NITROGEN LOADING MODELING FOR NASSAU COUNTY SUBWATERSHEDS

NASSAU COUNTY, NY

PREPARED FOR:
NEW YORK STATE
DEPARTMENT OF ENVIRONMENTAL CONSERVATION
ALBANY, NY 12233

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MEMORANDUM OF UNDERSTANDING BETWEEN THE NEW YORK DEPARTMENT OF STATE AND STONY BROOK UNIVERSITY

Contents

1. Executive Summary

Since the 20th century, delivery of excessive nitrogen (N) into Nassau County coastal waters has led to a host of environmental problems including: harmful algal blooms, hypoxic zones, bay water acidification, and habitat degradation and loss. Much of the N enters Nassau County surface waters from precipitation, stormwater (runoff from the land), atmospheric deposition, groundwater seepage - including seepage from septic systems and cesspools, and sewage treatment plant discharge. The quantity and sources of N from point and non-point sources of pollution to Nassau County surface waters have never been comprehensively quantified, making determination of the most effective course of N and water quality management a challenge.

This study was a first attempt to estimate the amount of N entering Nassau County surface waters from point and non-point sources of nitrogen. Each major bay or harbor watershed on the north and south shore of Nassau County was broken down into subwatersheds using United States Geologic Survey (USGS) Hydrologic Unit Codes (HUC) 12 to narrow the geographic scope and thus obtain accurate estimates of N loading and sources. The study used the Nitrogen Loading Model (NLM), land use, population characteristics, information on fertilizer use, and the most current science regarding N cycling and processes to estimate the relative contribution of wastewater from on-site septic systems, sewage treatment plants, fertilizer, and atmospheric deposition to total N loads in each subwatershed. This study also evaluated some N mitigation scenarios (changing the discharge from the South Shore Wastewater Reclamation Facility, previously known as the Bay Park Sewage Treatment Plant, changing fertilization rates) within each subwatershed.

Longer residence time and less flushing of estuarine waters can lead to greater rates of eutrophication of bay waters which is critical information in management decision making. Therefore, this study also modeled residence time of water within each bay using two different hydrodynamics models, FVCOM and EFDC Water quality data from the Town of Hempstead, Stony Brook University, Friends of the Bay, NYCDEP, CTDEEP, and other regional sources were compiled and compared to each other and to N loading rates. In addition, residence times of each water body were multiplied by the N loading rates to assess their potential influence on water quality as N loads that are not rapidly flushed from a water body are expected to have a more deleterious effect than the same N load delivered to a well-flushed water body. The waterbodies of Nassau County were ranked based on their mean summer water quality conditions (specifically, chlorophyll *a*, dissolved oxygen, and Secchi disc depths) and then further ranked based on their N residence times (volume-based N loading rates multiplied by residence times). Lastly, the amount of N reductions needed to achieve improved water quality were estimated using a ‘reference water body’ approach as well as by comparing existing water quality conditions relative to state and federal water quality standards.

Modeling determined that the N loads varied by more than an order of magnitude across Nassau County with West Bay on the south shore having, by far, the largest N load (2.3×10^6 kg N yr^{-1}), Cold Spring Harbor, Hempstead Harbor, and Manhasset Bay being an order of magnitude lower than West Bay (1.8×10^5 kg N yr^{-1}), and the remaining water bodies having lower annual loads (7 - 9×10^4 kg N yr^{-1}). Wastewater from onsite septic systems was the largest N source to all north shore bays, while sewage from the South Shore Wastewater Reclamation facility in Bay Park was the largest source to West Bay (98%). For other south shore sites, wastewater is diverted out of the watershed and fertilizer, primarily from homes, was the largest source of N. Surface run-off was isolated from atmospheric deposition and was found to account for a small fraction of N loads on the north shore (2 – 4%) but a larger fraction of the total on the more urbanized south shore (up to 20%). A proposed change in the recommended fertilizer application rate from 1 to 0.6 lbs per 1,000 square feet would decrease N loads up to 20% depending on the watershed. The diversion of sewage from the Bay Park treatment plant to the ocean outfall at the Cedar Creek wastewater treatment plant would decrease N loads by more than 98% and transform West Bay into a water body with the lowest N load on the south shore with most N emanating from fertilizers.

Residence times were determined and were found to range from 2 – 60 days depending on water body and whether flushing times were on 10% or 37% water retention. Summer water quality conditions were poorest in Hempstead Harbor, Cold Spring Harbor, and West Bay, although most water bodies displayed deviation from state and federal standards. Volume-based N residence times were found to be the largest for West Bay and Cold Spring Harbor, but were also elevated for Manhasset Bay, Oyster Bay, Middle Bay, and Hempstead Harbor. All six water bodies with elevated residence times required N reductions to achieve volume-based N residence times on par with reference water bodies in Suffolk County with good water quality. These same systems also required N reductions to achieve NYS and federal water quality guidelines and, while there was a significant correlation between the N load reductions required as determined by the two methods, the percent reductions required differed. The N loading rates to West Bay, Cold Spring Harbor, Hempstead Harbor, and Manhasset Bay were higher than the N loads to all but one comparable subwatershed in Suffolk County and West Bay had higher N load per unit volume of water than any water body anywhere for which comparable data was found. Manhasset Harbor and Middle Bay also had N load per unit volume that exceeded most known water bodies. These findings further emphasize the need for N reductions to these systems. Future efforts should consider more refined subwatersheds, as well as explore the efficacy of differing N mitigation measures.

2. Introduction

Nitrogen (N) found in coastal environments is derived from natural and anthropogenic sources. As the human population within a watershed grows so does the magnitude and proportion of anthropogenic nitrogen to coastal waters (Valiela et al., 1992, Valiela, 2006). Eutrophication of a waterbody is a natural process that occurs over very long periods and can become accelerated when there is an excessive input of anthropogenic nutrients, such as nitrogen. It is one of the most pressing contemporary environmental concerns in coastal areas. Microscopic marine plants, known as phytoplankton, are normally controlled by periodic nutrient limitation and predation, but in the face of nutrient overloading can become dense and pervasive in(?) waters (Valiela et al., 1992, Valiela, 2006). Such algal blooms can attenuate light penetration through the water column, decreasing the depth at which benthic phototrophs, such as seagrasses, can survive in waters (Valiela, 2006; 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 (Gobler and Baumann, 2016). 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 living in and on the sea floor (Diaz and Rosenberg, 2008).

Harmful algal blooms (HABs) are also an environmental problem initiated by nutrient overload, which have increased in their geographic extent, intensity, duration, and diversity in recent decades (Heisler et al., 2008; Anderson 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 (Heisler et al., 2008; Anderson et al., 2008). In some coastal areas such as Long Island, HABs promoted by N have become annual occurrences. The phytoplankton that compose these HABs are diverse and can affect ecosystem conditions, commercial and recreational fisheries, and human health. For example, wastewater-derived nitrogen (i.e. from sewage) has been shown to support the proliferation of saxitoxin-producing blooms of *Alexandrium catenella* that can cause paralytic shellfish poisoning (Hattenrath et al., 2010) and the toxin okadaic acid producing blooms of *Dinophysis acuminata* (Hattenrath et al., 2015).

Since nitrogen limits primary production (Nixon et al., 1995; Valiela et al., 2006) by plants at the base of the marine food web, it is often the nitrogen delivery rate (weight of nitrogen delivered per land area or water body volume per year) coupled with hydraulic flushing that influences the prevalence of algal blooms, intensity of hypoxia, and the loss of seagrass beds (Bowen and Valiela, 2001, 2004; Valiela et al., 1992; Valiela, 2006). In Suffolk County, NY, the major sources of nitrogen to waterbodies in the north shore, south shore, and east end are, in order, wastewater, fertilizer, and the atmosphere (Kinney and Valiela, 2011; Lloyd, 2014; Lloyd et al., 2016, SCSWP, 2019). However, the relative importance of a nitrogen source can vary over even small geographic distances (Kinney and Valiela, 2011; Lloyd, 2014; Lloyd et al., 2016, SCSWP, 2019). As a result, nitrogen loading models are required to predict the amount of nitrogen that various sources contribute to estuaries and how those spatial differences in nitrogen load relate to coastal land use.

Nassau County is situated in western Long Island, bordering New York City's borough of Queens to the west, and Suffolk County to the east (Figure 1). It is the most densely populated and second-most populous county in New York state outside of New York City, Nassau County county's population was estimated at 1,358,343 in 2018. All of Nassau County's bays have been identified as impaired according to the 2018 *New York State Section 303(d) List of Impaired/TMDL Waters* due to pathogens, although excessive nitrogen may also contribute toward water quality impairment of these systems[1]. Bays and harbors on NYSDEC's Priority Waterbody List (PWL) across Nassau County's north shore include Little Neck Bay, Manhasset Bay, Hempstead Harbor, Oyster Bay, and Cold Spring Harbor, all of which exchange tidally with Long Island Sound (Figure 1) and West Bay, Middle Bay, East Bay, and South Oyster Bay on the south shore.

Figure 1. Nassau County and its priority water bodies

Impairments of Nassau County waterbodies associated with excessive nitrogen have been documented in recent decades and have included hypoxia and harmful algal blooms caused by multiple phytoplankton species. The Stony Brook University study of the Western Bays, which are West Bay, Middle Bay, and East Bay of the South Shore Estuary Reserve, for NYSDEC documented a series of strong links between the overgrowth of *Ulva* and phytoplankton and excessive N loading (SoMAS, 2016). For example, mapping of the Western Bays showed that in regions where levels of nitrogenous compounds are high, *Ulva* covers the bottom of the bays (Figure 2). The *in-situ* growth rates of *Ulva* are high in the regions where N levels are high, and low in regions where N levels are low (Figure 3). Phytoplankton in this region are also strongly limited by N supply, as shown in Figure 4 where the addition of N increased their growth rate in the Western Bays (Figure 4), and together the overgrowth of *Ulva* and phytoplankton promotes anoxia and acidification in this region (SoMAS, 2016). There are number of ecological consequences associated with the overgrowth of *Ulva* including threats to human health associated with sulfide gas, the fouling of beaches, and the smothering benthic fauna or perhaps preventing settlement of fauna on the sea floor (Valiela et al., 1997). Experimental research has also shown that lowering N levels can decrease the intensity of algal blooms and *Ulva* growth in the Western Bays. For example, diluting bay water with ocean water leads to a decrease in the standing concentrations of N and, in turn, slow the growth of *Ulva* and phytoplankton (Figures 5, 6).

On the north shore, the Gobler lab has documented the regular occurrence of HABs and hypoxia in Hempstead Harbor and Cold Spring Harbor. Okadaic acid producing blooms of *Dinophysis acuminata* commonly occur in the water of Nassau County and have been shown to be promoted by N loading (Figure 7; Hattenrath et al., 2015). In addition, decades of research have shown that the growth of phytoplankton communities of Long Island Sound that tidally exchange into the north shore harbors are controlled by N (Figure 8; Gobler et al., 2006). It is the overgrowth of phytoplankton stimulated by N that settle to the benthos and cause hypoxia in this region on an annual basis (LISS, 1994; Gobler et al., 2006).

Despite the prevalence of environmental problems within Nassau County surface waters, the rates and sources of nitrogen loads to these waters have never been comprehensively quantified. This knowledge gap prohibits the formulation and evaluation of management plans to ameliorate nitrogen loads to these bays. Given the large costs associated with many nitrogen mitigation strategies, it is important to quantify the relative contribution of all the major sources of nitrogen to the bays. This information can then be used to determine cost effectiveness of different strategies for reducing nitrogen loads. Quantifying the current nitrogen loads entering Nassau County bays as well as quantifying how those loads would change under different nitrogen mitigation scenarios is a vital tool for proper water quality management.

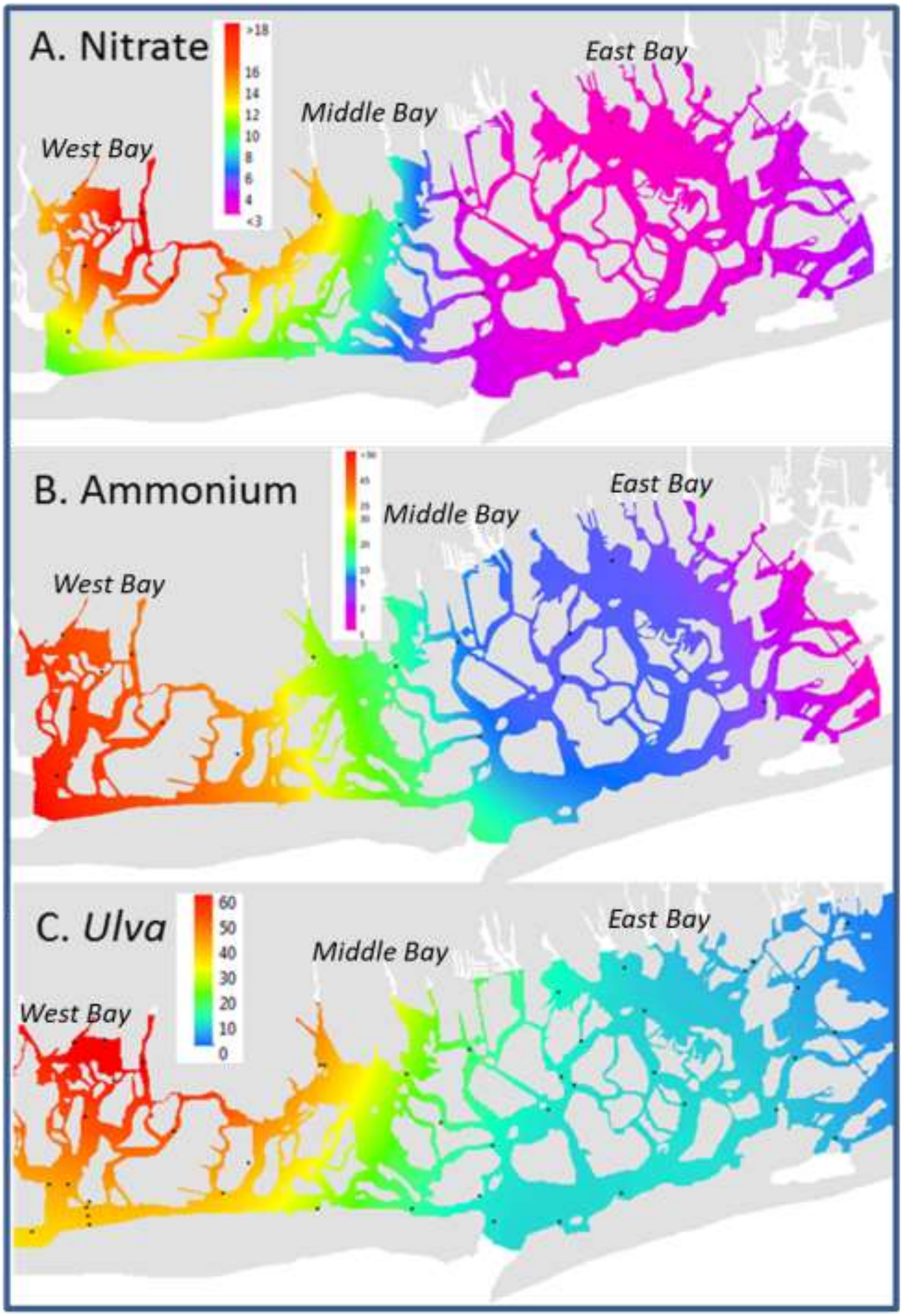


Figure 2. Dissolved nitrate and ammonium concentrations (µM) and percent coverage of *Ulva* across Western Bays during late September 2012.

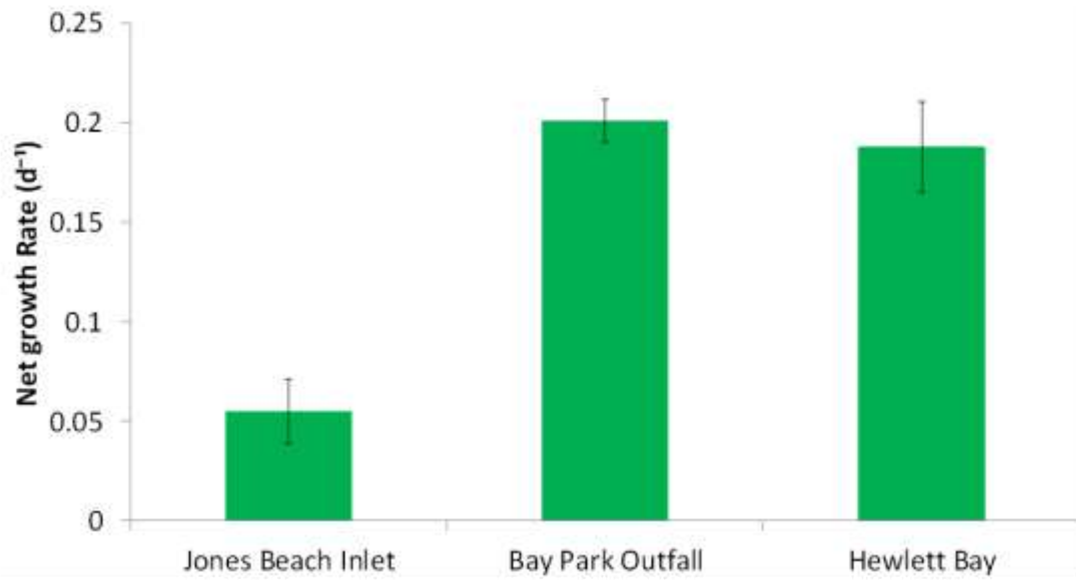


Figure 3. In situ growth of *Ulva* sp. incubated at 1 meter depth at three locations across Western Bays on July 20, 2011

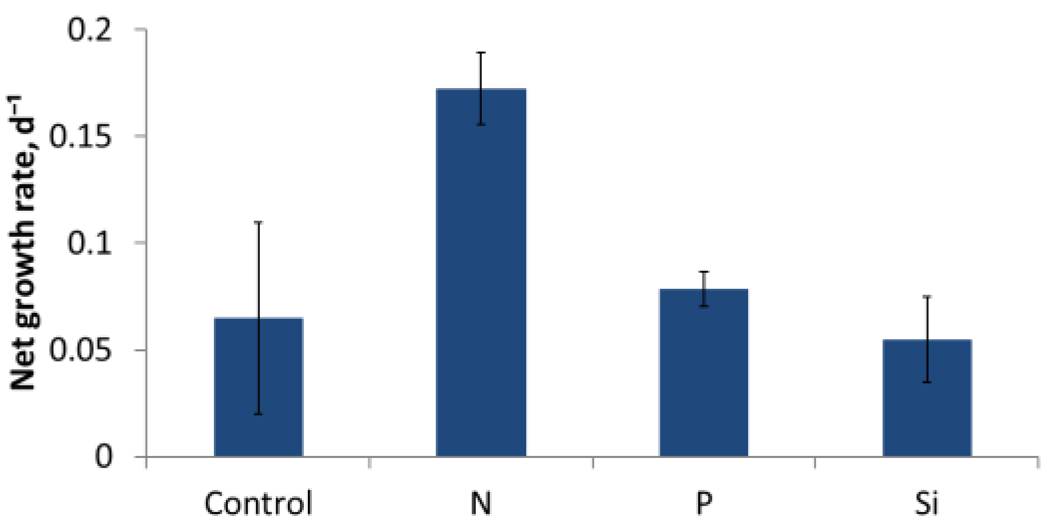


Figure 4. Effects of experimental nitrate, phosphate, and silicate loading on the entire phytoplankton population in Hewlett Bay in late May 2010.

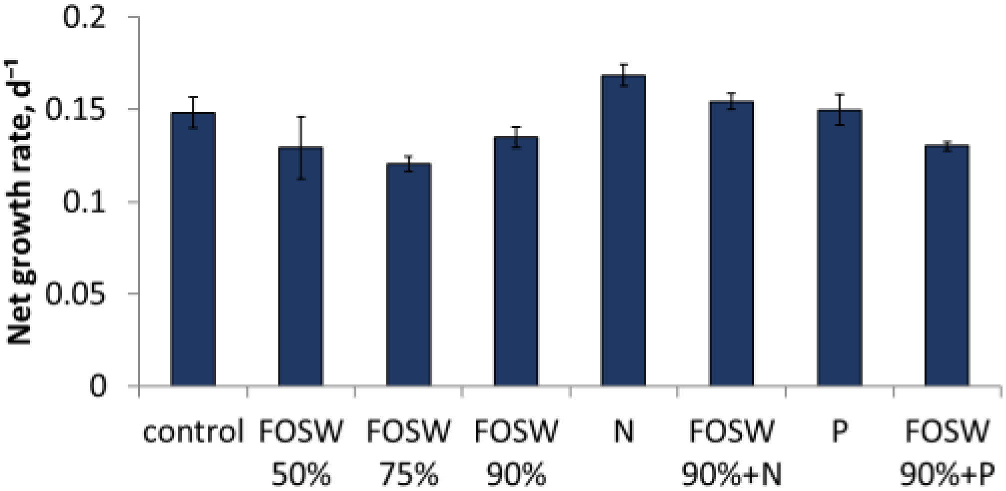


Figure 5. Effects of *Ulva* dilution experiments in Hewlett Bay comparing FOSW (filtered ocean seawater) to the addition of N or P.

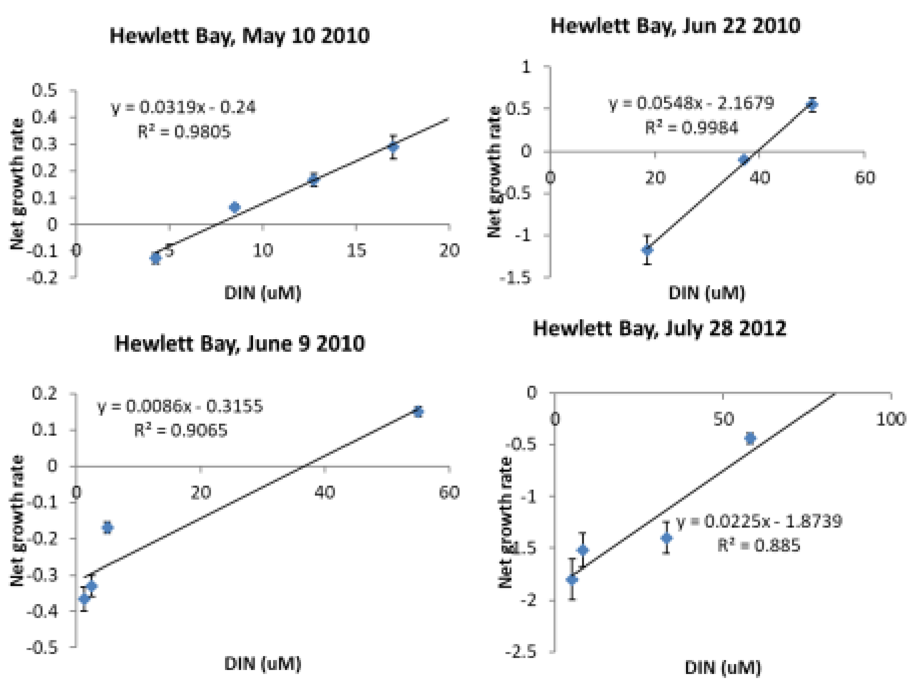


Figure 6. The relationship between dissolved inorganic nitrogen (DIN) and net growth rates of phytoplankton in Hewlett Bay. Differing levels of DIN were achieved by enriching West Bay water with nitrate or mixing Hewlett Bay water with Atlantic Ocean water. Growth rates within dilutions were corrected for reduced zooplankton grazing rates.

