



Water quality gradients and trends in New York Harbor

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ARTICLE INFO

Article history:

Received 7 June 2019

Received in revised form 29 October 2019

Accepted 30 October 2019

Available online 7 November 2019

ABSTRACT

New York Harbor is a complex of interconnected waterways that have supported the rapid development of a thriving megacity and metropolitan region. The water quality of New York, a partner city in the World Harbour Project, is a reflection of the combined impacts of this metropolitan region. Water quality health and trends were assessed between 1996–2017 in 9 different reporting regions using publicly available data. Analyses of New York Harbor water quality reveal strong persistent geographic gradients and long-term trends in improving water quality. Data was synthesized for five indicators throughout the New York harbor region including: total nitrogen (TN), total phosphorus (TP), dissolved oxygen (DO), chlorophyll *a* (chl_a), and water clarity (secchi disk depth). The health of the waterways surrounding New York City was evaluated and graded on a 0%–100% scale and displayed using a 'stoplight color scheme'. The best water quality in the region evaluated was in the area of the most exchange with the Atlantic Ocean in the Lower Bay near the harbor entrance. Conversely, the most degraded water quality was in the areas of lowest water exchange in dead end canals (Newtown Creek and Flushing Bay) and Jamaica Bay. The Hudson River, East River, Upper Bay, Newark Bay, and Raritan Bay had intermediate water quality. High nutrient levels (TN and TP) were observed throughout New York Harbor, but water clarity, DO and chl_a levels were variable. Overall, there were improving trends in many water quality parameters over the time period of our study, especially TN. Data used in this analysis can be used as a resource for environmental managers, educators and students to explore health of New York Harbor and its associated waterways. This analysis may be seen as a model for other important and threatened harbors and waterways including partner cities in the World Harbour Project by providing a comparable method for assessing and communicating water quality health.

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1. Introduction

New York City is one of the original “mega-cities”, defined as an urban population in excess of 10 million people (Sekovski et al., 2012). As a harbor partner in the World Harbour Project (WHP), an international project that looks to understand and link similar pressures and solutions across harbors throughout the world, this study quantifies water quality pressures that New York Harbor has experienced over the past twenty-one years (Steinberg et al., 2016). Central to the city's history of cultural and economic development are the complex waterways that comprise New York Harbor and the associated estuarine rivers that surround it. Given the extent of development over a period of four hundred years and exploitation of the harbor's resource over this time, it is not surprising that its waterways have experienced severe environmental degradation (O'Neil et al., 2016). However, significant progress has been made over the last few decades in establishing conservation and restoration plans for the harbor

including steps to improve water quality and to improve the overall health of the ecosystem. Consequently, the New York Harbor ecosystem is much healthier than it was 30 years ago (NYNJHEP, 2012).

Due to its long history of development, New York Harbor is one of the most well researched, monitored, and documented harbors in the world. The systematic documentation of the water quality of the waterways around the city began over a century ago by 'The Metropolitan Sewerage Commission (MSC)' (O'Neil et al., 2016). These comprehensive surveys of the condition of New York Harbor began in 1906, at which time it was determined that approximately 600 million pounds of untreated raw sewage were being dumped into the harbor each day (Waldman, 1999). To continue this monitoring effort, an annual Harbor Survey Program was implemented in 1909 with data collected on dissolved oxygen (DO), bacterial counts, turbidity, salinity, and temperature at 12 monitoring stations around the island of Manhattan (NYC DEP, 2010). The water quality surveys helped to identify the location and scale of where improvements were needed to develop what became a state of the art, comprehensive wastewater treatment system for the city (Brosnan and O'Shea, 1996). Due to these

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advances in technology and conservation efforts, water quality in New York's waterways has improved (Brosnan and O'Shea, 1996). The pioneering use of new engineering methods developed to treat the more than one billion gallons of wastewater produced every day by the city's more than 10 million residents and visitors (NYC DEP, 2010) has been adopted by cities around the world (NYC DEP, 2010), and the sewage treatment program continues to serve as a model for other megacities wishing to clean wastewater in a more efficient and effective manner.

Due to substantial investments in wastewater treatment infrastructure, average harbor-wide bacteria levels have decreased by over 99% from the early 1970s, and have remained stable since the mid-1990s (NYCDEP, 2009). Additionally, nutrient loading, chemical contaminants and dissolved oxygen problems in some areas (particularly semi-enclosed canals) are still ecological challenges throughout the harbor (O'Neil et al., 2016). Although bacteria issues have been publicized and documented well, many other water quality parameters are measured throughout the New York Harbor region and may benefit from synthesis. Although the New York City Department of Environmental Protection has produced regular reports on the measured water quality parameters, the data released is mostly in a raw, unsynthesized form and some interpretation is required to glean valuable information on the health of the estuary (NYCDEP, 2009).

