ABSTRACT

Title of dissertation:	SEA LEVEL RISE AND ITS ECONOMIC EFFECTS ON NAVAL INSTALLATIONS
	Angela Luzier Schedel, Doctor of Philosophy, 2015
Dissertation directed by:	Professor Gregory B. Baecher Department of Civil and Environmental Engineering

Global sea level is rising. Coastal lands are at risk from eventual inundation, property loss and economic devaluation. The threat is impending but not rapidly approaching. With sea level rise projections ranging from 0.1 meters to 2 meters by the year 2100, there are concerns but little action being taken to adapt and prepare. Given the potential economic impact of future flood events, it appears that many government agencies and municipalities are not taking enough action to prevent the threat of sea level rise.

Due to its large footprint of real estate within the coastal zone worldwide, one of the largest organizations threatened directly by sea level rise is the U.S. Navy. Adapting to sea level rise will require strategic planning and policy changes in order to prevent the encroaching sea from limiting naval operations and threatening national security.

This study provides a tool to aid Navy decision makers in Implementing Sea Level Adaptation (ISLA). The ISLA tool applies the methodology of decision trees and Expected Monetary Value (EMV), using probability to estimate the cost of potential flood damage and compare this cost to adaptation measures. The goal of this research is for ISLA to empower decision makers to evaluate various adaptation investments related to sea level rise.

A case study is used to illustrate the practical application of ISLA. The case study focuses on when to implement a variety of adaptation measures to one asset at the naval base at Norfolk, Virginia. However, its method can be applied to any asset in any location. It is not limited to only military bases.

ISLA incorporates a unique method for analyzing the implementation of adaptation measures to combat future coastal flooding which will be worsened by sea level rise. It is unique in its use of decision tree theory to combine the probability of future flood events with the estimated cost of flood damage. This economic valuation using Expected Monetary Value allows for comparison of a variety of adaptation measures over time. The projections of future flood damage costs linked to adaptation allows the decision maker to determine which adaptation measures are economically advantageous to implement and when to implement them.

SEA LEVEL RISE AND ITS ECONOMIC EFFECTS ON NAVAL INSTALLATIONS

by

Angela Luzier Schedel

Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2015

Advisory Committee:

Professor Gregory B. Baecher, Chair
Professor Kaye L. Brubaker
Professor Gerald E. Galloway, Jr.
Professor Lewis E. Link, Jr.
Professor Thomas Zeller

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ACC	Annualized Capital Cost
AMOC	Atlantic Meridional Overturning Current (or Circulation)
BFE	Base Flood Elevation
CSVR	Content-to-Structure Value Ratio
DDC	Depth Damage Curves
DFE	Design Flood Elevation
DOD	Department of Defense
EDC	Estimated Damage Cost
EMV	Expected Monetary Value
FEMA	Federal Emergency Management Agency
FIA	Federal Insurance Administration
FIMA	Federal Insurance and Mitigation Administration
FW	Flood Water
GIA	Glacial Isostatic Adjustment
GSLR	Global Sea Level Rise
IPCC	Intergovernmental Panel on Climate Change
ISLA	Implementing Sea Level Adaptation
LMFE	Local Maximum Flood Event
LMSL	Local Mean Sea Level
LMWL	Local Maximum Water Level
LSLR	Local Sea Level Rise
MDI	Mission Dependency Index
MFE	Maximum Flood Event
MLLW	Mean Lower Low Water
MSL	Mean Sea Level
MWL	Maximum Water Level
NACCS	North Atlantic Coast Comprehensive Study
NAVD	North American Vertical Datum of 1988
NAVFAC	Naval Facilities Engineering Command

NFIP	National Flood Insurance Program
NOAA	National Oceanic and Atmospheric Administration
NPV	Net Present Value
NS	Naval Station
NTDE	National Tidal Datum Epoch
OMB	Office of Management and Budget
PRV	Plant Replacement Value
RCP	Representative Concentration Pathways
RSLR	Relative Sea Level Rise
SERDP	Strategic Environmental Research and Development Program
STND	Station Datum
TS	Tropical Storm
USACE	U.S. Army Corps of Engineers
USGS	United States Geological Survey
USNA	United States Naval Academy

Chapter 1: Background

Hurricane Isabel: An Extreme Event or Foreshadowing of Events to Come?

On September 18, 2003 just after noon, Hurricane Isabel made landfall near Ocracoke Island, North Carolina, 150 miles south of Norfolk, Virginia and the mouth of the Chesapeake Bay. By 5PM, Isabel was downgraded to a tropical storm (TS), with Naval Station (NS) Norfolk observing sustained winds of 50 knots and peak gusts of 72 knots (Beven and Cobb 2004). However, it wasn't the high winds that weather forecasters in the Chesapeake Bay region were most concerned with. The forecast showed TS Isabel progressing inland on a northwest track, about 75 miles west of the Chesapeake Bay (Figure 1). The storm's low pressure region, strong southerly winds focused up the bay,

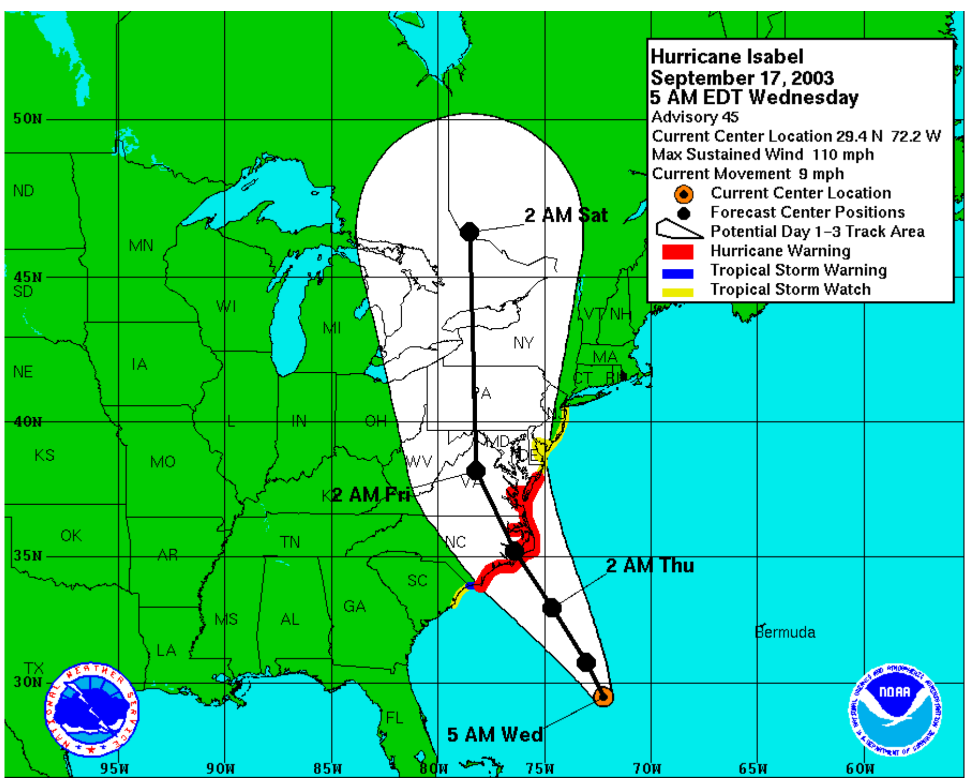


Figure 1: Hurricane Isabel Projected Storm Track

(Source: NOAA)

and bands of heavy rain foretold substantial flooding and storm surge for the coastal areas along the Chesapeake.

As the storm passed west of Norfolk, the water levels climbed 1.7 meters greater than the predicted astronomical tide level, and peaked at a total water elevation of 1.9 meters above the North American Vertical Datum of 1988 (NAVD). The storm surge flooded Norfolk's Midtown Tunnel as workers tried unsuccessfully to close its built-in flood protection gates. The tunnel, which runs underneath the Elizabeth River and carries approximately 50,000 cars per day, filled with 44 million gallons of water in 40 minutes (Kenyon 2012). After Isabel, this major transportation artery connecting Norfolk and Portsmouth was closed for over a month, including the 20 days it took to pump all the water out (Samuel 2012).

The U.S. Navy's largest installation, Naval Station Norfolk (Figure 2), sits several miles north of the Midtown Tunnel. TS Isabel caused over $16 million in damage to the base, flooding numerous buildings, roads and infrastructure. The majority of the ships and aircraft at the base were ordered to depart prior to the storm, in order to protect them from

Figure 2: Aerial view of Naval Station Norfolk
(Source: U.S.Navy)

harm. The unexpected damages to Naval Station Norfolk had not been budgeted for, and the funds were pulled from the Navy's emergency repair budget to pay for their restoration.

Overall, the Hampton Roads/Norfolk area is home to ten different naval installations. The complete cost of the Navy's damage in the mid-Atlantic region totaled $130 million as a result of this single tropical storm (Figure 3). The majority of these costs were directly due to the excessive water levels caused by storm surge which accompanied the storm (Schultz 2003).

Figure 3: Fleet parking lot at Naval Station Norfolk during TS Isabel
(Source: U.S.Navy)

Further up the Chesapeake Bay watershed, the U.S. Naval Academy (USNA) and the Washington Navy Yard braced for similar flooding damage. Due to the slow moving nature of Tropical Storm Isabel and reports of the damage in Norfolk, the emergency management authorities had time to prepare for the rain, wind, and storm surge. At the U.S. Naval Academy in Annapolis, Maryland, the U.S. Navy's future officers were busy sandbagging the entrances to their facilities, several of which were only 1 meter above

NAVD. They covered research computers and protected expensive laboratory equipment with plastic sheeting.

At USNA, the forecast was for the highest water level of 1.3 meters above NAVD to occur early in the morning on Friday, September 19. This forecast seemed realistic given Norfolk's storm surge the evening before, and the sandbagged academic buildings in Annapolis were expected to stay dry. However, when the coastal storm surge was fully developed by 8AM that day, the Naval Academy was enveloped in 1.96 meters of water above NAVD, which was 1.9 meters above the forecast astronomical tide. The damage was more extensive than imagined (Figure 4). The floodwaters did not recede below the 1.1 meter mark for more than 17 hours, leaving behind $120 million in damages at the USNA complex. The flood damage encompassed 18 different buildings and their contents, as well as roads, athletic fields and underground infrastructure (U.S. Army Corps of Engineers

Figure 4: Extensive flooding at the U.S. Naval Academy due to TS Isabel
(Source: U.S.Navy)

2006a). The buildings that flooded were all located within the 100 year floodplain. The estimated flood stage for the 100 year storm at the U.S. Naval Academy was 1.93 meters above NAVD, only 0.03 meters less than the maximum water level height caused by TS Isabel.

Thirty miles west of Annapolis on the Anacostia River, the Washington Navy Yard was affected by both coastal storm surge and riverine flooding during Tropical Storm Isabel. Excessive rainfall and storm surge caused the water level to rise 2.4 meters above forecasted astronomical tide. High water levels damaged many historic buildings and closed the base for several days after the storm.

These stories of flood damage to naval installations in the Chesapeake Bay during 2003's Tropical Storm Isabel are only one example of a single flood event. However, it was not an isolated incident. Other severe flood events have occurred before, and since, and they will continue to occur in the future.

Adjusting the Start Point: Future Sea Level Rise

Global sea level is rising and with an increase in the Mean Sea Level comes an increased probability of flood damage. If Mean Sea Levels are higher, then a storm event does not need to be as severe in order to achieve water levels that lead to flooding. For a given height of storm surge, starting from a higher Mean Sea Level results in higher overall water levels, which lead to more flood inundation and damage.

Historic data gathered from tidal gauge stations worldwide shows a positive trend in water level heights over the past century. The average Global Sea Level Rise (GSLR) trend from 1900-1999 is 1.9 ± 0.3 mm/year, according to a study of 1277 globally interspersed tidal gauge stations (Jevrejeva et al. 2014). Satellite altimetry data collected by NASA from 1993-2009 shows an increasing trend of 3.2 ± 0.4 mm/year (CCAR 2013), which agrees with Jevrejeva's land-based tidal gauge data analysis of 3.1 ± 0.6 mm/year during the same time period.

The Local Sea Level Rise (LSLR) trend at a given location, referred to also as Relative Sea Level Rise (RSLR) or Regional Sea Level Rise, often varies from the GSLR trend. LSLR measurements combine the GSLR trend with vertical land motion, such as ground subsidence or uplift. For example, the sea level rise trend in the mid-Atlantic region of the United States, particularly in the Chesapeake Bay, is increasing at a much greater rate than that of the Pacific Northwest. The Local Sea Level Rise trend in several stations in Washington, Oregon, and Eastern Canada is negative, as shown by the blue arrows facing down in Figure 5. In contrast, the LSLR rate in Eugene Island, Louisiana, is 9.65 mm/year, indicated by a red arrow on Figure 5. Naval Station Norfolk, in Southern

Virginia, shows a more moderate trend, with the LSLR rate from 1928-2014 of 4.61 mm/year, still more than twice the global average during the same period of time.

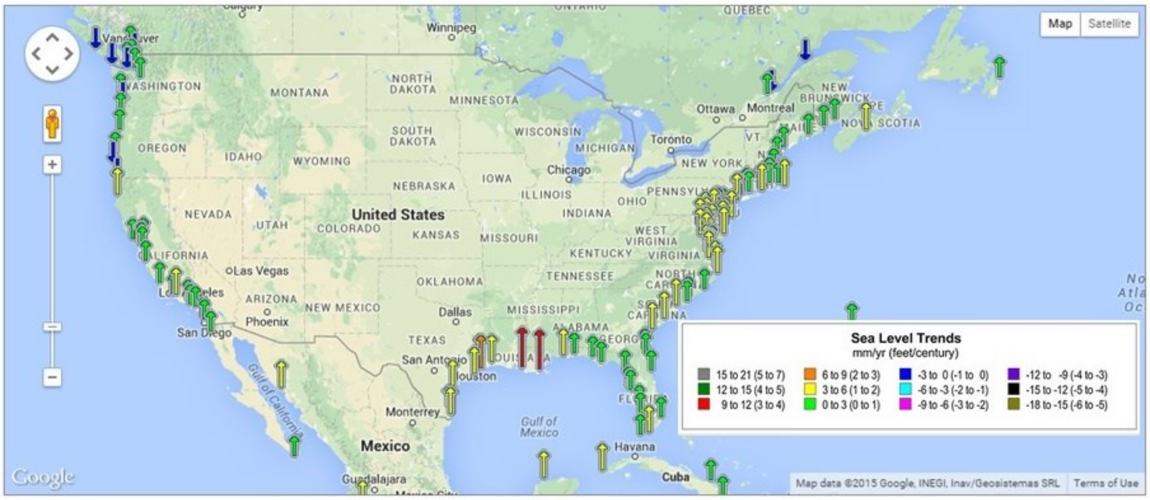


Figure 5: Sea level trends in the United States
(Source: NOAA)

Analysis of the NOAA tidal gauge record for Naval Station Norfolk shows the effect of sea level rise at this location. In March 1962, an unusually large flood event occurred with a maximum water level that registered 1.71 meters above the NAVD datum, while the monthly mean tide height was -0.04 meters. Subtracting the mean tide height from the maximum yields a residual flood event of 1.75 meters. Correlated with historic news archives for Norfolk, this major flood corresponds to the 1962 Ash Wednesday Storm which flooded downtown Norfolk with 2.7 meters of water (flood stage began at 1.5 meters), causing $200 million of damage in the region (NOAA 2014).

This Ash Wednesday Nor'Easter has been called one of the ten worst storms in the United States during the 20th century. This flood event is comparable in severity, with respect to the Mean Sea Level change, to the flooding caused by Tropical Storm Isabel in September 2003. Based on NOAA's tidal gauge data for Norfolk during TS Isabel, the maximum water level reached 1.91 meters above NAVD, with a monthly mean tide height of 0.20 meters, yielding a residual flood event of 1.71 meters. This water level is comparable to the 1962 storm's residual flood of 1.75 meters.

The Local Mean Sea Level in Norfolk rose 0.24 meters between 1962 and 2003. The analysis shows that the Ash Wednesday storm and Tropical Storm Isabel caused similar flood heights with the sea level rise component negated. However, the rise in mean sea level over time cannot be negated, and the severe flooding due to 2003's TS Isabel was 0.2 meters higher than the 1962 Ash Wednesday storm due to the increase in sea level between the two storm events.

Even though their flood heights were similar, these Norfolk storms were caused by distinctly different meteorological mechanisms. The extreme flooding caused by the 1962 Nor'easter occurred when precipitation occurred at such great intensity and long duration that it caused the Elizabeth and James Rivers to rise to historic levels during an unusually high spring tide. The flooding in Tropical Storm Isabel was due to long duration onshore gale force winds which caused an extreme storm surge in the Chesapeake Bay and the confluence of rising rivers in Norfolk Harbor. Despite the difference in the storms' causes, both caused millions of dollars in damage, with the more recent storm being more severe due to sea level rise.

Fighting Back: Mitigating the Effects of Sea Level Rise

With communities around the world threatened by sea level rise, it seems prudent to protect against this peril. Coastal lands are at risk of eventual inundation, property loss and economic devaluation. Fresh water supplies, native vegetation, and agricultural crops will ultimately be ruined by salt water intrusion. These problems are impending but not immediately threatening to most communities. With sea level rise projections ranging between 0.11 meters and 2 meters by the year 2100, there are concerns but little action being taken to adapt and prepare. Given the potential economic impact of future flood events, it appears that many government agencies and municipalities are not as concerned about sea level rise as they should be.

Coastal infrastructure and facilities are especially susceptible to sea level rise. Various options are available for preventing or mitigating the effects of the encroaching sea. Many privately owned properties take advantage of preventive measures, such as building seawalls or bulkheads to protect the erosion of their land from wave effects. Some homeowners take more extreme measures: adding fill to raise their land, or raising their existing house onto a higher foundation or pilings. In the case of public land where taxpayers' money is at stake, allowed inundation and staged retreat are sometimes viable options. While these may be acceptable choices for a public park, this is not the best option for every coastal property.

