Climate Change

And its Impact on the New York / New Jersey Harbor & Estuary Program

HUDSON RIVER FOUNDATION

NY/NJ HARBOR & ESTUARY PROGRAM

Acknowledgements

This report was produced by: Kate Boicourt and Robert Pirani with the help of Isabelle Stinnette and Ariane Giudecelli, all staff of the NY-NJ Harbor & Estuary Program. Our work greatly benefited from the insights and comments from all current and former staff, a project advisory committee (listed below). We would like especially to thank the students and faculty at the Workshop in Sustainable Development Class at Barnard College—Sabrina Ramkhelawan, Barsa Barsa, Mariah Castillo, Hannah Spierer, Tracie Brown and Professor Martin Stute—for their assistance in conducting an initial literature survey and assessment. This report references additional assessments conducted by David Yozzo of Glenford Environmental Science, Betsy Blair of Blair Environmental Consultants, and Phil Orton of Stevens Institute and David Ralston of Woods Hole Oceanographic Institute. Graphic design, mapping and data visualization by Sara Eichner and the Spatial Analysis and Visualization Initiative at Pratt Institute.

Although the information in this document has been funded by the United States Environmental Protection Agency under agreement with 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. The viewpoints expressed here do not necessarily represent those of the U.S. Environmental Protection Agency, nor does mention of trade names, commercial products, or causes constitute endorsement or recommendation for use.

November, 2018

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CITATION

Pirani, R and Boicourt, K., 2018. *Climate Change; And its Impact on the NY-NJ Harbor & Estuary Program*, Hudson River Foundation. New York, NY.

New York – New Jersey Harbor & Estuary Program • 17 Battery Place, Suite 915, New York, NY 10004
www.hudsonriver.org/NYNJHEPClimateVulnerability.pdf

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Introduction and Overview

The Estuary's ongoing challenges will be compounded by the likely impacts of a changing climate. These expected changes include warmer air and water temperatures, changes in precipitation patterns, increases in extreme weather events, rising sea levels, and ocean acidification.

Climate change is impacting the health of the New York–New Jersey Harbor and Estuary. Warmer air and water temperatures, increases in the number of extreme weather events, and rising sea levels are already changing baseline conditions and affecting people and wildlife. These changes are expected to increase in the future.

The Estuary's 250 square miles of open water and 1,600 miles of shoreline lie at the heart of the densely populated New York–New Jersey metropolitan region. Urban land uses, legacy contaminants, and large volumes of waste and polluted stormwater runoff pose significant obstacles to achieving the fishable and swimmable waters called for by the Clean Water Act.

The Estuary's ongoing challenges will be compounded by the likely impacts of a changing climate. These expected changes include warmer air and water temperatures, changes in precipitation patterns, increases in extreme weather events, rising sea levels, and ocean acidification. Understanding HEP's organizational vulnerability to these specific stressors will help shape how the Program allocates its resources and where it places staff and research emphasis for the next five years and beyond.

This report was prepared to gain a greater understanding of how the risks associated with climate change stressors will limit the ability of the New York–New Jersey Harbor & Estuary Program (HEP) to reach its goals for reducing pollution, improving and increasing habitat and public access, supporting maritime uses, and engaging communities. It is intended to inform the Program's 2017-2022 Action Agenda (www.harborestuary.org). In total, 17 risks were identified and evaluated by an advisory committee of climate experts and HEP's core partners. Seven of these risks are seen as having a relatively higher likelihood of occurrence andconsequence of impact and would affect all or most of the the Estuary. Numbers refer to the order of presentation by HEP Goal starting on Page 10:

- Sea level rise will reduce wetland and other coastal habitat, particularly in areas where there are barriers to upland migration. (pg. 21)
- Increased precipitation and extreme events may impact wastewater and stormwater infrastructure, reducing our ability to meet water quality goals for primary contact recreation, shellfish, and floatable debris. (pg. 16)
- Increases in temperature may exacerbate dissolved oxygen problems, impacting the ability to meet goals for fish survival and reproduction. (pg. 15)
- Maladaptive human responses to climate change can impair water quality, damage habitat, and reduce public access, limiting public enjoyment and appreciation. (pg. 29)
- Species' ranges will shift or be disrupted in response to changing habitat conditions, the impacts of which may be exacerbated by the effects of habitat fragmentation. (pg. 29)
- Increased extreme precipitation and frequency of floods and drought may result in increased erosion of stream banks and streamflow changes, adding stress to vulnerable streams and sediment to downstream waterbodies. (pg. 23)
- Higher temperatures, increased drought, and increases in the frequency of disruptive events may increase opportunities for invasive species and shifts in disease prevalence. (pg. 15)

HEP will be addressing the most critical of these risks in our 2017-2022 Action Agenda. We have started this process by commissioning three specific assessments: A Review of Climate Change Effects on Water Quality and Estuarine Biota of the NY-NJ Estuary; Research Opportunities and Next Steps Towards Protecting Wetland Migration Pathways; A Preliminary Evaluation of the Physical Influences of Storm Surge Barriers on the Hudson River Estuary. Summaries of these reports are in this document.

The process for identifying these stressors and assessing HEP's vulnerabilities was adapted from the methodology developed by the EPA Office of Water.[1] This vulnerability assessment is based on qualitative expert analysis of the likelihood of occurrence of a particular risk, the sensitivity of the particular system (i.e. "consequence of impact") to withstand the stresses posed by that risk, and the spatial extent of the risk.

Tasks included:

- Scoping of potential regional stressors based on previous regional climate projections and existing literature;
- Review of these stressors and background information by an expert committee;
- Discussion of potential climate vulnerabilities at public workshops conducted by HEP as part of its development of its draft Action Agenda;
- Preparation of an initial draft framework report;
- Reviewing the report with core partners and technical work groups focused on water quality, habitat, and public access to assess each risk in terms of the likelihood of occurrence; consequence of impact; and spatial extent of the impact for the year 2050;
- Creation of a consequence/probability matrix to identify the most important risks and using these findings to inform HEP's 2017–2022 Action Agenda.
- Undertaking additional assessments as to how best to mitigate the most important of these risks.

As referenced throughout this report, the assessment relies heavily on previous research conducted on the likely impacts of climate change in the Harbor Estuary. In addition, the following general reports on climate change projections and likely impacts were key resources:

- Intergovernmental Panel on Climate Change (IPCC): www.ipcc.ch
- US Global Change Research Program and the 3rd National Climate Change Assessment: www.globalchange.gov
- US Environmental Protection Agency Climate-Ready Estuaries: www.epa.gov/cre
- New Jersey Climate Adaptation Alliance: njadapt.rutgers.edu
- New York City Panel on Climate Change and their 2015 Report: onlinelibrary.wiley.com/doi/10.1111/nyas.2015.1336.issue-1/issuetoc
- New York State ClimAID: www.nyserda.ny.gov/climaid

1. *Being Prepared for Climate Change: A Workbook for Developing Risk-Based Adaptation Plans*, Climate Ready Estuaries EPA Office of Water, August 2014

Climate Stressors

Observations and projections for future scenarios of climate change are developed at multiple scales. On a global scale, the Intergovernmental Panel on Climate Change (IPCC) has observed a warming trend of land and ocean surfaces of 0.85°C (1.53°F) between 1880 and 2012. Additionally, the upper ocean (0 to 75 m) has overall warmed by 0.11°C (0.20°F) (Figure 1, IPCC 2014) every decade since 1971. It is very likely that regions of high surface salinity have become increasingly saline due to more evaporation (IPCC 2014).