As part of a National Science Foundation STEM-C (Science, Technology, Engineering, Mathematics and Computing) project, New York City public middle school students and citizen science groups have been using Oyster Restoration Stations (recently renamed Oyster Research Stations) (ORS) as part of a STEM-C curriculum designed to have students participate in place-based authentic research for both harbor restoration of oysters as key-stone species and educational purposes (Janis et al., 2016) (O'Neil et al., 2016, 2019, this volume). This partnership, the Curriculum and Community Enterprise for Restoration Science (CCERS), is led by a consortium of universities, educational and scientific agencies (O'Neil et al., 2019). The partnership has developed and tested a curriculum based on recurring visits to the ORSs and measurements taken by students at these sites. The ORS field trip curriculum includes 5 protocols for students to carry out on each of their visits to their school's ORS: Protocol (1) Site Conditions; students observe meteorological conditions, recent rainfalls, tide, currents as well as observations of land and water conditions including garbage; Protocol (2) Oyster measurements; students measure the growth of the tagged oysters originally provided in each ORS as well as estimation of bioaccumulation on the cage and determining if the oysters are alive or dead in the; Protocol (3) Mobile trap; students identify and count all organisms found in the mesh trap and on oyster shells in ORS; Protocol Settlement Tiles; students are responsible for identifying and recording the sessile organisms growing on each of the four settlement tiles; Protocol (5) Water Quality; Students measure water quality parameters including water temperature, dissolved oxygen (DO), salinity, pH, nutrients (total nitrogen (TN) and total phosphorus (TP) and turbidity (water clarity) (Janis et al., 2016; BOP, 2015; NYC DEP, 2019).

The 20 year data set analyzed in this study aligns closely to parameters collected in Protocol 5 of the ORS for water quality in the STEM-C curriculum. Information was analyzed to determine the time periods over which the data was most consistent in terms of both sampling and analytical techniques, so that data synthesis and integration were carried out to produce historical maps of water quality for the students to compare their data collected at specific ORS locations, to overall water quality in the New York Harbor waterways. For this reason the 100 year data set described above was not able to be fully analyzed for this study, and only the past 21 years, when the complete suite of

indicators was collected by the NYDEP were used. The resulting environmental assessment grade from our analysis provides a tangible summary and integration of the complex parameters in the long term data set. This allows students, as well as the general public, a way to compare the data from their local ORS or local waterways they interact with on a daily basis, to overall waterway health trends. The health of the waterways surrounding New York City was evaluated and graded on a 0%–100% scale, with a stoplight color scale of water quality (i.e., red for 'poor' health, yellow for 'fair' health; green for 'good health, Table 1). Regions were designated to ensure holistic sampling site coverage (minimum of three stations per region) and according to their regional affiliations (e.g. Jamaica Bay sites align with Jamaica Bay Wildlife Refuge waters) (Fig. 1).

2. Materials and methods

2.1. Study area context

The study region (Fig. 1) encompasses the estuaries that comprise the major tidal regions surrounding New York City. This area received an average of 55 inches of rainfall per year during the 20 year time period for which data was collected, and land cover is primarily developed with close to 72% impervious surface (NOAA, 2019). Data collected and analyzed from stations throughout this region show that all stations fall within the polyhaline salinity regime (between 18 and 30 practical salinity units yearly average) and station depths ranged from 0.15 m to 9.99 m (0.51 ft to 32.8 ft) (NYC DEP, 2019). Data was collected using New York Department of Environmental Protection sampling protocols (NYC DEP, 2019).

2.2. Indicators and thresholds

The indicators used in this analysis will help STEM-C students to connect field measurements they are collecting to a harbor health calculation, and ultimately help students put their results in the larger context of the general ecosystem health of New York Harbor. Each indicator measured can affect organisms that live in the open waters and tributaries of NYC, and students can then extend their knowledge and relate the water quality data to other parameters measured at their ORS including oyster survival and relationships to co-occurring organisms. This analysis can also be used by teachers and resource managers to focus on regions of specific interest, or poor health for monitoring and restoration. The data used in this analysis was collected by the New York City Department of Environmental Protection using established water quality monitoring protocols (NYC DEP, 2019).

It was determined that the indicators which had historical data with enough spatial (collected at all stations throughout the study region) and temporal (21 years of monitoring) resolution to use in the current analysis were DO, TN, TP, chlorophyll *a*, and water clarity (secchi disk depth). Although some of these indicators were monitored over much longer temporal scales, this comprehensive group of five indicators had consistent data for only the last two decades. Once these indicators were identified, targets or thresholds for each indicator were developed. Establishing targets for each indicator was done by evaluating the literature to estimate levels (thresholds) that indicate poor health in New York Harbor's waterways, or by using management goals as thresholds. A threshold ideally indicates a tipping point where current knowledge predicts an abrupt change in an aspect or some aspects of ecosystem conditions. From the perspective of choosing meaningful, health-related thresholds, this must be the point beyond which prolonged exposure to unhealthful conditions actually elicits a negative response. For example, prolonged



Fig. 1. Data from the above sampling stations from NYDEP were included in this water quality analysis of New York Harbor (NYC DEP, 2019). Sampling station names are shown as designated by NYDEP. Regions were designated to have a minimum of three sampling stations with continuous data, and to cover the nine important estuarine reporting areas.

Table 1

Indicator thresholds throughout the New York Harbor region.

Indicator	Sample location	Thresholds	Time period	Source
Total Nitrogen	Surface	0.4, 0.5, 0.6, 0.8, 1.2 mg/l	Year round	Mid-Atlantic Monitoring Protocol
Total Phosphorus	Surface	0.03, 0.05, 0.07, 0.09, 0.13 mg/l	Year round	Mid-Atlantic Monitoring Protocol
Chlorophyll A	Surface	5, 20 µg/l	Year round	National Coastal Assessment thresholds
Clarity (secchi)	Depth visible	0.7, 1.1, 2.4 m	Year round	National Coastal Assessment thresholds
Dissolved Oxygen	1 m off bottom	2, 3, 5 mg/l	Summer	Long Island Sound Report Card

exposure to DO concentrations below criteria thresholds elicits a negative response in aquatic systems by either compromising the biotic functions of an organism (reduced reproduction) or causing death (NYNJHEP, 2012).