There are a variety of questions regarding sea level rise adaptation which loom for an affected homeowner, business owner, or government agency. These questions include: What is the strategy for retreating from an expensive ocean side neighborhood? Who buys the houses and land? Who encourages homeowners to retreat? When is the most advantageous time to encourage this option? Is this strategy driven by the local government's stricter building codes and zoning laws or by the insurance industry? What mitigation and adaptation options are government agencies considering as they look to the future?

Since future flood damage cannot be accurately predicted or completely avoided, adaptation strategies are recommended in order to reduce or prevent the severity of damage. These strategies can be divided into two categories, non-structural and structural.

Non-structural measures include government acquisition of coastal property, to include building removal. This buyout option does not prevent flooding of the area, but prevents flood damage by removing buildings from the vulnerable shoreline. Relocation of buildings is another option to prevent flood damage. On Upper Captiva Island near Ft. Myers, Florida, a beachfront house which had been repeatedly damaged by flooding and storms was relocated further inland and elevated. This seems like an extreme measure, but often homeowners are willing to foot the bill to protect their properties. Another non-structural measure is to tighten zoning laws in flood-prone areas, protecting undeveloped land from future building projects. Municipalities can practice stricter land use management, buying undeveloped land and preserving it for use as public parks and beaches.

An additional non-structural method to protect against future flood damage is increasing flood insurance premiums to deter building or owning property in floodplains. However, recent reforms to the government-backed and bankrupt National Flood Insurance Program (NFIP) have proven unpopular and unsuccessful. In 2014, Congress passed the Homeowner Flood Insurance Affordability Act, which changed several key provisions of the 2012 Biggert-Waters Act. The Biggert-Waters Act began to eliminate government subsidies for flood-prone businesses and second homes, and it removed a grandfathering provision that allowed a property to keep its current flood insurance rate once sold to another owner (FEMA 2014). Constituents in coastal regions reached out to their congressmen after Biggert-Waters passed, and the result was the 2014 legislation, which delayed flood insurance rate increases and repealed the grandfathering provision.

Structural adaptation measures for reducing flood damage to existing structures mostly consist of building retrofits. These include elevating a structure, building a ringwall around a group of buildings, increasing the elevation of the entrances, and floodproofing potential areas of water intrusion. These options are typically very expensive, but they are effective at mitigating future flood damage. Temporary flood barriers, which can be deployed manually or automatically in advance of a storm, are often less expensive than other structural options. For example, after the damage to the U.S. Naval Academy due to TS Isabel, temporary door dams, also called stoplogs, were designed to protect the vulnerable ground floor entrances into several buildings. These stoplogs are installed when the forecast water level is higher than a pre-established threshold and the threat of flooding is imminent (Figure 6).

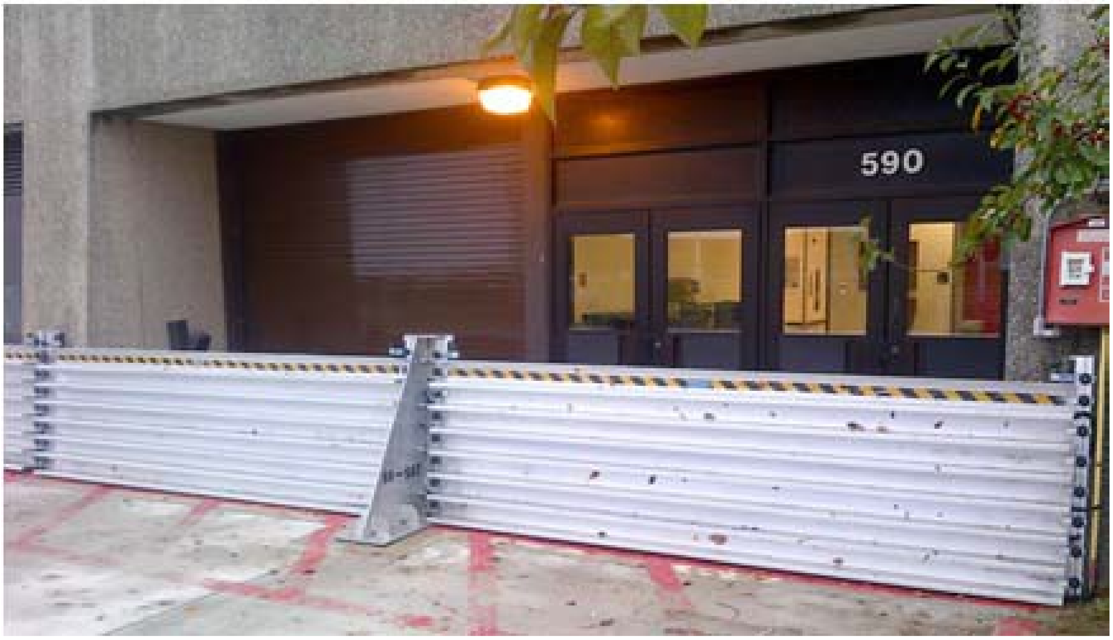


Figure 6: Temporary flood protection stoplogs installed at the U.S. Naval Academy
(Source: U.S. Navy)

In January 2015, the U.S. Army Corps of Engineers published the results of a comprehensive study undertaken in the North Atlantic region after 2012's Hurricane Sandy. The extensive property damage caused by the storm was surveyed and categorized according to building type (U.S. Army Corps of Engineers 2015a). As part of the study, a variety of preventive measures with their associated parametric unit costs were suggested for reducing the risk of damage in future storms (Figure 7).

Aggregated Measure Type[1]	Total Estimated First Construction Cost per Unit[2]	Total Estimated Annual Average Cost per Unit[3]	Units
Acquisition (building removal) and relocation	$349,000	$14,900	Building
Building retrofit (floodproofing)	$100,000	$4,200	Building
Building retrofit[4] (elevating structures)	$192,000	$8,200	Building
Building retrofit (ringwalls – commercial/ apartment building)	$3,680,000	$157,000	Building
Building retrofit (ringwalls – industrial building)	$4,840,000	$206,000	Building
Land use management/zoning and flood insurance[5]	Varies	Varies	
Deployable floodwalls	$5,500	$250	feet
Floodwalls[6]	$5,300	$240	feet
Levee	$1,600	$80	feet
Shoreline stabilization (seawalls, revetments, bulkheads)	$4,800	$250	feet
Storm surge barriers	Varies	Varies	
Beach restoration (beach fill, dune creation)	$3,500	$490	feet
Beach restoration and breakwaters	$9,200	$610	feet
Beach restoration and groins	$7,400	$530	feet
Drainage improvements[5] (e.g., channel restoration, water storage/retention features)	Varies	Varies	
Living shorelines	$1,400	$70	feet
Overwash fans (e.g., back bay tidal flats/fans)	$2,400	$100	feet
Reefs	$4,800	$200	feet
Submerged aquatic vegetation	$2,400	$100	feet
Wetlands[7]	$565,000	$26,900	acre

1 An extensive list of management measures was compiled as part of the NACCS Measures Working Meeting in June 2013. The measures presented here represent an aggregated list of the categories of measures and corresponding conceptual parametric unit cost estimates.

2 Regional factors, such as materials, labor, and fuel, may affect overall costs. The total construction cost estimates must take into account more localized costs of these factors as part of the development of project cost estimates.

3 Includes operations and maintenance costs for all measures as well as periodic renourishment costs for beach restoration measures.

4 The range of costs to elevate structures can vary considerably.

5 Costs could not be developed due to scale of the NACCS study.

6 The concept design identified for the floodwall category consists of a concrete structure. These structures might also require closure structures including stoplogs, miter gates, swing gates, or roller gates, which were not included in the development of the parametric unit cost estimate. A simple steel sheetpile I-wall may be more economical.

7 An annual average cost of $120 per foot was used in the Tier 1 evaluation assuming a nominal wetland width (i.e., dimension perpendicular to the shoreline) of 200 feet.

Figure 7: Flood adaptation measures with parametric unit cost estimates

(Source: U.S. Army Corps of Engineers 2015a)

Problem Statement: Assessing the Economics of Sea Level Rise Decisions

While the problem of sea level rise is global and far-reaching, the aim of this research is to assess a limited aspect of its effects. This study intends to look only at the economic effects of sea level rise and determine how best to implement preventive measures that mitigate flooding of existing infrastructure. With a limited amount of money available to protect flood-prone property, it is imperative to know when, where and how to apply resources to protect critical assets.

The economic focus will be accomplished by developing a method that combines past water level data with Global Sea Level Rise projections and depth damage curves. Historic tidal gauge records and sea level rise forecasts will be combined to create a probabilistic model of future flood events. Meanwhile, a building's ground floor elevation, type of construction, facility use and replacement value data, combined with depth damage cost relationships, allow prediction of the economic impact of these events, as well as the economic benefits of potential adaptation strategies. Based on the probabilistic economic analysis, decisions can be made as to where, when and how to protect vulnerable assets. The goal of this research is to develop a method and tool that aids in such decision-making.

Naval Station Norfolk was selected as a case study because it resides in a critical area of accelerated local sea level rise and is also the largest naval installation in the world. The variety of naval assets, including aircraft, submarines, and ships, onboard this Naval Station will permit the approach of this study to be translated to many different types of facilities with similar operational concerns.

With projections of future Global Sea Level Rise and increased frequency of occurrence of flood events, Tropical Storm Isabel-type flood events will affect naval installations more frequently in years to come. The goal of this research is to develop a method and tool that helps decision-makers answer two fundamental questions. How does the cost of preventive measures compare to the cost of repairing future damage to unprotected assets? What preparations should be undertaken, and when should they be implemented, to prevent future flood damage? By answering and acting upon these questions, future flood events will not be avoided but their impact may be lessened.

Chapter 2: Survey of Related Literature and Past Research

Global Sea Level Rise

There are many causes of Global Sea Level Rise (GSLR), but the most influential drivers are thermal expansion of the world's oceans and glacial ice melt. As the oceans warm, the volume of the water in the oceans increases and this increase is observed as a rise in water level globally. The melting of glaciers and land ice adds more water to the oceans and is registered on tidal gauges as a water level rise.

The contribution of thermal expansion is estimated to account for 30 to 55% of the total GSLR projection. Glacial melt contribution is estimated to have between a 15 and 35% contribution. The Intergovernmental Panel on Climate Change (IPCC) estimates the sea level rise component due to thermal expansion is between 0.7 and 1.1 mm per year (IPCC 2001). Glaciers are estimated to contribute between 0.04 and 0.23 mm per year (IPCC 2013).

The 2012 report, entitled "Global Sea Level Rise Scenarios for the U.S. National Climate Assessment," recorded the historic global sea level trend at approximately 1.7 mm/year, using tidal gauge records dating back to 1900 (Parris et al. 2012). According to Jevrejeva et al. (2014), the average Global Sea Level Rise (GSLR) trend from 1900-1999 is 1.9 mm/year. Additionally, satellite altimetry data gathered from 1992 to 2010 shows a GSLR trend of 3.2 mm/year during this more recent time period (CCAR 2013).

Many different studies analyze the historic rate of sea level rise and the projected sea level rise by the year 2100. An illustrative slide presented at a NOAA Digital Coast

Webinar in November 2011 by scientist Douglas Marcy shows the wide range of projections and the variety of researchers with Global Sea Level Rise estimates (Figure 8).

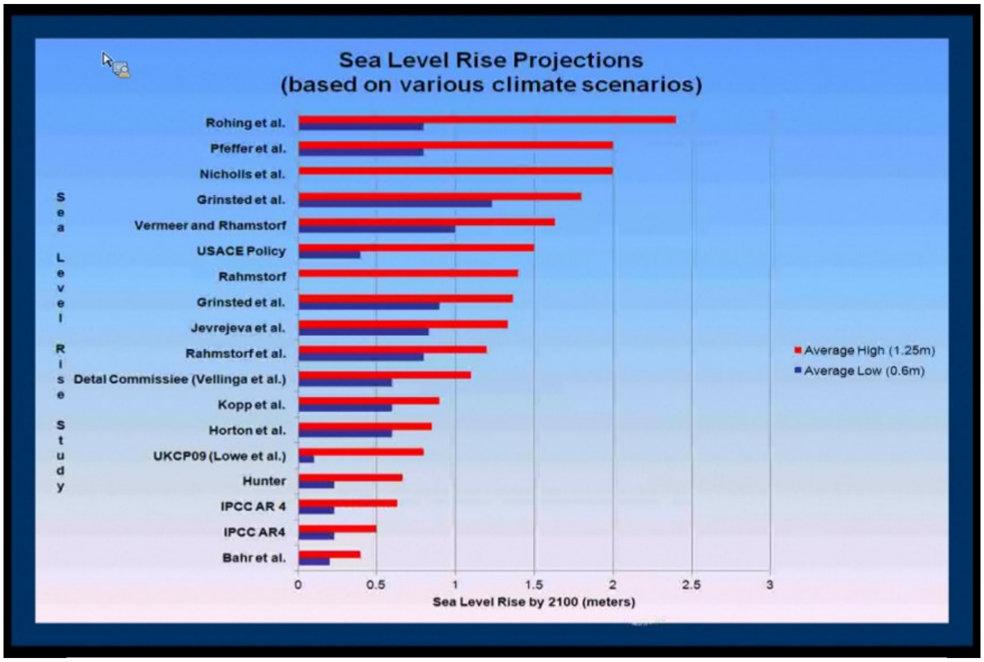


Figure 8: Sea level rise projections to the year 2100
(Source: NOAA)

Even though a majority of climate scientists would argue that sea level rise is accelerating, there are a select few who believe that the opposite is true. Robert Dean, a preeminent coastal engineer, and his colleague James Houston, presented evidence showing that sea level rise is decelerating (Houston and Dean 2011). This paper was highly disputed and received rebuttals from other scientists, who claimed there were inaccuracies in the satellite altimetry data used to find the sea level rise rate (Rahmstorf and Vermeer 2011). The art of predicting sea level rise remains a volatile subject, with a portion of the world's population refusing to believe that climate change exists (Rick, Boykoff, and Pielke Jr 2011).

Chapter 4 of this research will discuss Global Sea Level Rise projections in more detail. A large variety of expert opinions of GSLR by the year 2100 will be presented.

These opinions will be combined to estimate a future GSLR for the economic valuations created by this research method.

Local Sea Level Rise in Norfolk

The sea level is rising at different rates across the globe. As mentioned in Chapter 1, the Local Sea Level Rise (LSLR) rate in Norfolk, Virginia is 4.61 mm/year, more than twice that of the Global Sea Level Rise rate. There are multiple causes of this accelerated LSLR rate in the mid-Atlantic region, with post-glacial rebound, groundwater extraction, and sediment deposition having the greatest effects (Sella et al. 2007). More than half of the observed LSLR at Norfolk is due to land subsidence, with half of this subsidence due to groundwater extraction (U.S. Geological Survey 2013).

Post-glacial rebound, also referred to as Glacial Isostatic Adjustment (GIA), is one of the most influential causes of land subsidence in the mid-Atlantic region. The glaciers that once covered large portions of the Northern Hemisphere compressed the land underneath due to their great size and weight. Even though the Laurentide ice sheet which covered most of Canada and the northern United States melted ten thousand years ago, the earth's crust is still recovering. As the land in Canada is gradually rising, the land in the Chesapeake Bay is gradually sinking (Scott et al. 2010). Imagine the land as a see-saw, with its center point located in the center of the Great Lakes (Mainville and Craymer 2005). As the northern side rises slowly due to the removal of the glacier weight, the southern side is slowly sinking.

The contribution of GIA to the land subsidence in the mid-Atlantic region is approximated at about 1 mm/yr, but this rate is uncertain and not the same across the entire region (Engelhart and Horton 2012). The effects of GIA are most pronounced in North America along the U.S. East Coast (Figure 9). In this region, the rate of LSLR in Eastport, Maine is 2.0 mm/yr, while the rate of LSLR at the mouth of the Chesapeake Bay is 6.05 mm/yr (Zervas 2009).