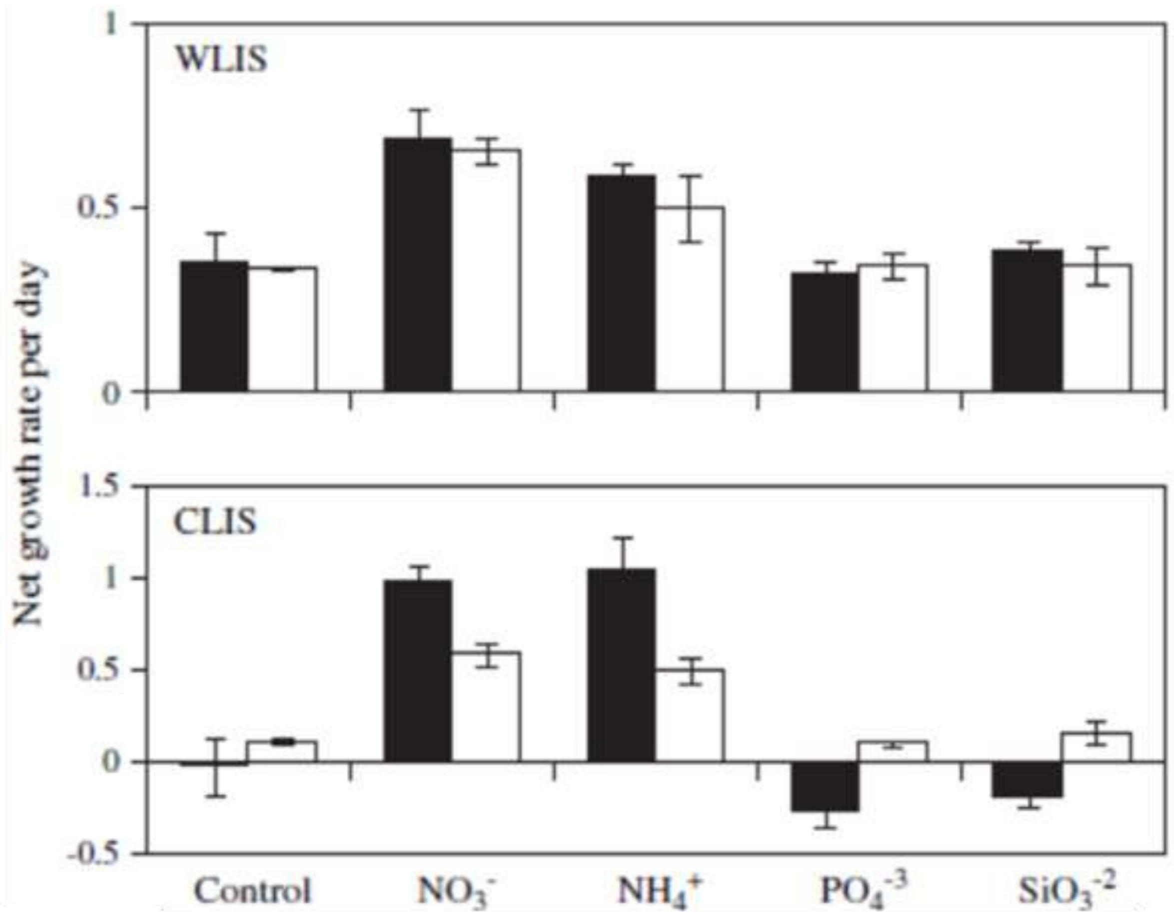


Figure 7. Growth rates of phytoplankton and planktonic carbon (black bars and white bars, respectively) in response to two forms of N, P, and silicon in the waters of western LIS and central LIS that tidally exchange with the north shore of Nassau County (Gobler et al., 2006).

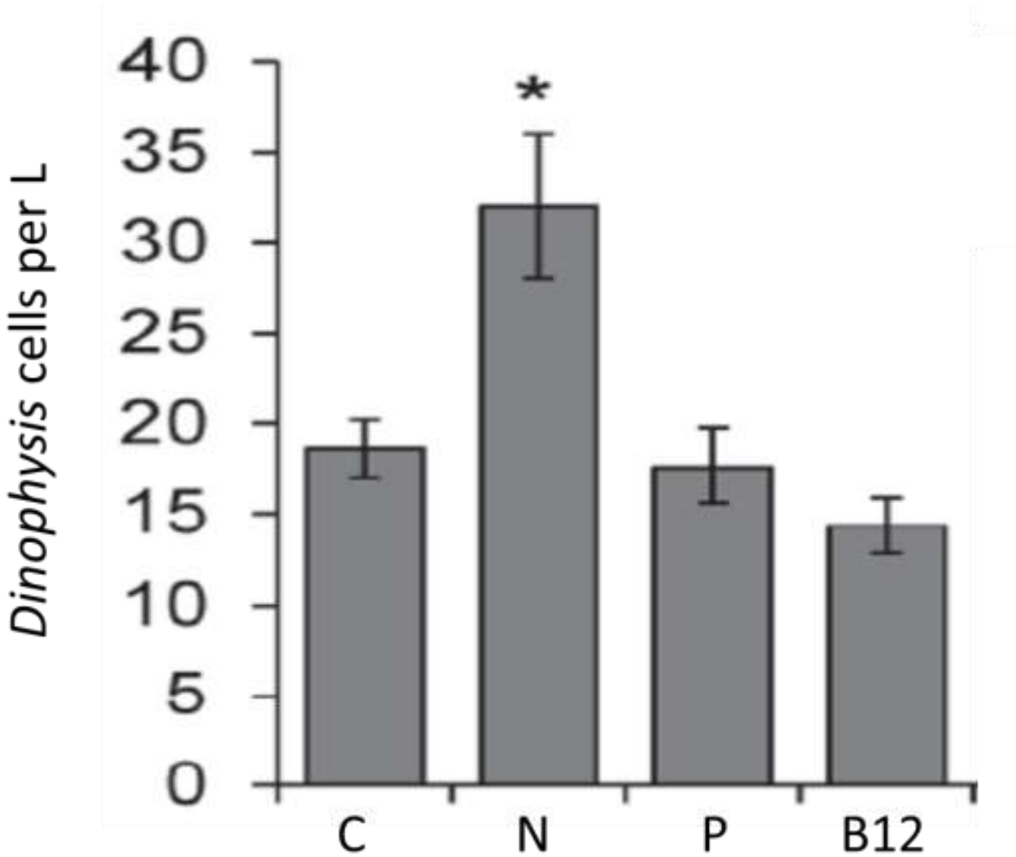


Figure 8. Densities of *Dinophysis* achieved in experiments in response to N, P, and vitamin B12 in Northport Harbor. Nitrogen significantly increased *Dinophysis* densities in 9 of 11 experiments performed by Hattenrath-Lehmann et al (2015).

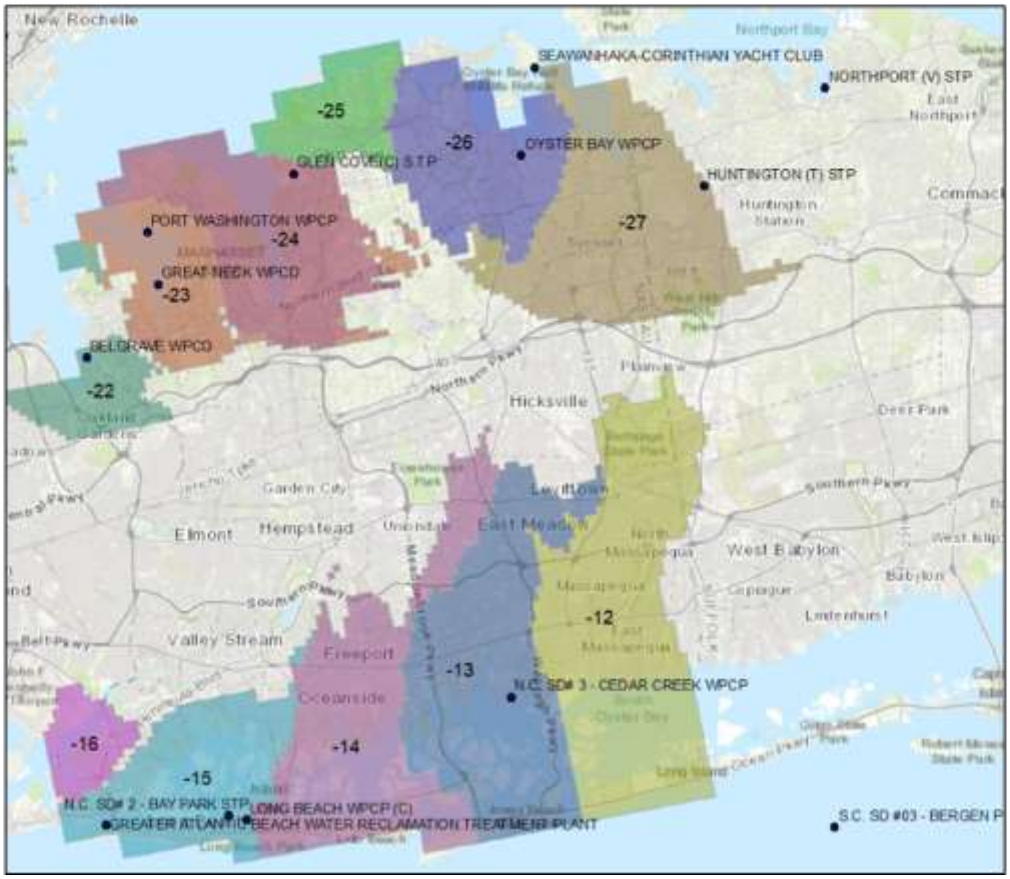
This project, therefore, quantified nitrogen loads to the Nassau County surface waters and determined the major sources of nitrogen. The watersheds of the north and south shores of Nassau County were broken down into 11 sub-watersheds. The study further assessed the spatial variability in water quality (algal biomass, dissolved oxygen, water clarity) and compared nitrogen loading rates from land to water to residence time data in order to determine the eutrophication vulnerability of each subwatershed. The residence times of each of these water bodies was also determined and these water bodies were ranked based on their water quality and their nitrogen residence times. Finally, some watershed management strategies were considered to understand how they would alter nitrogen loads to each subwatershed.

3. SCIENTIFIC APPROACH

3.1 Watershed/Subwatershed Delineation

The surface extents of the eleven watersheds in the study area were obtained from the U.S. Geological Survey regional MODFLOW model of 1968-1983. Watersheds that extended beyond the boarder of Nassau County were not clipped. Instead the study area was expanded to include the full extent of the watersheds so that all the N sources to the drainage areas were accounted for. We assume that groundwater flow roughly follows hydraulic gradients established by surface topography (Schubert, 1998). The resulting subwatersheds obtained from USGS followed the Hydrologic Unit Code (HUC) 12 delineation (Seaber et al., 1987; Figure 9).

Figure 9. Nassau County watersheds delineated as per the USGS MODFLOW study with sewage treatment discharge points shown.



3.2. Nitrogen Loading Model (NLM)

The model used to predict nitrogen load is the NLM described in Bowen et al. (2007) and recently used in Kinney and Valiela (2011), Lloyd (2014), Lloyd et al. (2016), Stinnette (2014), and Suffolk County (SDSWP, 2019) to quantify N loads to Long Island waterbodies. NLM has been used extensively by the US EPA in the Northeast US (Latimer and Charpentier, 2010) and altered significantly for use by NYSDEC Long Island Nitrogen Action Plan's study of nitrogen loading to Suffolk County subwatersheds by the consultants, CDM. The NLM uses information about land use in a defined watershed to predict both the amount of nitrogen that is released into the watershed from various sources and how much of it ends up in a corresponding bay. This model requires accurate local land-use information, such as area of agriculture, residential areas and impervious surfaces as well as other environmental data gathered from Long Island-based scientific literature via the Suffolk County subwatersheds study as well as from NYSDEC, NYS GIS portal, and Nassau County.

NLM assumes that the transport mechanism for nitrogen entering the bay from the watershed is primarily ground water. This is a good assumption for coastal regions of Nassau County, as geologically, Long Island is composed of unconsolidated sands that allow for relatively easy transport of groundwater to coastal zones (Kinney and Valiela, 2011; Stinnette, 2014). The NLM breaks down the nitrogen input into three sources: atmospheric deposition, wastewater and fertilizer. Valiela et al. (2000) validated this model by comparing its nitrogen load prediction to empirically measured nitrogen levels. They found NLM's results to be statistically indistinguishable from measured concentrations and found a linear relationship between the percent contribution from wastewater that NLM predicted and the stable isotope signature for wastewater expected from known values of $\delta^{15}N$ of nitrate in ground water.

The source of all data used within NLM are shown in Table 1. The details of all rates, attenuations, constants, and assumptions used within the NLM model for this project are found in Table 2. In nearly every case, the assumptions, rates, and constants used for this project matched those used for Suffolk County's subwatersheds study (SCSWP, 2019).

3.3. Atmospheric Deposition

Atmospheric nitrogen is delivered via precipitation (wet) or via dust (dry). Nitrogen that arrives in the watersheds through wet and dry deposition may have a varied contribution to waterbody nitrogen load depending on where the nitrogen lands. Different land use types (impervious, vegetation, developed) alters the amount of nitrogen that makes it to the waterbody. Nitrogen landing on vegetation has time to be assimilated by plants and organisms in the soils, and/or may be denitrified in the aquifer. Nitrogen that lands on impervious surfaces can runoff directly into a stream, or bay, skipping assimilation. It may also flow through a municipal separate stormwater sewer system (MS4) where it eventually seeps into sandy soils and discharges into coastal zones. In general, when atmospherically deposited nitrogen lands on impervious surfaces, significantly less is removed before entering the waterbodies. For this project, an effort was made to separate N from run-off given that once such N enters the water table, there is little N attenuation within the sandy aquifer of Long Island (Kinney and Valiela, 2011; SCSWS, 2019). Hence, to isolate N that is loaded to surface waters as a consequence of surface run-off, the sum of atmospheric N landing on impervious surfaces including roads, driveways, sidewalks, roofs, parking lots, and other impervious surfaces was summed and deemed N load from run-off.

Table 1. Data Sources for the Nassau County Nitrogen Loading Model.

Model attribute	Source	Value
Watershed area	USGS; ArcGIS®	Varied per subwatershed
Area of wetlands (freshwater)	Nassau County	Varied per subwatershed
Area of agriculture	Nassau County parcel dataset	Varied per subwatershed
Area of golf course lawn	Nassau County, Lawn Dataset (see residential lawns)	Varied per subwatershed
Area of parks and athletic fields (fertilized)	Nassau County parcel dataset, Lawn Dataset (see residential lawns)	Varied per subwatershed
Impervious surfaces total	Low NDVI created from USGS High Resolution Orthoimagery, open water areas removed.	Varied per subwatershed
Area of freshwater ponds	USGS National Hydrography Dataset	Varied per subwatershed
Waste Water Treatment Plants N Output	NYSDEC	Varied per subwatershed
Total Occupancy >200m of shore not on sewers	2010 census + Nassau county parcel dataset	Varied per subwatershed
Total Occupancy <200m of shore not on sewers	2010 census + Nassau county parcel dataset	Varied per subwatershed
Percent of buildings with cesspools	As per Suffolk County subwatershed consensus	50%
Area of residential lawns	High NDVI (USGS HRO), residential parcel areas where LiDAR height data was near zero (USGS LiDAR)	Varied per subwatershed
Percent of parcels with fertilized lawns	As per Suffolk County subwatershed consensus	85%
Area of roof per building	NYS GIS portal	Varied per subwatershed
Area of driveway per building	NYS GIS portal	Varied per subwatershed
Area of road	NYS GIS portal	Varied per subwatershed
Nitrogen inputs from wet and dry deposition	As per Suffolk County subwatershed consensus	0.04lb-N per 1,000sq ft per yr
Forest N leaching	As per Suffolk County subwatershed consensus	25%
Agriculture N leaching	As per Suffolk County subwatershed consensus	40%
Turf N leaching	As per Suffolk County subwatershed consensus	30%
Recharge from impervious surfaces as percent of precipitation	As per Suffolk County subwatershed consensus	50%
N released per person per year	As per Suffolk County subwatershed consensus	10 lbs N
Percent of N inputs released from septic tanks	As per Suffolk County subwatershed consensus	94%
Leaching ring effluent and plume	As per Suffolk County subwatershed consensus	90%
Fertilizer applied to lawns	As per Suffolk County subwatershed consensus	1.04lb-N per 1,000sq ft per yr
Fertilizer applied to golf courses	As per Suffolk County subwatershed consensus	3.89lb-N per 1,000sq ft per yr
Fertilizer applied to parks and athletic fields	As per Suffolk County subwatershed consensus	0.92b-N per 1,000sq ft per yr
Gaseous loss of fertilizer	As per Suffolk County subwatershed consensus	70% for residential & parks; 80% for Golf
Fertilizer application to agriculture	As per Suffolk County subwatershed consensus	0.46 - 5.742b-N per 1,000sq ft per yr
Denitrification in aquifer	As per Suffolk County subwatershed consensus	0% on south shore, 15% on North shore

Impervious land areas were estimated by finding where the Normalized Difference Vegetation Index (NDVI) was low (NDVI<90). The NDVI was created from the USGS's high resolution orthoimagery. Parcels that were known by land type to not have any impervious surfaces were removed to improve the accuracy. The removal included the classes open water, vacant land, preserved/forested land, and agricultural land. Road area was estimated by expanding road line data into polygons obtained from the US Census Bureau. Lines for primary road, secondary roads, local roads, and ramps were expanded to a width of 12.5m, 10m, 5m, and 5m, respectively. Areas of the polygons were then calculated and summed for each watershed. Residential impervious areas were estimated by limiting the impervious layer to residential parcels.

Table 2. Constants and rates used in NLM with sources color coded, light blue for atmospheric deposition, dark blue for wastewater, green for fertilizer..

Constants and Calculations		
N inputs from wet and dry deposition	5.37	*kg per ha per yr*
Forest N uptake	0.75	*percent of deposition retained*
Forest N release	0.25	*percent od deposition released*
Vadose N uptake	0	*percent of deposition retained*
Vadose N release	1	*percent of deposition released*
Turf N uptake	0.7	*percent of deposition retained*
Turf N release	0.3	*percent of deposition released*
Agriculture N release	0.38	*percent of deposition released*
N throughput from freshwater ponds to aquifer	0.45	*percent of inputs*
N throughput from wetlands to aquifer	0.25	*percent of inputs*
N released per person per year	4.536	*kg per cap per yr*
Percent of N inputs released from septic tanks	0.94	*percent of added N released*
Leaching field effluent	0.9	*percent of added N released*
N released from the plume of the septic system (aquifer loss)	0.94	*percent of added N released*
N released from s4 sewers (advanced individual sewers)	7.87	*kg per sewer per yr*
Percent of buildings with fertilized lawns	1	*percent*
Fertilizer applied to lawns	115	*kg per ha per yr*
Fertilizer applied to golf courses	189.2685186	*kg per ha per yr*
Fertilizer applied to Parks & Athletic Fields	89.65350881	*kg per ha per yr*
Fertilizer applied to agriculture	90.43951916	*kg per ha per yr*
Gaseous loss of fertilizer - residential lawns	0.3	*Percent fertilizer transported*
Gaseous loss of fertilizer - golf courses	0.3	*Percent fertilizer transported*
Gaseous loss of fertilizer - parks & athletic fields	0.3	*Percent fertilizer transported*
Gaseous loss of fertilizer - Agriculture	0.4	*Percent fertilizer transported*
Denitrification in aquifer	0.075	*percent of N entering the aquifer that is lost*
Denitrification in aquifer	0.925	*percent of N entering the aquifer that is released*

All other atmospheric deposition calculations based on land use areas were derivatives of the above processes or taken from source data. Area of turf was calculated from golf course, parks, and residential lawn area. The area of lawns was determined by combining NDVI data with LIDAR data. Any region with an elevated NDVI but was < 10 cm above road heights was deemed a lawn. Agriculture area was obtained from Nassau County parcel data. Ponds and wetland areas were obtained from the USGS National Hydrography Dataset. Any area that was not included in the above categories was considered natural vegetation. Each one of these categories had appropriate attenuation factors applied.

3.4. Wastewater

The contribution of nitrogen load to the bays from wastewater treatment plants was added directly to the model based on measurements of nitrogen output from the plants. Loads were assigned to the various watersheds based on the treatment plant outfall locations. The loads were not attenuated and were directly added to the total nitrogen load for the corresponding watershed.

For parcels that were not connected to the sewer system nitrogen output was calculated by multiplying the nitrogen released per person by the number of occupants in the watershed. The number of occupants for each parcel was determined from census tracks and parcel land use class. The total count of individuals for each census track was divided up among the residential parcels. The various types of residential parcels (one family, two family, apartment) were weighted accordingly. With each parcel assigned a number of occupants, parcels that were connected to sewer systems were removed. Then the total number of occupants in each watershed outside and within 200m of the water was tallied.

Differing levels of nitrogen were then removed from private sewer loading depending upon the type of on-site sewage disposal system (septic or cesspool) and the system's distance from shore, as there is significantly less nitrogen removed when septic tanks and cesspools are within 200m of coastal waters. Residential parcels have either an individual septic tank system or cesspool, which differ slightly in the fraction of nitrogen released to the underlying aquifer, with the less effective cesspools releasing more. Following the conclusions of the Suffolk County Subwatersheds study, it was assumed that half of the residential users were assumed to have cesspools.

The NLM breaks down the nitrogen removal in septic tank and cesspool-based systems into three steps: removal in the tank, removal in leach fields, and removal in septic plumes. Cesspools on Long Island are typically composed of cylinders arranged vertically, eliminating any traditional leach field and the associated nitrogen removal therein. Although there is a disposal pit associated with these vertically structured cesspools, only a small amount of nitrogen is removed in this part of the system (<10%).

3.5. Fertilizer

The NLM considers fertilizer input from agricultural uses, golf courses, parks and athletic field lawns, and manicured residential lawns. The area of each type was calculated using ArcGIS processes; residential lawn areas were found by limiting high NDVI areas (NDVI>80) to individual parcels and to areas where the LiDAR height layer was near zero (height<0.1m). The height of objects on properties (trees, buildings, decks, etc.) was determined by subtracting a Digital Elevation Model from a Digital Surface Model. These models were created from the same USGS LiDAR point cloud data. Golf course boundaries were provided by Nassau County and were combined with the lawn dataset to obtain golf course lawn area. Agricultural land was extracted from the Nassau County parcel data. Parks and athletic field parcels were also extracted from the Nassau County parcel dataset but were then further limited to lawn areas within those parcels with the same process used for residential lawns.

Details of the data sources used for the NLM appear below in Table 1. Many data sources have been generated as part of the NYSDEC Long Island Nitrogen Action Plan's nitrogen loading study of Suffolk County's subwatersheds. Based on that project it is assumed that fertilizer applications rates were 3.89 lbs per 1,000 square feet for golf courses and 1.84 lbs per 1,000 square feet for parks and athletic fields. For residential turf fertilization it was assumed that there is a 1.0 lbs per 1,000 square feet per application with the assumption that 49% of homes have, on average 3.5 applications per year, 31% of homes have 1 application per year, 4.5% of homes have 1 application every 3 years and 15.5% of homes do not use fertilizer (Vaudrey, 2015). Therefore, when adjusted to the mean number of applications per year per home, the residential application rate was 2.04 lbs per 1,000 square feet per year.

3.6. Pets

A module was added to NLM to consider the contribution of pets to watershed N loading. The assumptions of the module largely matched those of Suffolk County's subwatersheds studied including that each residence had, on average, one dog, and one indoor cat, and 0.74 outdoor cats per home. The 45-year old data regarding the N contribution of each animal type (Porter, 1978) was updated to reflect more recent findings (Beynen et al 2001, 2002).

3.7 Flushing times, residence times

Beyond the absolute N loads, a second parameter of critical importance with regard to the ability of N loads to impact a water body is residence time. Long residence times and slow flushing rates allow N to be assimilated by primary producers and increase the likelihood those primary producers will remain within the waterbody to form blooms, occlude light, senesce and sink onto sediments to contribute to low oxygen conditions (Valiela, 2006). These N residence times were calculated by multiplying the volume-based N load by the water body 10 percent flushing times, following the methodology used by the Suffolk County subwatersheds plan.

Hydrodynamic modeling was performed to calculate flushing times associated with tidal priority receiving water bodies defined by NYSDEC and USGS in order to support preparation of the Nassau County SWP. Environmental Fluid Dynamics Code (EFDC) models were developed for North Shore embayments in Nassau County and the existing FVCOM model was be applied to South Shore embayments in Nassau County. Four separate EFDC hydrodynamic models were made to calculate flushing rates in the North Shore Nassau County PWLs: Little Neck Bay, Manhasset Bay, Hempstead Bay and Oyster Bay. The existing FVCOM model was applied to the Nassau County South Shore PWLs, West Bay, Middle Bay, East Bay, and South Oyster Bay.
This model is described in detail in Hinrichs et al. (2018).

The method for calculating residence or flushing times for Nassau County tidal priority receiving water bodies was through the application of the hydrodynamic models EFDC and FVCOM. These models allow three-dimensional analysis of the tidal priority receiving water bodies based on freshwater inflow (surface water and groundwater), tidal and density driven circulation and also provide the foundation for future water quality modeling efforts. The calculation of priority receiving water body flushing times will facilitate the tiered ranking process on which priority receiving water bodies are the most at risk from nitrogen loading and require nitrogen management efforts.

