Assessing New Jersey's Exposure to Sea-Level Rise and Coastal Storms: Report of the New Jersey Climate Adaptation Alliance Science and Technical Advisory Panel

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October 2016

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EXECUTIVE SUMMARY

In response to a stakeholder engagement process between 2012 and 2014, Rutgers University, on behalf of the NJ Climate Adaptation Alliance (NJCAA), convened a Science and Technical Advisory Panel (STAP) to help identify planning options for practitioners to enhance the resilience of New Jersey's people, places, and assets to regional sea-level rise (SLR), coastal storms, and the resulting flood risk. The STAP's charge was to identify and evaluate the most current science on sea level rise projections and changing coastal storms, consider the implications for the practices and policies of local and regional stakeholders, and provide practical options for stakeholders to incorporate science into risk-based decision processes.

The STAP concluded that practitioners should use a range of SLR estimates, given the range of future exposures and vulnerabilities that exist among people, places, and assets in New Jersey communities. The majority of practitioners indicated it would be practical to use two or three SLR scenarios for most of their work. Certain applications require more detailed analysis that considers the full range of projections. The SLR values in Table ES-1 represent projections under continued fossil-fuel-intensive global economic growth through 2050 because differences in SLR projections between emissions scenarios are minor in the first half of the century (with low-emissions projections for 2050 being about 0.1 feet lower than high-emissions projections). Differences in projections related to greenhouse gas emissions are only germane for those practitioners with planning horizons that extend beyond 2050.

Table ES-1: Projected SLR Estimates for New Jersey (ft.)

	Central Estimate	**Likely Range**	**1-in-20 Chance**	**1-in-200 Chance**	**1-in-1000 Chance**
Year	*50% probability SLR meets or exceeds…*	*67% probability SLR is between…*	*5% probability SLR meets or exceeds…*	*0.5% probability SLR meets or exceeds…*	*0.1% probability SLR meets or exceeds…*
2030	0.8 ft	0.6 – 1.0 ft	1.1 ft	1.3 ft	1.5 ft
2050	1.4 ft	1.0 – 1.8 ft	2.0 ft	2.4 ft	2.8 ft
2100 Low emissions	2.3 ft	1.7 – 3.1 ft	3.8 ft	5.9 ft	8.3 ft
2100 High emissions	3.4 ft	2.4 – 4.5 ft	5.3 ft	7.2 ft	10 ft

Estimates are based on Kopp et al. (2014). Columns correspond to different projection probabilities. For example, the 'Likely Range' column corresponds to the range between the 17th and 83rd percentile; consistent with the terms used by the Intergovernmental Panel on Climate Change (*Mastrandrea et al., 2010*)*. All values are with respect to a 1991-2009 baseline. Note that these results represent a single way of estimating the probability of different levels of SLR; alternative methods may yield higher or lower estimates of the probability of high-end outcomes.*

The STAP has reached the following conclusions on SLR:

1. New Jersey coastal areas are likely (about 67% probability) to experience SLR of 0.6 to 1.0 ft. between 2000 and 2030, and 1.0 to 1.8 ft. between 2000 and 2050. There is about a 1-in-20 chance (5% probability) that SLR will exceed 1.1 ft. by 2030 and 2.0 ft. by 2050.
2. While differences in SLR projections under different emissions scenarios before 2050 are minor (<0.1 feet), SLR projections after 2050 increasingly depend upon the evolution of future global greenhouse gas emissions over the current and future decades.

3. Under a high-emissions scenario (RCP 8.5), coastal areas of New Jersey are likely (about 67% probability) to see SLR of 2.4 to 4.5 ft. between 2000 and 2100. There is about a 1-in-20 chance (5% probability) that SLR will exceed 5.3 ft.
4. Under a low-emissions scenario (RCP 2.6), coastal areas of New Jersey are likely (about 67% probability) to see an increase in SLR of 1.7 to 3.1 ft. between 2000 and 2100. There is about a 1-in-20 chance (5% probability) that SLR will exceed 3.8 ft. by 2100.
5. A worst-case SLR (defined as a 1 in 1000 chance) of 2.8 ft. by 2050 and 10 ft. by 2100 is physically possible in New Jersey

In addition, the STAP concluded that practitioners should also consider rates of SLR together with the magnitude of SLR. SLR rates are especially important for monitoring the adaptive capacity of ecological systems and habitats, such as marshes. Left unconstrained, these ecological systems—important for ecosystem services—could either collapse or they could adapt to SLR by migrating to more suitable habitats. Additionally, the rate of SLR also plays an important consideration in the design and management of nature-based infrastructure alternatives for coastal protection (United States Army Corps of Engineers, 2015), which may reduce flood exposure as sea levels rise.

The STAP has reached the following conclusions on rates of SLR:

1. New Jersey coastal areas are likely (about 67% probability) to experience SLR rates of 0.2 to 0.4 in/yr. over 2010–2030. There is about a 1-in-20 chance (5% probability) that SLR rates will exceed 0.5 in/yr over 2010–2030.
2. While differences in projected rates of SLR rise under different emissions scenarios before 2030 are minor, SLR projections after 2030 increasingly depend upon the pathway of future global greenhouse gas emissions.
3. Under a high-emissions scenario (RCP 8.5), New Jersey coastal areas are likely (about 67% probability) to experience SLR rates of 0.3 to 0.5 in/yr over 2030–2050, and there is about a 1-in-20 chance (5% probability) that they will exceed 0.6 in/yr.
4. Under a low-emissions scenario (RCP 2.6), New Jersey coastal areas are likely (about 67% probability) to experience SLR rates of 0.2 to 0.4 in/yr over 2030–2050, and there is about a 1-in-20 chance (5% probability) that they will exceed 0.5 in/yr over 2030–2050.
5. Under a high-emissions scenario (RCP 8.5), coastal areas of New Jersey are likely (about 67% probability) to see SLR rates of 0.3 to 0.7 in/yr over 2050–2100. There is about a 1-in-20 chance (5% probability) SLR rates will exceed 0.8 in/yr.
6. Under a low-emissions scenario (RCP 2.6), coastal areas are likely (about 67% probability) to see SLR rates of 0.2 to 0.4 in/yr over 2050–2100. There is about a 1-in-20 chance (5% probability) SLR rates will exceed 0.5 in/ yr.

The STAP likely ranges of SLR estimates are consistent with recent SLR guidance proposed by New York State and the federal SLR curves provided by an interagency working group that included the National Oceanic and Atmospheric Administration (NOAA), the United States Army Corps of Engineers (USACE), the United States Geological Survey (USGS), and other agency and academic partners. Should practitioners choose to use the 'federal curves', they may wish to evaluate exposure using the NOAA Intermediate-High Curve to represent the STAP's 'likely range' and either the NOAA or USACE 'High' curves for estimating the STAP's high-end scenarios (Huber & White, 2015).

Higher sea levels will increase the baseline for flooding from coastal storms and therefore the impacts of coastal storms. STAP members concluded that there was no clear basis for planning guidance for New Jersey to deviate from the Intergovernmental Panel on Climate Change (IPCC)'s conclusions regarding changes in future storms. The global frequency of tropical cyclones is not projected to increase, while maximum wind speeds will likely increase. Precipitation intensity during tropical cyclones is likely to increase. The global frequency of extratropical cyclones is not likely to change substantially. Changes to extratropical storm tracks in the North Atlantic are possible, but have not been reliably established (Stocker et al., 2013). Changes in the frequency, intensity, and tracks of storms is an area of active research and the STAP concluded there is no definitive consensus regarding such changes. The need to better understand projected changes to coastal storms has spurred several areas of active research that could influence scientific understanding of future projections, including changes in the Gulf Stream, changes in sea surface temperatures, changes in blocking patterns, and possible evidence of a poleward shift in storm tracks (Colle et al., 2013; Emanuel, 2007; Harvey et al., 2015; Maloney et al., 2014; Overland et al., 2015; Reed et al., 2015; Woollings et al., 2012). The STAP advised that planners and decision-makers review ongoing and emerging research in these areas that may revise current projections.

Practitioners consulted as part of the STAP process advised that decision-makers should incorporate the STAP SLR projections into projections of future flood levels for exposure assessment. The STAP concluded that any assessment of flood exposure should include the evaluation of at least one estimate in the 'likely range' and an additional SLR estimate that represents high-end outcomes (See Table ES-1). The 'likely range' of SLR may be more appropriate for planning scenarios that assess exposure of people, places and assets for which vulnerabilities to flooding are limited or for which the consequences of damage or failure are limited. High-end estimates of SLR may be used to develop planning scenarios that consider exposures of people, places and assets that are particularly vulnerable to flooding, or for which the consequences of damage and failure have significant magnitude.

Practitioners also stated that exposure assessments should evaluate future levels of tidal and extreme coastal flooding, as well as permanent inundation. This report discusses some example methods that practitioners may use to identify planning scenarios for exposure assessment that offer different methods to account for different planning horizons and risk preferences. Additionally, scientists and practitioners should revisit SLR projections on a periodic basis, preferably shortly after the releases of any relevant studies from the Intergovernmental Panel on Climate Change (IPCC) or the U.S. National Climate Assessment, to assure that the estimates remain consistent with scientific advances.

STATEMENT OF PURPOSE

Between 2012 and 2014, Rutgers University on behalf of the New Jersey Climate Adaptation Alliance (NJCAA) engaged a broad network of stakeholders to assess knowledge gaps to guide resilience and climate adaptation planning in New Jersey. The stakeholders sought to understand future projections of SLR and coastal storms more fully in order to plan for the resulting impacts in a comprehensive manner (New Jersey Climate Adaptation Alliance, 2014). Therefore, the NJCAA recommended convening a Science and Technical Advisory Panel (STAP) to help identify options for planning guidelines and criteria that practitioners could apply to enhance the resilience of New Jersey's people, places, and assets to rising sea levels, the potential change of coastal storms, and changes in the frequency and intensity of coastal flooding.

On behalf of the NJCAA, Rutgers University convened a group of scientists and technical experts with the following charge: *to identify and evaluate the most current science on SLR projections and changing coastal storms, consider the implications for the practices and policies of local and regional stakeholders, and provide practical options for stakeholders to incorporate science into risk-based decision processes*. Dr. Robert Kopp (Rutgers University, Earth and Planetary Sciences and Rutgers Energy Institute) chaired the Science and Technical Advisory Panel. The STAP considered its charge in light of reaching consensus on 5 questions:

1. What are the estimates of SLR and changing coastal storm hazards in New Jersey?
2. How probable are different levels of SLR and changes in coastal storm hazards?
3. How can stakeholders consider SLR and changes in coastal storms in light of different planning horizons, project types, and risk tolerances?
4. How can efforts to apply current science recognize scientific uncertainties and the ongoing nature of scientific learning, and how often should stakeholders reassess advances in scientific information for purposes of applying the latest science into practice?
5. Are there special considerations that stakeholders should address, including but not limited to uniquely vulnerable people, places, and assets when evaluating options for incorporating estimates for SLR and changes in coastal storms?