2.2.1. Dissolved oxygen

Dissolved oxygen is a key indicator of ecosystem health. Low dissolved oxygen levels can be deleterious to aquatic life, and also

cause changes in water chemistry that can trigger the release of nutrients from sediments into the water column. Low DO is often a result of nutrient (N and P) inputs into the water which fuel algal blooms, which upon decay are decomposed by microbial respiration, which depletes DO.

The DO threshold was determined using commonly accepted levels of dissolved oxygen that are protective of aquatic animals such as fish (Wicks et al., 2011). These threshold levels are similar to the National Coastal Condition Assessment and Mid-Atlantic

Tributary Assessment Coalition's Tidal protocol dissolved oxygen thresholds. Dissolved oxygen thresholds used were the following: <2.0 mg/L = fail, 2.0 – 3.0 mg/L = marginal, 3.0 – 5.0 mg/L = fair and >5.0 mg/L = pass. Raw (un-scored) data that measured below each threshold were scaled accordingly, so any DO measurement below 2 mg/L was scaled between 0 – 50 , any measurement between 2 and 5 was scaled between 50 – 100 and any measurement above 5 received a score of 100 . The time period assessed for DO was April to October and only samples collected from the lowest depth at each site were included. Constraining the data to the April through October time-frame, and to the bottom depth is useful to highlight only the areas and times when DO was at unhealthy levels in New York Harbor (IAN, 2016). Through this approach the stations that are healthiest and those that are most challenged during the summer months at lower depths, can be discerned.

2.2.2. Total phosphorus and total nitrogen

Nutrient loading is a critical factor in the health of New York Harbors ecosystems (O'Shea and Brosnan, 2000), which has been an intense focus of research and remediation, mainly in the form of sewage upgrades (Brosnan and O'Shea, 1996). Heavy nutrient loads, in particular nitrogen (N) and phosphorus (P), can lead to algal blooms and hypoxia, which can inhibit the colonization of shorelines by some taxa, while opening ecological niches to others, including at the microbial level (Cole et al., 2006; Findlay et al., 1992, 2003; Sinsabaugh and Findlay, 2003). Nutrient loading in the New York–New Jersey Harbor estuary is principally from municipal point sources and secondarily from tributaries, which carry their own municipal loadings, as well as fertilizer runoff from suburban lawns and farms (Lampman et al., 1999; Malone et al., 1996). Nonetheless, the relationship between nutrient inputs to surrounding watersheds and carbon-cycle dynamics in systems with the complex hydrology of New York Harbor is not well understood (Arrigoni et al., 2008).

When in excess, N and P can cause algal blooms, which upon decay, can lead to low DO and subsequent fish kills and other deleterious effects on biota. These algal blooms can also potentially be harmful to human health and therefore prevent waters from being swimmable (Fristachi et al., 2008).

A threshold for total phosphorus (TP) was established in the Mid-Atlantic Tributary Assessment Coalitions tidal indicator protocol (Wicks et al., 2011). The protocol divides TP thresholds into different salinity regimes, and depending on which regime a region falls into it is scored differently. New York Harbor falls completely within the polyhaline range for salinity. Total phosphorus thresholds used were the following: >0.13 mg/L = fail, 0.09 – 0.13 = poor, 0.07 – 0.09 mg/L = marginal, 0.05 – 0.07 mg/L = fair, 0.03 – 0.05 mg/L = good, <0.03 = pass. For each TP value the measurement was compared to the threshold and assigned a value from 5 (best) to 0 (worst) so that scores can be calculated. Raw data that measured below each threshold was scaled accordingly, so any TP measurement below 0.13 mg/L was scored a 0 , any measurement between 0.13 and 0.09 was scaled between 0 – 1 , and so on. The time period for this indicator is year round as nutrient pollution affects TP levels year round.

The threshold for total nitrogen (TN) was taken from the Mid-Atlantic Tributary Assessment Coalitions tidal indicator protocol (Wicks et al., 2011). The protocol divides TN thresholds into different salinity regimes. New York Harbor falls completely within the polyhaline range for salinity. Total nitrogen thresholds used were the following: >1.2 mg/L = fail, 0.8 – 1.2 mg/L = poor, 0.6 – 0.8 mg/L = marginal, 0.5 – 0.6 mg/L = fair, 0.4 – 0.5 mg/L = good, and <0.4 mg/L = pass. For each TN reading, the measurement was compared to the threshold and assigned a value from 5 (best) to 0 (worst) so that scores can be calculated. Raw data that

measured below each threshold was scaled accordingly, so any TN measurement below 1.2 mg/L was scored a 0 , any measurement between 1.2 and 0.8 was scaled between 0 – 1 , and so on. Similar to TP, the time period for this indicator is year round as nutrient pollution affects TN levels all year.

2.2.3. Chlorophyll *a*

Chlorophyll *a* is a key indicator of estuarine health, as it is indicative of phytoplankton (microalgae) biomass in the water column. Chlorophyll *a* (chl_a) values are controlled by factors such as light, nutrient (N and P) availability and water temperature.

The threshold for chlorophyll *a* was determined using the National Coastal Condition Assessment (USEPA, 2015), with levels higher than $20 \mu\text{g l}^{-1}$ being considered very unhealthy. The thresholds for chlorophyll *a* are 5 and $20 \mu\text{g l}^{-1}$. For each chlorophyll *a* reading, the measurement was compared to the threshold and assigned a value of 1 (best), 0.5 (fair), 0 (worst). For example, a measurement greater than $20 \mu\text{g l}^{-1}$ received a score of zero, and a measurement between 5 and $20 \mu\text{g l}^{-1}$ received a score scaled between 0 and 0.5 . The time period for this indicator is year round as high chlorophyll *a* values were found throughout the year even in cold winter months.