Model Development

Digital coastline and bathymetric data: Digital coastline data were obtained from both NOAA at https://www.ngdc.noaa.gov/mgg/shorelines/ and from the US Fish & Wildlife Service Wetlands Inventory at https://www.fws.gov/wetlands/data/State-Downloads.html. Bathymetry data used to develop the FVCOM model is describedin Hinrichs et al. (2018). The USGS sub-groundwatershed delineations used to define groundwater input in the EFDC models are currently available at http://dx.doi.org/10.3133/sir20165138 and are described in USGS Scientific Investigations Report 2016–5138 (Masuit and Monti, 2016). Groundwater input to the South Shore FVCOM model is described in Hinrichs et al. (2018).

Annual average surface water runoff: The USGS maintains a very limited number of daily streamflow gauges within the North Shore EFDC model domains. https://nwis.waterdata.usgs.gov/nwis/dv/?referred_module=sw. Annual average surface water runoff will therefore be estimated from annual rainfall and drainage areas plus additional point sources associated with WWTPs. The North Shore embayments have spring tide ranges > 3.2 m, and so may be characterized as high-mesotidal to low macro-tidal (Hayes, 1980). It is, therefore, anticipated that flushing times in most of the tidal priority water bodies are dominated by tidal flushing as opposed to freshwater flushing or wind driven flushing. Surface water input to the South Shore FVCOM model is described at http://po.msrc.sunysb.edu/GSB/forcing.htm and in Hinrichs et al (2018). It also relies primarily on estimates from annual rainfall and drainage areas to obtain distributed surface water input along the north shore of GSB.

Tidal boundary condition water elevation, salinity and temperature model inputs:

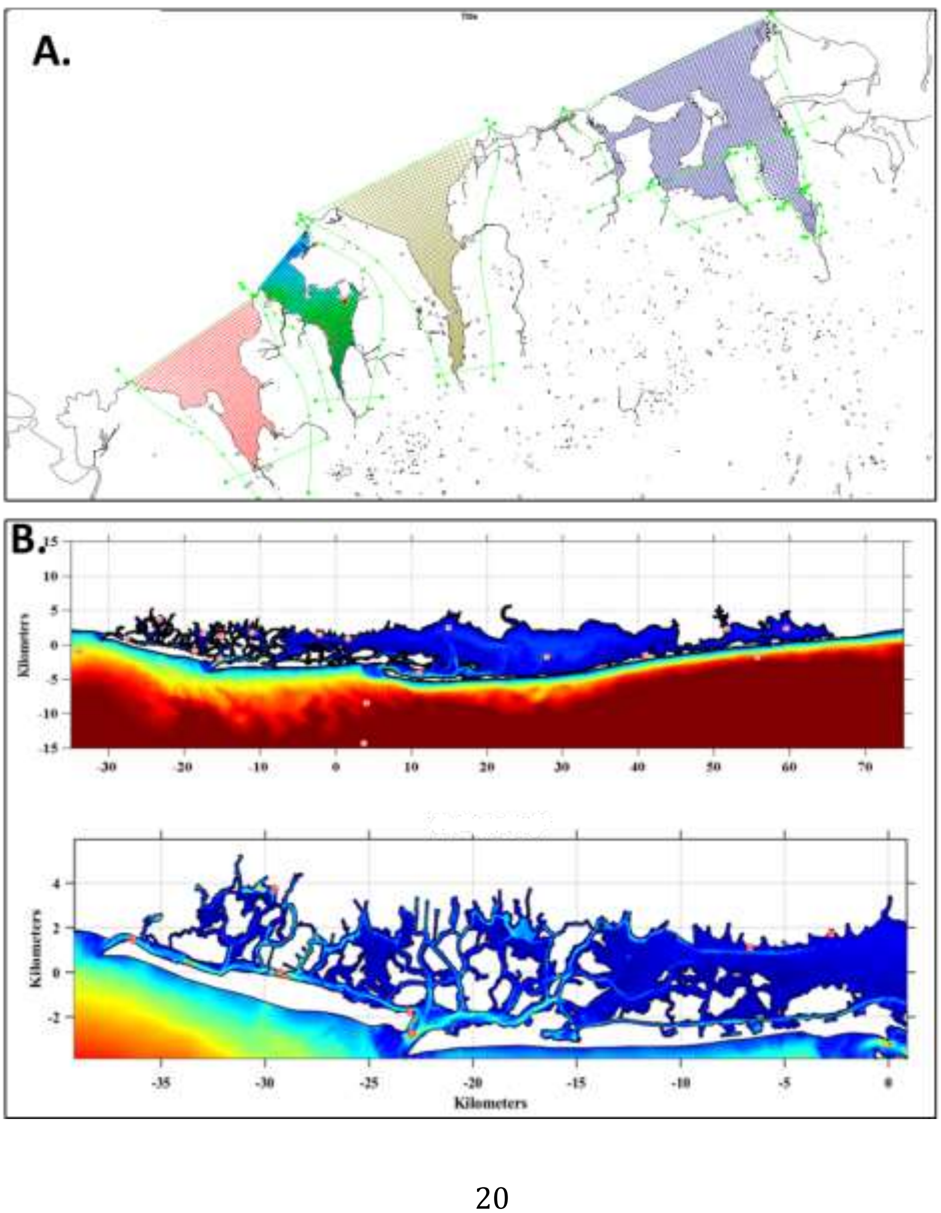
For the North Shore EFDC models in Nassau County, water elevation, salinity and temperature were obtained from the HDR Long Island Sound model (see Appendix A). The HDR Long Island Sound model also provided boundary conditions for the north shore EFDC models in Suffolk County. For the South Shore FVCOM model, open boundary conditions for water elevation, salinity and temperature are described at http://po.msrc.sunysb.edu/GSB/forcing.htm and in Hinrichs et al (2018).

Meteorological conditions (wind speed and direction):

The NOAA National Climatic Data Center (NCDC) has long established guidelines for measuring meteorological conditions and has supervision for quality assurance. Meteorological data used for model inputs will be obtained from the nearest NOAA NCDC data source to the EFDC and FVCOM modeled area.

With the EFDC models developed, flushing time calculations for the priority water bodies were completed. The model segments in each tidal priority receiving water body were assigned an initial constituent concentration of 1 mg/L. The concentration was trated as a conservative substance in the EFDC model. The model was run for the 60-day modeling time period; the calculated concentrations in all model segments and the volume averaged concentration versus time were determined. An example appears in Figure 10A. The time series of volume averaged concentration for the tidal priority receiving water body was used to calculate a flushing time based on one e-folding time (times when 36.8% of the initial mass exists in the tidal priority receiving water body) as well as based on when 10% of the initial mass exists in the tidal priority receiving water body. The resulting flushing time calculations were tabulated in EXCEL for each priority receiving water body along with PWL ID. Because of the complexity and dendritic nature of the South Shore Nassau County PWLs (e.g. Figure 10B), FVCOM was used to evaluate the flushing time patterns within 7 sub-domains to the west of PWL 1701-0173. Within those sub-domains, flushing times were defined at individual model nodes which can then be associated with an adjacent PWL.

Figure 10. A. EFDC model domains and grids for North Shore embayments. Each North shore embayment is colorized and gridded, smaller grids provide finer resolution of water flow. **B.** FVCOM Great South Bay model domain and sub-domain within Nassau County with bathymetry shown in color with dark blue the most shallow and red the deepest water.



Preliminary model calibration was completed for water elevations where data is available inside an EFDC modeling area. Available data was collected from available active and inactive NOAA water level stations. An acceptable level of preliminary model water elevation calibration was defined as a root mean square error (RMSE) of 25 cm. The South Shore FVCOM model has already been subject to extensive water level calibration as described by Hinrichs et al (2018). Hinrichs has reported RMSE values ranging from 8 to 16 cm for water level stations distributed around the perimeter of the model domain. It should be considered suitable for calculation of tidal receiving water body flushing times.

3.8. Tiered Priority Areas

3.8.1. Establish Baseline Water Quality

The data collected was analyzed to develop a water quality assessment of each subwatershed that informs watershed prioritization and next steps. Metrics were limited by data availability and included five potential indicators of nutrient enrichment:

- Surface water residence time
- Water clarity (such as Secchi depth)
- Total nitrogen
- Chlorophyll *a*
- Dissolved oxygen

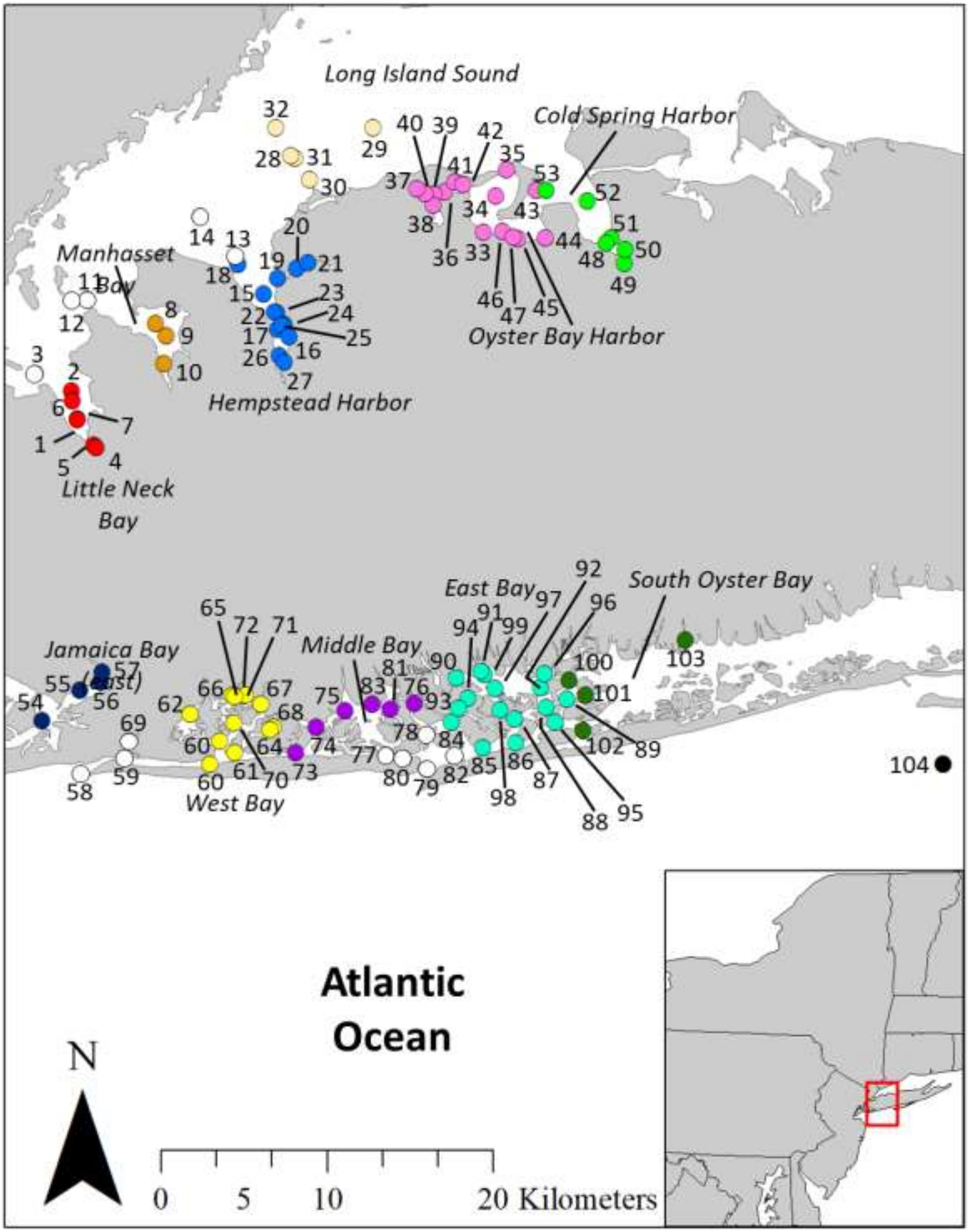
Prior work has demonstrated that for Long Island's Eastern Bays, these parameters tend to co-vary and thus may be considered as a suite of variables. Both mean and summer conditions were determined for each water body since summer months tends to experience high nitrogen, high chlorophyll, low oxygen and low water clarity, all of which contributed to impairment of water bodies and ecosystem services.

Surface water quality data was obtained from CTDEEP, NYSDEC, Stony Brook School of Marine and Atmospheric Sciences (SoMAS), the Town of Hempstead, estuary programs and NEIWPCC. Each of these agencies have their own quality assurance programs. The water quality monitoring stations are shown in Figure 11. For reference to open water conditions, a station outside of the Fire Island Inlet monitored by Suffolk County and stations in mid-Long Island Sound monitored by CTDEEP were examined as reference conditions of water that tidally exchanged with estuaries on the south and north shores, respectively.

3.8.2. Establish Primary Water Quality Indicators

From the water quality parameters identified above and the loadings evaluated for each waterbody, key indicators of overall water quality in the waterbodies were identified. Key indicators (chlorophyll *a*, Secchi disc depth, and dissolved oxygen) were a combination of characteristics that incorporated risk-based factors, as well as data sets and variables that were reliable. Total nitrogen data was scarce and suspect and thus was not collected and not used for this project.

Figure 11. Various sampling sites in Nassau County, NY, USA. Sites with white-filled circles indicate data were not used to calculate summer bottom dissolved oxygen, total chlorophyll *a*, and secchi depth. See tables 7,8, and 9 for details of data.



3.8.3. Rank Watersheds

The water quality metrics and identification of key indicators was used to develop a water body ranking, which quantifies an overall water quality index for each waterbody. The subwatersheds were then ranked according to the indicators, to prioritize the waterbodies that are most in need of nitrogen load reductions. Watersheds were ranked in two ways, one based on water quality conditions and the other based on residence times. Specifically, the residence times were multiplied by the N load per unit volume of the individual waterbody, resulting in a N load residence time that may provide an indication of the duration with which N was within a given ecosystem, is capable of manifesting itself as indicators of eutrophication (such as algal bloom which will lead to high chlorophyll, low water clarity, low dissolved oxygen, and loss of ecosystem services and habitats). Hence, it was expected that the two types of rankings would be highly similar. Further it was expected that regions with poor water quality would also have other, secondary indications of eutrophication such as no seagrass and diminished fisheries.

Waterbodies were also ranked based on each of the three major water quality characteristics as well as a mean of those three conditions. The mean values of each individual water quality parameter were compared against federal and state standards. Specifically, NYSDEC has a chronic dissolved oxygen standard of 4.8 mg L^{-1}. NYSDEC's Seagrass Task Force recommended a Secchi disc depth of 2 meters for all waterbodies (NYSDEC, 2009). Finally, NOAA and EPA have declared 4.8 µg chlorophyll *a* L^{-1} as eutrophic and have idealized a level of 10 µg chlorophyll *a* L^{-1} to minimize water quality impairment (Bricker et al., 1999, 2008). For any water body not meeting these guidelines levels of dissolved oxygen, Secchi disc depth, and chlorophyll *a*, a percent deviation from the guideline was calculated as % deviation = (observed mean value – guideline value) / guideline value. The mean deviation of the three water quality parameters was determined and used as a proxy for the percent N reduction that could restore water quality to guideline levels. While such a calculation has many caveats including the non-linear nature of N loading and water quality (Duarte et al 2009), this calculation was performed largely to compare to other approaches for assessing N mitigation scenarios.

These N residence times were determined by multiplying the volume-based N load by the 10% flushing times following the methodology used by the Suffolk County subwatersheds plan (SCSWP, 2019). During the Suffolk County subwatersheds study, a 'reference water body' approach was developed whereby more than two dozen waterbodies that had ideal water quality were identified. These waterbodies have had no harmful algal blooms in the past 10 years, mean Secchi disc depths > 2 meters, chlorophyll *a* of 5.5 µg L^{-1}, and dissolved oxygen of 4.8 mg L^{-1} (SCSWP, 2019). These sites had a mean N residence time of 0.12 mg L^{-1} and any site with a value above this require a reduction in N load commensurate with the amount the rate is over the threshold value. Percent (%) reduction = (water body volume-based N load– reference water body volume-based N load) / water body volume-based N load.

4. Results

4.1 Nitrogen Loading Model

Nitrogen loads varied greatly across the subwatersheds (Table 3). The largest nitrogen load came from West Bay on the south shore of Nassau County at 2.3 x 10^6 kg N yr^{-1} which was more than an order of magnitude larger than all other watersheds (Figures 12-18; Table 3). Several north shore waterbodies had loads that were ~ 1.8 x 10^5 kg N yr^{-1}, including Cold Spring Harbor, Hempstead Harbor, and Manhasset Bay while the remaining water bodies across Nassau County had loads of 8.6 10^5 kg N yr^{-1} or less (Figures 12-18; Table 3). It is important to note that the Long Island Sound and Little Neck Bay subwatersheds on the north shore, and the Jamaica Bay subwatershed on the south shore are all only a fraction of the total N load to these waterbodies, whereas the others represent the whole N load to the entire waterbody, due to the municipal boundaries not following watershed boundaries. As such, comparisons of total watershed loads of these three water bodies to the other eight water bodies are not equal.

Table 3. Volumes, areas, 37% and 10% residence times, and total N loads. Jamaica Bay and Long Island Sound are excluded as the watersheds in Nassau County connected to <1% of each water body and thus whole water body residence times were not applicable to this study.

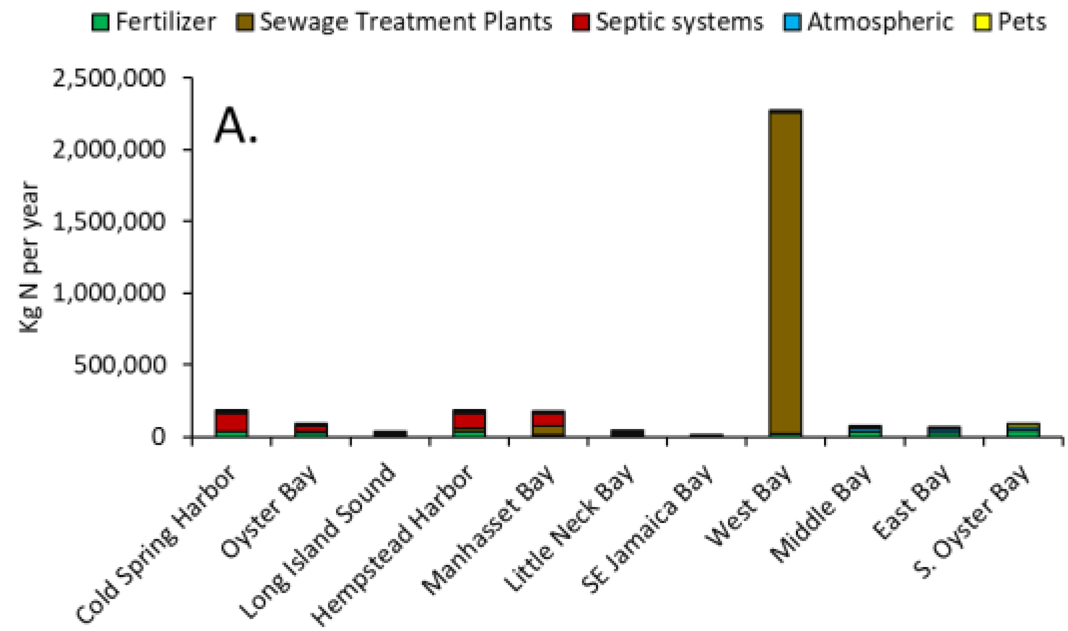
Water body	Shore	Volume m^3x10^6	Area m^2	Residence time R (37%) (days)	Residence time R (10%) (days)	N load kg/yr
West Bay	South	10.40	5.40E+06	9.3	22.3	2,277,919.38
Cold Spring Harbor	North	50.79	8.7118E+06	3.2	33.6	186,690.32
Oyster Bay	North	57.96	1.1145E+07	14.3	58.9	86,993.17
Manhasset Bay	North	26.16	7.8575E+06	2.1	11.4	179,978.86
Middle Bay	South	11.50	7.10E+06	4	9.5	77,224.44
Hempstead Harbor	North	70.98	1.1486E+07	3.5	21.8	183,452.18
S. Oyster Bay	South	40.30	2.14E+07	8	17.5	88,269.90
East Bay	South	31.80	1.16E+07	5.4	10.8	70,720.71
Little Neck Bay	North	38.40	6.0646E+06	1	3.1	41,712.68

To compare the nitrogen loading from the different subwatersheds areas, volume specific loading rates were quantified (kg N per ha of surface area). West Bay had the largest yield when normalized to watershed area at 448 kg N ha^{-1} yr^{-1} (Figures 19A&B; Table 3). This was an order of magnitude higher than the next tier of watersheds on the basis of area-specific loading as all of the north shore watersheds had area-specific loads of 17 - 47 kg N ha^{-1} yr^{-1} whereas the remaining south shore bays had very similar area specific loads of 7.9 – 9.8 kg N ha^{-1} yr^{-1} (Figures 19A&B; Table 3).

While the relative contribution of each nitrogen source varied across the subwatersheds, wastewater was consistently the largest N source for most subwatersheds with several distinct patterns emerging. First, West Bay was unlike all other subwatersheds as 98% of its N load emanates from sewage treatment plants (STP; Figure 17), with 90% coming from the Bay Park plant. Because the remaining south shore subwatersheds are sewered and have their N loads diverted out of the subwatershed to the Bay Park or Cedar

Creek (STP), there is hardly any wastewater contribution to N loads to other south shore subwatersheds. Instead, fertilizer represented approximately half of the N loads to the remaining south shore subwatersheds, followed by atmospheric deposition (29%) and pets (24%; Figure 18).

Figure 12. A. Total nitrogen load from each subwatershed in kilograms N per year. **B.** Total nitrogen load from each subwatershed in kilograms N per year, X-axis is cut-off to provide resolution of all sites; the West Bay N load is 2.3 x 10^6 kg N per year.



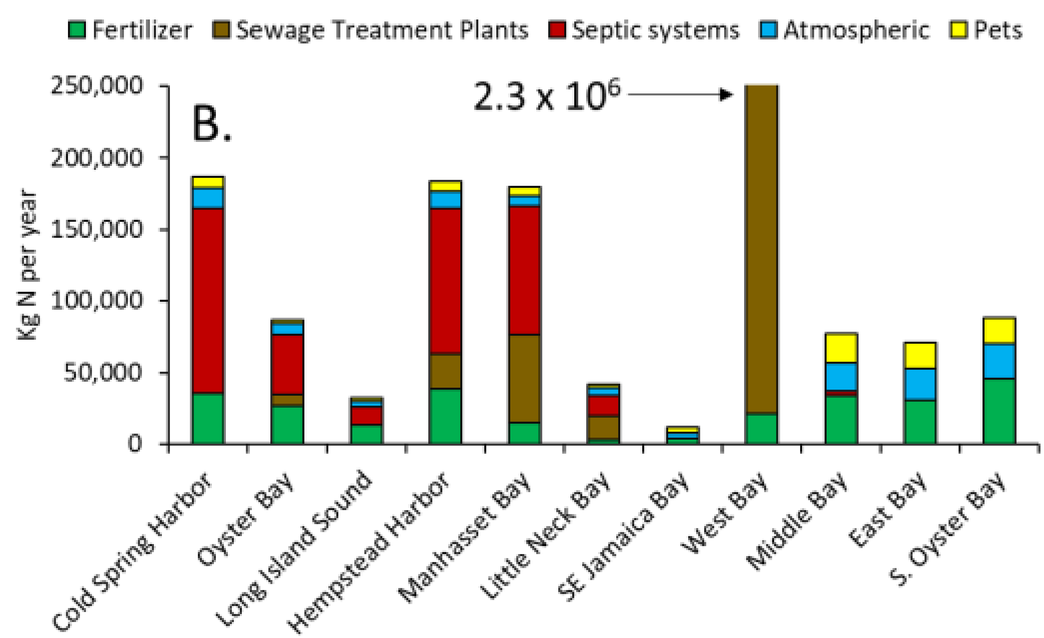
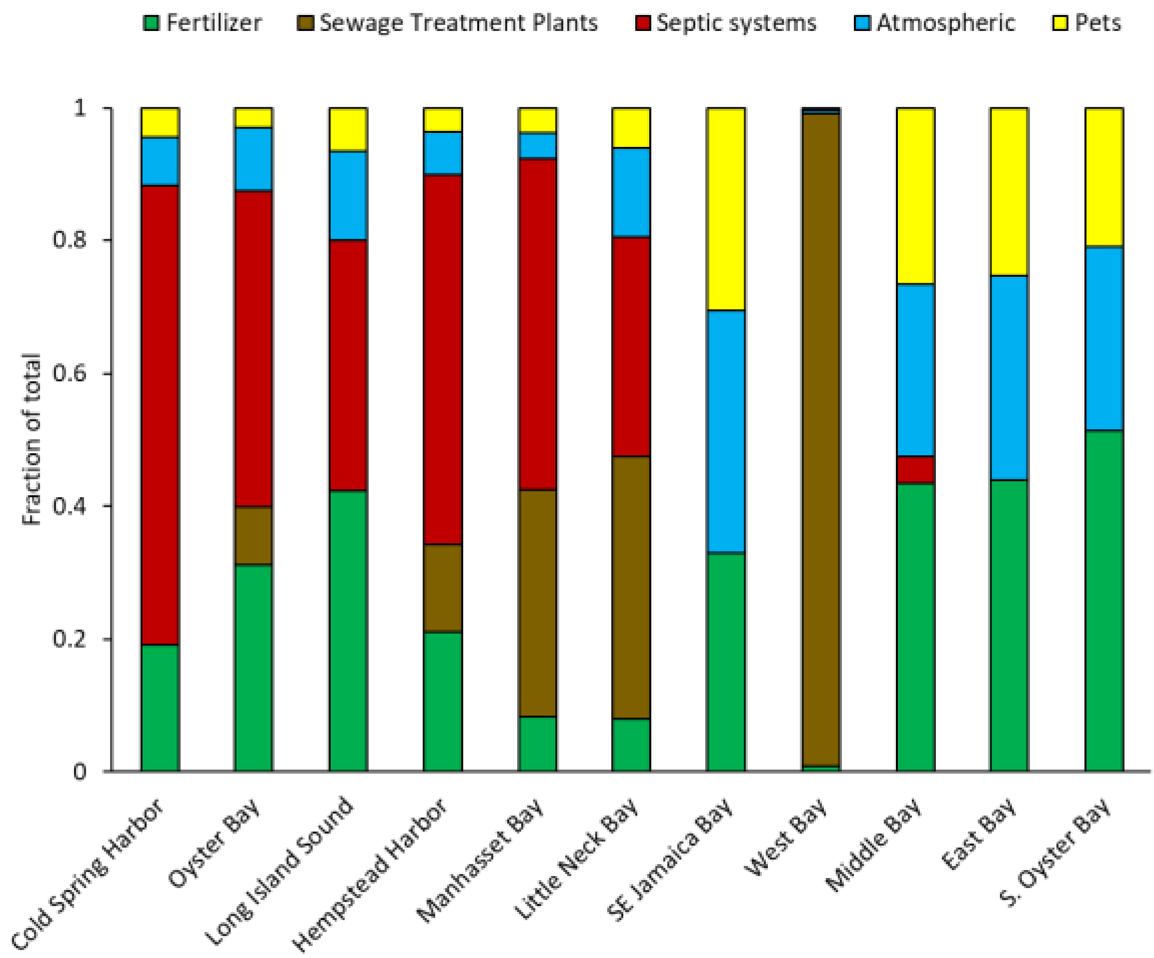


Figure 13. Relative contribution of fertilizer, sewage treatments plants, septic systems, atmospheric deposition, and pets to the total N load of each water body.