On behalf of the NJCAA, Rutgers University also convened a meeting of resilience practitioners, chaired by Dr. Clinton Andrews (Rutgers University, Edward J. Bloustein School of Planning and Public Policy), to provide insights on barriers and opportunities for integrating the STAP's conclusions into practice. The purpose of the meeting of practitioners was to gather input on the scientists' initial recommendations for planning and decision-making. The practitioners were asked to respond to 4 questions:

1. How can the STAP's consensus results be structured and communicated in ways to ensure effective integration into practice?
2. What are the barriers and opportunities associated with applying the results of the STAP's deliberations to state and local policymaking, practice and decision-making?
3. What additional science and technical information related to SLR and changing coastal storms would be helpful for enhancing resilience and climate adaptation actions in New Jersey's coastal region?
4. What additional issues outside the charge of the STAP do practitioners need to enhance coastal resilience and climate adaptation in policy, decision-making, and practice for New Jersey?

The STAP integrated the insights from the practitioner discussion in developing the findings outlined in this report.

HOW TO USE THIS DOCUMENT

The panel recommends that planners, engineers, elected officials, land managers and other practitioners use the guidance herein to consider community asset exposure to various levels of flooding, such as permanent inundation, tidal flooding, and extreme coastal flooding, both in the near and long-term.

Practitioners can use the STAP panel conclusions on projected SLR estimates and probabilities contained in **Part 1** in conjunction with methods to project resulting flood levels. Several frameworks for planning discussions incorporating such levels exist, including the Getting to Resilience process tailored specifically for New Jersey municipalities (http://www.prepareyourcommunitynj.org/).

Part 2 provides an example demonstrating two of many possible options for integrating SLR projections into practice to predict future water levels associated with permanent inundation, tidal flooding, and coastal storms. The example is illustrative and has been provided for consideration and discussion purposes as per the STAP charge to provide practical options for stakeholders to incorporate science into risk-based decision processes. Some practitioners may desire more detailed planning methods, using GIS to project the spatial extent of FEMA flood zones or equivalent hydrodynamic modeling.

PART 1: Consensus Science to Support Planning for SLR in New Jersey

IMPORTANT ASSUMPTIONS AND LIMITATIONS

The STAP analyzed two critical dynamics that will affect the hazards that coastal residents of New Jersey experience in the future: changing relative sea levels and changing coastal storms. The panel did not consider heat, inland flooding, disease, and other hazards associated with a changing climate. The panel considered literature prior to March 2016. The following section details the key factors, assumptions, and limitations related to the projection of future SLR and coastal storm conditions considered by the STAP.

Box 1: What contributes to SLR change?

Global factors include:

1. Thermal expansion of ocean water,
2. Mass loss from glaciers, ice caps, and ice sheets, and
3. Changes in land water storage.

Additional factors relevant in New Jersey include:

1. Glacial isostatic adjustment (GIA) (the ongoing adjustment of the solid Earth to the loss of the North American ice sheet at the end of the last ice age), of about 0.5”/decade across the region;
2. Vertical land motion due to natural sediment compaction and groundwater withdrawal along the Coastal Plain and in the Meadowlands, reaching up to about 0.4”/decade along the Coastal Plain;
3. Changes in ocean circulation and winds, and associated changes in the distribution of heat and salt within the ocean, which may add about 1’/century in the U.S. Northeast under high emissions scenarios; and
4. Static-equilibrium effects (changes in the height of Earth’s gravitational field and crust associated with the large shifts of mass from ice to the ocean), which diminish the effect of Greenland melt and increase the effect of Antarctic melt.

For additional details on these processes and their contribution to local estimates of sea-level rise, please consult Kopp et al. (2014).

Global Greenhouse Gas Emissions Scenarios: The STAP based the SLR projections upon different Representative Concentration Pathways (RCPs). An international collaboration of climate scientists and integrated assessment modelers developed the RCPs to characterize different plausible pathways of 21st century greenhouse gas (GHG) concentrations and air pollutant emissions, consistent with a range of different socioeconomic and policy futures (Moss et al., 2010). The STAP focused on the highest and the lowest of the RCPs. RCP 8.5, often referred to as a “Business-As-Usual” scenario, is consistent with a future in which there are few global efforts to limit or reduce emissions. Under RCP 8.5, global CO_2 emissions nearly double between 2015 and 2050. RCP 2.6 is more consistent with global policy aiming to keep the likely increase in global mean temperature above pre-industrial levels below 2°C (3.6°F); under RCP 2.6., global CO_2 emissions decline by about 70% between 2015 and 2050 (Moss et al., 2010; van Vuuren et al., 2011). In this document, we refer to RCP 8.5 and RCP 2.6 as ‘high-emissions’ and ‘low-emissions’ scenarios, respectively.

Maximum Planning Horizon of 2100: The panel selected 2100 as the maximum planning horizon to accommodate both near-term and long-term asset life-cycles for infrastructure and for consistency purposes with IPCC Fifth Assessment Report (AR5), the National Climate Assessment, and nearby state guidance (e.g., New York) (Horton et al. , 2014; IPCC, 2014; Parris et al., 2012). Similarly, the panel selected 2030 and 2050 as periods representative of near-term and mid-term projections for SLR for nearer term planning needs affirmed as relevant by discussions with practitioners.

Starting in 2000: Scientists measure sea level with respect to a geodetic datum. For the U.S. National Spatial Reference System, this datum is the North American Vertical Datum of 1988 (NAVD88). NOAA measures tidal datum levels such as Mean Sea Level (MSL), Mean Higher High Water (MHHW), and Mean Lower Low Water (MLLW) in relation to the NAVD88 geodetic datum over a time period referred to as the Tidal Epoch (e.g., 1983-2001). Tidal datum levels such as MHHW and MLLW serve as levels that practitioners use to communicate flood forecasts, coastal boundaries, and other information as points of reference for coastal communities and ecosystems. Scientists measure SLR in relation to the Mean Sea Level for a given Tidal Epoch.

The baseline for the projections in this report is the year 2000, or, more specifically, average relative sea level over 1991-2009. Due to atmosphere and ocean dynamics, the decadal average sea level at Atlantic City can change up to 0.6 inches around the mean. Year-to-year variability is up to 2.4 inches around the mean sea level. Since the average rate of change over 1990-2010 at Atlantic City is 2.0 ± 0.3 inches per decade, the 19-year average ‘climatological’ sea level in 2000 (i.e., the 1991-2009 average) was about 1.6 inches higher than the 1983-2001 tidal datum, and the ‘climatological’ sea level in 2015 (i.e., the estimated 2006-2024 average) was about 3 inches higher than in 2000 (Kopp et al., 2014; K. G. Miller et al., 2013). Users can adjust the STAP projections to the 1983-2001 tidal epoch by adding 1.6 inches or to a year 2015 baseline by subtracting 3 inches (See Figure 1).

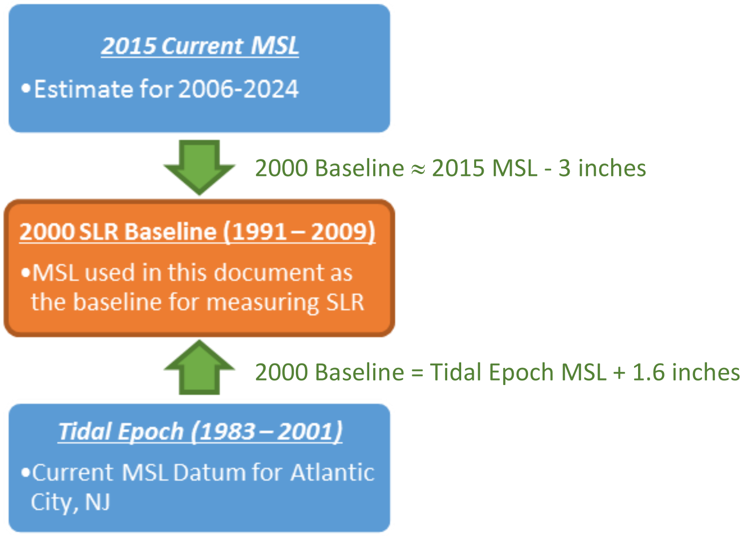

Figure 1: Relationship between SLR Projection Baseline (2000) and Other References to MSL

Atlantic City Tide Gauge: The science panel chose to use projections for the Atlantic City tide gauge to represent the entire state of New Jersey. Projections for two other New Jersey tide gauges (Sandy Hook and Cape May) differ minimally (Kopp et al., 2014). Projections for all three New Jersey gauges are higher than those at The Battery, New York City, by about 3 inches per century, due primarily to land subsidence associated with natural sediment compaction and groundwater withdrawal (K. G. Miller et al., 2013). As indicated in Figure 2, areas of New Jersey located to the east of the Fall Line[1] are subject to sediment compaction (Compactable Sediments - B), as are the Holocene sediments found in the Meadowlands, Newark Bay, and Hudson Waterfront (Compactable Sediments - A). Therefore, the use of the Atlantic City tide gauge for projections represents a conservative (protective) choice.

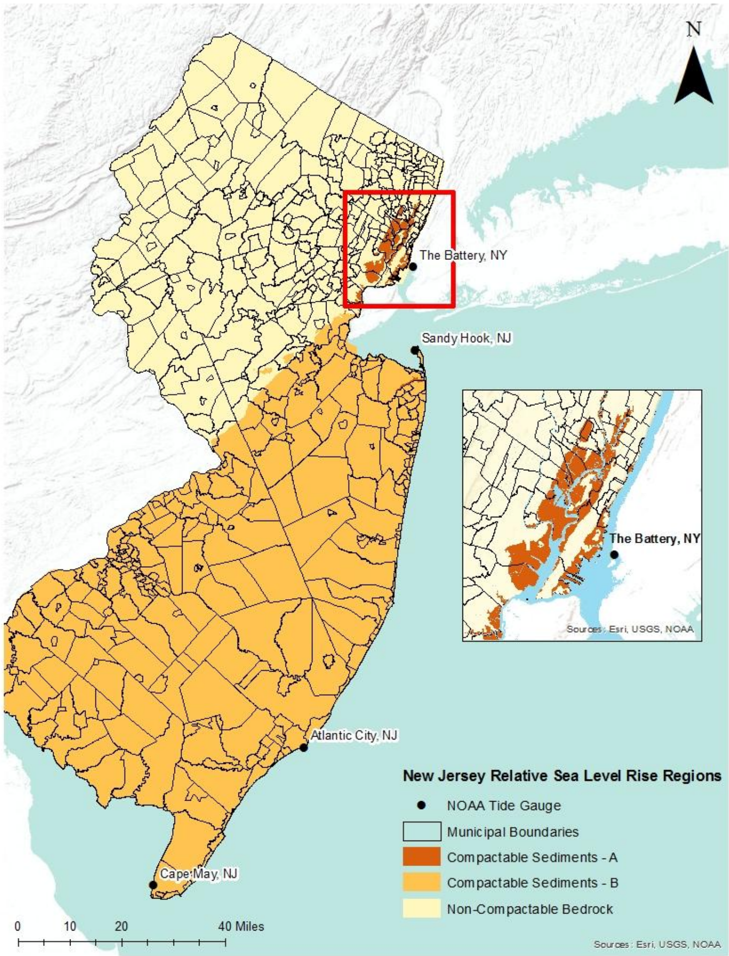

Figure 2: Map of Compactable Sediments in NJ

Future Coastal Storms: Higher sea levels will increase the baseline for flooding from coastal storms and therefore the impacts of coastal storms. In addition, climate change may change the characteristics of storm systems. The STAP discussed many of the aspects of both tropical (i.e., hurricane) and extra-tropical (i.e., nor'easter) coastal storm systems, as well as hybrid storms like Superstorm Sandy. The STAP noted the following conclusions of the IPCC that are relevant for planning in New Jersey:

