United States Naval Academy
Sea Level Rise Advisory Council

Report to Superintendent:

Initial Analysis and Recommendations to Prepare for 21st Century Sea Level Rise and Storm Tides

July 16, 2019

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Executive Summary

The United States Naval Academy (USNA), located at the confluence of the Severn River and Chesapeake Bay, is vulnerable to storm surge associated with major weather events and localized, nuisance flooding that is primarily the result of high tides and sustained easterly or southerly winds. Since 1929, the relative sea level in Annapolis has risen approximately 1.06 ft, which has significantly increased the occurrences of nuisance flooding from 2-3 times per year to 30-40 times per year and left USNA more vulnerable to major storms such as Hurricane Isabel in 2003. Recovery following the Hurricane took well over a year and cost over $120M. Impacts from storm surges and nuisance flooding affect daily operations through closures of flooded roads, sidewalks and building entry points. With greater frequency and increased amounts of water, the negative impacts are being increasingly felt throughout Naval Academy operations. Long-term, without future action, many of USNA's buildings and monuments as well as the effective execution of the mission of the Academy are at risk.

Generated primarily by glacier and ice sheet loss and thermal expansion of the ocean due to absorption of solar radiation and heat from the atmosphere, and exacerbated by the subsidence of land mass in the mid-Atlantic region, local or relative sea level rise in the Annapolis area is expected to continue well into the foreseeable future. In reviewing the current state of knowledge regarding future sea level rise scenarios, the Naval Academy's Sea Level Rise Advisory Council (SLRAC) focused on multiple comprehensive and peer-reviewed studies and consulted with several subject matter experts. In general, these studies and consultations provided various ranges of anticipated sea level rise based on future emissions scenarios, though they did not predict a most likely scenario. The studies are generally consistent in terms of the range of 21st century sea level rise values associated with stabilized and growing emissions scenarios, with the differences between the stabilized and growing emissions scenarios not pronounced until the latter half of this century.

The SLRAC believes it is prudent to plan for Mean Sea Level (MSL) rise values associated with a growing emissions ("Intermediate") scenario for projects with a relatively low risk tolerance. For this scenario, the 50% probability elevations above the currently defined mean sea level are approximately 1.8 ft in 2050, 3 ft in 2075, and 4.4 ft in 2100. This recommendation is in general agreement with the likely local values for Maryland Sea Level Rise identified by the Maryland State Climate Commission. Under this Intermediate scenario, an average daily high tide (Mean High Water) would reach the threshold for nuisance flooding of Ramsay Road by 2050. Of note, sea level rise (particularly the contribution from glacial melt) is an area of active research, and as such, the SLRAC recommends that estimates will likely need to be revised approximately every five years to incorporate new analysis and data.

In planning for flood protection measures, periodic storms should be considered in addition to MSL rise. The SLRAC recommends adopting the following estimates for storm tides: 1-year storm (2.4 ft), 10-year storm (3.7 ft), 50-year storm (5.2 ft), and 100-year storm (5.8 ft). These storm tide values are relative to MSL, so they must be added to future sea level rise projections. As an example, the water level of an annual flooding event (i.e., associated with a 1-year storm) would reach 4.2 ft above the currently defined MSL (1.8 ft sea level rise plus 2.4 ft storm tide) by 2050, sufficient to flood the Midshipmen Store parking lot, and 6.8 ft above the current MSL by 2100, which would produce flooding similar to Hurricane Isabel.

The SLRAC developed the following decision criteria to guide processes to incorporate sea level rise considerations in long-range planning, as well as infrastructure-based project prioritization and design within the installation:

- Long-term flood protection planning should address both coastal and stormwater flooding, recognizing that construction designs should also account for changes in precipitation patterns, in addition to sea level rise scenarios.
- Future repair projects should be planned and prioritized based on condition, elevation, and mission criticality.
- For practical purposes, the selection of a specific sea level rise scenario for project design should be based on anticipated project design life in concert with an analysis of flood protection (design storm) requirements (i.e., 50-year storm); risk tolerance; use requirements; and adaptability of design (e.g. future retrofit potential).

An ongoing example of this process includes the planned repair of a failed section of the seawall along the eastern side of Farragut Field. Similar planning is needed for flood protection of the Columbarium along Ramsay Road and at McNair Road. At present, both areas flood frequently. A near term decision needs to be made on whether to abandon Ramsay Road and relocate the Columbarium or to protect the area through the construction of an elevated seawall and roadway.

Sea Level Rise Advisory Council

Charter

The United States Naval Academy (USNA) Sea Level Rise Advisory Council (SLRAC) was constituted on July 8, 2015 by direction of the USNA Superintendent. The Council will provide analysis, guidance, and recommendations to the USNA Superintendent and Senior Leadership Team on issues surrounding sea level rise, coastal flooding and increased occurrences of severe weather events, with specific focus on the impacts to operational requirements of the Naval Academy. The focus area of the Council includes USNA lower yard, upper yard and the federal property on North Severn.

Mission

The mission of the Sea Level Rise Advisory Council is to develop a Sea Level Adaptation Plan for the USNA Superintendent on matters pertaining to flooding due to sea level rise and severe weather events in the Annapolis area. The council will provide analysis of data, identification of vulnerabilities, and prioritization of solution sets with the primary goal of minimizing negative impact to the daily operations of USNA and its support activities. This plan, developed in coordination with the City of Annapolis, the State of Maryland and key federal agencies, will suggest a path forward for planning for the impacts of sea level rise on the Naval Academy through 2100.

Membership

Co-Chairs:
Professor Gina Henderson, PhD, USNA Oceanography Dept
Professor David Kriebel, PhD, PE, USNA Naval Architecture and Ocean Engineering Dept

Members:
Mr. Alexander R. Davies, Instructor of Practical Applications, Oceanography Dept
Ms. Lisa Grieco, PE, City of Annapolis Public Works Dept
Mr. David Jarrell, PE, City of Annapolis Public Works Dept
Mr. Kevin Jenkins, NAVFAC Director of Facilities Management Division
Assistant Professor Tori Johnson, PhD, USNA Naval Architecture and Ocean Engineering Dept
Ms. Zoe Johnson, NAVFAC Subject Matter Expert on Sea Level Rise Planning
CAPT Emil Petruncio, USN (Ret.), PhD, USNA Oceanography Dept
Ms. Sara G. Phillips, RA. AIA, USNA Deputy for Facilities and Construction
Mr. Steve Vahsen, USNA Executive Director for Strategy
Ms. Alexandra Weinrich, NAVFAC Community Planner

Coordination with External Stakeholders

Local

Throughout the development of this study, members of the SLRAC have shared information and plans with the City of Annapolis. Staff members from the City's Planning Department and from the Public Works Department have participated in SLRAC meetings at USNA. Additionally, USNA staff and faculty, as well as staff members from the Annapolis Naval Facilities Engineering Command (NAVFAC), have ongoing consultations with the City through a variety of committees, public meetings and conferences on the subject matter of sea level rise planning.

Regional

Federal, State and County agencies in the Mid-Atlantic region have been consulted by the SLRAC for data and best practices. These include the Army Corps of Engineers, National Oceanic and Atmospheric Administration (NOAA), Maryland Department of Natural Resources (DNR), the City of Annapolis, Anne Arundel County Offices of Emergency Management, and Maryland Department of the Environment (MDE).

Other regional stakeholders include the Maryland Silver Jackets, who convened in 2010 and include participants from FEMA, National Weather Service, Army Corps of Engineers, Environmental Protection Agency, US Geological Survey, the Department of Agriculture, Maryland Department of the Environment, Maryland Emergency Management Agency, Maryland Department of Natural Resources, the State Highway Administration and the Maryland Historical Trust.

National and International

The members of the SLRAC participated in a wide variety of national and international studies and consultations with resiliency experts from the Netherlands, New Orleans, Florida, New York City, New Jersey, and Baltimore, among others.

Within the Department of Defense, SLRAC members have begun to apply findings from this work to new and on-going projects that are underway through coordination with Commander, Naval Installation Command (CNIC). Examples of these applications are discussed in other sections of this study. All current and future projects are being examined for opportunities to increase resiliency of the facilities in light of more frequent and greater amounts of water on the Yard.

The Naval Academy Superintendent provided expert testimony to Congress at the House Subcommittee on Energy and Power Field Forum on July 17, 2015. Other participants at this hearing included the Union of Concerned Scientists, the City of Annapolis, and the Chesapeake Bay Foundation.

On November 30, 2017, the SLRAC and Superintendent briefed the Advanced Education Review Board on plausible sea level rise scenarios for Annapolis and activities of the SLRAC. The Vice Chief of Naval Operations mentioned this briefing during a February 14, 2018 hearing of the Senate Armed Services Committee on current readiness of U.S. forces, highlighting the need to take action on sea level rise within the next 30 years.

Over the past year, the Superintendent has briefed the members of the Naval Academy's Board of Visitors (BOV) on the effects of increased flooding on the Yard. Recently, he outlined plans for increased sea wall height at the end of Farragut Field and around the Santee Basin. Additionally, the BOV was briefed on the concept plan being developed for a higher sea wall and roadway along Ramsay Road in front of the Columbarium. The BOV includes members of Congress as well as Presidential Appointees.

Moving forward, the SLRAC encourages continued interactions with this wide variety of stakeholders so that best practices and resources can be shared in the most efficient and effective manner.

Introduction

The United States Naval Academy (USNA), located at the confluence of the Severn River and Chesapeake Bay, is vulnerable to localized flooding and storm surge associated with major weather events and higher water levels, particularly during high tides. Today, approximately 44.5 acres (13 percent) of USNA lies within the 100-year floodplain (1% annual chance of flooding) and another 76.59 acres (22 percent) lies within the 500-year floodplain. The National Oceanic and Atmospheric Administration's (NOAA) Coastal Flood Exposure Mapper for the USNA regions that are vulnerable to composite flood hazards is shown in Figure 1.

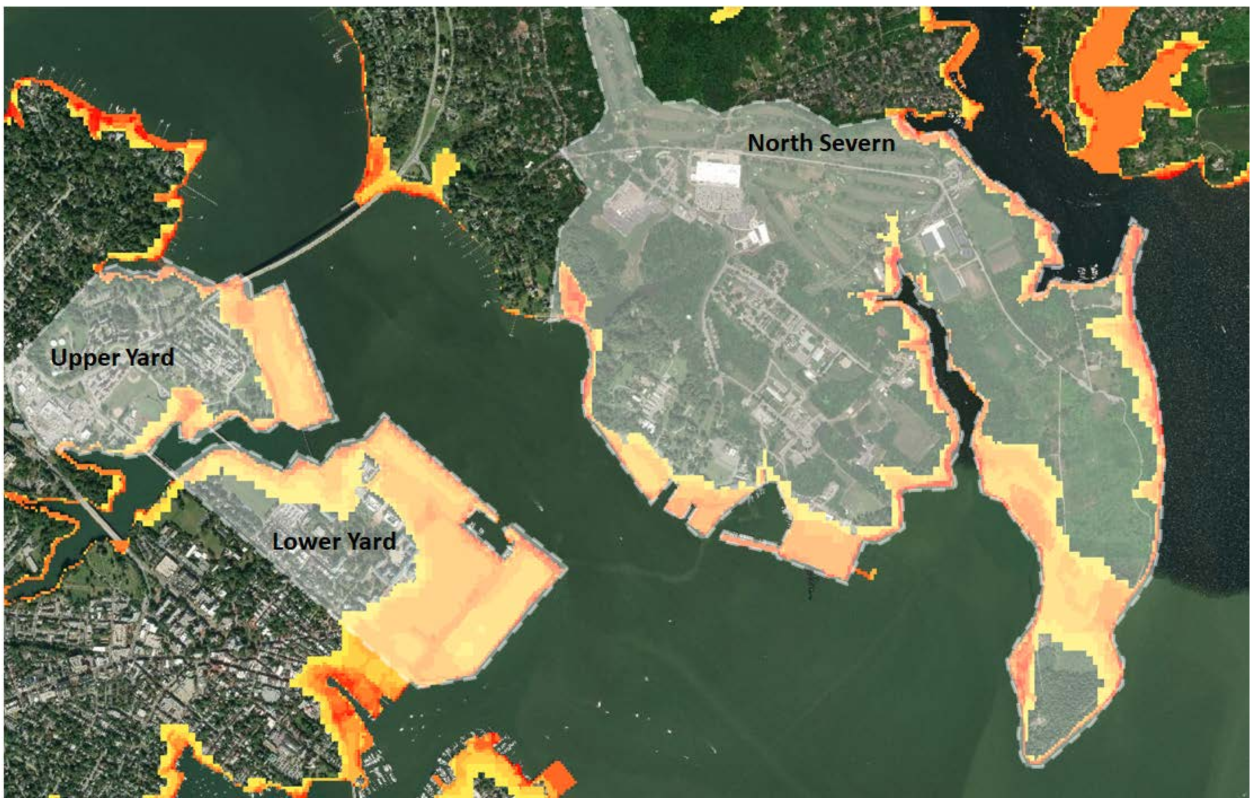

Figure 1. NOAA Coastal Flood Exposure Mapper for the United States Naval Academy Upper Yard, Lower Yard, and North Severn. Light grey shading indicates boundaries of USNA and NSA Annapolis. Shading from yellow to red indicates areas with increasing flood hazard composite score defined by NOAA, based on vulnerability to flooding from increasing numbers of flood hazards, including high tide flooding, 1% annual chance flooding, 0.2% annual chance flooding designated by FEMA, sea level rise of 1, 2, or 3 ft above Mean High High Water, and/or storm surge for category 1, 2, or 3 hurricanes. (Map accessed via https://coast.noaa.gov/digitalcoast/tools/flood-exposure.html).