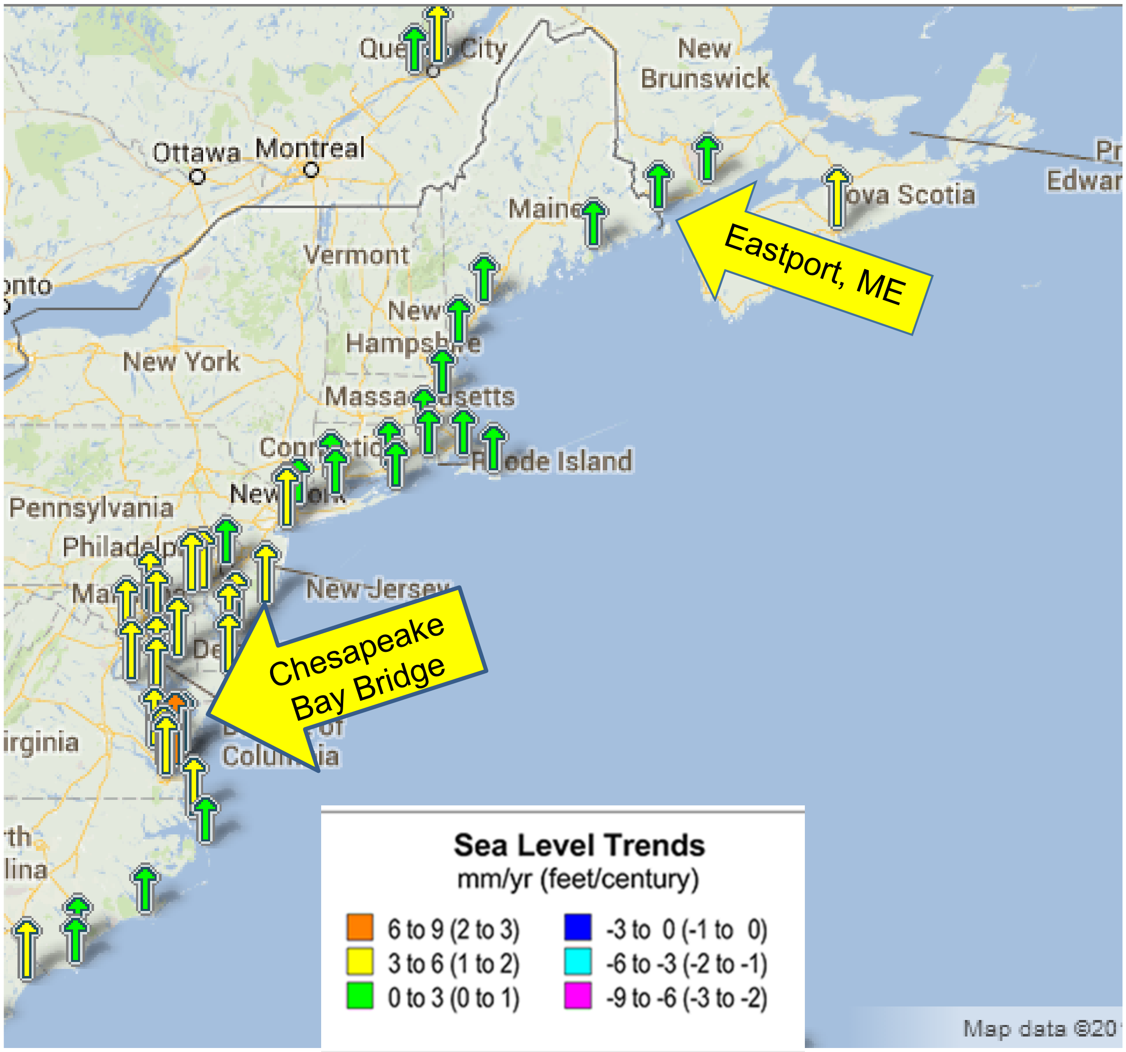


Figure 9: Sea level trends on the U.S. East Coast
(Source: NOAA)

In addition to glacial rebound, another factor causing ground subsidence in the Chesapeake Bay area is ground water extraction. Residents and businesses in this region rely heavily on ground water for irrigation and drinking. In Virginia, 37% of households have private wells, but on the national level only 15% of the U.S. population drinks from a privately maintained well (Virginia Department of Environmental Quality 2014). Residents of Southern Maryland and the Eastern Shore of Maryland rely exclusively on well water for both drinking and irrigation (Maryland Department of the Environment 2012). As groundwater is removed from aquifers, the heavy layers of ground above the aquifer compact the emptying aquifer layer, causing ground subsidence. The rate of subsidence in Virginia due to aquifer compaction has been measured at several different locations between 1.5 and 3.7 mm/yr, averaging 2.6 mm/yr (U.S. Geological Survey 2013).

Sediment deposition also contributes to an increase in the LSLR rate in the Chesapeake Bay. One characteristic of an estuary is that sediment is constantly being deposited on the sea floor downstream from the tributaries. The Chesapeake Bay is no exception. Copious amounts of runoff from the watershed contain silt and other matter from the land. This sedimentation of land material into the water is one of the causes of the Bay's highly-publicized decreasing oxygen levels, which are threatening the fragile ecosystem. An effect of this deposition is the decrease of water volume in the Bay, causing a slight rise of the water level (U.S. Geological Survey 2013). This effect may be small, but it accumulates over many years and contributes to the relative sea level rise of the land masses nearest the Bay.

In addition to glacial rebound and aquifer compaction due to groundwater extraction, the land at the southernmost portion of the Chesapeake Bay is sinking at a greater rate due to the seafloor disturbance from an ancient meteor (Scott et al. 2010). The Virginia Institute of Marine Science discovered evidence of a meteor strike 35 million years ago at the mouth of the Chesapeake Bay. The site, named the Chesapeake Bay Impact Crater, has several tidal gauge stations within its 50 mile radius which have reported an increased rate of relative sea level rise at the stations closest to the crater's edge (Boon et al. 2010). It is believed that the land within this impact zone is weakened and subsiding at a greater rate than other parts of the region. Naval Station Norfolk is located at the edge of the crater's outer rim (Figure 10). The exact rate and the probability of the relative sea

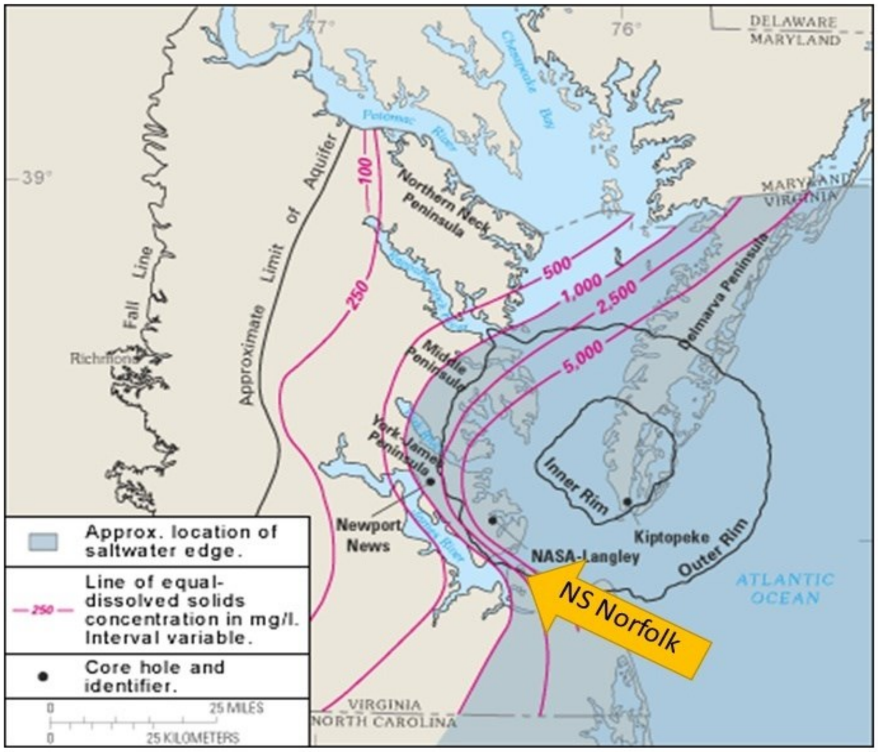


Figure 10: Chesapeake Bay impact crater location relative to NS Norfolk
(Source: U.S. Geological Survey 2003)

level rise rate in the Chesapeake Bay region are difficult to determine due to the mixture of diverse factors which are causing the land to subside.

Another occurrence causing the Local Mean Sea Level to be rising at a faster rate in Norfolk is the upwelling of the Atlantic Ocean along the U.S. East Coast. This upwelling is due to changes in the Atlantic Meridional Overturning Current (AMOC) (Goddard et al. 2015). The AMOC is a major ocean current which transports warm, salty water from the Tropics in a northbound flow, and cold, less salty water in a southbound flow (Figure 11). The current acts as a heat exchanger between the Northern and Southern Hemispheres. The AMOC has been slowing and causing a pressure gradient between the warm Gulf Stream ocean current and colder coastal waters. As this pressure gradient along the U.S. East Coast has been decreasing, coastal waters are rising in response. The AMOC is theorized to have

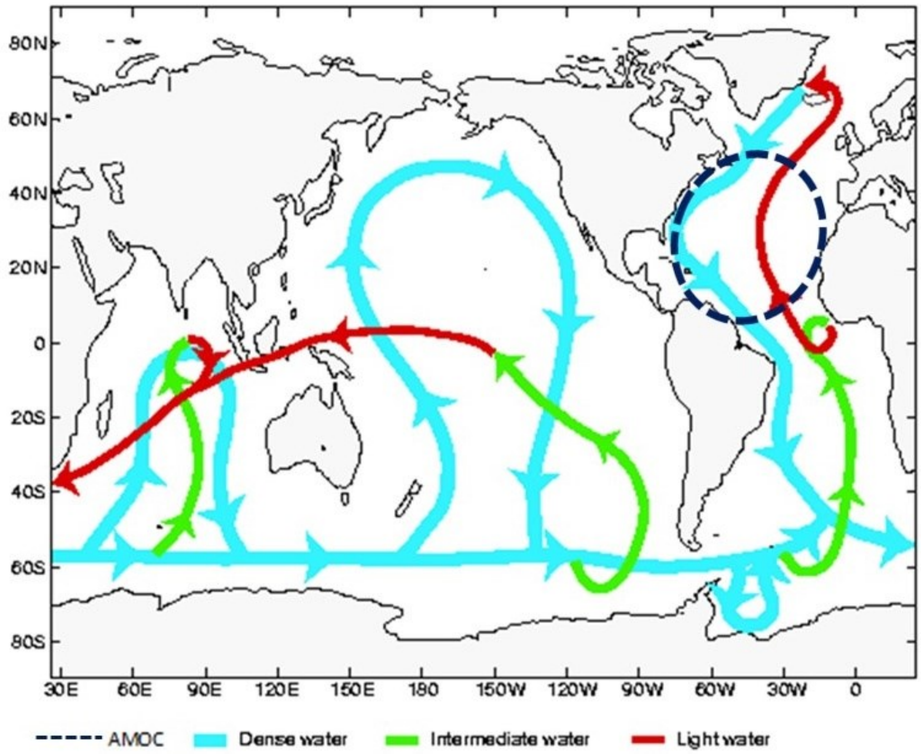


Figure 11: Atlantic Meridional Overturning Current (AMOC)
(Source: Adapted from NOAA)

shifted and slowed in the last decade due to changes in the ocean's temperature and salinity (Sallenger, Doran, and Howd 2012).

The combination of all these factors - post-glacial rebound, aquifer compaction, sediment deposition, the Chesapeake Bay Impact Crater, and the Atlantic Meridional Overturning Current, results in a rate of Local Sea Level Rise in Norfolk that is more than twice the global average. Thus, it is fitting, that Naval Station Norfolk should lead the way in preparing for and adapting to future sea level rise.

U.S. Government Responses to Sea Level Rise

The U.S. Government has not turned a blind eye to the problem of sea level rise. The Environmental Protection Agency (EPA) was one of the first government agencies to openly discuss sea level rise issues before climate change was a popular topic (Titus 1995). The Federal Emergency Management Agency (FEMA) hired a consulting firm to study the pertinence of including sea level rise in National Flood Insurance Program (NFIP) calculations (Batten et al. 2008). It was concluded that sea level rise was not significant enough at that time to be accounted for in NFIP products. The National Research Council panel studied how to best pool the nation's resources of climate scientists to obtain accurate projections of sea level rise (National Research Council 2010).

In 2009, the U.S. Army Corps of Engineers (USACE) introduced a policy requiring the consideration of future sea level rise for all civil works projects near the coast and has since revised this in 2011 and 2014 (U.S. Army Corps of Engineers 2009, 2011, 2014). The USACE was the first U.S. government agency to require concrete action in response to sea level rise, rather than just studying the problem. However, the USACE's policy to consider sea level rise only relates to new construction projects. It does not include a strategy for retrofitting existing assets which are threatened by sea level rise.

Even more pertinent to the study of U.S. Naval installations is the Oceanographer of the Navy's creation of Task Force Climate Change (TFCC) which published a Climate Change Roadmap, directly analyzing the effects of climate change on the U.S. Navy's assets and capabilities (Titley 2010). Chuck Hagel, the Secretary of Defense, issued a bold statement in the 2014 Climate Change Adaptation Roadmap, when he stated that the U.S. armed forces must prepare to adapt to the threat of sea level rise, as it threatens our coastal installations and ultimately, our national security (Department of Defense 2014). A Department of Defense Strategic Environmental Research and Development Program (SERDP) funded study of NS Norfolk, quantified the risk of flooding for the base (Burks-Copes et al. 2014). However, the Department of Defense has not yet mandated action in response to the threat of sea level rise.

The Economic Effect of Sea Level Rise

The costs of flood damage to homes and businesses have been well-documented over time, but these costs as they relate to sea level rise are not as well-developed due to the uncertainty involved. Created with flood insurance claim data, cost estimates of flood damage are publicly available in the form of FEMA's HAZUS program and the U.S. Army Corps of Engineers Depth Damage Curves (DDC). HAZUS and DDC provide generic flood damage estimates based on the height of floodwater inside a structure. The estimates are in the form of percentages of damage relative to the structure's replacement value. However, the cost of the rising seas is not accounted for in these estimates.

A study by Towson University Economics Professor Jeffrey Michael took a unique perspective and analyzed several different Chesapeake Bay coastal neighborhoods, incorporating the estimated result of sea level rise to discover the rising cost of periodic flooding to these areas (Michael 2007). With the added complication of sea level rise causing multiple flood events over a period of many years, the analysis was much different from the typical "fully-inundated with flood waters and total loss" scenario often simulated by FEMA. It was shown that the cost of many small floods over time due to sea level rise actually led to a greater expense than just one large flood event.

The NOAA Coastal Services Center funded research to answer the question "What Will Adaptation Cost?" This report provided an economic perspective assessing the costs associated with protecting a portfolio of assets in coastal regions (NOAA 2013). The research summarized a variety of case studies, in the United States and globally, which sought to answer the question which was the subject of the report. The wide range of economic factors used to estimate flood damage and SLR effects in these case studies was informative. It illustrated the value of what different stakeholders place importance on. While some organizations quantify the effects of SLR and flooding based on jobs and businesses lost or displaced, others look at the economic effects due to flood damage on structures (McFarlane 2013). Some studies look at metropolitan areas, while others study beachfront property and the loss of recreational beaches. The environmental effects, such as the salination of groundwater and the loss of farmland, can also be used as the source for economic valuation.

While these studies analyzed the potential economic impact of sea level rise, they only began to touch on the idea of the economics of adaptation strategies. These studies did not provide an extensive framework needed to help planners make adaptation decisions under a constrained budget. A tool which delivers economic information about which assets to protect, and how and when to protect them is necessary for adaptation planning.

Risk and Uncertainty Related to Climate Modeling

There are many methodologies for climate modeling, most involving a large degree of risk and uncertainty. The insurance industry leads government agencies in flooding and hurricane risk studies with several published climate change documents (Allianz Group 2006). The risk management community has become increasingly more interested in climate studies in the last decade due to the large degree of uncertainty involved (Lorenzoni, Pidgeon, and O'Connor 2005). A minor improvement in the projections of climate change and sea level rise could potentially save billions of dollars in damage costs and save many lives. Despite extensive computer models and advanced climate science, there are still many unknowns (Annan and Hargreaves 2007; Stamey, Wang, and Koterba 2007).

Due to the large degree of uncertainty involved with sea level rise projections, most institutions choose to use scenarios to model future sea level rise trends. The scenarios allow for the analysis of a variety of options, since there is no single solution to this problem and much uncertainty. The most widely referenced GSLR scenarios are those of the Intergovernmental Panel on Climate Change (IPCC) and the National Research Council. The 2013 IPCC report uses four different scenarios called Representative Concentration Pathways (RCPs). These RCPs take into account the severity of future greenhouse gas concentrations on global temperature (IPCC 2013). These RCP scenarios are then used to predict future sea level rise caused by corresponding increases in global temperature. The four RCP scenarios in the IPCC's 2013 report project a range of GSLR between 0.26 meters to 0.98 meters by the year 2100.

The National Research Council's report presents three GSLR scenarios, predicting 0.5 meters, 1 meters, or 1.5 meters of total rise by 2100 (National Research Council 1987). A wide range of Global Sea Level Rise projections will be presented in Chapter 4. Included in this discussion will be a method for quantifying the uncertainty in these projections.

Chapter 3: Adaptation Measures

Flooding is the most common natural hazard experienced in the United States. It is also one of the most costly to recover from. In most instances, flooding is one of the easiest natural hazards to predict, providing time for people to respond by preparing facilities to withstand flooding and evacuating. With the threat of Global Sea Level Rise, time is on the side of the proper planner. Enough time is available now to assess the growing threat of future flooding, anticipate, and take action to reduce the severity and impact of flood events.

New construction can be designed and built with flood damage prevention in mind. By taking into account global sea level change and raising the elevation of the finished first floor to a height above future flood projections, new buildings can be floodproofed when built. Existing infrastructure is more difficult to adapt; however, a variety of preventive measures exist for retrofitting structures to withstand and recover from flood events. The options for protecting existing structures from flooding can be divided into the following categories: wet floodproofing, dry floodproofing, barrier systems, elevation, relocation, and demolition (FEMA 2014). An explanation of the specific adaptation measures within each category, as well as the relative costs of each follows.

Wet Floodproofing

The lowest cost option for retrofitting an existing structure to withstand flood damage is wet floodproofing. In this alternative, the crawlspace, basement, or attached garage of a building is adapted to allow water to flow into it, flooding the structure as the water rises (Figure 12). An advantage of this option is that the building does not sustain extensive structural damage since the hydrostatic pressure of the water pushing on the building's exterior walls is equalized by the water pressure inside the building. This method also prevents a house from becoming buoyant and floating off its foundation.