> *Projections for the 21st century indicate that it is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged, concurrent with a likely increase in both global mean tropical cyclone maximum wind speed and*

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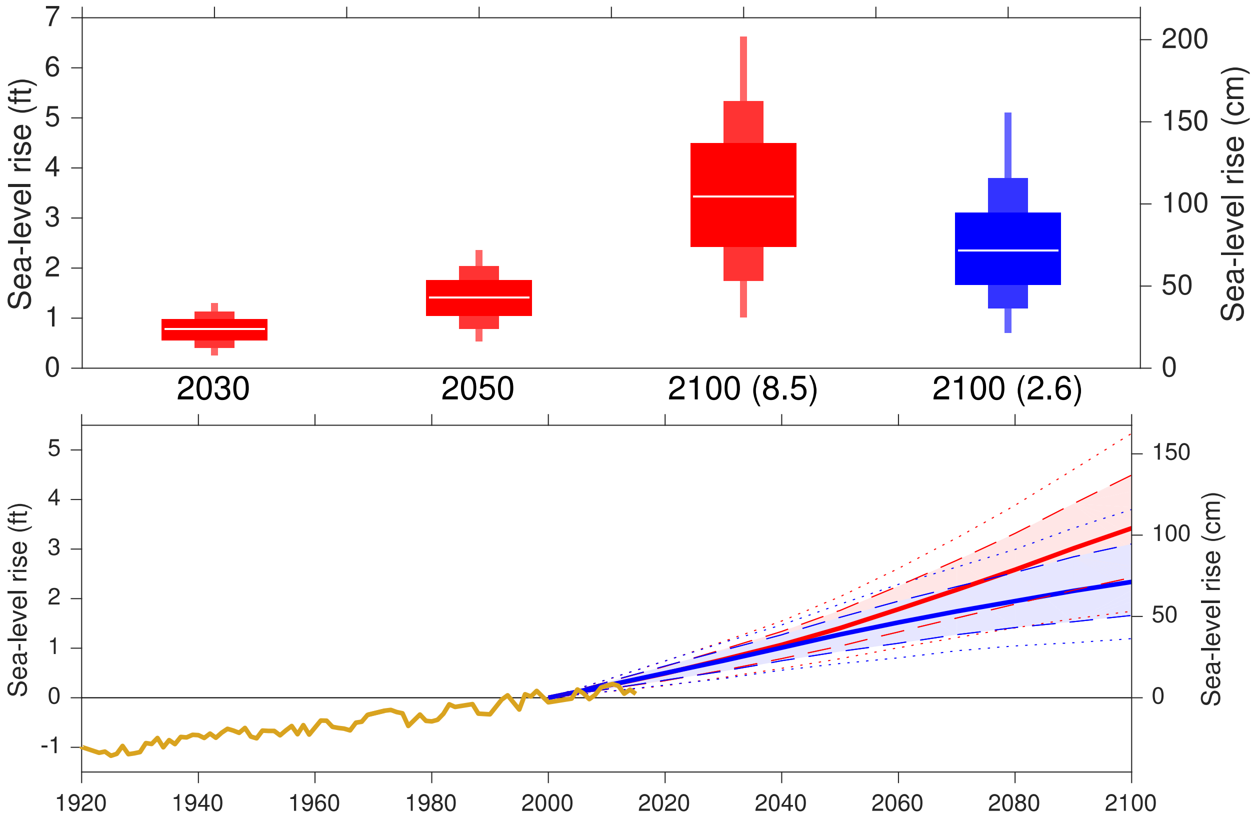
[1] The line that divides New Jersey's Piedmont and Coastal Plain running diagonally from Carteret to Trenton through Middlesex and Mercer Counties (http://www.nj.gov/dep/njgs/enviroed/inforcirc/provinces.pdf)

> *rain rates. The influence of future climate change on tropical cyclones is likely to vary by region, but there is low confidence in region-specific projections. The frequency of the most intense storms will more likely than not increase in some basins. More extreme precipitation near the centers of tropical cyclones making landfall is projected in North and Central America… (medium confidence).*
>
> *The global number of extratropical cyclones is unlikely to decrease by more than a few percent and future changes in storms are likely to be small compared to natural interannual variability and substantial variations between models…. It is unlikely that the response of the North Atlantic storm track in climate projections is a simple poleward shift…. There is low confidence in the impact of storm track changes on regional climate at the surface. More precipitation in extratropical cyclones leads to a winter precipitation increase in Arctic, Northern Europe, North America and the mid-to-high-latitude SH. (Stocker et al., 2013 pp. 107-108).*

STAP members concluded that there was no clear basis for deviating from the IPCC's conclusions when projecting changes in future storms to serve as planning guidance for New Jersey. Some recent studies have focused more specifically on conditions in the region, but more work will be required to assess their conclusions. For example, models disagree on whether changes in tropical cyclones will increase storm surges in the New York area (Lin et al., 2012). Some results suggest that the climate conditions of the late 20th and early 21st centuries have a greater propensity to generate tropical cyclones with extreme storm surges in the New York area than did conditions of the preceding millennium (Reed et al., 2015). Future changes in the frequency, intensity, and tracks of storms is an area of active research and the STAP concluded there is no definitive consensus regarding such changes. The need to better understand projected changes to coastal storms has spurred several areas of active research that could influence scientific understanding of future projections, including changes in the Gulf Stream, changes in sea surface temperatures, changes in blocking patterns, and possible evidence of a poleward shift in storm tracks (Colle et al., 2013; Emanuel, 2007; Harvey et al., 2015; Maloney et al., 2014; Overland et al., 2015; Reed et al., 2015; Woollings et al., 2012). The STAP advised that planners and decision-makers review ongoing and emerging research in these areas that may revise current projections. But it is of utmost importance to keep in mind that sea-level rise will exacerbate storm impacts even if there is little or no systematic change in the frequency, intensity, and tracks of storms. In addition, precipitation intensity during both tropical and extratropical cyclones is likely to increase.

HOW MUCH SEA-LEVEL RISE WILL NEW JERSEY EXPERIENCE OVER THIS CENTURY?

The STAP has identified a set of probabilistic SLR projections for the years 2030 and 2050; however, as different emission pathways give rise to significantly different levels of SLR beyond 2050, the STAP identified two sets of projections for 2100. Using the framework of Kopp et al. (2014), the science panel based the calculations of projected SLR for New Jersey on the data from the tide gauge at Atlantic City, NJ.



Figures 3a and 3b: SLR Projections for New Jersey (Atlantic City): *Figure 3a: SLR estimates for Atlantic City, based on Kopp et al., 2014, for 2030, 2050 and 2100. White Line = 50th percentile value. Boxes denote 17th – 83rd percentile, 5th – 95th percentile, and 1st – 99th percentiles. Red = high emissions (RCP 8.5); Blue = low emissions (RCP 2.6). Figure 3b: Time series of tide-gauge observations (orange) and projections for high-emissions (red) and low-emissions scenarios (blue), based on (Kopp et al., 2014). Solid Lines = 50th percentile; Shaded Area = likely ranges (17th – 83rd percentile); dotted lines denoted 5th – 95th percentile. All sea levels are with respect to a 1991-2009 baseline.*

Considering the projections of Kopp et al. (2014), as summarized in Figures 3a and 3b and in Table 1, the STAP has reached the following conclusions:

1. New Jersey coastal areas are likely (about 67% probability) to experience SLR of 0.6 to 1.0 ft. between 2000 and 2030, and 1.0 to 1.8 ft. between 2000 and 2050. There is about a 1-in-20 chance (5% probability) that SLR will exceed 1.1 ft. by 2030 and 2.0 ft. by 2050.
2. While differences in SLR projections under different emissions scenarios before 2050 are minor (<0.1 feet), SLR projections after 2050 increasingly depend upon the evolution of future global greenhouse gas emissions over the current and future decades.
3. Under a high-emissions scenario (RCP 8.5), coastal areas of New Jersey are likely (about 67% probability) to see SLR of 2.4 to 4.5 ft. between 2000 and 2100. There is about a 1-in-20 chance (5% probability) that SLR will exceed 5.3 ft.
4. Under a low-emissions scenario (RCP 2.6), coastal areas of New Jersey are likely (about 67% probability) to see an increase in SLR of 1.7 to 3.1 ft. between 2000 and 2100. There is about a 1-in-20 chance (5% probability) that SLR will exceed 3.8 ft. by 2100.
5. A worst-case SLR of 2.8 ft. by 2050 and 10 ft. by 2100 in is physically possible in New Jersey.

These results represent one consistent, scientifically justifiable way of estimating the probability of different levels of SLR. Alternative methods or new science may yield higher or lower estimates of the probability of high-end outcomes. For example, one recent study (Deconto & Pollard, 2016) suggested that physics involving ice cliffs and ice shelves, not previously incorporated into ice sheet models, could render the Antarctic ice sheet significantly more vulnerable to melt within the current century than ice sheet models had previously indicated. Taken at face value, the results of that paper would elevate likely sea-level rise for New Jersey in 2100 under high emissions (RCP 8.5) to about 4–8 ft., while having little effect by 2050 or under low emissions. While this is just one study, it highlights the dynamic nature of the scientific knowledge. Accordingly, the STAP advises that extra consideration be given to high-end outcomes when assessing highly vulnerable or highly consequential people, places and assets.

Table 1: Projected SLR Projections for New Jersey (ft.)

	Central Estimate	**'Likely' Range**	**1-in-20 Chance**	**1-in-200 Chance**	**1-in-1000 Chance**
Year	*50% probability SLR meets or exceeds…*	*67% probability SLR is between…*	*5% probability SLR meets or exceeds…*	*0.5% probability SLR meets or exceeds…*	*0.1% probability SLR meets or exceeds…*
2030	0.8 ft	0.6 – 1.0 ft	1.1 ft	1.3 ft	1.5 ft
2050	1.4 ft	1.0 – 1.8 ft	2.0 ft	2.4 ft	2.8 ft
2100 Low emissions	2.3 ft	1.7 – 3.1 ft	3.8 ft	5.9 ft	8.3 ft
2100 High emissions	3.4 ft	2.4 – 4.5 ft	5.3 ft	7.2 ft	10 ft

Estimates are based on (Kopp et al., 2014). Columns correspond to different projection probabilities. For example, the 'Likely Range' column corresponds to the range between the 17th and 83rd percentile; consistent with the terms used by the Intergovernmental Panel on Climate Change (Mastrandrea et al., 2010)*. All values are with respect to a 1991-2009 baseline. Note that these results represent a single way of estimating the probability of different levels of SLR; alternative methods may yield higher or lower estimates of the probability of high-end outcomes.*

RATES OF SEA-LEVEL RISE

The rate of SLR is particularly important to understand in order to assess the adaptability of ecological systems, such as the capacity of salt-water marshes to keep pace with SLR. Marshes provide critical functions including flood and storm protection; habitat for fisheries; and carbon and nitrogen storage, among other functions. However, the adaptability of these systems is locally dependent on other factors, including sediment accretion and organic matter accumulation from plant production (Haaf et al., 2015; Kirwan & Megonigal, 2013). Globally, salt marshes have been able to adapt to a widely varying range of rates of SLR, based on available sediment, nutrients, and other local conditions (Kirwan & Megonigal, 2013). Therefore, practitioners felt that information about rates of SLR for New Jersey would be a helpful outcome of the STAP, especially related to monitoring future responses of salt marshes and other natural resources to be able to better understand adaptation thresholds where resources begin to degrade.

