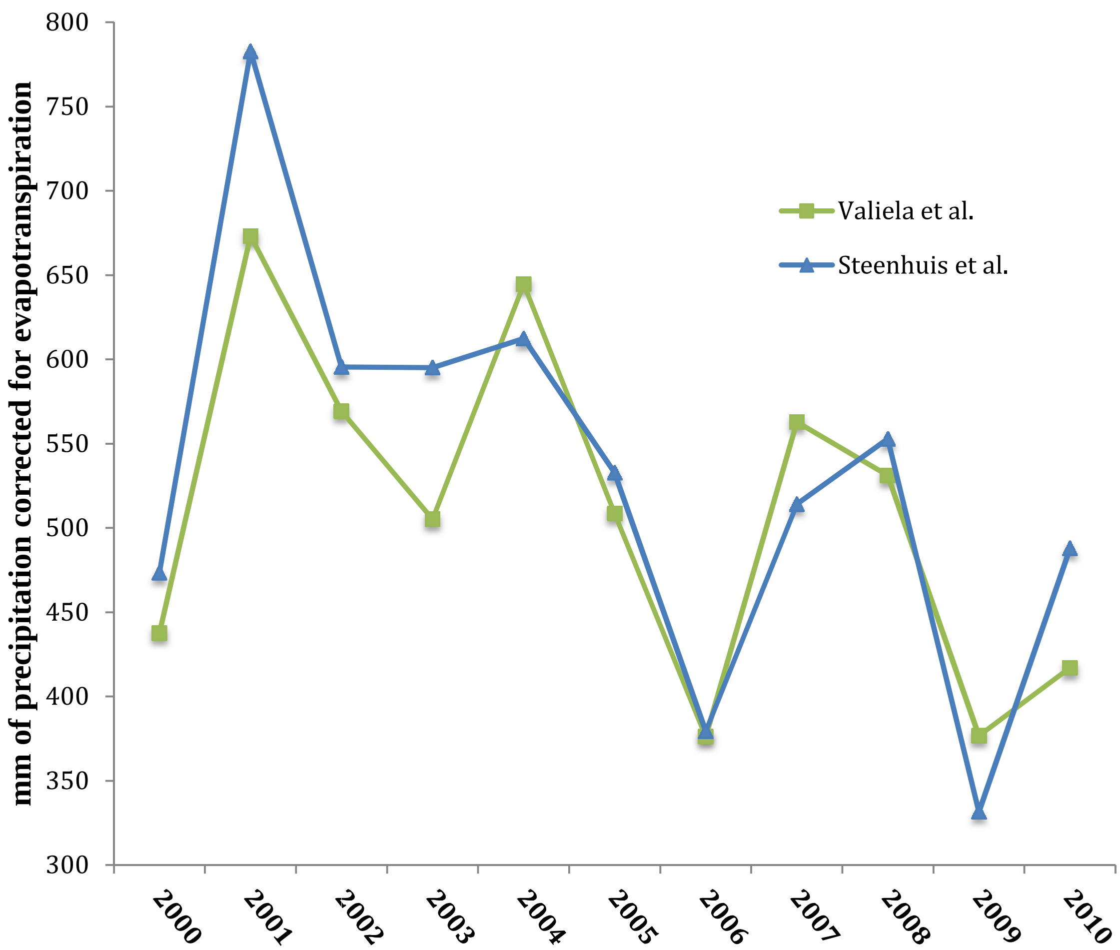


Figure 4. Nitrogen load yield per subwatershed (kg N ha^{-1} yr^{-1}) as determined by the NLM.

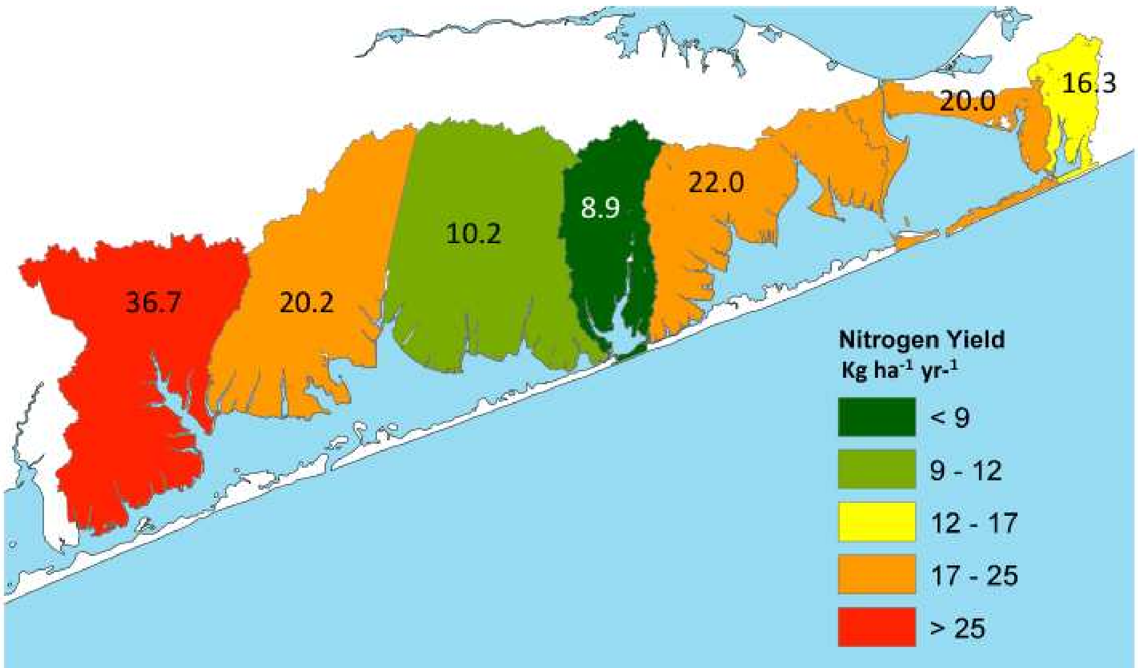


Figure 5. N load of a subwatershed compared to population. Population estimated based on number of buildings and occupancy rate and N load shown is the average of the NLM and VLM.