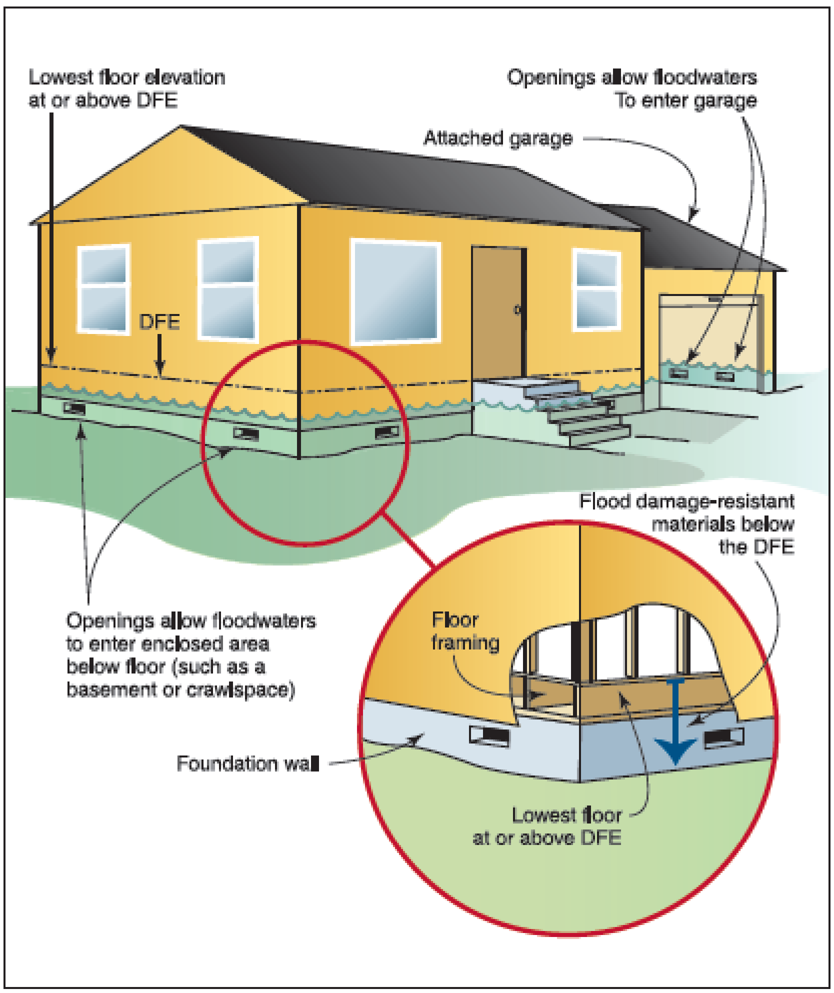


Figure 12: Example of wet floodproofing an existing structure
(Source: FEMA)

However, wet floodproofing is not well suited for every type of building. The structure must have a crawlspace or basement with the ability to allow floodwater to enter and exit freely without the use of pumps. A walkout basement, crawlspace, or attached garage below the area's Design Flood Elevation (DFE), are preferred areas for wet floodproofing. Often service equipment, such as hot water heaters, heating ventilation and air conditioning (HVAC), utility lines, and ductwork are found in these spaces. Any service equipment in the wet floodproofed area would need to be relocated to a higher elevation or protected by waterproof barriers or other anti-flooding measures.

The area which is to be wet floodproofed must be constructed of flood-damage resistant materials. Examples of flood damage resistant materials are: concrete, brick, concrete block, cement board, ceramic tile, decay-resistant lumber, and pressure-treated plywood. These materials can be flooded for an extended period of time, sustaining minimal or no damage, and are easy to clean during recovery from a flood event. Materials which are not resistant to flood-damage and are therefore unacceptable in the wet floodproofed area include engineered wood, laminate flooring, oriented-strand board (OSB), carpeting, wood flooring, paper-faced drywall, wood doors, particleboard doors, and wallpaper (FEMA 2014).

The wet floodproofing option is not the best choice for every type of structure or circumstance. Other preventive measures may make more sense given the type of flooding experienced in the building's area. For example, wet floodproofing is not advantageous in a beachfront location which is susceptible to the excessive wind, wave forces, and floating debris which accompany hurricanes. It is also not recommended in an area which is subject to flash flooding or fast velocity floods (>3 fps) (U.S. Army Corps of Engineers 2015b).

Dry Floodproofing

The next least expensive preventive flood measure is dry floodproofing. This option is the opposite of wet floodproofing. The building is sealed to prevent water from entering it, whereas wet floodproofing allows water to flow into and out of the building. The only type of construction that can be used in dry floodproofing is masonry. The building cannot have a basement either. Dry floodproofing is only to be used for retrofitting structures which are on a concrete slab or have a crawlspace. Similar to wet floodproofing, it is not recommended in a beachfront area which is subject to excessive wind and wave forces due to hurricanes. It is also not recommended in an area which is subject to flash flooding, moderate, or fast velocity flooding (greater than 3 fps) (U.S. Army Corps of Engineers 2015b).

As previously discussed, wet floodproofing allows for an equalization in hydrostatic pressure between the exterior walls and the inside of the building. Dry floodproofing causes excess pressure to build up on the exterior of the building during a flood, which can cause structural damage if the pressure is too great. The hydrostatic pressure can even build up underneath the slab of the building and cause it to become buoyant and float off its foundation. Buildings with basements will have greater forces exerted on them in a flood event due to the pressure of the saturated soil (Figure 13). This is why a building with a basement is not recommended for dry floodproofing. The maximum height for dry floodproofing is 3 feet above the lowest adjacent grade to reduce the amount of hydrostatic pressure on the structure (FEMA 2014).

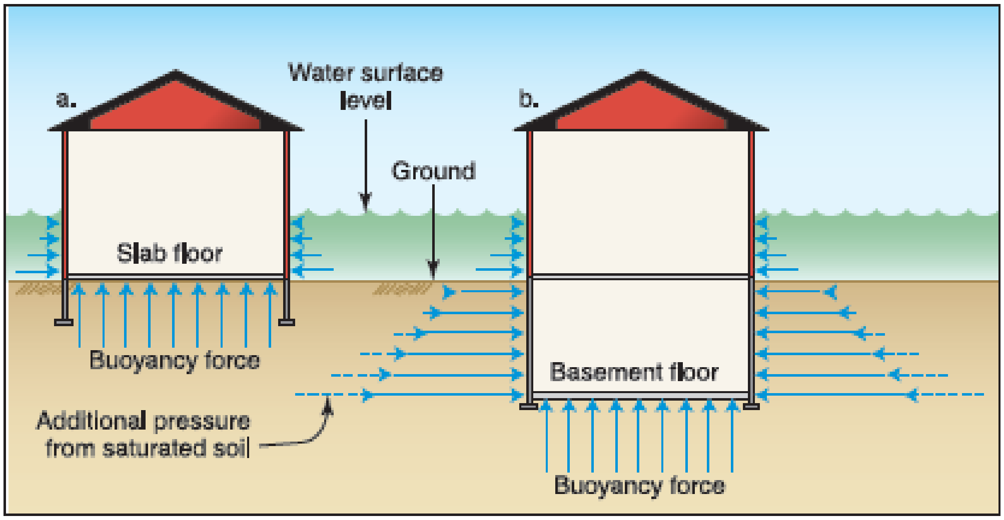


Figure 13: Example of hydrostatic pressure exerted on a dry floodproofed building
(Source: FEMA)

There are different methods for dry floodproofing a building. One approach for waterproofing masonry is to apply a sealant to the exterior or interior walls of the building. The types of sealants available are asphalt spray-on membrane, cement-based spread-on coating, or a clear coating of epoxy or polyurethane. The cement and asphalt sealants are not aesthetically pleasing, but are the best at keeping water out. A masonry veneer can be installed over these sealants for a more attractive, finished look.

A temporary method which can be used as a flooding preventative is to wrap the lower few feet of the home in a polyethylene sheet. This "wrapped home" technique is not the most durable and is only recommended for short term floods, less than 12 hours, and no more than a 1 foot flood next to the home. The polyethylene film must be securely fixed to the house at the top and bottom to be effective. In addition to the sheet wrapped around the house, a temporary drainage system must be installed underneath the sheet to drain any water which leaks through (FEMA 2014).

Once the exterior of the building has been waterproofed with a sealant, the doorways and windows need to be floodproofed. Temporary shields need to be designed and installed to cover each door and window to protect against water entry. The shields are typically made of metal with gaskets where they contact the building to provide for an adequate seal against water intrusion. These gaskets are a common failure mode of the shields and need to be maintained. The temporary shields come in many different varieties due to the types of entrances and windows they must protect (Figure 14). If the shields are especially large, such as those used to protect vehicle entrances, they can be installed

Figure 14: Types of temporary flood shields
(Source: FEMA)

permanently on hinges or rollers, for ease of installation. Automatic or passive flood shields are advantageous in that they require minimal or no human interaction for their deployment (FEMA 2013).

Dry floodproofing is more complex than wet floodproofing because it requires an additional internal drainage system to remove water that has leaked in. This water may trickle in through gaps in the sealant or faulty gaskets on door and window shields. The drainage system requires perforated pipes around the base of the foundation which drain to a low point with a sump pump for pushing the water out. The sump pump must be of large enough capacity to keep up with the demand. It is also recommended that the sump pump have the ability to be run by a backup power source in case the electricity is out (FEMA 2014). Any utilities located outside the dry floodproofed area, such as HVAC units, are recommended to be protected by relocating them or raising them.

Barrier Systems

A barrier system follows the same approach as dry floodproofing, which is to keep water out. It is similar to the temporary flood shields in that it can be either a temporary barrier installed in preparation for a predicted flood or one that is passive and always in service. Typical passive flood barrier systems include floodwalls and levees. Temporary flood barriers, which are less expensive than a permanent system, can consist of water-filled bags or sandbags. A large temporary barrier, such as the 500 meter-long Thames River Barrier, can be used to protect an entire region from flooding (Lowe et al. 2009).

The type of flood barrier varies depending on the building's use and the possible height and velocity of flood events common to that area. For example, a levee is not a good option in an area susceptible to high velocity flooding, which can erode the compacted earth and compromise the levee. A region with unstable soil or possible wave action, such as a beachfront, is also not feasible for a levee. A levee requires a large area around the building due to its width, and such property may not be available (Figure 15).

Figure 15: Levee protecting a building from flooding
(Source: FEMA)

Additionally, a levee or floodwall may limit accessibility. In Figure 15, the building is protected by a levee but it appears that the structure is inaccessible by motor vehicles. A flood barrier which permanently restricts vehicular traffic to a non-residential building may not be an option for many businesses.

Like levees, floodwalls are custom-designed by engineers to protect a building. However, floodwalls can integrate architectural details which help the wall seem like part of the building's design. Floodwalls are built of concrete, masonry, or a combination of both and are waterproofed with similar materials used for dry floodproofing. The walls often have openings to allow for pedestrian and vehicular access, which can be sealed with the temporary flood shields described in the previous section when a flood is impending (Figure 16).

Figure 16: Example of a floodwall and vehicular access flood shield in use
(Source: FEMA)

Floodwalls, often called ringwalls, have a need for a drainage system similar to that of dry floodproofing. However, in this case, the internal drains and sump pumps are located just inside the floodwall instead of inside the building. The internal drainage system protects the building from any seepage through the wall or flood shield gaskets. It is recommended to have a backup power source for the sump pump, in case of electrical outage. Similar to wet and dry floodproofing, utilities must be protected by either relocating to higher ground or placing them in a floodproof enclosure.

Temporary flood barriers are often the least expensive flood protection option available, depending on the size of the area and the topography needed to be protected. Sandbags are the most common, but require much manpower for deployment. Sandbags have a negative environmental impact since the sand will absorb contaminants (oil, gas, etc.) during a flood and must be disposed of as hazardous waste. Newer flood barriers, which are made of plastic and can be filled with water or gravel, are more environmentally friendly but require extensive preparation and advance warning before a flood (Figure 17).

Figure 17: Temporary flood barrier consisting of water-filled bags
(Source: FEMA)

Elevation, Relocation, or Demolition

The most expensive options available to protect structures from flooding are elevating, relocating, or demolishing and rebuilding an existing structure on higher ground. While these options are considered in the flood protection of a home, they are usually not cost-effective for non-residential properties. Non-residential buildings are typically too large for elevating. Relocating, or demolishing and rebuilding structures are also usually limited to smaller buildings due to the expense.

For elevating a structure, it is first detached from its foundation, then raised on hydraulic jacks above the base flood elevation. At the new design elevation, the house can be supported by either fill, masonry foundation walls, concrete columns, wood pilings, or concrete piers (Figure 18). The space under the building can be filled with items which can be moved quickly in case of an impending flood, such as cars, tractors, or bicycles.

Figure 18: Elevation of an existing structure onto masonry piers
(Source: FEMA)

Access to the raised first floor of the building is limited to ramps and stairs. Elevators which descend into the flood-prone area are typically not allowed.

Relocation, where a building is lifted off its foundation and moved to a new location, is another option for protecting a property from flooding. It is often too expensive for a large well-established property such as a school, hospital or military facility to be relocated. It could be an option for a smaller building within one of these compounds. Historic buildings that are solidly constructed and worth the extra expense of preserving are good candidates for relocation (Figure 19).

Figure 19: Relocating a building with lifting beams and wheels
(Source: FEMA)

Demolition and rebuilding is the most extreme option considered for protecting an existing building against flooding. If a building is often susceptible to floods or is already damaged, however, this can be the most prudent alternative. Investing in a new building outside of the floodplain can avoid any future flooding damage entirely.

Summary of Adaptation Options

The alternatives available for retrofitting existing buildings are numerous. The selection of which floodproofing measure to use is case-dependent. Many factors must be considered in the selection of which adaptation measure is best for a structure (Figure 20). These factors include: cost of floodproofing, building's foundation, building's framing

Construction Type	Existing Foundation	Measure	Retrofit	Relative Cost
Frame, Masonry Veneer, or Masonry	Crawlspace or Basement	Wet Floodproofing	Wet floodproof crawlspace to a height of 4 feet above lowest adjacent grade or wet floodproof unfinished basement to a height of 8 feet above basement floor	Lowest
Masonry Veneer or Masonry	Slab-on-Grade or Crawlspace	Dry Floodproofing	Dry floodproof to a maximum height of 3 feet above lowest adjacent grade	
Frame, Masonry Veneer, or Masonry	Basement, Crawlspace, or Open Foundation	Barrier Systems	Levee constructed to 6 feet above grade or floodwall constructed to 4 feet above grade	
Frame, Masonry Veneer, or Masonry	Basement, Crawlspace, or Open Foundation	Elevation	Elevate on continuous foundation walls or open foundation	
Frame, Masonry Veneer, or Masonry	Basement, Crawlspace, or Open Foundation	Relocation	Elevate on continuous foundation walls or open foundation	
Frame, Masonry Veneer, or Masonry	Slab-on-Grade	Elevation	Elevate on continuous foundation walls or open foundation	
Frame, Masonry Veneer, or Masonry	Slab-on-Grade	Relocation	Elevate on continuous foundation walls or open foundation	Highest
Frame, Masonry Veneer, or Masonry	Slab-on-Grade, Crawlspace, Basement, or Open Foundation	Demolition	Demolish existing building and buy or build a home elsewhere	Varies

Figure 20: Summary of flood adaptation measures and relative costs
(Source: FEMA 2014)

type, contents of the structure, type of flooding, velocity of flooding, depth of flooding, type of soil, and the structure's location. The costs of these floodproofing options vary widely, and are summarized in Figure 20.

The height of the floodproofing is another option which can greatly affect the cost. If the structure only needs to be protected against 0.3 meter (1 ft) of flooding, then the cost is significantly less than if the structure's floodproofing is desired above 1 meter (3.3 ft). For example, sandbags may be the most economical floodproofing option for the 0.3 meter flooding scenario, but not for the 1 meter flood. A location with frequent flooding might forgo the temporary solution of sandbags in favor of removable flood shields over the building's entrances.

Ultimately, the purpose of this study is to provide a tool that helps with the decision, from an economic standpoint, of which preventive measures to employ and when to employ them. The following chapters will detail the methods used to attain this conclusion.

Chapter 4: Aggregation of Global Sea Level Rise Projections

One of the issues regarding Global Sea Level Rise (GSLR) is the variability in projections of how much the sea level will eventually change. The most widely accepted time frame for projecting sea level rise is the year 2100 baseline. Instead of predicting the amount of sea level rise per year, decade, or century, it has become common for scientists to estimate what the level of the sea will be in a future year. Unlike forecasting daily weather or annual flood risk, where the risk of precipitation or flooding is quantified by a probability of occurrence or annual exceedance probability, scientists estimating sea level rise do not define it in stochastic terms. Instead, sea level rise is defined in terms of scenarios based upon the dynamics which influence the rate of rise. These factors which determine the rate of sea level rise include: glacial and ice sheet melt, thermal expansion of the oceans, glacial rebound, groundwater extraction, and sediment deposition. Each of these dynamics have unrelated driving factors, such as the amount of greenhouse gases in the atmosphere affecting the rate of ice sheet melt or the extensive population growth in coastal regions affecting the amount of subsidence caused by groundwater extraction.

Estimates of Global Sea Level Rise are made by incorporating a wide range of climate process models, each of which has epistemic uncertainty since historic data is often used to develop the model. Depending on the methodology of the climate model and the datasets chosen for the sea level rise projection, aleatory uncertainty may also be incorporated. This combination of epistemic and aleatory uncertainty is evident in most GSLR projections which have been published in peer-reviewed journals over the last three decades. Semi-empirical models are also used to predict the rate of sea level change as it directly relates to a chosen parameter, such as increased global temperatures. This type of

GSLR projection model is not preferred by the IPCC due to its aleatory nature of only choosing one parameter, in contrast to process-based models which compare a variety of inputs (IPCC 2013). As process-based models become more reliable, especially in estimating glacier and ice sheet loss, the uncertainty of GSLR projections can be reduced in the future.

According to analysis of 1277 worldwide tidal gauge records, annual GSLR occurred at a rate of 1.9 ± 0.3 mm/year from 1900 to 1999 (Jevrejeva et al. 2014). Continuing this same rate for an additional 101 years would predict a total rise of 0.19 meters between 1999 and 2100. In the same study, tidal gauge records were compared with data collected by the NASA Poseidon/TOPEX and both exhibited an increasing trend of GSLR from 1993 to 2009, with a rate of 3.2 ± 0.4 mm/year (CCAR 2013). Based on this GSLR trend, the worldwide sea level assuming no acceleration would be predicted to rise 0.29 meters between 2009 and 2100.

