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New York Harbor: Resilience in the face of four centuries of development

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abstract

New York Harbor is a large, iconic and complex body of water that has been extensively modified to support the development of a megacity. These modifications have affected the shorelines, water flow, water quality, habitats and living resources of the harbor. Changes in topography and bathymetry have altered the landscapes and seascapes of the region, largely to support an active shipping port and intense human settlement. New York Harbor has been transformed from a region dominated by marshy shorelines, extensive submersed oyster beds and obstructed entrances to the present-day harbor with hardened shorelines, dredged shipping channels and remnant oysters that are unsafe to consume. However, improvements in water quality, largely due to sewage treatment upgrades, combined with the natural flushing ability of the harbor, have served to help restore or improve the ecological resilience of New York Harbor. Social resilience of the region has been tested with both terrorist attacks and the widespread inundation associated with *Superstorm Sandy*. Both ecological and social resilience will need to be enhanced to sustain the future development of New York Harbor.

1. Introduction

It is no coincidence that the New York–New Jersey Harbor Estuary is home to one of the most vibrant and economically important metropolitan areas in the United States, and the world (NYNJHEP, 2012). The rich resources of the estuarine environment and the intricate shoreline, islands and protective harbors made this region ideal for human settlement (NYNJHEP, 2012). New York Harbor, with its iconic skyline, is one of the most recognizable ports globally, due to its long history as an economic and cultural hub for commerce and trade. Given the extent of development and exploitation of the harbor over this extended period of time, it is not surprising that it has experienced severe environmental degradation. *The urban context of the NYNJ Harbor Estuary makes it one of the most challenging restoration and conservation environments in the nation* (Boicourt et al., NYNJHEP 2015). However, significant progress has been made over the last few decades in establishing conservation and restoration plans for the harbor, including improvements in water quality, with the overall health of the ecosystem now much better than it was 30 years ago (NYNJHEP, 2012). New challenges have presented themselves as well, including climate change, especially the impacts of inundation due to sea level rise, and potential increase in severe storm activity. The effects that can occur were clearly made evident in October 2012 with the landfall of *Superstorm Sandy*, which revealed the vulnerability of the surrounding community and infrastructure to such events. This review highlights some of the major features and challenges

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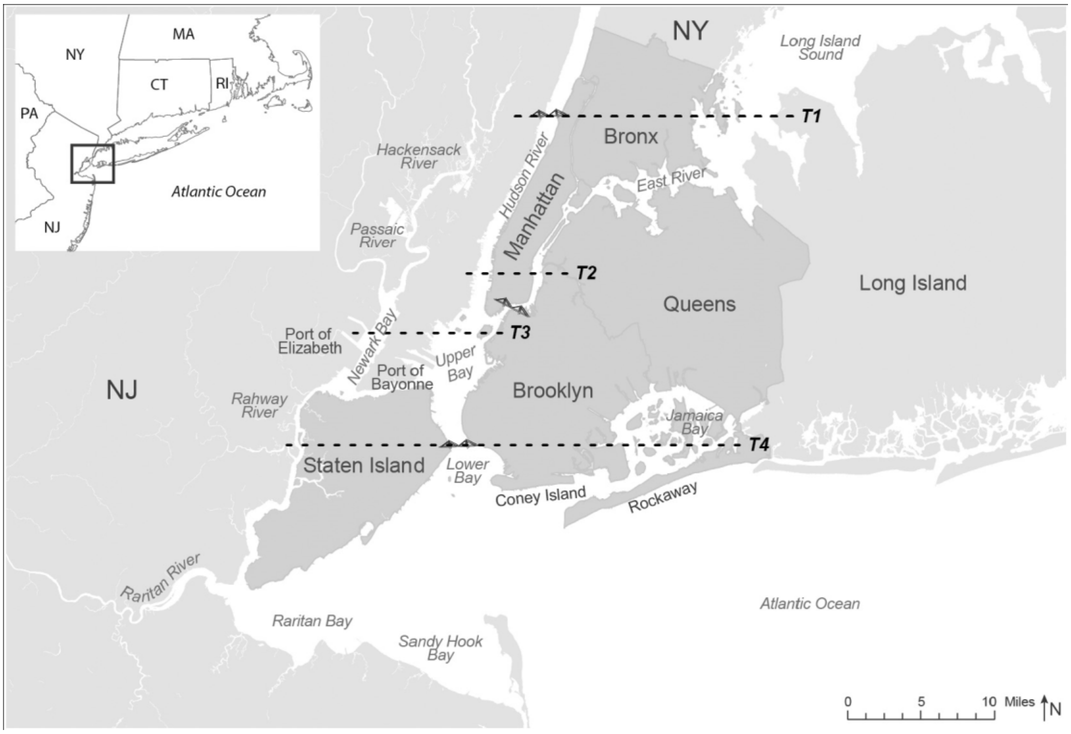

Fig. 1. The map of the New York Harbor region includes the five boroughs of New York City (Manhattan, Bronx, Queens, Brooklyn, Staten Island), Westchester County, New York, Nassau County on Long Island, New York and extensive regions of Northeast New Jersey. The complex waterways include the Hudson River and several New Jersey Rivers (Hackensack, Passaic, Rahway and Raritan Rivers), which all empty into New York Harbor. There are six bays that are contiguous with New York Harbor: Newark, Raritan, Sandy Hook, Lower New York, Upper New York and Jamaica Bays. There are two entrances into New York Harbor; Long Island Sound via the Western Narrows and East River, and the Atlantic Ocean via the Mid-Atlantic Bight and the entrance between Rockaway Point and Sandy Hook. Four parallel east–west transects were established to provide insights into the natural and man-made features of New York Harbor. From north to south, these transects were the following: T1-George Washington Bridge transect, T2-Mid-town Manhattan/Empire State Building transect, T3-Statue of Liberty transect, and T4-Verrazano Bridge transect. Each transect is described in following figures.

that face New York Harbor as a global partner in the World Harbour Project.

2. Geo-physical setting

2.1. Geomorphology

New York Harbor is in a unique geographic setting, adjacent to a large bight of the Atlantic Ocean between the states of New York and New Jersey and situated at the mouth of a major river (Hudson River), as well as several smaller rivers (Hackensack, Passaic, Rahway, Raritan Rivers). The Harbor is technically referred to as the 'New York–New Jersey Harbor Estuary'; however, for simplicity sake we will refer to it as 'New York Harbor'. New York Harbor comprises a large outer harbor (Lower Bay, Raritan Bay, Sandy Hook Bay, Rockaway Inlet) protected from the Atlantic Ocean by two sand barrier islands, Sandy Hook and Rockaway, and an inner harbor (Upper Bay), that is protected from the outer harbor by the Verrazano Narrows. New York Harbor is also situated at the head of a major estuary (Long Island Sound), and the region is dotted with islands and surrounded by coastal lagoons, like Jamaica Bay (Fig. 1).

The juxtaposition of so many geographic features in a relatively small area is quite unique, which makes New York Harbor so amenable to a diversity of activities and allows the region to support such a large and concentrated population. The availability of freshwater from the nearby Catskill Mountains, well-drained soils for food production on Long Island, and an abundance of fisheries, particularly oysters and finfish in the shallow waters in and around New York Harbor, have provided sustenance throughout its development (Sanderson, 2009).

New York Harbor has riverine features (Hudson River), estuarine features (Long Island Sound, Upper and Lower Bay) and oceanic features (Jamaica Bay, Sandy Hook, Rockaway Point). There are hills and low mountains nearby (New Jersey Palisades, Watchung Mountains), as well as extensive low-lying coastal land, with occasional rock outcrops. The tidal and non-tidal wetlands were extensive historically, with remnants still present. A complex mosaic of shallow waters and both natural and manmade deep channels are present (Steinberg, 2014).

2.2. Hydrology

New York Harbor is flushed by tides from the Atlantic Ocean and from Long Island Sound as well as by flow from the Hudson River. New York Harbor benefits from tidal flushing that occurs throughout the complex waterway network of the harbor. Diurnal tides provide a 1–2 m (3–6′) tidal range in the waters around Staten Island (e.g., Kill Van Kull, Arthur Kill, Raritan Bay), into Jamaica Bay through Rockaway Inlet, and throughout the Lower Bay and Upper Bay. The tide flushes the Hudson River all the way up to Troy, New York. Saltwater does not extend as far as the tide in the Hudson River, with the salt wedge migrating between Tappan Zee and Newburgh Bay, depending on freshwater flows (Levinton and Waldman, 2006). The tide also penetrates into the New Jersey rivers (e.g., Raritan, Rahway, Passaic and Hackensack).

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Another direction of tidal flushing into New York Harbor occurs from Long Island Sound. The tidal wave that propagates from Block Island Sound through the Race in Eastern Long Island Sound amplifies as it progresses westward. The tidal range is less than 1 m (3′) in Eastern Long Island Sound, but builds to 2–3 m (6–9′) in Western Long Island Sound, through the Narrows and into the East River. The timing of the tides from Long Island Sound and the Atlantic Ocean are offset, accounting for variations in the flood and ebb currents in the regions where the tidal energy overlaps (Steinberg, 2014).

The tides have provided a natural flushing of waste and pollutants discharged into New York Harbor, assisting populations of filter-feeding oysters, which require tidal flushing to feed. In addition, the tides were historically important for shipping, allowing sail-powered vessels to be carried into and out of the harbor on the tides, even when winds were unfavorable (Steinberg, 2014).

2.3. Habitats

Modern-day New York Harbor remains a complex of waterways, including rivers, coastal lagoons, and estuaries, with islands and peninsulas (Fig. 1). Four conceptual cross sections (east–west orientation) of New York Harbor were created to depict the salient features of modern day New York Harbor. The northern most transect, George Washington Bridge, extends from New Jersey, Hudson River, Manhattan Island, Harlem River, Bronx, Eastchester Bay, City Island, Long Island Sound, to Long Island (Fig. 2). The Mid-town Manhattan/Empire State Building transect extends from New Jersey, Hudson River, Manhattan, East River, to Brooklyn (Fig. 3). The Statue of Liberty transect extends from Newark Bay, Bayonne, Liberty Island, Hudson River, Governors Island, Buttermilk Channel, to Brooklyn (Fig. 4). The Verrazano Bridge transect extends from New Jersey, Arthur Kill, Staten Island, Verrazano Narrows, Brooklyn, Jamaica Bay to Queens (Fig. 5) (Crawford et al., 1994; Hurst et al., 2004; Levinton and Waldman, 2006; Muñoz and Panero, 2008; Sanderson, 2009; Strayer et al., 2012; Steinberg, 2014).

3. Historic and socioeconomic setting

3.1. History

New York Harbor was originally settled by the Lenape Native Americans. Europeans explored the region as early as 1524 (Giovanni Verrazano) and 1609 (Henry Hudson), with the initial European settlement beginning in 1624 by the Dutch (New Amsterdam), followed by English settlement. New York City has been a key entry point for immigration into the United States, both as an immigration center (e.g., Ellis Island), and as a settlement area (e.g., tenements) (Kurlansky, 2006).

When the early European explorers sailed into New York Harbor, they found massive oyster reefs and vibrant shallowwater ecosystems teeming with life. To the eyes of 17th century settlers the harbor and its many tributaries were a vast, seemingly limitless resource that served as not only a source of sustenance but also a convenient depository for their waste. This assessment of the Harbor was rather apt for the small colony of New Amsterdam; however, they could not have foreseen the creation of the metropolis that New York City is today and the major alterations of New York Harbor over the next 400 years (Kurlansky, 2006).