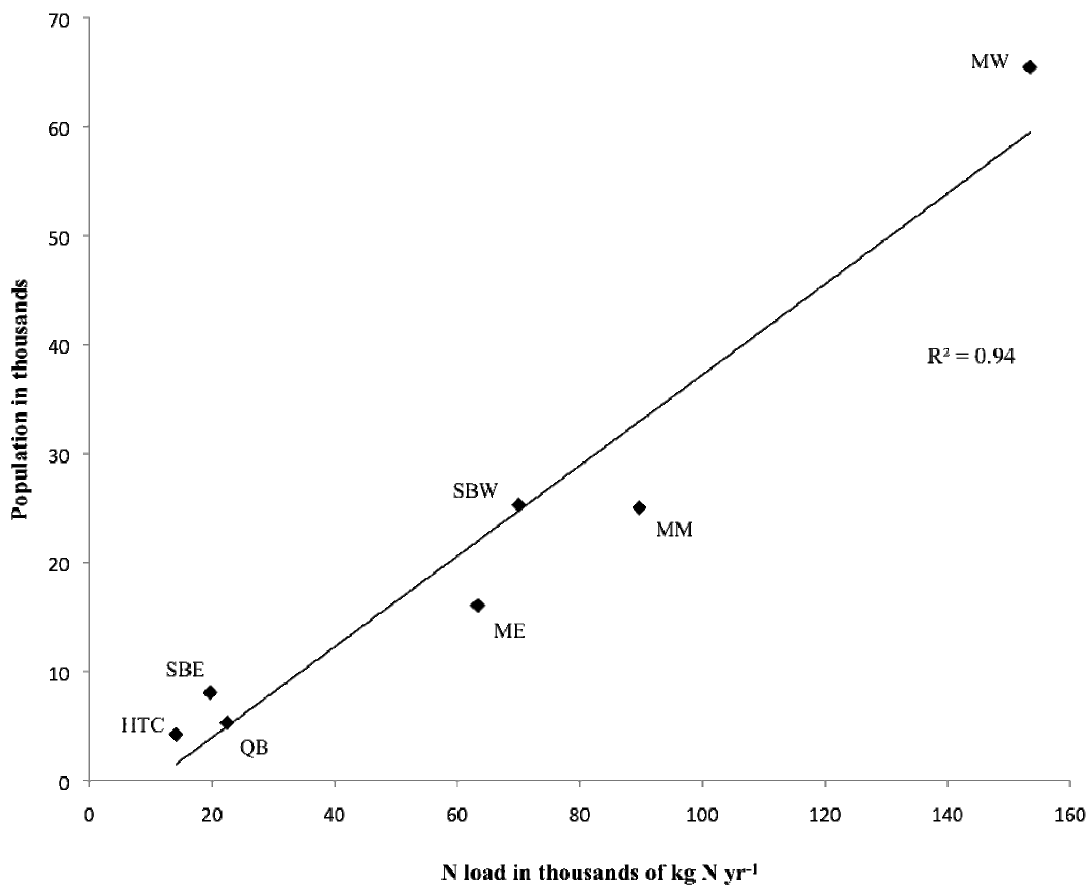


Figure 6. Nitrogen load by source (NLM). Direct Atmospheric Deposition refers to atmospheric deposition to the bay and Atmospheric Deposition represents atmospheric deposition to the watershed (land).

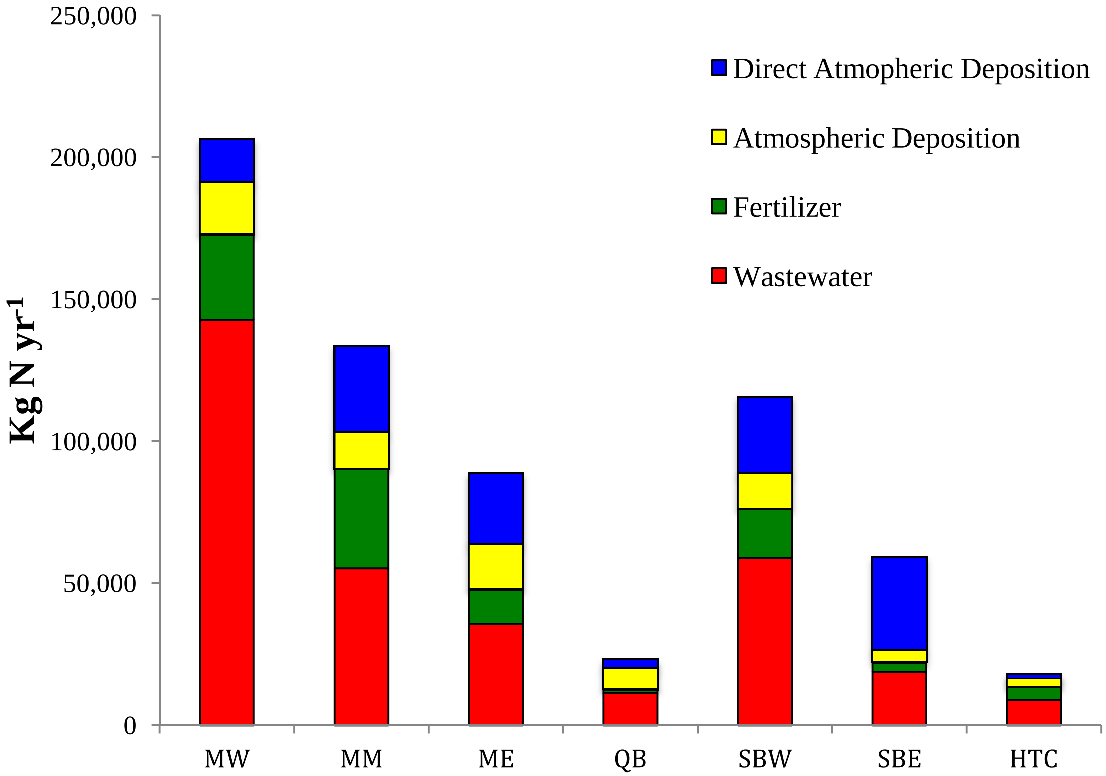


Figure 7. Relative contribution of atmospheric deposition, waste water and fertilizer to the total N load with fertilizer sources broken down into lawns, golf courses, parks, and agriculture.

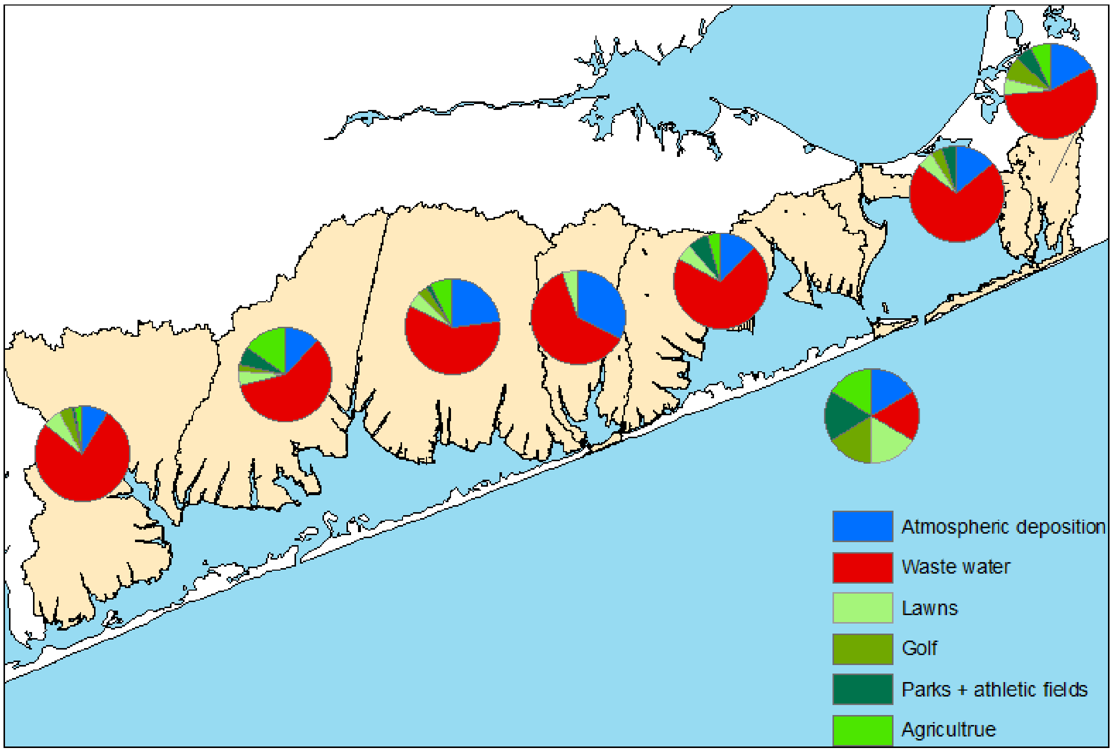


Figure 8. Map showing contour of total nitrogen concentrations in groundwater wells.

