Review of Climate Change Effects on Water Quality and Estuarine Biota of the NY-NJ Harbor & Estuary

September 18, 2018

Introduction and Problem Statement

Climate change is impacting the health and biological integrity of the New York – New Jersey Harbor Estuary. Rising average air and water temperatures, more frequent and extreme weather events, and steadily rising sea levels are already changing baseline conditions and affecting the Estuary's aquatic habitats and biota. The magnitude of these ecological changes is expected to increase in the future. The New York – New Jersey Harbor & Estuary Program (HEP) has identified gaps in understanding these projected Increases in temperature as a key vulnerability of its program to meet goals for fish survival and reproduction. The objective of this review is to summarize existing research on potential impacts of projected temperature and precipitation changes on estuarine biota (with emphasis on fish survival and reproduction) in NY/NJ Harbor Estuary, including changes in dissolved oxygen, harmful algae blooms, and other parameters. While the primary focus of the review is the NY/NJ Harbor Estuary the review includes research from nearby and/or comparable coastal ecosystems.

Projected Warming and Sea-Level Rise Rates within the NY/NJ Harbor Estuary

The ability of oceanic waters to maintain oxygen concentrations supportive of marine life is directly affected by warming. The Intergovernmental Panel on Climate Change (IPCC 2014) has documented an average global temperature increase among land and ocean surfaces of 0.85 °C (1.53 °F) between 1880 and 2012. Additionally, the upper ocean (0 to 75 m) has, on average, warmed by 0.11 °C (0.20 °F) every decade since the early 1970s. Throughout the mid-Atlantic coastal region, projected air temperature changes by 2050 (in comparison with a 1990 baseline) are anticipated to increase approximately 1.0 to 1.5 °C (2.7°F) (Najjar et al. 2000). Water temperatures in the lower Hudson River increased at a rate of approximately 0.12 °C (0.22°F) per decade between 1920 and 1990; this warming was consistent with global increases (Ashizawa and Cole 1994). Within the greater New York Bight, projected sea surface temperature changes by 2050 (in comparison with a 1980s baseline) are anticipated to increase approximately 1.0 - 1.8°C (1.8 - 3.2 °F) (Buonaiuto et al. 2011).

Along with projected temperature increases, impacts and direct losses to coastal wetlands and other nearshore and shallow-water habitats as a result of sea level rise merit concern (Scavia et al. 2002). Many estuarine/coastal fish and invertebrate species, including those which support economically important recreational and commercial fisheries, depend on coastal wetlands and adjacent habitats (e.g., intertidal and shallow subtidal mudflats, submerged aquatic vegetation, etc.) as forage, refuge and nursery habitat during specific portions of their life cycles. Projected impacts and losses of critical habitat as sea level increases will affect the distribution and biotic integrity of estuarine/coastal fish populations. Presently, the rate of sea level rise at the Battery (Manhattan Island) is approximately 2.8 mm/year with a 95% confidence interval of +/- 0.09 mm/year based on monthly mean sea level data from 1856 to 2017 (equivalent to a change of 0.93 feet in 100 years) (NOAA 2018). However, sea level rise rates for other regions of the Harbor Estuary are as high as 4.0 mm/year (Sandy Hook). These regional observations exceed the global average rate of 1.8 mm/year (Needelman et al. 2012; IPCC 2014). The higher observed rates of sea level rise in this region are partially the result of post-glacial rebound, exacerbating the amount of observed wetland/shoreline subsidence attributed to eustatic sea-level rise (i.e., that brought about by an increase in the volume of the world's oceans, because of the thermal expansion) alone (Hartig et al. 2002). Along with increases in mean sea level, storm intensity/frequency is predicted to increase and a shift in storm intensity towards Polar regions is anticipated, with more frequent and damaging storms expected to occur in the north Atlantic (NWF 2011).

Impacts to Fish and Other Aquatic/Marine Organisms in the Harbor Estuary

In addition to projected temperature increases, an important driver for projected changes to biotic resources and ecological processes in estuaries is the effect of climate change on seasonal and long-term patterns of precipitation and river discharge. Fish abundance and recruitment in estuaries is strongly influenced by riverine discharge (Vinagre et al. 2009, Reum et al. 2011, Seekell and Pace 2011, O'Connor et al. 2012, Feyrer et al. 2015). However, discerning climate-driven changes in marine fish distributions is challenging - the signal from climatic effects may be confounded by other factors. Even under nearly constant environmental conditions, fish distributions are not static. Population theory and observations indicate that fish populations occupy the most optimal habitats under low abundances but also disperse into less optimal habitats at high abundances (Sinclair 1988, MacCall 1990). This means that mid-Atlantic species that are only rarely or periodically seen in the Harbor Estuary may be driven there in response to higher densities/competition for resources in more southern waters and not necessarily because of favorable temperatures or hydrologic conditions. As conditions change, the strongest evolutionary responses to climate change will likely occur in fish species with short generation times, subject to high or consistent selection pressure, especially near peaks in natural cycles of abundance (Crozier and Hutchings 2014).

Evaporative cooling limits the level to which water temperatures can increase in already warm tropical waters; however, temperatures in temperate and boreal regions may rise to levels that are stressful or lethal to native aquatic biota; these may only represent increases of a few °C. (Kennedy et al. 2002). Oceanic warming simultaneously reduces the total amount of dissolved oxygen that can be held in water and increases the demand for oxygen in cold blooded aquatic animals, potentially exacerbating existing dissolved oxygen problems which affects fish survival and health (Najjar et al. 2000). Waterways within the Harbor Estuary that are poorly flushed and where major sources of fresh water include sewage treatment plants, such as Jamaica Bay, the Hackensack, and lower Passaic Rivers are especially susceptible to low DO conditions, including sustained, chronic hypoxia in association with seasonal stratification of the water column in deeper, channelized areas (GLEC 2017; NYCDEP 2017). Additional consequences of oceanic warming include increased proliferation of phytoplankton species associated with harmful algal blooms (HABs), which may impair fish survival (Hallegraeff 2010, O'Neil et al. 2012; Gobler et al. 2017) and elevated ocean acidity (reduction in pH) caused by increased atmospheric CO_2 absorbed by ocean surface waters.

Overview of Estuarine Climate/Fisheries Research

Changes in Fish Species Distribution – Global and Regional Patterns/Observations

Widespread changes in the distribution and abundance of estuarine and coastal fish populations in response to increasing oceanic temperatures have been documented extensively within the past several decades (Roessig et al. 2004, Nye et al. 2009, Nicolas et al. 2011, James et al. 2013, Koenigstein et al. 2016, Araujo et al 2018). For example, along the southeastern Brazilian coast, up to 50 individual fish species have been documented to have altered their distribution patterns, with subtropical species contracting their range in the north, and tropical species expanding their ranges to the south. Open water, planktivorous taxa (e.g. clupeids) showed the most changes, as they are highly mobile, and able to best exploit changing conditions, including altered patterns of food abundance (Araujo et al. 2018). A general shift northward in the migration patterns of many fish species has been documented for over 50 estuaries in Europe, from Portugal to Scotland, from the mid-1970s to the present (Nicolas et al. 2011). Within the Tagus Estuary, along the Portuguese Atlantic coast, an increase in sea surface temperatures for the period 1978-2006 was correlated with greater abundance and a northward range extension of sub-topical species and a decline in the abundance of temperate fish species (Vinagre et al. 2009). Tropical fish species are increasing in abundance within temperate estuaries along the coast of South Africa, and future projected changes in the intensity and periodicity of precipitation and river flow in these systems, along with projected increases in sea level rise and ocean acidification, is anticipated to strongly affect the composition and distribution of estuarine-dependent fish populations in this region (James et al. 2013).