3.2. Population

New York City, home to about 8.5 million residents (USCB, 2014), has the third-largest population of the 23 partner cities, to date, in the World Harbour Project (exceeded only by Shanghai and Jakarta). The population of the metropolitan New York City area, including Long Island, New Jersey, lower Hudson Valley in New York State and Connecticut, is much larger, with close to 20 million residents (USCB, 2014), qualifying New York as a coastal megacity (Sekovski et al., 2012). The population rose exponentially throughout the 1800s, from about sixty thousand at the start of the 19th century to three million at the beginning of the 20th century. This immense population growth also brought with it massive growth of detrimental inputs to New York Harbor and its tributaries, specifically from human and industrial waste disposal (Steinberg, 2014). After about 1950, the population growth in New York City declined precipitously, and, despite some significant fluctuations, the population as measured in the 2010 census was only about 3.5% larger than that registered in 1950 (USCB, 2010). Population growth for New York State as a whole has been similarly stable over approximately the last six decades, whereas rapid growth in New Jersey, on the western side of the harbor, continued through about the 1990s, slowing to about 0.4% per year since 2000 (USCB, 2010). New York has seen a surge of population in the past several years, mirroring high economic growth since the ''Great Recession''; however, this is unlikely a long-term-trend as The New York City Department of City Planning predicts longterm growth of about 0.3% (Salvo et al., 2013). Economic patterns in both the Hudson Valley and Raritan basin have shifted over the last fifty years from manufacturing toward services, including finance, healthcare, software development and transportation (Orr and Topa, 2006; BLS, 2015). It is anticipated that the major human impacts on the harbor over the next several decades (other than potential climate change effects), will be similar to those of the recent past.

3.3. Development of the harbor

Humans have been affecting the New York Harbor Estuary for over four hundred years, with the most significant influences occurring in ∼the last 150 years (Suszkowski and D'Elia, 2006). The development of New York Harbor can be split into four periods: Pristine Estuary (1609–1800), Expansion Period (1800–1900), Degradation Period (1900–1970), and the Improvement Period (1970–present). During the Pristine Estuary Period oyster reefs were so numerous that they presented navigational obstacles to shipping, extensive marshes filtered runoff and provided habitat to fish and shellfish, and the harbor seafloor was largely un-impacted. The Expansion Period (1800–1900) was when the population of New York City was exponentially rising, increasing from 60 thousand to 3 million (USCB, 1999). This rapid population growth was accompanied by increases in the disposal of human and industrial waste into the harbor. New York City residents began to view the harbor as a 'noxious eyesore', with regular beach closings and a dramatic loss of oysters. During this phase the city also responded to the expanding economic needs of shipping through dredging channels, as well as industry construction and the filling in of wetlands (Suszkowski and D'Elia, 2006). During the Degradation Period major shoreline alterations took place, and there were large discharges of untreated human sewage and industrial waste into the harbor. The Metropolitan Sewerage Commission began comprehensive surveys of the condition of New York Harbor in 1906 (see below), finding that around 600 million pounds of untreated raw sewage

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was being dumped into the harbor each day (Waldman, 1999). New York City began its annual Harbor Survey Program three years later in 1909, beginning with information on dissolved oxygen, bacterial counts, turbidity, salinity, and temperature gathered from 12 monitoring stations around Manhattan. The results found significantly degraded water quality, excessively high coliform levels, and low dissolved oxygen levels. The Improvement Period in the latter half of the 20th century began with the formation of the US Environmental Protection Agency in 1972, the passage of the federal Clean Water Act, and the establishment of various Non-Government Organizations, such as the Hudson River Sloop

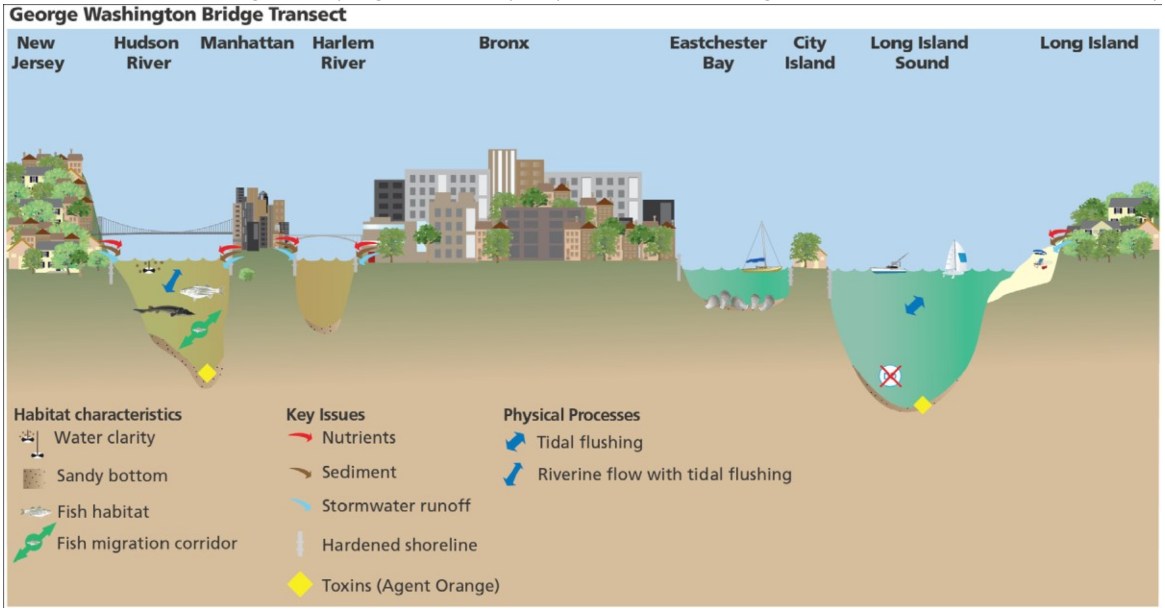

Fig. 2. George Washington Bridge transect (T1). A cross-section extending from Fort Lee, New Jersey, through the Hudson River, across the northern tip of Manhattan, through the Harlem River, across the Bronx, through the Western Narrows of Long Island Sound (including Eastchester Bay, City Island and Long Island Sound) and into Long Island is depicted. The New Jersey Palisades with residential development are adjacent to the George Washington Bridge (opened in 1931). The Hudson River is deep (18+ m; 60′) and turbid. Both sides of the northern tip of Manhattan have hardened shorelines and the Harlem River is relatively shallow (<5 m; <16′) and turbid. The Bronx is largely residential development with apartment buildings and houses, and hardened shorelines. The Western Narrows of Long Island Sound has a shallow (<2 m; <7′) embayment; Eastchester Bay, primarily residential City Island and a deep channel (30+ m; 100+′) between City Island and Long Island. The principal issues with Long Island Sound are hypoxic bottom water due to phytoplankton decomposition and toxic-laden sediments. Long Island beaches and residential development on glacial moraine derived sandy soils lead to groundwater inputs. Storm-water runoff and sewage treatment effluents lead to large nutrient inputs.

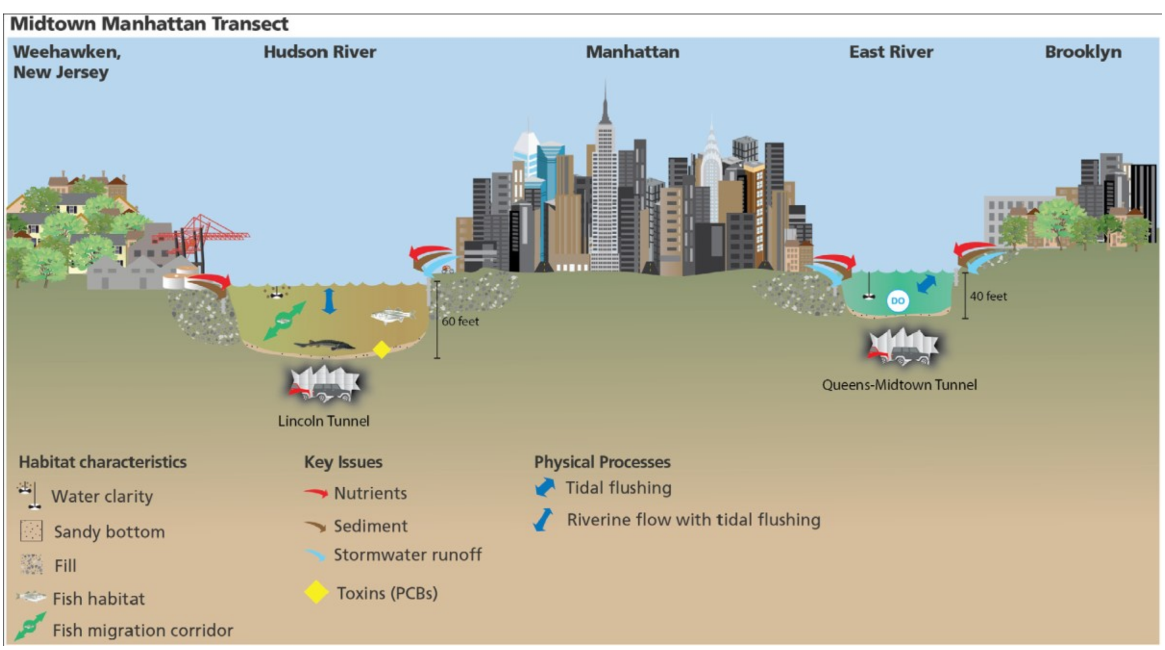

Fig. 3. Mid-town Manhattan/Empire State Building transect (T2). A cross-section extending from Weehawken, New Jersey, through the Hudson River, across midtown Manhattan Island and the Empire State Building (~33rd St), through the East River and into Brooklyn is depicted. The Lincoln Tunnel (opened in 1937), which is 30 m (100′ deep) under the Hudson River and Queens-Midtown Tunnel (opened in 1940), which is 30 m (100′ deep) under the East River are depicted as well. The New Jersey Palisades form a high bluff with residential development and the landfill along the Hudson River

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supports port development. The Hudson River is deep (15+ m; 50+′) and turbid with a combination of tidal flushing and river flow creating turbulence. Hudson River sediments have high levels of toxicants, in particular, PCBs from an upriver General Electric plant. Hudson River serves as a fish migration corridor, including Atlantic sturgeon and striped bass. Manhattan Island has hardened shorelines and landfill on both sides, supporting bikeways and roads and commercial buildings. The midtown skyscraper region of Manhattan has the Empire State Building (opened in 1931; 400+ m; 1454′) dominating the skyline. The East River (∼12 m; 40′) has vigorous tidal flushing from both Long Island Sound and New York Harbor. Brooklyn has a hardened shoreline and a combination of commercial and residential development. Inputs to the Hudson and East Rivers are dominated by storm-water runoff and sewage treatment effluents, resulting in high nutrient levels. The turbidity prevents excessive phytoplankton blooms and the turbulence due to tidal flushing prevents low dissolved oxygen levels.