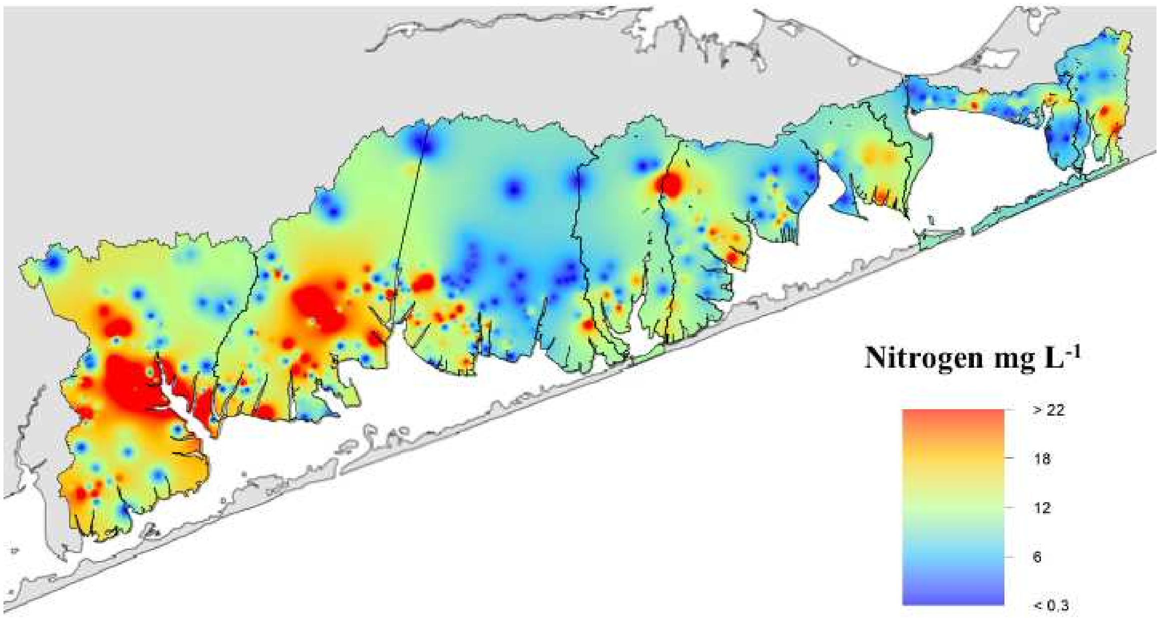


Figure 9. N load by source from the VFM.

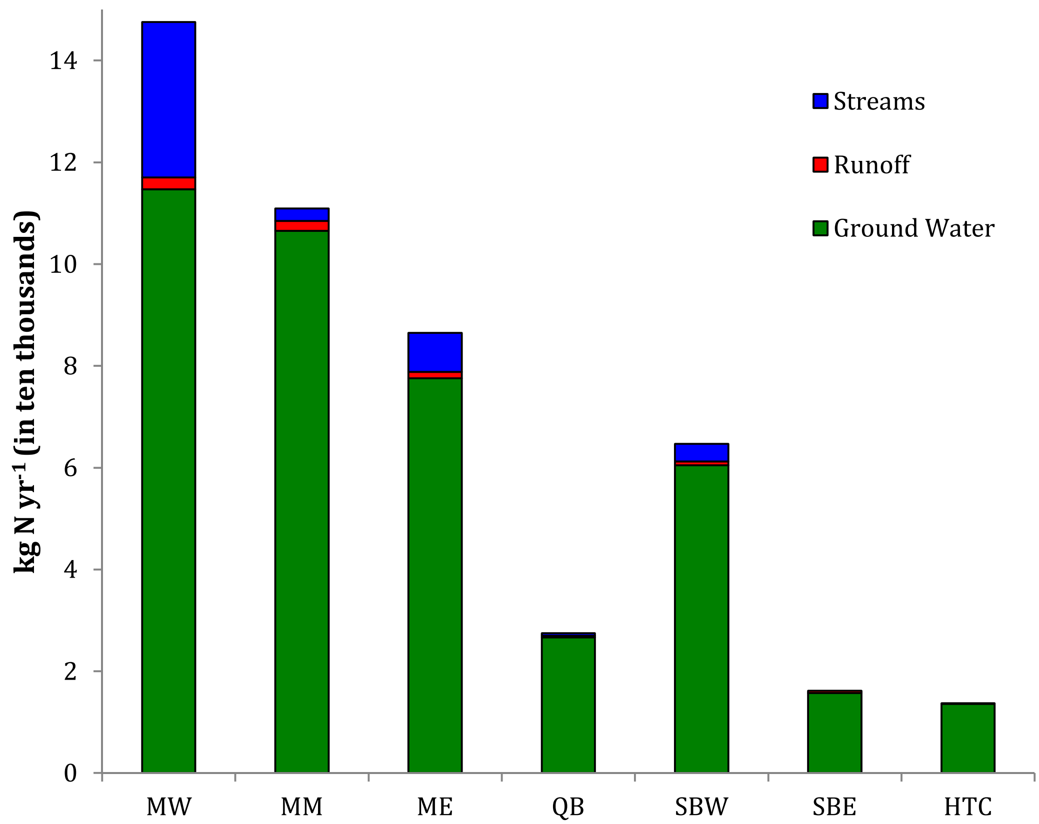


Figure 10. Nitrogen loading results by subwatershed from both models. Error bars indicate the standard error of each model.