On the north shore of Nassau County, the subwatersheds had a similar distribution of their N loads. There is sewering in some of the north shore subwatersheds. Little Neck Bay has the largest N loading from STP at 40% of the total load with an additional 33% from onsite septic systems (Figure 14,15). Manhasset Bay is next with 34% of N from STP and 50% from onsite septic systems (Figure 14,15). The small Long Island Sound subwatershed was an outlier for the north shore, having a near split between fertilizer and septic N load (42% and 38%, respectively (Figure 14,15). For the remaining north shore subwatersheds, onsite septic systems were the largest source of N load ranging from 50 – 70% of the load, even in Oyster Bay and Hempstead Harbor where STPs represented ~10% of the N load (Figure 12). While fertilizer was the largest N source for the small Long Island Sound subwatershed, it was the second largest N source elsewhere on the north shore, representing ~10 – 30% of the total N load (Figure 14,15).

Figure 14. A. Total nitrogen load from each north shore subwatershed in kilograms N per year. **B.** Relative contribution of each N source to the total nitrogen load from each north shore subwatershed.

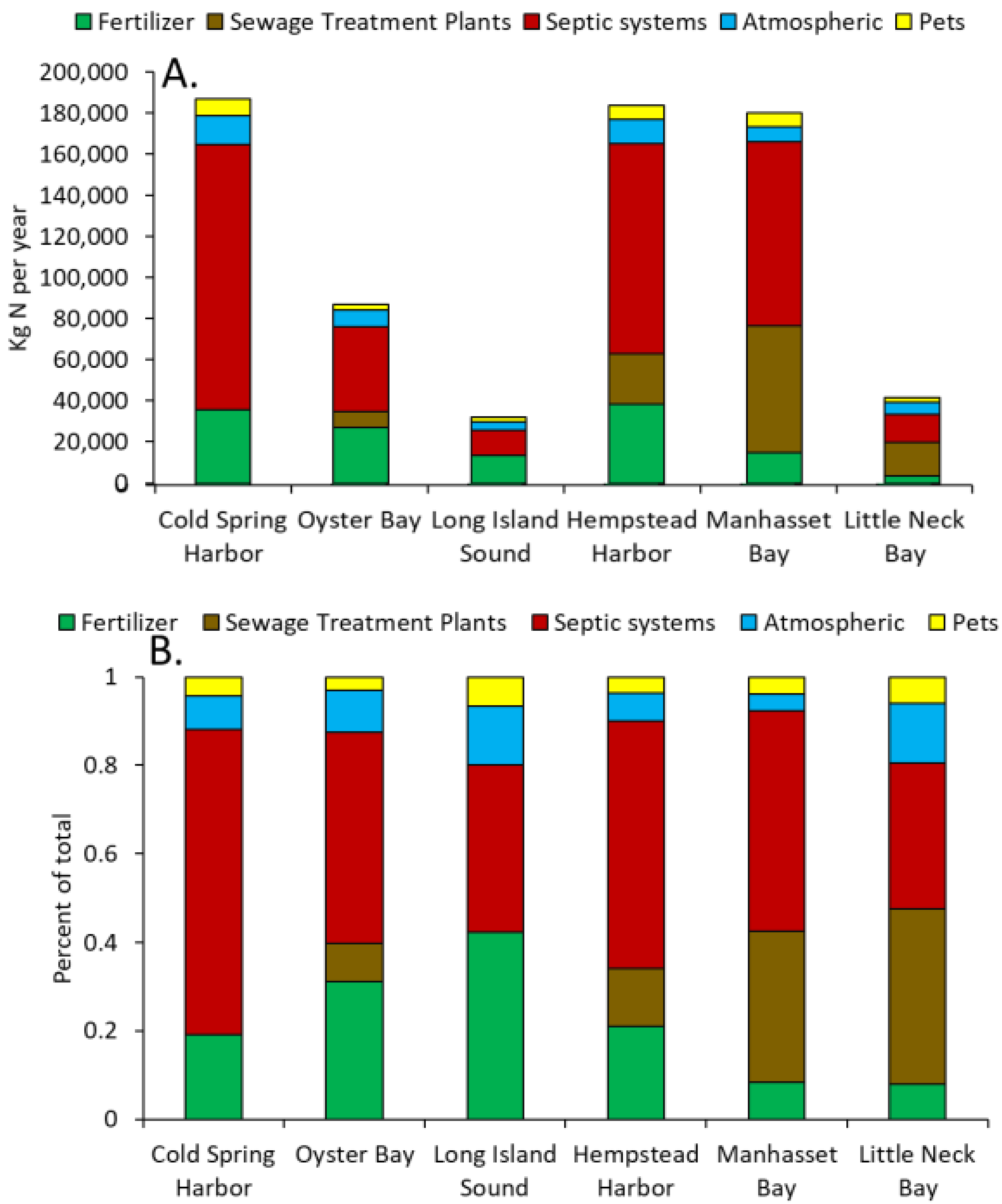
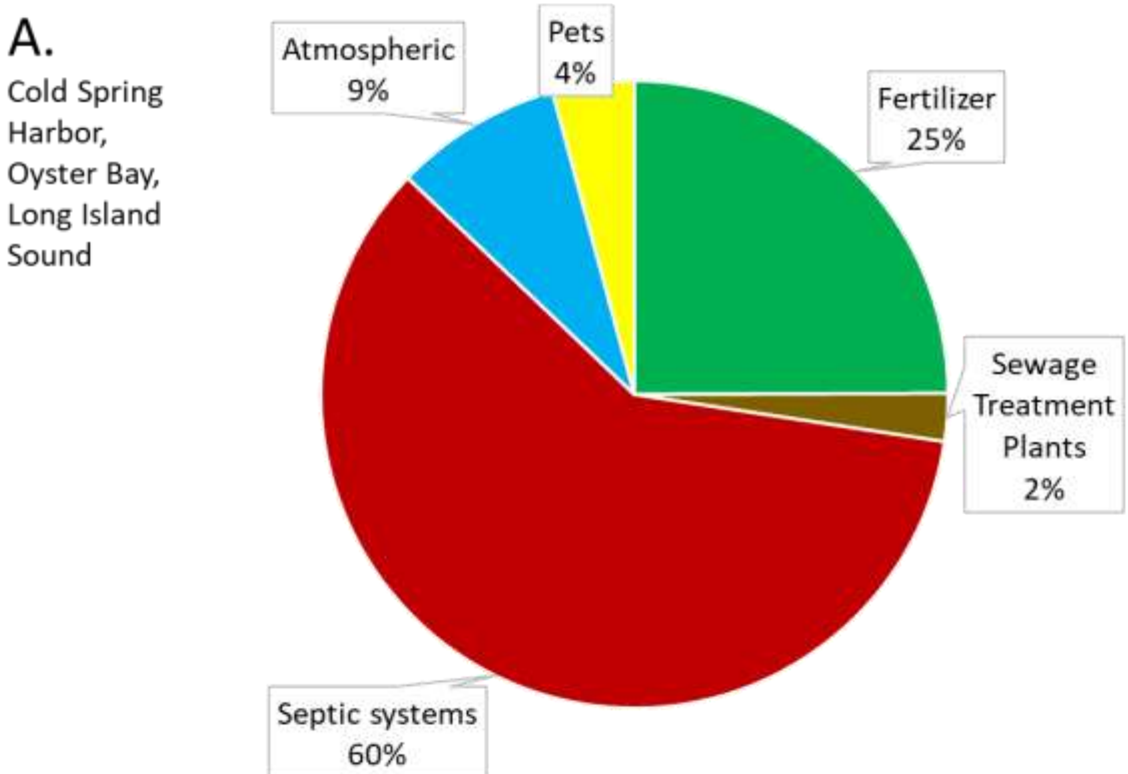


Figure 15. A. Relative contribution of each N source to the total nitrogen load from the Cold Spring Harbor, Oyster Bay, and Long Island Sound subwatersheds. **B.** Relative contribution of each N source to the total nitrogen load from Hempstead Harbor, Manhasset Bay, and Little Neck Bay Sound subwatersheds. A and B demonstrate the great prevalence of sewers for the western subwatersheds of the north shore.



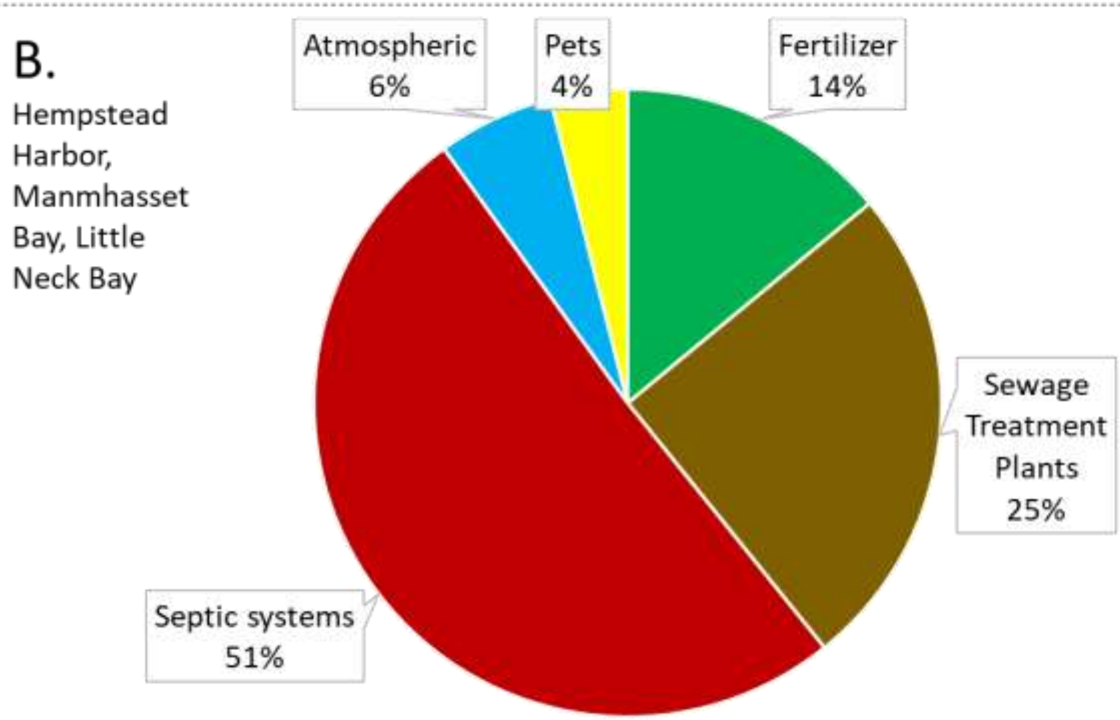


Figure 16. A. Total nitrogen load from each south shore subwatershed in kilograms N per year. **B.** Total nitrogen load from each south shore subwatershed in kilograms N per year, X-axis is cut-off to provide resolution of all sites; the West Bay N load is 2.3×10^6 kg N per year.

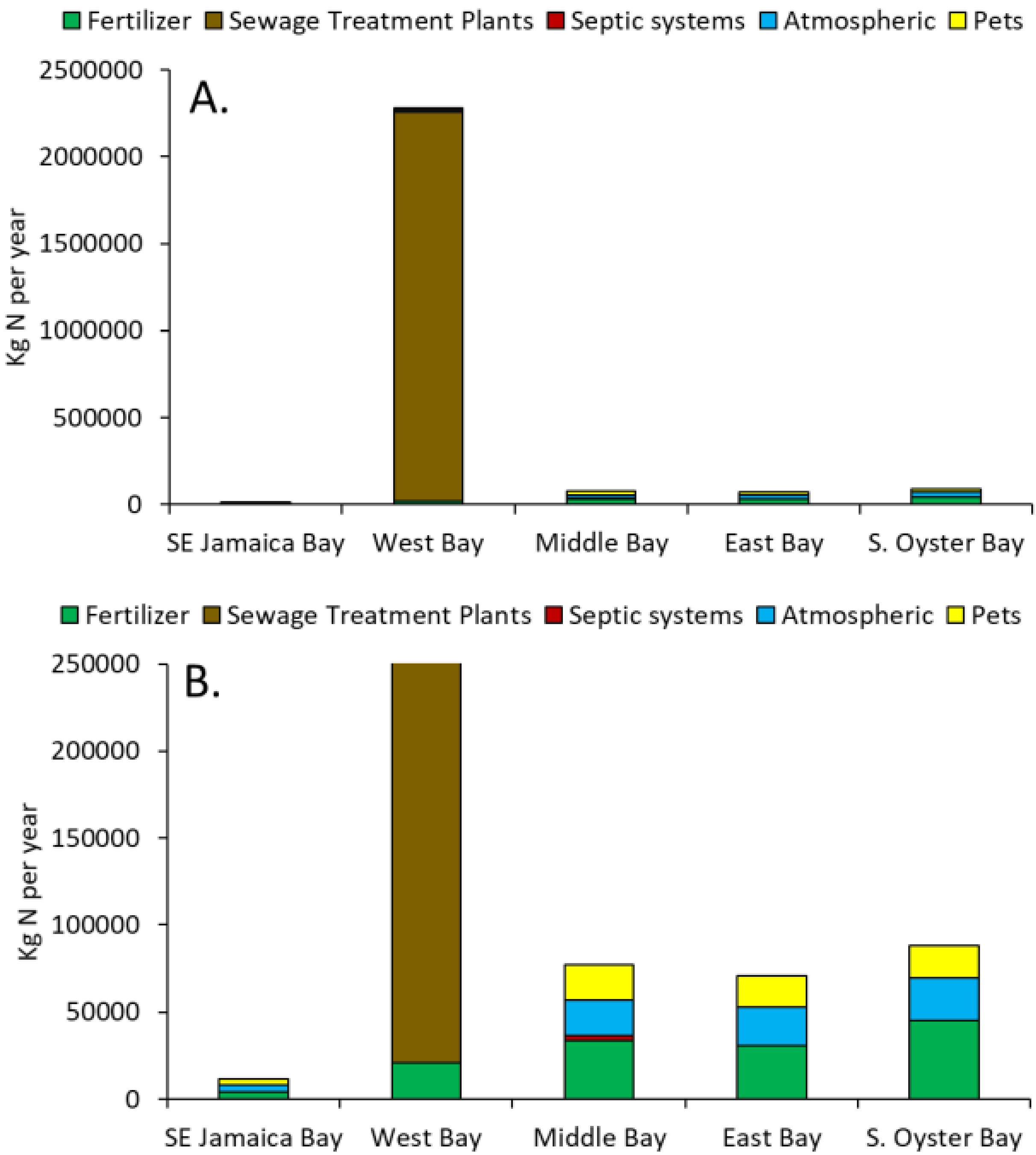


Figure 17. Relative contribution of each N source to the total nitrogen load from each south shore subwatershed.

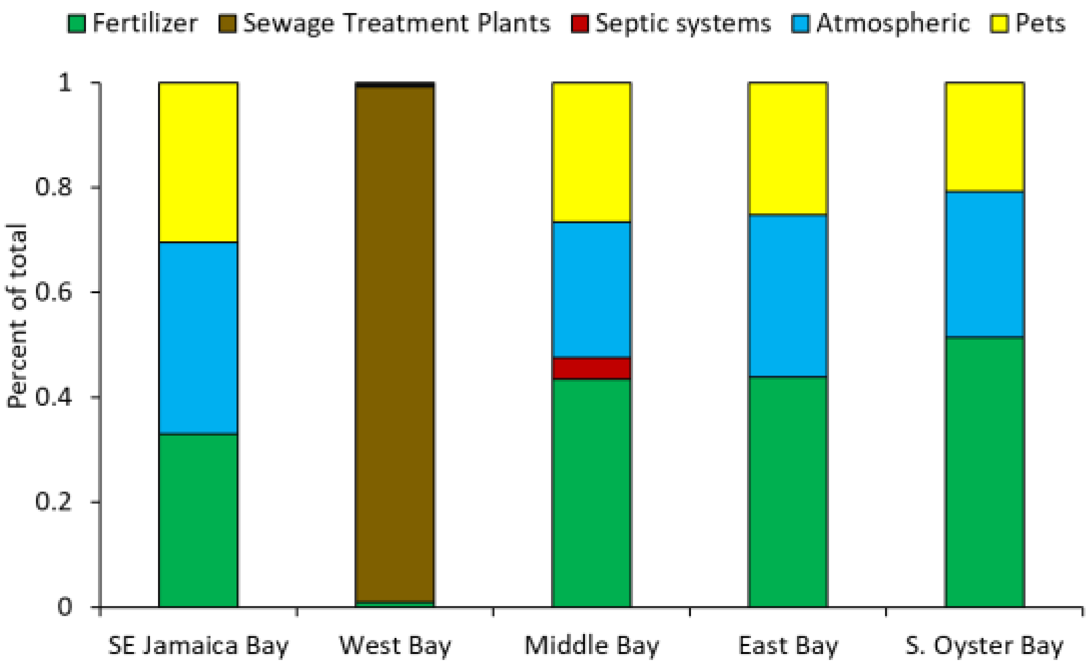


Figure 18. Relative contribution of each N source to the total nitrogen load from the south shore subwatersheds removing West Bay.

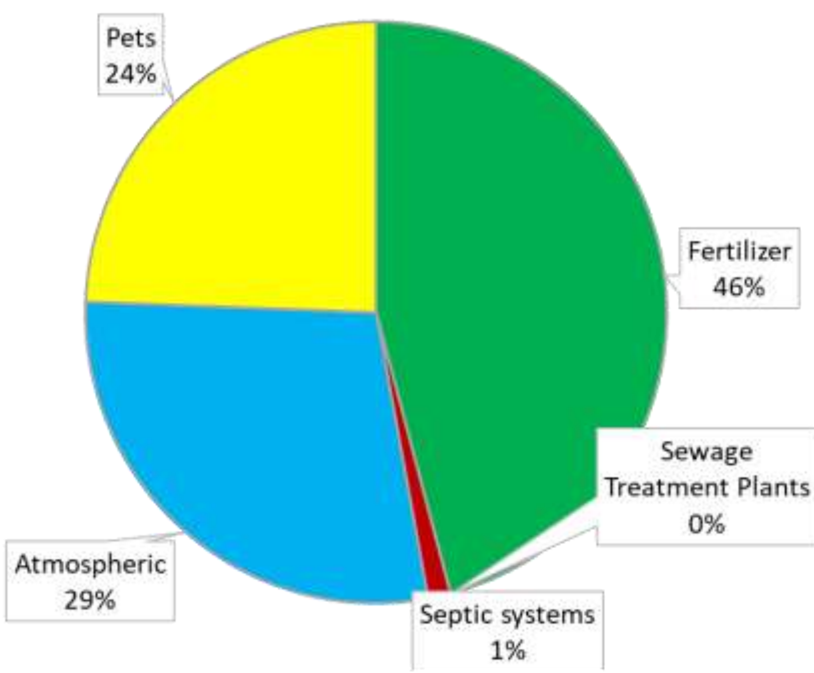
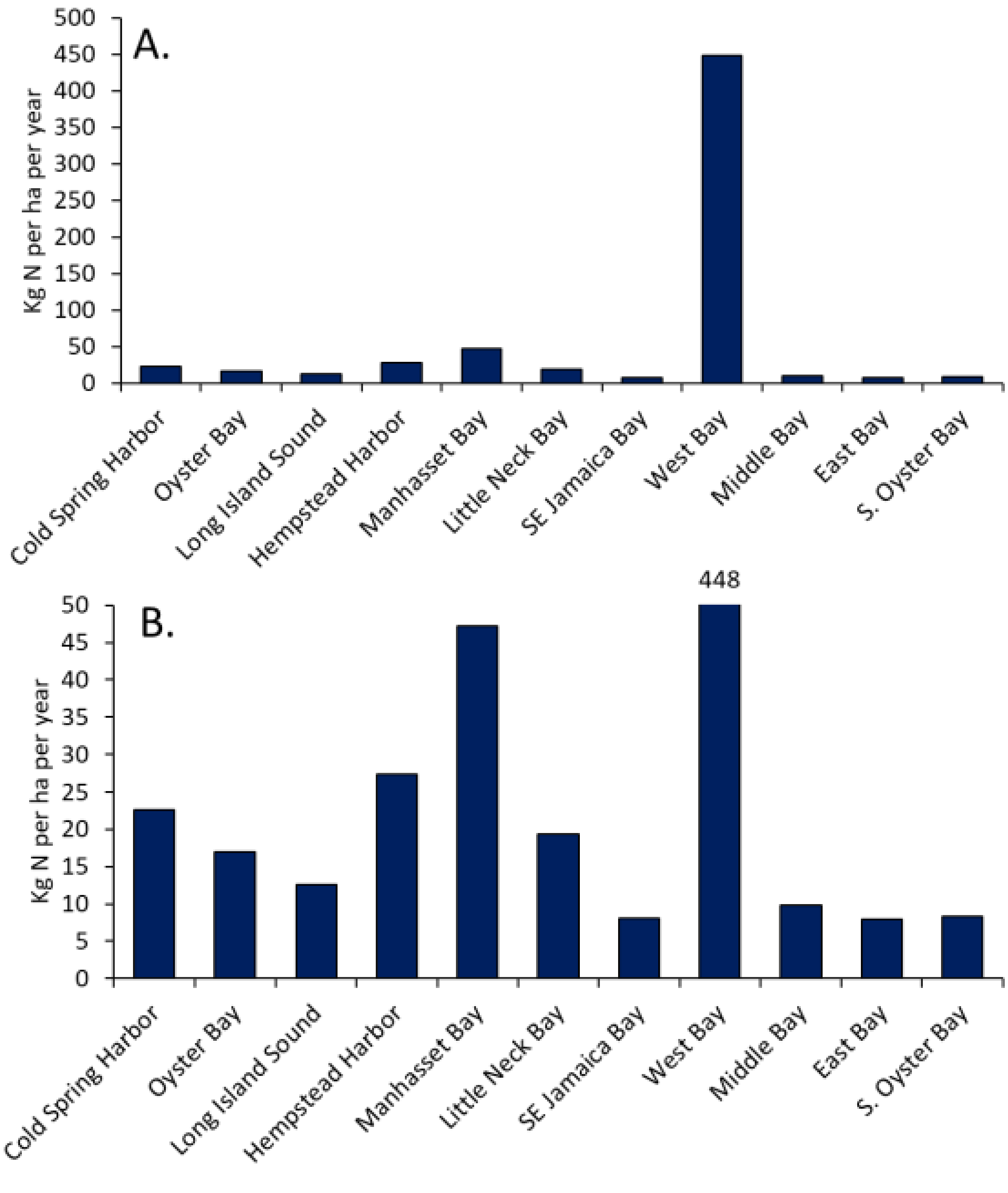


Figure 19. A. Total nitrogen load per hectare from each subwatershed in kilograms N per year. **B.** Total nitrogen load from each subwatershed in kilograms N per year, X-axis is cut-off to provide resolution of all sites; the West Bay N load is 448 kg N per hectare year.