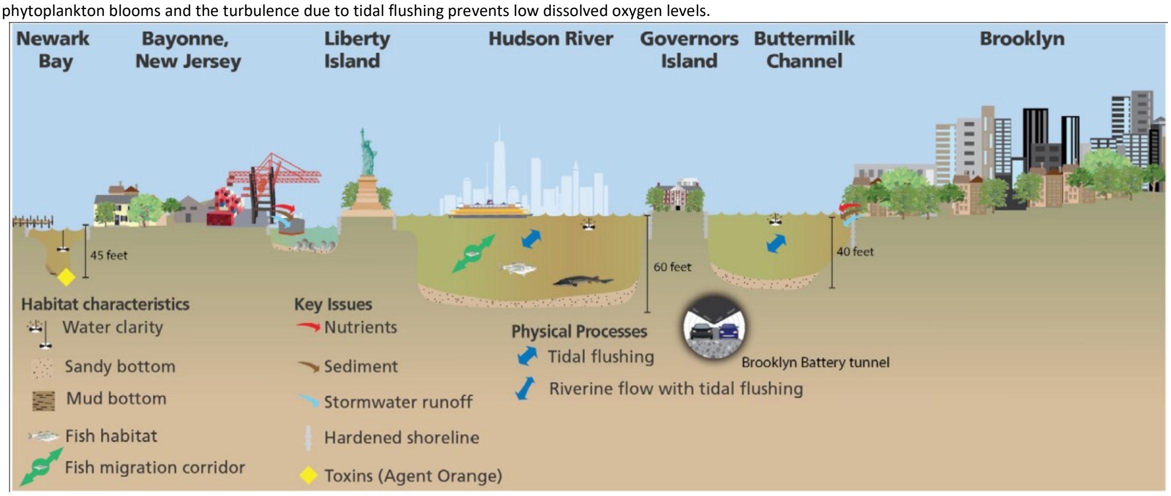

Fig. 4. Statue of Liberty transect (T3). A cross-section extending from Newark, New Jersey, through Newark Bay, across Bayonne, New Jersey, across Upper New York Bay with two islands (Liberty Island and Governors Island) and Buttermilk Channel and into Brooklyn is depicted. Newark Airport, oil storage tanks and oil tanker terminus are depicted on the Newark shoreline. Newark Bay is shallow (<3 m; <9′), apart from a deep shipping channel (North Reach = 6.5 m; 21′) with muddy sediments that contain toxins, particularly dioxins (e.g., Agent Orange). Bayonne, New Jersey is a low-lying residential and commercial developed area with hardened shorelines, landfill and container ship terminals. Liberty Bay is a shallow embayment of Upper New York Bay with oyster reefs. Liberty Island is known for the Statue of Liberty (opened in 1886), which is an iconic 93 m (305′) high monument. Liberty Island was formally known as Bedloe's Island or as one of the Oyster Islands, and was historically just above high tide. Landfill and hardened shorelines have stabilized the island so that it is 4 m (12′) above the high tide level. Upper New York Bay is 10–20 m (32–64′) deep and is transited by passenger ferries, water taxis and commercial shipping. Water quality is dominated by Hudson River flow and tidal flushing and the Upper Bay serves as a fish migration corridor. Governors Island was the landing place of the first European settlers, and is a former US Army base, US Coast Guard base and now owned by New York City and US National Park Service. The southern portion of Governors Island was created with landfill in the early twentieth century. The Brooklyn–Battery Tunnel, the longest underwater vehicular tunnel in North America, passes underneath Governors Island at a depth of 43 m (140′) with a large ventilation shaft on Governors Island. Buttermilk Channel separates Governors Island from Red Hook, Brooklyn. This channel was originally shallow enough for cattle to cross at low tide (hence the name), but now is deeper (12 m; 40′) and well flushed via the East River. Brooklyn has significant landfill and hardened shoreline with docks and piers, and a combination of commercial and residential development.

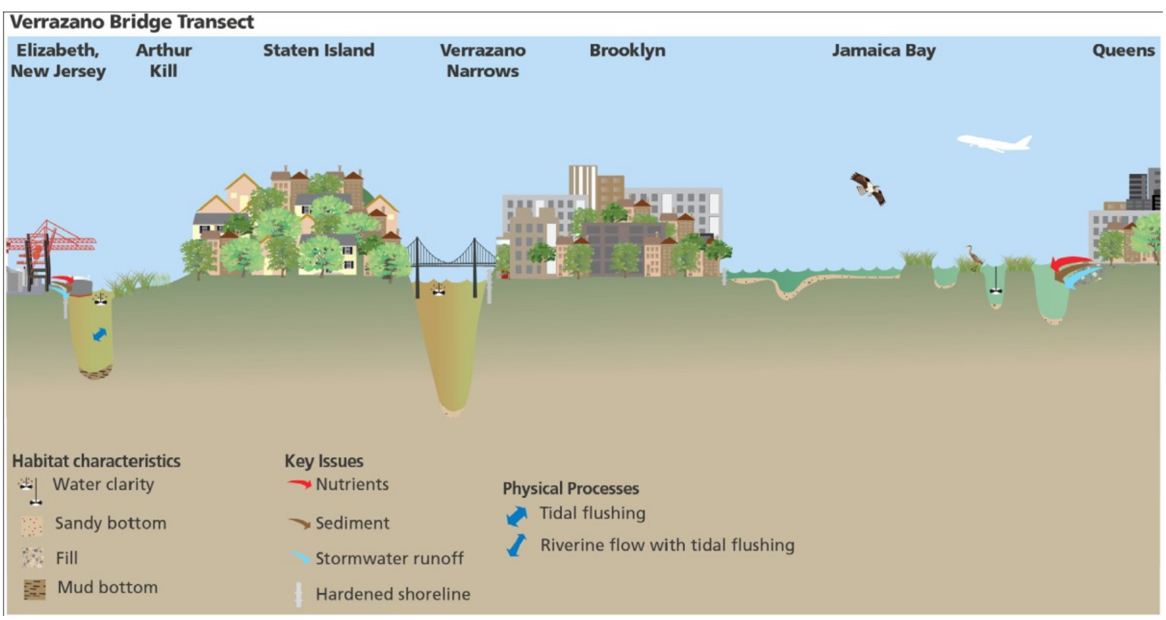

Fig. 5. Verrazano Bridge transect (T4). A cross-section extending from Elizabeth, New Jersey, through Arthur Kill, across Staten Island, through Verrazano Narrows separating Upper and Lower New York Bay, across Brooklyn, through Jamaica Bay and into Queens, is depicted. The Elizabeth, New Jersey shoreline is hardened and supports industrial development. Arthur Kill is maintained as a dredged shipping channel (11 m; 35′) with poor flushing. Staten Island has a marshy shoreline and primarily residential development with appreciable topography. The Verrazano Bridge (opened in 1964), spans the Verrazano Narrows (1298 m; 4260′), which is very deep (69.5 m; 228′) and is heavily used by commercial shipping. Brooklyn is primarily residential with houses and apartment buildings. Jamaica Bay is historically very shallow, but dredging has created some deep regions (15+ m; 50+′), especially near JFK International Airport. Jamaica Bay has extensive marshes and a landfill island in the center and is largely managed by the National Park Service as part of Gateway National Recreation Area (established in 1972). The New York City borough of Queens is east of Jamaica Bay and is
low-lying land with residential development.

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Clearwater. Wastewater treatment facilities were constructed and upgraded to reduce the organic and nutrient loading into New York Harbor. The production of dioxins and polychlorinated biphenyls (PCBs) was banned. Water quality improvements were observed, although residual persistent sediment contamination remains (Lodge et al., 2015). Another critical remaining issue is that of Combined Sewer Overflows (CSOs); this aging water infrastructure means that when rainfall events and associated storm-water runoff overwhelms the capacity of sewage treatment facilities, pulsed discharges of untreated sewage into the harbor result (Steinberg, 2014; NYCDEP, 2016).

4. Threats

4.1. Pollution

New York Harbor is one of the most well-researched, monitored, and documented harbors in the World Harbour Project. The wealth of information about the types and extent of pollution that this estuary has been subjected to over the last century began to be compiled over a century ago, with the realization of the obvious depletion of its resources. By the beginning of the 20th century New York City residents and business owners saw the harbor as a 'noxious eyesore', beaches were often closed and the oyster beds were all but gone (NYCDEP, 2009).

4.1.1. Sewage

The Metropolitan Sewerage Commission began comprehensive surveys of the condition of New York Harbor in 1906 (see above). Currently, the New York City Department of Environmental Protection conducts regular water quality monitoring at dozens of sites throughout the New York Harbor region. Today when New York City experiences high rain flows, some sewage flows into the Harbor without secondary treatment. At the present time 4500 of New York City's 6300 miles of sewer are combined into 730 CSOs around the harbor (Waldman, 1999). Redesigning a sewage treatment system used by 9 million people is an extremely expensive and timeconsuming process, although New York has been making strides by creating large storage tanks that hold between seven and thirty million gallons of overflows during wet periods until they can be treated during dry periods (Waldman, 1999). Average harbor-wide bacteria levels have fallen from the early 1970s due to considerable investments in wastewater treatment infrastructure, and have remained stable since the mid-1990s (NYNJHEP, 2012). However, many areas need substantial improvements before being considered safe for swimming. Additionally, contaminants and dissolved oxygen problems in some areas (particularly semi-enclosed canals) are still challenges throughout the harbor. Significant overflows occurred during *Superstorm Sandy* and plans are in place to upgrade infrastructure to deal with the problem of low-lying locations of the majority of the waste-water plants, and future scenarios of inundation (NYCEDC, 2013).

4.1.2. Nutrients

The New York Harbor and lower Hudson Estuary have a long history of biologically important nutrient pollution (Ayres and Rod, 1986; Ayres et al., 1988; Lee et al., 1982; Bopp and Simpson, 1989; Gottholm et al., 1993; Brosnan, 1991; Clark et al., 1992; Phillips and Hanchar, 1996; Rod et al., 1989). Water quality affects plant and animal colonization and growth. Nutrient loading, in particular, is a critical factor in the ecological health of harbor ecosystems (O'Shea and Brosnan, 2000), which has been an intense focus of research (e.g., Brosnan and O'Shea, 1996a,b) and remediation. Heavy nutrient loads 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 (Findlay and Sinsabaugh, 2003; Findlay et al., 1998; Clark et al., 1995; Cole and Caraco, 2006). Nutrient loading in the New York–New Jersey area 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, 1982). Nonetheless, the relationship between nutrient inputs to surrounding watersheds and carbon-cycle dynamics in the river is not well understood (Arrigoni et al., 2008).

Non-point-source nutrient runoff continues to be a major concern in the region. The federal Environmental Protection Agency has recently entered into Long-Term Control Plans with municipalities upstream of New York Harbor, including New York city and Newark, New Jersey's largest City, to address CSOs. These will ultimately reduce organic effluents and consequent oxygen depletion and nutrient pulses (NYSDEC, 2016a; NYCDEP, 2016). However, tertiary treatment to reduce nutrient loads from major waste processing facilities is not currently required. Despite municipal interest and several pilot programs (NYCDEP, 2011) there is no evidence of large-scale investment on a scale relevant to the NYC waste treatment system. Thus, in the near term we expect nutrient loading in municipal effluents to grow modestly with regional population. There are strong environmental movements in both states (e.g. Riverkeeper, 2016), which are likely to keep a focus on nutrient removal, and strong environmental agencies at the municipal and state level, especially on the New York side of the harbor. Thus, the long term (perhaps several decades in the future) prospects of addressing nutrients in the harbor are reasonable, limited mainly by infrastructure budgets.

4.1.3. Garbage

New York City's problem of waste disposal grew larger and larger as the population expanded over the city's four centuries of development. Two examples that highlight the way New York has dealt with its waste issues in relation to the Harbor are the creation of Deep Water Dump Site 106 and the fallacy of the 'garbage barge' incident of 1987. New York City's mindset throughout the 19th and 20th century was essentially 'out of sight, out of mind'; however, as is often the case, the effects of pollution come back 'into sight' when their impacts on the environment take hold (e.g. algae blooms and bacterial diseases from CSOs (Waldman, 1999) or fin rot from PCBs (Mahoney et al., 1973)).