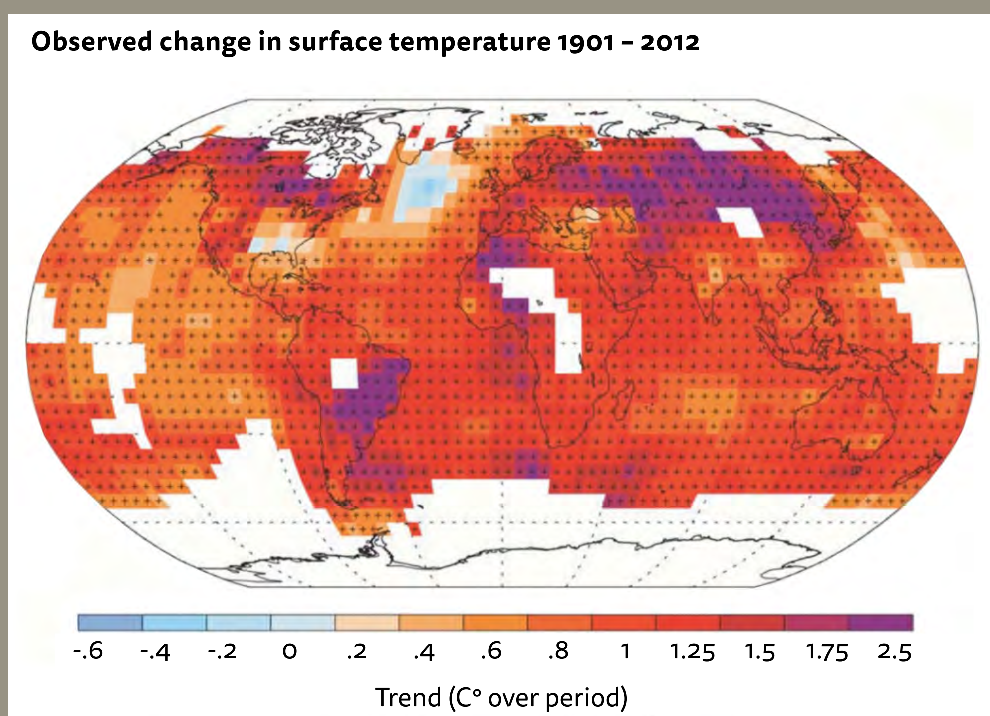


FIGURE 1: Overall changes in surface temperature throughout the world from 1901 to 2012. Areas in white represent data gaps. (International Panel on Climate Change 2014)

Climate stressor is defined as a shift in climatic process that potentially impacts built and natural systems. On a regional scale (based on down-scaled modeling and observational data), the following key climate stressors are expected: 1) increased temperature; 2) increased precipitation; 3) increased sea level rise; 4) increased extreme weather events; and 5) ocean acidification (Figure 2).

FIGURE 2: Key climate stressors for the NY-NJ Harbor region. Based on the New York City Panel on Climate Change (NPCC 2015) and the 2014 National Climate Assessment; specific quantitative projections are not assigned likelihood.

Key Climate Stressors

Increased temperature	**2050s:** Mean annual temperature projected to rise by 4.1° to 5.7°. **2080s:** Mean annual temperature projected to rise by 5.3° to 8.8°.
Increased precipitation	**2050s:** Mean annual precipitation projected to rise by 4 to 11%. **2080s:** Mean annual precipitation projected to rise by 5 to 13%.
Increased sea level	**2050s:** Projected to rise 11 to 21 inches. **2080s:** Projected to rise 18 to 39 inches.
Increased extreme events	**Overall:** More likely that the number of the most intense hurricanes and extended periods of draught will increase. **2080s:** The frequency of extreme precipitation days is projected to increase by ~1.5 x more annually than in 2015; a 10 – 15x increase in the frequency of 100-year coastal floods is projected.
Ocean acidification	**Overall:** Due to increased CO_2, surface pH of the ocean is already .1 unit lower than pre-industrial values. pH is projected to decrease by another .3 to .4 units by 2100.

Increased Temperature

At a regional level, temperatures have increased. In New York, the mean annual temperature increased at a rate of 0.3°F per decade between 1900 and 2013; with an overall warming of 3.4°F (Seekell 2011). In New Jersey, the 2012 average temperature for the state was the highest in 118 years of records (Figure 3).

In all climate change scenarios developed by the IPCC, average global temperature will increase by 2100. By 2100, the average U.S. temperature is projected to increase by about 3°–12°F (EPA 2015).

In both New York and New Jersey, the number of warm days, or days over 90°F, are very likely to increase, while the number of cold days (days below 32°F) are likely to decrease. Furthermore, the lengths of heat waves, defined as periods of extreme heat lasting at least three days, are expected to increase through 2080 (NPCC 2015). These changes will result in warmer winters, warmer summers, and—in combination with possible changes in precipitation—an increased frequency of drought.

Average Statewide Annual Temperature of New Jersey, 1900 – 2017

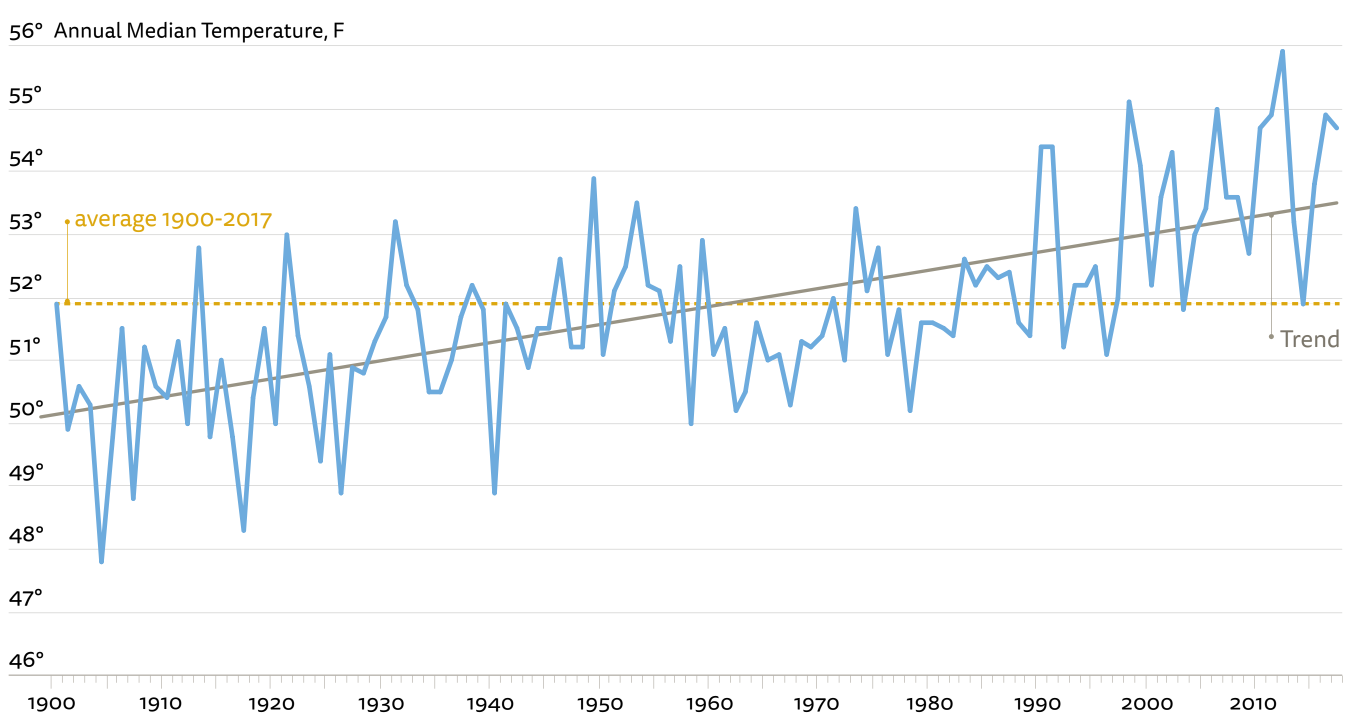


FIGURE 3: Rutgers Climate Institute, *State of the Climate: New Jersey*, 2017

Projected global average surface temperature change (Relative to 1986 – 2005)