For most NLM assessments, N loads to individual watersheds or subwatershed are considered. Given that the areas of each water body in this study was known, the rate of atmospheric deposition of N falling directly on each water body was also considered. The absolute N load from this source ranged from about 2,900 to 11,500 kg N per year for West Bay and South Oyster Bay, respectively (Figure 20A). These amounts were generally small, from 2 – 12% of the total N load of each waterbody, save for West Bay where is was 0.1% (Figure 20B). For the remainder of the study, the watershed derived N will only be considered.

Across all of Nassau County, fertilizer represented 1% (West Bay) – 51% (South Oyster Bay) of the total N load, with an average of about 30% (Figure 20). About two-thirds of the fertilizer load in Nassau County emanates from residential use (62%) whereas most of the remainder comes from golf courses and parks (37%; Figure 21). There is only one farm remaining in Nassau County and most of its N load is within the Hempstead Harbor watershed, although it is less than 2% of the total fertilizer load even within this watershed (Figure 21). It has been proposed by NYSDEC that the household fertilizer application rates on Long Island should be reduced from 1 pound per 1,000 square feet per application to 0.6 pounds per 1,000 square feet (LINAP, 2019). Doing so would reduce the total N loading rates across Nassau County from 3 – 16% except in West Bay where 98% of the load comes from sewage (Figure 22). The impacts would be the largest for many of the south shore subwatersheds where household fertilizer is a large portion of the total N loads. For example, this practice would reduce the N loads to Middle Bay, East Bay, and South Oyster Bay by 13 – 16% (Figure 22). It would have a lesser impact on the north shore (< 10%; Figure 22).

The model, NLM, ascribes N loads to three main categories: wastewater, fertilizer, and atmospheric deposition. Since wastewater is discharged below the ground or into surface waters and since fertilizer is applied to vegetative surfaces, surface runoff within NLM comes exclusively from atmospheric deposition. While the surface run-off component is traditionally not separated from the total N load in NLM, for this study, an effort was made to separate N from run-off given that once such N enters the water table, there is little N attenuation within the sandy aquifer of Long Island (Kinney and Valiela, 2011; SCSWS, 2019). Hence, to isolate N that is loaded to surface waters as a consequence of surface run-off, the sum of atmospheric N landing on impervious surfaces including roads, driveways, sidewalks, roofs, parking lots, and other impervious surfaces was summed and deemed N load from run-off. This represented about one-third of atmospheric deposition on the north shore, except for Little Neck Bay (Figure 23A). For Little Neck Bay and the entire south shore, run-off represented 62-83% of the atmospheric deposition N load, reflecting the more urbanized nature of watersheds on the south shore and along Little Neck Bay (Figure 23A). When compared to the total N load for each watershed, the load from run-off was 2-4% on the north shore, save for Little Neck Bay, and 15 – 24% on the south shore, save for West Bay where sewage is 98% of the total N load (Figure 23B).

Figure 20. A. Total nitrogen load from each subwatershed in kilograms N per year with atmospheric deposition to the waterbody added as a separate load. **B.** Relative contribution of fertilizer, sewage treatments plants, septic systems, atmospheric deposition, and pets with atmospheric deposition to the waterbody added as a separate load.

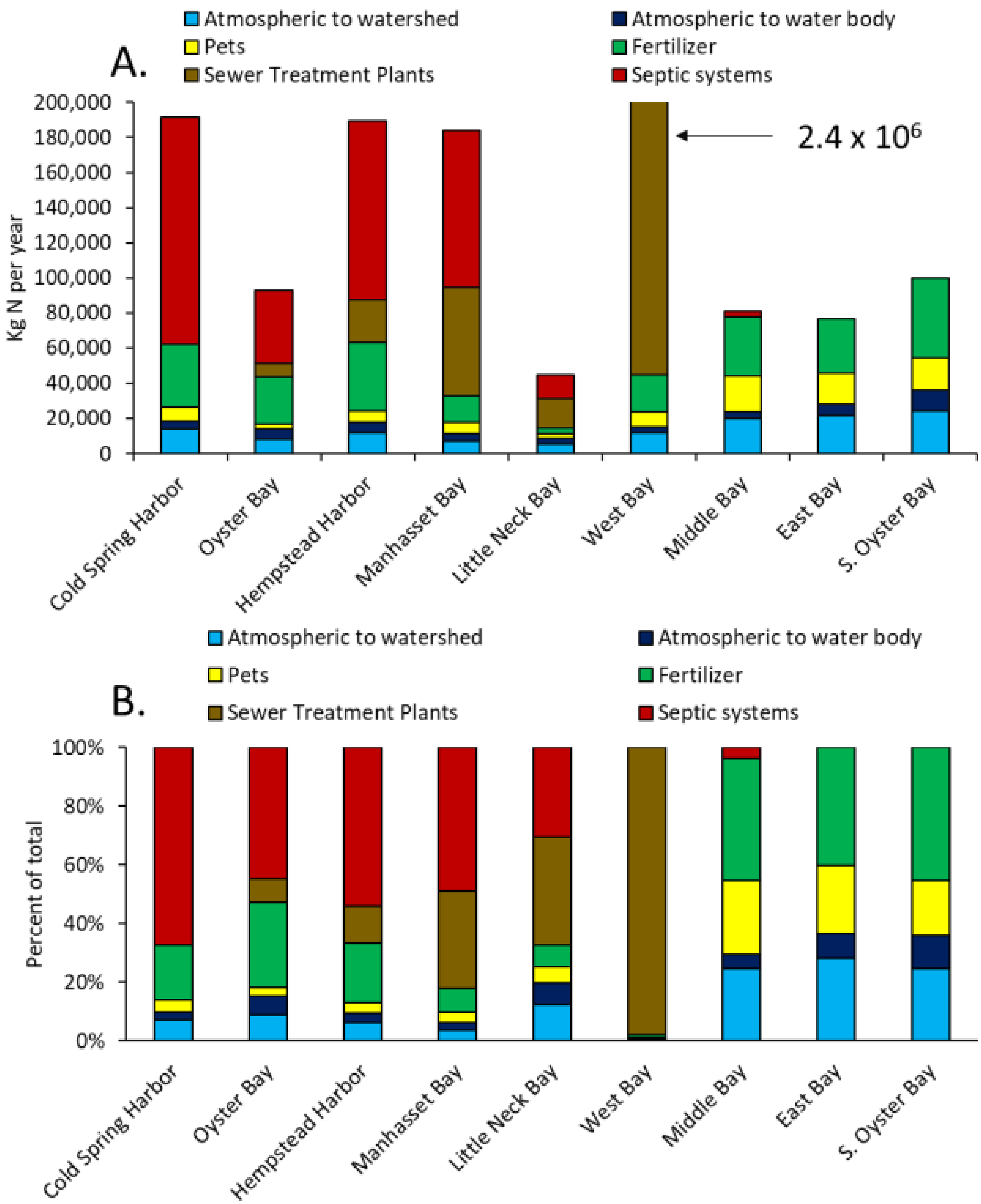


Figure 21. Relative contribution of residential lawns, agriculture, parks, and golf course to the total fertilizer N loading to each subwatershed.

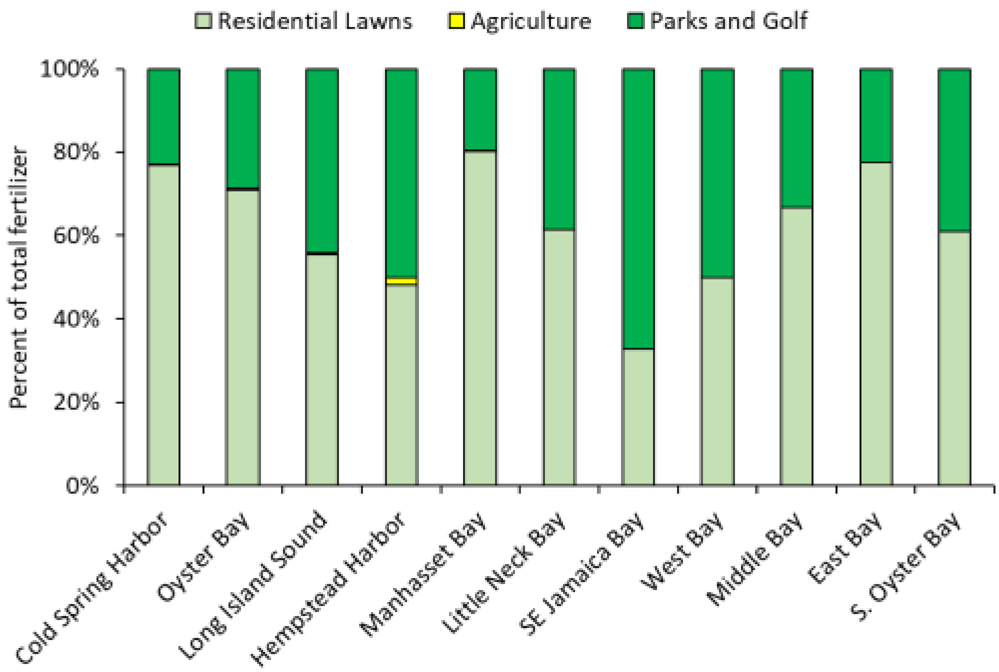


Figure 22. Reduction in total N load achieved by reducing the recommended N fertilizer rate from 1 lb per 1,000 square feet per application to 0.6 1 lb per 1,000 square feet per application.

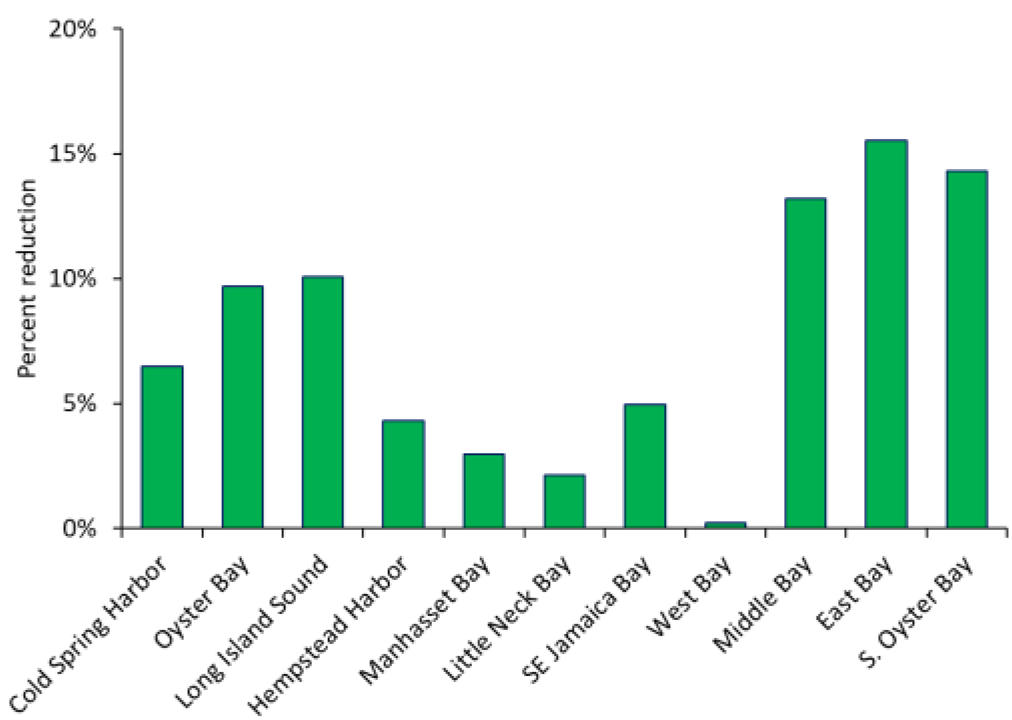
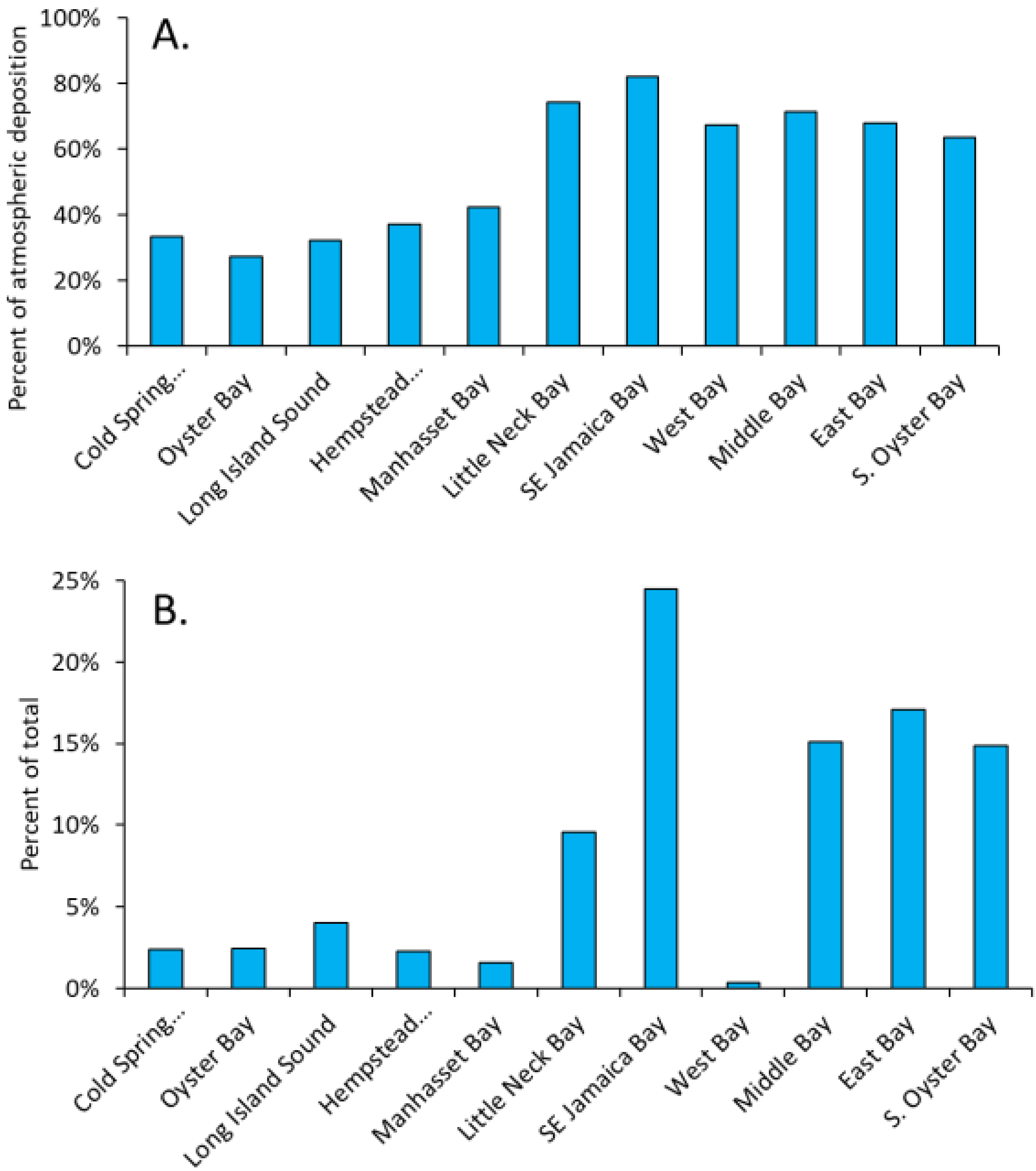


Figure 23. **A.** Fraction of atmospheric deposition N load emanating from surface runoff. **B.** Fraction of total N load emanating from surface runoff.



Recently, a plan has been put forth to utilize a subsurface aqueduct pipeline running along Sunrise Highway to divert sewage from the Bay Park sewage treatment plant to the Cedar Creek sewage treatment plant. The aqueduct was constructed in 1908 to deliver drinking water from Long Island to New York City and was last used in 1966. The action of diverting the South Shore Water Reclamation Facility sewage would have significant implications for the West Bay subwatershed. First, it would reduce the total N load by 2 x

10^6 kg N per year, transforming West Bay from the subwatershed with the highest N load in Nassau County to one with 90% lower N loading (Figure 24A). The relative contributions of the other sources to West Bay would be 85% from the remaining STPs, 8% from fertilizer, 5% from atmospheric deposition, and 3% from pets without the STP load (Figure 24B). The Long Beach sewage treatment plant becomes the most important N source under this scenario as it contributes 1.6 x 10^5 kg N per year (Figure 24B). Recent negotiations between Nassau County and the City of Long Beach has resulted in the execution of an Inter Municipal Agreement whereby the Long Beach Sewage Treatment Plant would be converted to a pumping station. The sewage from the City would then be diverted to the South Shore Water Reclamation Facility plant for treatment and eventual discharge to the Cedar Creek plants ocean outfall. Collectively, these projects would transform West Bay into one of the lowest N loading regions in Nassau County. Construction plans for these projects are rapidly developing with projected completion by end of 2022.

4.2 Residence times

Residence times varied across estuaries. Several of the north shore harbors have short residence times including Little Neck Bay, Manhasset Harbor, Cold Spring Harbor, and Hempstead Harbor, which had 37% flushing times of 1, 2.1, 3.5, 3.2 days, respectively. In contrast, South Oyster Bay, West Bay, and Oyster Bay had some of the longer flushing times at 8, 9 and 14 days (Fig 25; Table 4). While 37% is most commonly used to describe estuarine flushing times, the Suffolk County subwatersheds study used 10% flushing times. Interestingly, the relative differences in flushing times changes at the 10% cut-off. For example, while the shortest flushing time was still Little Neck Bay (3 days), the next two shortest were Middle Bay (10 days) and East Bay (11 days; Table 3). Some other systems had extremely long 10% flushing times including Hempstead Harbor, West Bay, Cold Spring Harbor, and Oyster Bay which had 10% flushing times of 22, 22, 34, and 59 days, respectively (Table 3).

4.3 Water Quality Data

Bottom dissolved oxygen

NYSDEC has a chronic DO standard of 4.8 mg L^{-1} and an acute DO standard of 3.0 mg L^{-1}. Bottom dissolved oxygen concentrations of the north shore sites were generally greater than the north shore reference site (4.0 mg L^{-1}), with the exception of Western Long Island Sound, which had an average concentration of 4.0 mg L^{-1} (Figure 26). The highest bottom dissolved oxygen concentrations occurred at Oyster Bay Harbor and Hempstead Harbor at 5.7 and 5.1 mg L^{-1}, respectively. Concentrations at Oyster Bay Harbor were significantly higher than at all sites (Figure 26; Tukey HSD; $p < 0.05$ for all; Table 4). Concentrations at Hempstead Harbor were significantly higher than all sites except Cold Spring Harbor and Little Neck Bay (Figure 26; Tukey HSD; $p < 0.05$ for all; Table 4). The neighbor waterbody to Oyster Bay Harbor, Cold Spring Harbor, had a lower dissolved oxygen concentration of 4.7 mg L^{-1}, which was significantly higher than at the north shore reference site (Figure 26; Tukey HSD; $p < 0.05$; Table 4) but not western Long Island Sound, Little Neck Bay or Manhasset Bay (Tukey HSD; $p > 0.05$ for all; Table 5). Little Neck Bay and Manhasset Bay had concentrations of 4.8 and 4.3 mg L^{-1}, respectively (Figure 26) and were not significantly different from each other (Tukey HSD; $p > 0.05$; Table 4).

Figure 24. Re-evaluation of N loads to south shore subwatersheds considering the diversion of sewage from the Bay Park STP that discharges in West Bay to the Cedar Creek STP that discharges to the ocean expressed as **A.** Absolute N loads, and **B.** Relative N loads per sources

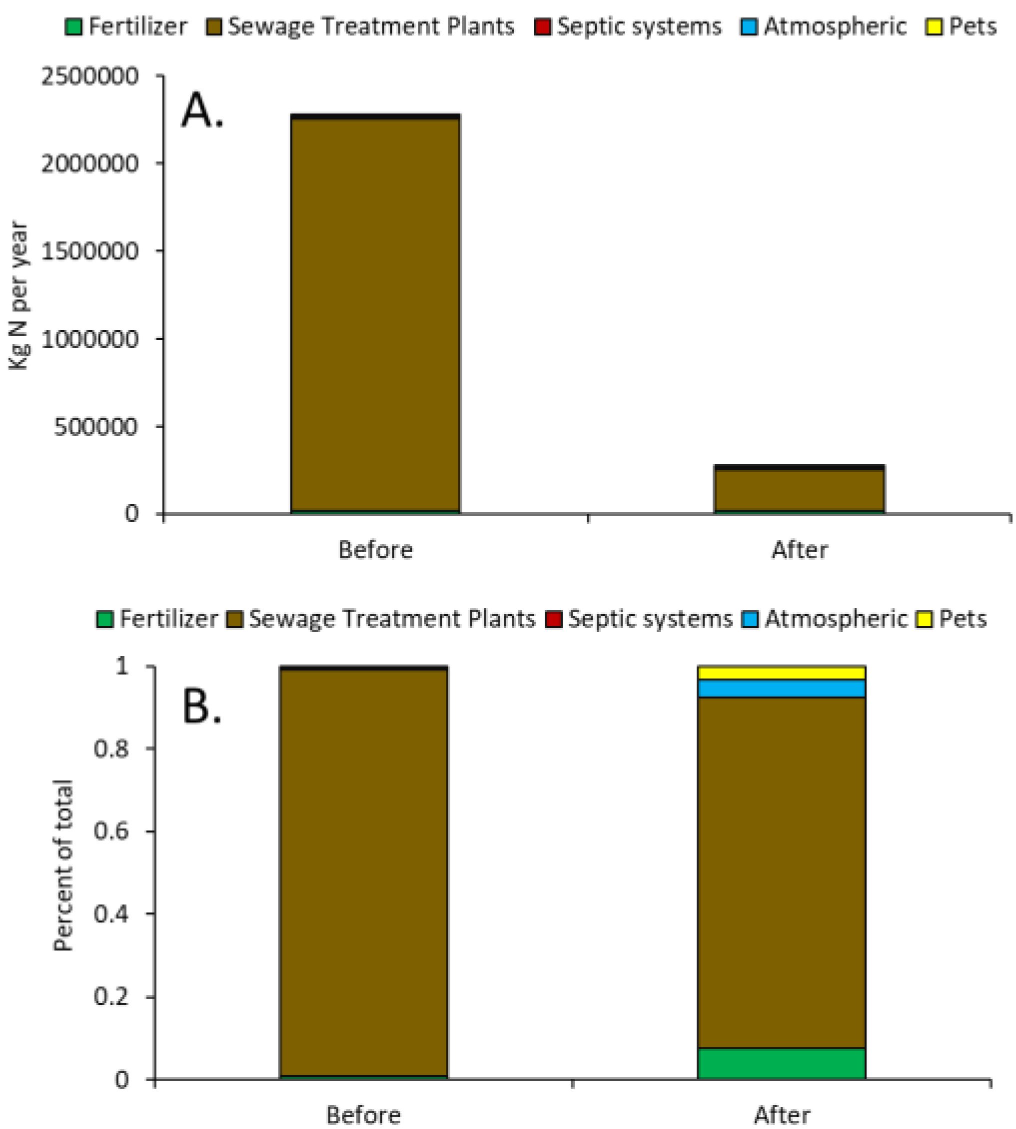
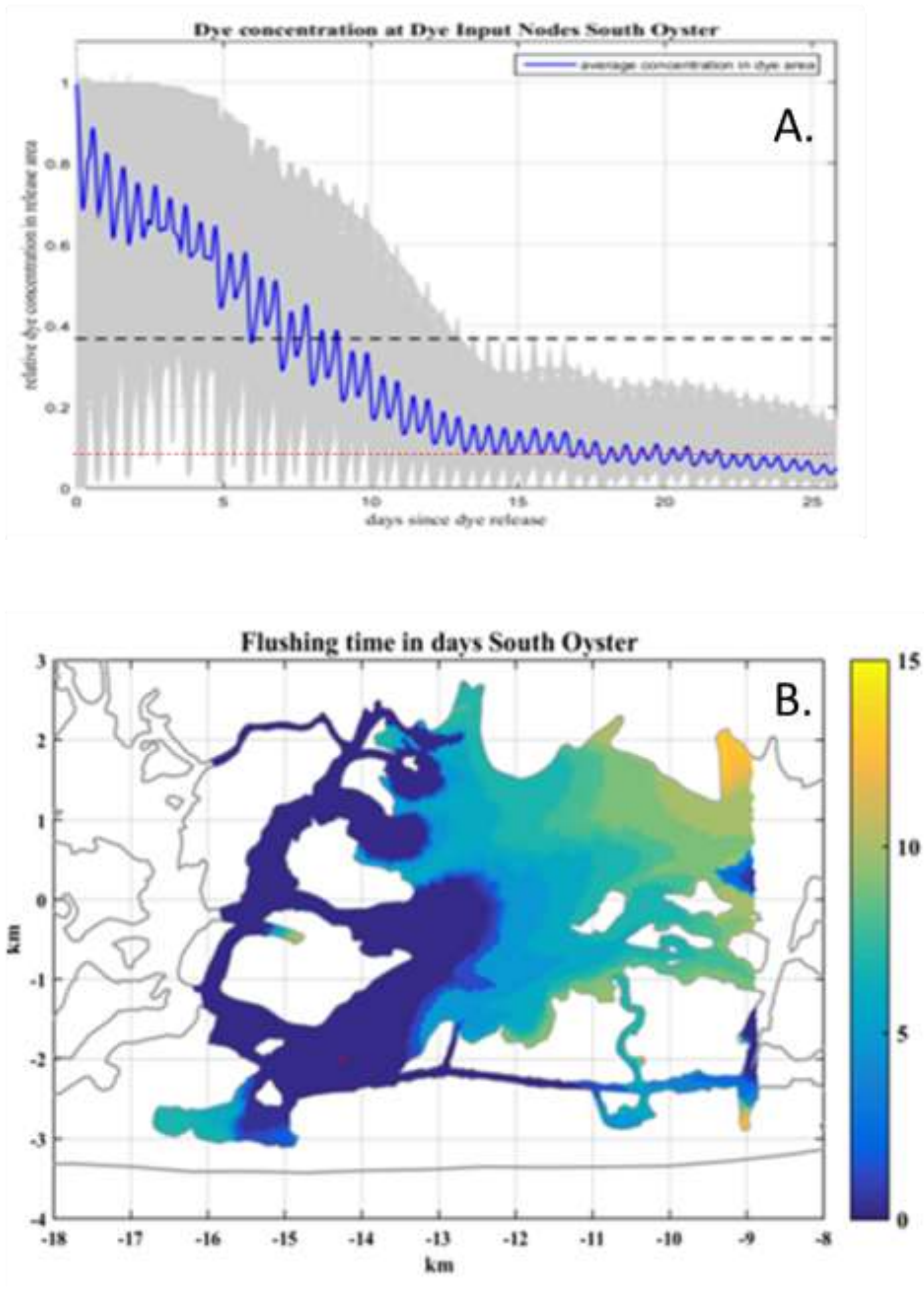


Figure 25. Example of N residence times for all of South Oyster Bay expressed **A.** as a dye release experiment with the 37% and 10% thresholds noted., and **B.** A map of the 37% residence times.