Populations of warm-temperate fish species in Atlantic coast drainages may benefit from climate changes that are impacting cooler-water species, by expansion of their range to more northern estuaries (Clay 2013). One of the most compelling examples of this phenomenon is Narragansett Bay, Rhode Island. Nye et al. (2009) documented changes in the abundance and latitudinal distribution for several NW Atlantic fish species which were historically abundant and characteristic of the Narragansett Bay fish community from 1968 -2007. These changes occurred along with a 90% decline in winter flounder (*Pseudopleuronectes americanus*) abundance (since 1980) in Narragansett Bay (Oviatt 2004), which has been linked to warmer average water temperatures in the Bay during winter (Taylor and Collie 2003, Jefferies et al. 2011, Narragansett Bay Estuary Program 2017). The observed temperature increase was correlated with declines in winter flounder, red hake (*Urophycis chuss*), and silver hake (*Merluccius bilinearis*)—demersal species that reside in Narragansett Bay in the winter months—and increases in butterfish (*Peprilus triacanthus*) and scup (*Stenotomus chrysops*)—warm-water species that migrate into the Bay in summer. In addition, many Narragansett Bay species shifted their habitat preferences to deeper (cooler) waters. Collie et al. (2008) concluded that, over an approximately 50-year period of observation, the character of the Narragansett Bay fish assemblage appears to be transitioning from a typical southern New England estuarine community to a Mid-Atlantic estuarine community. A similar shift in fish community composition has been documented for the nearby Peconic Estuary (NY). Since 1987 the average number of warm-adapted fish species has increased in the Peconic system while the average number of cold-adapted species has decreased (Peconic Estuary Program 2017).

Fish Assemblage Changes within the NY/NJ Harbor Estuary

Within the NY/NJ Harbor Estuary, some faunal shifts already have occurred. These include the extirpation late in the 20th century of rainbow smelt (*Osmerus mordax*), in the Hudson River (Waldman 2006) and in tributary streams to Long Island Sound. Another cold- water species, Atlantic tomcod (*Microgadus tomcod*), has also diminished in the Hudson River (Waldman, 2014). In contrast, gizzard shad (*Dorosoma cepedianum*), historically rare north of Sandy Hook, colonized the Hudson River during the 1970s and has become established as far north as the Merrimack River, Massachusetts. Channel catfish (*Ictalurus punctatus*), another species most often associated with aquatic habitats (including large coastal river basins) to the south of the Hudson drainage, became increasingly abundant in the tidal Hudson river during the mid to late 1990s (Daniels et al. 2005). A few species, once common in NY waters and targeted by anglers prior to the 20th century, appear to be returning, including sheepshead and black drum and both are closely associated with oyster reefs, which declined sharply at the same time (Waldman 2014). Both warming waters and increasing numbers of oysters (naturally occurring and through restoration projects) may result in increased abundances of these fish in New York, along with other reef-associated species such as skilletfish (*Gobiesox strumosus*), oyster toadfish (O*psanus tau*), and feather blenny (*Hypsoblennius hentz*). Additional species in the drum family (Sciaenidae), including Atlantic croaker (*Micropogonias undulatus*), spotted seatrout (*Cynoscion nebulosus*), and red drum (*Sciaenops ocellatus*) are most often associated with estuaries to the south such as Delaware Bay and Chesapeake Bay, and Albemarle-Pamlico Sound. Yet, they have been occurring with increasing regularity in NY/NJ Harbor waters in recent years (Daniels et al. 2005, Waldman 2014). Additional warm-water species that are sometimes observed in NY/NJ Harbor include Atlantic tarpon (*Megalops atlanticus*), Spanish mackerel (*Scomberomorus maculatus*), cobia (*Rachycentron canadum*), gray triggerfish (*Balistes capriscus*), and cownose ray (*Rhinoptera bonasus*). With a warming climate, it can be expected that these species may also occur with greater regularity (Waldman 2014). Finally, an increase in the frequency of tropical marine strays [e.g., African pompano (*Alectis ciliaris*), angelfish (*Pomacanthus spp.*)] entering the Harbor, most often in late summer/early fall has been noted, and these occurrences are anticipated to occur with greater frequency, and with a greater diversity of species represented (Waldman 2014).

Some notable patterns and observations of characteristic fish (and invertebrate) species in response to climate change in the Hudson Estuary include:

> **White perch -** A common estuarine resident species in the Harbor Estuary, white perch (*Morone americana*) has shown particular resilience to climate change. This species can adjust its life history (for example by undertaking limited or “partial” migration) and adjust its distribution patterns because of broad environmental tolerances (Secor and Gallagher 2017). In recent years, interactions between climate variables (especially variations in the timing and extent of riverine flow) and impacts to food resources resulting from the zebra mussel (*Dreissenia polymorpha*) invasion of the upper (freshwater) portion of the tidal Hudson River in the early 1990s has altered the age/size structure and spatial/seasonal distribution of the Harbor Estuary’s white perch population. Overall the population remains stable, while several other species have declined over the same time period, and in response to similar climatic and ecological drivers.
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> **Striped bass –** Over the past several decades striped bass (*Morone saxatilis*) movements and distribution in the Hudson River Estuary and New York Bight have been highly variable, depending on weather patterns, prey availability, river discharge, and population size/age structure. However, climate change is likely to affect recruitment success of this species in in future years (Waldman 2006, 2014). One discernible climate-related change in striped bass ecology to date is that the onset of striped bass spawning has been observed to occur at an earlier period in the spring in Chesapeake Bay and other mid-Atlantic spawning estuaries, including the Hudson River Estuary (Kennedy et al. 2002). While the Hudson River striped bass stock is anticipated to remain stable, overall, in future years, it has been noted that localized spawning and a general increase

in numbers of striped bass have been documented at the northern extent of their range, in Nova Scotia and New Brunswick coastal rivers, in recent years (Waldman 2014).

River herring – Alewife (*Alosa pseudoharengus*) and blueback herring (*Alosa aestivalis*) - collectively termed “river herring” populations in mid-Atlantic estuaries, including the NY/NJ Harbor Estuary are also susceptible to warming oceanic temperatures - the marine distributions of the adult life stage of these species may shift seaward, resulting in longer migration periods for the fish to return to their spawning areas in coastal drainages. Annual recruitment of river herring is strongly affected by spawning stream temperatures and river flow (O’Connor et al. 2012). Evidence of this in the NY region is provided by recent observations of unusually early (February) alewife spawning runs on the south shore of Long Island (Waldman 2014).