The primary cause of major coastal flooding at USNA is weather systems that produce winds from the south and east, according to a report by the DoD Strategic Environmental Research and Development Program (SERDP, 2014). The most likely events causing this are tropical (i.e., hurricane) and extratropical storms. In 2003, Hurricane Isabel caused over $120 million (2003 costs) of water and storm damage to the installation. Extratropical storms such as nor'easters as well as other low pressure/cold front systems that track up the Chesapeake Bay with strong winds and heavy precipitation can create potentially damaging storm surge conditions at USNA (NSAA, 2018).

Climate change and sea level rise will likely result in an increase in the number and magnitude of coastal flood events in the years ahead, leading to additional damage to land and infrastructure. Protective measures will be necessary to reduce potential damage from these events, particularly on the land south of College Creek (the "Lower Yard"), where the buildings and mission activities are more susceptible to storm surge and flooding (NSAA, 2018).

Sea Level Science

Historic and Current Relative Sea Level Rise

Since 1928, sea level as measured at the Annapolis tide gauge has risen with a long-term linear rate of 0.14 inches (3.61 mm) per year, which is equivalent to 1.18 feet (0.36 meters) per century (NOAA, 2019a and Figure 2). This measurement of sea level relative to land, or "relative sea level," includes the effects of local land subsidence as well as changes in global (or absolute) sea level. Approximately half of the relative sea level rise in Annapolis since 1928 is attributed to land subsidence (Boon, Brubaker, and Forrest, 2010, and Boesch et al., 2013).

Regional changes in relative sea level have raised the levels of Chesapeake Bay and the Severn River to the "brim," such that onshore and southerly wind events coupled with high tide now result in frequent flooding of low-lying areas, such as the City Dock in downtown Annapolis, and Ramsay and McNair Roads at USNA. The frequency of this nuisance flooding has increased from three times a year in the 1960s to 30-40 times a year in the current decade (Sweet et al., 2014).

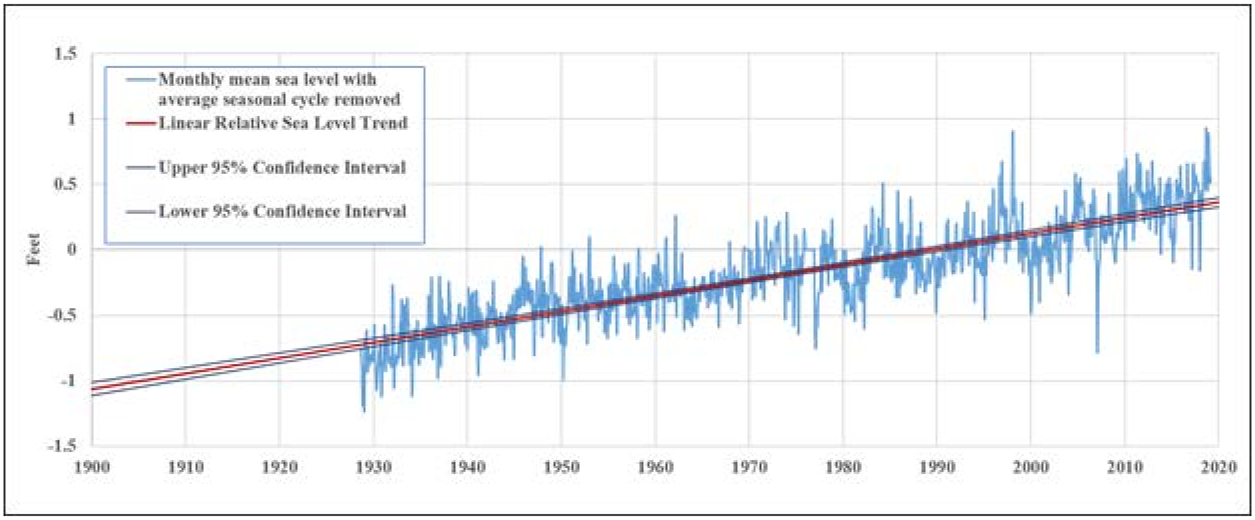

Figure 2: Relative Sea Level Trend for Annapolis, MD. Monthly mean sea level (light blue) observed with the tide gauge in Annapolis (station 8575512), with seasonal fluctuations removed. The long-term linear trend is also shown (red line), with its 95% confidence interval (dark blue lines). The values are plotted relative to the most recent Mean Sea Level datum established by NOAA. The long-term linear trend is 1.18 +/- 0.07 feet per century (3.61 +/- 0.20 mm/yr) based on monthly mean sea level data from 1928 to 2018. (NOAA 2019a)

To put the rate of current sea level rise into perspective, it is helpful to review changes since the last glacial maximum. Over the past 20,000 years, global sea level has risen approximately 400 ft (120m). This rise occurred episodically, with surges or "melt water pulses" resulting in maximum rates of approximately 15 ft per century (Sweet et al., 2107a). Sea level change had been relatively constant for the past 4000 years, but began rising again with the onset of the industrial revolution. The rate of rise over the last century is the greatest in at least 2,800 years (Sweet et al., 2017a).

Factors in Global and Regional Sea Level Rise

The primary physical processes contributing to global sea level change are thermal expansion of the ocean due to absorption of solar radiation and heat from the atmosphere, the addition of mass from melting land ice (i.e., glacial and ice sheet loss), and losses or gains due to ground water storage or extraction (Figure 3). Between 1993 and 2010, glacier and ice sheet loss was the dominant factor, accounting for approximately 50% of global sea level rise (Sweet et al., 2017a). Thermal expansion accounted for 37%, and 13% was attributed to ground water storage.

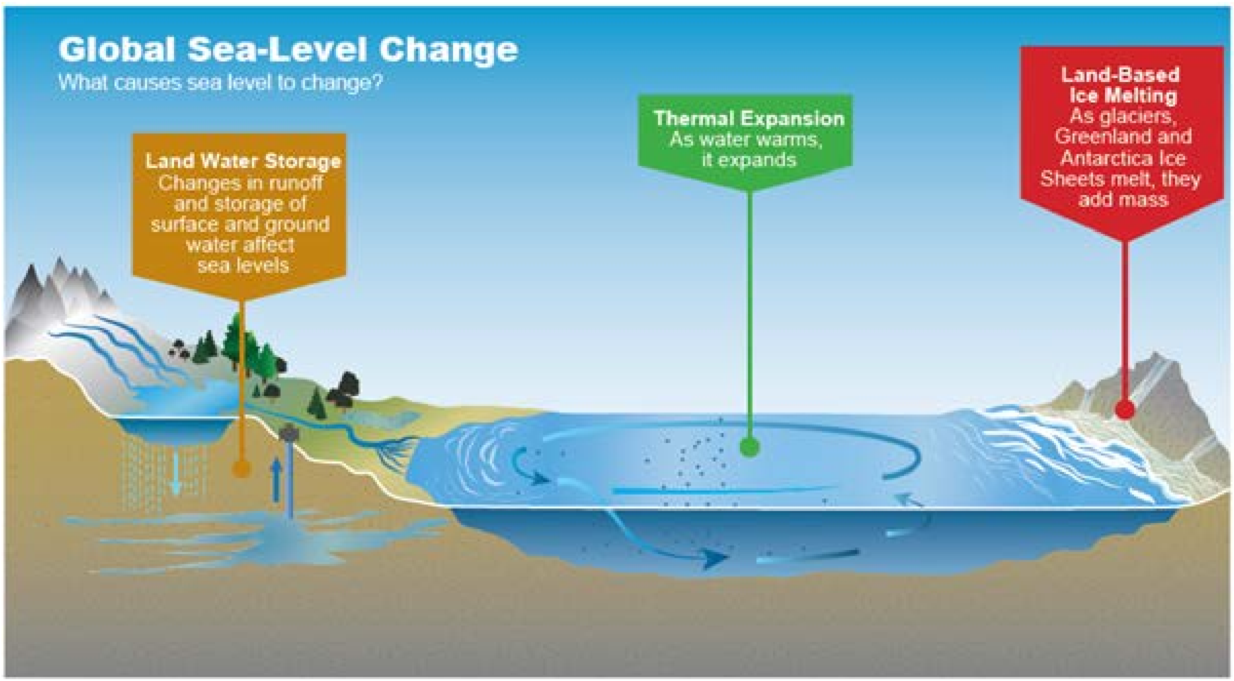

Figure 3: Factors in Global Sea Level Change. Primary contributors to global mean sea level variation are land based ice (glaciers and ice sheets) and thermal expansion. Residual contributions are attributed to changes in ground water storage. (Figure 2.5 in Hall et al., 2016)

Additional factors which affect sea level on a regional level are dynamic oceanography (changes in surface and deep ocean circulation), vertical land motion (glacial isostatic adjustment), and the local expression of glacial melt (since gravitational effects and earth's rotation result in uneven distribution of glacial melt water) (Figure 4). Uncertainties regarding future sea level rise include human behavior (future greenhouse gas emissions), atmospheric forcing (cloud type, cloud cover, and aerosols), and the physical system response (most notably, the rate of loss of Antarctic ice shelves and glaciers).