On the south shore, the bottom dissolved oxygen concentrations of all sites were lower than the south shore reference site (7.8 mg L^{-1}), except for East Bay due to a lack of data (Figure 26). All south shore sites had dissolved oxygen concentrations significantly lower than at the south shore reference site (Tukey HSD; $p < 0.05$ for all; Table 4). The lowest of these values was at Hewlett/West Bay, which had a dissolved oxygen concentration of 2.8 mg L^{-1} and was significantly lower than at all other south shore sites

(Tukey HSD; $p < 0.05$ for all; Figure 26; Table 4). Concentrations in Eastern Jamaica Bay, Middle Bay, and South Oyster Bay were 5.4, 6.0, and 6.8 mg L^{-1}, respectively (Figure 26). The concentrations at South Oyster Bay were significantly higher than at Middle Bay and Eastern Jamaica Bay (Tukey HSD; $p < 0.05$ for both; Table 4). Concentrations at Middle Bay were significantly higher than at Eastern Jamaica Bay (Tukey HSD; $p < 0.05$; Table 4).

Figure 26. Summer (June through September) surface and bottom dissolved oxygen concentrations (mg L^{-1}) at various waterbodies across Nassau County, Long Island, NY. References sites are in orange while Nassau water bodies are in red. Upper and lower dashed lines indicate chronic (4.8 mg L^{-1}) and acute (mg L^{-1}) DO standards for marine water bodies set by NYSDEC.

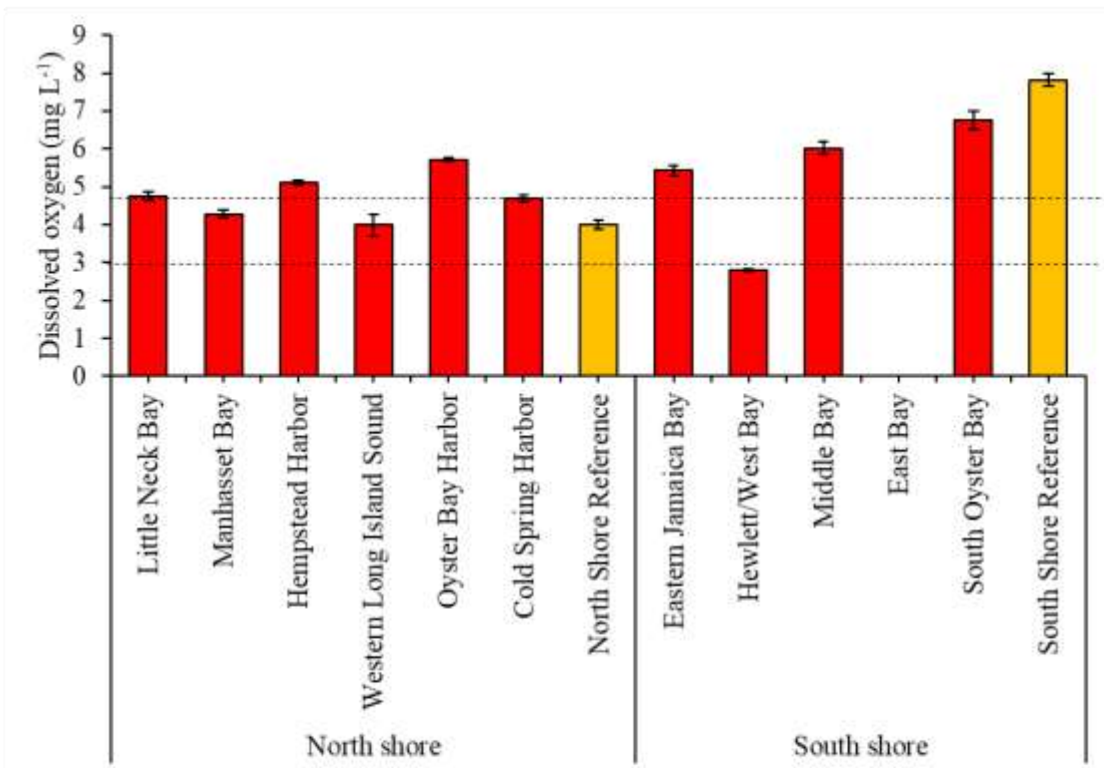


Table 4. Tukey Honest Significant Difference tests for comparison of summer (June through September) bottom dissolved oxygen concentrations at various waterbodies across the north and south shores of Nassau County, Long Island, NY. Asterisks (*) next to p-values indicate significant difference ($p < 0.05$).

North Shore				
Comparison	**Difference**	**Lower**	**Upper**	**P-value**
Hempstead vs. Cold Spring	0.398	0.098	0.697	0.002*
Long Island Sound vs. Cold Spring	-0.769	-1.682	0.144	0.165
Little Neck vs. Cold Spring	0.076	-0.452	0.603	1.000
Manhasset vs. Cold Spring	-0.396	-0.799	0.007	0.058
N. Shore reference vs. Cold Spring	-0.680	-1.118	-0.242	<0.001*
Oyster Bay vs. Cold Spring	1.040	0.734	1.346	<0.001*
Long Island Sound vs. Hempstead	-1.166	-2.060	-0.272	0.002*
Little Neck vs. Hempstead	-0.322	-0.816	0.172	0.465
Manhasset vs. Hempstead	-0.794	-1.151	-0.436	<0.001*
N. Shore reference vs. Hempstead	-1.078	-1.474	-0.681	<0.001*
Oyster Bay vs. Hempstead	0.642	0.399	0.885	<0.001*
Little Neck vs. Long Island Sound	0.844	-0.150	1.838	0.157
Manhasset vs. Long Island Sound	0.373	-0.561	1.307	0.903
N. Shore reference vs. Long Island Sound	0.089	-0.861	1.038	1.000
Oyster Bay vs. Long Island Sound	1.809	0.913	2.705	<0.001*
Manhasset vs. Little Neck	-0.471	-1.034	0.091	0.170
N. Shore reference vs. Little Neck	-0.756	-1.344	-0.167	0.003*
Oyster Bay vs. Little Neck	0.964	0.467	1.462	<0.001*
N. Shore reference vs. Manhasset	-0.284	-0.764	0.196	0.584
Oyster Bay vs. Manhasset	1.436	1.073	1.799	<0.001*
Oyster Bay vs. N. Shore reference	1.720	1.319	2.121	<0.001*
South Shore				
Comparison	**Difference**	**Lower**	**Upper**	**P-value**
South Oyster Bay vs. Middle Bay	3.508	3.099	3.917	<0.001*
S. Shore reference vs. Middle Bay	5.020	4.262	5.777	<0.001*
Hewlett/West vs. Middle Bay	2.634	2.174	3.094	<0.001*
S. Shore reference vs. South Oyster Bay	1.512	0.661	2.363	<0.001*
Hewlett/West vs. South Oyster Bay	-0.874	-1.476	-0.271	0.001
Hewlett/West vs. S. Shore reference	-2.386	-3.263	-1.509	<0.001*

Secchi disc depth

The NYS seagrass task force indicated that Secchi disc depths of 2 meters or greater are needed for the growth and maintenance of the dominant eelgrass on Long Island, *Zostera marina* (NYSDEC, 2009). On the north shore, Secchi depths at the reference site, Western Long Island Sound, Manhasset Bay, and Little Neck Bay were 2.6, 2.9, 2.9, and 2.6 m (Figure 27). Overall, there were no significant differences in Secchi depths between the north shore reference site, western Long Island Sound, Manhasset Bay, and Little Neck Bay (Tukey HSD; $p > 0.05$ for all; Table 4). Secchi depths at Hempstead Harbor, Oyster Bay Harbor, and Cold Spring Harbor were 1.2, 1.3, and 1.4 m, respectively (Figure 27). There were no significant differences in Secchi depths between Hempstead Harbor, Oyster Bay Harbor, and Cold Spring Harbor (Tukey HSD; $p > 0.05$ for all; Table 6). Secchi depths at Little Neck Bay, Manhasset Bay, and western Long Island Sound were each significantly higher than at Hempstead Harbor and Oyster Bay Harbor (Tukey HSD; $p < 0.05$ for all;

Table 5) but not Cold Spring Harbor due to variability in the data (Tukey HSD; $p > 0.05$; Table 5).

Comparatively, the Secchi depths on the south shore varied by site. Eastern Jamaica Bay and the south shore reference site had Secchi depths of 3.8 and 5.1 m, respectively, while Hewlett/West Bay, Middle Bay, East Bay, and South Oyster Bay had Secchi depths of 1.8, 1.9, 2.2, and 1.8 m, respectively (Figure 27). All sites had Secchi depths significantly lower than at the south shore reference site (Tukey HSD; $p < 0.05$ for all; Table 5). Additionally, all sites, save for the reference site, had significantly lower Secchi depths than at Eastern Jamaica Bay (Tukey HSD; $p < 0.05$ for all; Table 5). East Bay had significantly higher Secchi depths than at Hewlett/West Bay, Middle Bay, and South Oyster Bay (Tukey HSD; $p < 0.05$ for all; Table 5). South Oyster Bay had significantly lower depths than at Middle Bay (Tukey HSD; $p < 0.05$; Table 5) but significantly higher than at Hewlett/West Bay (Tukey HSD; $p < 0.05$; Table 5). There was no significant difference in Secchi depth between Hewlett/West Bay and Middle Bay (Tukey HSD; $p > 0.05$; Table 5).

Figure 27. Summer (June through September) secchi disk depths (m) at various waterbodies across Nassau County, Long Island, NY. References sites are in light blue while Nassau water bodies are in dark blue.

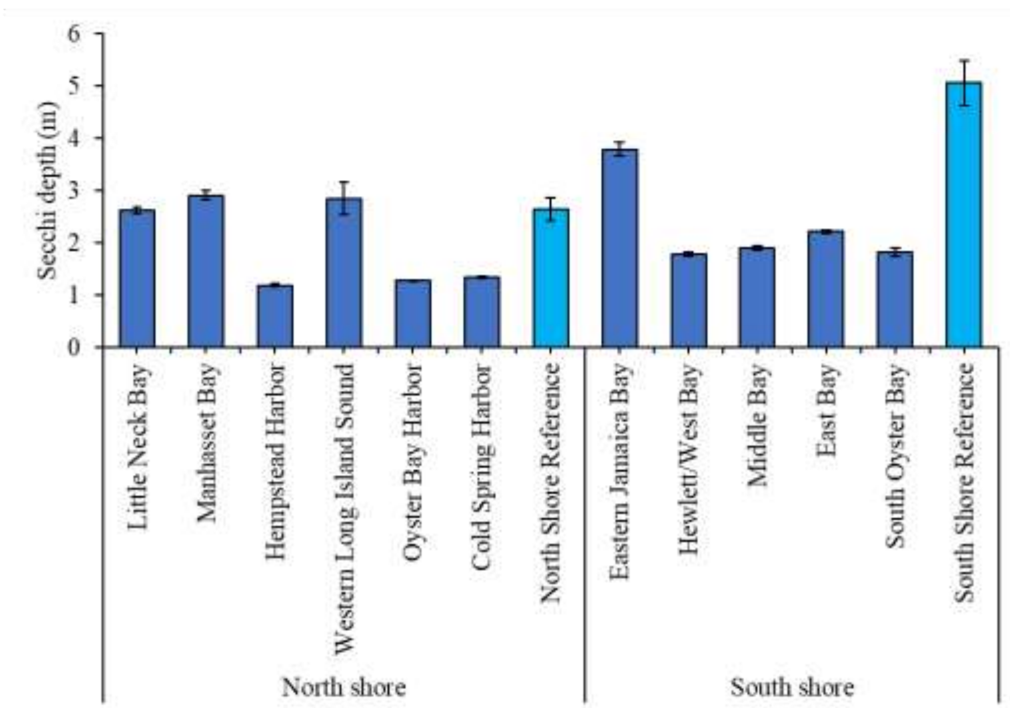


Table 5. Tukey Honest Significant Difference tests for comparison of summer (June through September) secchi disk depths at various waterbodies across the north and south shores of Nassau County, Long Island, NY. Asterisks (*) next to p-values indicate significant difference ($p < 0.05$).

North Shore				
Comparison	**Difference**	**Lower**	**Upper**	**P-value**
Hempstead vs. Cold Spring	0.398	0.098	0.697	0.002*
Long Island Sound vs. Cold Spring	-0.769	-1.682	0.144	0.165
Long Island Sound vs. Hempstead	-1.166	-2.060	-0.272	0.002*
Little Neck vs. Cold Spring	0.076	-0.452	0.603	1.000
Little Neck vs. Hempstead	-0.322	-0.816	0.172	0.465
Little Neck vs. Long Island Sound	0.844	-0.150	1.838	0.157
Manhasset vs. Cold Spring	-0.396	-0.799	0.007	0.058
Manhasset vs. Hempstead	-0.794	-1.151	-0.436	<0.001*
Manhasset vs. Long Island Sound	0.373	-0.561	1.307	0.903
Manhasset vs. Little Neck	-0.471	-1.034	0.091	0.170
N. Shore reference vs. Cold Spring	-0.680	-1.118	-0.242	<0.001*
N. Shore reference vs. Hempstead	-1.078	-1.474	-0.681	<0.001*
N. Shore reference vs. Long Island Sound	0.089	-0.861	1.038	1.000
N. Shore reference vs. Little Neck	-0.756	-1.344	-0.167	0.003*
N. Shore reference vs. Manhasset	-0.284	-0.764	0.196	0.584
Oyster Bay vs. Cold Spring	1.040	0.734	1.346	<0.001*
Oyster Bay vs. Hempstead	0.642	0.399	0.885	<0.001*
Oyster Bay vs. Long Island Sound	1.809	0.913	2.705	<0.001*
Oyster Bay vs. Little Neck	0.964	0.467	1.462	<0.001*
Oyster Bay vs. Manhasset	1.436	1.073	1.799	<0.001*
Oyster Bay vs. N. Shore reference	1.720	1.319	2.121	<0.001*
South Shore				
Comparison	**Difference**	**Lower**	**Upper**	**P-value**
Jamaica Bay vs. East Bay	1.576	1.294	1.857	<0.001*
Middle Bay vs. East Bay	-0.308	-0.503	-0.113	<0.001*
South Oyster Bay vs. East Bay	-1.554	-2.095	-1.013	<0.001*
S. Shore reference vs. East Bay	2.839	2.330	3.347	<0.001*
Hewlett/West vs. EB	-0.432	-0.606	-0.257	<0.001*
Middle Bay vs. Jamaica Bay	-1.884	-2.164	-1.604	<0.001*
South Oyster Bay vs. Jamaica Bay	-3.130	-3.707	-2.552	<0.001*
S. Shore reference vs. Jamaica Bay	1.263	0.716	1.810	<0.001*
Hewlett/West vs. Jamaica Bay	-2.007	-2.274	-1.741	<0.001*
South Oyster Bay vs. Middle Bay	-1.246	-1.786	-0.705	<0.001*
S. Shore reference vs. Middle Bay	3.147	2.639	3.655	<0.001*
Hewlett/West vs. Middle Bay	-0.123	-0.296	0.050	0.323
S. Shore reference vs. South Oyster Bay	4.393	3.677	5.109	<0.001*
Hewlett/West vs. South Oyster Bay	1.122	0.589	1.656	<0.001*
Hewlett/West vs. S. Shore reference	-3.270	-3.771	-2.770	<0.001*

Chlorophyll *a*

Several federal agencies have declared that chlorophyll *a* levels exceeding 20 µg L^{-1} leads to eutrophication of marine water bodies (Bricker et al., 1999, 2008). On the north shore, chlorophyll *a* concentrations were comparatively higher at all locations, except for Oyster Bay Harbor, than the north shore reference site (~17.8 µg L^{-1}; Figure 16). Oyster Bay Harbor had the lowest chlorophyll *a* concentration ~10 µg L^{-1} while Western Long

Island Sound had the highest (28.2 µg L^{-1}). Cold Spring Harbor, the neighbor waterbody to Oyster Bay Harbor, had double the chlorophyll *a* concentrations (~20 µg L^{-1}; Figure 28). Concentrations at Little Neck Bay, Manhasset Bay, and Hempstead Harbor were 22.8, 19.4, and 24.4 µg L^{-1}, respectively (Figure 28). Due to variability, the only significant differences between sites was that chlorophyll *a* was significantly lower at Oyster Bay Harbor than at Little Neck Bay and Hempstead Harbor (Tukey HSD; $p < 0.05$ for both; Table 6). For all other north shore sites, there was no significant differences in chlorophyll *a* concentrations (Tukey HSD; $p > 0.05$ for all; Table 6).

The south shore sites had comparatively lower chlorophyll *a* concentrations for most locations. The reference site for the south shore only had a concentration of 2.4 µg L^{-1}, while Eastern Jamaica Bay, Middle Bay, and South Oyster Bay had concentrations at 7.5, 8.2, and 5.3 µg L^{-1}, respectively (Figure 28). The highest chlorophyll *a* concentrations on the south shore occurred at Hewlett/West Bay (14.5 µg L^{-1}) and East Bay (10.4 µg L^{-1}) (Figure 28). Concentrations were significantly higher at East Bay, Middle Bay, and Hewlett/West Bay than at the south shore reference site (Tukey HSD; $p < 0.05$ for all; Table 6). Concentrations at Hewlett/West Bay were significantly higher than at South Oyster Bay, Middle Bay, and Eastern Jamaica Bay (Tukey HSD; $p < 0.05$ for all; Table 6), but not East Bay (Tukey HSD; $p > 0.05$; Table 6). For all other sites, there were no significant differences in chlorophyll *a* concentrations (Tukey HSD; $p > 0.05$ for all; Table 6). Across all sites and locations, there was a significant inverse correlation between concentrations of chlorophyll *a* and dissolved oxygen (p<0.05; Figure 29).

Figure 28. Summer (June through September) chlorophyll-a concentrations (µg L^{-1}) at various waterbodies across Nassau County, Long Island, NY. References sites are in light green while Nassau water bodies are in dark green.

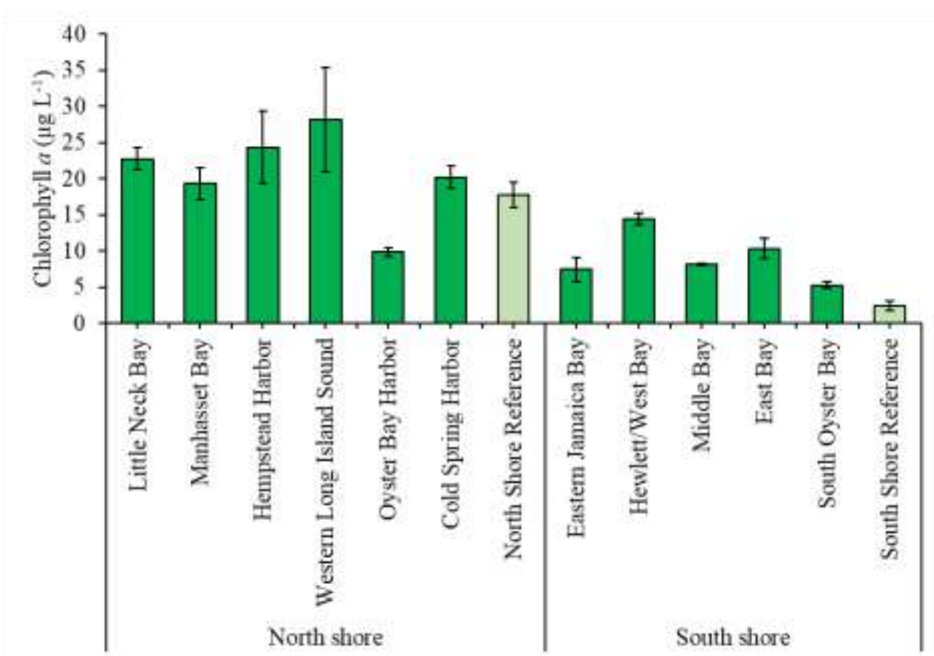
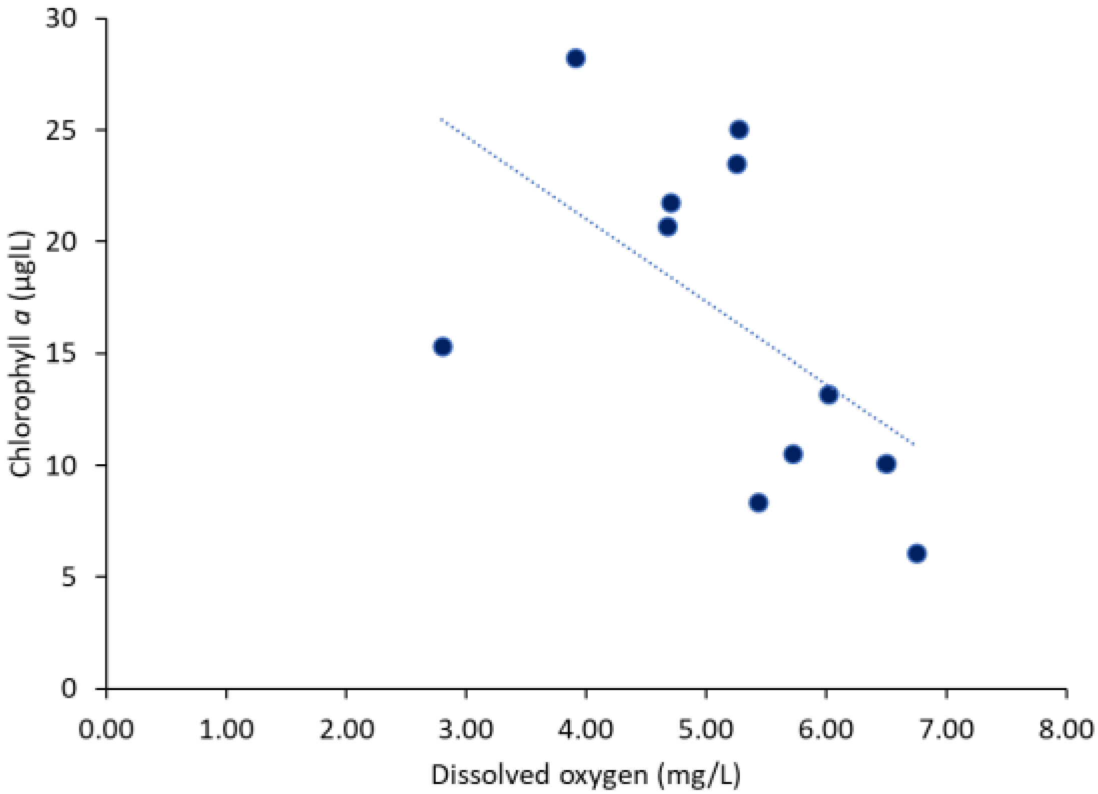


Table 6. Tukey Honest Significant Difference tests for comparison of summer (June through September) chlorophyll-*a* concentrations at various waterbodies across the north and south shores of Nassau County, Long Island, NY. Asterisks (*) next to p-values indicate significant difference ($p < 0.05$).