2.2.4. Water clarity

Water clarity is a measure of how much light penetrates through the water column. It is dependent upon the amount of suspended particles (e.g., sediment and plankton) and colored (chromaphoric) dissolved organic matter (CDOM) present. Clear water is critical to allow sunlight to penetrate throughout the water column for the growth and survival of benthic plants as well as fish, crabs, and other aquatic organisms that use these macrophytes as habitat.

The threshold for water clarity was determined using the New York Harbor Coastal Condition Assessment (USEPA, 2015). The thresholds for water clarity, measured as secchi depth, are 0.7 , 1.1 , and 2.4 m, with measurements below 0.7 scoring a failing grade, measurements between 1.1 and 2.4 receiving a moderate grade, and measurements above 2.4 scoring a healthy grade. For each water clarity reading, the measurement was compared to these thresholds and assigned a value of 3 (best) to 0 (worst), so that scores can be calculated. The time period for this indicator is year round as water clarity is affected by nutrient pollution and chlorophyll levels year round.

2.3. Indicator scoring

Data was downloaded from the New York City Open Data website, and were cleaned in order to eliminate outliers or unrealistic measurements and data that was not relevant for this analysis (for example, DO was only analyzed for summer months so values for DO over winter months were removed) (NYC DEP, 2019).

Once thresholds were identified, sampling data from 1996–2017 were scored using the multiple threshold scoring method described above for each indicator. Multiple thresholds are used to score indicators based on a gradient of healthy to unhealthy conditions. For example, TP is an indicator of the amount of phosphorus in the water system. However, the amount of phosphorus, from acceptable levels, to just a little bit too much, to a truly excessive amount, can have different levels of effects on the ecosystem. Therefore, when the measured value of TP is compared to multiple thresholds, it can score low, medium, or high. This is similar to a grading scale, in which an A is excellent, a B is good, and a C is average. In this way, indicators can be assessed with greater precision than using a pass/fail method. Applications of multiple thresholds work well if divided into

Table 2

Indicator thresholds throughout the New York Harbor region and detailed scoring and descriptions relating grades to the health of an ecosystem.

What do the scores mean?					Insufficient data
80–100% Excellent A- to A+	60–80% Good B- to B+	40–60% Fair C- to C+	20–40% Poor D- to D+	0–20% Very poor F	
All or almost all ecosystems and communities indicators meet desired levels. Conditions in these locations are unimpacted or minimally impacted.	Most ecosystems and communities indicators meet desired levels. Conditions in these locations are lightly impacted.	Some ecosystems and communities indicators meet desired levels. Conditions in these locations are moderately impacted.	Few ecosystems and communities indicators meet desired levels. Conditions in these locations are very impacted.	Very few or no ecosystems and communities indicators meet desired levels. Conditions in these locations are severely impacted.	

several categories, corresponding to specific percentiles in the frequency distribution of the data (Tables 1, 2).

Once each indicator is compared to a multiple threshold scale, assigned a score, then averaged into a sub-region score, a grade can be assigned. For all indicators in the report card, the grading scale follows a 100-point grade scale of 0%–100%, with equal interval breaks until <20%, which is an F (Table 2). The grades that correspond to each score are also provided (Table 2). Additionally, each grade corresponds to a narrative explanation about corresponding ecological health (Table 2).

2.4. Trend analysis

Trends were assessed using a two tailed Mann–Kendall test. This test is regularly used in statistics to assess consistently decreasing or increasing time series trends, and allows us to assess the level of confidence (p value) in a trend over time (Colella et al., 2016). This test also provides a slope value for each trend, allowing us to determine whether each indicator had an improving or declining trend in health scores for over the 21 years we analyzed. Trends in nitrogen, phosphorus and chlorophyll *a* shown in Table 1 were considered to be “improving” if their raw collected values were decreasing, all other trends were considered to be improving if their calculated scores were increasing.

3. Results

3.1. New York Harbor's water quality health

Water quality health was assessed yearly from 1996–2017 in the 9 reporting regions of New York Harbor (Fig. 1). Based on this assessment, the best water quality was in the Lower Bay near the Atlantic Ocean entrance, and the most degraded water quality was in the dead end canals (Newtown Creek and Flushing Bay) and Jamaica Bay (Figs. 2; 3). The Hudson River, East River, Upper Bay, Newark Bay, and Raritan Bay were intermediate in water quality. Excess nutrient levels (TN and TP) were observed throughout New York Harbor, but water clarity, DO and chl *a* levels were variable (Fig. 2, Table 3). Water quality trends were also assessed between 1996–2017 in 9 different reporting regions. Overall, there were improving trends in many water quality parameters, especially TN.

Dissolved oxygen scores were generally very good in open waters of New York Harbor (Fig. 3d). The most severe degradation occurred in areas with minimal flushing in the dead end canals of Brooklyn and Queens (Newtown and Flushing Creeks). The East River and the Western Narrows of Long Island Sound also had poor to fair DO, as well as degradation in eastern portions of Jamaica Bay. Poor flushing likely also caused the slight depression in DO scores in Arthur Kill west of Staten Island.