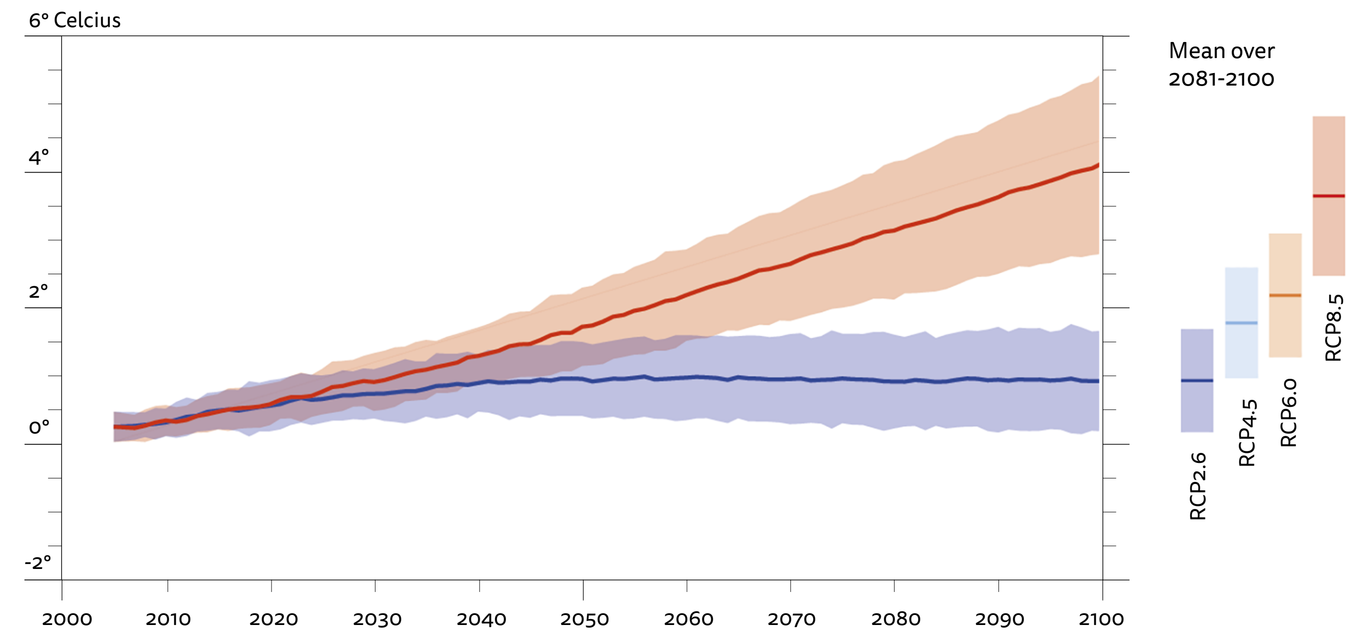


FIGURE 4: Projected temperature change for the highest and lowest IPCC scenarios RCP (2014). RCP2.6 is representative of a scenario that aims to keep global warming below 2°C above pre-industrial temperatures. Representative Concentration Pathways (RCPs) are the range of greenhouse gas concentration trajectories adopted by the IPCC for its fifth Assessment Report in 2014.

New Jersey Statewide Annual Precipitation (1900 – 2017)

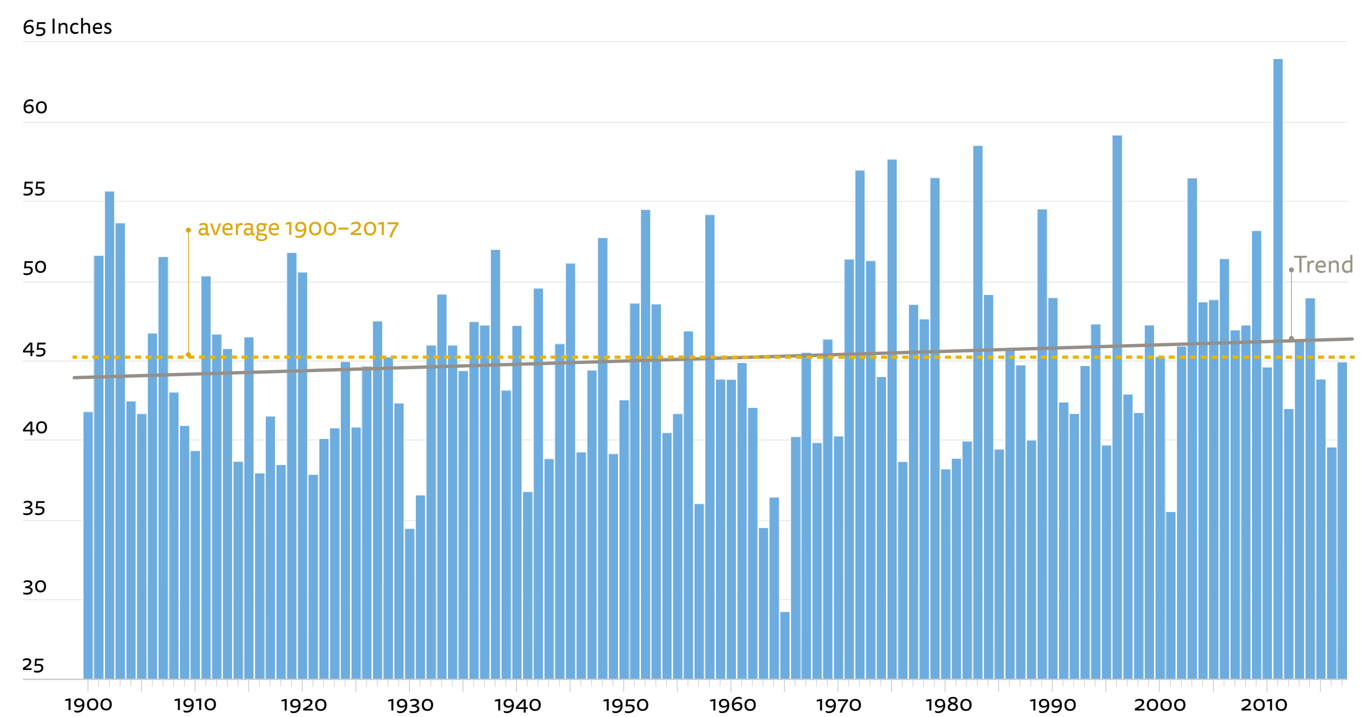


FIGURE 5: New Jersey State Climatologist. (New Jersey Department of Environmental Protection, *Climate Change in New Jersey: Temperature, Precipitation, Extreme Events and Sea Level*, Updated 8/2017).

Sea level rise

Over the period of 1901–2010, global sea level has risen 7.5 inches, driven primarily by the thermal expansion of the ocean and the melting of glaciers. The rate of sea level rise has increased more recently, at an average of 0.04 inches per year between 1993 and 2010 (IPCC 2014). At a regional scale, sea level rise is exacerbated or mediated by factors such as land subsidence or glacial rebound. In the New York–New Jersey Harbor Estuary, sea level is rising faster than the global average. All projections at the global and local level expect a rise in sea level, ranging from 11–21 inches expected by the 2050s to a worst case projection of up to six feet by 2100 (IPCC 2014; NPCC 2015; Figure 6; Table 1).

Increased extreme events

Changes in many extreme weather and climate events have been observed since about 1950. Extreme events are defined as statistically rare at a particular place and time of year, and can include cyclones, droughts, and heat waves. At a global scale, observed trends in extremes include longer heat waves and a higher number of heavy precipitation events (IPCC 2014).

While the likelihood of any changes to the frequency and intensity of tropical storms is of lower certainty, increases have been observed (IPCC 2014; NPCC 2015). Sea level rise also raises the baseline of risk for many low-lying areas that already experience frequent flooding. Surge levels formerly associated with 10-year and 100-year storms are likely to occur with more frequency and impact a larger area.

The frequency and duration of heat waves, defined as three or more consecutive days with maximum temperatures at or above 90°F, are very likely to increase. It is more likely than not that late-summer short-duration droughts will increase in the New York metropolitan region by 2100 (Rosenzweig et al. 2011). The same study concluded that it is unknown how multiyear drought risk in the New York metropolitan region may change in the future.