A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research (CCSP, 2009) noted that many wetlands in the Mid-Atlantic will become stressed at a SLR rate of 0.2 to 0.25 inches/year, and will likely not survive a SLR rate of 0.4 inches/year. Coastal wetlands in New Jersey are already experiencing a SLR rate of 0.2 inches/year. By 2040, the 20-year average SLR rates are likely to be between 0.3 and 0.5 inches/year under high emissions and between 0.2 and 0.4 inches/year under low emissions. Intensive marsh monitoring for sites in New Jersey indicates that sediment rich systems, such as some coastal wetlands in the uppermost Delaware Bay, may be able to keep pace or retreat at the current rate of sea-level rise; whereas in the Barnegat Bay, which lacks in sediment supply, the marshes will not be able to keep pace at the current rate of sea-level rise and they have limited options in terms of retreat (Maxwell-Doyle, 2016). There is also increasing evidence that the sediment supply that is sustaining some (vertical) marsh accretion in the Delaware Estuary may be derived from marshes that are eroding along their seaward edge. The Delaware Estuary is currently losing about an acre of marsh per day, which may be associated with increasing rates of sea level rise as a result of increases in fetch that promote more erosive wave energy and increases in tidal flushing volumes that promote more erosive hydrodynamics (Kreeger, 2016; Miller et al., 2012).

Changes in sea-level rise versus time are used to compute rates. Based on these rates, the STAP has reached the following conclusions:

7. New Jersey coastal areas are likely (about 67% probability) to experience SLR rates of 0.2 to 0.4 in/yr. over 2010–2030. There is about a 1-in-20 chance (5% probability) that SLR rates will exceed 0.5 in/yr over 2010–2030.
8. Rates of SLR after about 2030 depend upon global greenhouse gas emissions.
9. Under a high-emissions scenario (RCP 8.5), New Jersey coastal areas are likely (about 67% probability) to experience SLR rates of 0.3 to 0.5 in/yr over 2030–2050, and there is about a 1-in-20 chance (5% probability) that they will exceed 0.6 in/yr.
10. Under a low-emissions scenario (RCP 2.6), New Jersey coastal areas are likely (about 67% probability) to experience SLR rates of 0.2 to 0.4 in/yr over 2030–2050, and there is about a 1-in-20 chance (5% probability) that they will exceed 0.5 in/yr over 2030–2050.
11. Under a high-emissions scenario (RCP 8.5), coastal areas of New Jersey are likely (about 67% probability) to see SLR rates of 0.3 to 0.7 in/yr over 2050–2100. There is about a 1-in-20 chance (5% probability) SLR rates will exceed 0.8 in/yr.
12. Under a low-emissions scenario (RCP 2.6), coastal areas are likely (about 67% probability) to see SLR rates of 0.2 to 0.4 in/yr over 2050–2100. There is about a 1-in-20 chance (5% probability) SLR rates will exceed 0.5 in/ yr.

The impacts on coastal areas will be highly dependent on local environmental dynamics. Nonetheless, it is important to consider speed in understanding how natural systems adaptability will be affected, especially in the design of natural infrastructure alternatives.

WHEN IS SEA-LEVEL RISE GOING TO EXCEED X FT. IN NEW JERSEY?

In addition to the projected likely range of SLR for a given year, practitioners stated that it would also be helpful to be able to communicate when a particular level of SLR is projected to occur. More specifically, practitioners must be able to respond to the question, “When is sea-level going to exceed X ft. in New Jersey?” Tables of probabilities that reflect SLR meeting or exceeding stated thresholds from 1 foot through 10 ft. (See Table 2) (Kopp et al., 2014).

Table 2: Probability that SLR at Atlantic City will Meet or Exceed Stated Values in Stated Years

High emissions (RCP 8.5)

	1 ft.	2 ft.	3 ft.	4 ft.	5 ft.	6 ft.	7 ft.	8 ft.	9 ft.	10 ft.
2020	0.1%									
2030	14%									
2040	60%	0.1%								
2050	86%	6%	0.1%							
2060	95%	33%	1%	0.1%						
2070	98%	62%	10%	0.7%	0.1%					
2080	99%	79%	29%	4%	0.5%	0.2%	0.1%			
2090	99%	88%	50%	15%	3%	0.6%	0.2%	0.1%	0.1%	
2100	99%	92%	66%	30%	8%	2%	0.7%	0.3%	0.2%	0.1%

Low emissions (RCP 2.6)

	1 ft.	2 ft.	3 ft.	4 ft.	5 ft.	6 ft.	7 ft.	8 ft.	9 ft.	10 ft.
2020	0.1%									
2030	12%									
2040	52%	0.1%								
2050	78%	3%	0.1%							
2060	89%	14%	0.4%	0.1%						
2070	94%	31%	2%	0.2%	0.1%					
2080	96%	46%	5%	0.7%	0.2%	0.1%				
2090	97%	59%	12%	2%	0.5%	0.2%	0.1%	0.1%		
2100	97%	69%	20%	4%	1%	0.5%	0.2%	0.1%	0.1%	0.1%

Estimates are based on (Kopp et al., 2014). All heights are with respect to a 1991-2009 baseline. Values refer to a 19-year average centered at the specified year. Gray shaded areas have less than a 0.1% probability of occurrence.

The data in Table 2 present the same information about SLR illustrated in Figures 3a and 3b above, in a fundamentally different way. Instead of providing a range of projected sea-level rise for a given future year, the tables present a range of timings for a given level of sea-level rise. For example, under a high-emissions scenario (RCP 8.5), there is a 60% chance SLR will exceed 1 ft. by 2040, an 86% chance it will do so by 2050, and a 95% chance it will do so by 2100. Similarly, there is a 33% chance it will exceed two ft. by 2060, a 79% chance it will do so by 2080, and a 92% chance it will do so by 2100. This information is helpful for practitioners that want to be able to communicate their confidence in a given amount of SLR. It is also helpful to remind users that differences in SLR projections under different emissions scenarios before 2050 are minor (<0.1 feet), while SLR projections after 2050 increasingly depend upon the evolution of future global greenhouse gas emissions over the current and future decades.

As with the projected levels of sea-level rise presented previously, these results represent one way of estimating the probability of different levels of SLR. Alternative methods or new science may shift the timing of different levels of sea-level rise nearer or further in time. Accordingly, the STAP advises that extra consideration be given to high-end outcomes for critical applications.

HOW DO THE CONSENSUS SEA-LEVEL RISE PROJECTIONS FOR NEW JERSEY COMPARE WITH OTHER REGIONAL AND NATIONAL PROJECTIONS?

Federal climate projections rely on the study *Global Sea-level Rise Scenarios for the United States National Climate Assessment* (Parris et al., 2012) available through the USACE Sea-Level Change Curve Calculator[2] along with curves established for USACE guidance (Huber & White, 2015). Using the Atlantic City tide gauge, the calculator produces SLR projections based on different assumptions about future climate impacts. Generally, the higher curves represent more extreme climatic responses to emissions (i.e., faster ice sheet melt) and the lower curves represent an almost linear trend over time (Huber & White, 2015). The federal curves do not have associated probability estimates, whereas the projections by Kopp et al. (2014) do provide probability estimates. Table 3 presents the values for 2030, 2050, and 2100 for all federal curves, and identifies the closest corresponding percentile for the projections cited by the STAP (Kopp et al. 2014) in 2100.

Table 3: Federal SLR Projections Compared with STAP Projections (Ft.)

	USACE Low	*USACE Int*		*USACE High*	
Year	*NOAA Low*	*NOAA Int Low*	*NOAA Int High*		*NOAA High*
2030	0.5	0.6	0.9	1.0	1.2
2050	0.7	1.0	1.7	2.0	2.5
2100	1.4	2.4	4.7	5.7	7.3
Closest corresponding STAP projection	RCP 8.5, 1% RCP 2.6, 3%	RCP 8.5, 10% RCP 2.6, 37%	RCP 8.5, 81% RCP 2.6, 98%	RCP 8.5,95% RCP 2.6, 99%	RCP 8.5, 99.3% RCP 2.6, 99.8%

Federal Estimates are based on data from the Sea-Level Change Curve Calculator (2015.46) available at http://www.corpsclimate.us/ccaceslcurves.cfm. Federal estimates are expressed in feet relative to Local Mean Sea Level for the year 2000 at the Atlantic City, NJ tide gauge using NOAA's regional rates.

New York State recently released SLR projections under the provisions of the Community Risk and Resiliency Act (6 NYCRR Part 490) based on a review of federal, regional, and local studies, including the work of Kopp et al. (2014) and Parris et al. (2012). New York State has selected the projections of NY State Energy Research and Development Authority (NYSERDA) available for three different regions in the New York based on Horton et al. (2014).[3] Table 4 presents the regional SLR estimates for New York City (the area closest to New Jersey) associated in the New York State proposal.

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[2] The tool v(2015.46) is available at: http://www.corpsclimate.us/ccaceslcurves.cfm

[3] Details of the legislation are currently available at: http://www.dec.ny.gov/regulations/103889.html

Table 4: New York State SLR Projections Compared with STAP Projections (ft.)

	Low	*Low - Medium*	*High – Medium*	*High*
Year / Percentile	**10th**	**25th**	**75th**	**90th**
2020	0.2	0.3	0.7	0.8
2050	0.7	0.9	1.8	2.5
2100	1.3	1.8	4.2	6.3
Closest corresponding Kopp et al., 2014 projection for the Battery	RCP 8.5, 4% RCP 2.6, 15%	RCP 8.5, 10% RCP 2.6, 37%	RCP 8.5, 83% RCP 2.6, 98%	RCP 8.5,99% RCP 2.6, 99.8%

Comparing the STAP recommended values to the federal projections, the likely range for a high-emissions scenario identified by the STAP (2.4 – 4.5 ft. by 2100) are consistent with the intermediate scenarios set forth in the federal climate projections (2.4 – 4.7 ft. by 2100). Comparing the STAP values to the New York State Projections and accounting for the difference in sea-level rise between New York City and the Jersey Shore, the likely range identified by the STAP (which corresponds to 2.1 - 4.2 ft. under high emissions at the Battery) is similar to the New York State projections, which use the 25th to 75th percentile range (1.8 – 4.2 ft. by 2100). The STAP likely ranges of SLR estimates are similar to the recent SLR guidance proposed by New York State and the federal SLR curves provided by an interagency working group that included the National Oceanic and Atmospheric Administration (NOAA), the United States Army Corps of Engineers (USACE), the United States Geological Survey (USGS), and other agency and academic partners. Should practitioners choose to use the federal ‘curves’, they may wish to evaluate exposure using the NOAA Intermediate High Curve to represent the ‘likely range’ and either the NOAA or USACE ‘High’ curves for estimating high-end scenarios (Huber & White, 2015).

Despite this consistency, we again remind practitioners that alternative methods or new science may yield higher or lower estimates of the probability of high-end outcomes.

HOW OFTEN SHOULD PRACTITIONERS REASSESS SCIENTIFIC DATA?

The IPCC has developed five assessment reports since it formed in 1988. It released its Fifth Assessment Report (AR5) between September 2013 and November 2014 (IPCC, 2014). The STAP recommends that practitioners, in conjunction with a similarly constituted set of scientific advisors, review relevant SLR and coastal storm data and projections shortly after future IPCC assessment reports, or every five years at a maximum. Similarly, practitioners and a set of scientific advisors should monitor the publication of federal climate projections and research, such as the projections set forth in the National Climate Assessment, for any major changes in assumptions or projections related to SLR and coastal storms. Such reassessment of data can assist stakeholders in their efforts to incorporate advances in scientific information for purposes of applying the latest science into practice.