Total nitrogen scores were generally very poor throughout New York Harbor waters (Fig. 3c). The only locations that had

slightly better scores (fair to poor) were the well flushed waters near Coney Island and Rockaway Point near the mouth of New York Harbor and in the Western Narrows of Long Island Sound (part of the Lower Bay region). High nutrient concentrations were found at all Hudson River sites, East River sites and around Staten Island, likely due to wastewater effluent sources.

Total Phosphorus scores were very poor throughout New York Harbor waters (Fig. 3b). Even worse than TN scores, the TP scores only had one location that did not score in the ‘very poor’ range. The location of the only ‘fair’ score was off of Rockaway Point at the approach to New York Harbor, where the Atlantic Ocean waters flush the harbor waters.

Chlorophyll *a* scores had the highest degree of variability of any water quality parameter investigated, with scores that ranged from ‘very good’ to ‘very poor’ (Fig. 3f). However, the ‘good’ and ‘very good’ scores are likely a result of turbidity that shaded out phytoplankton, rather than reduced eutrophication. The dead end canals off the East River and Jamaica Bay all scored ‘very poor’ with regard to chl *a*. The Hudson River and Upper Bay had ‘good’ to ‘very good’ scores; however, this is likely a result of excessive turbidity. The ‘good’ and ‘fair’ scores near Rockaway Point were likely a result of oceanic flushing.

The water clarity scores generally fell in the ‘very poor’ category throughout New York Harbor waters (Fig. 3e). The only locations that scored slightly better were near Coney Island, and the only ‘good’ score was at the Atlantic approach to New York Harbor. These locations benefited from oceanic flushing. The ‘poor’ water clarity scores were likely due to a combination of light absorption by excessive chl *a* (dead end canals, Jamaica Bay, around Staten Island, East River) and by excessive turbidity due to suspended sediments (Hudson River, Upper and Lower Bay).

The overall Water Quality Index was variable, with scores ranging from ‘good’ to ‘very poor’ (Fig. 3a). The best score (‘good’) was located at the approach to New York Harbor near Rockaway Point. The next best score (‘fair’) was located at two sites adjacent to Coney Island. There were ten sites with ‘poor’ scores, located in the Upper Bay and Lower Bay and one in the Western Narrows of Long Island Sound. The remaining thirty-five sites were located in Jamaica Bay, around Staten Island, Hudson River, and the East River.

The patterns of water quality conform with the flushing patterns that result from the complex tidal actions from Long Island Sound and the Atlantic Ocean that affect New York Harbor and from river flow from the Hudson River as well as the New Jersey rivers (e.g., Hackensack, Passaic, Rahway, Raritan Rivers). Other inputs include wastewater from multiple sewage treatment facilities and storm-water runoff from the largely impervious surfaces of New York City and surrounding urban development.

The best water quality was in the Lower Bay near the Atlantic Ocean entrance, and the most degraded water quality was in the dead end canals (Newtown Creek and Flushing Bay) and Jamaica Bay. The Hudson River, East River, Upper Bay, Newark Bay, and Raritan Bay were intermediate water quality. Excess nutrient