The same report calculated an acceleration of Global Sea Level Rise at a rate of 0.02 ± 0.01 mm/yr^2 by analyzing tidal gauge records from 1807 to 2009 (Jevrejeva et al. 2014). Combining the more recent GSLR trend of 3.2 ± 0.4 mm/year with the acceleration rate of 0.02 ± 0.01 mm/yr^2 over 91 years yields a rise of 0.374 meters by the year 2100.

The equations used to calculate this change in global sea level are adapted from the basic kinematic physics formulas regarding position, velocity, acceleration and time:

$$x_f = x_0 + v_0 \Delta t + \frac{1}{2} a \Delta t^2 \quad (1)$$

in which x_f is the final position, x_0 is the initial position, v_0 is the initial velocity, Δt is the time elapsed between the initial and final positions, and a is the constant acceleration.

$$GSL_{2100} = GSL_{2009} + v_{2009}(2100 - 2009) + \frac{1}{2}a_{2009}(2100 - 2009)^2 \quad (2)$$

$$GSL_{2100} = GSL_{2009} + 3.2\,\frac{mm}{yr} \cdot (91) + \frac{1}{2} \cdot 0.02\,\frac{mm}{yr^2} \cdot (91)^2 \quad (3)$$

$$GSL_{2100} - GSL_{2009} = \Delta_{GSL_{2100-2009}} = 0.374\ meters \quad (4)$$

in which GSL_{2100} is the mean global sea level in the year 2100, GSL_{2009} is the mean global sea level in the year 2009, v_{2009} is the rate of sea level rise in 2009, and a_{2009} is the constant acceleration of sea level rise over the selected time period.

The U.S. Army Corps of Engineers uses a similar method of extrapolating sea level trends combined with various GSLR scenarios from a 1987 National Research Council study. The USACE method will be discussed in detail in Chapter 5.

The estimates of future GSLR based on current sea level trends constitute the most conservative of published projections. More often, projections of GSLR are based on process-based models of future events, such as the degree of warming of the world's oceans or the amount of glacial ice melt. These future events may or may not occur within the time frame and the severity predicted, and may have a more significant impact on future GSLR rates.

To account for the uncertainty related to future global sea level rise rates, many estimates of GSLR are presented in a multiple-scenario format. For example, the aforementioned National Research Council report used by the USACE for GSLR estimates, uses three GSLR scenarios, predicting 0.5 meters, 1 meters, or 1.5 meters of total rise by the year 2100 (National Research Council 1987). The 2013 Intergovernmental

Panel on Climate Change report presents four different scenarios called Representative Concentration Pathways (RCPs). The RCP scenarios use coupled ocean-atmospheric models which take into account the severity of future greenhouse gas concentrations and their effects on ocean thermal expansion and glacier/ice sheet melting (IPCC 2013). These process-based models are then used to project the range of future Global Sea Level Rise.

Despite the uncertainty of how much GSLR will occur in the future, climatologists, geologists, oceanographers, historians and other researchers are historically unwilling to assign probability to estimated projections of sea level rise. Multiple papers published every year for the last two decades predict GSLR scenarios and best guess estimates of the amount of sea level rise by the year 2100. These estimates are often presented in peer-reviewed journals, scientific committees, and the mainstream media and are constantly updated as more scientific evidence presents itself. The diversity and quantity of sea level rise estimates is overwhelming, and it changes almost daily. Even though there are a large number of published GSLR estimates, there is no way to validate which is the most accurate since they refer to events that are decades in the future. This study proposes a method for consolidating these GSLR estimates which can be updated as more accurate projections become available in the future.

Variety of Expert Data

The most comprehensive studies published about climate change within the past two decades have been conducted by large committees consisting of scientists, engineers, public policy experts, economists, and city planners. These committees are most often funded by governments, insurance companies or other private entities with a stake in understanding changes to the coastal landscape. It is important to note that the political opinions and economic interests of the stakeholders have the ability to influence the climate change studies' results (Morano 2013). Viewing these published reports provides insight into the particular climate change drivers on which these expert panels decide to place importance.

The differences in the GSLR estimates from the 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment and the 2013 IPCC Fifth Assessment illustrate how much the inclusion or exclusion of one type of modeling can affect the projection. The Intergovernmental Panel on Climate Change Fourth Assessment estimated that GSLR in 2100 would fall between 0.2 m and 0.6 m (IPCC 2007). This estimate is among the lowest in the last decade, because the committee chose not to include any contributions from Antarctic and Greenland ice sheet melt due to a high degree of uncertainty in the glacial and ice sheet mass loss modeling at the time. However, the most recent Intergovernmental Panel on Climate Change Fifth Assessment with different experts on the committee, considered the effects of glacial and ice sheet melt to be substantial, accounting for 65% of GSLR from 1901-1990 and 90% of GSLR from 1971 – 2010 (IPCC 2013). Including glacial and ice sheet melt contributions, the panel's revised estimates of GSLR by 2100 were between 0.26 m (0.85 ft) and 0.98 m (3.2 ft). This committee's projection is still lower than other published estimates, some of which predict GSLR as high as 2.5 m (8.2 ft) by 2100 (Rohling et al. 2009). Difficulties arise when aggregating expert opinions since the variety of diverse committees choose to include and exclude differing source data for their projections. This study attempts to aggregate expert opinions using an unbiased method.

Who Are These Experts?

Sea level rise research does not originate from only one body of science or affect only one geographic region as other forms of research may. Published research concerning climate change and specifically sea level rise is conducted by oceanographers, climatologists, physicists, geologists and engineers representing a variety of nationalities. For example, Dr. Svetlana Jevrejeva, an Estonian-born oceanographer employed by the National Oceanography Centre in Liverpool, UK, was a lead author of the 2013 IPCC chapter on Sea Level Change. Dr. John Church is an oceanographer with Australia's Commonwealth Science and Industrial Research Organizations (CSIRO) Marine and Atmospheric Research Center. He was one of the coordinating co-lead authors for the chapters on Changes in Sea Level in the IPCC Third and Fifth Assessment Reports. Similarly, Dr. Stefan Rahmstorf, an oceanographer who teaches at Potsdam University, serves on the German Advisory Council on Global Change. The lead author of the 2007 IPCC Fourth Assessment Report coastal systems chapter, Dr. Robert Nicholls, is a professor of Coastal Engineering at the University of Southampton in the UK. Two often cited researchers, Dr. Aslak Grinsted and Dr. John Moore, are both climatologists studying glaciers and ice sheets for the Center for Ice and Climate in Copenhagen. In the United States, Dr. Radley Horton is an earth scientist at the Center for Climate Systems Research at Columbia University, and Carling Hay is a post-doctoral fellow at Harvard's Department of Earth and Planetary Sciences. Sea level rise is a global multi-disciplinary problem.

Combining Expert Opinions

Previous research on combining expert opinions has been conducted extensively in the fields of risk analysis, economics, insurance, psychology, engineering, and the sciences. This type of analysis is not innovative, but GSLR estimates are distinguished from others as lacking accurate sample data. This complicates using the same methods that other researchers have employed in the past. One approach calibrates individual expert data by comparing forecasts with actual results (Morris 1983). For example, did it rain 70% of the time when the meteorologist predicted a 70% chance of rain? Unfortunately, sea level rise future projections are close to one hundred years away from validation of the projection compared to actual results.

Another approach, which is inclusive of a variety of projections, is to combine the projections of multiple experts. While this method does increase the sample size of the data surveyed, it can be viewed as subjective depending on which experts' data are included and whose are excluded in the analysis (Clemen and Winkler 1999). In their study of aggregating risk analysis projections, Clemen and Winkler use several methods to combine expert opinions, including axiomatic, Bayesian, behavioral, and empirical evidence.

Sources of Expert Data

The number of GSLR studies published since the 1980's is large. For the year 2014 alone, Google Scholar reports 37,700 scholarly references to the search term "sea level rise." This raises several questions when trying to decide which projections to further examine. Are all estimates equally credible? How does one choose which projection is better than others? Sea level rise has also become a common topic in the mainstream media, with articles regularly appearing in newspapers, magazines and television news programs. This study includes only academic writings from scholarly conference presentations and peer-reviewed journals.

The GSLR estimates compiled in this study were not chosen at random. When deciding which projections to choose for this study's compilation, it seemed prudent to reference reports which were cited most often by other reliable sources. Since the case study in this thesis is focused on U.S. government assets, GSLR projections referenced in several recent U.S. government funded studies were considered. The four main U.S. government funded reports on GSLR from 2011 to 2014 are: (1) USACE 2011 Sea Level Change Considerations for Civil Works Programs Circular, (2) 2012 NOAA Digital Coast SLR Webinar, (3) 2012 Global Sea Level Rise Scenarios for the U.S. National Climate Assessment, and (4) 2014 SERDP Project RC-1701 Report. The GSLR estimates chosen for inclusion and summarized in Table 1 are those which are cited in the reports listed above. The one exception to this dataset is the 2013 IPCC Fifth Assessment Report. It was published after the U.S government reports previously listed. Since the 2001 and 2007 IPCC reports were cited, it is likely that the 2013 IPCC report would also have been selected had it been available.

Table 1: Global Sea Level Rise projections from a variety of sources

Author (Listed in order of publication)	Year 2100 GSLR Estimate Min (m)	Year 2100 GSLR Estimate Max (m)	2011 USACE Sea Level Change Circular	2012 NOAA Digital Coast SLR Webinar	2012 GSLR Scenarios for US NCA	2014 SERDP Project RC-1701 Report
National Research Council 1987	0.5	1.5	X		X	
IPCC 2001	0.11	0.77	X	X	X	X
Jevrejeva et al 2006	0.24	0.5				X
IPCC 2007	0.18	0.59	X	X	X	X
Rahmstorf 2007	0.5	1.4	X	X	X	X
Grinsted 2008	0.9	1.3		X		X
Horton et al 2008	0.5	0.9	X	X	X	X
Pfeffer et al 2008	0.8	2	X	X	X	X
Rohling et al 2008	0.8	2.5		X	X	
Bahr et al 2009	0.2	0.4		X		
DeltaCommissiee 2009	0.6	1.1		X		
Grinsted et al 2009	0.8	2		X	X	
Kopp et al 2009	0.6	0.9		X	X	
Siddall et al 2009	0.07	0.82				X
UKCP09 2009	0.1	1.9		X		
Vermeer & Rahmstorf 2009	0.75	1.9	X	X	X	X
Hunter 2010	0.2	0.6		X		
Jevrejeva et al 2010	0.6	1.6	X	X	X	X
Moore et al 2010	1.0	2.0				X
Nicholls et al 2011	0.5	2		X	X	
Rahmstorf et al 2012	0.8	1.2		X	X	
IPCC 2013	0.26	0.98				

(Authors in italics were cited by only one source and are not included in the aggregated expert prediction.)

Of the twenty-two GSLR projections in Table 1, some may be more credible than others. To ensure that only the most trusted values are included, the projections were narrowed down to only those that were cited in at least two of the four major U.S. government funded studies. These 15 papers, noted in bold in Table 1, were considered trusted sources for the purposes of this research and were included in the compilation of expert data discussed in the following section. The dataset of fifteen trusted sources is presented graphically (Figure 21).

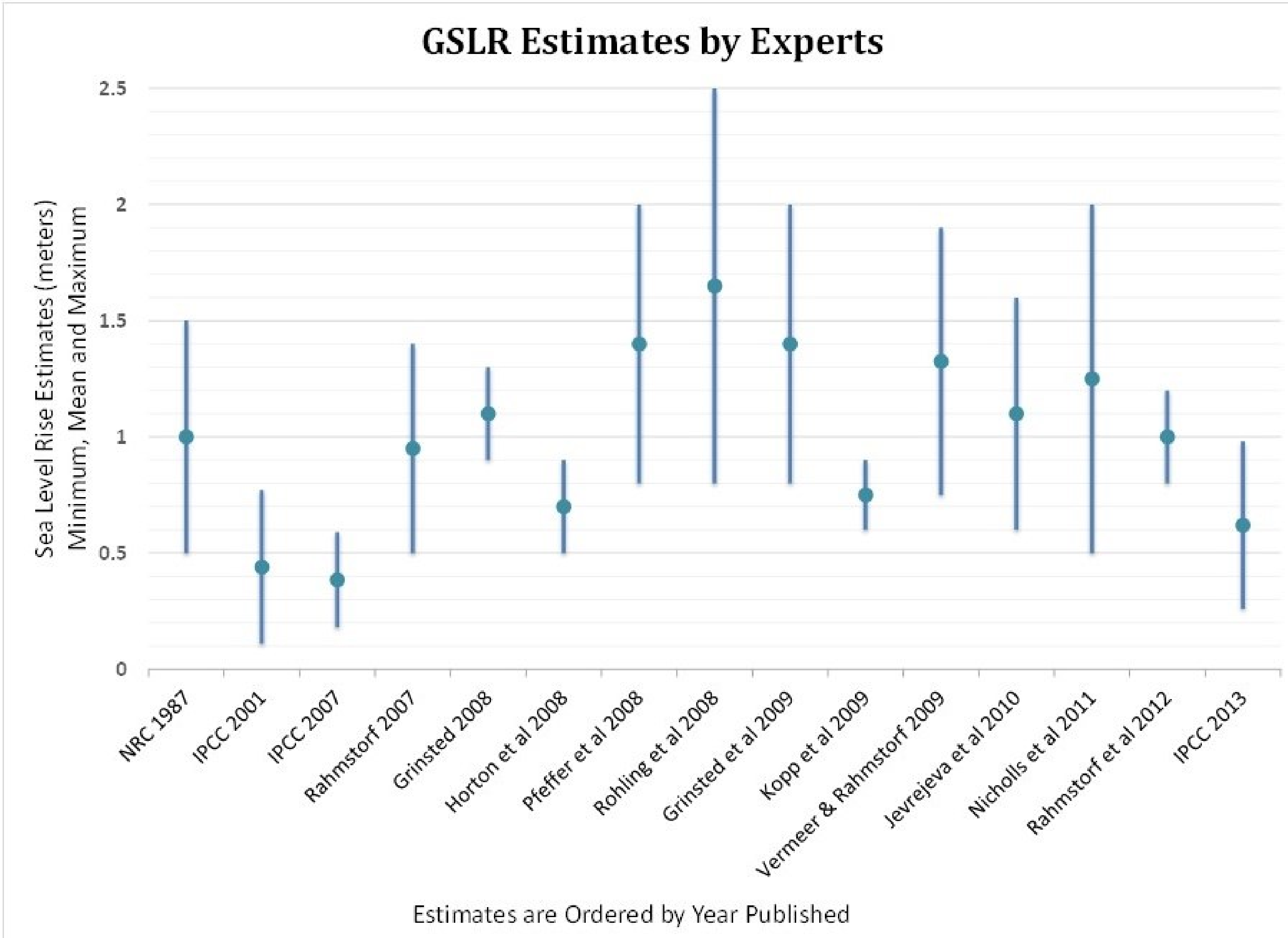


Figure 21: Illustration of GSLR estimates by experts- minimum, mean, and maximum by the year 2100
(Data from sources listed)

Method for Condensing Expert Data

The GSLR estimates from the chosen papers were condensed into one dataset containing the minimums and the maximums. Each GSLR estimate was then treated as a continuous probability distribution, with the mean halfway between the only two data points, the minimum and the maximum. These min, mean and max estimates were modeled as beta distributions, triangular distributions, uniform distributions, and normal distributions. For example, the first and earliest estimate listed in Table 1 is that from a 1987 National Research Council report. The panel predicted a minimum sea level rise of 0.5 m (1.6 ft) and a maximum rise of 1.5 m (4.9 ft) by 2100. The mean of this estimate, therefore, is 1.0 m (3.3 ft). Modeling this estimate as a beta, triangular, uniform, and normal distribution produces the distributions shown in Figure 22.

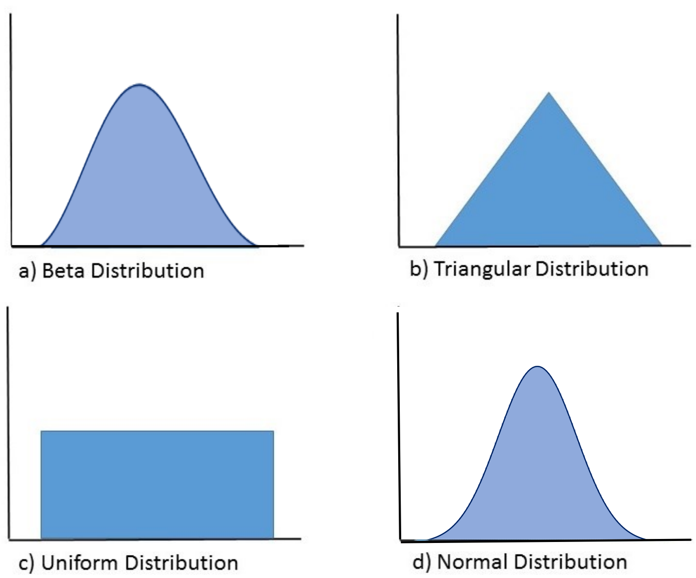


Figure 22: Modeling GSLR projections as various probability distributions

Each of the fifteen trusted source estimates was modeled as each of the four types of distributions shown in Figure 22. For each Global Sea Level Rise estimate, because the mean was assumed to be halfway between the maximum and minimum, the variance based on each type of distribution was calculated according to the following equations:

$$\sigma_{Beta}^2 = \left(\frac{Max - Min}{6}\right)^2 \tag{5}$$

$$\sigma_{Triangle}^2 = \frac{(Min^2 + Mode^2 + Max^2 - Min * Mode - Min \cdot Max - Mode * Max)}{18} \tag{6}$$

$$\sigma_{Normal}^2 = \left(\frac{Max - Mean}{2}\right)^2 = \left(\frac{Max - Min}{4}\right)^2 \tag{7}$$

$$\sigma_{Uniform}^2 = \frac{(Max - Min)^2}{12} \tag{8}$$

The last column in Table 2 is a variance randomly selected from the beta, triangle, normal and uniform variance for each GSLR estimate.