Projected Global Mean Sea Level Rise (Relative to 1986–2005)

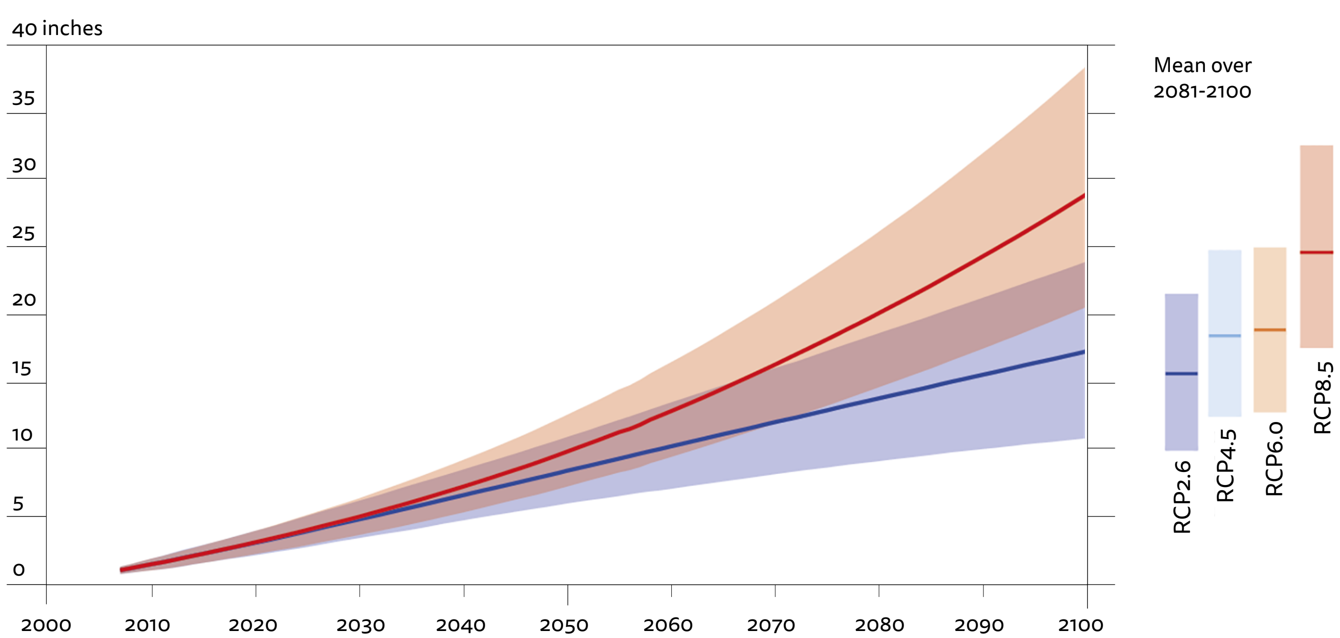


Figure 6: Projected Global Mean Sea Level Rise through 2100 (International Panel on Climate Change, 2014). Representative Concentration Pathways (RCPs) are the range of greenhouse gas concentration trajectories adopted by the IPCC for its fifth Assessment Report in 2014.

Ocean acidification

Increasing atmospheric CO2 concentrations are absorbed by ocean waters. Confidence is very high that oceans are absorbing about a quarter of emitted CO2 (National Climate Assessment 2014), and the acidity of the oceans has increased by about 30% in the last 250 years (Orr et al. 2005). This absorption lowers oceanic pH and carbonate ion concentrations, with ecological implications, including making it more difficult for clams and other calcifying species to make their shells and exoskeletons and potentially harming the development of sensitive fish and oyster larvae (National Climate Assessment 2014). Acidification can be exacerbated or mediated by different factors in estuaries. In eutrophic, or high nutrient systems such as Jamaica Bay, the degradation of algal biomass adds a second source of CO2 compounding the problem of acidification. (Wallace et al. 2014).

New York City Sea Level Rise Projections

Baseline	Low estimate (10th percentile)	Middle range (25th to 75th percentile)	High estimate (90th percentile)
2050	8 in	15 in	22–50 in
2100	11–21 in	30 in	75 in

Table 1: New York City Panel on Climate Change (NPCC), 2015

How HEP's Goals are Challenged by Climate Change

The Program has identified five long term generational goals in its 2017–2022 Action Agenda:

- Reduce the sources of pollution so that the waters of the Harbor Estuary will meet the fishable/swimmable goal of the Clean Water Act, where attainable;
- Protect and restore the vital habitat, ecological function, and biodiversity that provide society with renewed and increased benefits;
- Improve public access to the waters of the Estuary and the quality of experience at public spaces along the waterfront;
- Support port and associated maritime operations so that they are both economically and ecologically viable; and
- Foster community stewardship and involvement in decisions about the Harbor.

Achieving these goals requires addressing numerous management challenges presented by current and historic urban land uses and pollution. Such challenges include restoring the ecological characteristics lost from the filling of over 80% of pre-European settlement wetlands habitat (Bain et al. 2007) and reducing the impacts of stormwater runoff from impervious surfaces on local waterways (Walsh et al. 2005).

Temperature, sea level rise, precipitation, storms, and ocean acidification will further stress ecological processes and the health of the Harbor Estuary, and present a new set of challenges to achieving these goals. The following sections detail the ways in which our progress toward each of the five goals may be impacted by climate stressors. With the help of our expert advisory committee and the Barnard College studio, 17 specific risks were identified by HEP.

For each identified risk, the members of the advisory committee and HEP's partners on the Management Committee, Technical Work Groups, and Citizens Advisory Committee were asked to rank each risk on a scale of 5 (higher) to 1 (lower) to the likelihood of occurrence; consequence of the impact; and spatial extent of the impact. To align the results of the survey with HEP's CCMP revision, these probabilities and consequences are based on changes anticipated by the year 2050 with considerations for likely future impacts.

The following guidance was offered to these expert participants to assist them in this qualitative assessment.

Likelihood of Occurrence: *the chance of the risk actually occurring based on the qualitative judgement of expert partners.*

- **Higher:** Virtually certain, extremely likely, or very likely based on strong evidence and scientific consensus;
- **Medium:** Likely or more likely than not based on suggestive evidence, limited consensus, competing schools of thought;
- **Lower:** Less likely based on inconclusive, limited evidence, disagreement or lack of opinions among experts.

Consequence of the Impact: *the severity of the resulting impact on our ability to meet HEP goals.*

- **Higher:** Major disruption; progress towards goal is non-attainable or reversed;
- **Medium:** An important challenge; progress will be slowed considerably;
- **Lower:** Not as critical or important as other challenges, could adjust.

Spatial extent: *how widespread the impacts will be relative to the Estuary and its watershed.*

- **Extensive:** Most of the Estuary and its watershed will be affected;
- **Local:** Impacts will be felt primarily in specific waterbodies/sub-watersheds, or on a municipal or community board scale;
- **Site:** One or a few specific properties or neighborhoods within the estuary will be affected.

The relative rank from all respondents to this assessment is included following the specific description of each risk. HEP compiled these results to create the consequence/probability matrix on the following page.

Risk Matrix

Consequence of Risk/ Likelihood of Occurrence

More Likely

Likelihood of Occurance

Less Likely

Climate change may increase public awareness of estuary issues, but an increase in extreme events may focus attention on hazard mitigation at the expense of other estuary values.
Risk #16 Community Engagement

Maladaptive human responses to climate change can impair water quality, damage habitat, and reduce public access, limiting public enjoyment and appreciation.
Risk #17 Community Engagement

Increase in temperature and extreme precipitation events may alter the delivery to and cycling of nutrients within the Estuary.
Risk #3 Water Quality

Increased extreme precipitation and frequency of floods and drought may result in increased erosion of stream banks and streamflow changes, adding stress to vulnerable streams and sediment to downstream waterbodies.
Risk #10 Habitat

Increased temperature and frequency of extreme events may inhibit eelgrass restoration.
Risk #9 Habitat

Species' ranges will shift or be disrupted in response to changing habitat conditions, the impacts of which may be exacerbated by the effects of habitat fragmentation.
Risk #6 Water Quality

Sea level rise will reduce wetland and other coastal habitat, particularly in areas where there are barriers to upland migration.
Risk #7 Habitat

Increased precipitation and extreme events may impact wastewater and stormwater infrastructure, reducing our ability to meet water quality goals for primary contact recreation, shellfish, and floatable debris.
Risk #4 Water Quality

Increases in temperature may exacerbate dissolved oxygen problems, impacting the ability to meet goals for fish survival and reproduction.
Risk #1 Water Quality

Sea level rise and flooding due to extreme events may shift the extent and type of public access to and from the water.
Risk #11 Public Access

Higher temperatures, increased drought, and increases in the frequency of disruptive events may increase opportunities for invasive species and shifts in disease prevalence.
Risk #5 Water Quality

Increased precipitation and frequency of heat waves may increase demand for water-based recreation and decrease its safety.
Risk #12 Public Access

Shifts in species ranges and seasonality may demand a shift in the timing of no-dredging windows.
Risk #15 Port and Maritime

Shifts in sediment delivery and remobilization may impact the management of sediment quality.
Risk #14 Port and Maritime

Frequency of extreme events and shifts in sediment delivery may increase the need for navigational dredging.
Risk #13 Port and Maritime

Increases in temperature, extreme precipitation, and sea level may create new sources of toxic contamination as well as reduce our ability to limit exposure.
Risk #2 Water Quality

Ocean acidification, exacerbated by eutrophication, may impact oyster reef restoration efforts as well as growth and survival of other shellfish, phytoplankton, and juvenile finfish.
Risk #8 Habitat

Smaller Impact **Consequence of Impact** *Larger Impact*

Water Quality

Reduce the sources of pollution so that the waters of Harbor Estuary will meet the fishable/swimmable goal of the Clean Water Act, where attainable.