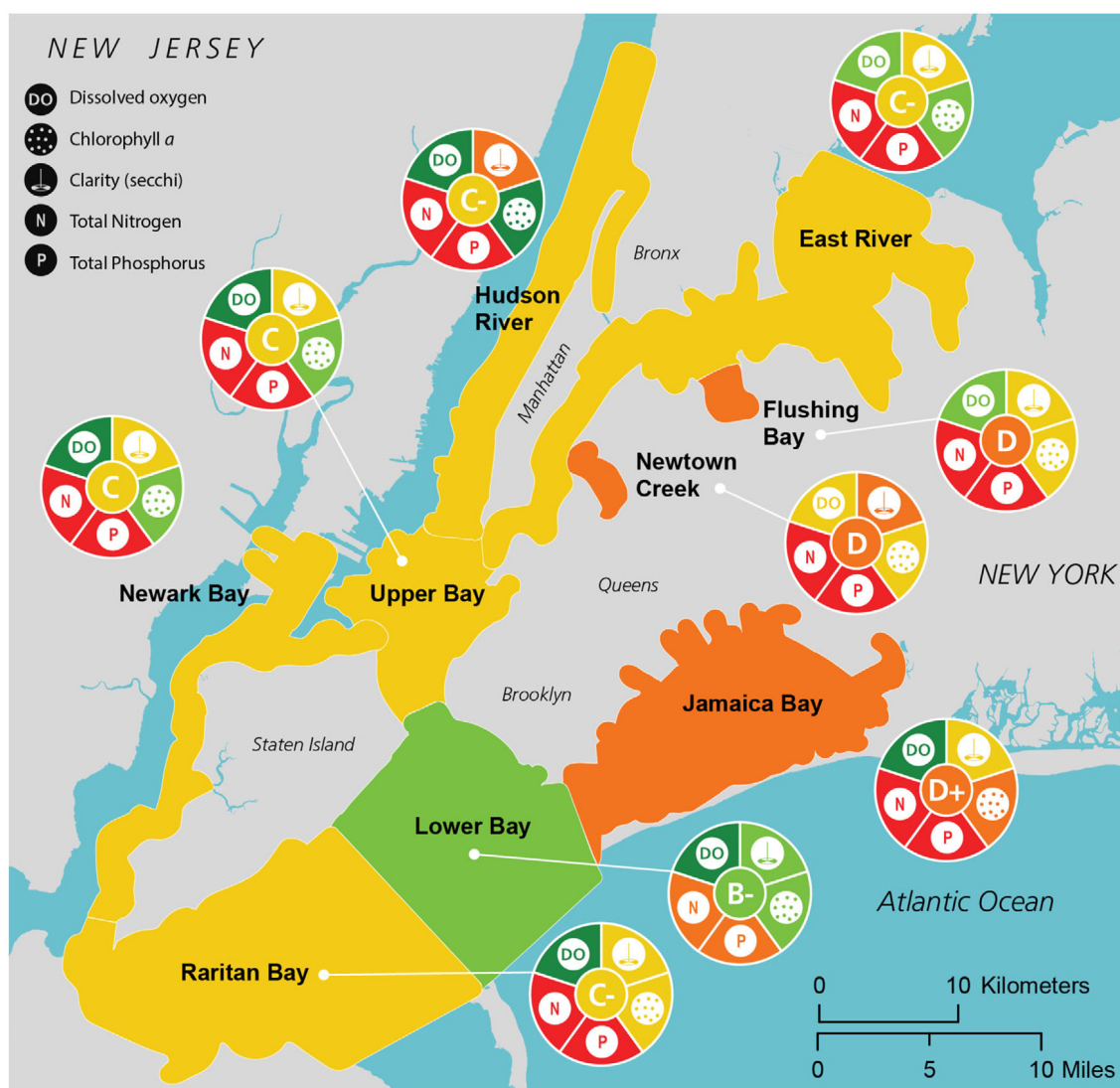


Fig. 2. Overall health (center circle color and grade), and health by indicator for each of 9 reporting regions from 1996–2017.

Table 3

Median measured values throughout each region from 1996–2017, along with trend and corresponding p -value (only trends with $p \leq 0.05$ were considered detectable) for trend estimation using the Mann–Kendall test. Colors of p -value boxes indicate whether a trend was not detectable (yellow), positive (green) or negative (red).

Region	TP (mg/l)	TP Trend	TN (mg/l)	TN Trend	chlA ($\mu\text{g/l}$)	chlA Trend	Clarity (meters)	Clarity Trend	DO (mg/l)	DO Trend
East River	0.17	0.23	1.26	0.00	5.80	0.40	1.21	0.00	5.28	0.73
Flushing Bay	0.23	0.75	1.60	0.00	9.74	0.05	0.91	0.07	5.38	0.76
Hudson River	0.13	0.09	1.21	0.01	2.71	0.05	0.76	0.13	5.97	0.53
Jamaica Bay	0.25	0.01	1.63	0.02	24.33	0.00	1.14	0.00	6.15	0.65
Lower Bay	0.09	0.97	0.86	0.02	5.80	0.04	1.91	0.06	6.95	0.03
Newark Bay	0.17	0.00	1.59	0.00	3.74	0.45	1.22	0.25	6.01	0.76
Newtown Creek	0.24	0.42	1.70	0.00	15.50	0.92	0.76	0.16	3.97	0.01
Raritan Bay	0.15	0.22	1.34	0.01	13.17	0.07	1.22	0.11	6.54	0.01
Upper Bay	0.14	0.69	1.26	0.05	2.81	0.06	1.41	0.00	6.11	0.86
Overall	0.17	0.87	1.34	0.02	5.80	0.07	1.22	0.00	6.01	0.24

levels (TN and TP) were observed throughout New York Harbor, but water clarity, DO and chl a levels were variable. Almost all regions showed improving trends throughout the 21 year time span, with the exception of the two healthiest regions, the Lower and Upper Bays.

Gradients in station health in Jamaica Bay, Lower Bay and Raritan Bay generally show improvement in water quality in well flushed, deep areas of the region while stagnant shallow water generally has poor water quality (Fig. 3). Regions throughout New York Harbor show patterns of healthier water quality in better

flushed areas and poorer water quality areas that are heavily influenced by runoff and are not well flushed.

3.2. Trends in water quality scores

Nitrogen inputs throughout New York Harbor waterways show a statistically significant improving trend ($p = 0.001$). Although on average, nitrogen scores were 'very poor', the score has improved significantly over the last two decades (Fig. 2, Table 3 shows raw measurement improvements). Many regions showed improvements from scores of 0 or 5 to close to 20. All regions