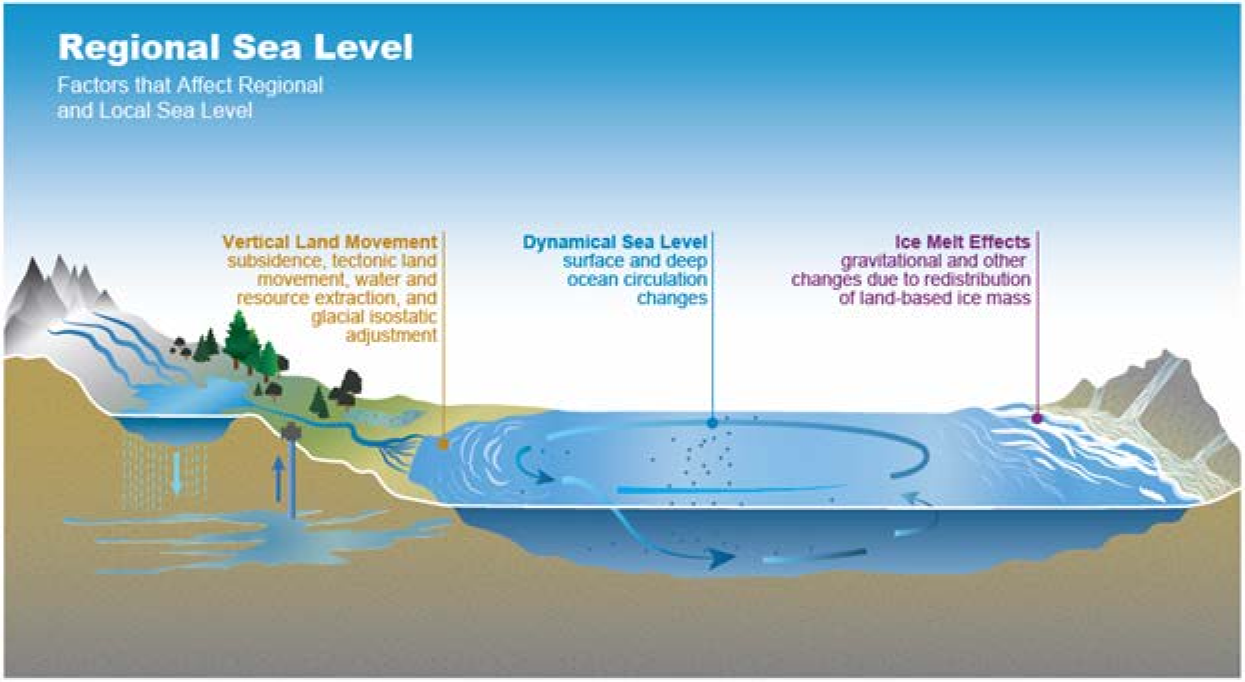

Figure 4. Additional Factors that Affect Regional Sea Level Change. Sea level does not occur uniformly across the globe. In addition to the factors which affect global mean sea level, adjustments to account for regional sea level changes include vertical land movement, dynamical sea level (changes in ocean circulation and location of water masses), and local redistribution of land ice melt. (Figure 2.6 in Hall et al., 2016)

Annapolis Specific Factors

Vertical Datum for Defining Infrastructure Elevations

The elevation of roads and buildings, as well as the elevation of water levels, are usually defined relative to a common reference elevation, termed a "datum." The vertical datum adopted for land and infrastructure elevations at USNA is the North American Vertical Datum of 1988, or NAVD88. All recent elevation surveys taken by LiDAR or by direct GPS elevation measurements use NAVD88 as the reference elevation (elevation 0.00 feet).

The NAVD88 datum is determined by fitting a smooth shape to the Earth's gravitational field, and is termed a geodetic datum. It serves as a useful reference elevation because it remains fixed in time as sea level rises and as the ground subsides. In Annapolis, NAVD88 is nearly identical to mean sea level at present. As mean sea level rises in the future, and as the ground continues to subside, MSL will rise above and depart increasingly from NAVD88.

The NAVD88 datum supersedes earlier vertical datums in use at USNA. Within the last decade, elevations of buildings and other infrastructure at USNA were usually referenced to a local vertical datum known as the Severn River Naval Command Datum (SRNC). Starting after about

2010, elevations have been referenced to NAVD88. The current NAVD88 datum is 1.40 ft (0.42m) above the SRNC datum. As an example of the use of the two datums, some older elevation surveys show the ground floor of Rickover Hall as 5.00 ft (1.52m) above SRNC, which is equivalent to 3.60 ft (1.10m) above NAVD88.

Average Tide Levels

Tidal data for USNA are associated with measurements from the NOAA tide gauge for Annapolis, located in the Hendrix Oceanography Laboratory at Santee Basin (see www.tidesandcurrents.noaa.gov, Station 8575512). Water levels have been measured at this location since 1928.

Normal astronomical tides are caused by the gravitational attraction between the sun, moon, and earth. Tides in Annapolis are mixed, predominantly semi-diurnal (two high tides and two low tides per day, of unequal amplitude), but also include weekly, monthly, yearly, and longer variations. Tides fundamentally oscillate over a complete astronomical cycle of 18.6 years, termed a tidal epoch. The amplitudes and phases of the various constituents of the astronomical tides are computed from water level measurements obtained over the length of the tidal epoch. Important to sea level rise projections, the tidal epoch in current use by NOAA extends from 1982-2001, centered on 1992.

Typical tidal elevations are defined by mean or average tide levels computed over the length of the 18.6 year tidal epoch:

MHHW = Mean Higher High Water (average of the daily highest tides over the tidal epoch)
MSL = Mean Sea Level (average water level over the tidal epoch)
MLLW = Mean Lower Low Water (average of the daily lowest tides over the tidal epoch)

Common values for these reference elevations are listed in Table 1. The difference between MHHW (0.66 ft (0.20m) above NAVD88) and MLLW (0.77 ft (0.23m) below NAVD88) defines the typical maximum daily tidal range (the height difference between the highest high and lowest low tides) for Annapolis as 1.43 ft (0.44m). Sea level rise could change the tidal range in the future, but this change cannot be predicted with confidence at present (Lee, Li, and Zhang, 2017). Due to this uncertainty, the existing datums shown in Table 1 are adopted for future planning.

Because elevations of land-based infrastructure are measured from the fixed NAVD88 datum, it is useful to show water level datums relative to NAVD88, as given in the second column of Table 1. Note that the MSL datum based on the tidal epoch currently in use is just 0.05 ft (0.02m) below the NAVD88 datum. Therefore, for most practical applications in Annapolis during the current tidal epoch, elevations can be referenced to either NAVD88 or MSL without conversion.

Datum	**Elevation in feet from NAVD88**	**Elevation in feet from MSL**
MHHW	0.66	0.71
NAVD88	0.0	0.05
MSL	-0.05	0.0
MLLW	-0.77	-0.72

Table 1: Comparison of Annapolis tidal datums to NAVD88 and Mean Sea Level

Departures from Astronomical Tide Predictions

Figure 5 shows an example of hourly tide data for 2018 at the Annapolis tide gauge. The predicted astronomical tides are shown in blue, while the measured or actual water levels are shown in green. The horizontal dashed lines show the MHHW and MLLW datums.

Observed water levels differ significantly and in several ways from the astronomical tide predictions. First, the mean water level in 2018 (the average of the green curve) was 0.44 ft (0.13m) above NAVD88, or 0.49 ft (0.15m) above MSL. This is due mainly to the relative sea level rise that has occurred between 1992 (the middle year of the tidal epoch) and 2018. In plain terms: in the past 25 years, the Naval Academy has experienced approximately 6 inches of relative sea level rise.

Second, the measured peak high tides are often substantially higher than the astronomically predicted high tide. These water level excursions are due primarily to local weather conditions, such as low barometric pressure and sustained southeasterly wind forcing. The impact of wind on the observed water levels is shown in Figure 6. Generally, sustained wind forcing out of the south and east (between approximately 45^{o} through 225^{o}) results in higher than predicted water levels, whereas sustained wind forcing out of the northwest (between approximately 290^{o} through 340^{o}) generally result in water levels below what is predicted. Occasionally, strong nor'easters or tropical storms travelling up the Atlantic seaboard can affect water levels throughout the Chesapeake Bay and its tributaries. Local seasonal variations also occur, with somewhat higher mean sea levels in August-October and lower mean sea levels in January-March.

This comparison of astronomical tides and observed water levels illustrates that for flooding analysis, daily weather conditions cause tides to depart from astronomical predictions almost every day. Relying upon astronomical predictions or established tidal datums such as Mean High Water or Mean Higher High Water alone to plan infrastructure projects would be unwise. For example, the lowest portions of Ramsay Road near the Columbarium and McNair Road near Alumni Hall have an elevation of about 2.0 ft (0.61m) above NAVD88 (the red line in Figure 5). The astronomically predicted tides did not exceed this level in 2018, but actual water levels greater than or equal to 2.0 ft NAVD88 occurred on 36 days (approximately 210 hours) in 2018, producing low level nuisance flooding of the roadways. Plans to address these flooding events must consider observed and future sea level rise, as well as meteorological effects on local water levels.

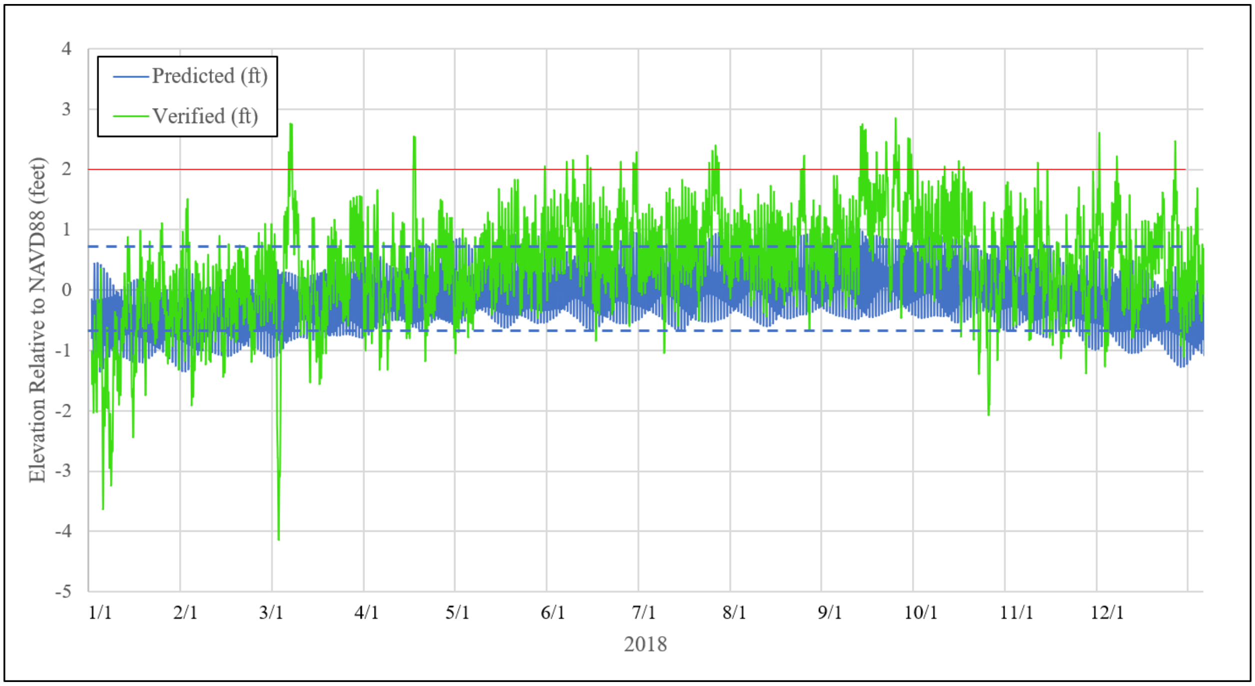

Figure 5: Hourly astronomical tide predictions (blue) and observed water levels (green) in feet relative to NAVD88 for Annapolis, MD, 1 January through 31 December, 2018. The horizontal dashed lines indicate the MHHW and MLLW datums for the current tidal epoch. The red horizontal line indicates the level at which flooding of Ramsay Road and McNair Road at the U.S. Naval Academy begins. Source: NOAA (2019a)

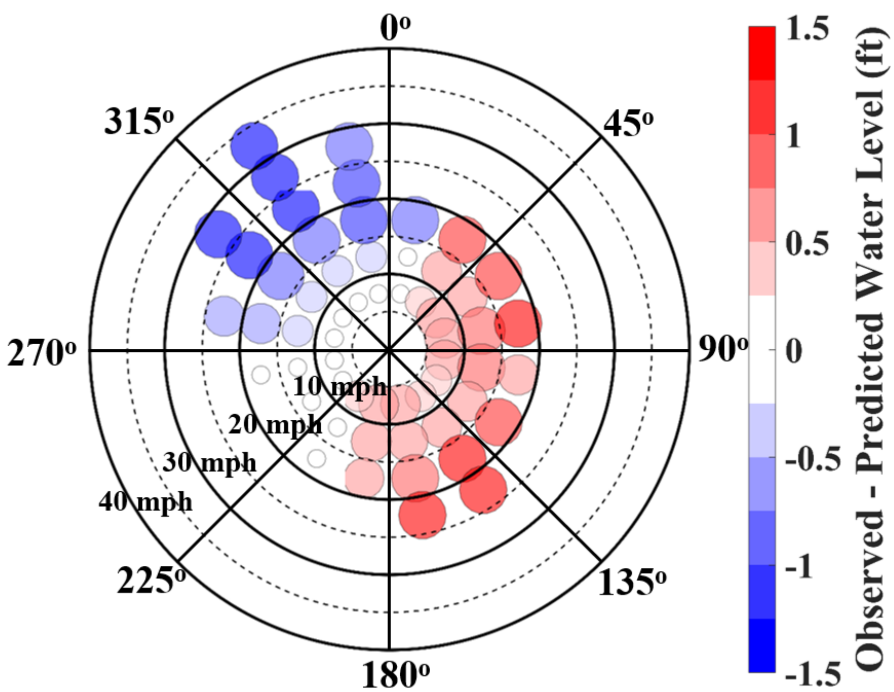

Figure 6: The impact of sustained wind forcing over six hours on water levels in Annapolis, MD. Water level observations and predictions at the NOAA tide gauge are matched with the prior six-hour averaged wind observations from the KNAK ASOS station between 2003 and 2018. Only instances where the wind direction did not deviate from +/- 22.5 degrees during the previous six hour period are considered. The matched observations are then bin-averaged to 22.5 degree x 5 mph bins. The difference between the water level observation and predictions are plotted in wind speed and direction space, with dot color and size indicative of the magnitude of the difference. Red (blue) observations indicate instances where the observed water level is higher (lower) than what was predicted.