Rainbow smelt – One of the most tangible indicators of climate change on fish of the Hudson Estuary is the case of rainbow smelt, a sub-arctic, anadromous specs, documented as abundant throughout the Hudson and its tributaries throughout most of the 20th century, By the 1970s, smelt abundance in HR tributaries began to decline, although they could still be collected in the mainstem of the river. Smelt continue to decline rapidly throughout the 1980s and 1990s, with the last recorded specimen in the Hudson collected in 1998 (Daniels et al 2005, Waldman 2006, 2014). Concurrently smelt also began to disappear from tidal rivers and their tributaries along the Connecticut coastline of Long Island sound (Daniels et al. 2005).

Atlantic Tomcod – Occupying a similar geographic range as smelt, tomcod tend to remain in estuaries rather than migrate offshore. Historically, tomcod was very abundant throughout the Harbor Estuary, and were reported as far south as the lower Chesapeake Bay (Virginia); however, there are no recent reports of spawning in any of the Atlantic coast drainages south of the NY/NJ Harbor Estuary (Daniels et al. 2005). The Hudson river tomcod population is currently exhibiting a sharp decline; a contributing factor may be the species’ naturally short lifespan at this extreme southern portion of their distributional range (most Hudson River tomcod only live one year). As with rainbow smelt, tomcod populations are also declining in nearby estuaries and coastal areas, including Long Island sound. It is expected that the Hudson River population will further diminish, and perhaps become extirpated entirely in the coming decades (Daniels et al. 2005).

Summer flounder – Locally referred to as “fluke,” summer flounder (*Paralichthys dentatus*) is an offshore spawning species, often sought after by anglers in the South Shore bays of Long Island (including Jamaica Bay) Historically, summer flounder were rarely encountered in Long Island Sound or the lower Hudson River and NY/NJ Harbor waters. However, since the 1970s, this species has been increased its distributional range northward (Waldman 2014).

Winter flounder – Prior to the late 1970s, winter flounder was one of the most abundant species sought after by inshore anglers throughout the Harbor Estuary and adjacent coastal waters. Within the past few decades, winter flounder have declined sharply throughout the southern portion of their range, from New Jersey to Rhode Island (Jefferies et al. 2011, Waldman 2014). Winter flounder spawn in estuaries at temperatures ranging from 1-10 °C, with optimal spawning conditions at 2-5 °C. The evolution of cold water spawning in winter flounder is considered to be a mechanism for avoiding predation on newly emerged/metamorphosing larvae, principally by sand shrimp (Crangonidae), which actively feed during warmer seasons. Thus, an increase in winter water temperatures in estuaries supporting winter flounder populations is potentially a critical threat to recruitment, because of increased susceptibility to predation. Warmer waters are also associated with greater egg mortality rates in winter flounder, reduced larval growth rates, and diminished larval condition (Keller and Klein-McPhee 2000). Winter flounder have historically exhibited long-term cyclical abundance patterns; however, periods of low abundance are now of longer duration and abundance peaks have diminished in recent decades.

Crabs and Lobsters - Estuarine macroinvertebrates (including those supporting important recreational and commercial fisheries) are also subject to population adjustments in response to oceanic warming. Blue crabs (*Callinectes sapidus*) are well-adapted to the warmer waters of the mid-Atlantic region to the south of the Harbor Estuary and are not anticipated to decline because of higher temperatures (Kennedy et al. 2002). However, American lobsters (*Homarus americanus*) are at the southern edge of their inshore range in New York and have already shown declines in recent years that may be linked to warming waters (Howell et al. 2005).

Habitat Loss and Degradation

Although many direct impacts to fish populations resulting from an increase in coastal water temperatures have been documented, indirect impacts through loss of critical habitat (including coastal wetlands) may also contribute to the decline of many species. For example, eelgrass (*Zostera marina*), while presently scarce within the Harbor Estuary, is recognized elsewhere in the mid-Atlantic region as an important nursery and forage habitat for a variety of estuarine resident and estuarine-dependent fish and macrocrustacean species (e.g., summer flounder, blue crab), and has been the focus of several restoration/recovery efforts within the Harbor in recent years. Increased mid-summer temperatures in shallow coastal bays can stress existing eelgrass beds or inhibit success and future potential for eelgrass restoration. This has been documented recently in Jamaica Bay, where mid-summer temperatures were considered a primary limitation to the survival and coalescence of transplanted eelgrass beds (Pickerell and Schott 2013). Moore and Jarvis (2008) reported that eelgrass beds in a Virginia tributary of Chesapeake Bay (Lynnhaven River) were growing at the species' physiological limits. They postulated that the combined effects of short-term exposures to very high summer temperatures, compounded by reduced oxygen and light conditions, may ultimately lead to long-term declines of eelgrass at or near its southern limit.

Coastal wetlands (e.g. salt and brackish marshes) throughout the Harbor Estuary provide critical forage, refuge and nursery habitat for many species of fish and macrocrustaceans, including striped bass, white perch, bluefish (*Pomatomus saltatrix*), weakfish (*Cynoscion regalis*) and blue crab. Most of these organisms are seasonal inhabitants, entering tidal marshes as juveniles in the spring and leaving in the fall (Neumann et al. 2004). Common resident prey species include various killifishes (*Fundulus* spp.) and grass shrimp (*Palaemonetes* spp.), which inhabit shallow creeks and pools within the marshes throughout the year and provide an important forage base for larger predatory fish and wading birds, such as herons and egrets (Raichel et al. 2003, Osgood et al. 2006).

Existing coastal wetlands throughout the Harbor Estuary will continue to erode or subside in the face of rising sea level; Presently, the rate of sea level rise in the Harbor Estuary ranges from 2.7 to 4.0 mm/year, which exceeds the global average of 1.8 mm/year from the 1900s to the present (NOAA 2018). In areas where wetlands are bordered by natural upland areas, they may be able to gradually migrate inland to some extent, as uplands are eventually converted to intertidal habitats. However, throughout much of the Harbor Estuary, especially in the urban/suburban core, the potential for natural migration of coastal landforms is severely restricted from centuries of shoreline development and re-alignment (Titus et al. 2009).

Tabak et al. (2016) simulated local and regional scale changes in tidal wetland response to sea level rise throughout the Hudson River Estuary, (including a portion of the NY/NJ Harbor Estuary) using the Sea Level Affecting Marshes Model (SLAMM). The SLAMM model results indicated that there may be considerable opportunity for inland wetland migration and localized wetland resilience in the lower Hudson River, based on the availability of low-gradient floodplains, should current rates of SLR not increase substantially. The SLAMM model projected losses of existing wetlands throughout the estuary at less than 15% by the year 2100; these losses would be offset by gains in new marsh. However, net losses are expected to occur over a longer time frame, as sea level rise outpaces accretion, and migrating wetlands eventually meet with steeper valley slopes.