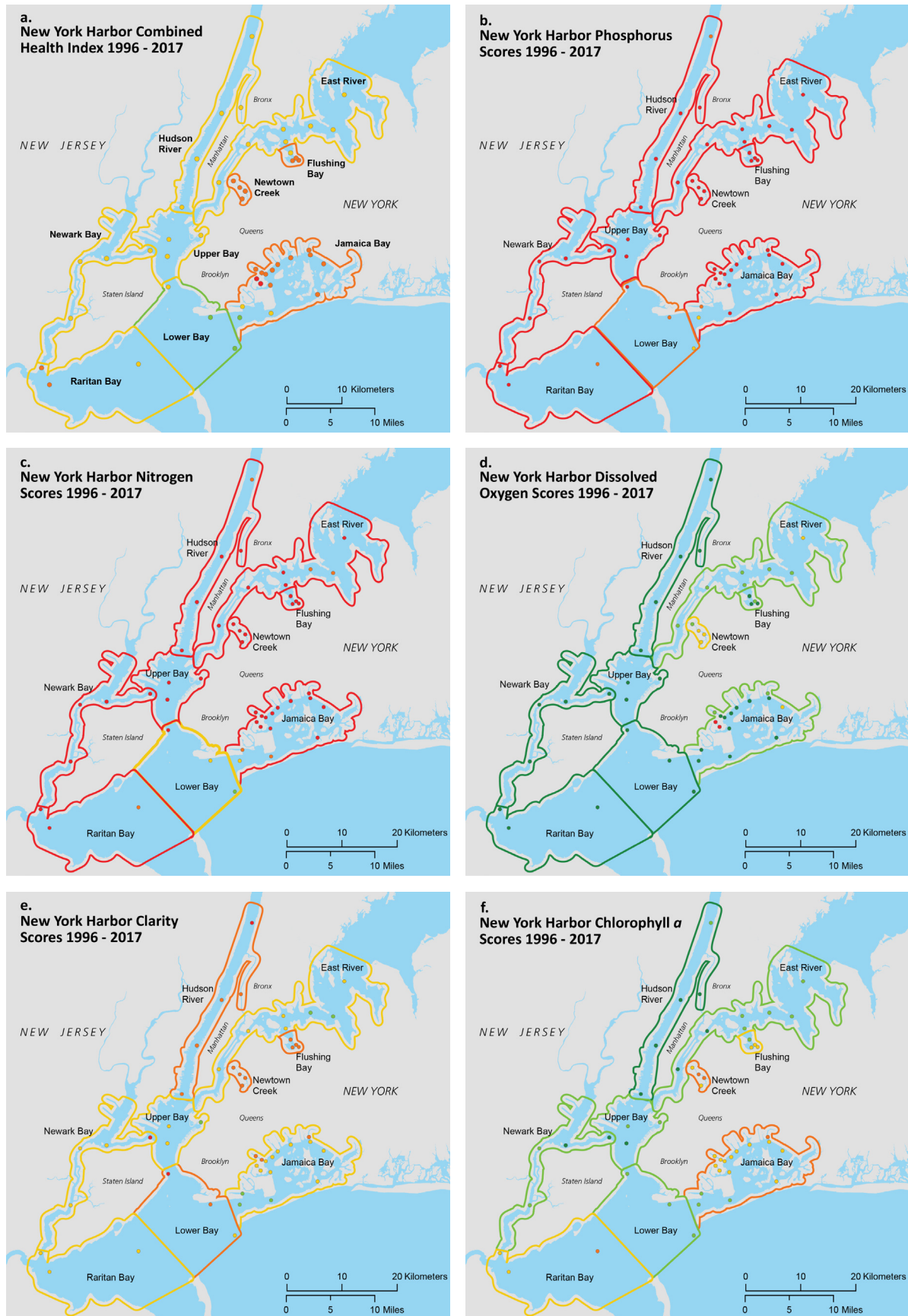


Fig. 3. Maps a-f show: a) 1997–2016 combined health index and specific indicator scores for each station within a reporting region; b) Total Phosphorus (TP); c) Total Nitrogen (TN); d) Dissolved Oxygen (DO); e) Water Clarity (as determined by Secchi Disk Depth values); f) Chlorophyll *a* (Chl_a). Regional outlines show region's overall health for each indicator, while the colors of each station show gradients in water quality throughout a region and differences in station health for each indicator.

showed a statistically significant improvement in TN indicating reduction in TN throughout the entire New York Harbor watershed defined in this analysis. Nitrogen improvements may have been aided by the long term effects of the implementation of both the Clean Air and Water Acts in 1970 and 1972, respectively.

Phosphorus inputs throughout the New York Harbor showed no significant trend, although they have a fairly low p -value ($p = 0.08$) that indicates more years of low P inputs could show an improving trend. The largest improvements in TP scores were found within Newtown Creek, Newark Bay, Raritan Bay, and the Hudson River. No regions showed a decline in TP scores within the New York Harbor watershed defined in this analysis, making it by far, the lowest scoring (worst) indicator within the watershed.

Water clarity measures (measured using secchi disk depth) throughout the Harbor have a declining trend, that is the visibility seems to be getting worse with a statistically significant downward trend ($p = 0.021$). The only regions throughout the harbor that do not show a declining trend in clarity scores are the Hudson River, Newtown Creek, Newark Bay and Raritan Bay.

Chlorophyll a levels throughout the Harbor show a statistically significant improving trend ($p = 0.032$). The only regions that do not show an improving trend for chlorophyll a throughout the Harbor are the Upper Bay, East River and Newtown Creek. Overall New York Harbor chlorophyll a scores improved from a C- in 1996 to a B- in 2017. This indicator is one of the major drivers in improvements in overall Harbor health.

Dissolved oxygen levels throughout the harbor show no significantly improving or declining trend. Dissolved oxygen is by far the healthiest indicator in the analysis. The only regions showing statistically significant improvements in dissolved oxygen were the Hudson River ($p = 0.024$) and Newtown Creek ($p = 0.003$). Newtown Creek region seems to be the only region suffering from critically low levels of DO.

4. Discussion and conclusions

The past two decades of water quality data analyzed in this study represent incremental changes in water quality, compared with the past couple of hundred years. New York Harbor water quality has experienced wide fluctuations over the course of European settlement (O'Neil et al., 2016). The largest changes occurred with the implementation of sewage treatment, and are likely not captured in this analysis. This analysis presents a foundation for understanding the health of the New York Harbor ecosystem and provides students and teachers with a resource to compare their field data to and to also encourage a deeper understanding of the science context in and out of the classroom. Additionally, it allows comparison with other regions and urban harbors, and provides a model mechanism for assessing the health of other waterways.