The Central Limit Theorem was then applied to each data set of fifteen distributions of the same type. The mean and variance for each distribution was calculated by summing the individual values of mean and variance and taking the average (Table 2). The standard deviation of each distribution type was then calculated by taking the square root of the average variance. Based on the Central Limit Theorem, a normal distribution, with the average mean and standard deviation, could then be modeled to account for the entire dataset.

The results of the Central Limit Theorem application exhibited consistency between datasets. Modeling each estimate as a uniform distribution, with both the minimum and maximum GSLR estimates having equal likelihood of occurrence, provided the highest value of standard deviation and thus, most conservative result, with a normal distribution of μ=1.00 m (3.30 ft) and σ= 0.277 m (0.910 ft). Additionally, by modeling each as a uniform distribution, the entropy is maximized.

However because the actual shape of the probability distribution is not known for many of the estimates, a more realistic result occurs when each estimate is randomly modeled as either a beta, triangular, uniform, or normal distribution, and then the Central Limit Theorem is applied to the results. The result of this random distribution analysis yields a normal distribution with μ=1.00 meters and σ=0.277 meters. Though the standard

Table 2: GSLR estimates represented as probability distribution functions

Min (m)	Max (m)	Mean (m)	Beta Variance	Triangle Variance	Normal Variance	Uniform Variance	Random Variance
0.5	1.5	1	0.0278	0.0417	0.0625	0.0833	0.0278
0.11	0.77	0.44	0.0121	0.0182	0.0272	0.0363	0.0182
0.18	0.59	0.39	0.0047	0.0070	0.0105	0.0140	0.0105
0.5	1.4	0.95	0.0225	0.0338	0.0506	0.0675	0.0675
0.9	1.3	1.1	0.0044	0.0067	0.0100	0.0133	0.0044
0.5	0.9	0.7	0.0044	0.0067	0.0100	0.0133	0.0067
0.8	2	1.4	0.0400	0.0600	0.0900	0.1200	0.0900
0.8	2.5	1.65	0.0803	0.1204	0.1806	0.2408	0.2408
0.8	2	1.4	0.0400	0.0600	0.0900	0.1200	0.0400
0.6	0.9	0.75	0.0025	0.0037	0.0056	0.0075	0.0037
0.75	1.9	1.33	0.0367	0.0551	0.0827	0.1102	0.0827
0.6	1.6	1.1	0.0278	0.0417	0.0625	0.0833	0.0833
0.5	2	1.25	0.0625	0.0938	0.1406	0.1875	0.0625
0.8	1.2	1	0.0044	0.0067	0.0100	0.0133	0.0067
0.26	0.98	0.62	0.0144	0.0216	0.0324	0.0432	0.0324
AVG (m)=>	**1.00**	**VARIANCE (m^2)=>**	0.0256	0.0385	0.0577	**0.0769**	0.0518
		STANDARD DEV (m)=>	0.160	0.196	0.240	**0.277**	0.228

(Data from sources in the same order as listed in Figure 21.)

deviation is slightly smaller, it is still within 25% of the highest, most conservative estimate for standard deviation.

A larger sample size, inclusive of all twenty-two GSLR estimates, shows similar behavior. The results of the Central Limit Theorem analysis of the larger dataset exhibit similar variances for each assumed distribution shape, but with a slightly smaller mean, μ=0.963 m (3.16 ft).

For the remainder of this paper, net Global Sea Level Rise by 2100 will be modeled as a normal distribution with μ=1.00 m (3.30 ft) and σ=0.277 m (0.910 ft). This standard deviation was chosen because it is the highest, and thus the most conservative, standard deviation of all the possible distribution shapes considered. This estimate of GSLR by 2100 is not an authoritative sea level projection due to the simplifying assumptions made when combining multiple expert opinions. This GSLR estimate is merely a synthesized end product for this study to use when forming the economic decision making model developed in future chapters.

The normal distribution is widely accepted throughout many academic disciplines as a consistent method for modeling the combination of multiple probability distributions. Other sea level rise studies have used a normal distribution to model GSLR estimates, due to the ease in combining the means and variances. The UK 2012 Climate Projections report, the 2013 IPCC report, and USACE emeritus coastal engineer Dr. James Houston all chose to use normal distributions for sea level rise projections (Houston 2013). Until a more accurate forecasting technique is presented in the body of sea level rise research, the normal distribution remains an acceptable method for combining multiple sea level rise projections.

Chapter 5: Predicting Future Increases in Local Mean Sea Level

The aggregation of expert data detailed in the previous section provides a probability distribution which can be used to predict future increases in global sea level. The result of the aggregation is for a predicted sea level rise by the year 2100. For this projection to be useful for economic comparisons in this case study, it would be best if the projection translated to a future water level in a given year. Predicting the future sea level requires having a starting point of the current sea level. Since the experts' projections of sea level rise out to year 2100 were not published in the same year, a starting year for this dataset was selected as the mean year in which all of the aggregated sea level rise projections were published. This mean starting year was 2008. As updated sea level rise projections are added over time, this start year can be easily updated within the decision analysis tool.

Past Projections in Local Sea Level Trends

Sea level rise and its effects on the U.S. coastline are not new concerns in 2015. This phenomenon has been studied by scientists for many decades. One of the earliest and most frequently cited academic reports on local sea level projections is the National Research Council's "Responding to Changes in Sea Level" (National Research Council 1987). This 28 year old report is still applicable, as predictive sea level rise equations originating in it are referenced in the most recent U.S. Army Corps of Engineers technical letter (U.S. Army Corps of Engineers 2014). These equations detail the combination of eustatic (Global) Sea Level Rise with Local Sea Level Rise.

The basic equations used by the 1987 National Research Council report are detailed below:

$$T(t) = E(t) + L\,(t) \quad (9)$$

where T (t) is the total relative sea level change above present levels at time t, E(t) is the eustatic sea level change at time t, and L is the local sea level change at time t (National Research Council 1987).

$$E(t) = (GSLR\ Rate) * t + \frac{1}{2}(GSLR\ Acceleration) * t^2 \quad (10)$$

$$E(t) = 0.0012t + bt^2 \quad (11)$$

where the value 0.0012 was the accepted Global Sea Level Rise rate of 0.0012 meters per year at the time the report was written, and b is a coefficient related to the future sea level rise acceleration rate in meters per year^2. For example, b is equal to 0.000028 m/yr^2 for the National Research Council's scenario of 0.5 meters of sea level rise by the year 2100. The panel's report presented three different scenarios of possible sea level rise to the year 2100: rises of 0.5 meters, 1.0 meters, and 1.5 meters.

Combining the eustatic (Global) Sea Level Rise estimate with the Local Sea Level Rise and the future predicted scenario of increased sea level rise yields:

$$T(t) = (GSLR\ Rate + LSLR\ Rate) * t + \frac{1}{2}(GSLR\ Acceleration) * t^2 \quad (12)$$

$$T(t) = (0.0012 + \frac{M}{1000})t + bt^2 \quad (13)$$

M is defined as the derivative of the local sea level (L) in millimeters over time t:

$$M = \frac{dL}{dt} \ (mm/year) \tag{14}$$

The U.S. Army Corps of Engineers has used a version of Equation (11) for the past decade when estimating global sea level change for building projects. However, they have updated the eustatic sea level rise estimate from 0.0012 m/yr to 0.0017 m/yr to reflect current water level data. The most recent USACE technical letter used this equation for estimating global sea level change over the course of a project:

$$E(t_2) - E(t_1) \ = 0.0017(t_2 - t_1) + b(t_2^2 - t_1^2) \tag{15}$$

where t_2 is the future year in which one wants a sea level rise estimate (typically related to the life of the project) and t_1 is the baseline year of 1992. USACE uses 1992 as their base year, since it is the median year of the NOAA 1983 – 2001 National Tidal Datum Epoch (NTDE). Tidal datums on the NOAA Tides and Currents website, such as Mean Lower Low Water (MLLW) and local MSL, are defined by data collected during the aforementioned NTDE period (U.S. Army Corps of Engineers 2014).

It is important to note that USACE still recognizes the equations originated in the 1987 National Research Council report as authoritative. Local sea level trends require a less generalized approach than that used in Equation (11), which is why Equations (12), (13) and (14) are set apart to use water level data specific for each locale. USACE recognizes the differences in sea level changes depending on the project's location, and incorporates an online "Sea Level Change Curve Calculator" (Figure 23) which provides for these differences. The results of the calculator incorporate three GSLR scenarios with LSLR trends at a specific locale to project future SLR to the year 2100.

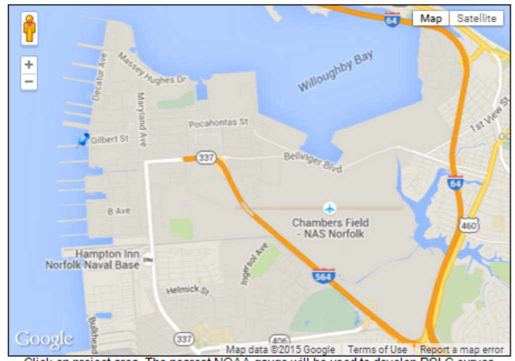
EC 1165-2-212, Equation 2: $E(t) = 0.0017t + bt^2$

This on-line Sea Level Change Calculator has several added features which are detailed in the User's Manual. The superseded calculator is available here... You can plot both the USACE and NOAA curves in feet or meters relative to either NAVD88 or LMSL. The West Coast NRC2012 projections are available when a west coast gauge is selected. The NPCC2013/2015 projections for New York City are also available when the NOAA gauge, "The Battery" is selected. This calculator also develops the SLC curves between the user entered dates using equation #3 in ER 1100-2-8162.

USACE Sea Level Change Curve Calculator (2015.46)

Item	Display
SLC Curve Chart	☑
SLC Curve Table	☑
Gauge Datum Chart	☑
Gauge Datum Table	☑
SLC Curves	☑
SLC Table	☑
NOAA EWL Chart	☑
Gauge Map	☑

Project Name: Enter Project Name
Select NOAA Gauge: Sewells Point, VA
FEMA BFE (meters): ? Information 0 (NAVD88) Search for BFE here
Project Start Year: 2015
Interval Year: 5
Project End Year: 2100
Output Units: ○ Feet ◉ Meters
Output Datum: ○ LMSL ◉ NAVD88
Output Agency: ◉ USACE ○ NOAA ○ Both
SLC Rate: ◉ Published ○ Regionally Corrected or User Entered: (m/yr)
Display Data
EWL Type: ◉ Highs ○ Lows
EWL Source: NOAA Website ◉ NOAA (GEV) ○ USACE (Percentile) 100 yr difference (m) = 0.15
Chart Size: Height 600 Width: 800 Display Data
Plot EWL/BFE/Tides: None Select Curve: USACE High
Critical Elevation #1 (meters): 0.0000 NAVD88 - Description:
Critical Elevation #2 (meters): 0.00 NAVD88 - Description:
User's Index (meters): ? 0.000 Description:
Datum Shift from NAVD88 to MSL: 0.08 meters



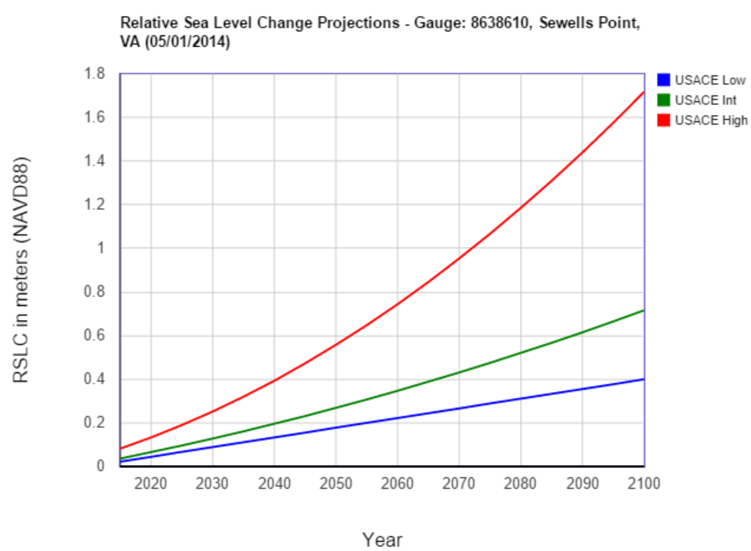
Click on project area. The nearest NOAA gauge will be used to develop RSLC curves based on ER 1100-2-8162, Incorporating Sea Level Change in Civil Works Programs, 31 Dec 2013 and NOAA Technical Report OAR CPO-1, Global Sea Level Rise Scenarios for the United States National Climate Assessment, Dec 2012
*** note - there may be factors other than proximity to consider when selecting a gauge ***
Compliant
Inactive
< 40yrs

8638610, Sewells Point, VA
NOAA's Published Rate: 0.00444 meters/yr
All values are expressed in meters relative to NAVD88

Year	USACE Low	USACE Int	USACE High
2015	0.02	0.04	0.08
2020	0.04	0.07	0.13
2025	0.07	0.10	0.19
2030	0.09	0.13	0.25
2035	0.11	0.16	0.32
2040	0.13	0.20	0.39
2045	0.16	0.23	0.47
2050	0.18	0.27	0.56
2055	0.20	0.31	0.65
2060	0.22	0.35	0.74
2065	0.24	0.39	0.85
2070	0.27	0.43	0.95
2075	0.29	0.48	1.07
2080	0.31	0.52	1.19
2085	0.33	0.57	1.31
2090	0.36	0.62	1.44
2095	0.38	0.67	1.58
2100	0.40	0.72	1.72

Print Table

8638610, Sewells Point, VA
NOAA's Published Rate: 0.00444 meters/yr



Print Curves

Figure 23: USACE sea level change curve calculator and projections
(Source: www.corpsclimate.us/ccaceslcurves.cfm)

Historic Local Sea Level Trend

Water level data is publicly available for hundreds of coastal locations in the United States at the National Oceanic and Atmospheric Administration (NOAA) Tides and Currents website. This data can be analyzed to obtain the Local Sea Level Rise trend and significant monthly flood events for a given location. For this study of Naval Station Norfolk, the Sewells Point, Virginia (NOAA #8638610) tidal gauge data was used. This water level station is located on the south end of Pier 6 at the naval station near the confluence of the James and Elizabeth Rivers as shown in Figure 24. The NOAA dataset which was used in this research included verified monthly mean water levels and monthly extreme events, both the highest and lowest, dating back to mid- July 1927. The dataset shows a few gaps and errors in the years of 1930, the period 1942-1943, 1945 and the period 1961-1969, but otherwise appears consistent.

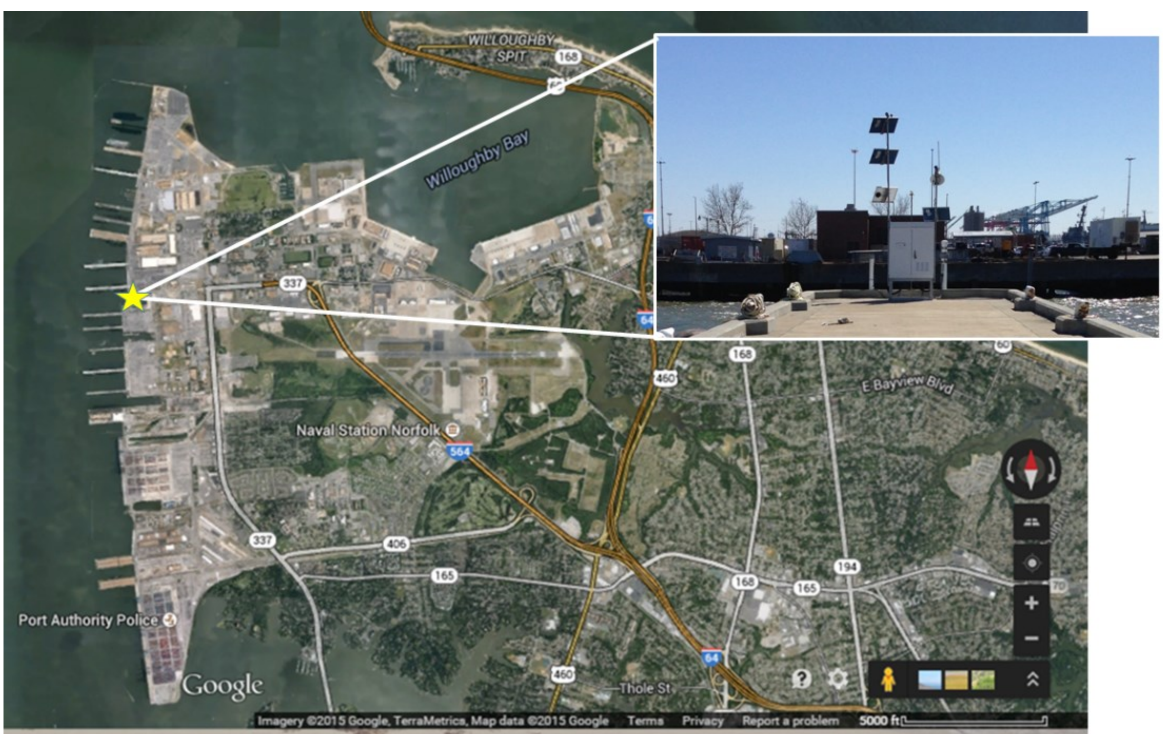


Figure 24: Location of Norfolk tidal gauge station
(Source: Google map, photo taken by author)

Assuming that the tidal gauge data is reliable and that the station has not been relocated over time, this data can be graphed to show a historic Local Sea Level Rise (LSLR) trend at Naval Station Norfolk. The LSLR trend includes Global Sea Level Rise and vertical land motion, such as subsidence due to glacial isostatic adjustment and aquifer compaction. Since the tidal gauge station is affixed to ground which may have changed in height over the period of data gathering, the interaction between the land height and the water level height varies spatially and temporally and is best graphed over time.