An additional source of uncertainty in forecasting the loss of coastal wetlands in the Harbor Estuary is the occurrence of non-linear response patterns (Needelman et al. 2012). Often, impacts to wetlands and other coastal habitats are not necessarily observed until a disturbance threshold is reached. This may explain the rapid and recent loss of salt marsh islands in Jamaica Bay, a back-barrier system with limited sediment sources. Jamaica Bay's wetlands were subjected to impacts associated with dredging, coastal development and wastewater inputs for several decades before exhibiting tangible degradation; however, once the impact threshold was reached, perhaps in the late 1990s, the system reached a tipping point, and degradation became readily discernible. In the future, Jamaica Bay will likely continue to experience rapid erosion and/or subsidence of wetlands in the face of rising sea level. The continuation of anthropogenic activities such as dredging, channelization and shoreline hardening can also exacerbate or accelerate disturbance response times, mainly by altering patterns of sediment distribution.

Dissolved Oxygen Dynamics

Oceanic warming simultaneously reduces the total amount of dissolved oxygen that can be held in water and increases the demand for oxygen in cold blooded aquatic animals, potentially exacerbating existing dissolved oxygen problems which affects fish survival and health (Najjar et al. 2000). Fish are subjected to additional physiological stress in warming estuaries, especially during summer (Najjar et al. 2000, Roessig et al. 2004, Koenigstein et al. 2016). Changes in dissolved oxygen dynamics also affect predator-prey dynamics in estuaries. For example, periodic hypoxic events are increasing in frequency and duration in the Chesapeake Bay and tributaries. This change has been associated with elevated surface water temperatures which have altered macro-zooplankton (jellyfish) seasonal abundance and distribution patterns, resulting in higher predation rates of jellyfish on larval fish (Pyke et al. 2008).

Areas that are poorly flushed and which receive significant inputs of fresh water from wastewater treatment plans (WWTPs) such as Jamaica Bay, the Hackensack, and lower Passaic Rivers are highly susceptible to thermal impacts (including increased frequency and magnitude of hypoxia) on resident and transient biota (Whitehead et al. 2009). Dead-end canals and basins in densely populated or industrialized areas of the Harbor are especially problematic; because they are typically constructed to be deeper than surrounding estuarine waters, they are characterized by poor circulation, high pollutant loading, and chronic hypoxia. Periodic (seasonal) fish kills are a common occurrence in dead-end canals and basins within the Harbor Estuary, and many such areas have been proposed as candidate sites for bathymetric recontouring using dredged material as a means of increasing circulation and alleviating seasonal hypoxia (Yozzo et al. 2004). The Hackensack River/Newark Bay and portions of the Arthur Kill have been identified as locations with DO conditions that might impact juvenile/adult aquatic life survival, growth and reproduction (including larval recruitment) based on the USEPA's established acute and chronic limits for marine DO at (2.3 mg/L and 4.6 mg/L, respectively) (USEPA 2000, GLEC 2017). However, these criteria are based on the premise of continuous exposure, which is not a realistic assumption for most well-mixed tidal waters, including those of the Hackensack River and Arthur Kill, where DO (along with temperature and salinity) vary diurnally and tidally. Most mobile estuarine biota (e.g., fish and macrocrustaceans) are broadly distributed throughout the NY/NJ Harbor Estuary, according to their preferences for currents, depth salinity, and certain habitats. Thus, it is challenging for resource managers to relate observed low DO conditions to impacts on marine/estuarine biota, as the effects of low DO are influenced by intermittent exposures (vs. continuous exposure to low DO).

A comprehensive survey of fish population of the Hackensack River was conducted in the mid-to late 1980s and repeated in the early 2000s. The comparison of the two surveys over a 15-year range coincident with a documented increase in coastal water temperatures in the Harbor Estuary provides a unique opportunity to assess changes in the fish fauna of a NY/NJ Harbor sub-estuary affected by anthropogenic stressors (Bragin et al. 2005). The later studies documented a more even distribution of species than the 1980s studies, suggesting improvements in water quality and ecosystem stability over the 15-year interval between the two surveys; however, dominance by only a few opportunistic/generalist taxa in the upper reaches of the river were still considered indicative of a stressed ecosystem. The relative abundance of white perch, gizzard shad and striped bass increased during the 2000s study in comparison to the initial study. White perch and striped bass are regarded as especially resilient and opportunistic species, able to adapt to and occupy a wide range of freshwater estuarine and coastal habitats. Gizzard shad is a relatively recent invader to the Harbor Estuary but is expected to expand into more northern waters in the future, along with several other southern species which have become established in the Harbor Estuary in recent years. However, a few species were noted as more abundant in the 1980s study, including Atlantic tomcod, and blueback herring, both of which have been identified as potentially at risk from projected climate change impacts in the Harbor Estuary.

Ocean Acidification

Within the last two decades, "ocean acidification" i.e., an ongoing decrease in the pH of oceanic surface waters due to anthropogenic increases in atmospheric CO_2, has raised concern among climatologists, marine ecologists and coastal resource managers. However; while acidification in the open ocean is driven by external, atmospheric CO_2 loading, the contribution of atmospheric CO_2 in temperate estuaries and coastal zones is thought to be relatively minor compared to internal loading processes such as organic matter production (Wallace et al. 2014). For example, in portions of the Harbor Estuary, notably Jamaica Bay, expansive nuisance macroalgae blooms (predominantly *Ulva* sp.) occur seasonally and rapidly decompose, releasing nutrients and providing a large CO_2 subsidy.

The primary consequence of reduced oceanic (or estuarine) pH is a reduction in available carbonate concentrations, which threatens bivalve and gastropod mollusks and other calcifying species by inhibiting their ability to form shells and exoskeletons. An increase in surface water acidity may also impair the survival and development of sensitive fish and invertebrate larvae (Wallace et al. 2014). A nearby example of the potential impact of ocean acidification on a coastal fishery is illustrated by the collapse (and subsequent lack of recovery, despite intensive restoration efforts) of the bay scallop (*Argopecten irradians*) fishery in NY waters. The fishery was devastated in the 1980s by an outbreak of algae blooms ("brown tides") (Gobler et al. 2005) however, it is believed that the failure of this fishery to recover may be due, in part, by increased oceanic acidification (Talmage and Gobler 2011, Gazeau et al. 2013).

Predator-Prey interactions

Altered temperature regimes in coastal waters and estuaries may induce changes in the relationship between vertebrate and invertebrate predators and their prey. A compelling example of this phenomenon has been shown to be an important driver of a pronounced (greater than 90%) decline in winter flounder abundance in Narragansett Bay since the late 1970s. (Oviatt 2004, Taylor and Danila 2005, Jefferies et al. 2011). Winter flounder lay their eggs during winter, when predators such as sand shrimp (*Crangon septemspinosa*) are either absent or dormant. As winter water temperatures have increased over the past several decades, sand shrimp remained active and continued to prey on winter flounder larvae (Taylor and Collie 2003). In addition, winter water temperatures in the Bay have risen above the optimal temperature range for winter flounder egg survival/hatching, further exacerbating predation impacts on winter flounder recruitment (Keller and Klein-MacPhee 2000).