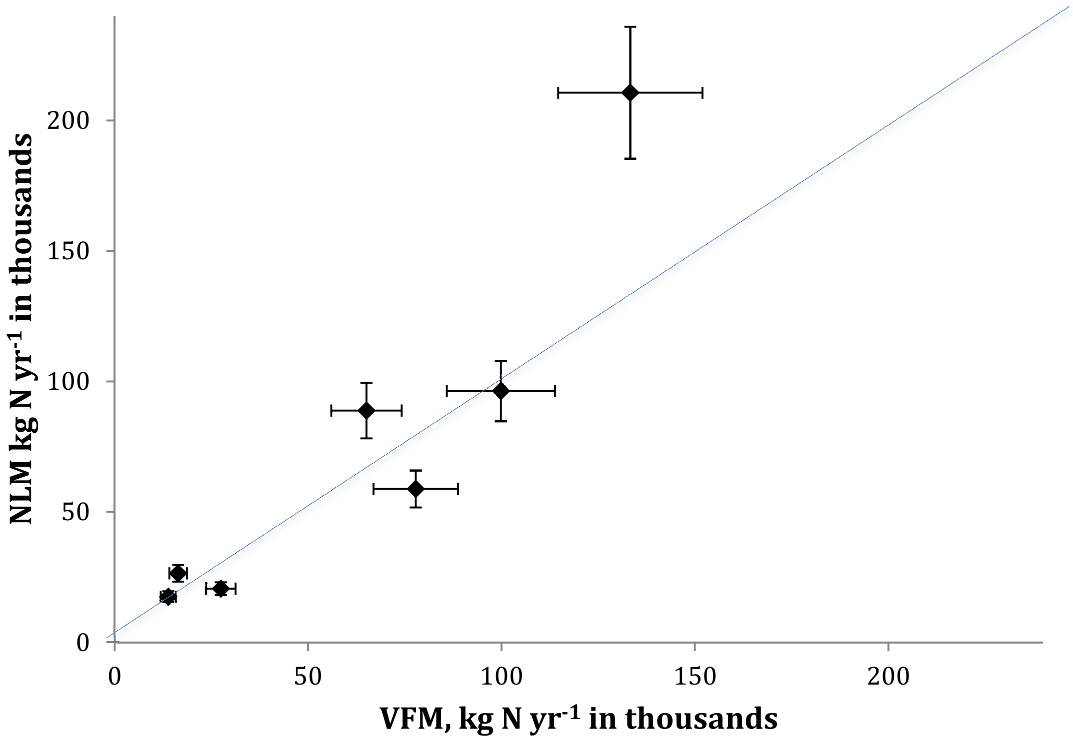


Figure 11. Results from the Estuarine Loading Model (Valiela et al. 2004). Red points from the MW subwatershed are plotted on the left axis.

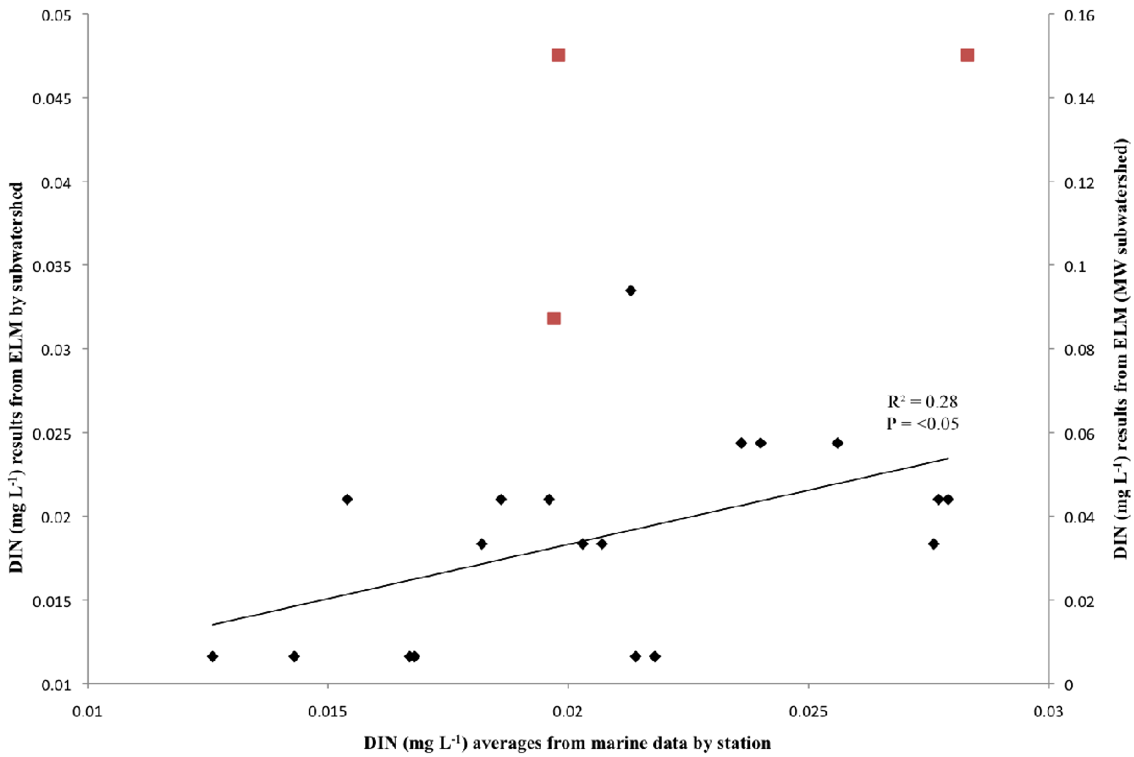


Figure 12. Percent decrease in N load with percent of the watershed that is connected to the sewer. The blue lines represent the outfall in the ocean; the orange lines represent the outfall in the bay. Tertiary treatment was assumed for wastewater treatment.

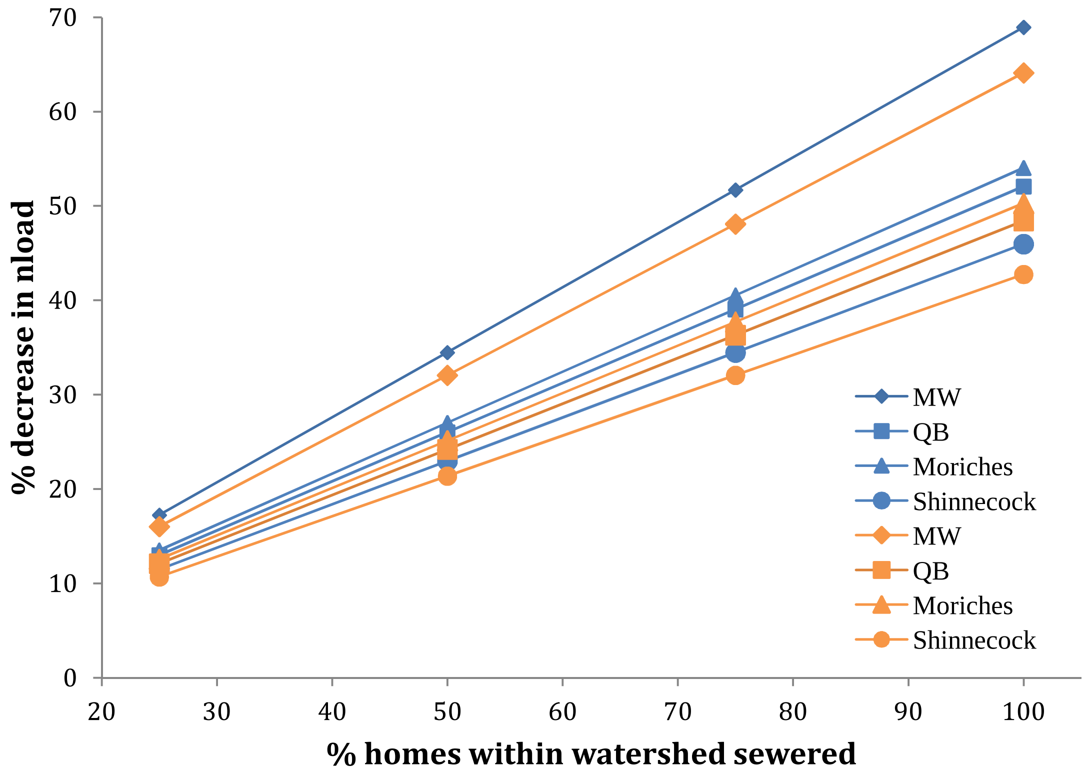


Figure 13. Percent decrease in N load with various septic system upgrading scenarios.