The raw data of monthly mean water level from January 1928 through December 2014 was graphed with a best fit line (Figure 25). The monthly mean water level is defined

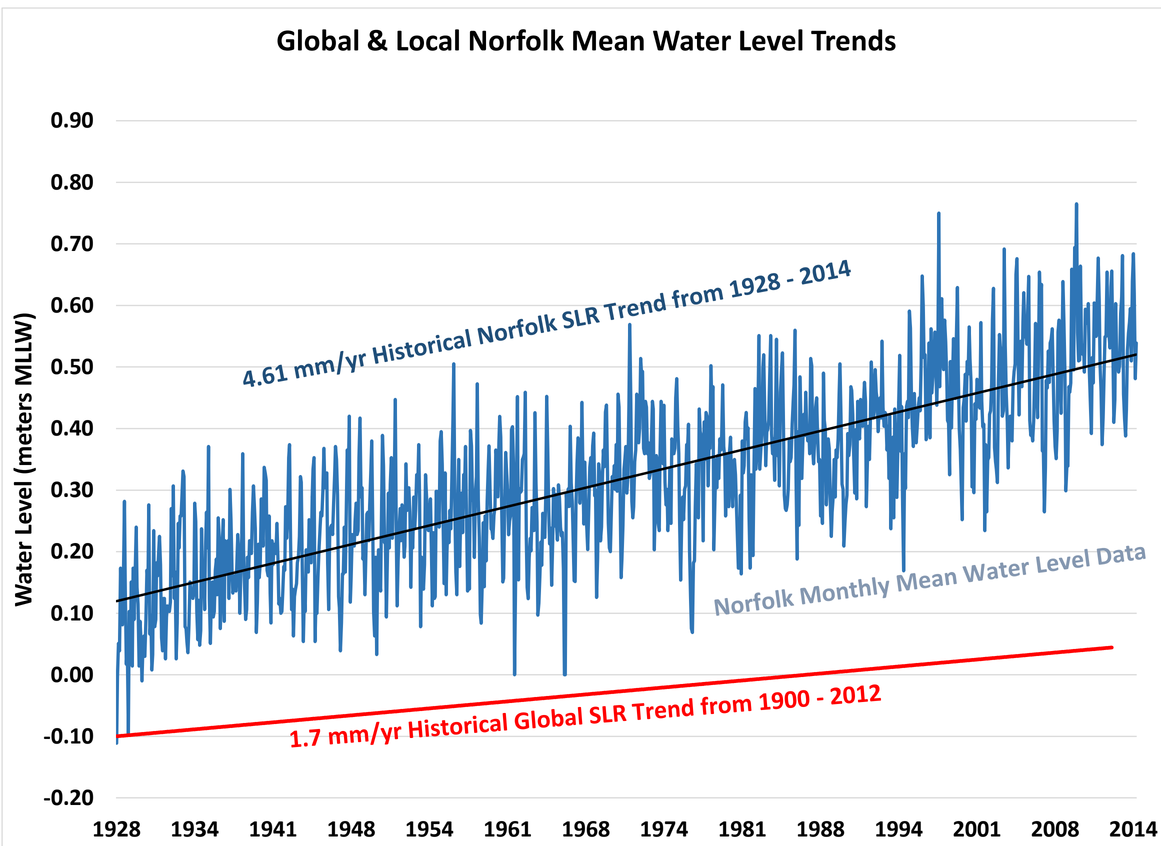


Figure 25: Global SLR & monthly mean water level trend at Naval Station Norfolk, 1928 – 2014
(Sources: Norfolk monthly mean water level data from NOAA, Sewells Point, VA, Station #8638610, Global SLR Trend from 2012 GSLR Scenarios for the U.S. National Climate Assessment (Parris et al. 2012))

by NOAA as the average of the month's hourly water level readings from the fixed tidal gauge instrument. The chart shows that the mean water level at Naval Station Norfolk has a significant upward trend over the past 86 years. A trendline illustrating Global Sea Level Rise over the same time period, as reported by the 2012 Global Sea Level Rise Scenarios for the National Climate Assessment, is plotted simultaneously for comparison (Parris et al. 2012). The monthly mean water level data exhibits regular seasonal variation caused by changes in water temperature, ocean currents, salinity, and wind patterns. In Norfolk, the highest water levels are observed in the months of September and October, while the lowest occur from December to March.

The equation of the best fit line through the mean water level data is:

$$y = (Annual\ Rise) \cdot (\#of\ yrs\ since\ dataset\ start) + MSL_{Dataset\ Start} \tag{16}$$

$$y = \left(0.00461 \frac{m}{year}\right) * x + 0.1212\ m \tag{17}$$

where y is the annual mean water level projection and x is the number of years since 1928.

The slope of the best fit line, 0.00461 meters/year, shows the mean water level at Naval Station Norfolk rising at an average rate of 4.61 millimeters per year over the past 86 years. This is equivalent to 0.231 m in 50 years or 0.461 m over 100 years (0.1820 inches per year, 9.08 inches in 50 years, or 1.513 ft over 100 years).

Based on data from 1928-2014, the rate of sea level rise does not appear to be significantly increasing. Figure 26 plots the average rate of sea level rise for moving 20 year periods. For example, the value of 4.67 mm per year for 1993 is the slope of the best fit line through all water level data from 1983 to 2003. If anything, Figure 26 shows a somewhat sinusoidal pattern in the rate of sea level rise. Though the moving averages in the past few decades are above the mean value, their values are below the moving average in the early years of the data set.

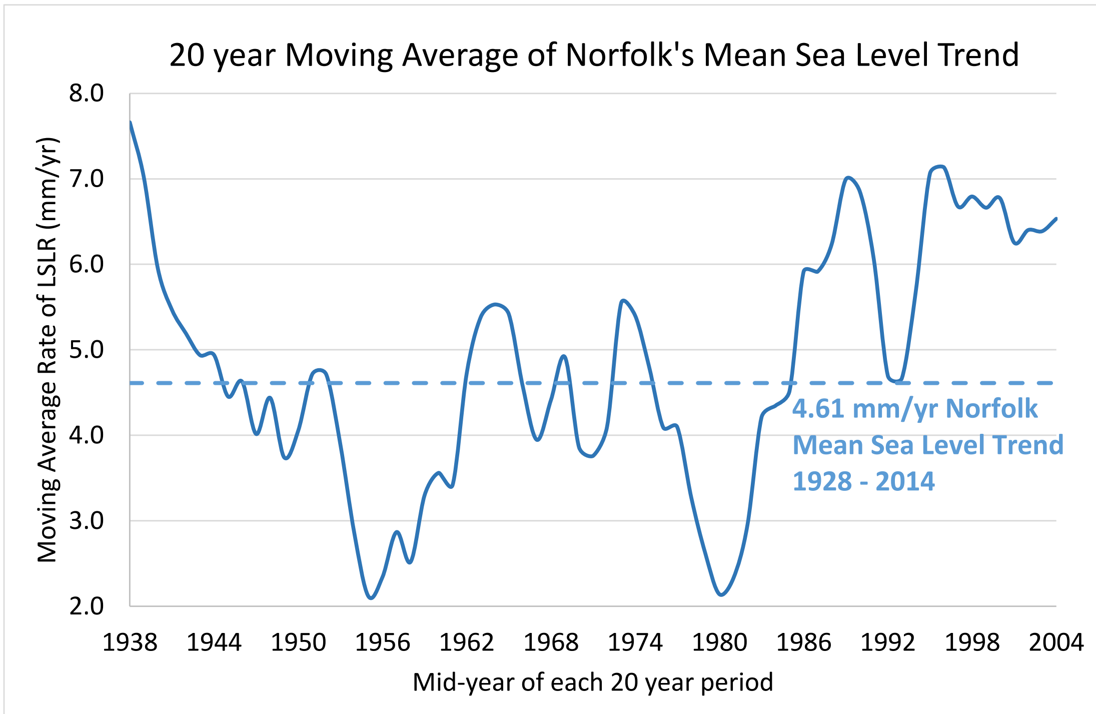


Figure 26: Moving 20 year average of Norfolk's Mean Sea Level trend
(Source: Norfolk monthly mean water level data from NOAA, Sewells Point, VA, Station #8638610)

A different analysis of the monthly mean water level data at Norfolk which is useful to this study is that of probability distribution fitting. The water level data was evaluated with Palisade Decision Tools @RISK software, an Excel plug-in which allows for the use of probability distribution analysis within each of a spreadsheet's cells. The Norfolk monthly mean water level dataset from 1928-2014, a sampling of 1044 data points, was input into @RISK's "best fit" analysis. The analysis showed that the data is well suited to both Weibull and Normal distributions, with μ=0.320 meters (1.05 ft) and σ=0.146 meters (0.910 ft) for both (Figure 27). Since the previous chapter on aggregating expert opinions of Global Sea Level Rise resulted in a normal distribution, it was decided to model

Norfolk's monthly mean water level data as a normal distribution in order to simplify the equations for future water level projections.

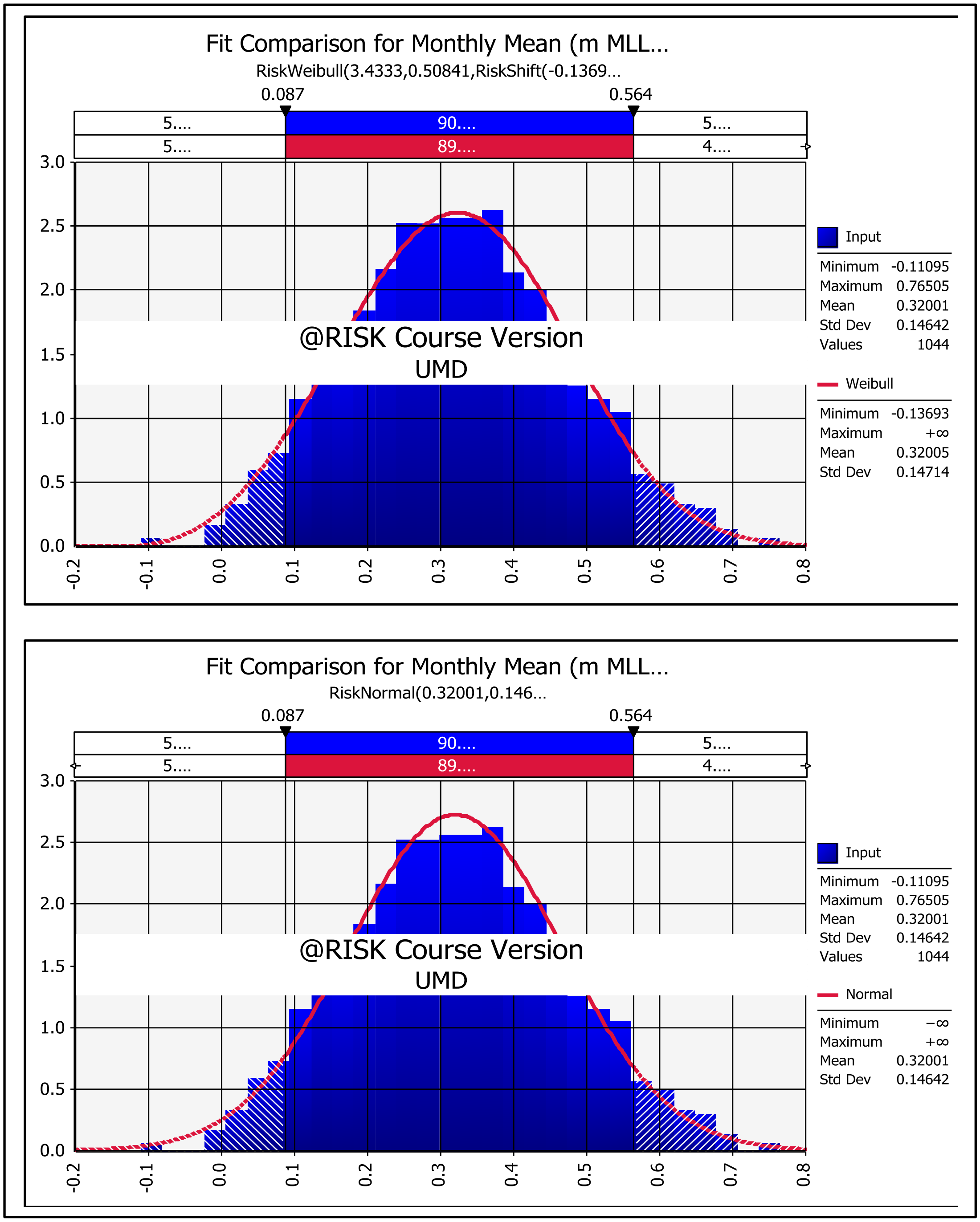


Figure 27: Fitting monthly mean water level data to Weibull and normal distributions with @RISK
(Source: Norfolk monthly mean water level data from NOAA, Sewells Point, VA, Station #8638610)

Adding Future Global Sea Level Rise to Local Sea Level Values

The results of the two previous sections, aggregation of expert Global Sea Level Rise projections and analysis of historic NOAA water level data, can be combined to predict future sea level rise. For this study, the mean of the aggregated experts' sea level rise projection by the year 2100 is assumed to behave linearly over time. There is no consensus among the experts on whether this rise will be linear, escalating over the years, or slowing down over this future time period. Thus, for simplicity, a linear trend was assumed.

The experts' projections of sea level rise to the year 2100 were not published in the same year. Therefore, 2008, the mean year in which the selected sea level rise projections were published is used as the baseline year for calculations in this study. Thus, with 1.00 meter of predicted sea level rise between the 92 years from 2008 to 2100, the average annual sea level rise, based on an assumed linear rise, was predicted to be:

$$\Delta_{GSLR} = \frac{Mean\ of\ GSLR\ Estimates}{Mean\ of\ timeframe\ for\ GSLR\ Estimates} \quad (18)$$

$$\Delta_{GSLR} = \frac{1.00\ m}{92\ years} = 0.01092\,\frac{m}{year} \quad (19)$$

Due to the seasonal variance of monthly tidal levels, the global sea level rise rate was calculated in a monthly format. The 1.00 meters of predicted sea level rise between the 1104 months from January 2008 to January 2100 was predicted to be:

$$\Delta_{GSLR} = \frac{1.00\ m}{1104\ months} = 0.000910\,\frac{m}{month} \quad (20)$$

Note that the predicted amount of sea level rise in the next century (0.01092 meters/year from Equation 19) is more than double the rate that has been observed at

Norfolk Naval Station over the past 86 years (0.00461 meters/year from Equation 17). The tidal gauge observations are a combination of the global (eustatic) sea level rise and the local sea level rise. Since the aggregated experts' projection of Global Sea Level Rise at approximately 11 mm/year is much larger than Norfolk's measured local sea level trend of 4.61 mm/year, the larger estimate will be used for all future sea level projections in this research.

The local sea level trend of 4.61 mm/yr is used to establish the baseline Local Mean Sea Level, which combines Global Sea Level Rise with the tidal gauge's vertical land motion, such as subsidence. Applying the equation of the mean water level best fit line for Norfolk and plugging in the number of years between 1928 and 2008 for the value of x, the following result is achieved:

$$y = \left(0.00461 \frac{m}{year}\right) * x + 0.1212\, m \tag{17}$$

$$y_{2008} = \left(0.00461 \frac{m}{year}\right) * (2008 - 1928) + 0.1212\, m \tag{21}$$

$$y_{2008} = 0.490\, m = \ LMSL_{2008} = \mu_{2008} \tag{22}$$

This 2008 calculated local mean water level of 0.490 meters is used as a starting point for the aggregated experts' sea level rise projections. Finding the Local Mean Sea Level in Norfolk in any future year, n, assumes a linear relationship of sea level rise between 2008 and 2100 and can be characterized by the following equation:

$$LMSL_{year\ n} = LMSL_{2008} + \Delta_{annual\ GSLR} * (years\ since\ 2008) \tag{23}$$

Incorporating the values previously calculated for the mean water level in 2008 (Equation 22) and the average annual sea level rise (Equation 19) yields:

$$LMSL_{year\ n} = 0.490\ m + 0.01092\frac{m}{year} * (n - 2008) \qquad (24)$$

The method for finding the monthly mean water level in a given month, m, and year n, is similar:

$$LMSL_{month\ m, year\ n} = LMSL_{2008} + \Delta_{monthly\ GSLR} * (months\ since\ January\ 2008) \qquad (25)$$

Incorporating the values previously calculated for the monthly mean water level in January 2008 (Equation 22) and the average monthly sea level rise (Equation 20) yields:

$$LMSL_{month\ m, year\ n} = 0.490\ m + 0.000910\frac{m}{month} * \big(((n - 2008) * 12\big) + (m - 1)) \qquad (26)$$

Determining Standard Deviation of Sea Level Projections

The methods used above to predict future local sea level at Naval Station Norfolk can be applied to other coastal regions with similar historic water level tidal gauge data. As more experts publish updated projections of future sea level rise, these projections can also be added within the framework of this approach. The decision making tool produced by this research is meant to be easily adapted to other locations and more recent projections. Since the previous section merged the normal distribution representing Global Sea Level Rise projections with the best fit line of the Local Mean Sea Level trend, the standard deviation of both of these datasets must be combined in order to apply the central limit theorem.

In this study, standard deviation of the sea level projection in a future year is calculated by taking the square root of the sum of the variances of the two predicted water level datasets for that year. These two datasets are the aggregated expert Global Sea Level Rise projections and the local Mean Sea Level trend. The combination of the experts' GSLR projections produced a normal distribution with μ=1.00 m (3.30 ft) and σ=0.277 m (0.910 ft) of Global Sea Level Rise by the year 2100 (Table 2). The Mean Sea Level in a future year is calculated as shown in Equation (21). For example, the Mean Sea Level in the starting year of 2008 was predicted to be μ_{2008} = 0.490 m (1.608 ft), the result shown in Equation (22).