To the south, in the Chesapeake Bay and its tributaries, increased surface water temperatures which have altered macro-zooplankton (jellyfish) abundance and distribution patterns, resulting in changes in predation rates of jellyfish on larval fish (Pyke et al. 2008). The NY/NJ Harbor Estuary supports a variety of gelatinous macro-zooplankton species in common with Chesapeake Bay and other mid-Atlantic estuaries; therefore, similar impacts to larval fish resulting from an increase in jellyfish may be a future condition within the Harbor Estuary as warming continues.

Newly established oyster reefs (and remnant native oysters) in the NY/NJ Harbor estuary and adjacent marine waters are subject to predation by a variety of marine organisms These include sea stars, oyster drills, boring sponges, and blue crabs. Altered temperature and salinity patterns associated with climate change in the Estuary can potentially result in expansion of the range of some of these predators, especially the gastropods and echinoderms, and encroach upon oyster reefs in areas previously unavailable (Kennedy et al. 2002, Pyke et al. 2008). Blue crab is a species which is anticipated to thrive in the NY/NJ Harbor Estuary and in estuaries located to the north, as seas surface temperatures in the western North Atlantic continue to rise (Buonaiuto et al. 2011).

Plankton Dynamics and Nuisance/Harmful Algae Blooms

Increased surface water temperature, along with changing patterns of precipitation and riverine hydrology may alter the timing and magnitude of phytoplankton production in estuaries, favoring production by species known to form harmful algal blooms (HABs) (Pyke et al. 2008, O'Neil et al. 2012). Higher rates of phytoplankton production have been observed in the Hudson River during dry summers when freshwater discharges are lower, and the effective depth of the photic zone is maximized (Howarth et al. 2000). Changes in riverine (Hudson River) discharge and associated nutrient and sediment inputs will continue to alter phytoplankton production dynamics and residence time under a projected warming trend (Howarth et al. 2014, Swaney et al. 2012).

Surface water warming is the primary trigger for the onset of HABs, as most bloom-forming species generally have well-defined seasonal temperature windows (Gobler et al. 2017). However, once a bloom has commenced, other factors such as nutrients, hydrodynamics, and grazing determine the magnitude and duration of the event (Hallegraeff 2010). Toxic effects vary; some forms may exhibit toxicity to fish and aquatic biota even at low cell concentrations, while others may be essentially nontoxic but present a nuisance through high biomass production – these are sometimes referred to as "ecosystem disruptive algal blooms" (EDABs), because they interfere with grazing by zooplankton and alter patterns of nutrient supply and elemental recycling. The greatest concern for human communities in the coastal zone is algal species that produce neurotoxins; these can transmit through consumption of shellfish and fish and produce a variety of gastrointestinal and neurological illnesses. For many HAB species, significant blooms can facilitate range expansions via natural currents, or transport considerable distances (even across oceans) in ship ballast water (Hallegraeff 2010).

Nuisance cyanobacteria (blue-green algae) blooms are also becoming more frequent and problematic in both coastal and freshwater environments; cyanobacteria blooms have increased in recent years within the Hudson River Estuary, especially in the (freshwater tidal) reaches and non-tidal tributaries. These events are typically triggered by high mid-summer temperatures in combination with high levels of nutrient (P) loading (Gobler et al. 2017). The increasing prevalence of cyanobacteria blooms in estuarine surface waters is a potential ecological and human health concern as many genera are known to produce harmful compounds and metabolites including hepatotoxins and neurotoxins (O'Neil et al. 2012).

Parasitism and Infectious Diseases in Marine/Estuarine Organisms

Climate change is predicted to have important effects on parasitism and disease in freshwater and marine ecosystems, with successive potential impacts on human health and socio-economics. The distributional ecology of parasites and pathogens will be affected directly by warming waters, and indirectly, through changes in host range and abundance (Marcogliese 2008). Warming enhances parasite metabolism and may affect (diminish) the magnitude of immune response in aquatic/marine organisms (Lohmus and Bjorklund 2015). Perhaps the most damaging effect of climate change-induced alterations in estuarine/marine parasite and disease ecology is the potential for cumulative or synergistic effects, in combination with other stressors (e.g., low DO, contaminant uptake, thermal stress, etc.) (Pyke et al. 2008).

Of particular concern to resource managers and scientists engaged in ongoing oyster restoration efforts in the NY/NJ Harbor Estuary is the potential effect of climate change and specifically, increased water temperature on the distributional ecology and incidence of two protozoan oyster diseases, "MSX" and Dermo." The former is caused by *Haplosporidium nelsoni*; the latter is caused by *Perkinsus marinus*. Both parasites organisms affect oysters by impairing feeding ability, growth and respiration. Dermo was first documented in the 1940's in the Gulf of Mexico; since 1991, this parasite has been found in oysters from Connecticut, New York, Massachusetts and Maine (Ford and Tripp 1996). Dermo is most prevalent in conditions of high temperature and high salinity, proliferating rapidly above 20 °C and in salinities above 12-15 ppt (Paynter and Burreson 1991). Cook et al. (1998) reported that high winter temperatures are more critical to the development of *P. marinus* than are high summer temperatures. MSX was first documented in 1957 in Delaware Bay and has since spread from Maine to Florida (Ford and Tripp 1996). As with Dermo, temperature and salinity play an important role in regulating MSX, with most infections acquired above 20 °C and at salinities above 15 ppt (Ford 1985).

Contaminant Mobilization and Bioaccumulation

Urbanized or "built" environments are recognized as drivers of environmental change (Grimm et al. 2008). Areas of impervious surface cover alter the hydrology and geomorphology of drainage systems, whereas municipal and industrial discharges increase loads of nutrients, heavy metals, pesticides and other contaminants in receiving surface water courses Potential impacts on urban water quality will be driven largely by changes in short-duration rainfall intensity overwhelming drainage systems, as well as rising sea levels affecting combined sewerage outfalls. The former could result in greater incidence of foul water flooding of domestic property, or uncontrolled discharges of untreated sewage with concomitant impacts on ecosystems. There could also be major implications for water quality monitoring protocols, environmental standards, compliance and reporting (Crane et al. 2005).

Within the NY/NJ Harbor Estuary, ongoing and projected warming of estuarine surface waters has been linked to potential increases in the bioaccumulation of organic legacy contaminants, including TCDD and PCBs, in Atlantic tomcod (Brown et al. 2017), a species at the southern limit of its range in this region and considered likely to be extirpated in the coming decades. Warmer sea surface temperatures could also result in greater in bioaccumulation of methyl mercury (MeHg) in fish, and consequently, result in increased human exposure of this potent neurotoxin (Dijkstra et al. 2013). Certain areas of the Harbor Estuary are known to contain exceptionally high concentrations of methyl mercury in sediments and estuarine biota (e.g. the lower Hackensack River), with fish consumption advisories in place, including a number of fish species harvested by recreational anglers.