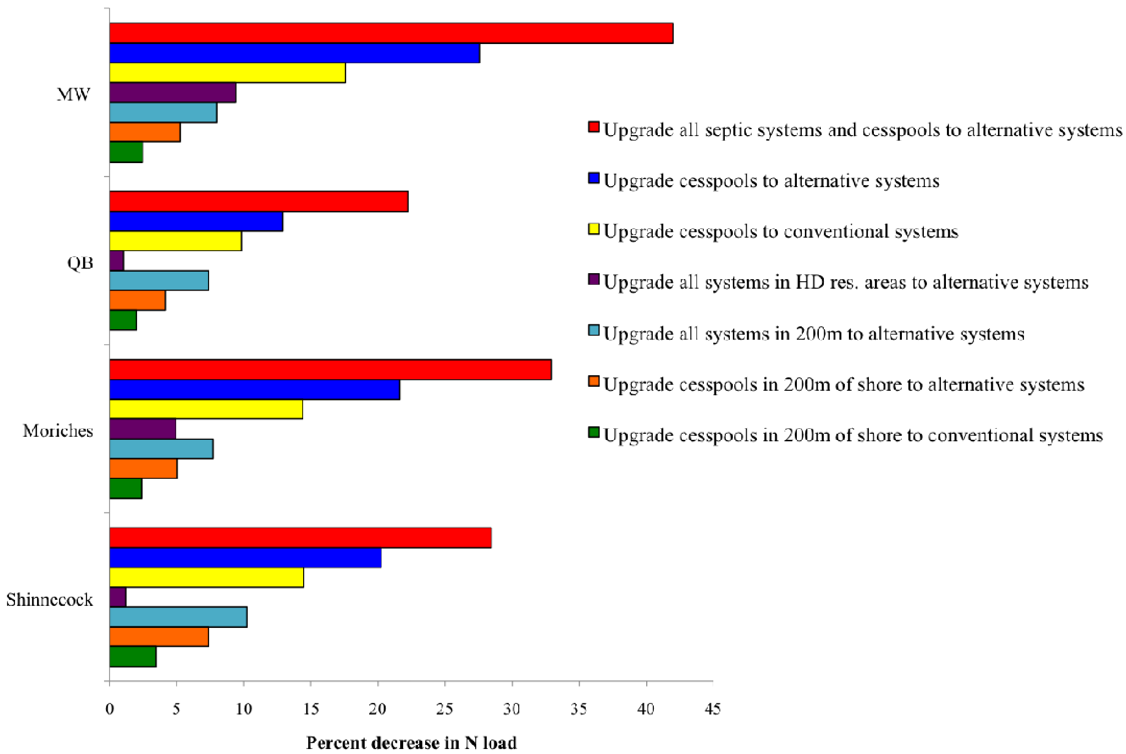


Figure 14. Percent decrease in N load with various fertilizer reduction scenarios including overall decrease in fertilizer by 25, 50, and 75%, reduction in the percentage of fertilized lawns from 50%, the current assumption, to both 25% and 0%, and a 100% reduction in fertilizer use in parks and athletic fields.

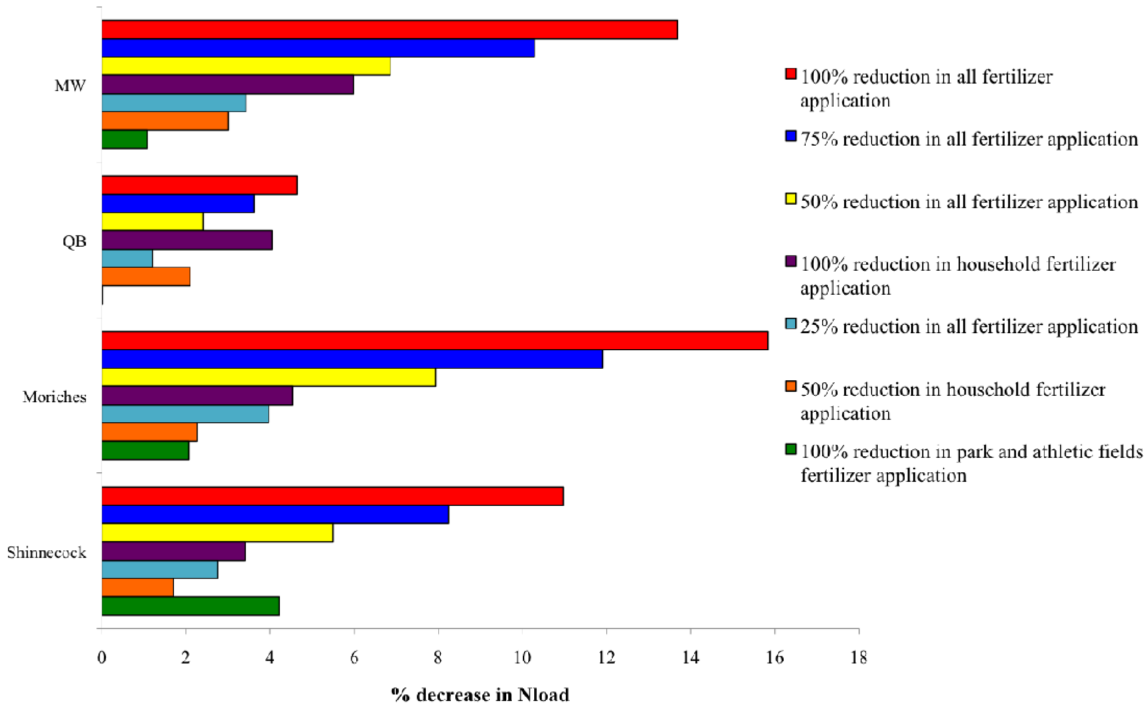


Figure 15. Percent increase in N load with different lot sizes.

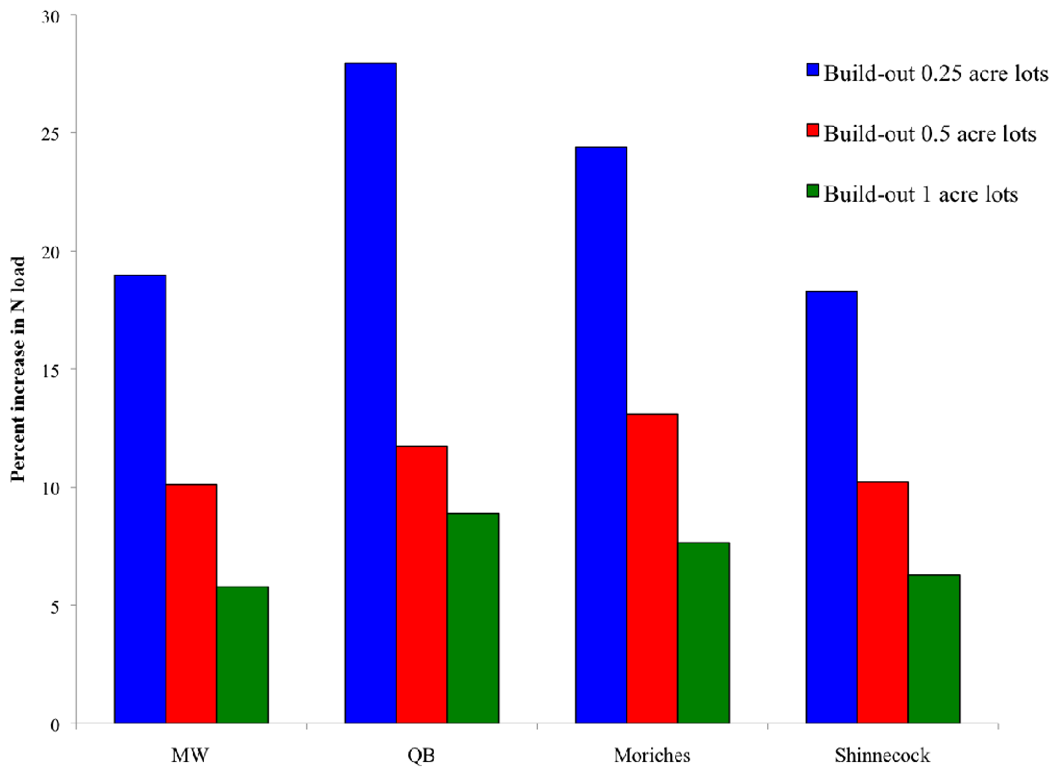


Figure 16. Contoured marine data from SCDHS including a. Total nitrogen b. Salinity c. Secchi depth d. Bottom dissolved oxygen