Achieving HEP's Water Quality goal will require additional support, financially and through coordination, collaboration, research and communication with numerous stakeholders to address the four pollutants that currently limit public use and ecological health of the Estuary—pathogens, nutrients, toxics, and floatable debris—as well as possible impairments from emerging contaminants. As described in the 2017-2022 Action Plan, the heavily urbanized Harbor Estuary faces many challenges associated with these pollution sources.

Pathogenic bacteria, derived largely from combined sewer overflows and stormwater runoff, can reduce the safety of water-based (contact) recreation and consumption of shellfish. The presence of toxics and heavy metals (contaminants) in the New York – New Jersey Harbor region is generally pervasive, while varied in terms of type and distribution. This presence is also changing—both in terms of what is considered to be a contaminant (numerous chemicals that are widespread within the environment are considered "emerging contaminants," for which there exists little information or monitoring) and in terms of concentration over time (Lodge et al. 2015). Excess nutrients (nitrogen and phosphorous) enter the Estuary through sewage effluent (both treated and untreated contain varying amounts), as well as through applied fertilizer and chemicals used in industrial processes. These nutrients are a nuisance and sometimes algal blooms lead to dissolved oxygen problems, fish kills and marine habitat loss. Finally, floatable debris can impair habitat quality, become ingested by biota (e.g. plastics), and create navigational hazards.

Climate change stressors combined with the Estuary's underlying water quality issues are expected to result in the following key potential risks to our ability to meet goals for pollution reduction:

Risk #1:
Increases in temperature may exacerbate dissolved oxygen problems, impacting the ability to meet goals for fish survival and reproduction.

Likelihood of occurrence: **Higher**
Consequence of impact: **Higher**
Spatial Extent: **Local**

Temperature increases reduce 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). In particular, areas that are less well-flushed and where the main sources of fresh water are sewage treatment plants, such as Jamaica Bay, the Hackensack, and lower Passaic Rivers are more susceptible (Whitehead et al. 2009). There is also some evidence that rising coastal water temperatures may favor the phytoplankton species that create harmful algal blooms, which could similarly impact fish survival (O'Neil et al. 2011; Hallegraeff 2010; Gobler et al. 2017).

Risk #2:
Increases in temperature, extreme precipitation, and sea level may create new sources of toxic contamination as well as reduce our ability to limit exposure.

Likelihood of occurrence: **Medium**
Consequence of impact: **Higher**
Spatial Extent: **Site**

Increases in extreme precipitation events as well as increased frequency of inundation could increase the scouring of the banks of urban waterfronts (often built with filled material), and the flooding of landfills and other severely contaminated sites, increasing the total amount of contaminants entering the Estuary. Higher rates of river flow can also remobilize sediment below the surface, making buried contaminants accessible to fish, wildlife, and people (Farley et al. 2017). The risk of flooding of active and former industrial areas with contaminated substances, such as transfer stations, is of particular concern in many environmental justice areas within the Harbor (Noyes et al. 2009; Brunciak et al. 2001; Carpenter and Welfinger-Smith 2011; Schiedek et al. 2007). Approximately 30% of all open industrial facilities in New York City are sited within the FEMA preliminary work maps of the 100-year floodplain; 60% flooded during Hurricane Sandy in 2012 (NYC Department of City Planning 2014). There also is evidence that increased temperatures increase uptake of pollutants by biota (Kennedy and Walsh 1997; Schiedek et al. 2007).

Risk #3:
Increases in temperature and extreme precipitation events may alter the delivery to and cycling of nutrients within the Estuary.

Likelihood of occurrence: **Medium**
Consequence of impact: **Lower**
Spatial Extent: **Local**

Climate change can affect sources of pollution and the ways in which nutrients cycle throughout the ecosystem. The projected increase in extremes could shift the timing and delivery of nutrients, with longer periods of air temperature-induced drought leading to high-intensity flushes of applied fertilizer via runoff following storm events (Lee et al. 2016). There is some evidence that despite increased overall precipitation, average stream flow may decrease due to anticipated increases in transpiration and evaporation and reduced groundwater flows. Along with periods of drought, this will reduce fresh water inputs in the tidal estuary and increase residence time of nutrients, magnifying their impact (Howarth et al. 2016).

Risk #4:
Increased precipitation and extreme events may impact wastewater and stormwater infrastructure, reducing our ability to meet water quality goals for primary contact recreation, shellfish, and floatable debris.

Likelihood of occurrence: **Higher**
Consequence of impact: **Higher**
Spatial Extent: **Extensive**

Increased precipitation and high intensity storms will lead to greater volumes of polluted stormwater directly entering the Estuary and increasing the number and volume of discharges from combined sewers, when waters in combined stormwater and sewage lines are diverted to receiving waters before overwhelming the capacity of sewage treatment plants (Van Abs 2016). In addition, an increased frequency of extreme events and associated heavy rains or inundation could contribute to more litter and trash entering waterbodies through CSO and direct stormwater discharge. The operations of wastewater treatment infrastructure also may be affected, as was exhibited following Hurricane Sandy, in which some sewage treatment plants were offline or otherwise impacted for an extended period of time, leading to a total of 11 billion gallons of partially treated or untreated sewage flowing into the Estuary (Kenward et al. 2013).

Climate Change Effects on Water Quality and Estuarine Biota 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.

David Yozzo of Glenford Environmental Science was asked to summarize existing research on potential impacts of projected temperature and precipitation changes on estuarine biota (with emphasis on fish survival and reproduction) in the Hudson-Raritan Estuary, including changes in dissolved oxygen (DO), harmful algae blooms, and other parameters. The review, available at **www.hudsonriver.org/publications**, includes research from the Estuary as well as nearby and/or comparable coastal ecosystems. It is important to note that 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; fish populations occupy the most optimal habitats under low abundances but also disperse into less optimal habitats at high abundances.

Temperatures in temperate regions may rise to levels that are stressful or lethal to native aquatic biota; these may only represent increases of a few degrees Celsius. 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.

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 dissolved oxygen conditions, including sustained, chronic hypoxia in association with seasonal stratification of the water column in deeper, channelized areas. Additional consequences of oceanic warming include increased proliferation of phytoplankton species associated with harmful algal blooms (HABs), which may impair fish survival and elevated ocean acidity (reduction in pH) caused by increased atmospheric CO_2 absorbed by ocean surface waters.

Future climate projections and vulnerability may require a re-evaluation of current agency standards for dissolved oxygen, especially DO-based standards which are limited by their failure to consider episodic as well as continuous DO conditions, and thermal effluent the Harbor Estuary. 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.

To date, there is no comprehensive monitoring metric or approach to track the individual status of Hudson River 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.

Habitat and Ecological Health

Protect and restore the vital habitat, ecological function, and biodiversity that provide society with renewed and increased benefits

The Harbor Estuary is an ecologically significant resource, despite its location at the heart of the North America's largest metropolitan area. The more than 250 square miles of open water and countless tidal tributaries are home to more than 100 fish species for some or all of their lifecycles, including 16 for which the Estuary provides essential habitat. Lining the 1,600 miles of shoreline are shallow mudflats and about 7,600 acres of wetlands that shelter shellfish, fiddler crabs, juvenile fish, and resident and migratory birds. There are 68 small islands critical to nesting shorebirds and hundreds of acres of rare coastal and maritime forests and grasslands.