Deep Water Dump Site 106 is a Municipal Sewage Sludge dumpsite about 106 miles southeast of New York Harbor just over top of the continental slope (Bruno, 1996). Sewage sludge was discharged in this location at depths of about 2200–2700 m from 1986 to 1992; the controversy over the effect of the harmful particles began at the outset and continues to be researched today. The bulk of solids discharged at the site were fine-grained, slowly settling sludge particles, which disturbed the biology of deep-sea communities by attracting more benthic communities that could consume the sludge-derived organic matter (Collie and Russo, 2000). Studies over the next few years showed high uptake of toxic chemicals in the rich and diverse communities of the deep sea (Collie and Russo, 2000).

In the spring of 1987 the issue of garbage disposal in New York City became so dire that a municipal waste manager decided to bundle up three thousand tons of garbage and ship it to southern states. This business idea turned into a worldwide spectacle as city after city rejected the barge, as attention and fears of biohazardous waste grew. The barge became a symbol for the United States' growing waste disposal problems and was the beginning of a surge in recycling and awareness of the need for responsible and sustainable garbage disposal.

In the wake of this historic pollution, actions have been taken to stem the tide. The Ocean Dumping Ban Act was passed in 1988 and enforced in 1992, ending dumping in what would be the largest dump of sludge ever to occur in the deep ocean (Bruno, 1996). Additionally, in 1989, a working group of federal, state, and local partners convened by the NYNJ Harbor & Estuary Program developed a Floatables Action Plan (FAP) that has resulted in the removal of over 400 million pounds of floatable debris since its inception (NYNJHEP, 2012). Additionally, beach closures declined significantly after the FAP implementation. In 2014, the US Environmental Protection Agency launched an effort to control, reduce, and track down sources of garbage through its *Trash Free Waters* initiative, a highly collaborative effort focusing on targeted reductions in waste.

4.1.4. Chemical contamination

Industrial contamination has been a major source of pollution in New York Harbor. Large quantities of polychlorinated biphenyls (PCBs) and dioxins were found in dredged sediments in the mid20th century. PCBs and dioxins deposited in New York Harbor sediments bioaccumulate and pass upwards through the food chain, eventually finding their way into human diets (Bopp et al., 2013). New York State Department of Health has issued annual fish consumption advisories for many species of fish such as weakfish, bluefish, striped bass, and blue crab in the area, more often than not recommending with signage that people ''DON'T EAT'' (NYSDOH, 2015). Since 1997, data have been collected through the Contamination Assessment and Reduction Project (CARP) to better understand how contamination is distributed and moves throughout the system (Lodge et al., 2015). Although water quality indicators such as dissolved oxygen, nitrogen, phosphorus, and chlorophyll *a* are not currently indicative of a declining trajectory and may be improving, PCBs, dioxins and furans, mercury, and polyaromatic hydrocarbons (PAHs) are perpetual problems because of 'estuarine trapping' (Lodge et al., 2015). Estuarine trapping is the process by which contaminants in New York Harbor are re-suspended each tidal cycle and carried back upstream into the Hudson River, only to be brought back down to the Harbor once more at the end of the cycle. General Electric's plants on the upper Hudson River deposited a total of 1.3 million pounds of PCBs into the Hudson River between 1940 and 1977 (EPA, 2002). PCBs continued to leak from the two plants over the next 30 years and remain in the ecosystem to date (EPA, 2002). Removal of some of this and other areas of contamination is in process or planned for the coming years through the Superfund Program, targeted dredging, or other efforts to control sources, but contamination remains a long-term challenge.

4.2. Shoreline development and threats to biodiversity and function

New York Harbor is an extensively modified harbor, providing oceanic access through two separate entrances; one via Long Island Sound and the East River, and another via the Atlantic Ocean gateway between Sandy Hook and Rockaway Point and through the Verrazano Narrows. Historically, shoals in front of the Atlantic Ocean harbor entrance, as well as the islands in the Hell Gate portion of the East River, made navigation difficult and dangerous. Steam dredging of the Ambrose Channel and demolition of Hell Gate obstructions in the late nineteenth-century facilitated navigation. Twentieth-century dredging and coastal landfills served to provide port facilities for the New Jersey, Staten Island, Manhattan and Brooklyn shorelines. The current area of Upper New York Bay is only 75% of its historic area due to extensive filling activities. Beginning with the iconic Brooklyn Bridge and the Holland Tunnel, the waterways of New York Harbor have been repeatedly spanned by pioneering engineering feats. Dredging, development, filling, and pollution caused habitat loss, notably a loss of 85% of tidal wetlands in the New York–New Jersey Harbor Estuary in the past century (NYCEDC, 2012).

4.2.1. Hardening of shorelines

There was minimal consideration of shoreline ecology in the designs and materials used in traditional shoreline stabilization techniques (Chapman and Underwood, 2011). Humans often alter shore zones to protect human life and property and to facilitate activities such as shipping, construction of roads and buildings and water-based recreation. In the New York Harbor estuary, surge from coastal storms are recognized as the most significant climate-related risk to coastal areas and parklands in the coming years (NYCEDC, 2013). In 2006, it was estimated that 36% of all shoreline in the NY–NJ Harbor Estuary was hardened, though that number reached as high as 87% in the Upper Bay (Bain et al., 2007). Coastal protection initiatives outlined by the City of New York to mitigate future storm impacts include hardening or otherwise modifying shorelines, reinforcing or redesigning bulkheads and retrofitting or hardening waterfront park facilities (NYCEDC, 2013). Thus, examination of the potential ecological impacts of shoreline modification is key to developing effective coastal protection and storm mitigation that also minimizes negative impacts on habitat quality and ecological communities.

Generally, it seems likely that biodiversity and biogeochemical processes are highest in shoreline types that are wide and gradually sloping (rather than narrow and steep), physically complex and heterogeneous, physically continuous (rather than fragmented by inhospitable habitat like smooth, vertical steel metal or concrete), well-vegetated (preferably with native plants), are capable of retaining wrack and driftwood in the long term, where recreational use is modest and/or localized, and where the physical energy inputs and hydrologic regime have not been dramatically altered (Bulleri and Chapman, 2010; Strayer et al., 2012). It is worth noting that many built shore types (e.g., bulkheads) that are common around New York Harbor score poorly on many or all of these criteria.

Alterations to shorelines within urban estuaries often produce a characteristic set of changes including narrowing and stabilization of shore zones (Tockner and Stanford, 2002; Airoldi and Beck, 2007; Winn et al., 2005; Miller et al., 2006; Fujii and Raffaelli, 2008), changes to the natural hydrological regime (Nilsson et al., 2005), shortening and simplification of the shoreline (Sedell and Froggatt, 1984; Tockner and Stanford, 2002; Miller et al., 2006), hardening and steepening of the shoreline (Miller, 2005; Airoldi and Beck, 2007; Strayer et al., 2012), 'tidying' of the shore zone (e.g., removing wrack and driftwood, cutting vegetation; Malm et al., 2004), increasing inputs of physical energy to the shore zone (as a result of increased boat traffic, dredging, and building out into the channel; Strayer and Findlay, 2010), pollution by a wide range of substances including xenobiotics (Strayer and Findlay, 2010), disturbance from recreational use of the shore zone (Asplund, 2000; Pinn and Rodgers, 2005; Davenport and Davenport, 2006), introduction of nonnative species (Hill et al., 1998; Airoldi and Beck, 2007), magnified effects of climate change (including local heat island effects), (Strayer and Findlay, 2010; Kirwan and Megonigal, 2013), and construction of buildings and impervious surfaces in and near the shore zone, thereby fragmenting remaining shore zone habitats (Strayer and Findlay, 2010).

These changes in turn probably cause a characteristic set of changes to ecological functioning of urbanized shore zones, although an 'urban shore zone syndrome' analogous to the 'urban stream syndrome' of Walsh et al. (2005) has not been systematically described. Nevertheless, the following effects on ecological functioning have been demonstrated in some cases, or seem likely. Activities such as narrowing of the shore zone, shortening and simplifying of the shoreline, and increased disturbance from recreation, should decrease local biodiversity and rates of many biogeochemical processes. Changes to hydrological and disturbance regimes, pollution, climate change, and species invasions could substantially change biodiversity and biogeochemical cycling in unpredictable ways, depending on the details of these changes. Steepening shorelines and increasing physical energy inputs to shorelines may select for a more disturbance-resistant biota. Increased cover by impervious surfaces will degrade rates of biogeochemical processes and habitat quality for species, as well as causing rapid runoff of water and pollutants after storms, potentially leading to local erosion or toxicity in the shore zone. Many of these activities should substantially reduce the effectiveness of urban shore zones as dispersal corridors. The net effect of these changes on the ecological functioning of urban shore zones may be large and often complex (Bulleri and Chapman, 2010; Strayer et al., 2012).

4.2.2. *Ecological function in urban shore zone*

Analyses of ecological functioning in the urban shore zones of New York Harbor have often found differences between the highly modified areas and more 'natural' areas of shoreline habitat (Kurlansky, 2006). For example, passive fish traps were used to show that juvenile fishes preferentially inhabit wooden pile fields and open-water habitats over those under large piers (Able et al., 1998). Specifically, only 14 of the 25 fish species found during the study occurred under piers (Able et al., 1998). However, despite anthropogenic disturbances, some habitats in the lower Hudson River still appear to act as a nursery area for some fish species (Able et al., 1998, 1999). Conversely, Reid et al. (2015), as part of their development of a standardized habitat assessment protocol for urban shorelines, found no clear differences in the biological communities occupying hardened shorelines and those occupying 'enhanced' or more natural shorelines, such as riprap, in the New York Harbor Estuary. Moreover, site-specific differences were much more pronounced than any effects of local habitat modification (Reid et al., 2015). Although data from this study were insufficient to attribute causal mechanisms, simply modifying habitat at small scales may be insufficient to bring about lasting ecological change along shorelines. Rather, consideration of local conditions such as water quality, flow rates and directional water movement and sedimentation, as well as long range factors such as larval supply, will also be important (Bone, 2015).

4.2.3. *Shoreline restoration*

Over the past 40 years, there has been increasing interest in restoring aquatic ecosystems (e.g. Bohn and Kershner, 2002; Elliot et al., 2007), coinciding with a situation where much of the existing shoreline stabilization infrastructure requires maintenance or rebuilding. As shorelines are replaced, new and ecologically enhanced designs may be viable in some situations. Considerably more estuarine research has been devoted to restoration of softsediment ecosystems than to those with hard substrates, but it is recognized that in many locations it is not feasible to return hardened shorelines to unconsolidated sediment (Chapman and Blockley 2009; Bulleri and Chapman, 2010; Brown and Chapman, 2011). Increasing the habitat complexity and/or using more natural materials on hardened shorelines may prove beneficial to natural communities (Airoldi et al., 2005; Bulleri and Chapman, 2010; Chapman and Underwood, 2011), and is the focus of numerous experimental and construction projects in urban estuaries globally. Regionally, there has been much interest in shifting toward these lower-impact stabilization alternatives, shown by efforts such as Hudson River Sustainable Shorelines, the development of Waterfront Edge Design Guidelines, and efforts to develop methods to assess the habitat quality of urban shorelines. The *Hudson–Raritan Estuary Comprehensive Restoration Plan* (US Army Corps, Port Authority and NY/NJ HEP 2014) outlines 12 target ecosystem characteristics (TECs) in recognition of the complexity of any habitat rehabilitation project within the New York Harbor region.