Repetitive Minor (Nuisance or High Tide) Flooding

The number of high tide events causing flooding of McNair and Ramsay Roads have been increasing over time due to relative sea level rise. Figures 7 and 8 show examples of flooding at these locations. Both roads flood when abnormally high tides exceed the road elevation. In most cases, water from the Severn River flows in reverse through storm outfall pipes and rises up from storm drains. In some cases, water flows over the top of the seawalls, particularly near the Columbarium on Ramsay Road.

Figure 7. Nuisance Flooding at McNair Road.

Figure 8. Nuisance Flooding at Ramsay Road.

This type of flooding is generally termed "nuisance" or "high tide" flooding, which NOAA (2014) defines as repetitive flooding which causes "such public inconveniences as frequent road closures, overwhelmed storm drains and compromised infrastructure." Based on data from the NOAA tide gauge at Santee Basin, the number and duration of high tide events flooding McNair and Ramsay Roads each year can be determined by comparing measured high tide elevations to the road elevations which, as noted, are now at about +2.0 ft NAVD88.

The number of flooding events and the number of hours at or above flood stage have been increasing in Annapolis, as well as at numerous other sites around the United States (Sweet and Park, 2014). Figure 9 shows the number of high tide flood events at McNair and Ramsay Roads from 1928 to 2018, and Figure 10 depicts the number of hours per decade with minor and moderate flooding in Annapolis between 1930 and 2018. The data indicate that high tide flooding has been increasing at an exponential rate in recent years.

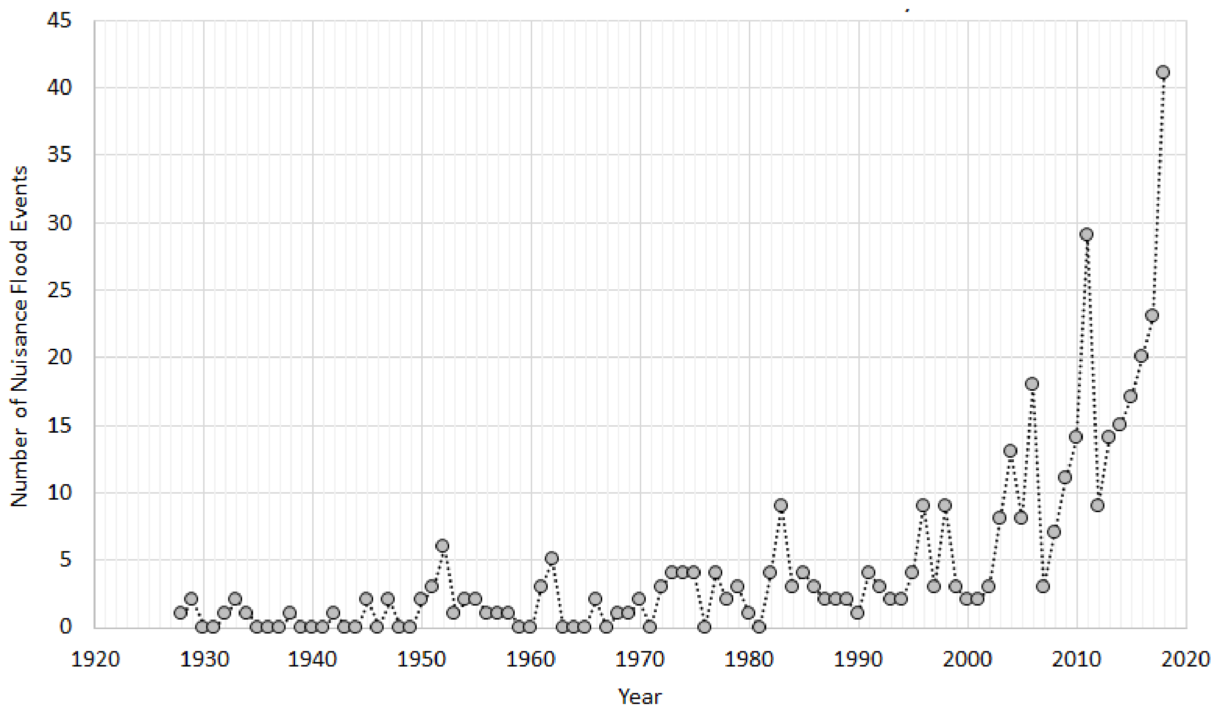

Figure 9. Annual Nuisance / High Tide Flood Events at McNair and Ramsay Roads at USNA

From 1928 to 1950, the annual number of events was typically less than 3, with many consecutive years having no tides over the road elevations, and with an average of just one high tide flood every other year. From 1950 to 2000, the average annual number rose through the decades to an average of 4 per year in the 1990's. Since about 2000, the number of annual flood events has increased dramatically, with about 8 per year from 2000-2010, to an average of 20 per year between 2010 and 2018. In 2018, a record high 41 flooding events occurred. With two high tides per day, flooding in 2018 occurred on almost 6% of high tide events.

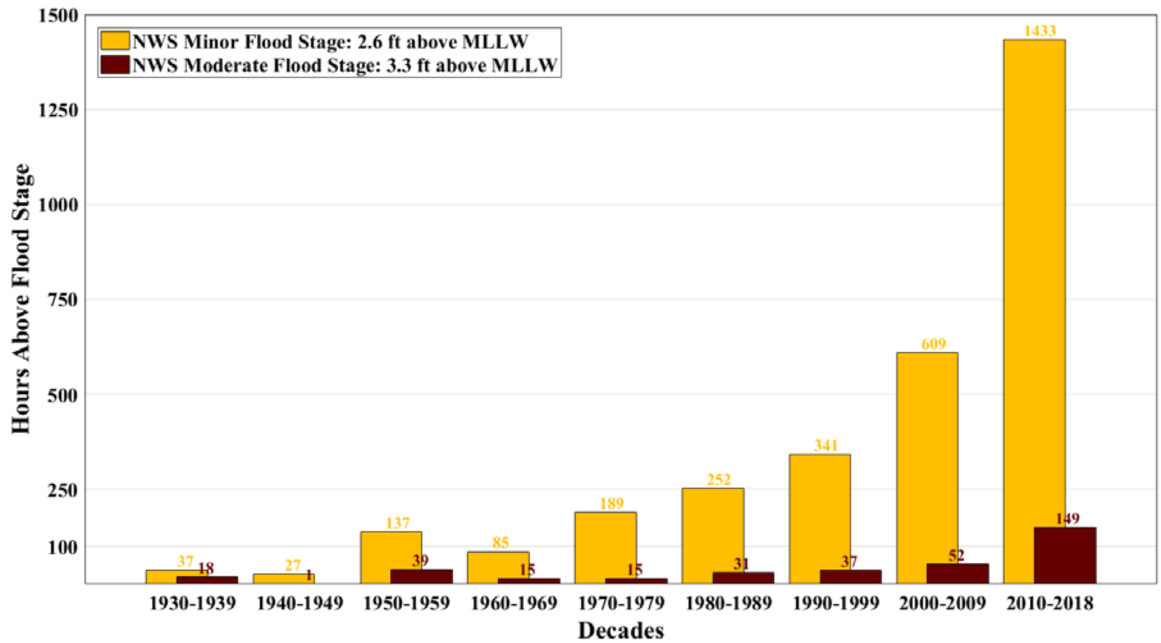

Figure 10. Hours above flood stage by decade in Annapolis, MD. The number of hourly water level observations in Annapolis, MD above minor (yellow) and moderate (dark red) flood stages by decade. Note that the 2010's decade only spans January 1, 2010 through December 31, 2018. Flood stages are determined by the National Oceanic and Atmospheric Agency (NOAA). (https://tidesandcurrents.noaa.gov)

Figure 10 shows that Annapolis has experienced a nearly exponential increase in hours above flood stage in recent decades. In the 1930's, Annapolis experienced only 37 total hours of minor coastal flooding over the entire decade, which is currently defined by the National Weather Service to be water levels 2.6 feet (0.8m) above MLLW. The number of hours above minor flood stage have been rising steadily since the 1960's. Between 1990-1999 and 2000-2009, the hours above minor flood stage nearly doubled, and Annapolis has already experienced more than a doubling of hours above minor flood stage from 2000-2009 to 2010-2018. In addition, the hours above moderate flood stage (defined as 3.3 ft (1.0m) above MLLW) also accelerated at the turn of the century. During 2000-2009, Annapolis experienced 52 hours above moderate flood stage (more than any prior decade by ~30%), and this value nearly tripled between 2010-2018.

A prognosis for future high tide flooding is shown in Figure 11. The blue data points show the number of high tide events each year that reach and exceed different elevations from the NAVD88 datum based on a statistical analysis of measured high tides relative to the existing mean sea level. For an elevation of +2.0 ft for McNair and Ramsay Roads, existing conditions give an average of about 20 high tide flood events per year. With future relative sea level rise, the expected number of flood events per year rises dramatically. With the next 6 inches of relative sea level rise, the number of annual flood events will likely increase to about 90 per year. With the next foot of sea level rise, the number jumps to about 340 per year so that nearly one out of every two high tides would cause flooding – an operational impact for which the term "nuisance" is no longer appropriate.