Through the Hudson-Raritan Estuary Comprehensive Restoration Plan, HEP and its partners have set goals for the conservation and restoration of 12 Target Ecosystem Characteristics (TECs) including wetlands, habitat for waterbirds, tributary connections, and maritime forest. Consideration of these TECs provides a path to "preserve, manage, and enhance the Estuary's vital habitat, ecological function, and biodiversity so that the Harbor is a system of diverse natural communities" (Baron et al. 2016). Progress towards these goals has been varied. Conserving these resources and restoring their ecological characteristics is difficult. Much of the Estuary's habitats are already heavily impacted by fragmentation and degradation associated with development and human use. While the benefits of restored habitat are magnified in urban areas, urban restoration is expensive and technically challenging.

Climate change will compound these challenges, by further stressing the biota, changing baseline conditions, and adding uncertainty to already difficult conditions for conservation management and restoration practices:

Risk #5: Higher temperatures, increased drought, and increases in the frequency of disruptive events may increase opportunities for invasive species and shifts in disease prevalence.

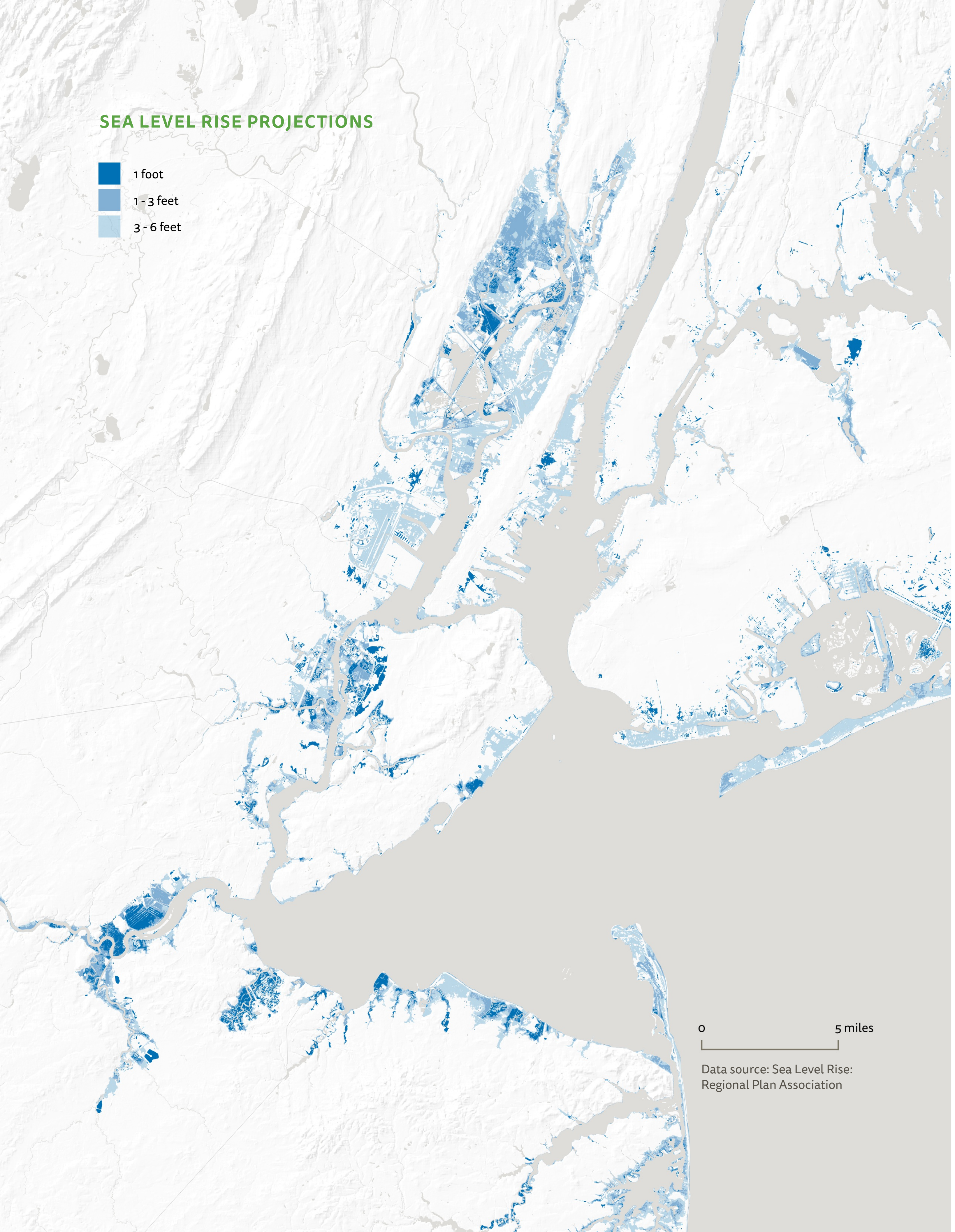
Likelihood of occurrence: **Higher**
Consequence of impact: **Medium**
Spatial Extent: **Extensive**

Invasive species are generally opportunistic, taking advantage of disruptions in existing ecosystems. Changes in temperature, increases in carbon dioxide, scouring and shoreline erosion, drought, and wildfire and other climate-driven changes can all lead to opportunities for invasive species to arrive and establish (Hellman et al. 2008; Farnsworth and Meyerson 2003; Meyerson et al. 2009; Ziska 2003). Changes in precipitation and water temperature may also increase disease prevalence in oysters, and possibly other organisms (Levinton et al. 2011; Cook et al. 1998; Burreson et al. 2004).

Risk #6: Species' ranges will shift or be disrupted in response to changing habitat conditions, the impacts of which may be exacerbated by the effects of habitat fragmentation.

Likelihood of occurrence: **Higher**
Consequence of impact: **Medium**
Spatial Extent: **Extensive**

Overall increases in temperature and changes in precipitation patterns, as well as extreme events, may mean that conditions that were formerly optimal for some species may become intolerable. Other species will expand their range into the Estuary. Species at the southern end of their range may become less frequent (e.g. Atlantic tomcod); where as those at the northern end of their ranges may become more frequent. Observations of changes in the past 150 years have been observed, though factors such as development and changes in water quality complicate conclusions (Daniels et al. 2005). There are also potential impacts to the diversity, stability, and reproduction rates of a variety of fish species (O'Connor et al. 2012; Poff et al. 2002). Though the direction of change is less certain, increased precipitation, drought and sea level rise may shift freshwater habitats to more brackish or vice versa (Najjar et al. 2000; Levinton et al. 2011), potentially affecting aquatic vegetation and other habitats (Osborne 2015). Fragmentation of habitat due to obstructions to fish passage, hardened shorelines which eliminate shallow water habitat or urban development in terrestrial habitats creates barriers to this movement.



Opportunities to Advance Wetlands Migration Pathway Protection in the New York – New Jersey Harbor Area

Tidal wetlands are a keystone element of the ecology of the New York – New Jersey Harbor and its estuaries. In many places, the area's salt, brackish, and freshwater tidal wetlands have been overwhelmed by human activities, however many thousand acres remain. Accelerated sea level rise is a significant challenge for these tidal wetlands which must keep up through sediment accretion or move upslope and landward to remain resilient and persist in our landscape. The protection of pathways for tidal wetlands to gradually move upslope as sea level rises is a necessary component of strategies to promote coastal wetland resiliency.

The New York – New Jersey Harbor & Estuary Program commissioned Betsy Blair, former manager of the Hudson River National Estuarine Research Reserve, to interview a cross-section of researchers, environmental conservation leaders, and pubic agency officials at the municipal, county, state, and federal levels in the HEP region about wetland migration pathway protection. Through 14 interviews with 23 people, the study explored current activities to advance pathway protection, perceptions of the issue's importance and priority, needs related to addressing the issue, suggestions for HEP, and intent to work on this topic in the future. The study is available at www.hudsonriver.org/publications.