4.3. *Sea level rise/inundation and potential climate change effects*

The threats of flooding, shoreline erosion and increased inundation to coastal communities due to rising sea level are of major concern world-wide (Woodruff et al., 2013; Brandon et al., 2014, 2016). The specter of future conditions expected for New York Harbor in terms of severe storm inundation became apparent in October 2012, when Hurricane Sandy (colloquially referred to as *Superstorm Sandy*), made landfall just south of New York City. Hurricane Sandy had devastating impacts, resulting in extensive damage to infrastructure, large flood zones and the loss of life and property in the region. There were ~117 deaths from the hurricane on the east coast of the US with ~87 of those deaths in the New York–New Jersey regional area (FEMA, 2012); with 43 of the regional deaths specifically New York City residents (NYCEDC, 2013).

Recent studies on sedimentary reconstructions of storm overwash within New York Harbor provide evidence for significant increases in wave-derived over-wash coincident with the European settlement and consequent destruction of oyster bars in the region (Brandon et al., 2016). Oyster beds were one of the most noteworthy features of New York Harbor when European explorers arrived, and were particularly abundant in the outer portion of the Harbor in Raritan Bay (Fig. 1). These beds were depleted rapidly in the 1600–1700s (Kurlansky, 2006; Kirby, 2004; Brandon 2016). As a *Washington Post* reporter quipped in a newspaper article describing this work: ''*This New York storm barrier could have slowed down Sandy. But European settlers ate it*'' (Fears, 2016). The destruction of these oyster beds and reefs that covered ~900 km^2 in the estuary and reached several meters in height above the harbor bottom not only offered shoreline protection, but stimulated ecosystem and economic development as well (Kurlansky, 2006; Brandon et al., 2016). Efforts are underway to try and restore oyster reefs in New York Harbor (Billion Oyster Project; see Section 4.5.2 below).

4.4. *Invasive/alien/exotic species*

Species not native to a given environment that have been moved out of their original range by human activity are termed alien, invasive or exotic (Strayer, 2006). These organisms are often introduced to ecosystems through: transport in the solid ballast; ship ballast water; fouling organisms on hulls or equipment, or by other means, either incidentally or deliberately (e.g. to enhance a population for fishing, etc.). This process has likely been occurring since the advent of shipping from Europe in the sixteenth century (Strayer, 2006). Non-native organisms can often cause ecosystem disruption through directly preying on or outcompeting local species for resources, leading to a decrease in biodiversity. Pathogens can also be introduced, to which native populations are not resistant (NYNJHEP, 2012). There are some

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regulations in place including the 'National Invasive Species Act of 1996', which requires treatment of ballast water retained with the ship to reduce introductions (Strayer, 2006), as well as some programs to manage and monitor those invaders already present; however once in a system, they are extremely difficult to eliminate. Invasive species that have been recorded in the New York Harbor Estuary system include finfish, crustacean and invertebrate species, with species numbers estimated to be over 100 (Strayer, 2006). Finfish examples include black bass (*Micropterus spp.*), and channel catfish (*Ictalurus punctatus*), both of which were stocked in many regions for fishing. As a predatory species in the Hudson River, they may be responsible for the observed decline in smaller fish in local tributaries.

A crustacean non-native example is the Asian shore crab (*Hemigrapsus sanguineus*), which was first described in the New Jersey region in 1988 (McDermott, 1991; Strayer, 2006) and detected in 1994 in Western Long Island Sound (Fig. 1). It is a native of East Asia and its introduction is thought to have been a result of ballast water exchange, in its planktonic, larval stage (Strayer, 2006). By 2000, it had significantly affected species diversity in Western Long Island Sound, most notably a 95% decrease of the native flatback mud crab (*Eurypanopeus depressus*) population in the region (Kraemer et al., 2007).

In terms of invertebrates, zebra mussels (*Dreissena polymorpha*) have been introduced from Europe to the entire East Coast of North America, appearing in the Hudson River in 1991. Although they are strictly freshwater, they are thought to have affected the diversity and abundance of fish species throughout the Hudson estuary (Strayer et al., 2004). They have also caused a significant economic impact attaching to water intakes, boat hulls and other submerged structures (Strayer, 2006). Another alien bivalve species with similar ecological effects to the zebra mussel, is the estuarine clam Atlantic rangia (*Rangia cuneata*), which is native to the Gulf of Mexico coast, first reported in the mid-Atlantic region in the mid1950s and the Hudson River in 1988. Since that time they have become widespread in estuaries from Florida to New York (Strayer, 2006). It is thought that they may have been introduced on oyster shell brought in for re-establishment purposes, as well as through ballast water or as food or bait (Carlton, 1992). Education and public outreach initiatives have been implemented throughout the region to help stop the spread of invasive species. Although most of the current management concentrates on freshwater species, there is a realization that coastal threats are an area of potential future concern with the increase of global shipping and international trade (NYNJHEP, 2012).

4.5. *Resource utilization (shipping, fishing, recreation)*

4.5.1. *Shipping*

The Port of New York and New Jersey is the United States' largest port for oil import and the nation's third largest for container ships and cargo (PANYNJ, 2015). The port provides jobs for hundreds of thousands of workers from communities in both New York and New Jersey (NYNJHEP, 2012). Combining the ports of all five boroughs of New York and those across the Hudson River in New Jersey was a process formalized in 1921, under the auspices of one, bi-state organization, the Port Authority of New York and New Jersey (PANYNJ, 2015). Although New York, and Brooklyn in particular, were the major commercial ports until the mid20th century, the shipping facility at the Port Newark–Elizabeth Marine Terminal, located in New Jersey on Newark Bay, has surpassed both New York and Brooklyn to become the largest port on the Eastern Seaboard. With the decline of passenger transport, the transition of cargo transport to containers, and the rise of Port Newark, usage patterns have shifted, requiring major infrastructure investments both along the shoreline and in the harbor's waters. A $1.5Bn deepening project was recently completed and ongoing maintenance dredging continues along the major shipping channels (e.g.: Kaysen, 2012; Army Corps of Engineers, 2015, 2016). Widening of the Panama Canal and the continued internationalization of manufacture bode well for continued growth of traffic to the Port (e.g. Kaysen, 2012). The Port Authority also oversees the three major airports in the NY–NJ regions at Newark's Liberty Airport and New York's La Guardia and Kennedy International Airports. Runoff from these facilities, including de-icing agents and airplane exhaust through atmospheric deposition can also have implications for water quality, with volumes of runoff increased through the large impervious surfaces from these complexes. The Port Authority has an environmental department that monitors, evaluates and works to mitigate these impacts from both the airports, and the thousands of ships that come into the port.

4.5.2. *Fisheries*

Fishing has traditionally been a mainstay of the population of the region. Particularly before agriculture was introduced, the diverse fish resources of the adjacent waterways were an important local source of protein for sustenance (Limburg et al., 2006). New York Harbor historically has supported a range of fishery populations, including the keystone eastern oyster (*Crassostrea virginica*) and finfish of major commercial importance, including sturgeon, striped bass and shad; all of which have seen major declines due to overharvesting coinciding with harbor development, as well as many anthropogenic stressors such nutrient and chemical pollution (Kurlansky, 2006).

The original Native Americans, the Leni Lenape, as well as the early European settlers, used the abundant oysters and fish as staples of their diets. In the 1700s many of the lower class in New York City survived *solely on oysters from the Harbor and a little bit of bread* (Waldman, 1999). As the waters of New York Harbor became more polluted and the need for dredging and expanding shipping channels increased, the estimated 350 square miles of oyster reef that existed throughout the Harbor at the end of the 19th century were decimated (Waldman, 1999). The popularity of consuming finfish such as sturgeon, striped bass and shad rose throughout the 19th and 20th century, creating a robust commercial and recreational fishery (Waldman, 1999). The anthropogenic pressures put on New York Harbor throughout the 19th and 20th century (discussed in Section 4.1: Pollution) led to the loss of almost all oyster reefs and the contamination of the few remaining sanctuaries. Fish throughout the harbor and further into New York Bight have been plagued by fin rot and heavy metal contamination (Mahoney et al., 1973) with few fish currently allowed to be harvested for consumption from harbor waters.

Despite the contamination and commercial depletion issues, New York Harbor's estuarine system is still home to a surprisingly diverse assemblage of fish species, although the overall abundance of fish has declined in the past 400 years (Waldman, 1999). Tom Lake, an editor of *the Hudson River Almanac*, has documented 218 fish species within just the Hudson Rivers drainage north of the Battery (Waldman, 1999) A team from the non-profit group *The River Project* has been documenting fish caught in their killifish traps under Hudson River Pier 40, finding fish from 30 separate genera and 25 different families ranging from butterfly-fish to sea horses (Waldman, 1999). New York Harbor's extremely unhealthy conditions over the past century and a half seemingly have not been extremely detrimental for species richness, but rather for abundance and overall fish health.

4.5.2.1. Eastern Oysters and Striped Bass. Two very important estuarine health indicators (and keystone species), that stand out in New York

Harbor's ecosystem are the eastern oyster (*Crassostrea virginica*) and striped bass (*Morone saxitallis*) (Kurlansky, 2006). The abundances of both the eastern oyster and striped bass throughout the ecosystem have declined greatly from overfishing, shipping pressures and the deposition of sludge that occurred throughout the 19th and 20th century (Waldman, 1999). Oyster reefs create a dynamic environment that provides vital habitat and protection for juvenile fish and crustaceans, feeding grounds for larger predators, and substrate on which many organisms may settle or lay their eggs (Hua, 2006). Oysters also naturally improve water quality and clarity by filtering water through their gills to consume algae and nutrients found in the water. An adult eastern oyster can filter up to 50 gallons of water each day (CBF, 2016).

Although the Chesapeake Bay is the Atlantic spawning location for about 70% of the anadromous (i.e. those species that move from marine waters to spawn in freshwater) eastern striped bass population, the Hudson River competes with the Delaware River for the second-largest spawning area for this iconic fish.

In addition to the many striped bass that spawn in the Hudson River, hundreds of thousands pass along the Atlantic coast and stop in the harbor to feed during their spring and fall migrations. A significant amount of research was conducted on the migration of striped bass over the last few decades, given that as diadromous fish, which migrate between fresh and marine waters, they are exposed to a large number of threats including damming in rivers, overfishing and pollution (Wingate and Secor, 2007; Limburg and Waldman, 2009). By the mid-1970s overfishing and poor water quality was depleting not only the New York Harbor striped bass stocks but those to the south in Chesapeake Bay as well, and the future of the fishery appeared bleak. The dire state of the fish stocks at that time prompted legislation that allowed the New York Harbor, as well as the Chesapeake Bay, striped bass populations to make a remarkable recovery over the last thirty years. This recovery can largely be attributed to the creation of striped bass limits, seasons and size minimums outlined in the 1979 Emergency Striped Bass Act and many Fisheries Management Plans adopted in subsequent years following this act (Levinton and Waldman, 2006). A moratorium on striped bass fishing was also implemented in the Chesapeake Bay and by 1995 the entire coastal fishery was declared restored (Levinton and Waldman, 2006). Although the striped bass population has been steadily recovering, it is still threatened by nutrient overloading and metal contamination of New York Harbor waters, causing fin rot and reducing dissolved oxygen (Waldman, 1999). The variability in their migration patterns (Wingate and Secor, 2007) may be part of the their resilience, and their recovery may serve as a model for other anadromous fish (Waldman et al., 2016).