SUMMARY

STAP members identified a distribution of sea level rise estimates for New Jersey through the year 2100. Additional decadal projection information is available in Appendix A for practitioner reference. STAP members concluded that there was no clear basis for deviating from the IPCC’s conclusions when projecting changes in future storms for New Jersey. They also concluded that higher sea levels will increase the baseline for flooding from coastal storms, thus increasing their impacts. Practitioners should use these estimates as a consistent basis for accepted estimates and integrate this information into their preferred planning or design methods to account for unique geographic or professional considerations. The STAP recommends that practitioners and scientists review these estimates on a regular basis, not to exceed 5 years as well as after the publication of any global (i.e., IPCC) or national (i.e., National Climate Assessment) assessments related to sea level rise and coastal storms relevant to New Jersey.

PART 2: Examples Illustrating the Effects of SLR on future Flood Exposure Assessment in New Jersey

The STAP has provided illustrative examples of different methods for applying the SLR projections, in response to feedback from the meeting of practitioners. The following section provides example methods for incorporating SLR into flood exposure assessments for people, places, and assets in New Jersey. Figure 5 depicts the sequence of questions that practitioners will need to consider for exposure assessment, and are used to develop an example herein for illustrative purposes only. The example methods do not account for local environmental or physical infrastructure conditions (e.g., shoreline erosion, wetland migration, presence of floodwalls / levees, etc.). The first example approach illustrates community level exposure assessment consistent with federal guidance (Eastern Research Group & NOAA, 2013; United States Army Corps of Engineers, 2016). In Appendix B, we also present an emerging approach under development for decisions using the concept of 'sea-level rise allowances' in Atlantic City, NJ (Buchanan, et al., 2016; Hunter, 2012).

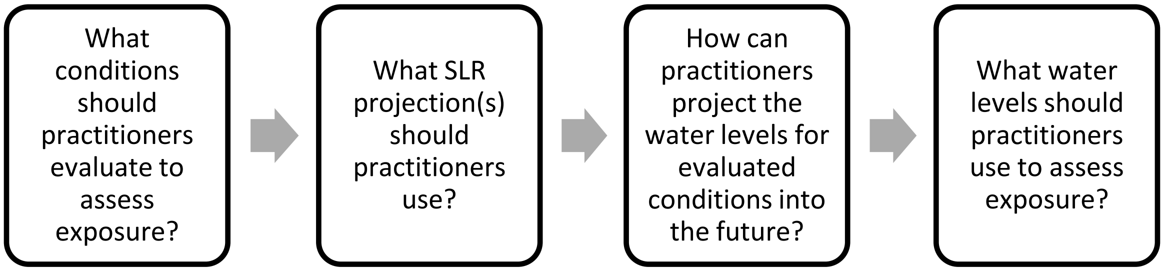


Figure 5: A Sequence of Important Questions for Exposure Assessment

WHAT CONDITIONS SHOULD PRACTITIONERS EVALUATE TO ASSESS EXPOSURE?

Practitioners should evaluate at least one water level that is representative of each of three flooding conditions: permanent inundation, tidal flooding, and coastal storms. Practitioners suggested that using the three different types of flood hazards allows them to talk about future flooding that might occur on a daily basis, in addition to the larger impacts of coastal storms that may occur less frequently. The practitioners also desired more consistency in the measurement and communication of water level heights that are used in real-time forecasting (i.e., flood forecasts) and scientific communications.

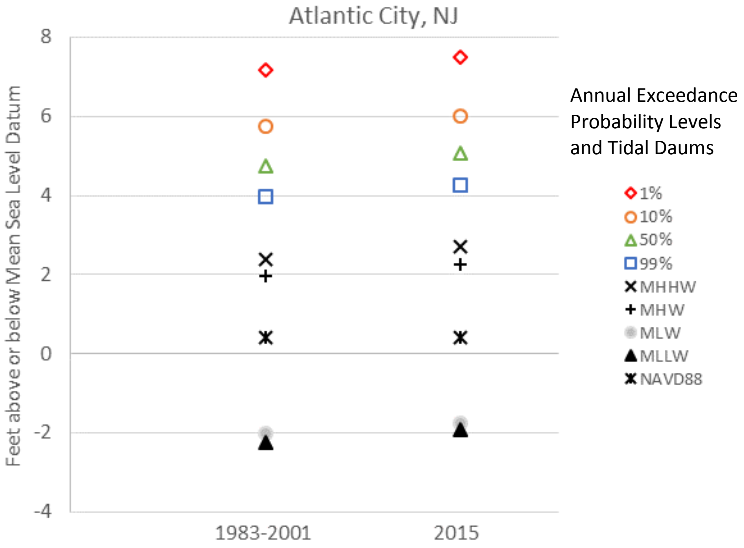


Figure 6: Exceedance Probability Levels and Tidal Datum levels for Atlantic City, NJ (Ft.)

Figure 6 displays water levels for the example site, Atlantic City, in ft. relative to Mean Sea Level over the National Tidal Datum Epoch (1983-2001) and a projection to 2015 using the estimation method detailed in Figure 1 (NOAA, 2016). In response to practitioner feedback, developing water levels that practitioners could easily reference (with appropriate caveats) to FEMA information was a high priority in developing an exposure evaluation approach. Therefore, the example application of SLR projections for Atlantic City reflect the heights of water levels in ft. above NAVD88 to maintain a common baseline datum for the assessment of changes in tidal heights and to allow for easy cross-referencing with other important elevations, such as the FEMA Base Flood Elevations.

While different locations in New Jersey will experience similar sea level rise dynamics (e.g. Atlantic City and Cape May), those same locations will have different characteristic flood levels. When using gauge data, like those presented in Figure 6, practitioners should choose a nearby tide gauge to where the water conditions most closely resemble the conditions that the subject location will experience, noting that local hydrology and morphology will also influence the magnitude of the flood event (Pugh, 1996).

WHAT SLR PROJECTIONS CAN PRACTITIONERS USE?

A practical approach practitioners can choose is to use at least two projections, with one being a SLR estimate in the likely range and one being a high-end estimate, in order to assess exposure to a range of future flood conditions. The use of at least two different SLR estimates allows practitioners to consider the vulnerability of the different types of people, places, and assets exposed to sea level rise and the consequences of flooding exposure within their study area.

People, places and assets that are vulnerable will experience greater damages from flooding than those that are less vulnerable, all else equal. For example, a pier that is designed to be continually exposed to water and storms may be less vulnerable than a road that has not been designed to endure permanent inundation. Damages to people, places and assets that are highly consequential have larger social, environmental, and economic impacts associated with their failure or impairment than those that are less consequential. Using our example above, the road that has a high vulnerability may not have high consequences of failure if it only serves as access to a recreational facility. On the other hand, a pier may serve to transfer cargo to be distributed to the nation, and thus have comparatively higher consequences. Practitioners with highly vulnerable or consequential people, places, and assets in their communities should assess exposure to high-end SLR estimates as a conservative and protective practice. While the STAP did not opine on the various different methods for assessing vulnerability and consequences, nor the processes for agreeing upon their magnitudes under different planning conditions, we refer the reader to "Disaster Resilience: A National Imperative" and the "North Atlantic Coast Comprehensive Study" as starting points for understanding these issues.

The Atlantic City example herein analyzes projections for a 3.4 foot rise by 2100 (Central Estimate), as an example of the 'likely range', and a 5.3 foot rise by 2100 (1-in-20 Chance estimate), as an example of a high-end outcome scenario, to determine differences in exposure under possible future conditions (Table 6). Practitioners may also wish to evaluate higher magnitude low-probability, high-consequence SLR projections (e.g., 1-in-1000 Chance) to account for additional flood attributes that are not quantified using this methodology (e.g. changes in shoreline, wave action, development patterns, etc. (See Box 2)) and to account for uncertainty related to advances in climate science that may result in an increase in the magnitude of high-end outcomes. The consideration of high-end outcomes is particularly important because alternative methods or new science may yield higher (or lower) estimates of the probability of high-end outcomes.

Table 6: Projected SLR for New Jersey (ft.)

Vulnerable
Limited Consequence ⟷ **Most Vulnerable**
High Consequence

	Central Estimate	**'Likely' Range**	**1-in-20 Chance**	**1-in-200 Chance**	**1-in-1000 Chance**
Year	*50% probability SLR meets or exceeds…*	*67% probability SLR is between…*	*5% probability SLR meets or exceeds…*	*0.5% probability SLR meets or exceeds…*	*0.1% probability SLR meets or exceeds…*
2030	0.8 ft	0.6 – 1.0 ft	1.1 ft	1.3 ft	1.5 ft
2050	1.4 ft	1.0 – 1.8 ft	2.0 ft	2.4 ft	2.8 ft
2100 Low emissions	2.3 ft	1.7 – 3.1 ft	3.8 ft	5.9 ft	8.3 ft
2100 High emissions	3.4 ft	2.4 – 4.5 ft	5.3 ft	7.2 ft	10 ft

Estimates are based on (Kopp et al., 2014). Columns correspond to different projection probabilities. For example, the 'Likely Range' column corresponds to the range between the 17th and 83rd percentile; consistent with the terms used by the Intergovernmental Panel on Climate Change (Mastrandrea et al., 2010). *All values are with respect to a 1991-2009 baseline. Note that these results represent a single way of estimating the probability of different levels of SLR; alternative methods may yield higher or lower estimates of the probability of high-end outcomes. Users should evaluate exposure for those people, places or assets of concern that are most vulnerable or consequential using low probability SLR projections (e.g., 1-in-1000 Chance) to account for additional flood attributes that are not quantified using this methodology and to account for uncertainty related to advances in climate science*.

HOW CAN PRACTITIONERS PROJECT THE WATER LEVELS FOR THOSE CONDITIONS INTO THE FUTURE?

Future Permanent Inundation represents the conditions under which normal high tide submerges currently dry land at a specified point in the future as a result of projected SLR. Permanent inundation is a large concern for communities and natural-resource managers that depend on low-lying lands and ecosystems to provide economic, ecological, and social community benefits now and into the future.

Practitioners can project the future water level for permanent inundation by incrementing the current MHHW elevation. At Atlantic City, for example, MHHW is 2.4 ft. above NAVD88 (NOAA, 2016) (See Table 7). To project future permanent inundation, stakeholders should use the available MHHW water level for the nearest tide gauge (e.g. Cape May, Atlantic City, Sandy Hook, or The Battery (NY)) and add the projected SLR above MHHW for a given year to determine the projected daily permanent inundation water level in the future (See Table 7: Rows 1A and 2A). Practitioners were increasingly concerned with monitoring the occurrence of nuisance flooding events. In particular, practitioners may wish to compare the projected MHHW level, reflecting daily permanent inundation, to the local Nuisance Flood Threshold to estimate when areas susceptible to nuisance flooding may become permanently inundated (Sweet et al., 2014).

Future Tidal Flooding (i.e., nuisance or recurrent flooding) is a flood condition that occurs absent a particular storm event. Examples of such events include "king tides" and other tidal influenced flooding conditions that occur in the absence of severe storms (Sweet et al., 2014). Future projections of water levels that represent tidal flooding could represent the increased water levels associated with conditions that may currently cause only moderate flooding (e.g., flooded storm drains in coastal areas).