One of the most significant improvements in water quality trends is the reduction in TN that has occurred throughout the waters of New York Harbor, which is also evident in nearby Long Island Sound (IAN, 2016) and in the Chesapeake Bay (IAN, 2018). Much of this improvement in TN in the Chesapeake region has been attributed to reductions in atmospheric nitrogen deposition (Eshleman et al., 2013; Paerl et al., 2002). The decline in nitrogen deposition has been linked to less atmospheric nitrous oxides resulting from (a) reductions in power plant nitrogen emissions due to smokestack scrubbers and (b) reductions in automotive exhaust nitrogen due to catalytic converters (Taylor, 1993). The New York Harbor airshed includes the tri-state metropolitan area of the New York/New Jersey/Connecticut region, but also extends into the Ohio River Valley with numerable power plants and automobile traffic. Thus, the broad scale application of the U.S. Clean Air Act has likely helped make a broad regional impact on

the east coast and New York Harbor water quality has benefited from this management action as well, although this study does not directly link reductions in nutrient loads to improving air quality.

In contrast to improving TN and DO scores, the water clarity in New York Harbor is inexplicably declining. A similar strong decline in water clarity is occurring in Chesapeake Bay (Testa et al., 2019). The decline in water clarity observed in Chesapeake Bay is not simply due to increased phytoplankton, measured as chl a , nor due to an increase in total suspended solids (TSS). While there have, as of yet, not been any detailed water clarity analyses in New York harbor, similar trends in Chesapeake Bay may be indicative of a broad regional change that leads to water clarity declines (e.g. potentially increased rainfall and sediments runoff). Rainfall is transported via the Hudson and East Rivers into New York Harbor, which also transports nutrients and sediment, as well, that may affect water clarity (NYNJHEP, 2012). However, additional research is needed to elucidate the cause(s) of water clarity patterns and trends.

New York Harbor is composed of many different water bodies and the water quality patterns reflect this complexity. The Hudson River is a massive extended estuary. The New York/New Jersey Harbor Estuary (Hackensack, Raritan, Passaic Rivers) form estuaries in the western portions of New York Harbor (O'Neil et al., 2016). Jamaica Bay is a coastal lagoon separated from the ocean by a sandy barrier island. Western Long Island Sound represents the head of an extended open water sound. There are several dead end canals with restricted flushing like Newtown Creek, Flushing Bay and numerous canals in Jamaica Bay. There are also various narrow waterways (e.g., East River, Harlem River, Arthur Kill, Kill van Kull) that serve to connect waterways in New York Harbor. New York Harbor waterways have very different water depths, very different flushing times, and have been highly altered since European settlement (O'Neil et al., 2016). These factors have significant influence on the resulting water quality patterns. In addition to the diversity of waterways, there are a variety of significant point source inputs like the sewage treatment plant effluents and diffuse sources like stormwater runoff from the highly urbanized watershed that also influence water quality trends.

New York City operates multiple major sewage treatment facilities, which are generally at the level of secondary treatment. Secondary treatment removes the organic carbon through microbial degradation, but is not as effective in terms of the nutrient removal that is provided by tertiary treatment. In order to achieve further nutrient load reduction, New York will need to consider initiating widespread tertiary sewage treatment (Hall et al., 1999).

The water quality improvements in New York Harbor are a good start toward full ecosystem restoration that also include sediment rehabilitation and may lead to restoration of key habitats like the historic oyster reefs and salt marshes. The degree of sediment contamination with chemicals such as dioxins and PCBs in Newark Bay, will make this a difficult proposition, as will the restoration of oyster reefs and salt marshes (Lodge et al., 2015). But the water quality is an important step in ecosystem restoration.

The improving water quality trajectory that New York harbor has initiated with the upgrades in sewage treatment and stormwater controls should continue into the future for sustained impact (Waldman, 1999). Furthermore, positive ecological feedbacks will likely accelerate the positive trajectories. For example, improvements in water column DO can avoid anoxic surface sediments, which would cause release of nutrients from the sediments to the water column. Additional positive feedbacks include the restoration of oysters which can subsequently serve as biofilters (Janis et al., 2016). As long as bacterial contamination of New

York waters remains high, oysters and other shellfish are not considered edible, thus shellfish population increases and restoration for ecosystem services will contribute to the biofiltration capacity and enhance the water quality.

On a global scale, it is encouraging to see that the iconic port city of New York has improving water quality in some parameters. New York City has been an international, cultural hub with global impact, and a vibrant economic engine for the United States (Sekovski et al., 2012). New York City can serve as a model for ecosystem restoration, especially if improvements continue and biotic communities such as oysters are restored. However, predictions about the future health of the harbor are difficult, as the magnitude of climate-change leads to different scenarios for the region that will affect the estuary in different ways: one drier and the other more wet (Fitzpatrick and Dunn, 2019).

The World Harbour Project (WHP) is an international project that looks to understand and link similar pressures and solutions across harbors throughout the world (Steinberg et al., 2016), and this paper has quantified changes New York City has made to improve their ecosystem health (O'Neil et al., 2016). This analysis also provides a way of comparing other iconic harbors and waterways that have been collecting water quality data such as the Chesapeake Bay, Boston Harbor, Delaware Bays, and many more bays around the world. New York represents a place where green engineering, education, and ecosystem restoration can come together to provide a model for the growing number of coastal megacities on the planet.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank: P. Steinberg, E. Tanner (SIMS) and K. Leung (HKU) of the World Harbour Project for organizing this series of papers; B. Ranheim of the New York City Department of Environmental Protection (NYC DEP) for help with access to monitoring data. This work was supported by the National Science Foundation, USA STEM-C project DRL 1440869. This is UMCES Contribution #5717.

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