As noted in the first case study (Section 5.1): The Billion Oyster Project, attempts to restore the eastern oyster have been implemented in New York Harbor.

4.5.2.2. Sturgeon. The Hudson is also home to the resident shortnose sturgeon, (*Acipenser brevirostrum)* and the larger Atlantic sturgeon (*Acipenser oxyrinchus*), which spends a significant amount of its life-time out in the Atlantic and was harvested extensively for its valuable roe (e.g. caviar). The shortnose sturgeon is federally listed as endangered, partly due to habitat degradation (Woodland and Secor, 2007). Atlantic sturgeon females were specifically targeted for their eggs, consequently the population was decimated in the Hudson River estuary after the 1890s which was the height of the 'international caviar craze' (Limburg and Waldman, 2009). Fishing continued at a much diminished and sporadic level through the 1980s (Limburg et al., 2006), however with low reproduction rate, the population showed little recovery (Secor and Waldman, 1999). The fishery was closed by the State of New York in 1996. Two years later in 1998, in a cooperative agreement with adjoining Atlantic coast states, a 40-year moratorium on sturgeon fishing was enacted. The Atlantic sturgeon was officially listed as an endangered species in 2012, although more sturgeon have been observed since 2008, and females are returning to spawn (NYSDEC, 2016b). According to the NY State Department of Environmental Conservation; *the moratorium will offer protection until these youngsters mature and launch a third generation 20 years from now* (NYSDEC, 2016b). Shortnose sturgeon population estimates in the 1990's from the Hudson River indicated that the spawning population had increased substantially from that observed in the 1970s with approximately a 4-fold increase in population over an 18-year period from 1979 to 1997, which shows a promising trend (Woodland and Secor, 2007). Future potential threats from climate change include reduced nursery habitat due to warming temperatures and decreases in oxygen in regions with invasive zebra mussels due to increased benthic oxygen demand by these bivalves (Woodland and Secor, 2007).

4.5.3. Recreation

Enjoyment of the NY–NJ Harbor Estuary for recreation purposes historically faced many impacts due to inaccessibility and pollution. However, cleaner water, shifting economies, and desire by residents for recreation have led to a renaissance of recreational opportunities in the Harbor Estuary. Between 2009 and 2014, over 500 acres of the waterfront were opened to the public (Boicourt et al., 2015). In 2016, it was estimated that 37% of the linear shoreline of the Harbor Estuary was comprised of parks or other public waterfront spaces, at a total of 41,078 acres (Boicourt et al., 2016). Access to and from the water is not only important for improving the quality of life for residents, but also for fostering a critical connection to, and stewardship of, the Harbor Estuary. Multiple public boating programs for rowing, kayaking, canoeing, and sailing operate from Hoboken to the Bronx. However, in many areas, public access is either lacking (e.g., stretches of the Passaic River extend miles without public waterfront access), or impacted due to physical conditions, safety concerns, poor water quality, and limited resources. Investments in supporting recreation and stewardship, both onsite as well as by establishing connections between surrounding communities and their waterfront, are needed to strengthen the identity of the Harbor Estuary as ''New York City's 6th Borough''. Boating, including sailing, has long been a popular recreational activity in New York Harbor. Kayaking and small boating have been increasing in popularity with expanded public access to the waterfront, including rental businesses as well as improvement in water quality. Recreational fishing remains one of the largest pastimes in New York Harbor, with an estimated $250 million spent in the 1970s on this pastime (Squires, 1981). Recent estimates of New York Recreational Fisheries Economics indicate totals of more than $381 million spent annually on recreational fishing alone (USDOC, 2014).

5. Case study: aquaculture and the Billion Oyster Project(restoration, education and community enterprise)

5.1. The Billion Oyster Project

The Billion Oyster Project is a combined ecosystem restoration and education project spearheaded by the New York Harbor Foundation, which is based on Governors Island in New York Harbor. The goal of the project is to restore one billion live oysters to the waters of New York Harbor. The project lifecycle begins with students at Urban Assembly New York Harbor School, a NYC Department of Education public high school specializing in marine science and technology, which produce aquaculture oyster spat that are then distributed throughout the waters of New York Harbor. Students at numerous partner schools, including those involved in a novel National Science Foundation (NSF) sponsored project (see below), then place these oysters in the harbor and conduct scientific monitoring on field trips using cages, traps and state-of-the-art internet data entry and analysis tools.

The Billion Oyster Project recognizes the key role that oysters played in the ecology and original human settlement of the region (Kurlansky, 2006). Oyster reefs once covered 90,000 hectares (220,000 acres) of the Hudson River estuary and the bio-filtration of these oyster beds provided a natural filtration of harbor waters, leading to improvements in water quality. In addition, the habitat value of the three-dimensional structure of oyster reefs was important for biodiversity and as a natural barrier to wave energy, protecting the shoreline. In order to achieve its goals, *The Billion Oyster Project* is expanding the production of oysters, construction and monitoring of oyster reefs, and collection of oyster shell. In addition, the engagement of the New York City Public School System and public citizen science programs will expand the number of people involved in harbor restoration.

The educational focus of this project is on STEM-C (Science, Technology, Engineering, Mathematics and Computing) learning outcomes. The CCERS project is developing and testing a model of curriculum and community enterprise addressing science issues built around environmental restoration within the nation's largest urban school system. Middle school students will study New York Harbor, and the extensive watershed that empties into it, as well as carrying out field research in support of restoring native oyster habitats. The project builds on the existing *Billion Oyster Project* (BOP), and is currently being implemented by a broad partnership of institutions and community resources.

Within the BOP CCERS project, the concept of New York Harbor estuary literacy forms the interdisciplinary structure of the curriculum. This consists of eight core modules across eight distinct subject areas; (1) Geography, (2) Social Studies, (3) History, (4) Environmental Engineering, (5) Technology, (6) Mathematics and Computer Science, (7) Science and (8) English, Literature and Arts (Fig. 6). Integrated into the foundation of the curriculum development is Bybees's 5E Model (Bybee et al., 2006).

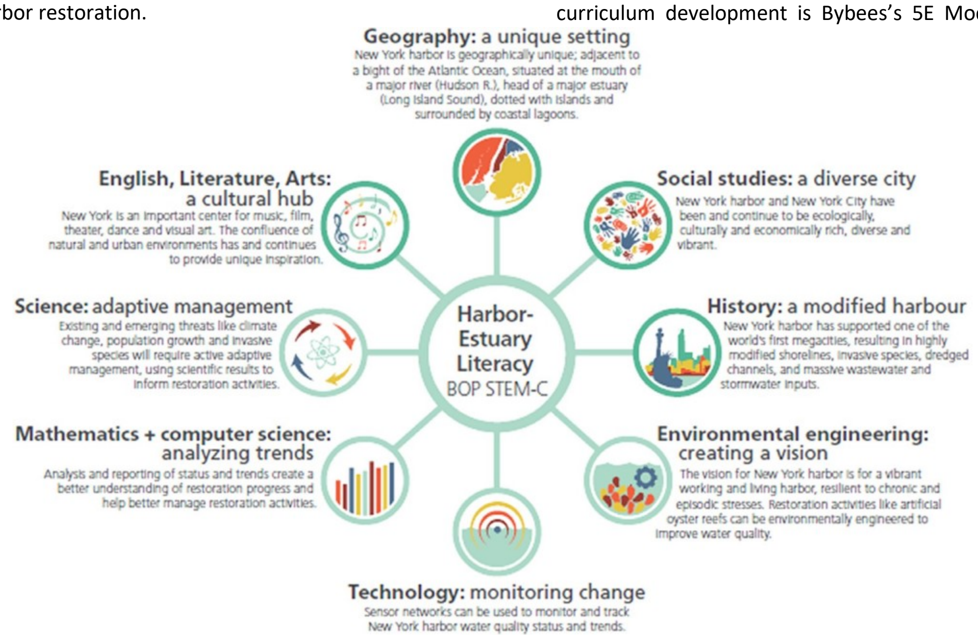

Fig. 6. Curriculum and Community Enterprise for Restoration Science curriculum structure (BOP = Billion Oyster Project; STEM-C = Science, Technology, Engineering, Mathematics-Computing).

5.2. *Curriculum and community enterprise for restoration science*

The Curriculum and Community Enterprise for Restoration Science (CCERS) is a US National Science Foundation (NSF) funded project, focused on the expansion of concepts embedded within *The Billion Oyster Project*. The project, led by Pace University and New York Harbor Foundation with multiple partners, is developing five teaching and educational pillars: (1) STEM teacher training, (2) Field science research, (3) Digital platform—an online interface for data input and analysis, (4) After-school STEM mentoring programs and, (5) Estuary and museum exhibitions. These educational pillars, combined with collaboration between teachers, scientists, STEM education professionals, researchers, industry leaders and evaluators, are developing a fully scalable and transferable education model, adaptable to other locations and species both nationally and internationally.

Establishing entry points for students in all subject areas creates more opportunities for students to explore their own areas of interests, engage in environmental restoration and gain critical research skills while participating in data collection in the field. Exposure for middle-school students to field science in the New York Harbor and engagement of a broad community of professional and citizen scientists substantiate the broader impact of this ambitious project. Currently, the CCERS-supported *Billion Oyster Project* Schools network includes more than 65 teachers across 35 schools engaging approximately 6000 students, with 42 citizen scientists actively supporting the program of Oyster Restoration Stations (ORS) field science and data collection.

This signature New York City project, with its assemblage of collaborative stake-holders, allows for the creation of an interdisciplinary curriculum through the exploration of environmental restoration science. Additionally, it is anticipated that the combination of hands-on field experiments, with the application of inquirybased learning in STEM subject

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matter, will ultimately attract more students into STEM fields. Ultimately, the project seeks to create a unique learning environment and establish it as a viable model for field-science-driven learning and instructional practice in an urban setting.

6. Conclusion

New York Harbor is an iconic region due to its complex natural ecosystems and intense human development. Presentday New York Harbor conditions, depicted with conceptual cross sections, are a result of a long history of environmental challenges, including fisheries depletions, shoreline modifications, dredging and water quality degradation. In spite of historic environmental degradation, a variety of activities are taking place to make New York Harbor the 6th borough of New York City, including oyster restoration (e.g., *Billion Oyster Project*), education programs (e.g., Curriculum and Community Enterprise for Restoration Science), and recreation programs (e.g., boating). Developing an understanding of the human and ecological interactions in New York Harbor can serve as a model for coastal megacities around the world.

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References

Able, K.W., Manderson, J.P., Studholme, A.L., 1998. The distribution of shallow water juvenile fishes in an urban estuary: the effects of manmade structures in the lower Hudson River. Estuaries 21, 731–744.

Able, K., Manderson, J.P., Studholme, A.L., 1999. Habitat quality for shallow water fishes in an urban estuary: the effects of man-made structures on growth. Mar. Ecol. Prog. Ser. 187, 227–235.

Airoldi, L., Beck, M.W., 2007. Loss, status and trends for coastal marine habitats of Europe. Oceanogr. Mar. Biol. Annu. Rev. 45, 345–405.

Airoldi, L., Abbiati, M., Beck, M.W., Hawkins, S.J., Jonsson, P.R., Martin, D., Moschella, P.S., Sundelöf, A., Thompson, R.C., Åberg, P., 2005. An ecological perspective on the deployment and design of low-crested and other hard coastal defence structures. Coast. Eng. 52, 1073–1087.