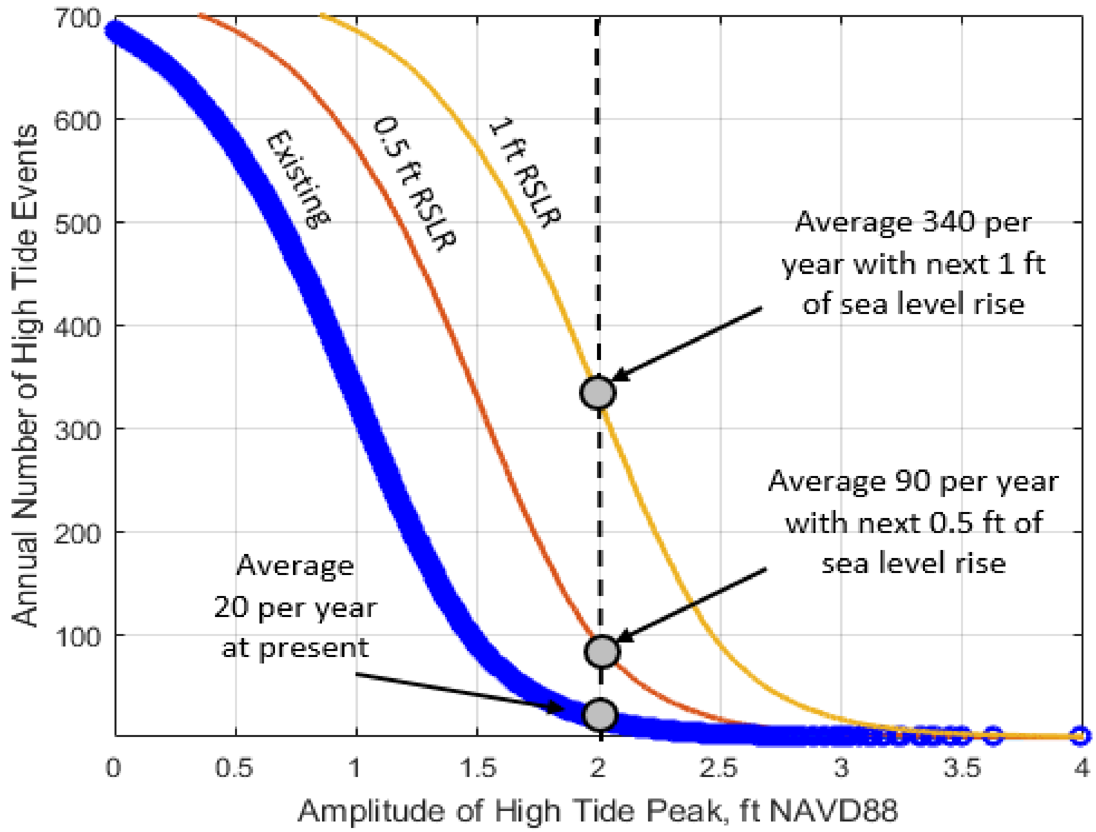

Figure 11. Annual number of high tide events reaching or exceeding NAVD88 elevations. Blue: present conditions; red: 6 inches of sea level rise (approximately 2030, under the intermediate SLR scenario of Sweet et al., 2017b); yellow: 12 inches of sea level rise (approximately 2043, under the same SLR scenario). Vertical black dashed line indicates elevation of McNair and Ramsay Roads.

21st Century Scenarios

In reviewing the current state of knowledge regarding future sea level rise scenarios, the SLRAC drew mainly upon three studies which summarize recent research in this area: U.S. Army Corps of Engineers guidance on civil construction projects (USACE, 2014), a DoD-led interagency study on sea level rise scenarios for military installations (Hall et al., 2016), and a NOAA technical report on global and regional sea level rise scenarios which informed the recent National Climate Assessment (Sweet et al., 2017b). The Council also reviewed projections for Maryland Sea Level Rise prepared by the Maryland State Climate Commission (Boesch et al., 2018) and consulted with the following subject matter experts: Mr. John Hall (OSD), Mr. William Sweet (NOAA), and Dr. Robert Kopp (Rutgers University).

To deal with the uncertainty in future sea level rise scenarios, USACE (2014) advocated the use of three scenarios for the year 2100 (elevation increases of 1.6 ft (0.5m), 3.3 ft (1.0m), and 4.9 ft (1.5m) above MSL), and factoring in a local adjustment for vertical ground motion. USACE (2014) recommended determining an acceptable level of risk for a given project, based on assessment of the three scenarios, and allowing for adaptation of a project based on evidence as the future unfolds. A sea level rise calculator enables the user to interpolate values along a curve for each of these scenarios.

The Hall et al. (2016) study, formally titled “Regional Sea Level Scenarios for Coastal and Risk Management: Managing the Uncertainty of Future Sea Level Change and Extreme Water Levels for Department of Defense Coastal Sites Worldwide,” was sponsored by SERDP and prepared by authors from SERDP, NOAA, USACE, and the Oceanographer of the Navy staff. Hall et al. (2016) presented six global scenarios for 2100 sea level rise, based on a 2012 NOAA study: 1 ft (0.3m) (a linear extrapolation of the current global rate of sea level rise, as measured by tide gauges), 1.6 ft (0.5m), 3.3 ft (1.0m), 4.9 ft (1.5m), and 6.6 ft (2.0m). These scenarios were then tailored for U.S. military installations worldwide, factoring in dynamic oceanography effects, local vertical ground motion, and the regional “fingerprints” of glacial and ice sheet loss. For Annapolis, these sea level rise scenarios range from 1.4 to 8.3 ft by 2100. Hall et al. (2016) considered these scenarios to encompass the range of plausible sea level rise scenarios based on peer-reviewed literature, and made no attempt to identify a most likely scenario. Hall et al. (2016) also provided useful projections for extreme water levels due to storm events, as modified by each sea level rise scenario.

A recent NOAA technical report (Sweet et al., 2017b) considered scenarios similar to those used by Hall et al. (2016), but added a sixth sea level rise scenario of 8.2 ft (2.5m) by 2100, based on recent findings on the potential for rapid ice sheet collapse and glacial melt in Antarctica. The NOAA study provided projections for a number of U.S. cities, including Annapolis, and also added probabilistic projections, providing the 17%, 50%, and 83% probability value for each sea level rise scenario. For Annapolis, the 50% probability values for 2100 range from 0.9 ft (0.3m) to 11.7 ft (3.6m) (Figure 12). Like Hall et al. (2016), no attempt was made by Sweet et al. (2017b) to predict a most likely scenario, but the scenarios were related to emissions scenarios (“Radiative Concentration Pathways”) used by the global community of climate modelers. For example, the “Intermediate” scenario corresponds to a growing emissions scenario, in which greenhouse gas emissions continue at their current rate throughout the 21st century. The “Intermediate Low” scenario corresponds to a stabilized emissions scenario, in which greenhouse gas emissions level out around 2050. It should be noted that sea level rise may not proceed in a smooth manner as depicted in the curves for the various scenarios; rapid ice melt due to ice sheet collapse and acceleration of glacial movements could result in sharp increases in sea level over the course of several decades.

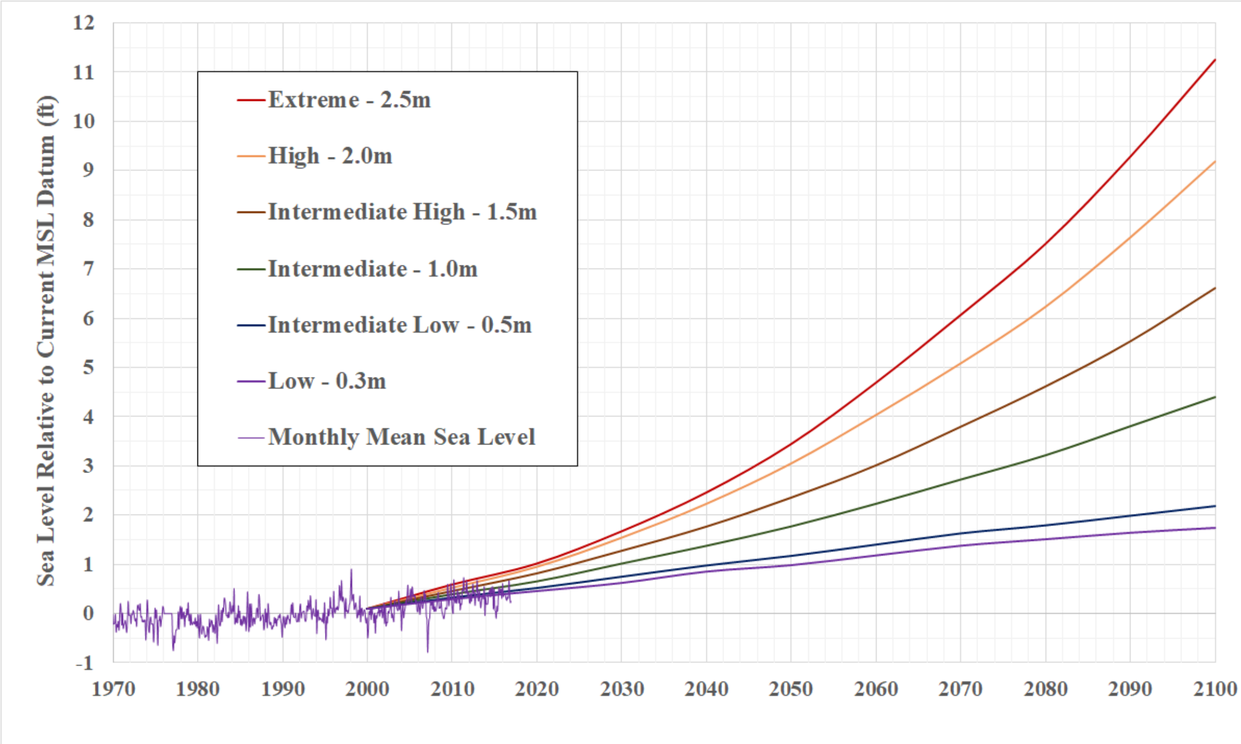

Figure 12: Relative Sea Level Rise Scenarios for Annapolis Based on Six Global Scenarios. Monthly mean sea level observed with the tide gauge in Annapolis is presented with the six sea level rise scenarios published by NOAA (Sweet et al., 2017b). Each scenario has been adjusted for regional effects of vertical ground movement, dynamical oceanography, and the distribution of land ice melt. The curves represent the 50% probability value for each scenario. The legend indicates the corresponding global mean sea level value in meters. Sea level rise values for Annapolis range from 0.9 ft to 11.7 ft (0.3m to 3.6m) in 2100. These curves, originally referenced to mean sea level in 2000, have been adjusted to the current MSL datum established by NOAA.

The rate of ground subsidence at Annapolis is assumed to have remained constant at approximately 0.074 inches per year (1.88 mm/yr) over the past century (Boon, Brubaker, and Forrester, 2010), and will likely remain so in the century ahead (Boesch et al., 2013). Recent analysis of sea level between 1969 and 2014 indicates an acceleration in the rate of sea level rise in Annapolis with a value of approximately 0.007 inches / yr^2 (0.18 mm / yr^2), which would raise sea level approximately 19 inches (51 cm) by 2050, relative to the current Mean Sea Level datum established by NOAA (Boon and Mitchell, 2015), or 14 inches above the average water level computed for 2018. This projection for local sea level in 2050 is slightly less (2 inches lower) than the value for the Intermediate scenario depicted in Figure 12, but the rate of acceleration could be expected to increase with growing greenhouse gas emissions.

Conclusions

We draw the following conclusions from a review of the literature on future sea level rise scenarios:

- The studies are generally consistent in terms of the range of 21st century sea level rise values associated with stabilized and growing emissions scenarios.
- The differences between the stabilized and growing emissions scenarios are not pronounced until the latter half of this century.
- Sea level rise (particularly the contribution from glacial melt) is an area of active research, and estimates will likely need to be revised every 5 years or so.
- Even if greenhouse gas emissions are stabilized in this century, it is a near certainty that sea level will continue rising after 2100 under all sea level rise scenarios, due to lags in the responses of atmospheric heating and ocean expansion.

For planning purposes, it is also worth noting the following statements in the recent National Climate Assessment (Sweet et al., 2017a):

- For almost all future sea level rise scenarios, relative sea level rise in the U.S. Northeast (including Annapolis) and the western Gulf of Mexico is likely to be greater than the global average.
- Rates of increase are accelerating in over 25 Atlantic and Gulf Coast cities (including Annapolis) (*very high confidence*). Tidal flooding will continue increasing in depth, frequency, and extent this century (*very high confidence*).
- Assuming storm characteristics do not change, sea level rise will increase the frequency and extent of extreme flooding associated with coastal storms, such as hurricanes and nor'easters (*very high confidence*).