These interviews demonstrated there is a growing recognition of the vital importance of protecting and managing low elevation adjacent lands as pathways for wetland migration. About two-thirds of the interviewees said they "understand a good deal about the topic" and a third "are somewhat aware of the topic." More than 9 out of 10 perceived protection of wetland migration corridors to be an important environmental protection objective, regardless of their level of knowledge about it. Interviewees and their organizations had been active on many projects relevant to pathway protection including pathway identification, land acquisition, documentation of lands conserved under mitigation projects, land management and restoration, planning, and science and monitoring.

Most people interviewed said more information and/or tools would help them engage in wetland pathway protection, especially locations of projected pathway; a list of priority projects; information materials; communication tools and guidance; technical guidance; pertinent research; information about policy, regulation and planning avenues; and funding for protection, restoration and maintenance of pathway lands. Interviewees provided specific ideas for HEP to advance pathway protection in the following categories: convene forums, explore the potential for novel funding mechanisms, help funding sources identify low-hanging fruit, and leverage other projects. The report includes key contacts, resources, and places to advance wetland pathway protection, including flood-prone communities in the lower Raritan watershed; Keyport, NJ; Staten Island; and Jamaica Bay.

Risk #7:
Sea level rise will reduce wetland and other coastal habitat, particularly in areas where there are barriers to upland migration.

Likelihood of occurrence: **Higher**
Consequence of impact: **Higher**
Spatial Extent: **Extensive**

Sea level rise will affect habitats throughout the Estuary in different ways. For example, wetlands in areas with sufficient sediment supplies have a better chance at persisting than in areas where sediment influx is insufficient to keep pace with sea level rise over time, as in the case of Jamaica Bay (Chant 2016). Other dynamics limiting an individual wetland's ability to withstand sea level rise include structural stability and spatial extent (New York City Department of Parks & Recreation 2017). Loss of coastal wetland habitat has negative implications for the fish and other organisms that depend on these areas for nursey grounds and forage. Structural barriers (including those built in response to climate change) can impede habitat migration into upland areas (Needelman et al. 2012; Titus et al. 2009). Similar to wetlands habitat, coastal and maritime forests and shoreline and shallow water habitats may face obstacles to upland migration because structural barriers, such as roads and development for coastal forests and bulkheads for shallow water habitat, impede movement. However, in the absence of structural barriers, wetland acreage may increase due to inundation of low lying undeveloped land (Tabak et al. 2016). Expansion of the littoral zone may occur in some, more natural areas following increases in extreme events, as was experienced following Sandy (American Littoral Society 2012).

Risk #8:
Ocean acidification, exacerbated by eutrophication, may impact oyster reef restoration efforts as well as growth and survival of other shellfish, phytoplankton, and juvenile finfish.

Likelihood of occurrence: **Medium**
Consequence of impact: **Medium**
Spatial Extent: **Local**

Lower pH concentrations may impact calcifying organisms such as oysters that rely on a particular pH to develop their shells (IPCC 2014; Orr et al. 2005). The extent to which this is of consequence to potential success of current oyster restoration efforts in the Harbor Estuary is unknown. While the physiological response to ocean acidification is unknown for most other marine species, there is particular and growing concern about the impact on planktonic species at the base of the marine food web and on juvenile fish vulnerable to environmental stresses (Chambers 2016). The impacts of falling oceanic pH may exacerbate existing problems in eutrophic areas such as Jamaica Bay (Wallace et al. 2014).

Risk #9:
Increased temperature and frequency of extreme events may inhibit eelgrass restoration.

Likelihood of occurrence: **Lower**
Consequence of impact: **Lower**
Spatial Extent: **Site**

Eelgrass beds have been difficult to re-establish in the Estuary, and are sensitive to temperature stress, which may further challenge re-establishment (Moore and Jarvis 2008; Carr 2012). Further, populations of submerged aquatic vegetation have been shown to be suppressed for a year or more following severe storms (Strayer et al. 2014; Orth and Moore 1984).

Risk #10:
Increased extreme precipitation and frequency of floods and drought may result in increased erosion of stream banks and streamflow changes, adding stress to vulnerable streams and sediment to downstream waterbodies.

Likelihood of occurrence: **Higher**
Consequence of impact: **Medium**
Spatial Extent: **Site**

Increases in overall and extreme precipitation may contribute to increased scour and erosion of stream edges. This will lead to increased sediment and nutrients loads, increased likelihood of contaminants in the waterways as well as difficulties achieving riparian restoration success.

Extended periods of drought and potential reductions in stream flow due to higher air temperatures may limit the ability of migratory fish to migrate to and from spawning areas. Water quality and oxygen demand may be affected by these changes as well, especially in smaller, eutrophic systems (Howarth et al. 2016).

Public Access and Stewardship

Improve public access to the waters of the Estuary and the quality of experience at public spaces along the waterfront

HEP seeks to ensure that all residents of the Harbor Estuary are within a short walk or public transit trip from the waterfront by 2050. In particular, the Program is focused on increasing the quantity and the quality of public access opportunities in underserved areas.

While over 500 acres of access have been opened or established in the Estuary since 2009 alone, nearly 60% of our linear shores are inaccessible and 17% of the population living within one half mile of the waterfront lacks access (Boicourt et al. 2016). Moreover, these existing parks, public spaces and access sites are not evenly distributed across the Estuary. This inequity is of particular significance given the differing socioeconomic characteristics of the estuary's waterfront populations. Only about nine percent of the waterfront is accessible for the more than 500,000 residents in higher need areas around the bi-state estuary (Boicourt et al. 2016).

Climate change, and efforts to mitigate associated hazards, will alter people's relationship with the Estuary and its waterfronts. Specific risks include:

Risk #11:
Sea level rise and flooding due to extreme events may shift the extent and type of public access to and from the water

Likelihood of occurrence: **Lower**
Consequence of impact: **Lower**
Spatial Extent: **Local**

Many waterfront parks and public access sites are vulnerable to sea level rise and coastal storms (Great Ecology 2012). In the short-term, maladapted public waterfront spaces may be impacted directly by periodic flooding or coastal storms, damaging infrastructure, public safety, and leading to temporary closure, particularly of docks and boating infrastructure. Many of these areas were flooded during Hurricane Sandy, and have been flooded in far less extreme, annual events such as the "king tide," or perigean spring tide (Blumberg et al. 2014). In the longer term, sea level rise raises the baseline from which these events will occur much more frequently (Lopeman et al. 2015). A common solution, the creation of berms and sea walls, may increase the visual and physical barriers between the water and the land. However, acquisitions of flood-prone properties also have the potential to provide opportunities for new public access development as may happen with properties acquired after Hurricane Sandy.

Risk #12:
Increased precipitation and frequency of heat waves may increase demand for water-based recreation and decrease its safety.

Likelihood of occurrence: **Lower**
Consequence of impact: **Lower**
Spatial Extent: **Local**

Higher temperatures and extended heat waves may reduce the safety of outdoor recreational activities on the water just as more people seek to cool off in the water. Rising temperatures, especially in urban areas with heat islands of paved surfaces and buildings, will possibly affect the likelihood of individuals joining in recreational activities on the water (Oleson et al. 2015). Public access to the water is limited in many urban neighborhoods due to poor water quality, lack of waterfront parks or other public space, and limited recreational and appropriate recreational infrastructure and programming (Boicourt et al. 2016). Moreover, stormwater discharges and combined sewer overflows are already problematic after rain events in the near-shore areas where most people recreate. The increased levels of pathogens resulting from these discharges may increase with increase in precipitation (Juhl et al. 2013).

Port and Maritime

Support port and associated maritime operations so that they are both economically and ecologically viable

The Port of New York and New Jersey and associated maritime activities are an integral and complementary part of the New York–New Jersey Harbor Estuary. HEP strives to help the Port of New York and New Jersey be environmentally sustainable, economically efficient, and safe for commercial and recreational navigation.

Supporting this critical industrial activity requires careful attention to the Harbor Estuary and surrounding waterfront communities. In particular, the management of the quantity and quality of sediment that flows into navigation channels and berthing areas, both for the large container ships as well as smaller tugboats and barges, can substantially reduce the costs of dredging while reducing the exposure of people and wildlife to toxic materials. Shifts in sediment dynamics, and potential short- or long-term interruptions to operations, can result in increased costs, maintenance, and ecological sensitivity (Becker et al. 2011; PEER 2006).