North Shore				
Comparison	**Difference**	**Lower**	**Upper**	**P-value**
Hempstead vs. Cold Spring	4.151	-7.982	16.284	0.951
Long Island Sound vs. Cold Spring	8.012	-11.610	27.634	0.891
Little Neck vs. Cold Spring	2.520	-6.957	11.996	0.986
Manhasset vs. Cold Spring	-0.884	-10.485	8.717	1.000
N. Shore reference vs. Cold Spring	-2.576	-12.657	7.504	0.989
Oyster Bay vs. Cold Spring	-10.362	-22.428	1.704	0.147
Long Island Sound vs. Hempstead	3.861	-16.047	23.770	0.998
Little Neck vs. Hempstead	-1.631	-11.688	8.425	0.999
Manhasset vs. Hempstead	-5.035	-15.208	5.139	0.766
N. Shore reference vs. Hempstead	-6.727	-17.354	3.900	0.499
Oyster Bay vs. Hempstead	-14.513	-27.039	-1.986	0.012*
Little Neck vs. Long Island Sound	-5.493	-23.903	12.918	0.975
Manhasset vs. Long Island Sound	-8.896	-27.371	9.578	0.788
N. Shore reference vs. Long Island Sound	-10.588	-29.316	8.140	0.635
Oyster Bay vs. Long Island Sound	-18.374	-38.242	1.493	0.091
Manhasset vs. Little Neck	-3.404	-10.194	3.386	0.755
N. Shore reference vs. Little Neck	-5.096	-12.548	2.357	0.401
Oyster Bay vs. Little Neck	-12.882	-22.857	-2.906	0.003*
N. Shore reference vs. Manhasset	-1.692	-9.302	5.917	0.995
Oyster Bay vs. Manhasset	-9.478	-19.572	0.616	0.082
Oyster Bay vs. N. Shore reference	-7.786	-18.337	2.765	0.306
South Shore				
Comparison	**Difference**	**Lower**	**Upper**	**P-value**
Jamaica Bay vs. East Bay	-2.899	-8.797	2.999	0.726
Middle Bay vs. East Bay	-2.167	-7.527	3.192	0.859
South Oyster Bay vs. East Bay	-5.051	-11.015	0.913	0.151
S. Shore reference vs. East Bay	-7.931	-14.899	-0.964	0.015*
Hewlett/West vs. East Bay	4.090	-1.343	9.522	0.263
Middle Bay vs. Jamaica Bay	0.732	-1.836	3.300	0.965
South Oyster Bay vs. Jamaica Bay	-2.152	-5.818	1.514	0.549
S. Shore reference vs. Jamaica Bay	-5.032	-10.172	0.107	0.059
Hewlett/West vs. Jamaica Bay	6.989	4.272	9.705	<0.001*
South Oyster Bay vs. Middle Bay	-2.883	-5.601	-0.166	0.030*
S. Shore reference vs. Middle Bay	-5.764	-10.276	-1.252	0.004*
Hewlett/West vs. Middle Bay	6.257	5.105	7.409	<0.001*
S. Shore reference vs. South Oyster Bay	-2.881	-8.096	2.335	0.615
Hewlett/West vs. South Oyster Bay	9.141	6.282	11.999	<0.001*
Hewlett/West vs. S. Shore reference	12.021	7.423	16.619	<0.001*

Figure 29. Correlation between mean summer chlorophyll *a* and dissolved oxygen levels at various waterbodies across Nassau County, Long Island, NY ($p<0.05$).



4.4 Tier priority areas for N load mitigation

The general water quality conditions of the 11 waterbodies considered were ranked and compared to state and federal guidelines for dissolved oxygen, chlorophyll *a*, and Secchi disc depth. Regarding dissolved oxygen, West Bay had the lowest mean summer dissolved oxygen level at 2.8 mg L^{-1}, which is below the acute minimum standard set by NYSDEC of 3.0 mg L^{-1} (Table 7). Three other north shore sites, western Long Island Sound, Cold Spring Harbor, and Manhasset Bay all had mean summer dissolved oxygen level below the NYSDEC chronic standard of 4.8 mg L^{-1} (Table 7; NYSDEC, 2007). Regarding Secchi disc depth, Hempstead Harbor has the shallowest summer mean Secchi disc depth of 1.04 meters (Table 8). Six other locations including Oyster Bay, Cold Spring Harbor, Manhasset Bay, West Bay, Middle Bay, and South Oyster Bay all had summer mean Secchi disc depths of less than two meters (Table 8), the threshold recommended by the NYS seagrass task force as ideal for seagrass growth in estuaries (NYSDEC, 2009). With regard to summer chlorophyll *a* concentrations, levels on the north shore were generally higher than the south shore (Table 9). For example, western Long Island Sound, Hempstead Harbor, Little Neck Bay, Manhasset Bay, and Cold Spring Harbor all had means above 20 µg L^{-1} (Table 9), the eutrophic threshold set by both NOAA and EPA

(Bricker et al., 1999, 2008). The remaining sites, however, had levels above 5 µg L^{-1}, a level thought to be desirable for maximizing food present for food webs but assuring an absence of organic carbon overloading that can promote hypoxia and light occlusion from high levels of suspended phytoplankton (Table 9; Bricker et al., 1999, 2008).

Table 7. Ranking of water bodies based on mean summer dissolved oxygen levels. Red indicates sites below the acute dissolved oxygen standard of 3.0 mg/L, whereas yellow values indicates sites above the acute dissolved oxygen standard of 3.0 mg/L but below the chronic dissolved oxygen standard of 4.8 mg/L, and green are sites that were always above both standards.

Average summer conditions	DO (mg/L)	Rank
Hewlett/West Bay	2.80	1
Western Long Island Sound	3.91	2
Cold Spring Harbor	4.68	3
Manhasset Bay	4.70	4
Little Neck Bay	5.25	5
Hempstead Harbor	5.27	6
Jamaica Bay (East)	5.43	7
Oyster Bay Harbor	5.72	8
Middle Bay	6.02	9
East Bay	6.50	10
South Oyster Bay	6.75	11

When considering and giving equal weight to all three water quality parameters, Hempstead Harbor, West Bay, and Cold Spring Harbor were ranked with the lowest water quality (Table 10). Consistent with this finding, of the 11 water bodies considered here, these are also the only three locations that have hosted blooms of harmful algal blooms during the past decade (Table 10). Specifically, all three locations experience dense blooms of *Dinophysis*, *Heterosigma*, and *Prorocentrum* on an annual basis (Table 10; Gobler Lab, personal observation 2014-2019) with the levels of *Dinophysis* being elevated enough to lead to the accumulation of the toxin okadaic acid in shellfish in Cold Spring Harbor (Hattenrath-Lehmann et al., 2018). In addition, densities of the saxitoxin-producing dinoflagellate, *Alexandrium* have exceeded 100 cells per L^{-1} in West Bay and Hempstead Harbor (Gobler Lab, personal observation 2008-2019), a density high enough to lead to shellfish toxicity (Anderson et al., 2005).

Table 8. Ranking of water bodies based on mean summer secchi disc depths. Yellow values indicate sites below the NY Seagrass Task Force recommendation of 2 meters where as green values are sites that were above 2 meters. Red values would be < 1 m as per NYSDEC Seagrass Task Force.

Average summer conditions	Secchi (m)	Rank
Hempstead Harbor	1.04	1
Oyster Bay Harbor	1.28	2
Cold Spring Harbor	1.34	3
Manhasset Bay	1.43	4
Hewlett/West Bay	1.58	5
Middle Bay	1.75	6
South Oyster Bay	1.82	7
East Bay	2.18	8
Little Neck Bay	2.54	9
Western Long Island Sound	2.85	10
Jamaica Bay (East)	3.79	11

Table 9. Ranking of water bodies based on mean summer chlorophyll *a*. Red values indicates sites above the eutrophic threshold of 20 ug/L whereas yellow are sites below that threshold.

Average summer conditions	Chlorophyll (ug/L)	Rank
Western Long Island Sound	28.24	1
Hempstead Harbor	25.05	2
Little Neck Bay	23.51	3
Manhasset Bay	21.75	4
Cold Spring Harbor	20.69	5
Hewlett/West Bay	15.32	6
Middle Bay	13.18	7
Oyster Bay Harbor	10.51	8
East Bay	10.11	9
Jamaica Bay (East)	8.36	10
South Oyster Bay	6.10	11

Table 10. Ranking of water bodies based on mean summer water quality conditions, including dissolved oxygen, chlorophyll *a*, and secchi disc depth. Harmful algal blooms observed in each water body also shown.

Waterbody	Rank	HABs	Genera
Hempstead Harbor	1	Yes	*Alexandrium, Dinophysis, Heterosigma, Prorocentrum*
West Bay	2	Yes	*Alexandrium, Dinophysis, Heterosigma, Prorocentrum*
Cold Spring Harbor	3	Yes	*Dinophysis, Heterosigma, Prorocentrum*
Oyster Bay	4	No	
Manhasset Bay	5	No	
East Bay	6	No	
South Oyster Bay	7	No	
Little Neck Bay	8	No	
Middle Bay	9	No	
Long Island Sound	10	No	
SE Jamaica Bay	11	No	

Volume-based N loads are thought to be highly representative of the extent to which N can manifest into symptoms of eutrophication as a large N load delivered into a large water body or a very small water body will experience differential dilution and thus result in differing standing concentrations of N. West Bay had the largest load when normalized to water body volume at 0.22 kg N m^{-3} yr^{-1} (Table 11). Comparing other volume-specific loads, there larger differences between the north and south shore with Manhasset and Middle Bay being 30-fold lower than West Bay, but more than double any other water body at 0.007 kg N m^{-3} yr^{-1} (Table 11). These bays were followed by Cold Spring Harbor

0.004 kg N m^{-3} yr^{-1} (Table 11). The remaining water bodies had similar volume-specific N loads of 0.0015 – 0.0026 kg N m^{-3} yr^{-1} (Table 11).

Table 11. Volume-based N nitrogen loads, nitrogen residence times, and N reductions required to achieve the reference water body N residence time of 0.12 mg/L.

Water body	Volume-based N load kgN/m^3 /yr	Nitrogen Residence Time concentration mg/L	N load reduction goal %
West Bay	0.219031	13.3819	**99.1**
Cold Spring Harbor	0.003676	0.3384	**63.3**
Oyster Bay	0.001501	0.2422	**48.7**
Manhasset Bay	0.006880	0.2149	**42.2**
Middle Bay	0.006715	0.1748	**28.9**
Hempstead Harbor	0.002585	0.1544	**19.5**
S. Oyster Bay	0.002190	0.1050	-18.3
East Bay	0.002224	0.0658	-88.9

Beyond volume-based N loads a second parameter of critical importance with regard to the ability of N loads to impact a water body is residence time. Long residence times and slow flushing rates increase the likelihood that N assimilated by primary producers will remain within the water body to allow the formation of algal blooms that occlude light and eventually senesce and sink to sediments to contribute to low oxygen conditions (Valiela, 2006). The N residence times were calculated by multiplying the volume-based N load by the water body 10% flushing residence times, following the methodology used by the Suffolk County subwatersheds plan (SCSWP, 2019). Using this approach, consistent with the volume-based residence times, West Bay had, by far, the largest N residence time (Table 11) followed by Cold Spring Harbor which had a level that was more than 30-fold lower (Table 11). Five other water bodies had similar N residence times of 0.15 – 0.24 mg L^{-1} (Table 11). Of note for these calculations, time from the annual load (year) and time from the residence time (days) cancel each other, yielding final units of mg L^{-1} (Table 11).

During the Suffolk County subwatersheds study, a 'reference water body' approach was developed whereby more than two dozen water bodies that had ideal water quality were identified. These water bodies had no harmful algal blooms in the past 10 years, mean Secchi disc depths > 2 meters, chlorophyll *a* less than 5.5 µg L^{-1}, and dissolved oxygen greater than 4.8 mg L^{-1} (SCSWP, 2019). These sites had a mean N residence time of 0.12 mg L^{-1} and any site with a value above was deemed to require a reduction in N load commensurate with the amount the rate was over the threshold value (SCSWP, 2019). Using this approach on the Nassau County waters, most sites required some level of N reduction with the exception of East Bay and South Oyster Bay. While Little Neck Bay was also in this category, N loads were determined for the eastern shoreline of this bay, meaning a more detailed assessment of this subwatershed is required (Table 11). Of the remaining water bodies, West Bay required a 99% N reduction, Cold Spring Harbor required a 66% reduction, Oyster Bay required a 49% reduction, Manhasset Bay required a 42% reduction, Middle Bay required a 28% reduction, and Hempstead Harbor required a 20% reduction (Table 11).

A second approach to estimate N load reductions required to achieve improved water quality was to assess the deviation of existing water quality conditions to state and federal standards. More specifically, conditions within each water body were compared to the NYS standard of 4.8 mg L^{-1} dissolved oxygen (NYSDEC, 2007) and 2 m Secchi disc depth (NYSDEC, 2009) and the federal standard of 5 µg chlorophyll *a* L^{-1} (Bricker et al., 1999, 2008) The variance of mean conditions within each water body relative to these guideline values was determined for each parameter and the mean percent variance was determined (Table 12). Using this method, target N load reductions ranged from highs of 32% and 36% for West Bay and Hempstead Harbor, to lows of 0% and 3% for East Bay and South Oyster Bay (Table 12). While these percent reductions differ from the percentages estimated using the reference water body method, there was a highly significant correlation between the percent reductions determined with the two methods ($p<0.001$; Figure 30) when Hempstead Harbor was omitted. A similar correlation exists between the ranking of the water bodies based on water quality conditions and residence time of N concentrations ($p<0.001$; Figure 31), again when Hempstead Harbor was omitted. Reasons for Hempstead Harbor represented an outlier are discussed below.

Table 12. Percent reductions in N loads determined via the reference water body method, based on variance of chlorophyll a values from federal guidelines, secchi disc depth from NYS guidelines, dissolved oxygen from NYSDEC guidelines, the average of these water quality reductions and the average percent reduction determined via the reference water quality method and water quality method.

Water body	Reference water body	Chlorophyll	Secchi	DO	WQ average	Ref and WQ AVG
West Bay	99%	35%	21%	42%	32%	66%
Cold Spring Harbor	63%	52%	33%	3%	29%	46%
Oyster Bay	49%	5%	36%	0%	14%	31%
Manhasset Bay	42%	54%	28%	2%	28%	35%
Middle Bay	29%	24%	12%	0%	12%	21%
Hempstead Harbor	19%	60%	48%	0%	36%	28%
East Bay	0%	1%	0%	0%	0%	0%
Little Neck Bay	0%	57%	0%	0%	19%	10%
S. Oyster Bay	0%	0%	9%	0%	3%	2%

Figure 30. Correlation between percent reduction in N loading determined via the reference water body method and via the water quality guideline methods (p<0.005).

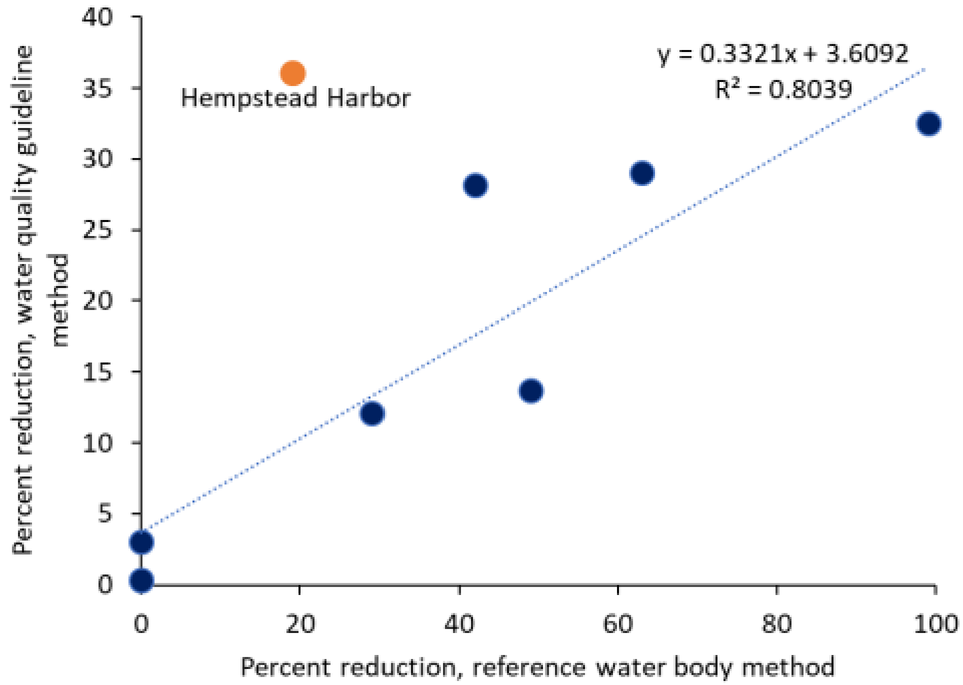
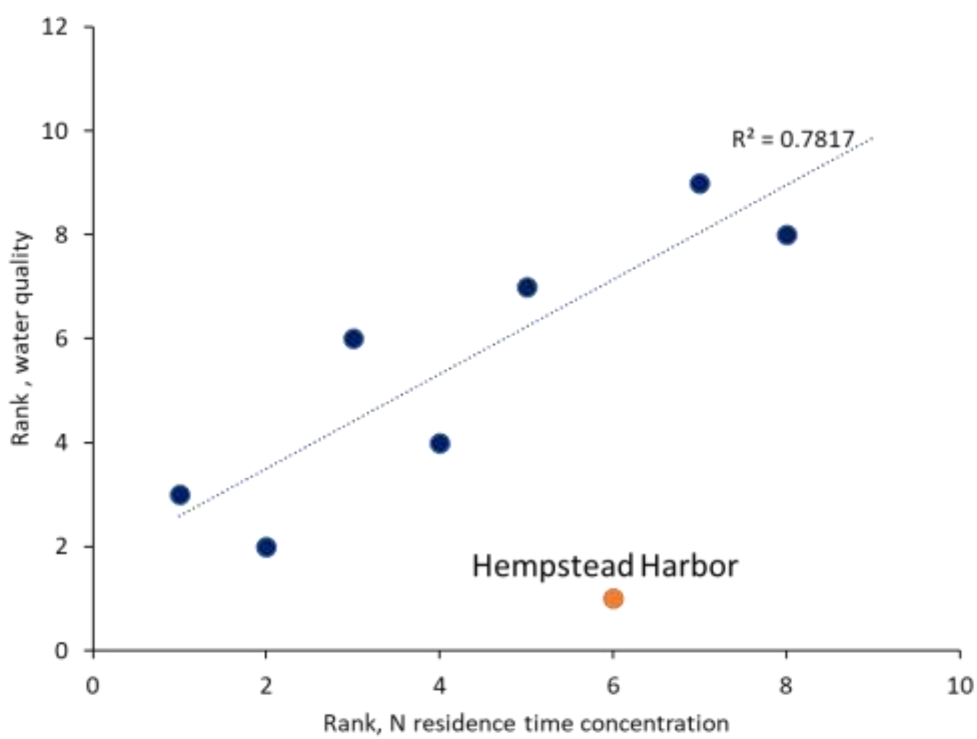


Figure 31. Correlation between ranking of water bodies based on N residence times and based on mean summer water quality conditions (p<0.005).



4.5 Comparisons to other water bodies

Nitrogen loading rates to Nassau County water bodies were generally higher than those in Suffolk County (Figure 32). West Bay, Manhasset Bay, Cold Spring Harbor, and Hempstead Harbor had four of the five highest nitrogen loads among water bodies compared across Long Island (Figure 32). When comparing N loading rates per unit area, only West Bay stood out among the highest tier of water bodies compared globally (Figure 33). However, N loading rates per area of water body are of little ecological significance, as the depth of a water body will influence the relative dilution of nutrients into that water body, and deep coastal water water bodies may be aphotic beyond a given depth. Hence, in contrast to area specific N loads, N loads per unit volume of water body is generally a realistic measure of the effect the N will have in an ecosystem. When comparing N loading rates per unit volume, West Bay had the highest loading rate of any system compared across the globe (Figure 34). Manhasset Bay and Middle Bay were also in the top tier of water bodies, whereas South Oyster Bay, East Bay, and Oyster Bay had among the lowest (Figure 34).

Figure 32. Comparison of total N loads to larger water bodies in Nassau County (red bars) and Suffolk County (blue bars) to other estuaries.

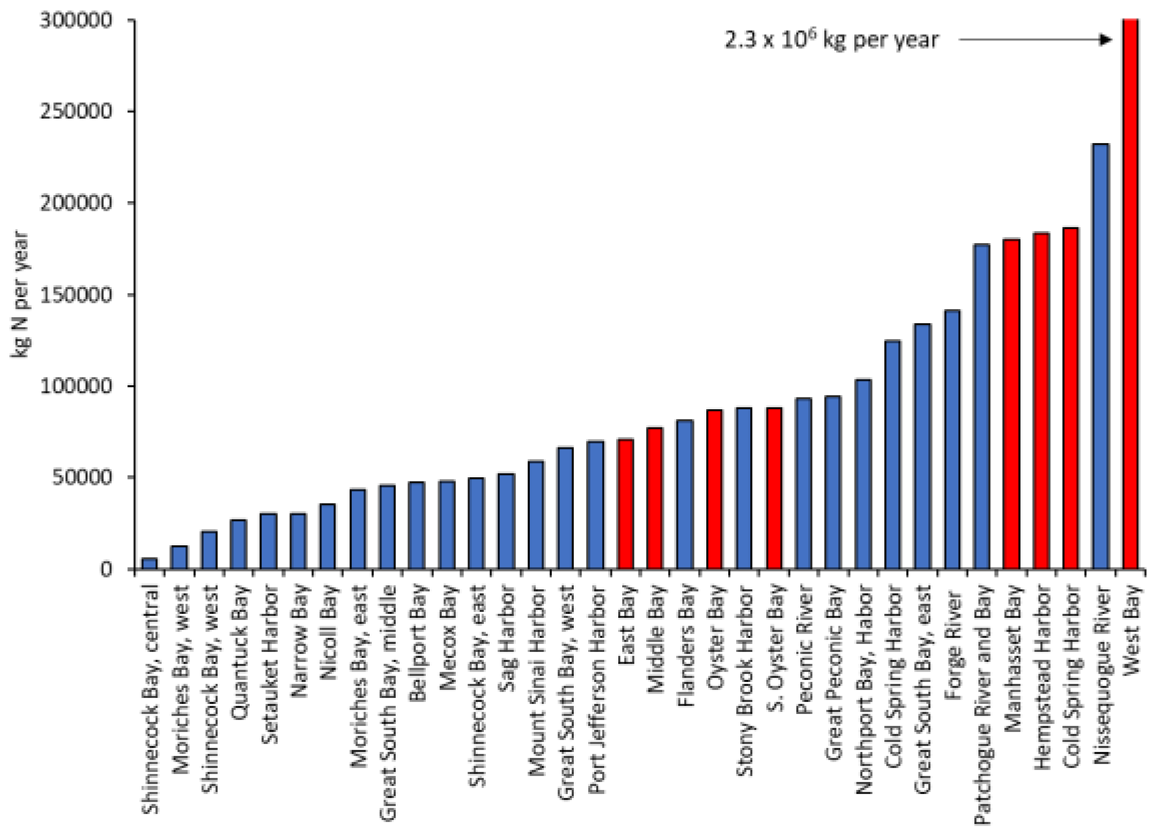


Figure 33. Comparison of total N load per hectare per year to water bodies in Nassau County (red bars) to other estuaries.