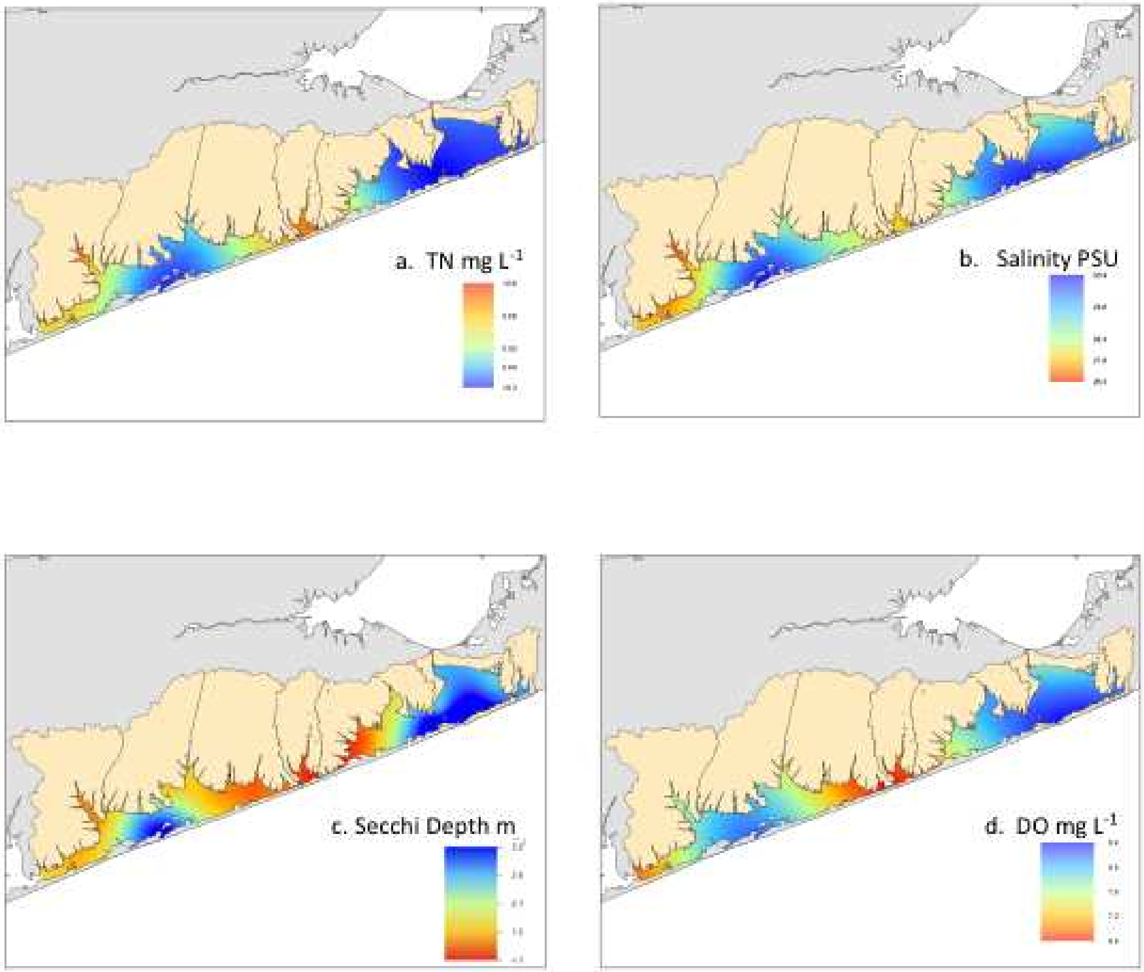


Figure 16 (continued): Contoured marine data from SCDHS including e. Chlorophyll *a* f. *Aureococcus anophagefferens* g. *Alexandrium fundyense.*

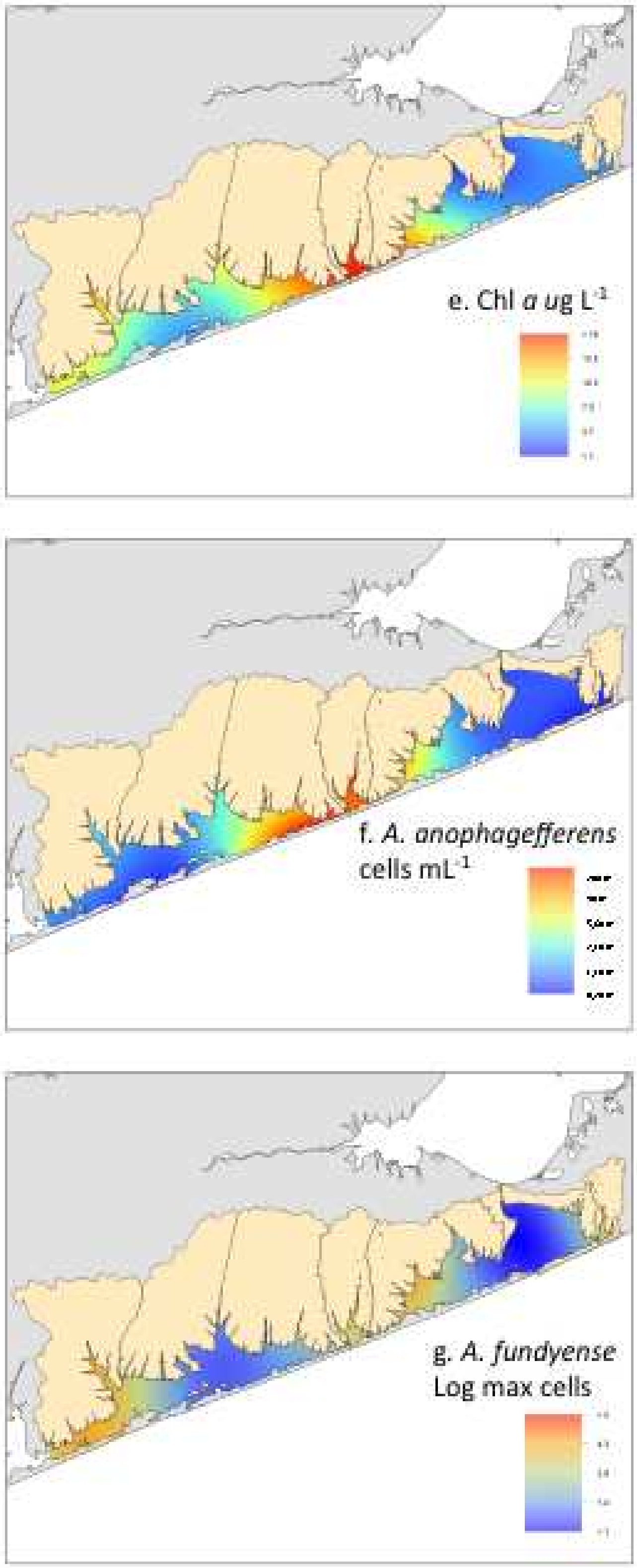


Figure 17. Flushing times (days) for each section of Moriches, Quantuck and Shinnecock Bays.