Areas within the Estuary experiencing increased intensity/volume of precipitation will generally experience lower levels of air pollution but will receive greater deposition of airborne contaminants (e.g. mercury, lead) to surface waters, as well as greater degree of runoff containing contaminants (e.g. pesticides, PAHs, etc.) from adjacent lands into tributaries and shoreline areas (Noyes et al. 2009). Furthermore, elevated water temperatures may alter the transformation of contaminants entering the Estuary to more bioactive metabolites and impair homeostasis in aquatic/marine organisms.

Regulatory/Permitting Challenges

Thermal pollution occurs when any process increases or decreases ambient water temperature sufficiently to harm fish, plants, or other aquatic organisms. Under the Clean Water Act, thermal effluent – including waters discharged during open-cycle cooling at nuclear, coal-fired, or natural gas generating stations located along rivers, lakes or coastal waters – is regulated as a pollutant, and facilities wishing to discharge thermal effluent into a water source must apply for a NPDES permit. Under CWA Section 316(a), a thermal discharger to obtain a thermal effluent variance by demonstrating that less stringent thermal effluent limitations would still protect aquatic life. Thermal discharging entities are most often power-generating facilities; however, in New York City, there are several non-energy producing facilities which use Hudson River/East River water for industrial/commercial heating and cooling purposes. Nationwide, a substantial portion steam-electric generating capacity currently operates under Section 316(a) variances (Kray 2011). Under a projected warming scenario for receiving water in the NY/NJ Harbor Estuary, meeting existing thermal effluent standards may represent an increasing challenge for energy utilities and other permittees, should regulatory agencies adopt more stringent (protective) criteria within a warming estuary. However, new technologies and operational procedures are being implemented by utilities in the Harbor Estuary region (and elsewhere), reducing cooling water requirements, and thermal discharge volumes (Con Edison 2017, PSEG 2018). In addition, increased reliance on emerging alternative energy sources (e.g., hydropower, solar and wind energy produced outside of the NY/NJ metropolitan area) and improved, more efficient transmission technology including long-distance sub-aqueous power cable systems will offset much of the energy demand historically provided by steam-electric power plants in the Harbor Estuary region. Many such facilities have already been decommissioned or are currently operating in a stand-by or emergency demand mode (e.g. the former Lovett and Bowline Generating Stations in Rockland County and the Roseton-Danskammer plants in Orange County).

Future climate projections and vulnerability may require a re-evaluation of current Federal, state (NY and NJ) and municipal water quality (dissolved oxygen) standards for the Harbor Estuary. Current Federal (USEPA) criteria for aquatic biota ["Ambient Aquatic Life Water Quality Criteria for Dissolved Oxygen (Saltwater): Cape Cod to Cape Hatteras"] criteria stipulate that a minimum ambient DO concentration of 2.3mg/L is required to insure survival of marine life (acute criterion), and that 4.8mg/L is required to protect reproduction and growth (chronic criterion). HEP's Dissolved Oxygen Workgroup developed a water quality model to assess the likelihood of compliance with the criteria in all of the major areas of the Harbor, including the tidal portion of the tributaries. When that model was used to identify areas of compliance and projected non-compliance with USEPA's marine DO criteria, several areas of the Harbor were identified as being persistently out of compliance. However, biological/water quality surveys and anecdotal observations often document the presence of various life stages of marine and estuarine species in areas that are frequently do not meet established marine DO criteria throughout the year (GLEC 2017). In addition, other water quality factors (e.g., low pH) may interact with episodic low DO to impair reproduction, growth and survival or aquatic organisms. For example, simultaneous acidification and low DO have been shown to synergistically depress survival rates of bivalves (Wallace et al. 2014). Thus, present-day management guidelines implemented within the Harbor Estuary (and elsewhere) based strictly on DO may not be fully protective of estuarine biota.

An additional regulatory challenge under a warmer climate scenario in the Harbor Estuary involves the applicability of existing restrictions on in-water construction or maintenance dredging operations. "Environmental windows" have been established to minimize potential adverse impacts on important fisheries resources. Regulators (USACE, NOAA, NYSDEC, NJ DEP, and cooperating agencies) typically set windows which allow dredging and construction activities during periods determined to ensure minimal impacts on designated species. Some of these windows have been in place for more than thirty years. In general, the windows are set using a policy that emphasizes risk avoidance when possible, risk management when avoidance is not possible, and lastly, mitigation when necessary to offset unavoidable impacts (Tanski et al. 2014). Priority species of concern include American eel (*Anguilla rostrata*), Atlantic menhaden (*Brevoortia tyrannus*), Atlantic sturgeon (*Acipenser oxyrinchus*), blue crab, American lobster, river herring, summer flounder, tautog (*Tautoga onitis*) weakfish, and winter flounder, many of which are expected to respond to warming estuarine conditions by altering their seasonal and spatial distribution patterns (Tanski et al. 2014). As these target species populations in the Harbor Estuary respond to climate change, existing operational windows may require re-evaluation and adjustment.

State (NY and NJ) Water Quality Regulations and Criteria:

The individual states (NY and NJ) with regulatory authority encompassing the marine and estuarine waters of the Harbor Estuary have established water quality criteria to categorize and regulate natural resources and human activity, including industrial/commercial practices and recreational activities such swimming, angling and boating.

For the purposes of regulating energy production and industrial /commercial practices using riverine or estuarine waters, NYSDEC defines "cooling water" as: "the water used for contact or non-contact cooling, including water used for equipment cooling, evaporative cooling tower makeup, and dilution of effluent heat content. The intended use of the cooling water is to absorb waste heat rejected from the process or processes used, or from auxiliary operations on the facility's premises." In a conventional power plant or other industrial cooling operation water is drawn from a source water body (river lake, estuary) passed through a series of pumps ad condensers to generate steam (or simply to absorb excess heat) and discharged back into the source water body. The volume of cooling water and the temperature differential between the intake vs. the discharge point are inversely related in open-cycle ("once-through") cooling systems. The total heat exchange needed to produce one kW of electricity is relatively constant; thus decreasing the flow of cooling water increases the temperature differential between the source and the discharge (McDowell 1984).