For the example tidal flooding projections at Atlantic City, practitioners could examine the available nuisance flooding threshold level (3.7 ft. above NAVD88 as determined by the National Weather Service: see Sweet et al. (2014)) and determine how often that level will be exceeded in the future under different scenarios. To do so, practitioners should add the projected SLR estimates to water levels commensurate with high likelihood exceedance probability events. For this example, we use the 1-year return-period flood (99% AEP) to determine the projected water level that will result from similar tidal conditions in the future (NOAA, 2016) (See Table 7: Rows 1B and 2B).

Future Coastal Storms include hurricanes, nor'easters and other events that are associated with the generation of a 'storm tide'. Practitioners can project future coastal storm conditions by adding the SLR projections to the flood level for the nearest tide gauge with a specified Annual Exceedance Probability (AEP) level (Eastern Research Group & NOAA, 2013) . The 1% AEP flood height is the height of a '1-in-100-year' flood, and the 10% AEP flood height is the height of a '1-in-10-year' flood.

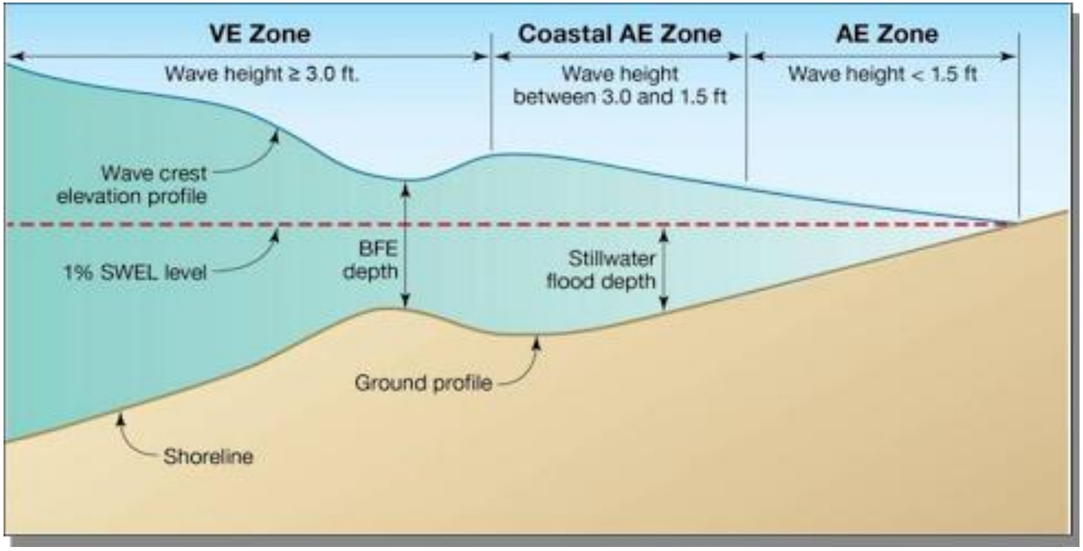
Alternatively, practitioners may also use the SLR projections to extend the area currently contained within different FEMA flood zones; for example, for a 2 foot SLR, they might identify the topographic contour 2 ft. above the current AE zone to estimate the location of the new AE zone (FEMA Region II, 2016). The AE zone corresponds to the area with a 1% annual probability of flooding, taking into account the propagation of floodwaters and waves.

Lastly, practitioners can project water levels from historic coastal storms into the future in the same manner as described above for the 10-year and 100-year water levels using the "Top Ten Levels" data available at the nearest tide gauge, or in the same manner as for the contours of FEMA flood zones (NOAA, 2016). Adding the SLR projection to the historic water level provides a rough estimate of "What would happen if this storm occurred in this future year?"

Box 2: What is Included in the Example Water Level Projections?

The example water levels in this document for future coastal storms reflect ‘storm tides’, which combine the astronomical tide, the storm surge, and limited wave setup caused by breaking waves. The methods do not account for wave effects. Therefore, when assessing exposure to water levels, it is important to understand that the levels (i.e. the storm tide for a 100-year storm) more closely corresponds to FEMA's Still Water Flood Elevations (SWEL) and not the Base Flood Elevations (BFE).

Figure B2: Illustration of Water Levels



The red-dashed line above represents the water level generated by a 1-in-100 year storm, including storm tide. A separate overland wave modeling analysis is needed to accurately develop coastal Special Flood Hazard Areas (SFHAs) and BFEs, accounting for water depth, wind speed, vegetative cover, building density, and other factors to predict the heights of waves, which will affect coastal BFEs and flood zone boundaries. (Source: FEMA)

Additional Information:
NOAA: https://tidesandcurrents.noaa.gov/est/stickdiagram.shtml?stnid=8534720
FEMA: http://www.region2coastal.com/resources/coastal-mapping-basics/

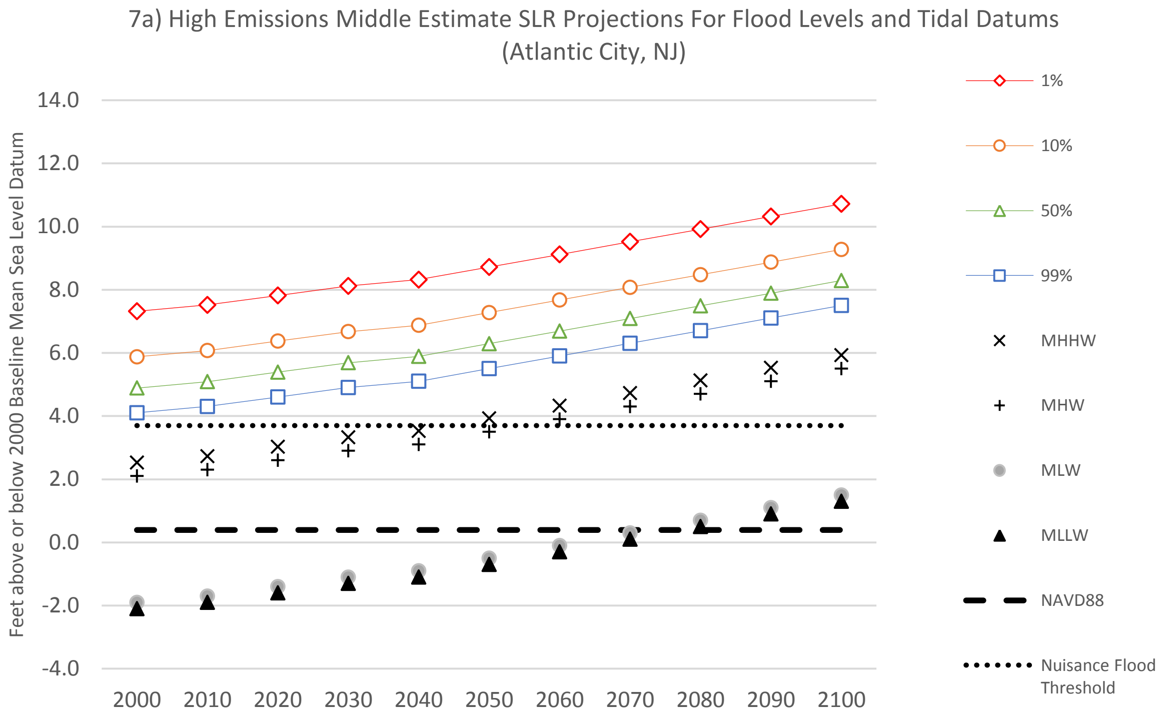
For the Atlantic City tide gauge, the 1% AEP is estimated to be 7.2 ft. above NAVD88, and the 10% AEP is 5.7 ft. above NAVD88 (Table 7: Rows 1F, 1C, 2F, and 2C). The highest water level reading at the Atlantic City tide gauge for Hurricane Sandy was 6.14 ft. above NAVD88, while highest-ever water level reading occurred during the 1992 Nor’easter (6.7 ft. above NAVD88) (Table 7: Rows 1D, 1E, 2D, and 2E).

Table 7: Atlantic City Example Table of Water-Level Projections by Year (ft. above NAVD88)

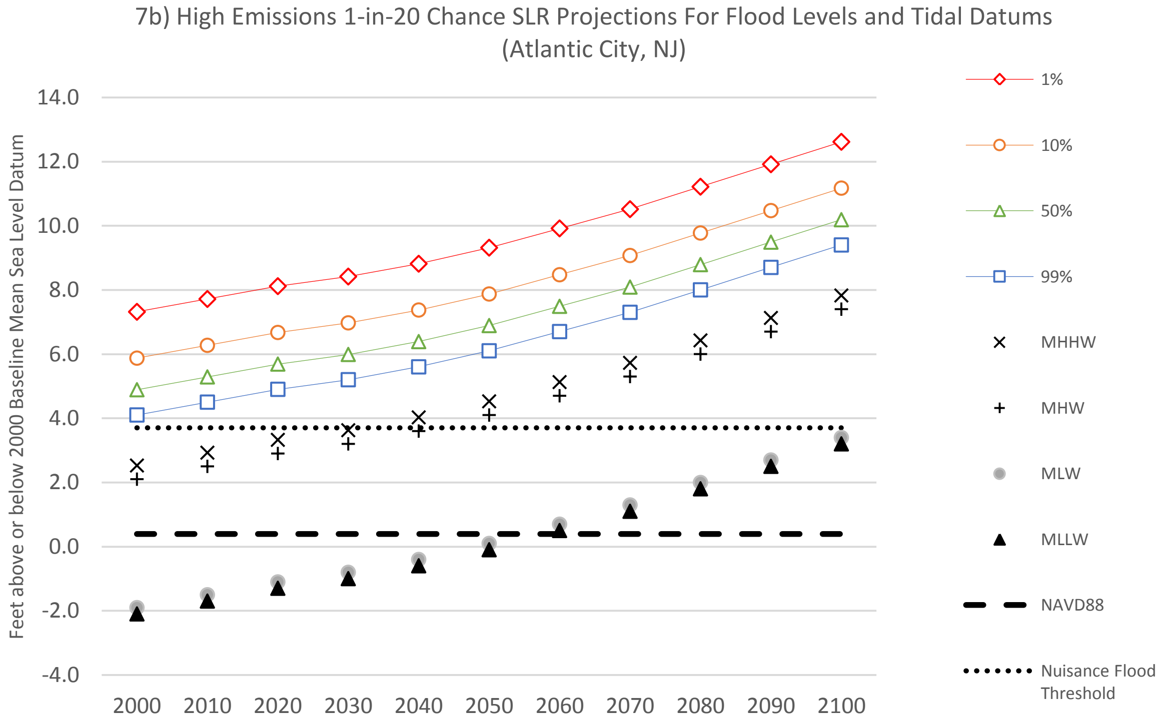
Scenario / Year	2015	2030	2050	2100
High-Emissions Central Estimate - 3.4 Ft. SLR by 2100				
1F: 100-year flood (1% AEP)	7.2	8.0	8.6	10.6
1E: 1992 Nor'easter Storm Tide (Atlantic City, NJ)	6.7	7.5	8.1	10.1
1D: Sandy Storm Tide (Atlantic City, NJ)	6.1	6.9	7.5	9.5
1C: 10-year flood (10% AEP)	5.7	6.5	7.1	9.1
1B: Annual flood (99% AEP)	4.0	4.8	5.4	7.4
1A: Permanent Inundation (MHHW)	2.4	3.2	3.8	5.8
High-Emissions 1-in-20 Chance Estimate - 5.3 Ft. SLR by 2100				
2F: 100-year flood (1% AEP)	7.2	8.3	9.2	12.5
2E: 1992 Nor'easter Storm Tide (Atlantic City, NJ)	6.7	7.8	8.7	12
2D: Sandy Storm Tide (Atlantic City, NJ)	6.1	7.2	8.1	11.4
2C: 10-year flood (10% AEP)	5.7	6.8	7.7	11.0
2B: Annual flood (99% AEP)	4.0	5.1	6.0	9.3
2A: Permanent Inundation (MHHW)	2.4	3.5	4.4	7.7

Table 7 provides an example summary of the water level projections discussed above through 2100 for the two sea-level rise scenarios given permanent inundation, tidal flooding, and coastal storm conditions. To reiterate, a 3.4 foot rise by 2100 (High Emissions Central Estimate) scenario demonstrates the 'likely' range of SLR, while a 5.3 foot rise by 2100 (High Emissions 1-in-20 Chance Estimate) scenario demonstrates a high-end scenario, to determine differences in exposure under possible future conditions (Table 6). There are a total of 48 current and projected water levels provided for comparison. This table represents only the effects of SLR on the height of a given event, with all other variables and modeling conditions held constant. In order to calculate the water level for each year, one must add the projected estimate for that year to the present water level.