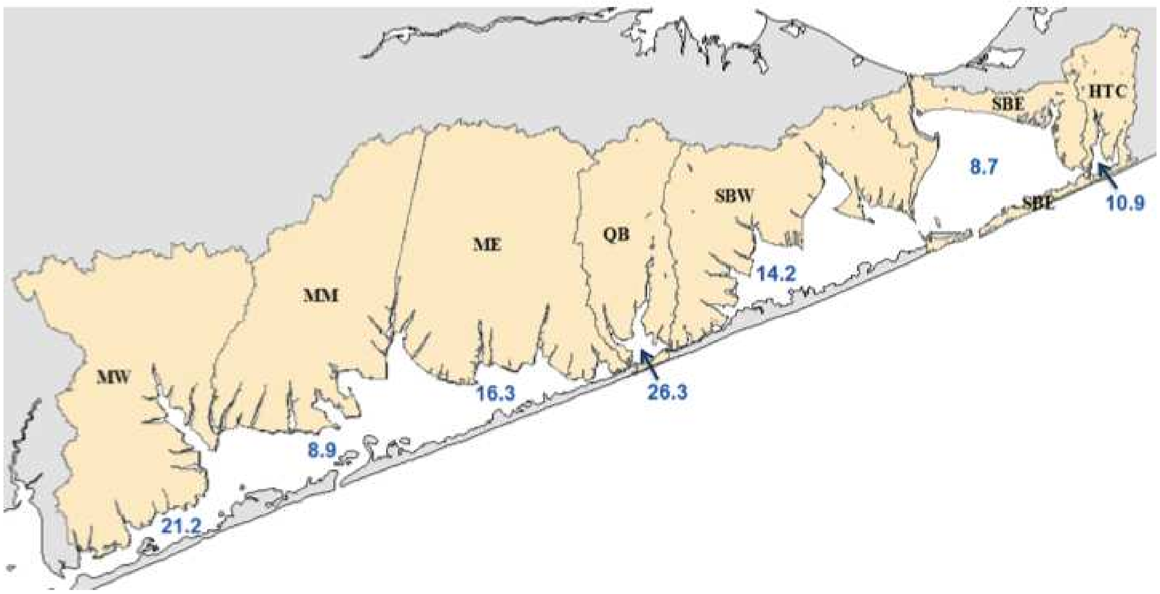


Figure 18. Correlations between flushing time, N load ha^{-1} and the water quality data. The correlation between flushing time and DIN and N load ha^{-1} and *A. anophagefferens* are not significant ($p>0.05$).

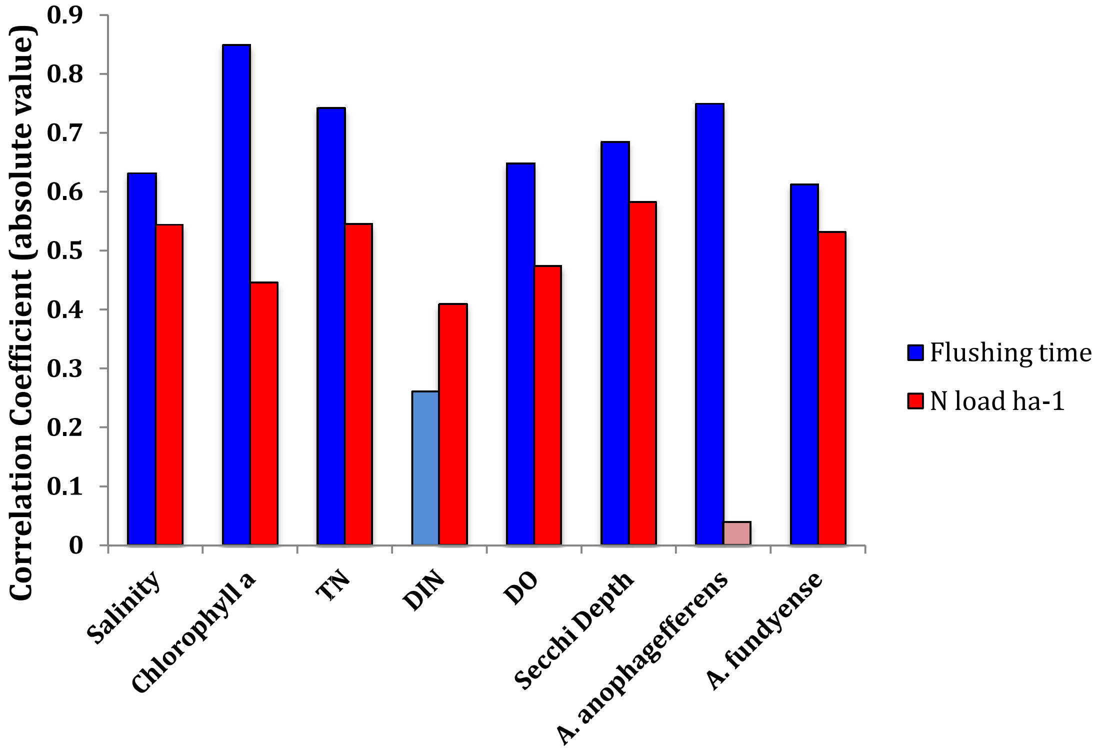
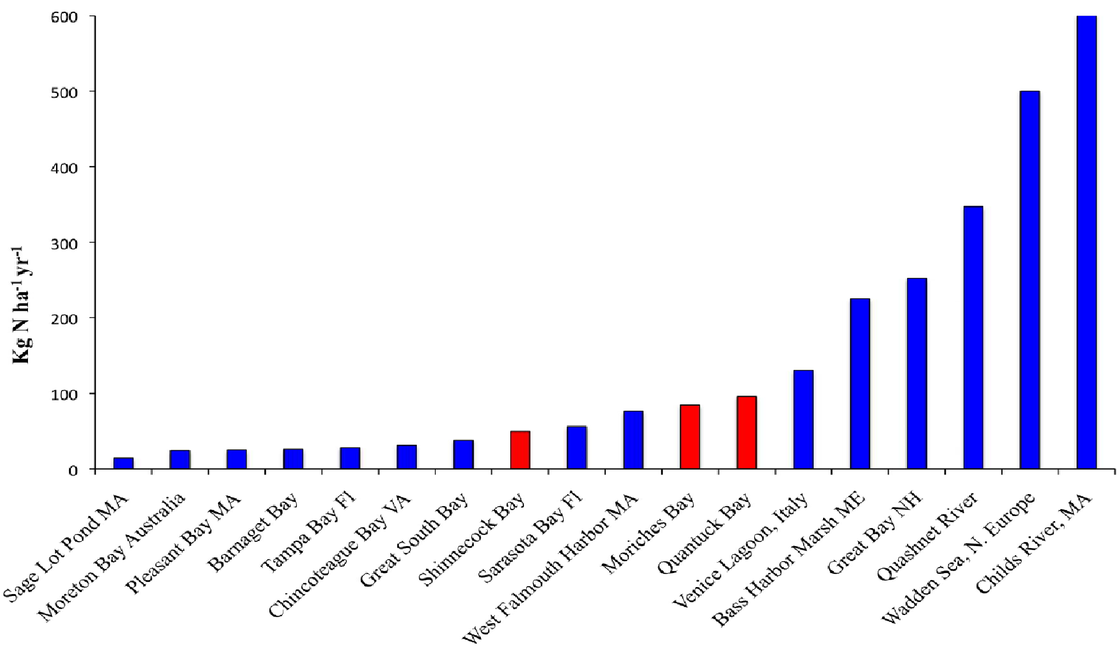


Figure 19. Nitrogen loads for this study and comparables. a. Nitrogen loads are expressed in kg N per *area of the waterbody* and include direct atmospheric deposition to the bay. Chart adapted from Kinney and Valiela (2011). b. Nitrogen loads are expressed in kg N per *volume of the waterbody*. The N load value for Bass Harbor Marsh is 0.045 Kg N m^{-3} yr^{-1}.

a.



b.