Army Corps of Engineers. 2015. Army Corps announces contract award for maintenance dredging in Newark Bay, NJ. Accessed May 21, 2016 at: http://www.nan.usace.army.mil/Media/NewsReleases/tabid/3948/Article/ 620702/army-corps-announces-contract-award-for-maintenance-dredgingin-newark-bay-nj.aspx .

Army Corps of Engineers. 2016. FACT SHEET—New York and New Jersey Harbor (50 ft. deepening). at: http://www.nan.usace.army.mil/Media/FactSheets/ FactSheetArticleView/tabid/11241/Article/487407/ fact-sheet-new-york-and-new-jersey-harbor-50-ft-deepening.aspx (Accessed on 05.21.2016).

Arrigoni, A., Findlay, S., Fischer, D., Tockner, K., 2008. Predicting carbon and nutrient transformations in tidal freshwater wetlands of the Hudson River. Ecosystems 11 (5), 790–802.

Asplund, T.R., 2000. The effects of motorized watercraft on aquatic ecosystems. Wisconsin Department of Natural Resources and University of WisconsinMadison. PUBL-SS-948-00. Madison, WI. p. 21.

Ayres, R.U., Ayres, L.W., Tarr, J.A., Widgery, R.C., 1988. An Historical Reconstruction of Major Pollutant Levels in the Hudson-Raritan Basin: 1880–1980, Volume 1: Summary, Vol. 43. National Oceanographic and Atmospheric Administration Technical Memorandum NOS OMA, Rockville, Maryland.

Ayres, R.U., Rod, S.R., 1986. Patterns of pollution in the Hudson–Raritan Basin. Environ. Rep 28, 15–25.

Bain, M., Lodge, J., Suszkowski, D.J., Botkin, D., Brash, A., Craft, C., Diaz, R., Farley, K., Gelb, Y., Levinton, J.S., Matuszeski, W., Steimle, F., Wilber, P., 2007. Target Ecosystem Characteristics for the Hudson Raritan Estuary: Technical Guidancefor Developing a Comprehensive Ecosystem Restoration Plan. A report to the Port Authority of NY/NJ. Hudson River Foundation, New York, NY, p. 106.

Bohn, B.A., Kershner, J.L., 2002. Establishing aquatic restoration priorities using a watershed approach. J. Environ. Manag. 64, 355–363.

Boicourt, K., Baron, L., Pirani, R., 2015. Restoring the New York—New Jersey Harbor Estuary: Ensuring Ecosystem Resilience and Sustainability in a Changing Environment. New York—New Jersey Harbor & Estuary Program, Hudson River Foundation. New York, www.harborestuary.org/watersweshare/reportRestoringNYNJHarborEstuary.htm.

Boicourt, K., Pirani, R., Johnson, M., Svendsen, E., Campbell, L., 2016. Connecting with Our Waterways: Public Access and its Stewardship in the New York-New Jersey Harbor Estuary. Report of The New York-New Jersey Harbor & Estuary Program. Hudson River Foundation, New York, NY.

Bone, E.K., 2015. Urban Shorelines Assessment Protocol Piloting Final Report. Webinar presented at Hudson River Foundation, June 30, 2015. Available at http://www.harborestuary.org/aboutestuary-habitats-shorelines.htm [Accessed 02/11/2016].

Bopp, R.F., Simpson, H.J., 1989. Contamination of the Hudson River, the sediment record. In: Contaminated Marine Sediments—Assessment and Remediation. National Research Council, National Academy Press, Washington, D.C, pp. 401–416. Committee of Contaminated Marine Sediments (eds.).

Bopp, R.F., Simpson, J.H., Olsen, H.R.N.T., 2013. Contamination of the Hudson River ecosystem compilation of contamination data through. ''Hudson River Natl. Res. Damage Assess. 2013, 31. The Hudson River Natural Trustees.

Brandon, C.M., Woodruff, J.D., Donnelly, J.P., Sullivan, M.R., 2014. How unique was Hurricane sandy? Sedimentary reconstructions of extreme flooding from New York harbor. Sci. Rep. 4, 7366. http://dx.doi.org/10.1038/srep07366 1.

Brandon, C.M., Woodruff, J.D., Orton, P.M., Donnelly, J.P., 2016. Evidence for elevated coastal vulnerability following large-scale historical oyster bed harvesting. Earth Surf. Process. Landf. http://dx.doi.org/10.1002/esp.3931.

Brosnan, T.M., 1991. New York Harbor Water Quality Survey 1988–1990. NTIS No. PB91-228825. New York City Department of Environmental Protection, Marine Sciences Section, Wards Island, New York.

Brosnan, T.M., O'Shea, M.L., 1996a. Sewage abatement and coliform bacteria trends in the lower Hudson-Raritan Estuary since passage of the Clean Water Act. Water Environ. Res. 68, 25–35.

Brosnan, T.M., O'Shea, M.L., 1996b. Long-term improvements in water quality due to sewage abatement in the Lower Hudson River. Estuaries 19, 890–900.

Brown, M.A., Chapman, M.G., 2011. Ecologically informed engineering reduces loss of intertidal biodiversity on artificial shorelines. Environ. Sci. Technol. 45, 8204–8207.

Bruno, M.S., 1996. Offshore disposal results of the 106-mile dumpsite study. Environ. Eng. 2 (3–4), 181–282.

Bulleri, F., Chapman, M.G., 2010. The introduction of coastal infrastructure as a driver of change in marine environments. J. Appl. Ecol. 47, 26–35.

Bureau of Labor Statistics (BLS). 2015. Economic and Employment Projections, 2014-2024. http://www.bls.gov/news.release/ecopro.toc.htm (Accessed 05.21.2016).

Bybee, R.W., Taylor, J.A., Gardner, A., Van Scotter, P., Powell, J.C., Westbrook, A., Landes, N., 2006. The BSCS 5E Instructional Model: Origins, Effectiveness, and Applications. http://www.bscs.org/bscs-5e-instructional-model.

Carlton, J.T., 1992. Introduced marine and estuarine mollusks of North America: an end-of-the-20th-century perspective. J. Shellfish Res. 11, 489–505.

Chapman, M.G., Underwood, A.J., 2011. Evaluation of ecological engineering of armoured shorelines to improve their value as habitat. J. Exp. Mar. Biol. Ecol. 400, 302–313.

Chesapeake Bay Foundation (CBF). 2016. Eastern Oyster. www.cbf.org/3.-aboutthe-bay/chesapeake-bay/creatures-of-the-chesapeake/oysters.

Clark, J.F., Simpson, H.J., Bopp, R.F., Deck, B.L., 1992. Geochemistry and loading history of phosphate and silicate in the Hudson Estuary. Estuar. Coast. Shelf Sci. 34, 213–233.

Clark, J.F., Simpson, H.J., Bopp, R.F., Deck, B.L., 1995. Dissolved oxygen in the lower hudson estuary: 1978–93. J. Environ. Eng. 121, 760–763.

Cole, J.J., Caraco, N.F., 2006. Primary production and its regulation in the tidalfreshwater Hudson River. In: Levinton, J.S., Waldman, J.R. (Eds.), The Hudson River Estuary. Cambridge University Press, New York, New York, pp. 107–120.

Collie, M., Russo, J., 2000. Deep-Sea Biodiversity and the Impact of Ocean Dumping. NOAA Undersea Research Program. www.nurp.noaa.gov.spotlight/opendumping.htm.

Crawford, D.W., Bonnevie, N.L., Gillis, C.A., Wenning, R.J., 1994. Historical changes in the ecological health of the Newark Bay estuary, New Jersey. Ecotoxicol. Environ. Safety 29, 276–303.

Davenport, J., Davenport, J.L., 2006. The impact of tourism and personal leisure transport on coastal environments: A review. Estuar. Coast. Shelf Sci. 67, 280–292.

Elliot, M., Burdon, D., Hemingway, K.L., Apitz, S.E., 2007. Estuarine, coastal and marine ecosystem restoration: confusing management and science—a revision of concepts. Estuar. Coast. Shelf Sci. 74, 349–366.

EPA (U.S. Environmental Protection Agency. 2002. Record of Decision on Hudson River PCBs Site. Region 2, United States Environmental Protection Agency, New York, NY.

Fears, D., 2016. This New York storm barrier could have slowed down Sandy. But European settlers ate it.' Energy and Environment Section: The Washingotnt Post. March, 10, 2016. https://www.washingtonpost.com/news/energyenvironment/wp/2016/03/10/how-European-settlers-ate-the-storm-barrierthat-could-have-saved-new-york/?tid=a_inl.

Federal Emergency Management Agency (FEMA). 2012. Hurricane Sandy: timeline;2012. Washington, Dc: US Department of Homeland Security, FEMa; 2012. www.fema.gov/jurricane-sandy-timeline.