As an example, Row 1B represents the projected height of floodwaters for the Annual Flood level (99% AEP) that is currently 4.0 ft. above NAVD88 in Atlantic City. To project this value forward to 2030 using the Central Estimate, one would add 0.8 ft. (see Table 6) to the present value of 4.0 ft. to arrive at a 4.8 foot estimated water level for the Annual Flood in 2030. Similarly, to project this value forward to 2050 using the Central Estimate one would add 1.4 ft. (see Table 6) to the present value of 4.0 ft. to arrive at a 5.4 ft. estimated water level for the Annual Flood in 2050. All else equal, Table 7 suggests that an Annual Flood event in 2100 would result in a water height of 7.4 ft. above NAVD88, assuming the High Emissions Central Estimate (of 3.4 ft) for SLR. However, practitioners should note that the planning scenarios above represent an approach that accounts for the additive effect of SLR onto current flood levels. The calculation of actual future AEP levels consists of a detailed statistical methodology that incorporates many other variable in addition to rising sea levels (Lin et al., 2012; Tebaldi et al., 2012), and may differ from the values in Table 7.



7a) High Emissions Middle Estimate SLR Projections For Flood Levels and Tidal Datums (Atlantic City, NJ)



7b) High Emissions 1-in-20 Chance SLR Projections For Flood Levels and Tidal Datums (Atlantic City, NJ)

Figures 7a and 7b: Example Water Level Projections for Atlantic City, NJ: *Trend lines represent Annual Exceedance Probabilities (1, 10, 50, 99 percent) for flooding. Black and gray points represent tidal datums for Mean Higher High Water (MHHW), Mean High Water (MHW), Mean Low Water (MLW), Mean Lower Low Water (MLLW). The* *nuisance flooding threshold level is 3.7 ft. above NAVD88 as determined by the National Weather Service* (Sweet et al., 2014).

When MHHW levels surpass the nuisance flooding threshold, one can infer the communities will experience recurring flood impacts during normal tidal cycles. In our examples, projected MHHW levels, reflective of daily inundation, surpass the current nuisance flooding threshold level (3.7 ft.) between 2030 and 2050 (Figures 7a and 7b). Regardless of the process used to generate projected water levels through 2100, practitioners suggested that using increments of whole ft. would be an appropriate level of resolution for planning purposes. These water levels could represent several different conditions based on the four methods for generating the projections above (See Table 8).

WHAT WATER LEVELS SHOULD PRACTITIONERS USE TO ASSESS THE EXPOSURE OF PEOPLE, PLACES, AND ASSETS TO SLR AND COASTAL STORMS?

Table 7 and Figures 7a and 7b above demonstrate different projections of approximate water levels that reflect tidal flooding and coastal storm conditions accounting for two sea-level rise projections (a likely estimate and a conservative estimate). Given the range of values in Table 7, practitioners in this Atlantic City example would need to map the extent of water levels for each whole foot increment between 2 ft. and 12 ft. above NAVD88 to assess exposure to the various conditions through 2100. As an alternative, practitioners could also demonstrate several different future conditions using a subset of maps. Table 8 demonstrates an example of a subset of water levels that could be mapped to assess exposure, for cases where time or money to create analyses or conduct planning discussions is limited.

Table 8: Atlantic City Example Table of Selected Water Levels for Exposure Assessment

Water Level Height Above NAVD88 at Tide Gauge	**What Does This Height Represent?**
4 ft.	• Permanent inundation (MHHW) in 2050 (Central Estimate) • Current Annual Flood (no additional sea-level rise)
7 ft.	• Annual flood in 2100 (Central Estimate) • 10-year flood in 2050 (Central Estimate) • Sandy Storm Tide in 2030 (Central Estimate) • Current 100-year flood (Central Estimate)
12 ft.	• 100-year flood in 2100 (1-in-20 Chance estimate of sea-level rise) • 1992 Nor'easter in 2100 (1-in-20 Chance estimate of sea-level rise)

Summarizing the scenarios in this manner will help practitioners assess the common water level characteristics of different events to draw comparisons during planning discussions. Practitioners thought it would be important to have methods that reference past, present, and future conditions to make resilience discussions more relatable for participants. For example, a water height of 4 ft. above NAVD88 at the Atlantic City tide gauge is close to the current nuisance flooding threshold. Practitioners near Atlantic City, in this example, might expect to experience such impacts as a more regular part of the daily tidal cycles between 2030 and 2050 because of the MHHW level surpassing the nuisance flooding threshold level as a result of SLR. A water height of 7 ft. above NAVD88 also allows for comparisons across event types and time horizons. A 7 foot water level represents the current 100-year flood, an equivalent Sandy Storm Tide projected to likely sea-level rise in 2030, a 10-year flood in 2050 incorporating likely sea-level rise, and an annual flood in 2100 incorporating likely sea level rise. When drawing comparisons, it is also important to discuss the permanence and frequency of the water levels so that participants clearly understand the planning implications related to the people, places, and assets in their community.

SUMMARY

There are several methods that practitioners can use to assess future potential community and environmental exposure to higher water levels from inundation, recurrent flooding, and coastal storms resulting from SLR. Some methods apply exposure and develop estimates based on a common event experienced by a community (Eastern Research Group & NOAA, 2013; FEMA Region II, 2016; Huber & White, 2015), while others specify risk tolerance and apply modeling estimates to individual assets (Buchanan et al., 2016; Lin et al., 2012).

Practitioners supported the idea of using scenarios that include at least two SLR projections, with one SLR estimate in the likely range and one worst-case estimate, in order to assess exposure to future flood conditions while accounting for differences in community asset vulnerability and consequences. In addition, practitioners felt it was important to evaluate at least one water level that is representative of each of three flooding conditions: permanent inundation, tidal flooding, and coastal storms. There are several options for determining the water levels associated with future events, including NOAA's Annual Exceedance Probability (AEP) at a nearby tide gauge, FEMA's Base Flood Elevation (BFE), or in reference to an historic event storm tide (e.g., Hurricane Sandy, 1992 Nor'easter). Using a scenario-based framework of future event conditions allows for a discussion of trade-offs among events that have differences in frequency, magnitude, and permanence that are important for community stakeholders to understand. Readers are referred to Appendix B for further discussion of a newly emerging framework that would allow for individual asset-specific determination based on an individual's risk preferences. Ideally, these two frameworks work in tandem, with individuals assessing their asset specific tolerance for risk beyond a common community threshold based on event scenarios.

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Appendix A: Detailed SLR Projections

Table A1: Projected SLR Projections for New Jersey under high emissions [RCP 8.5] (ft.)

	Likely Range	*1-in-20 chance*	*1-in-200 chance*	*Worst Case*
	17th – 83rd (50th)	**95th**	**99.5th**	**99.9th**
2010	0.2 – 0.3 (0.2)	0.4	0.4	0.5
2020	0.3 – 0.6 (0.5)	0.8	0.9	1.0
2030	0.6 – 1.0 (0.8)	1.1	1.3	1.5
2040	0.8 – 1.3 (1.0)	1.5	1.8	2.0
2050	1.0 – 1.8 (1.4)	2.0	2.5	2.8
2060	1.3 – 2.3 (1.8)	2.6	3.2	4.0
2070	1.6 – 2.8 (2.2)	3.2	4.1	5.4
2080	1.9 – 3.3 (2.6)	3.9	5.1	6.9
2090	2.2 – 3.9 (3.0)	4.6	6.1	8.5
2100	2.4 – 4.5 (3.4)	5.3	7.2	10.3
2110	3.0 – 4.5 (3.7)	5.3	8.1	11.5
2120	3.3 – 5.1 (4.1)	6.1	9.4	13.5
2130	3.6 – 5.7 (4.5)	6.8	10.9	15.7
2140	3.8 – 6.3 (4.9)	7.6	12.5	18.1
2150	4.2 – 6.9 (5.3)	8.4	14.1	20.6
2160	4.5 – 7.5 (5.8)	9.3	15.7	23.2
2170	4.7 – 8.1 (6.2)	10.1	17.5	26.1
2180	5.0 – 8.7 (6.6)	11.0	19.3	28.8
2190	5.2 – 9.3 (7.0)	11.9	21.3	31.4
2200	5.5 – 10.0 (7.5)	13.0	23.4	34.4

Table A2: Projected SLR Projections for New Jersey under low emissions [RCP 2.6] (ft.)

	Likely Range	*1-in-20 chance*	*1-in-200 chance*	*Worst Case*
	17th – 83rd (50th)	**95th**	**99.5th**	**99.9th**
2010	0.2 – 0.3 (0.2)	0.4	0.4	0.5
2020	0.4 – 0.6 (0.5)	0.8	0.9	1.0
2030	0.5 – 1.0 (0.8)	1.1	1.3	1.5
2040	0.8 – 1.3 (1.0)	1.5	1.8	1.9
2050	0.9 – 1.6 (1.3)	1.9	2.4	2.7
2060	1.1 – 1.9 (1.5)	2.3	2.9	3.7
2070	1.3 – 2.2 (1.7)	2.6	3.5	4.7
2080	1.4 – 2.5 (1.9)	3.0	4.2	5.8
2090	1.5 – 2.9 (2.2)	3.4	5.1	7.0
2100	1.7 – 3.1 (2.3)	3.8	5.9	8.3
2110	1.9 – 3.1 (2.5)	3.9	6.7	9.8
2120	2.0 – 3.4 (2.7)	4.4	7.8	11.5
2130	2.2 – 3.8 (2.9)	5.0	9.0	13.4
2140	2.3 – 4.1 (3.1)	5.5	10.3	15.4
2150	2.4 – 4.5 (3.3)	6.1	11.7	17.5
2160	2.4 – 4.8 (3.5)	6.7	13.1	19.8
2170	2.5 – 5.2 (3.7)	7.3	14.6	22.2
2180	2.6 – 5.6 (3.9)	8.0	16.3	24.7
2190	2.6 – 6.0 (4.1)	8.7	18.0	27.3
2200	2.7 – 6.4 (4.3)	9.4	19.8	30.0

Table A3: Projected SLR Projections for New Jersey under high emissions [RCP 8.5] (cm)