New York State regulations (6 CRR-NY 704.1, 704.2) provide extensive guidance and list criteria governing thermal discharges as follows:

A. *Water quality standards for thermal discharges.*

> *(i) All thermal discharges to the waters of the State shall assure the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife in and on the body of water.*
>
> *(ii) The criteria contained in this Part shall apply to all thermal discharges and shall be complied with, except as provided in this Part.*

B. *General criteria (applies to all waters of the State receiving thermal discharges)*

> *(i) The natural seasonal cycle shall be retained.*
>
> *(ii) Annual spring and fall temperature changes shall be gradual.*
>
> *(iii) Large day-to-day temperature fluctuations due to heat of artificial origin shall be avoided.*
>
> *(iv) Development or growth of nuisance organisms shall not occur in contravention of water quality standards.*
>
> *(v) Discharges which would lower receiving water temperature shall not cause a violation of water quality standards.*
>
> *(vi) For the protection of the aquatic biota from severe temperature changes, routine shut down of an entire thermal discharge at any site shall not be scheduled during the period from December through March.*

C. *Coastal waters*

> *(i) The water temperature at the surface of coastal waters shall not be raised more than four Fahrenheit degrees from October through June nor more than 1.5 Fahrenheit degrees from July through September over that which existed before the addition of heat of artificial origin.*
>
> *(ii) The water temperature at the surface of coastal waters shall not be lowered more than four Fahrenheit degrees from October through June nor more than 1.5 Fahrenheit degrees from July through September from that which existed immediately prior to such lowering.*

D. *Estuaries or portions of estuaries.*

> *(i) The water temperature at the surface of an estuary shall not be raised to more than 90 degrees Fahrenheit at any point.*
>
> *(ii) At least 50 percent of the cross sectional area and/or volume of the flow of the estuary including a minimum of one-third of the surface as measured from water edge to water edge at any stage of tide, shall not be raised to more than four Fahrenheit degrees over the temperature that existed before the addition of heat of artificial origin or a maximum of 83 degrees Fahrenheit whichever is less.*

> *(iii) From July through September, if the water temperature at the surface of an estuary before the addition of heat of artificial origin is more than 83 degrees Fahrenheit an increase in temperature not to exceed 1.5 Fahrenheit degrees at any point of the estuarine passageway as delineated above, may be permitted.*
>
> *(iv) At least 50 percent of the cross-sectional area and/or volume of the flow of the estuary including a minimum of one-third of the surface as measured from water edge to water edge at any stage of tide, shall not be lowered more than four Fahrenheit degrees from the temperature that existed immediately prior to such lowering.*

E. Enclosed bays.

> *(i) No additional temperature change except that which occurs naturally shall be permitted in enclosed bays.*

In New Jersey, temperature criteria for "saline/estuarine waters" are summarized in "Surface Water Quality Standards" [N.J.A.C. 7:9B-1.14(d)] and "Stormwater Management" [N.J.A.C. 7:8]. As defined in the New Jersey regulations:

> *"Heat dissipation area" means a mixing zone, as may be designated by the Department, into which thermal effluents may be discharged for the purpose of mixing, dispersing, or dissipating such effluents without creating nuisances, hazardous conditions, or violating the provisions of this chapter, the Surface Water Quality Standards. "Thermal alterations" means the increase or decrease in the temperature of surface waters, above or below the natural temperature, that may be caused by the activities of man.*
>
> *(i) Temperatures shall not exceed a daily maximum of 22 degrees Celsius or rolling seven-day average of the daily maximum of 19 degrees Celsius, unless due to natural conditions*
>
> *(ii) Temperatures shall not exceed a daily maximum of 25 degrees Celsius or rolling seven-day average of the daily maximum of 23 degrees Celsius, unless due to natural conditions*
>
> *(iii) Temperatures shall not exceed a daily maximum of 31 degrees Celsius or rolling seven-day average of the daily maximum of 28 degrees Celsius, unless due to natural conditions*
> *(iv) No thermal alterations which would cause temperatures to exceed 29.4 degrees Celsius (85 degrees Fahrenheit) Summer seasonal average*
>
> *(v) No thermal alterations which would cause temperatures to exceed 26.7 degrees Celsius (80 degrees Fahrenheit) Summer seasonal average*

Local/Municipal Initiatives to Address Climate Change Impacts and Adaptations:

The city of New York has, in recent years, taken steps to reduce a substantial source of thermal effluent (and other pollutants) into its receiving waters – combined sewer overflows, or "CSOs." Combined Sewer systems collectively route stormwater runoff, domestic sewage, and industrial wastewater to municipal wastewater treatment facilities. However, they are designed to overflow during extreme rain events, and the excess water discharged directly into streams, rivers, estuaries, and coastal waters.

An important component of New York City's effort to reduce stormwater discharge (and therefore alleviate thermal impacts and low DO conditions within estuarine receiving waters) includes implementation of Best Management Practices (BMPs) intended to reduce stormwater runoff entering combined sewer systems, authorized in a 2005 Consent Order to develop Long-Term Control Plans (LTCPs) for CSO upgrades to improve the water quality throughout the Harbor, including Flushing Bay, Jamaica Bay, and tributaries to the East River, Long Island Sound, and Outer Harbor (NYCDEP 2017). In 2011, the Consent Order was updated to include a range of BMPs, such as adoption of "gray-water" reuse programs within NYC offices and facilities; installation of permeable surfaces to absorb runoff (e.g., "porous pavements"); "greening" of streetscapes, public recreation areas and municipal building roofs to absorb, rather than convey stormwater; construction of vegetated swales and retention basins along roadways; and encouraging city residents to participate by distributing "rain barrels" to capture water from roofs to be repurposed for gardening and lawn care. Within the past decade, NYC has implemented several major capital infrastructure improvements, including massive subsurface storage facilities to capture and detain combined stormwater and municipal wastewater during storm events. However, the various LTCPs recognize that traditional infrastructure upgrades alone would not fully satisfy the objectives of the plan, especially in the face of project regional changes in the patterns of precipitation intensity and periodicity, and explicitly states that incorporation of the BMPs would be an essential component of the plan (NYCDEP 2017).

Previous and ongoing programs within NYC have also sought to alleviate stormwater discharge into the receiving waters of the Harbor Estuary. The Staten Island "Bluebelt" program, which began in 1997 is a showcase of nearly 50 individual BMPs and habitat restoration efforts intended to enhance water conveyance, storage and filtration via vegetated coastal upland and wetland habits (NYCDEP Undated). Similarly, the Jamaica Bay Watershed Protection Plan, implemented in 2007, seeks to combine traditional infrastructure upgrades with innovative BMPs to achieve a significant overall reduction in the amount of combined wastewater and stormwater entering four municipal treatment plants discharging into Jamaica Bay (NYCDEP 2007).

In New Jersey, the state's Stormwater Management rules at (N.J.A.C. 7:8) require all municipalities to adopt a stormwater control ordinance to address stormwater on individual development sites. The rules set minimum design and performance standards; however, municipalities have the authority to adopt more stringent stormwater control ordinances to address local needs, including local ordinances to promote the implementation of green infrastructure alternatives on public and private land (NJDEP 2018). In addition, the New Jersey Department of Environmental Protection (NJDEP) has taken steps to integrate green infrastructure in the development and implementation of LTCPs throughout the state, including municipalities located within the Harbor Estuary and watershed. The NJDEP LTCP requires individual municipalities (permittees) to evaluate alternatives that will reduce or eliminate CSO discharges and provides technical assistance, guidance and training to CSO permittees to facilitate LTCP implementation, including the application of green infrastructure, project financing, and community engagement strategies (NJDEP 2018). Green infrastructure strategies being promoted to communities in the New Jersey portion of the Harbor Estuary and watershed include: rain gardens/bioretention basins, vegetated swales, green roofs, pervious pavements and riparian buffer enhancement.