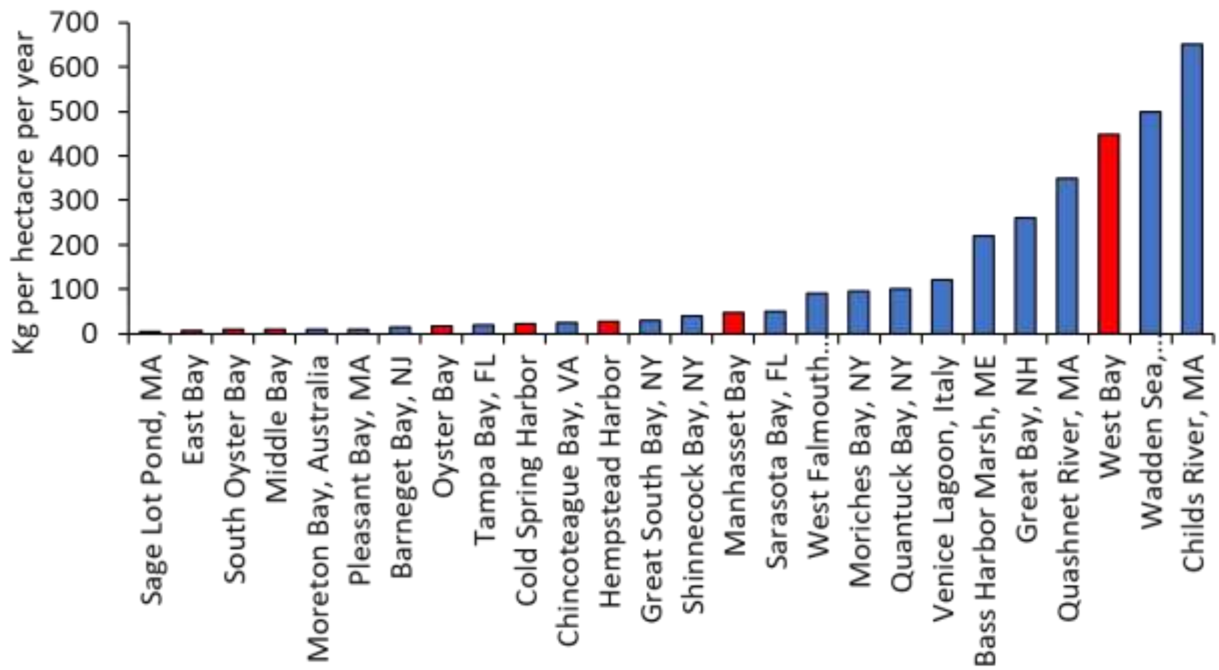
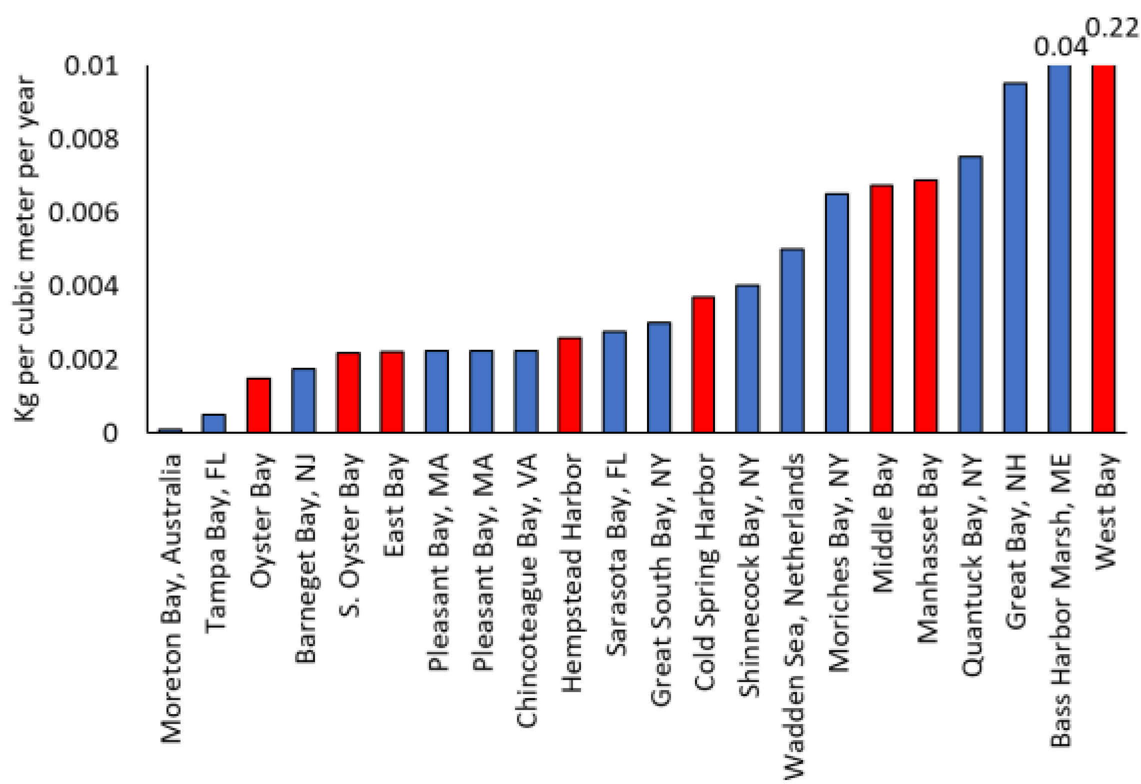


Figure 34. Comparison of total N load per cubic meter to water bodies in Nassau County (red bars) to other estuaries.



5. Discussion

5.1 Nitrogen Sources

This study demonstrated that wastewater is the largest source of N from land to sea in Nassau County, a finding consistent with every other N load study performed on Long Island (Kinney and Valiela, 2011; Lloyd, 2014; Lloyd et al., 2016; NOYDOS, 2016; SCSWP, 2019). On the north shore, onsite septic systems were the largest source of N to all 'complete' subwatersheds. One exception was the Little Neck Bay subwatershed, which is only a fraction of the eastern shore of this water body where sewage treatment plants were the largest source and onsite systems were second (40% vs 33% of total N load). The other exception was the small Long Island Sound subwatershed where fertilizer was the largest source of N and onsite septic systems s were the second largest source (42% and 38%). On the south shore, the N load from the Bay Park sewage treatment plant is so large (2.2 million kilograms of N per year) it exceeds to total N load from all other sources and all other subwatersheds on the north and south shore combined. This finding alone, therefore, demonstrates wastewater is the largest source of N from Nassau County to surface waters. Given that other south shore subwatersheds are sewered with their wastewater transported to STPs (Bay Park, Cedar Creek), other subwatersheds on the south shore have almost no wastewater N load, save for a small, unsewered region within the Middle Bay watershed. Instead, fertilizer is the largest N load from land to sea in these regions. Across all of Nassau County, the largest source of N among the three types of fertilizer (agriculture, parks/golf, residential) was residential, being 50-80% of the fertilizer N load except within the small Nassau County watershed that discharges to Jamaica Bay where it was only one-third.

Atmospheric deposition was never the largest source of N but was more prominent among the sewered subwatersheds on the south shore where wastewater N loads had been removed (~one third of N loads) compared to the north shore where it was never more than 10%. For this project, an effort was made to specifically ascribe the N loads that come from surface run-off. Because wastewater is injected below the ground or into surface waters and because fertilizer is applied to vegetative surfaces where it is assimilated and attenuated, only N delivered via atmospheric deposition contributes to surface run-off within the N-Load model. For this study, atmospheric deposition on any impervious surface was considered surface run-off, as the sandy soils of Long Island permit very little denitrification once N enters the aquifer (Young et al., 2013; SCSWP, 2019). Using this approach, about half of atmospheric deposition was determined to become a run-off N source to bays on the south shore of Nassau County, where as this value was about a third of atmospheric deposition on the less urbanized north shore. Beyond the atmospheric deposition that falls on land and runs into surface waters, this study also considered the atmospheric deposition of N directly onto water bodies and found this to be a small fraction of the total N load; usually $\leq$ 5% except on East Bay and South Oyster Bay where water bodies were slightly larger relative to the watersheds and the total was around 10%.

It is common to acknowledge a certain amount of uncertainty that occurs when making predictions using modeling studies. In this study, the standard percent errors for nitrogen loading models (12% NLM) were considered. However, with so many inputs to the model a true assessment of uncertainty is difficult to assess, and a certain amount of error propagation may occur.

5.2 Comparing Nitrogen Loading Rates

One way of assessing the magnitude of the N loads to Nassau County water bodies is to compare them to other ecosystems. In doing so, normalization of N loading rates per water body is often desirable, as the same N load into two different sized water bodies can have very different effects due to dilution and tidal flushing. The Suffolk County subwatersheds study split up the county into approximately 200 subwatersheds. For this study, the N loads from the Nassau County subwatersheds were compared to the large subwatersheds studied by Suffolk County. Larger subwatersheds were chosen to allow for a realistic evaluation as some of the Suffolk County subwatersheds for small creeks, lakes, and ponds were quite small compared to the 11 subwatersheds studied here. Among the comparably sized subwatersheds, Nassau County had four of the five largest N loads across Long Island with West Bay being, by far, the largest, and Cold Spring Harbor, Manhasset Harbor, and Hempstead Harbor being the others (Figure 32). Other Nassau County subwatersheds were more similar to the N loads of many Suffolk County subwatershed (Figure 32).

Nitrogen loads have been calculated for waterbodies all over the world that range in size by orders of magnitude (Valiela et al., 1997; Stinnette, 2014). To facilitate comparisons among waterbodies of differing sizes, nitrogen loading rates to waterbodies can be normalized to the volume of the receiving waterbody, an approach that creates a more realistic comparison as it accounts for dilution of the load into the estuary. This comparison revealed that the West Bay N load was five-fold larger than any of the 22 other water bodies across the US and beyond for which data was available (Figure 34). Manhasset Bay and Middle Bay also ranked extremely high, being surpassed by two shallow estuaries from the northeast US, and Quantuck Bay (Figure 34), a Suffolk County waterbody known to have annual harmful algal blooms (Gobler et al., 2011). Cold Spring Harbor and Hempstead Harbor fell into a category that also included some unsewered Suffolk County water bodies including Great South Bay, Shinnecock Bay, and Moriches Bay, whereas Oyster Bay, South Oyster Bay, and East Bay had some of the lowest N loading rates per unit volume of water body (Figure 34).

5.3 Effects of Marine Nitrogen Loading

Nassau County bays have experienced multiple types of harmful algal blooms hypoxia, loss of salt marshes, and declines in bivalve populations (NYSDEC 2009, 2014; Hattenrath-Lehmann et al., 2018). Excessive N has been shown to promote the growth of phytoplankton, toxic algae blooms, toxins from algal blooms, and the overgrowth of *Ulva* in Nassau County's north shore and south shore waters (Gobler et al. 2006; Hattenrath-Lehmann et al., 2015; SoMAS, 2016). In addition, reducing N levels has been shown to lessenlessen the growth of *Ulva* (SoMAS, 2016). While this study has assessed N loads in the bays, the distribution of algal blooms in surface waterbodies are controlled not only by N load but also by biological (e.g. predation) and physical processes (flushing of water bodies). If total N concentrations are high in a given area of a bay, it may be due to an excessive N input, a small N export rate, or a combination of these factors.

Comparing water quality measurements across Nassau County revealed that several water bodies are in need of N mitigation. Several water bodies had summer dissolved oxygen levels that failed the NYSDEC acute (3 mg L^{-1}; West Bay) and chronic thresholds (4.8 mg L^{-1}; Cold Spring Harbor, Manhasset Bay, Long Island Sound). Most water bodies did not achieve the 2-meter Secchi disc depth desired for optimal growth of seagrass (NYSDEC, 2009) and most water bodies had double digit chlorophyll *a* levels that are higher than desirable according to guidance by NOAA and US EPA (Bricker et al 1999, 2008). Given that N is the primary limiting element in these ecosystems (Ryther and Dunston, 1971; Gobler et al., 2006; SoMAS, 2016) and given that excessive primary production creates high levels of chlorophyll *a* that occlude light penetration and create shallow Secchi disc depths and is eventually respired and creating low oxygen concentrations, N mitigation is a logical approach to improve water quality conditions.

Studies have associated low dissolved oxygen, declining water clarity, and harmful algal blooms with excessive N loading (Valiela et al., 1992; Valiela, 2006; Heisler et al., 2008). This Nassau County bays study demonstrates that water quality impairments in shallow bays with moderate to higher nitrogen loading rates are most likely to manifest themselves in bays with the longest residence time and highest N loads. In systems with high nitrogen loads and modest residence times such as West Bay, the overgrowth of macroalgae is a common water quality impairment since these organisms are typically able to attach to bottom substrates and thus are not subject to the same flushing action that microalgae are. While macroalgae may also be prominent on the north shore of Nassau County, robust surveys have not been conducted in this region. In practical terms, while N loading rates are high enough to stimulate algal growth in some bays, strong tidal residence in zones near or between ocean inlets remove nitrogen supplies and/or algal biomass prior to it accumulating to high levels. East Bay and South Oyster Bay are two prime examples of such conditions and had the best water quality in Nassau County.

5.4 Prioritizing regions for Nitrogen Mitigation

The multiple symptoms of eutrophication and impairments across the Nassau County bays have been shown to be interrelated in this study and have been shown to be closely tied to N loading rates from subwatersheds (Figure 1). Estuarine regions with algal blooms also generally have low water clarity and low oxygen (Valiela, 2006). In fact, there was a statistically significant inverse correlation between chlorophyll *a* levels and dissolved oxygen levels across all waterbodies ($p<0.05$). These collective impairments also contribute to the loss of seagrass and salt marshes and diminished fisheries (NYSDEC 2009; 2014). Given this, the final section of this report focuses on mitigating N loads from each watershed to the receiving waterbody to improve water quality conditions.

One of the prime goals of this project was to prioritize subwatersheds for N mitigation. One mechanism for achieving this goal was to compare water quality among the bays and harbors studied here and rank them based on their existing water quality. As described above, as N limited systems, restricting N loads would have the greatest chance of improving water quality conditions. Considering the mean chlorophyll *a*, Secchi disc depths and dissolved oxygen conditions among all waterbodies, West Bay, Hempstead Harbor, and Cold Spring Harbor were shown to have, on average, the poorest water quality conditions. Perhaps not as a coincidence, these same three waterbodies have hosted harmful algal blooms caused by multiple genera of phytoplankton during the past decade including *Prorocentrum*, *Heterosigma*, and *Dinophysis*, with the later genus being known to produce the toxin, okadaic acid, on Long Island (Hattenrath-Lehmann et al., 2013, 2017, 2018). Prior research has demonstrated that blooms of *Dinophysis* on Long Island are strongly promoted by excessive N loading (Hattenrath-Lehmann et al., 2015).

Beyond existing water quality, a second approach used to rank regions in need of N mitigation was to assess the N residence times of each water body. This approach utilized water residence times and volume-adjusted N loads and assumed that the longer a N load remains within a given water body, the greater the likelihood it would manifest itself as water quality impairment related to algal blooms, light reductions, organic carbon accumulation, hypoxia, and acidification (Valiela 2006; Heisler et al., 2008; Gobler and Baumann, 2016). This approach generally aligned well with water quality assessments, as the two waterbodies with the largest N residence times were West Bay and Cold Spring Harbor which also had the poorest water quality. Interestingly, however, Hempstead Harbor was ranked sixth of eight water bodies regarding N residence times. When comparing the two approaches used for ranking water bodies, there was a highly significant correlation between the two methods ($p<0.01$) with Hempstead Harbor excluded from the comparison. Hempstead Harbor is nearly 10 km long with a north-south gradient in water quality, partly due to a spit of land that separates the northern and southern regions of the harbor that likely restricts flushing of the southern portion of the harbor and worsens water quality in that region. Hence, there may be an overrepresentation of stations within the southern extent of this system (Figure 11). Alternatively, the presence of the spit may complicate the flushing of this harbor, making it slower than the value determined by the EFDC model. Regardless, the chronic presence of harmful algal blooms, anoxia, and fish kills, even on the north side of the spit in Hempstead Harbor during summer (Gobler lab, 2014-2019), affirms it is a highly eutrophic water body in need to N mitigation.

A final modeling approach utilized in this project was to estimate N mitigation needed to achieve improved water quality. This was done using two approaches that gave somewhat similar results. The first method borrowed the Suffolk County subwatersheds ‘reference water body’ approach that gave results that were largely consistent with many other findings from this study: West Bay and Cold Spring Pond needed the largest N reduction at 99 and 63%, respectively, and South Oyster Bay and East Bay required no N mitigation. These findings are consistent with many other observations made during this study as West Bay and Cold Spring Pond had some of the poorest water quality, the largest N loads corrected for volume and when compared to other Long Island waterbodies. Further, South Oyster Bay and East Bay had the lowest N loads and the best water quality. A second approach for estimating N load mitigation required to improve water quality was to consider the deviation of existing water quality conditions from NYS and federal standards, an approach that gave an outcome similar to the ‘reference water body’ approach although the estimated N reduction required were ~three-fold lower than the ‘reference water body’ approach. This difference was not surprising as there is no *a priori* reason to assume that deviations from water quality standards would be linearly related to N loads given the complex biological, chemical, and physical processes by which N loads yield water quality conditions. Moreover, the units of measurements for water quality are on differing scales compared to each other and compared to N loads. Still, there was a statistically significant correlation between N reductions required for water quality improvements via the two methods when Hempstead Harbor was excluded from the analyses ($p<0.01$), providing support for the need and relative magnitude of reductions needed for six watersheds across Nassau County. As described above, the mean water quality conditions or residence times within Hempstead Harbor may have mis-represented actual conditions perhaps partly due to the spit across the majority of the southern half of the harbor.

Collectively, all assessments of Nassau County waterbodies yielded similar conclusions and provide a similar assessment of the need to mitigate N loads. West Bay and Cold Spring Harbor are in the greatest need of N mitigation while East Bay and South Oyster Bay may not need any N mitigation at this time. Between these waterbodies are a middle tier of water bodies needing intermediate levels of N mitigation including Manhasset Harbor, Hempstead Harbor, Middle Bay, and Oyster Bay with models differing on the degree of mitigation needed. The fact that N loads per unit volume for Manhasset Harbor and Middle Bay were among the highest quantified globally, further emphasizes the need for N mitigation there. The chronically poor water quality (harmful algal blooms, hypoxia, fish kills) in Hempstead Harbor also supports the need for N mitigation in this system.

While N mitigation actions likely to be most effective may seem obvious from an assessment of the total N loads to each subwatershed, all options should be considered since some options, such as reduction in fertilizer use, are simpler and less costly to implement than others. For all north shore subwatersheds, upgrading onsite septic systems to innovative and alternative systems that reduce effluent by up to 90% would lead to the N reductions recommended by the two N models used in this study. Given the lack of wastewater N loads for most of the south shore, fertilizer reductions would be required in these regions.

5.5 Pending N mitigation measures

Knowing the N loads of Nassau County subwatersheds into its estuaries is the first step in considering effective mitigation measures. This study considered two N mitigation measures that have already been proposed. The first was the diversion of sewage from the South Shore Water Reclamation Facitliyto the ocean outfall at Cedar Creek plant in Wantagh that discharges the plant's sewage several miles off-shore into the Atlantic Ocean. This mitigation measure would reduce the N load to West Bay by more than 90%. There have also been discussions of connecting the Long Beach STP to Bay Park in which case the next largest N source to this bay would be mitigated and loading would be reduced by 98%, changing this estuary from having some of the highest N loading rates in the world to some of the lowest in Nassau County. This change holds the potential for this estuary to be transformed. It currently experiences hypoxia, acidification, and harmful algal blooms (SoMAS, 2011) and its salt marshes are in a state of decay (NYSDEC, 2014) likely due to N overloading (Deegan et al 2012; NYSDEC, 2014). Further, there is no known seagrass in this Bay. A 98% N reduction would likely make West Bay no longer subject to intense algal blooms, decreasing the chance of hypoxia and acidification, and allowing for more benthic light penetration. This could lead to the recolonization of West Bays by seagrasses and salt marshes. These enhanced habitats will provide the coastal communities in and around the Western Bays with heightened protection against waves, storm surge, and coastal flooding.

A second mitigation measure considered for this study is the recommendation that fertilizer application rates be decreased from 1 to 0.6 pounds per 1,000 square feet per application. This would reduce the total N load by 5 to 15% with the biggest change observed for the south shore subwatersheds where there is no wastewater N load. It should be noted that more data is needed to refine this calculation. For this study, it was assumed that 49% of homes have 3.5 fertilizer applications per year, 31% of homes have one application per year, 4.5% of homes have one application every three years and 15.5% of homes do not use fertilizer (Vaudrey, 2015). This information was estimated from a survey of homeowners in Suffolk County; Nassau County-specific information would help refine this estimate.

5.6 Next steps and recommendations

Through this study, priority regions and activities for nitrogen mitigation in the Nassau County bays have been identified. Below, a series of next steps and complementary activities that can be undertaken to improve water quality and ecosystem functions are outlined. One next step would include refining the nitrogen loading models (NLM) presented here based on new and emerging information. For this study, watersheds were drawn to capture major waterbodies using subwatersheds determined decades ago. Presently, the USGS is redefining these subwatersheds by using state of the art hydrological models to ensure they best reflect groundwater and streamflow. Since future water quality management plans are needed on a watershed-by-watershed basis, it will be highly useful to apply the nitrogen loading models developed by this research project to the newly defined subwatersheds.

While efforts are being made to reduce the flow of nitrogen from land to sea, it will take more than a decade for groundwater contaminated with nitrogen to flow through the aquifers and for groundwater with lower levels of nitrogen to begin to enter the bays. Hence, the implementation of multiple 'in the water' solutions for mitigating and removing nitrogen outlined below may be desirable. As such projects are implemented, their effectiveness in mitigating N loads to given systems could be determined quantitatively via the use of the models generated by this project.

One of the symptoms of heavy N loading to the Nassau County bays is the overgrowth of algae. Although microalgae and phytoplankton are the main primary producers in poorly flushed parts of estuaries, macroalgae or seaweeds overgrow estuaries in regions with faster flushing times causing a series of environmental problems including low oxygen and death of marine life (Valiela et al., 1992). In some areas, seaweeds can cover the entire bottom of estuaries. For example, two species of macroalgae, *Ulva* and *Gracilaria*, grow quickly and rapidly in the southwestern bays of Nassau County during May through November. Preliminary calculations based on elemental analyses of these seaweeds suggest that their weekly removal could represent a potentially significant faction of the total N load to this system. Alternatively, seaweed aquaculture is a growing field that can sequester high levels of N (Kim et al. 2014). Detailed research regarding precise yields of harvesting on a per pound of N basis is needed to better understand the feasibility of such approaches for mitigating N loads and is being considered as part of NYSDEC's Long Island Nitrogen Action Plan's nutrient bioextraction initiative.

Finally, dense populations of filter-feeding bivalves have shown the potential to remove nitrogen from estuaries by consuming phytoplankton. There are presently efforts to replant natural populations of hard clams, *Mercenaria mercenaria*, as well as Eastern oysters, *Crassostrea virginica*, in different estuaries across Long Island, including South Oyster Bay, West Bay, and Middle Bay as part of NYSDEC's Long Island Shellfish Restoration Program. Sebastino et al (2015) recently determined that covering 2,500 acres of Great South Bay with cultivated adult oysters from June through October would mitigate 75% of the nitrogen loads to this estuary. Given that some regions have smaller nitrogen loads and smaller volumes of water, a significantly smaller region of cultivated oysters would be needed to mitigate nitrogen loads in these systems. All these mitigation options must also take into account future climate change. Increased temperature and precipitation due to climate change may make nitrogen loading worse in bay systems and could offset mitigation efforts.[2] Further research should be conducted to determine the impact of climate change on N loading in these bays so that mitigations plan can be properly informed.

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