	Likely Range	*1-in-20 chance*	*1-in-200 chance*	*Worst Case*
	17th – 83rd (50th)	**95th**	**99.5th**	**99.9th**
2010	5 – 10 (7)	11	13	14
2020	10 – 19 (15)	23	27	29
2030	17 – 30 (23)	35	41	45
2040	24 – 41 (32)	47	56	62
2050	32 – 54 (43)	62	76	86
2060	40 – 69 (54)	80	99	123
2070	49 – 84 (66)	98	126	164
2080	58 – 101 (79)	118	154	209
2090	66 – 119 (92)	140	186	259
2100	74 – 137 (104)	163	220	313
2110	91 – 138 (112)	163	247	350
2120	100 – 155 (125)	185	288	413
2130	109 – 174 (138)	208	333	480
2140	117 – 192 (150)	232	382	551
2150	127 – 210 (163)	256	429	627
2160	136 – 228 (176)	282	478	708
2170	144 – 248 (189)	309	533	795
2180	152 – 266 (201)	336	589	877
2190	160 – 284 (214)	364	648	957
2200	168 – 306 (228)	396	712	1049

Table A4: Projected SLR Projections for New Jersey under low emissions [RCP 2.6] (cm)

	Likely Range	*1-in-20 chance*	*1-in-200 chance*	*Worst Case*
	17th – 83rd (50th)	**95th**	**99.5th**	**99.9th**
2010	5 – 10 (7)	11	13	14
2020	11 – 19 (15)	23	27	30
2030	16 – 29 (23)	34	41	45
2040	23 – 39 (31)	45	54	59
2050	28 – 49 (39)	58	72	82
2060	34 – 59 (46)	70	89	113
2070	39 – 68 (53)	80	107	143
2080	43 – 77 (59)	91	127	176
2090	47 – 87 (66)	104	154	214
2100	51 – 95 (71)	116	181	253
2110	59 – 95 (75)	119	205	298
2120	62 – 105 (82)	135	238	349
2130	66 – 116 (88)	151	275	407
2140	69 – 126 (94)	168	315	469
2150	72 – 137 (101)	186	357	533
2160	74 – 147 (106)	203	398	602
2170	76 – 159 (113)	223	445	676
2180	79 – 172 (120)	244	496	753
2190	80 – 183 (125)	265	549	831
2200	81 – 195 (131)	286	604	913

Estimates are based on (Kopp et al., 2014). Columns correspond to different projection probabilities. For example, the "17th – 83rd" column correspond to the 17th and 83rd percentile; in IPCC terms, the likely range (Mastrandrea et al., 2010)*. 50th percentile projections are in parentheses. All values reflect 19-year running averages and are with respect to a 1991-2009 baseline. Note that these results represent a single way of estimating the probability of different levels of SLR; alternative methods may yield higher or lower estimates of the probability of high-end outcomes.*

Appendix B: An Emerging Approach: Projecting Flood Levels Based on the Full Distribution of Projected Sea Level Rise and the Provision of Asset-specific "Freeboard" to Offset SLR.

Buchanan et al. (2016) provide practitioners with estimates of future flood levels that account for the full probability distribution of local SLR (instead of just the likely range or a single percentile of the range). These flood levels can be used to guide resilience decision-making at the community level. They can also provide flood mitigation guidance for specific assets by incorporating practioners' preferences about flood risk tolerance, asset lifetimes, and precaution against worst-case SLR. This guidance takes the form of a 'SLR allowance', which is simply the vertical adjustment to an asset or its flood defense needed to offset enhanced coastal flooding from SLR (Hunter, 2012; Buchanan et al, 2016). This method provides an amount of freeboard for decision-makers to maintain their flood risk tolerance, where freeboard is defined as "a buffer in height to accommodate uncertainty in the estimated design flood level" (United States Army Corps of Engineers, 2015). The SLR allowances metric is another approach that can be applied by decision-makers such as homeowners, businesses, and municipal planners to apply probabilistic sea-level rise projections for resilience decision-making.

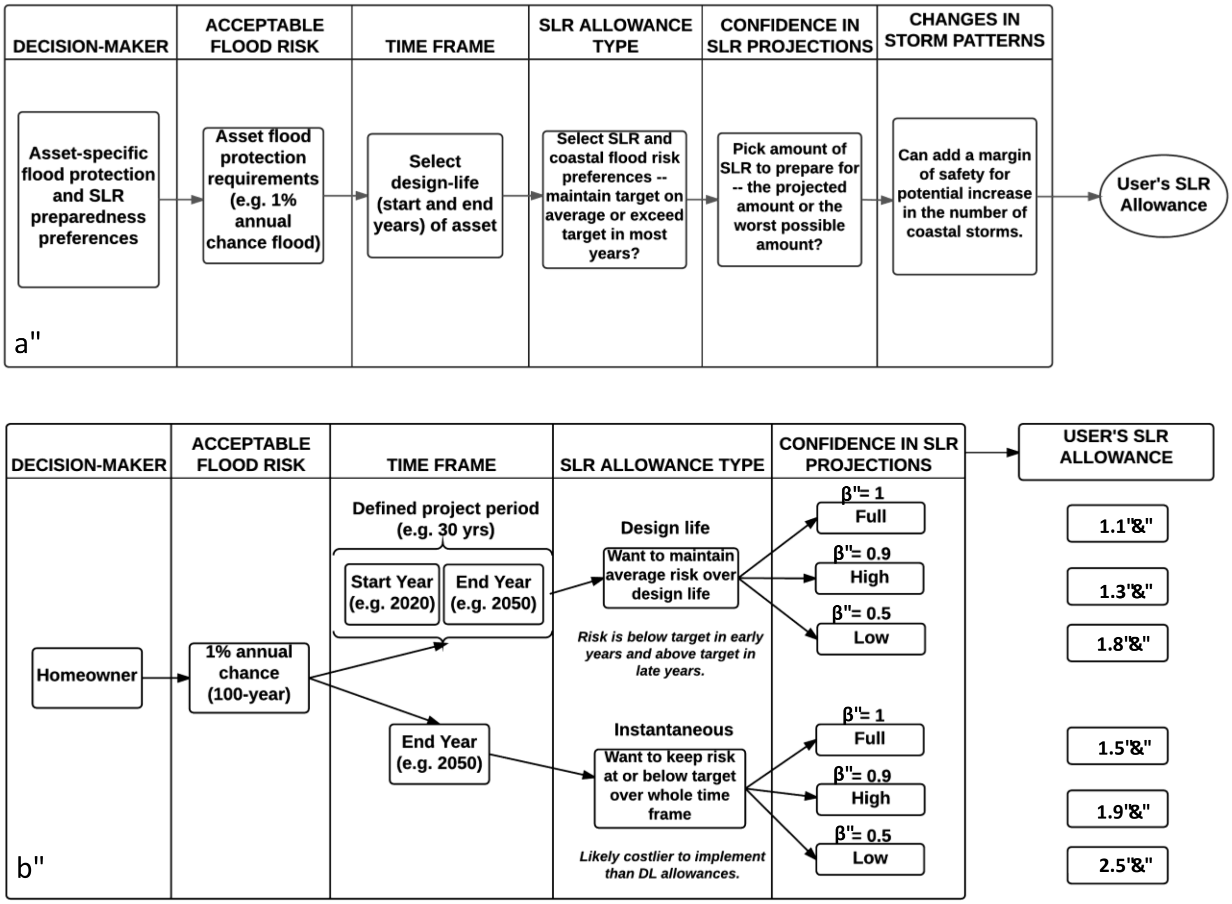
SLR allowances are heights by which to elevate a specific structure (e.g., a house, sea wall) to maintain the current level of flood risk (Hunter, 2012). SLR allowances reflect the design-life of an asset (e.g., a 30-year mortgage; a 70-year critical facility), the users' risk tolerance level (e.g., whether to mitigate against the historic 100-year or 500-year flood levels), and the user's adversity against the high-end SLR outcome.

The framework involves:

1. Selecting risk tolerance based on choosing the flood risk level the user wants to plan for. (e.g. 10-, 100-, 500-year event).
2. Choosing to maintain the desired flood risk over the design life of the asset or, more conservatively, beyond the life time of the asset.
3. Accounting for SLR uncertainty by integrating across all possible futures reflected in the probabilistic sea-level rise projections (e.g., Kopp et al., 2014).
4. Accounting for preferences to protect against projected SLR or worst-case SLR using a "beta" (β) parameter. A beta of 1 represents preparation for projected estimate of SLR and a beta of 0 represents preparation against the worst-case scenario (i.e., the 99.9th percentile of projected SLR).

Figure B1 illustrates the framework for a 100-year event.

Figure B1: Illustration of the sea level rise allowance framework



a) A flow chart of the combined SLR allowance framework, and b) a simple example of its application for a homeowner in Atlantic CIty seeking to maintain 1 % AEP flood hazard over a mortgage from 2020 to 2050. Allowances are in units of ft above Mean High Higher Water.

Tables 9 and 10 illustrate extreme flood levels with sea-level rise allowances for a 30-year mortgage and for 70-year critical facility using the different risk preferences. Table 9 demonstrates illustrative allowances for an individual decision-maker that wishes to maintain a particular flood risk tolerance over the design life of the asset or for a particular year (e.g. instantaneous allowance for 2050).

Table B1: Atlantic City Example Table of Water-Level Increases by Year Calculated Using the Allowance Framework to Maintain Average Risk over Design Life (meters above MHHW)

Design-life SLR Allowance (from start year)	**2020-2030**	**2020-2040**	**2020-2050**	**2020-2060**
30-year Residential Mortgage (with tolerance for the historic 100-year flood)	0.24 m	0.31 m	0.41 m	0.62 m
Design-life SLR Allowance (from start year)	**2020-2030**	**2020-2040**	**2020-2050**	**2020-2060**
Critical facility (with tolerance for the historic 500-year flood)	0.23 m	0.29 m	0.38 m	0.54 m

All allowances are calculated using β = 0.9.

Table B2: Atlantic City Example Table of Water-Level Increases by Year Calculated Using the Allowance Framework to Maintain Risk No Higher than Present through End of Design Life (meters above MHHW)

Instantaneous SLR Allowance (for end year)	**2030**	**2040**	**2050**	**2060**
30-year Residential Mortgage (with tolerance for the historic 100-year flood)	0.29 m	0.41 m	0.58 m	0.87 m

Instantaneous SLR Allowance (for end year)	**2030**	**2040**	**2050**	**2060**
Critical facility (with tolerance for the 500-year flood)	0.28 m	0.39 m	0.55 m	0.81 m

All allowances are calculated using β = 0.9.

Appendix C: Members of the Science and Technical Advisory Panel

Last Name	First Name	Organization
Kopp	Robert	Rutgers University, Earth and Planetary Sciences
Broccoli	Anthony	Rutgers University, Environmental Sciences
Horton	Benjamin	Rutgers University, Marine and Coastal Sciences
Kreeger	Danielle	Drexel University, Biodiversity, Earth and Environmental Sciences
Leichenko	Robin	Rutgers University, Geography
Miller	John	NJ Association of Floodplain Managers
Miller	Jon	NJ Sea Grant and Stevens Institute of Technology, Civil, Environmental and Ocean Engineering
Orton	Philip	Stevens Institute of Technology, Civil, Environmental and Ocean Engineering
Parris	Adam	Science and Resilience Institute at Jamaica Bay
Robinson	David	Rutgers University, Geography
Weaver	Chris	US EPA and US Global Change Research Program