Recommendations

Given the current rates of greenhouse gas emissions and sea level rise, the SLRAC believes it is prudent to plan for sea level rise values associated with a growing emissions scenario (the Intermediate scenario presented in Sweet et al., 2017b) for projects with a low risk tolerance. This scenario is in general agreement with the likely values for 21st century Maryland Sea Level Rise identified by the Maryland State Climate Commission (Boesch et al., 2018). The 50% probability MSL elevations in Annapolis for this scenario are approximately 1.8 ft (0.5m) in 2050, 3 ft (0.9m) in 2075, and 4.4 ft (1.3m) in 2100, relative to the current MSL datum established by NOAA (Figure 12). The approximate extent of flooding at USNA associated with a water level of 4.4 ft (1.3m) relative to NAVD88, assuming no adaptation measures are implemented, is depicted in Figures 13a and 13b.

Figure 13a: Approximate extent of flooding at USNA associated with a water level of 4.4 ft (1.3m) relative to NAVD88, without adaptation measures. Under the Intermediate sea level rise scenario in Sweet et al., 2017b, this level would be reached by an annual storm tide event by 2050 and by MSL by 2100. Roads which would be impacted by flooding are labelled. Figure produced with the mapping data provided by Professor Peter Guth (USNA Oceanography Department), tailored for viewing in Google Earth. (https://www.usna.edu/Users/oceano/pguth/website/storm_surge/flooding.htm)

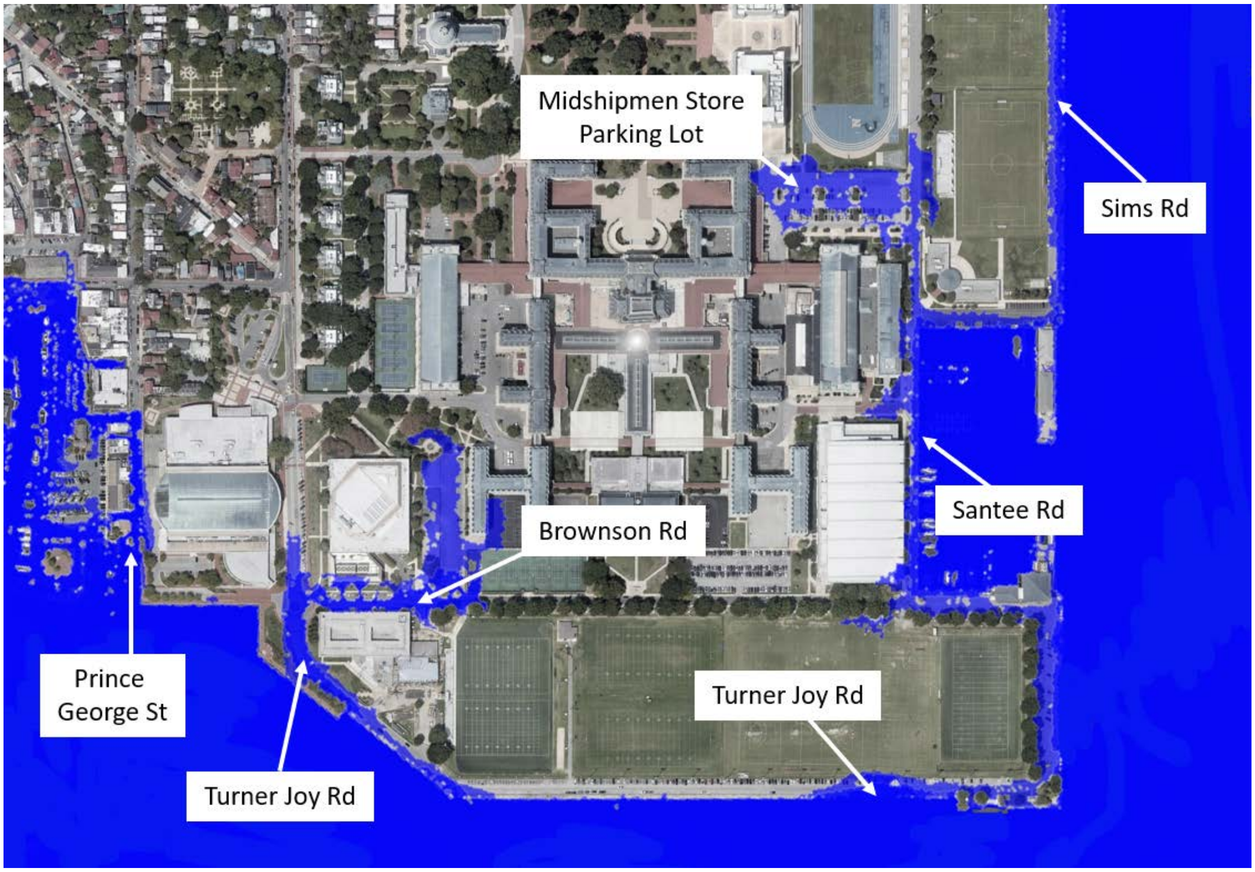

Figure 13b: As in Figure 13a, approximate extent of flooding at USNA (Lower Yard) associated with a water level of 4.4 ft (1.3m) relative to NAVD88, without adaptation measures.

Under this Intermediate scenario, an average high tide (Mean High Water) would reach the threshold for flooding of Ramsay Road (2 ft (0.6m) above NAVD88) by 2050. The water level of an *annual* flooding event would reach 4.2 ft (1.3m) above NAVD88 by 2050 (a level sufficient to cause flooding nearly equivalent to that depicted in Figures 13a and 13b) and 6.8 ft (2.1m) above NAVD88 by 2100 (which would produce flooding similar to Hurricane Isabel).

Storm Tides and Extreme Tide Elevations

As sea level rises, storm tides resulting from major and minor storm events (hurricanes, nor'easters, tropical storms, strong frontal systems) will rise to higher elevations relative to the existing built infrastructure. The term "storm tide" refers to the total water levels in a storm, including normal astronomical tides plus any storm effects. It is the elevation of the total storm tide above ground (or above a road or building floor) that determines flood depths and flood frequencies.

The storm of record at the Naval Academy occurred on September 19, 2003 as the remnants of Hurricane Isabel passed west of the Chesapeake Bay. During Hurricane Isabel, the NOAA tide gauge in Annapolis (at USNA) recorded a peak water level of 6.39 ft (1.95 m) above NAVD88.

Storm tides are commonly characterized by their annual probability of occurrence, or equivalently by their recurrence interval or "return period." As an example, a term in common use is the so-called "100-year" storm event. This event has a 1% chance of occurrence in any year and would occur with an average interval of once every 100 years. The 100-year storm could occur this year and next, or even twice in any year, but over the long term would occur with an annual probability of 0.01.

Storm tides and associated recurrence intervals for Annapolis are available from several sources. One source is FEMA, which establishes elevations of the 1% annual chance (100-year) and 2% annual chance (50-year) floods for Annapolis and other communities. FEMA initially established flood elevations in 1981, with 50- and 100-year elevations of 5.4 and 6.4 ft (1.6 and 2.0m) above MSL respectively (FEMA, 1981). FEMA subsequently re-established new flood elevations for Annapolis and substantially decreased 50 and 100-year values to 4.3 and 4.8 ft (1.3 and 1.5m) above MSL, respectively (FEMA, 2015). NOAA evaluated data from the Annapolis tide gauge to develop curves for extreme water levels versus recurrence intervals (NOAA, 2019b). From these curves, estimates for elevations associated with various storm tides can be made, and these elevations are in between the older and revised FEMA estimates. For example, the 50 and 100 year values are 5 ft (1.5m) and 5.7 ft (1.7m) above MSL, respectively.

As part of the SLRAC's efforts, tide gauge data from the Annapolis tide gauge from 1928 to 2017 was independently analyzed to establish empirical storm tide elevations for the Naval Academy. Analysis followed standard methods outlined in the USACE *Coastal Engineering Manual* (USACE, 2001). Maximum storm tide elevations were first obtained for each storm event during the analysis period. Since earlier storms occurred at a time of lower mean sea level, the linear sea level rise trend was removed so that peak storm tides could be obtained relative to the prevailing mean sea level at the time. Measured storm tide values were then plotted using methods outlined by the USACE, essentially establishing return periods for each event based on the data sample length. Results are plotted as blue data points in Figure 14.

In order to establish a smooth trend curve through the data, a Generalized Extreme Value distribution was fitted to the data points following methods outlined by the USACE. The resulting smooth distribution is given by the red curve in Figure 14. The curve passes through most measured data points and passes below the point for Hurricane Isabel as well as the point for the second highest event on record, a hurricane occurring in 1933.

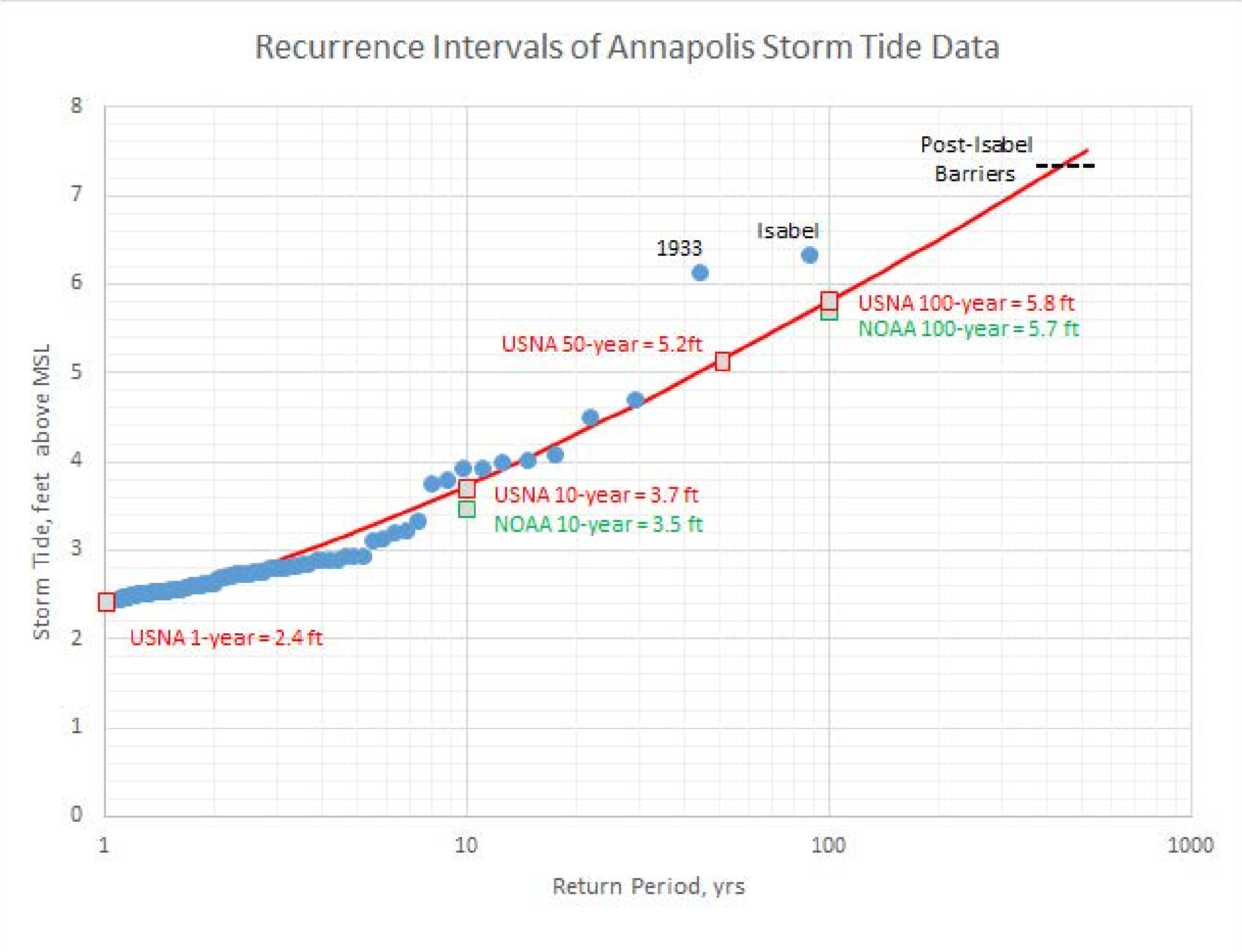

Figure 14: Recurrence Intervals of Annapolis Storm Tide Data

Based on the curve fit, a 100-year storm tide of 5.8 ft (1.8m) above MSL was obtained, essentially identical to the value retrieved from the NOAA curve (5.7 ft (1.7m) above MSL). Similarly, the 10-year value of 3.7 ft (1.1m) is nearly identical to the NOAA value of 3.5 ft (1.1m) above MSL. Values for 50 and 100-year events are approximately 0.5 ft lower than the older (1981) FEMA values (5.4 ft at 50-year and 6.4 ft at 100-year) but 0.7 and 1.0 ft higher, respectively, than the revised (2015) FEMA analysis (4.3 ft at 50-year and 4.8 ft at 100-year).