Climate change will alter these dynamics, posing the following risks:

Risk #13:
Frequency of extreme events and shifts in sediment delivery may increase the need for navigational dredging.

Likelihood of occurrence: **Lower**
Consequence of impact: **Lower**
Spatial Extent: **Site**

Increased long periods of drought followed by heavy rainfall and flash floods, causing increased erosion and scour along unprotected stream banks, can affect the amount of sediment entering a system (Central Dredging Association 2012). However, it has also been observed that large influxes of sediment can be contained or delayed in the tidal fresh portion of the river. Immediately following storms Irene and Lee, for example, about two thirds of the 2.7 megatons of sediment produced upstream remained trapped in the tidal fresh portion of the river for more than one month, with only one fifth reaching the saline portion of the Estuary (Ralston et al. 2013). While sediment contribution to the Harbor from the upper Hudson following extreme events may be more mediated than previously thought, extreme events still add large amounts of new sediment into the system, potentially increasing the need for dredging of navigation channels.

Risk #14:
Shifts in sediment delivery and remobilization may impact the management of sediment quality.

Likelihood of occurrence: **Lower**
Consequence of impact: **Lower**
Spatial Extent: **Site**

Much of the higher sediment concentration observed in the lower harbor water column following a storm is due to remobilized bed sediment (Ralston et al. 2013). This remobilized bed sediment could increase the exposure of biota to contamination, particularly if large storm events occur more frequently (Rutgers University 2014). At the same time, new loads of cleaner sediment may bury more contaminated sediment and the concentrations of legacy contaminants are expected to decrease over time overall, complicating a more precise prediction (Lodge et al. 2015). Though the dynamics of contaminated sediments in a climate change scenario are less understood, the potential for new/additional sources of sediment and remobilization of previously-buried sediment suggest increased challenges to addressing sediment contamination.

Risk #15:
Shifts in species ranges and seasonality may demand a shift in the timing of no-dredging windows.

Likelihood of occurrence: **Lower**
Consequence of impact: **Lower**
Spatial Extent: **Site**

Seasonal no-dredging windows have been established by NOAA, New York State DEC, and NJ DEP to protect critical fisheries resources. As the seasonality of the fisheries upon which they are based shifts, the result could be greater uncertainty and perhaps a mismatch with current windows. Many fish at the southern end of their range may become less frequent whereas others will expand their range into the Estuary. These changes and the uncertainty will pose an important challenge to creating scientifically valid and consistent approaches to the use of seasonal no-dredging windows.

Community Engagement

Foster community stewardship and involvement in decisions about the Harbor

HEP seeks to engage the public and especially civic organizations in the stewardship of the Estuary. There are more than 146 civic organizations offering a broad array of programs that help engage people with the Harbor Estuary through public outreach and stewardship activities. While each is small in size, with an average budget of less than $50,000, these organizations in aggregate represent more than 900 paid staff, 237,000 members, and more than 116,000 volunteers contributing about 5,000 hours per organization (Boicourt et al. 2015).

Climate change, and the response of society to those changes, will alter the relationship of these civic and community organization with the Estuary. Recreational patterns will shift with species and water quality. Persistent flooding may alter community character and commuting. Sea level rise and coastal storms will require consideration of adaptive responses ranging from altering homeowner behavior to construction of floodwalls and tidal barriers.

Risk #16: **Climate change may increase public awareness of estuary issues, but an increase in extreme events may focus attention on hazard mitigation at the expense of other estuary values.**

Likelihood of occurrence: **Medium**
Consequence of impact: **Higher**
Spatial Extent: **Extensive**

Education and engagement in estuarine stewardship can be a critical element in increasing social resilience by helping people understand their proximity to the water, the possible impacts of climate change and adaptation measures, helping reduce the risk to our communities and natural resources (Kettle and Dow 2014). Community responses to extreme events such as Hurricane Sandy have been shown to increase interest in stewardship of public resources and public knowledge about climate change (DuBois and Krasny 2014; McPhearson and Tidball 2014). This increased public awareness and funding can focus hazard mitigation or it may come at the expense of other estuary values, like improvements to water quality, habitat restoration, or public access (Svendsen et al. 2015).

Risk #17: **Maladaptive human responses to climate change can impair water quality, damage habitat, and reduce public access, limiting public enjoyment and appreciation of a healthy estuary.**

Likelihood of occurrence: **Medium**
Consequence of impact: **Higher**
Spatial Extent: **Extensive**

Structural means of mitigating increased hazards associated with climate change, such as sea level rise, shoreline erosion, hurricanes and other extreme events may impact existing habitat and public access efforts. For example, increased hardening of infrastructure and rebuilding in the flood plain would negatively impact habitat. Raising seawalls without carefully considering public access and sight lines has ramifications for public access. Storm surge barriers, tide gates and other hardened structures may impact habitat and water quality. At the same time, efforts to reduce flooding and erosion through natural and nature-based features offer an opportunity to mitigate hazards while improving ecological quality. Deployment of this integrated technology, such as living shorelines, wetlands/sill systems, and breakwaters, can offer a means to achieve restoration targets while protecting people and property (Baron 2016; ARCADIS 2014).

Preliminary Evaluation of the Physical Influences of Storm Surge Barriers on the Hudson River Estuary

Storm surge barriers, such as those being evaluated by the U.S. Army Corps of Engineers as an option for flood risk reduction under the *New York/New Jersey Harbor & Tributaries Focus Area Feasibility Study,* have the potential to cause large-scale changes to the Hudson River Estuary ecosystem. Gates in these barriers are left open under normal conditions to allow exchange of water due to the tides and smaller storm surge events, but can be closed when extreme storm surges are expected. However, even when the surge gates are open, fixed infrastructure remains in place and partially blocks the waterway. To avoid unintended negative consequences for the Estuary, a rigorous scientific evaluation of potential physical, chemical and biological effects is needed in parallel with the assessment of other factors such as flood risk reduction and costs for the barrier configuration alternatives.

The NY–NJ Harbor & Estuary Program and the Hudson River Foundation commissioned Philip M. Orton of Stevens Institute and David K. Ralston of Woods Hole Oceanographic Institution to examine the potential physical alterations to conditions in the Hudson River Estuary associated with storm surge barriers in various configurations at the mouth. Most barrier systems that have been constructed to protect coastal cities around the world have been in well-mixed estuaries that are relatively shallow and have large tides, or are on freshwater tidal rivers, and effects of barriers on partially mixed estuaries like the Hudson have received little rigorous evaluation. The full report is available at **www.hudsonriver.org/publications**.

The assessment sought to preliminarily identify and evaluate possible hydrodynamics changes resulting from a large barrier at the entrance to the Harbor, as well as to evaluate the utility of existing models, data gaps, and research needs. This was done by reviewing the existing scientific literature as well as adapting existing hydrodynamic models of the Hudson to qualitatively evaluate potential changes. Representative barriers at the mouth of the Harbor with varying degrees of closure were examined to characterize a range of potential impacts. Results of this preliminary research are intended to inform discussion and future work on how potential hydrodynamic changes associated with barriers would affect water quality, fish migration, larval recruitment, contaminant transport, and other topics of interest in the Hudson.

Both the modeling and literature provide consistent qualitative conclusions on the physical effects of surge barriers on the Hudson River Estuary. More restrictive barriers lead to:

- Stronger tidal currents and mixing near the barrier gate openings;
- Widespread reductions in tidal range, currents and mixing through the rest of the Estuary;
- Increased stratification in the Estuary due to the reduction in tidally-driven mixing in the Estuary;
- Greater salinity intrusion due to the stronger stratification and estuarine circulation;
- More pronounced changes during spring tides than neap tides.

These results are consistent with other studies of effects of barriers on estuaries and are consistent with basic processes in estuarine physics. These preliminary results provide a starting point for more in-depth studies of physical processes and for interdisciplinary studies of related effects. Discrepancies between model results reflect a need for additional model development to create tools specifically designed to address these issues.

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