Findlay, S.E.G., Sinsabaugh, R.L., 2003. Response of hyporheic biofilm bacterial metabolism and community structure to nitrogen amendments. Aquat. Microb. Ecol. 33, 127–136.
Findlay, S., Sinsabaugh, R.L., Fischer, D.T., Franchini, P., 1998. Sources of dissolved organic carbon supporting planktonic bacterial production in the tidal freshwater Hudson River. Ecosystems 1, 227–239.
Fujii, T., Raffaelli, D., 2008. Sea-level rise, expected environmental changes, and responses of intertidal benthic macrofauna in the Humber estuary, UK. Mar. Ecol. Prog. Ser. 371, 23–35.
Gottholm, B.W., Harmon, M.R., Turgeon, D.D., 1993. Toxic Contaminants in the Hudson-Raritan Estuary and Coastal New Jersey Area. Draft Report. National Status and Trends Program for Marine Environmental Quality, National Oceanographic and Atmospheric Administration, Silver Spring, Maryland.
Hill, N.M., Keddy, P.A., Wisheu, I.C., 1998. A hydrological model for predicting the effects of dams on the shoreline vegetation of lakes and reservoirs. Environ. Manag. 22, 723–736.
Hua, S., 2006. Oyster and Oyster Reef Restoration in the East River. In: DanoffBurg, J.A. (Ed). Restoring New York City Proposals for Improving Ecological and Human Health Department of Ecology, Evolution, and Environmental Biology, Columbia University http://www.columbia.edu/itc/cerc/danoffburg/RestoringNYC/RestoringNYC_EastRiver.html 20Dec2006.
Hurst, T.P., McKown, J.A., Conover, D.O., 2004. Interannual and long-term variation in the nearshore fish community of the Mesohaline Hudson River Estuary. Estuaries 27, 659–669.
Kaysen, R., 2012. A $650 Million Expansion of Port Newark Spurs Interest in its Environs. New York Times, New York. at: http://www.nytimes.com/2012/08/22/realestate/commercial/a-650million-expansion-of-port-newark-spurs-interest-in-its-environs.html?_r=0 (Accessed 05.21.2016).
Kirby, M.X., 2004. Fishing down the coast: Historical expansion and collapse of oyster fisheries along continental margins. PNAS 101, 13096–13099.
Kirwan, M.L., Megonigal, J.P., 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504, 53–60.
Kraemer, G.P., Sellberg, M., Gordon, A., Main, J., 2007. Eight-Year Record of Hemigrapsus sanguineus (Asian Shore Crab) Invasion in Western Long Island Sound Estuary *Northeastern Naturalist*, Vol. 14, no. 2, 2007, pp. 207-224.
Kurlansky, M., 2006. The Big Oyster: History on the Half Shell. Random House Publishing, New York, p. 307.
Lampman, G., Caraco, N.F., Cole, J.J., 1999. Spatial and temporal patterns of nutrient concentration and export in the tidal Hudson River. Estuaries 22, 285–296.
Lee, R., Longwell, , Malone, A.C., Murphy, T.C., Nimmo, D.R., O'Connors Jr., H.B., Peters, L.S., Wyman, K.D., 1982. Effects of pollutants on plankton and neuston. In: Mayer, G.F. (Ed.), Ecological Stress and the New York Bight: Science and Management. Estuarine Research Federation, Columbia, South Carolina, pp. 39–52.
Levinton, J.S., Waldman, J.R. (Eds.), 2006. The Hudson River Estuary. Cambridge University Press, New York, p. 471.
Limburg, K.E., Waldman, J.R., 2009. Dramatic declines in North Atlantic diadromous fishes. Bioscience 59, 955–965.
Limburg, K.E., Hattala, K.A., Kahnle, A.W., Waldman, J.R., 2006. Fisheries of the Hudson River. In: Levinton, J.S., Waldman, J.R. (Eds.), The Hudson River Estuary, 2006. Cambridge University Press, New York, pp. 189–204.
Lodge, J., Landeck Miller, R.E., Suszkowski, D., Litten, S., 2015. Contamination Assessment and Reduction Project Summary Report. Hudson River Foundation, New York, NY, p. 38.
Mahoney, J.B., Midlige, F.H., Deuel, D.G., 1973. A fin rot disease of marine and euryhaline fishes in the New York bight. Trans. Am. Fish. Soc. 102 (3), 596–605.
Malm, T., Råberg, S., Fell, S., Carlsson, P., 2004. Effects of beach cast cleaning on beach quality, microbial food web, and littoral macrofaunal biodiversity. Estuar. Coast. Shelf Sci. 60, 339–347.
Malone, T.C., 1982. Factors influencing the fate of sewage-derived nutrients in the Lower Hudson Estuary and New York Bight. In: Mayer, G.F. (Ed.), Ecological Stress and the New York Bight: Science and Management. Estuarine Research Federation, Columbia, South Carolina, pp. 389–400.
McDermott, J.J., 1991. A breeding population of the western Pacific crab *Hemigrapsus sanguineus* (Crustacea: Decapoda: Grapsidae) established on the Atlantic coast of North America. Biol. Bull. 181, 195–198.
Miller, D., 2005. Shoreline inventory of the Hudson River. Hudson River National Estuarine Research Reserve, New York State Department of Environmental Conservation.
Miller, D., Ladd, J., Nieder, W.C., 2006. Channel morphology in the Hudson River estuary: historical changes and opportunities for restoration. In: Waldman, J.R., Limburg, K.E., Strayer, D.L. (Eds.), Hudson River Fishes and their Environment. In: Symposium, 51. American Fisheries Society, pp. 29–37.
Muñoz, G.R., Panero, M.A., 2008. Sources of Suspended Solids to the New York/New Jersey Harbor Watershed. The New York Academy of Sciences, New York.
Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the world's large river systems. Science 308, 405–408.
NYCDEP (New York City Department of Environmental Protection). 2009a. New York Harbor Survey Program: Celebrating 100 Years: 1909-2009. Flushing, NY: City of New York, Dept. of Environmental Protection, NYC Department of Environmental Protection.
NYCDEP (New York City Department of Environmental Protection). 2011. New York City's Wastewater Treatment System. NYC Department of Environmental Protection (http://www.nyc.gov/html/dep/pdf/wwsystem.pdf).
NYCEDC (New York City Economic Development Corporation). 2012. PlaNYC: New York City Wetlands Strategy: 3-73. May 2012.
NYCEDC (New York City Economic Development Corporation). 2013. A Stronger More Resilient New York. http://www.nycedc.com/resource/stronger-moreresilient-new-york.
NYCDEP (New York City Department of Environmental Protection). 2016. Reducing Combined Sewer Overflow in New York City- DEP's Lont Term Control Plan. http://www.nyc.gov/html/dep/html/cso_long_term_control_plan/index.shtml.
NYNJHEP (New York-New Jersey Harbor & Estuary Program). 2012. The State of the Estuary: Environmental Health and Trends of the New York-New Jersey Harbor Estuary. www.harborestuary.com.
NYSDEC (New York State Department of Environmental Conservation). 2016a. CSO Long Term Control Plan (LTCP). http://www.dec.ny.gov/chemical/48985.html.
NYSDEC (New York Department of Environmental Conservation). 2016b. New York Sturgeon. http://www.dec.ny.gov/animals/37121.html.
NYSDOH (New York State Department of Health). 2015. New York City Region Fish Advisories.
Orr, J., Topa, G., 2006. Challenges facing the New York metropolitan area economy. Curr. Issues Econ. Financ. 12 (1), 1–7. Accessed at: https://www.newyorkfed.org/medialibrary/media/research/current_issues/ ci12-1.pdf (May 21, 2016).
O'Shea, M.L., Brosnan, T.M., 2000. Trends in indicators of eutrophication in western Long Island Sound and the Hudson-Raritan estuary. Estuaries 23 (6), 877–901.
Phillips, P.J., Hanchar, D.W., 1996. Water Quality Assessment of the Hudson River Basin in New York and Adjacent States—Analysis of Available Nutrient, Pesticide, Volatile Organic Compound, and Suspended Sediment Data, 1970–90. Water Resources Investigations Report 96–4065. US Geological Survey, Troy, New York.
Pinn, E.H., Rodgers, M., 2005. The influence of visitors on intertidal biodiversity. J. Mar. Biol. Assoc. UK 85, 263–268.
Port Authority of New York and New Jersey (PANYNJ). 2015. Port of NewYork- New Jersey. http://www.panynj.gov/port/.
Reid, D.J., Bone, E.K., Thurman, M.A., Newton, R., Levinton, J.S., Strayer, D.L., 2015. Development of a Protocol to Assess the Relative Habitat Values of Urban Shorelines in New York – New Jersey Harbor. Prepared for the Hudson River Foundation and New York—New Jersey Harbor & Estuary Program, New York. p. 169.
Riverkeeper. 2016. Combined Sewage Overflows (CSOs). Riverkeepers Incorporated, Ossining, NY. http://www.riverkeeper.org/campaigns/stop-polluters/sewagecontamination/cso/).
Rod, S.R., Ayres, R.U., Small, M., 1989. Reconstruction of Historical Loadings of Heavy Metals and Chlorinated Hydrocarbon Pesticides in the Hudson-Raritan Basin, 1889–1980. Final Report to the Hudson River Foundation, New York.
Salvo, J.J., Lobo, A.P., Maurer, E., 2013. New York City Population Projections by Age/Sex & Borough, 2010-2040. The City of New York, Department of City Planning. NYC. Accessed on May 5, 2016 from: www1.nyc.gov/assets/planning/download/pdf/data-maps/nycpopulation/projections_report_2010_2040.pdf.
Sanderson, E.W., 2009. Manahatta: A Natural History of New York City. Abrams Books, New York.
Secor, D.H., Waldman, J.R., 1999. Historical abundances of Delaware Bay Atlantic sturgeon and potential rate of recovery. Am. Fish. Soc. Symp. 23, 203–216.
Sedell, J.R., Froggatt, J.L., 1984. Importance of streamside forests to large rivers: the isolation of the Willamette River, Oregon, U.S.A., from its floodplain by snagging and streamside forest removal. Verh. Int. Ver. Theor. Angew. Limnol. 22, 1828–1834.
Sekovski, I., Newton, A., Dennison, W.C., 2012. Megacities in the coastal zone: Using a driver-pressure-state-impact-response framework to address complex environmental problems. Estuar. Coast. Shelf Sci. 96, 48–59.
Squires, D.F., 1981. The Bight of the Big Apple. New York Sea Grant Institute, Albany.
Steinberg, T., 2014. Gotham Unbound: The Ecological History of Greater New York. Simon & Schuster, New York, p. 544.
Strayer, D.L., 2006. Alien species in the Hudson River. In: Levinton, J.S., Waldman, J.R. (Eds.), The Hudson River Estuary. Cambridge University Press, Cambridge, pp. 296–310.
Strayer, D.L., Findlay, S.E.G., 2010. The ecology of freshwater shore zones. Aquat. Sci. 72, 127–163.
Strayer, D.L., Findlay, S.E.G., Miller, D., Malcom, H.M., Fischer, D.T., Coote, T., 2012. Biodiversity in Hudson River shore zones: influence of shoreline type and physical structure. Aquat. Sci. 74, 597–610.
Strayer, D.G., Hattala, K., Kahnle, A., 2004. Effects of an invasive bivale (*Dreissena polymorpha*) on fish populations in the Hudson River estuary. Can. J. Fish. Aquat. Sci. 61, 924–941.
Suszkowski, D.J., D'Elia, C.F., 2006. The history and science of managing the Hudson river. In: Levinton, J.S., Waldman, J.R. (Eds.), The Hudson River Estuary. Cambridge University Press, Cambridge, pp. 313–334.
Tockner, K., Stanford, J.A., 2002. Riverine floodplains: present state and future trends. Environ. Conserv. 29, 308–330.
US Army Corps, NY-NJ Port Authority and NY-NJ Harbor Estuary Program. 2014. Hudson-Raritan Estuary Comprehensive Restoration Plan Executive Summary. Web.

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US Census Bureau (USCB). 1999. Population of the 100 Largest Cities and Other Urban Places in the United States: 1790 to 1990. https://www.census.gov/population/www/documentation/twps0027/twps0027.html.

US Census Bureau (USCB). 2010. http://www.census.gov/population/www/documentation/twps0027/twps0027.html NYC Planning: http://www1.nyc.gov/assets/planning/download/pdf/data-maps/nyc-population/census2010/t_pl_p1_nyc.pdf).

US Census Bureau (USCB). 2014. Annual Estimates of the Resident Population: April 1, 2010 to July 1, 2014.

US Department of Commerce. National Oceanic and Atmospheric Administration and National Marine Fisheries Service. 2014. Fisheries Economics of the United States 2012. Economics and Sociocultural Status and Trends Series. Waldman, J.R., 1999. Heartbeats in the Muck: The History, Sea Life, and Environment of New York Harbor. Empire State Editions, Fordham Press.

Waldman, J.R., Wilson, K.A., Mather, M., Synder, N.P., 2016. A resilience approach can improve anadromous fish restoration. Fisheries 41, 116–126.

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., Morgan, R.P., 2005. The urban stream syndrome: current knowledge and the search for a cure. J. North Amer. Benthol. Soc. 24, 706–723.

Wingate, R.L., Secor, D.H., 2007. Intercept Telemetry of the Hudson River Striped Bass Resident Contingent: Migration and Homing Patterns. Trans. Am. Fish. Soc. 136 (1), 95–104. http://dx.doi.org/10.1577/T06-056.1.

Winn, P.J.S., Edwards, A.M.C., Young, R.M., Waters, R., Lunn, J., 2005. A strategic approach to flood defence and habitat restoration for the Humber estuary. Arch. Hydrobiol. Suppl. 155, 631–641.

Woodland, R., Secor, D.H., 2007. Yeer class strength and recovery of endangered Shortnose sturgeon in the Hudson River, NY. Trans. Am. Fish. Soc. 136, 95–104.

Woodruff, J.D., Irish, J.L., Camargo, S.J., 2013. Coastal Flooding by tropical cyclones and sea-level rise. Nature 50, 44–52.