The revised FEMA estimates relied on numerical hydrographic modeling while the USNA and NOAA estimates are derived from statistical analysis of measured water levels from the Annapolis tide gauge. While a modeling approach might be more appropriate to determine extreme water levels for a location with little elevation data available, the rich data set from the Annapolis tide gauge spans more than 90 years. The SLRAC recommends that the Naval Academy use the statistically-derived elevation values, rather than the model-derived values provided in the revised FEMA guidance.

For use in planning of flood protection measures, it is recommended that the USNA analysis values be adopted. These are summarized in Table 2. These values of storm tide are shown relative to MSL so that they may be added to any future sea level rise scenario. For example, storm tide elevations associated with the Intermediate sea level rise scenario of Sweet et al. (2017b) for the years 2050 and 2100 can be estimated by adding 1.8 ft and 4.4 ft, respectively (the 50% probability Mean Sea Level values for this scenario), to the current storm tide elevations. These estimated values are included in Table 2.

Storm Tide Recurrence Interval	Elevation above current MSL datum (ft)	50% probability elevations in 2050 under the Intermediate SLR scenario (Sweet et al., 2017b)	50% probability elevations in 2100 under the Intermediate SLR scenario (Sweet et al., 2017b)
100 year	5.8	7.6	10.2
50 year	5.2	7.0	9.6
10 year	3.7	5.5	8.1
1 year	2.4	4.2	6.8

Table 2. Elevations of Storm Tide Events relative to MSL.

The lowest return period in the table indicates that storm tides of about 2.4 ft (0.7 m) above MSL should be expected to occur each year on average. This value is consistent with the sample of tide data shown in Figure 5, where the peak water level in 2018 was 2.85 ft (0.9 m). The 1-year value of 2.4 ft (0.73m) above MSL is suggested as a basic planning value for annual events. Providing protection to an elevation of +2.4 ft above MSL would reduce the number of annual nuisance flooding to less than 5 per year.

The 10-year storm tide of 3.7 ft (1.1m) above MSL is representative of minor storm events. This event has a 10% annual chance of occurrence. Events of this magnitude have so far not caused major damage at the Naval Academy. For example, the 5th highest data point in Figure 14, with a storm tide elevation of about 4.1 ft above MSL, was due to the passing of Hurricane Fran in 1996. Flooding occurred on Holloway Road and reached a height of about 8 inches above the lab deck floor of Rickover Hall, but little to no flood damages occurred, as sandbags were used to keep most water (all but a trickle) out of Rickover Hall.

The 100-year storm tide 5.8 ft above MSL is representative of major storms that can produce large scale damage. Events of this magnitude or higher have only occurred twice since the tide gauge was installed, one in a 1933 hurricane (damages are not known for this event) and then in Hurricane Isabel when over $120 million (2003 costs) in damages occurred. Door dam protection for several buildings, including Rickover and Chauvenet Halls, was provided to an elevation of "Isabel plus 1 foot" or about +7.4 ft NAVD88.

Planning Guidance

The Naval Academy's 338 acres includes 286 acres of land designated as a National Historic Landmark District. Within this boundary, 139 facilities comprised of buildings and monuments, are contributing elements of the National Historic Landmark District. In addition to the historical significance of USNA, there are 77 facilities categorized as critical or significant to the installation's mission per the Mission Dependency Index, which is based on an operational risk metric measuring criticality relative to installation mission. Addressing the site's vulnerability through this assessment is essential to the installation's future adaptability to protect over $2.1 billion of assets and the execution of the Naval Academy's mission.

Beginning with the U.S. Army Corps of Engineers' Flood Reduction Analysis for USNA (2006), the Installation has undertaken a series of location-specific sea level rise and flood research, planning and studies. Collectively, these studies, reports and data collection efforts (see Table 3), provide the foundation of the USNA sea level rise response planning effort.

Year	**Project**	**Lead**
2006	Flood Damage Reduction Analysis for the USNA	USACE
2009-2013	Lower Yard Door Dam System (installed in 3 phases)	NAVFAC
2013	High Resolution Topographic Data acquired (LiDar)	NAVFAC
2014	USNA Annapolis DON & DOD Sea Level Rise & Climate Change Study	SERDP
2014	Lower Yard Flood Elevation study	USACE
2017	Design for proposed Lower Yard stormwater repairs	NAVFAC, NSAA PWD
2018-2019	Flood Elevation & Stormwater Modeling	USACE
2019	Columbarium and Ramsay Road Flood Concept Study	USNA, Naval Academy Alumni Foundation
2019	Farragut Seawall Design	NAVFAC, NSAA PWD
2019	Environmental Assessment for Seawall Repair and Restoration at NSAA	NAVFAC, NSAA PWD

Table 3. Summary of USNA Sea Level Rise and Flood Control Planning Efforts

To highlight one of the studies listed above, in July 2017, the US Army Corps of Engineers (USACE) completed an elevation survey of the USNA stormwater system and developed a two-dimensional hydrologic and hydraulic model, using XPSWMM, of the system to determine areas at risk of stormwater flooding and future sea level rise. The survey and modeling data collected are of great use and will serve as the foundation for further investigation and development of courses of action to remedy chronic flooding problems, including Porter Road. USACE is planning to model various courses of action under the current 10-year, 24-hour rainfall event, with a current tidal condition and a projected tidal condition to account for future sea level rise. These models will enable visualization and analysis of the stormwater flooding and various courses of action.

As part of this project, USACE also collected ground and seawall elevation data on both the upper and lower yards. This data is being used to verify existing LiDar elevation data and to more accurately identify areas vulnerable to both stormwater and coastal flooding now and into the future.

In addition to site specific planning studies, research and design efforts, the Navy has also issued a number of overarching planning strategies, guidance, as well as new authorities that are applicable to USNA sea level rise planning and implementation efforts. For example, in 2017, the Naval Facilities Engineering Command (NAVFAC) released a guidance document, *Climate Change: Installation Adaptation and Resilience*, providing Navy master planners with a framework for considering climate change in their plans. This included a detailed methodology for evaluating various scenarios and assessing potential impacts. The document presents a number of climate adaptation strategies, ranging from structural approaches (i.e., levees and storm surge barriers) to nature-based approaches (i.e., marshes and coastal vegetation) and facilities modifications to withstand flooding, to changes in land use planning (i.e., siting facilities out of flood-prone areas). The guidance can be used by the USNA to inform the assessment of potential climate change effects and the range of potential responses.

Additionally, the 2018 NSAA (Naval Support Activity Annapolis) Installation Development Plan (IDP) recognized that the “increased incidence with flooding owing to climate change, coupled with potential for sea level rise over the long range, necessitates measures to protect vulnerable assets against flooding.” The 2018 IDP referenced that flooding due to sea level rise and stormwater events poses a significant threat to critical facilities and infrastructure on the USNA Lower Yard and that phased projects are planned for implementation over the next 20 years. Projects are likely to include stormwater engineering solutions, pump stations, and seawall repair and restoration. The IDP is the official planning document that guides the installation’s physical development activities over a 20-year planning horizon. The 2018 IDP establishes near-term priorities, including a comprehensive seawall planning effort to assess condition and to recommend necessary rehabilitation projects; as well as a comprehensive stormwater study to address deficiencies in the stormwater management infrastructure throughout the installation.

Additionally, at the federal level, the National Defense Authorization Act for Fiscal Year 2019 enacted several new sea level rise and climate change related provisions for military installation master planning and infrastructure projects. Section 2805 included new requirements for a flood risk disclosure for military construction; minimum flood mitigation requirements; incorporation of changing environmental condition projections in military construction designs and modifications; and inclusion of consideration of energy and climate resiliency efforts in master plans for major military installations. Specifically related to sea level rise projections for use in military construction designs, Section 2805 stipulated that the Unified Facilities Criteria be updated, specifying that during the design life of existing or planned new facilities and infrastructure, projections from reliable and authorized sources such as the U.S. Global Change Research Office and National Climate Assessment shall be considered and incorporated into military construction designs and modifications.

As part of its charge, the SLRAC reviewed the culmination of commissioned studies, reports, plans and designs (Table 3), as well as overarching Navy sea level rise planning and design guidance. Based on this review, the SLRAC recommends the following principles to guide the incorporation of sea level rise considerations in long-range planning, as well as infrastructure-based project prioritization and design within the installation.

- Design with a long-term vision in mind, recognizing vulnerabilities of today are very likely to intensify in the future: nuisance flooding; episodic coastal flooding/storm surge; stormwater (precipitation-based) flooding; and extreme events (hurricanes, nor'easters). See Figure 18.
- Long-term flood protection planning should address both coastal and stormwater flooding, recognizing that construction designs should also account for changes in precipitation patterns, in addition to sea level rise scenarios, and should implement a multi-layered response: land use planning, infrastructure design standards, emergency response.
- Future repair projects should be planned and prioritized based on condition, elevation, and mission criticality.
- Selection of sea level rise scenarios for military construction design purposes should be in accordance with the Unified Facilities Criteria, with application guided by the processes laid out in the NAVFAC Handbook.
- For practicable purposes, the selection of a specific sea level rise scenario for project design should be based on anticipated project design life in concert with an analysis of flood protection (design storm) requirements (i.e., 100-year flood); risk tolerance; use requirements; and adaptability of design (e.g., future retrofit potential).
- Address both water quantity and water quality challenges, prioritizing design features that provide co-benefits (resiliency and nutrient/sediment reduction). Wherever practical,

promote implementation of a combination of green (natural) solutions as well as grey (built) infrastructure to reduce vulnerability.

- Incorporate multi-functional elements into the design (e.g., floodwall used for walking/running trails, floodwalls incorporated into perimeter building walls).
- Implement scalable adaptation measures. For example, seawalls should be designed to accommodate phased elevation increase over time; or as necessary, in the event of an impending storm (deployable top system).