The electrical power generation industry in the NY/NJ Metropolitan region represents a major component of a comprehensive regional approach to managing thermal effluent discharge to coastal waters of the Harbor Estuary. This industry has already begun a proactive approach to thermal effluent reduction in the context of a changing global and regional climate. For example, the regional electrical utility company Con Edison (and its subsidiary, Orange & Rockland Utilities) operates steam electric generation facilities throughout the NY/NJ Harbor Estuary. Con Edison explicitly considers and incorporates water use reduction as part of its Sustainability Plan, primarily through ongoing technology upgrades and implementation of efficiency improvement projects. Con Edison has reported a total reduction in cooling water use/discharge of 38 million gallons/year (MGY) in both 2016 and 2017 and anticipates a total reduction of 295 MGY beginning in 2018 (Con Edison 2017). Con Edison is currently undertaking a study to understand the vulnerability of energy systems to climate change and to identify adaptation options (including revisions to existing design standards and operating processes) to enhance resiliency – their analysis will project future weather scenarios out to 2080.

Con Edison, PSEG and other utilities within the NY/NJ Harbor region can take advantage of a NY-focused version of EPRI's U.S. Regional Economy, Greenhouse Gas, and Energy model (US-REGEN) which simulates the performance of the regional energy supply system under different projected climate conditions (e.g., 2030 and 2050 time frames). The REGEN model integrates climate-related constraints and allows the user to determine least-cost electric system scenarios under projected climate changes. The REGEN model results can indicate the potential magnitude of thermal (and other) impacts and vulnerability when changing climate conditions are anticipated, informing the decision-making process and adaptation strategy for utility operations. Adaptation measures which may be considered to streamline operations and reduce cooling water use may include investment in additional capacity, incorporation of more advanced cooling technologies, and changes in the mix of available power generation options (Young 2017).

Data Gaps, Future Research and Monitoring

The historic fish assemblages of the NY/NJ Harbor Estuary are well documented, in comparison to nearby Atlantic coast drainages, in part due to an extensive monitoring program undertaken by the Hudson River Utilities (primarily Con Edison/O&R, and Central Hudson Gas & Electric). The monitoring program was initiated in the late 1960s to support the Utilities' opposition to construction and operation of closed-cycle cooling towers at Hudson River power plants. Originally focused on sampling both adult and early life stages of fish within the direct vicinity of power plants along the river, the program was expanded from near-field (power plant vicinity) sampling to include more comprehensive, river-wide sampling by the mid-1970s (McDowell 1984). A settlement agreement was reached between the USEPA, NYSDEC, the Attorney General of the State of New York, and several environmental groups in December 1980. This agreement postponed the cooling tower issue, authorized mitigation measures to compensate for loss of fishery resources from the continued operation of "once-through" cooling facilities and authorized the long-term continuation of annual fisheries monitoring in the Hudson River Estuary through 2018; however, the program has been substantially reduced in scope in its final two years and will end in 2019 (Gregg Kenney, NSDEC, pers. comm). In addition to the Utilities monitoring program, much has been learned about the ecology of Hudson River fish communities through basic and applied research funded by the Hudson River Foundation, which was endowed as a condition of the 1980 Settlement agreement (McDowell 1984).

The availability of this varied and long-term fisheries dataset is advantageous for researchers and resource managers responsible for tracking and forecasting future changes in the Estuary's fish assemblages, and for HEP to implement strategic planning and management programs. However, additional research and monitoring may complement or refine these efforts. While NYSDEC has monitored and generated young-of-the-year indices for select Hudson River species (striped bass, alewife, blueback herring and American shad), there is no comprehensive monitoring metric or approach to track the individual status of many other fish species at risk (or potentially increasing) in the Hudson river Estuary. An example approach is currently in use for Narragansett Bay – where a weighted mean preferred temperature index is used to monitor changes in fish populations over time (Collie et al. 2008). The Narraganset Bay index uses the temperature preference of each species weighted by its annual mean abundance. In addition to routine monitoring and surveys, this approach provides another metric by which to confirm trends in relation to climate and could potentially be implemented in ongoing or future fisheries monitoring programs within the Hudson River Estuary.

In combination with continuous, multi-parameter data records available from the Hudson River Environmental Conditions Observing System (HRECOS), and other long-term data collection and monitoring efforts undertaken by Universities and research institutions (e.g., Cary Institute of Ecosystem Studies' long-term Hudson River Ecosystem Study program) an individual species-based temperature index could be used to monitor and manage fish and aquatic resources of the NY/NJ Harbor Estuary into the future. Interpretation of fish community monitoring data within the Harbor Estuary as ocean temperatures increase will represent a challenge for ecologists and research managers. The cumulative impacts of rising ocean temperatures, river flows, ocean acidification, altered coastal circulation patterns and sea-level rise are still poorly understood and potentially confounded by synergistic interactions and non-linear relationships (Reum et al. 2011). Furthermore, the indirect effects of climate change on trophic interactions may be especially difficult to anticipate. Future climate conditions may redistribute prey and predator populations or increase the abundance of competitors, potentially generating novel ecological interactions with unknown outcomes (Reum et al. 2011). Although many recent trends in coastal/estuarine fish distribution and abundance are consistent with anthropogenic climate change, these trends might not continue in a linear fashion. Short-term trends easily nest within longer climate cycles, and the majority of ecological studies or monitoring programs encompass only parts of these cycles (Crozier and Hutchings 2014). Ultimately, many species may be able to adapt to long-term warming trends overlaid on natural climate oscillations. Continuation of existing long-term fisheries monitoring programs by NYSDEC and/or implementation of new, climate-focused monitoring by other agencies or collaborative research programs will be necessary to assess response patterns and formulate management approaches for individual fish species within the Hudson River and Harbor Estuary. As indicated previously, it may be prudent for federal and state regulatory agencies to re-evaluate the current status of water quality criteria/standards, especially DO-based standards which are limited by their failure to consider episodic as well as continuous DO conditions. An evaluation of thermal effluent criteria/standards is use currently by New York and New Jersey may also be necessary in a warming climate scenario to be fully protective of aquatic/marine resources.

Acknowledgements

The NY/NJ Harbor & Estuary Program would like to thank the following individuals for their contributions and reviews of a preliminary draft version of this chapter: William Dey (ASA, Inc.); Gregg Kenney and Richard Pendleton (NYSDEC); Dr. Daniel Millemann and Metthea Yepsen (NJDEP). Although the information in this document has been funded wholly or in part by the United States Environmental Protection Agency under agreement to the Hudson River Foundation, it has not undergone the Agency's publications review process and therefore, may not necessarily reflect the views of the Agency, and no official endorsement should be inferred.

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