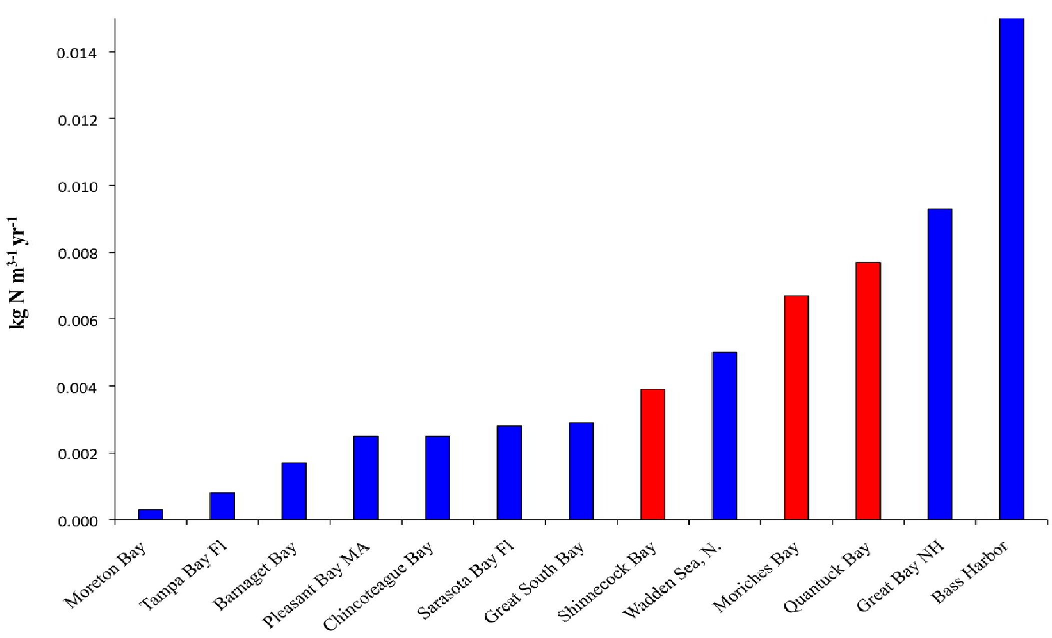


Figure 20. The Moriches West subwatershed is dominated by residential properties. The white areas are other land-use parcels including transportation, institutional, recreation and open space, vacant, agricultural or commercial.

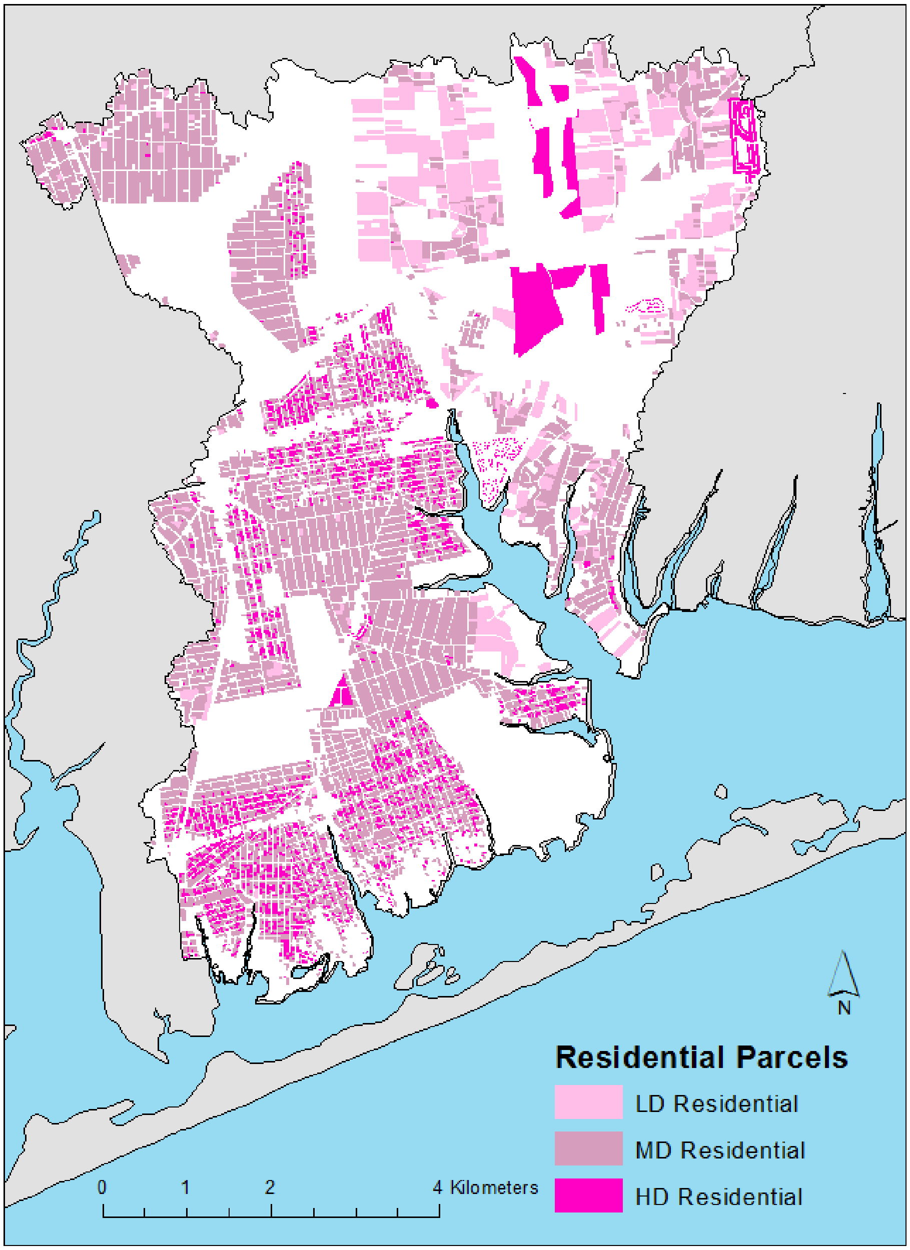


Figure 21. Quantuck Bay subwatershed can be broken into thirds north to south. The northernmost third is preserved parkland, the airport is the large gray area just to the south, and residential areas (buildings represented by black dots) make up the area closest to the shore. 8% of the watershed could be further developed.