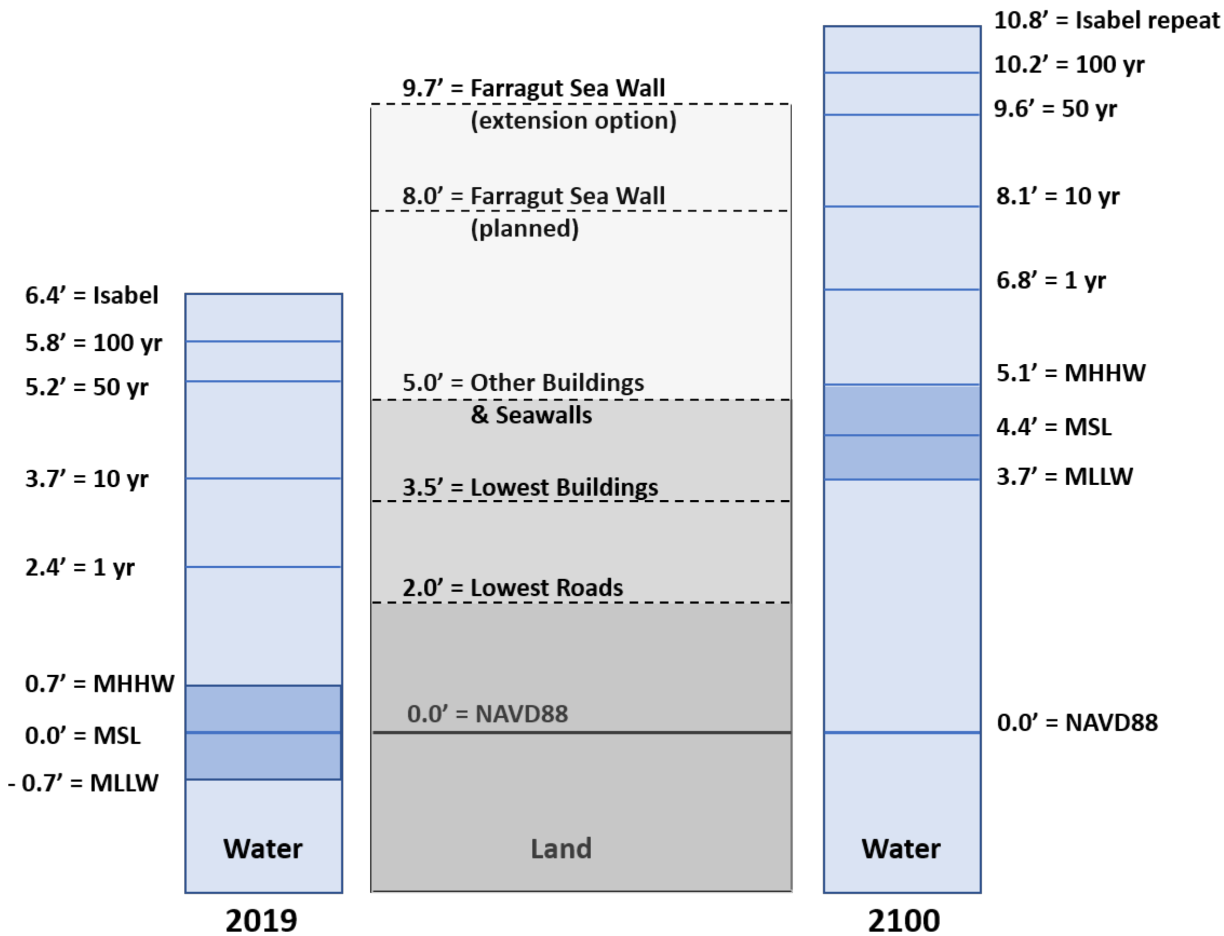

Figure 18: A comparison of current and planned infrastructure elevations to current and future water level datums and storm tide levels, based on the intermediate sea level rise scenario (50% probability Mean Sea Level in 2100) provided in Sweet et al., 2017b. Elevations are given in feet.

The SLRAC recommends that all project development, from initial concepts to full design and construction, incorporate sea level rise planning considerations. This includes analysis of the project life cycle, a determination on tolerable risk to the mission and an analysis of sea level rise over the course of the project life cycle. Past planning studies, reports and established planning guidance, as well as the principles laid out above, should guide the processes to incorporate sea level rise considerations in long-range planning, as well as infrastructure-based project prioritization and design within the installation. Examples of how USNA is putting these recommended resiliency planning principles into practice are outlined in the following section.

Resiliency Projects at the Naval Academy

Past studies, reports and data collection efforts, as well as established planning guidance, provided the foundation of the USNA flooding and storm surge response planning efforts with some implementation of those to date. In 2003, Hurricane Isabel showcased the urgent need to prepare and mitigate against future storms of such magnitude. Lessons learned from Hurricane Isabel recovery and the planning studies and completed reports provided the foundation for the planning principles recommended in the previous section. Long term planning for sea level rise was initiated in 2015 with the establishment of the Sea Level Rise Advisory Council. Below is a summary of resiliency projects undertaken at the installation over the past 15 years, showcasing implementation of these planning principles.

Post Hurricane Isabel Adaptations

In September, 2003, Hurricane Isabel impacted the Mid-Atlantic region with high winds and a significant storm surge that flooded low lying areas of the coast in Virginia, Maryland and North Carolina. At the Naval Academy, the storm surge caused over $120 million (2003 costs) in damage to buildings, fields and equipment. Flooding was prevalent on the Lower Yard and on the perimeter athletic fields of the Upper Yard.

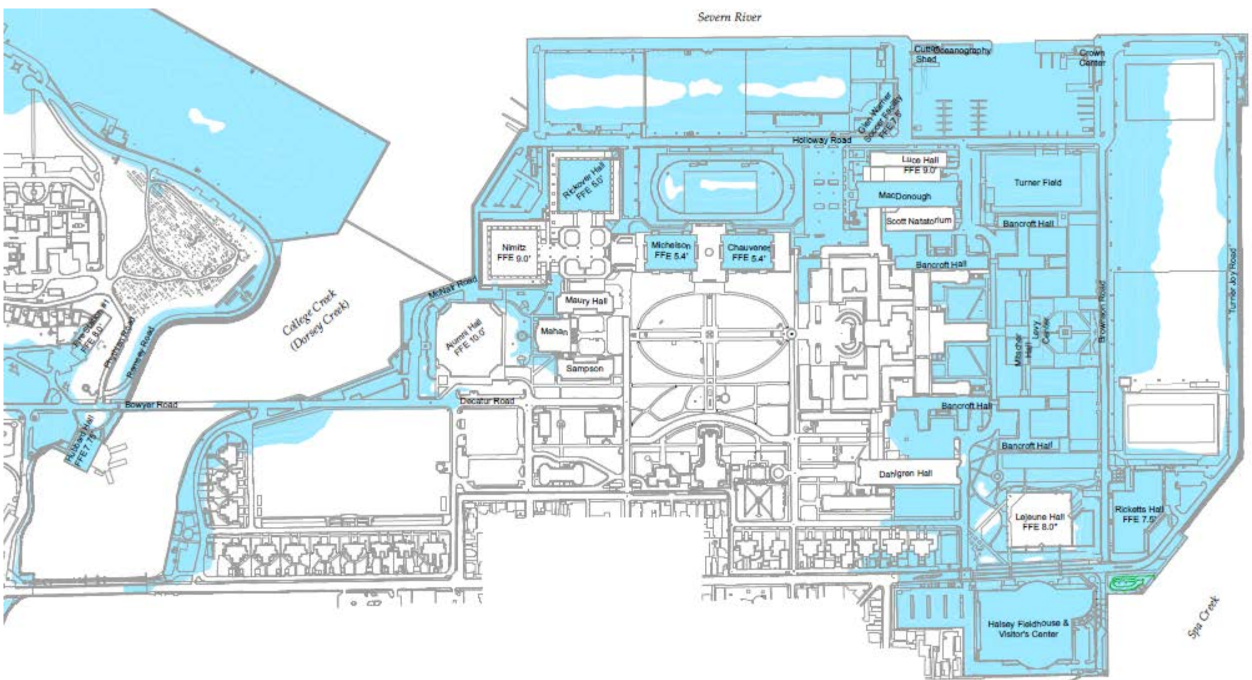

Figure 15. Hurricane Isabel Flood Inundation Map of USNA

Following the storm, the Naval Academy, in partnership with the Army Corps of Engineers, developed mitigation strategies, such as wet and dry flood proofing, that were designed to address major storms and stormwater surge (USACE, 2006). At that time, the Naval Academy was not planning to future impacts from sea level rise, but those impacts are now being included in all project planning on the Yard.

Cooper Road Underground Reservoir

One of the Naval Academy's first steps in addressing these challenges was to manage the combination of heavy rain and high tides through better stormwater management. To control recurring storm and tidal flooding on Cooper Road, an underground reservoir was created to collect and discharge stormwater. The reservoirs are essentially large french drains that are filled with gravel and open on the bottom, allowing the water to seep into the water table in the immediate area. These reservoirs have been effective in managing stormwater on this road that used to regularly flood due to backflow from the stormwater system.

Door and Window Dams (Dry floodproofing)

Another effective tool that the Academy uses for stormwater management is to block the water from entering the buildings at low lying door and window openings (Figure 16). A deployable door dam system was installed at these openings. The door dams are deployed when significant rain storms or high tide events are predicted. These door dams are effective in holding surface runoff out of buildings until the storm system can process the water through normal conveyance piping. They can withstand water sitting against them for several hours before leaking into the building. For that reason, they are not effective during a prolonged flood event or in the case of perpetual flooding from sea level rise.

Figure 16: Door dam deployment in Fall, 2018. Photo credit: Zoe Johnson, NAVFAC.

Wet Floodproofing Measures

Some strategies adopted to mitigate the effects of water intrusion in facilities include:

- Raising ground floor elevations on new construction.
- Locating mechanical and electrical equipment above the floodplain elevation or on roofs.
- Raising electrical outlets on ground floors of buildings.
- Use of flood proof building materials on ground floors.
- Instituting operational protocol of moving lab and classroom equipment out of ground floor spaces in preparation for major storms.

Ongoing Planning

At this time, all project development, from initial concepts to full design and construction, incorporate sea level rise planning. This includes analysis of the project life cycle, a determination on tolerable risk to the mission and an analysis of sea level rise over the course of the project life cycle.

Farragut Seawall
The section of seawall along the eastern side of Farragut Field has failed. The road adjacent to the wall has significant large holes where the road bed and fill material has been lost to the river (Figure 17).

Figure 17: USNA Farragut Seawall. Photo Credit: Alex Weinrich, NAVFAC

The planned repair of this seawall will include raising the elevation to approximately 8 ft above NAVD88 (~2.6 ft above its current height) during the work that is planned for FY2020. Given an approximate 75-year seawall life, the design will allow the wall to be raised an additional 1.7 ft in the future, as conditions warrant to address both sea level rise (under the intermediate sea level rise scenario of Sweet et al., 2017b) and the storm tide of a 50-year storm (Figure 18).

Columbarium and Ramsay Road
Ramsay Road, which runs along the front of the Columbarium on the Upper Yard, is the site of the most frequent and problematic tidal flooding at this time. In September 2018, this road was flooded 16 times, requiring road closures and causing operational impact to the Academy.

In 2018 and early 2019, USNA conducted a study to examine options to address tidal flooding and future sea level rise at this site. The options examined included installation of a new seawall and raising the road. The proposed seawall would have structural capacity to raise it to a higher elevation later as needed. The area behind the road would have several groundwater pumping stations to discharge stormwater from the Columbarium area. The SLRAC recommends that a decision on proceeding with a plan to adapt or abandon this area must be made in the near future.

Going Forward

Future work at the Academy must focus on the protection of the perimeter property line on both the water and land sides of the Academy. Generally, the SLRAC recommends a combination of higher seawalls with pumps that discharge stormwater, raised roadways, and backflow preventers at stormwater outfalls. Additionally, natural and nature-based solutions, such as living shorelines and vegetated berms, should be adopted where appropriate.

While the SLRAC clearly sees the threat of sea level rise from the waterways that surround USNA, we also see a risk of flooding from the City and private land that borders the Academy's perimeter wall at City Dock. These walls and boundary conditions need to be fortified to act as a flood barrier in the event of flooding on either the City or the Academy side of the wall.

Low-lying openings in the perimeter wall, such as the large vehicle and pedestrian access area at Gate 1, need to be examined in light of the risks of recurring and daily flooding. Operationally, the closure or relocation of this access point onto the Yard needs to be examined and decisions made regarding fortification of this area from recurring stormwater overflow from King George and Randall Streets.

Additionally, recent examination of the Naval Academy's existing stormwater system reveals that the entire storm system needs to be upgraded to modern standards with larger conveyances that do not create backflow issues onto paved and landscaped surfaces.

In summary, the Naval Academy is at risk of high tides, storm surge and rising sea levels. In coordination with our external partners, the SLRAC will continue to monitor the science associated with sea level rise, identify risks and prioritize effective solutions to these and future vulnerabilities. Specifically to ensure the effective execution of the United States Naval Academy mission, we recommend the following actions:

- Establish a long term vision for sea level rise adaptation on the Yard through 2100 and beyond;
- Develop an integrated plan for the variety of infrastructure and facility options across the Yard;
- Prioritize short term projects within the integrated plan; and,
- Revisit plans periodically as new data, sea level rise and other climate change science are available.

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