The variance of the monthly Mean Sea Level dataset away from the best fit line of local sea level trend was calculated using:

$$\sigma_{LMSL}^2 = \frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{(n-1)} \tag{27}$$

where y_i is the actual monthly mean water level in a given month i, $\bar{y}$ is the value calculated from the best fit line for that month, and n is the number of samples. The variance and standard deviation of monthly mean water level data versus the best fit line were calculated as σ^2=0.00789 m^2 and σ=0.0888 m, respectively.

Two simplifying assumptions are required before summing the variances of the sea level rise projections. First, the variance of the sea level rise at the start of the baseline year, 2008, equals the variance of monthly mean water level data versus the best fit line, as calculated in Equation (27). Due to the seasonal variation in tides, monthly variance is a more accurate reflection of the range of tidal fluctuations than annual. Second, since the mean of the aggregated experts' sea level rise projection was assumed to have a linear rise, the increase in the projection's variance over time is assumed to be linear from 2008 to 2100. As the standard deviation of the combined expert's sea level rise projection for 2100 was σ=0.277 m (0.910 ft) then the variance is:

$$\sigma^2_{GSLR-2100} = (0.277\ m)^2 = 0.0769\ m^2 \tag{28}$$

The standard deviation for the predicted sea level in a given year, *n*, can be calculated by taking the square root of the sum of the variance of the baseline 2008 water level plus the variance of the sea level rise projection in year *n*:

$$\sigma_{LMSL,year\ n} = \sqrt{\sigma^2_{LMSL\ 2008} + (Percent\ of\ total\ yrs\ passed) * \sigma^2_{GSLR-2100}} \tag{29}$$

Substituting the values previously calculated for the variance of the 2008 local mean water level projection Equation (27) and the variance of the predicted sea level rise to 2100 Equation (28) yields:

$$\sigma_{LMSL,year\ n} = \sqrt{0.00789\ m^2 + \frac{(n-2008)}{92\ yrs} * 0.0769\ m^2} \qquad (30)$$

The process for calculating the standard deviation of local Mean Sea Level projection in a given month, m, and year n, is similar:

$$\sigma_{LMSL,month\ m,year\ n} = \sqrt{\sigma^2_{LMSL\ 2008} + (Percent\ of\ total\ months\ passed) * \sigma^2_{GSLR-2100}} \qquad (31)$$

Incorporating the values previously calculated for the variance of the 2008 local mean water level (Equation 27) and the variance of the predicted sea level rise to 2100 (Equation 28) yields:

$$\sigma_{LMSL,month\ m,year\ n} = \sqrt{0.00789\ m^2 + \frac{(n-2008)*12+(m-1)}{92\ yrs * 12} * 0.0769\ m^2} \qquad (32)$$

Combined Results of Local Mean Sea Level and Standard Deviation

The equations from the previous two sections can be used to predict the mean and standard deviation of the predicted water level in any year at any locale. For example, in 2020 (n=2020), the local Mean Sea Level in Norfolk is calculated using Equation (24):

$$LMSL_{year\ n} = 0.490\ m + 0.01092 \frac{m}{year} * (n - 2008) \tag{24}$$

$$LMSL_{n=2020} = 0.490\ m + 0.01092 \frac{m}{year} * (2020 - 2008) \tag{33}$$

$$LMSL_{n=2020} = 0.621\ m \tag{34}$$

The standard deviation in 2020 in Norfolk is calculated using Equation (30):

$$\sigma_{LMSL,year\ n} = \sqrt{0.00789\ m^2 + \frac{(n - 2008)}{92\ yrs} * 0.0769\ m^2} \tag{30}$$

$$\sigma_{LMSL,n=2020} = \sqrt{0.00789\ m^2 + \frac{(2020 - 2008)}{92\ yrs} * 0.0769\ m^2} \tag{35}$$

$$\sigma_{LMSL,n=2020} = 0.1339\ m \tag{36}$$

For the randomly chosen years of 2020, 2046, 2086, and 2100, the predicted mean water levels are summarized in Table 3.

Table 3: Local Mean Sea Level and standard deviation predictions for a given year for Norfolk

Year	LMSL (m)	σ_{LMSL} (m)
2020	0.6212	0.1339
2046	0.9051	0.1991
2086	1.3419	0.2704
2100	1.4948	0.2912

Figure 28 illustrates the observed Local Mean Sea Level at Norfolk, both the monthly and annual values. Plotted to the right is the 1 meter of predicted Local Mean Sea Level from 2008 until 2100, with uncertainty bands of plus or minus 1σ, which is inclusive of 16% - 84% of the predicted values.

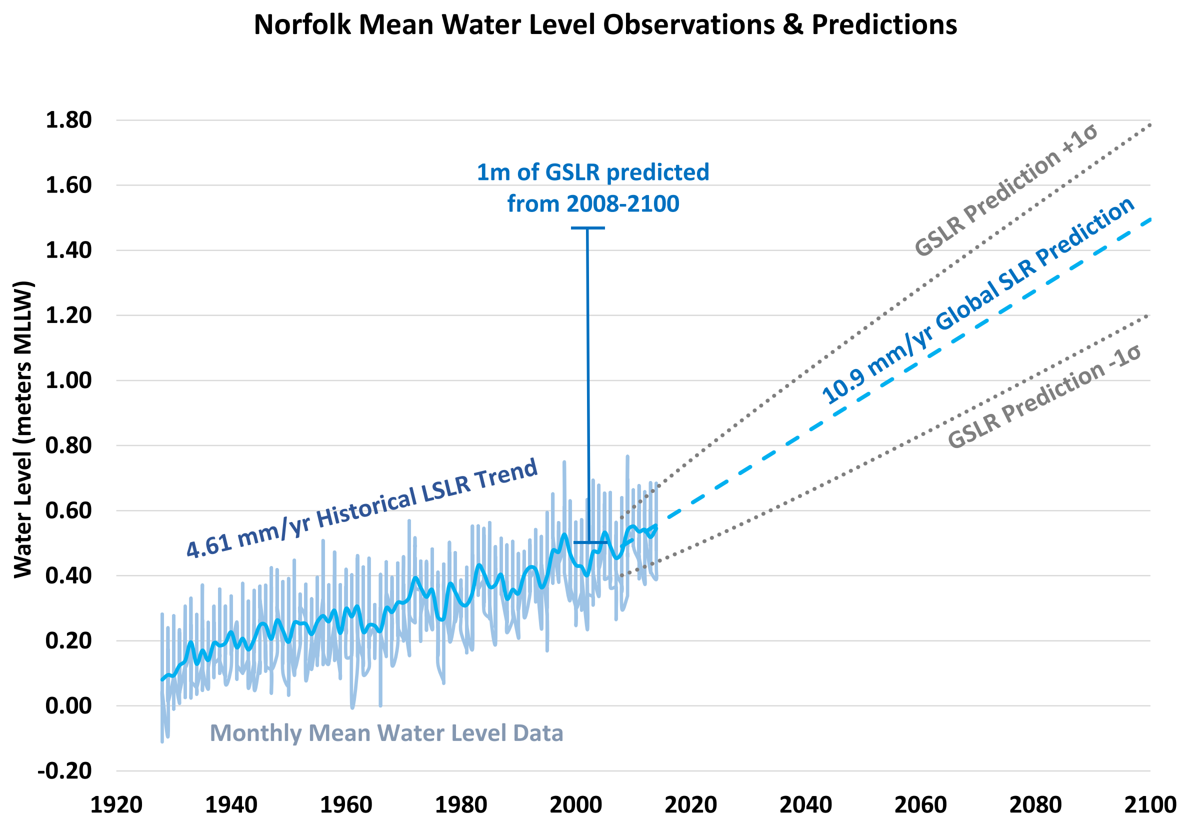


Figure 28: Predictions of Norfolk's LMSL incorporating aggregated GSLR with local sea level trend
(Source: Norfolk monthly mean water level data from NOAA, Sewells Point, VA, Station #8638610)

Chapter 6: Predicting Local Extreme Flood Events

Combining Local Mean Sea Level with Global Sea Level Rise projections was accomplished in the previous chapter. These two elements are not the only things that affect local water levels though. Extreme flood events caused by storms must also be accounted for. The NOAA dataset of historic monthly water levels contains a mean, minimum, and maximum water level for each month. The historical flood data for Norfolk is unique, because the confluence of the James, Nansemond, and Elizabeth Rivers occur where Norfolk meets the Chesapeake Bay (Figure 29). The simultaneous flooding of all three rivers due to pluvial runoff, coinciding with a storm surge from the bay, causes Norfolk-specific extreme flood events which are captured in the monthly maximum water level dataset.

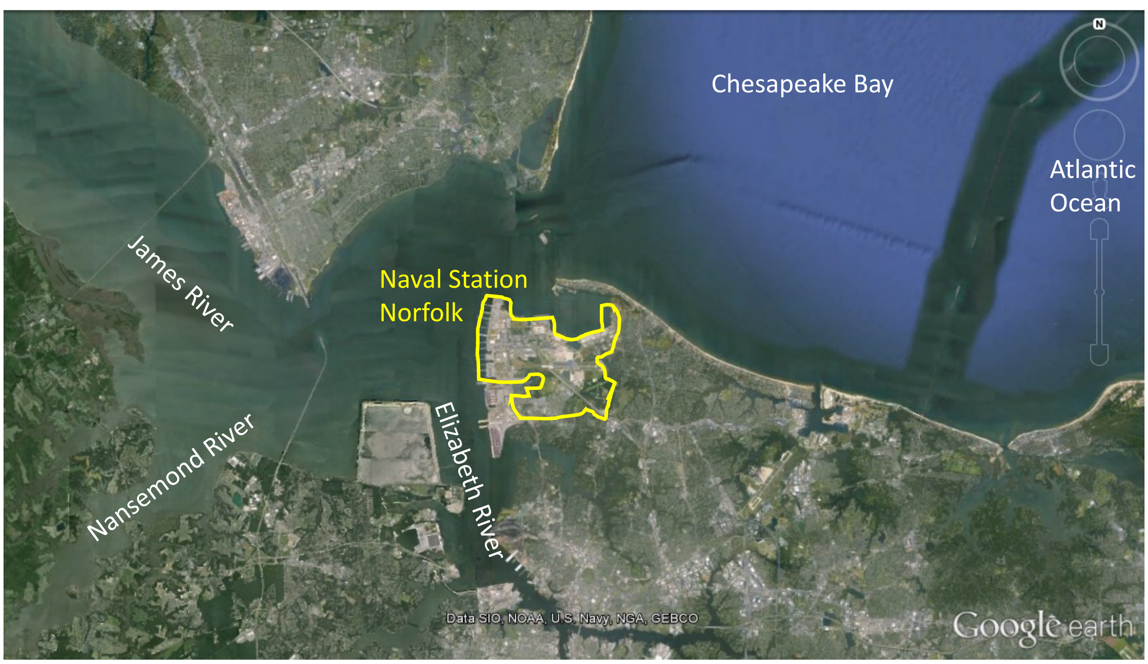


Figure 29: Proximity of James River, Nansemond River, Elizabeth River, Chesapeake Bay, and Atlantic Ocean to Naval Station Norfolk
(Source: Google Earth map annotated by the author)

Using publicly available NOAA water level data, a location-specific monthly Maximum Flood Event (MFE) can be calculated from the data by detrending the monthly Maximum Water Level (MWL) with respect to the monthly Mean Sea Level (MSL). Subtracting the monthly mean tide height from the monthly maximum tidal data, the residual shows the record of extreme flood events without the linear trend in sea level rise. The MFE component is useful for performing statistical analysis of past extreme flooding events (Kriebel and Geiman 2013).

$$MFE_{monthly} = MWL_{monthly} - MSL_{monthly} \qquad (37)$$

For Norfolk Naval Station from January 1928 to December 2014, the raw data of monthly maximum and monthly mean are plotted with their corresponding best fit lines in the upper panel of Figure 30. The monthly mean water level, plotted on the bottom of the upper panel, has a slope of 4.61 mm/year (0.182 inches per year). The R^2 value comparing the data to the best fit line is 0.626. The monthly Maximum Water Levels are plotted at the top of the chart. The slope of the monthly Maximum Water Levels, at 4.43 mm/year (0.175 inches per year), is similar to the monthly mean water level slope. The R^2 value of the Maximum Water Level trendline is 0.207.

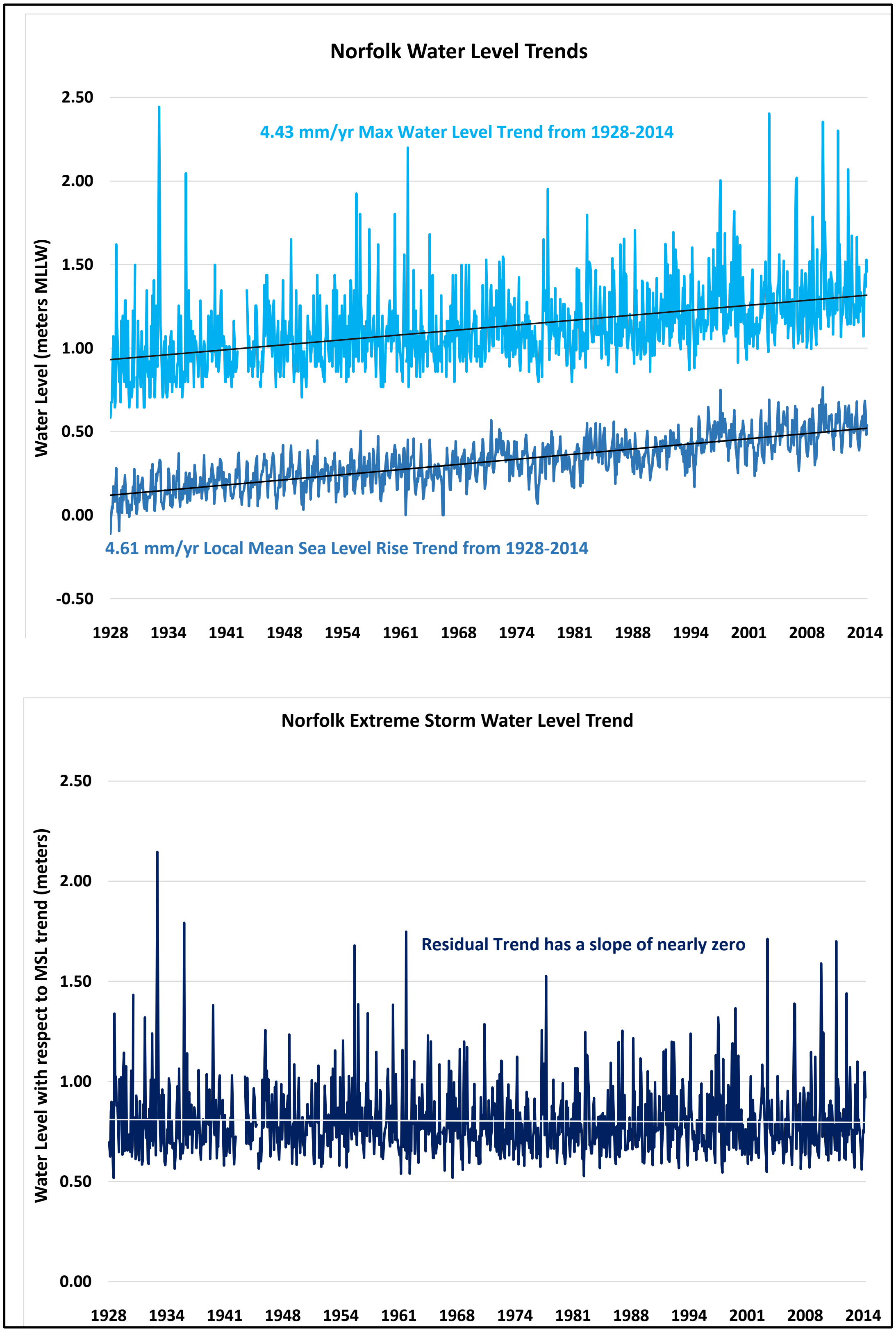


Figure 30: Mean, maximum, and storm water level trends at Naval Station Norfolk, 1928 – 2014

(Source*:* Monthly water level data from NOAA, Sewells Point, VA, Station #8638610)

The monthly MFE, also called the residual or extreme storm water level, as calculated in Equation (37), is plotted with its linear trendline in the lower panel of Figure 30. The calculated monthly Maximum Flood Event (MFE), or the residual has a flat slope of -0.1621 mm/year. This indicates no significant increase in the extreme flooding caused by storm events during this time period. The Mean Sea Level in Norfolk has been rising. However, the height of flood events with respect to Mean Sea Level has held steady over the past 85 years.

The tidal gauge data shown in Figure 30 illustrates that the monthly Maximum Water Level has been gradually increasing. It has been increasing at a rate similar to that of the Mean Sea Level at Norfolk. However, based on a different analysis of the same dataset from 1928-2014, the rate of Maximum Water Level rise has not always been increasing. Figure 31 plots the average rate of Maximum Water Level rise for moving 20 year periods. For example, the value of 6.61 mm per year for 1993 is the slope of the best fit line through all water level data from 1983 to 2003. If anything, Figure 31 shows a somewhat sinusoidal pattern in the rate of Maximum Water Level rise. This is similar to the moving average chart of sea level rise previously presented in Figure 26.

The data in these two charts illustrates that over the past 85 years the trend of the monthly Maximum Water Level and monthly mean water levels has been gradually increasing. However, the monthly Maximum Flood Event (MFE), which is the difference between the maximum and mean water levels each month, is not changing significantly over time. There has been little or no change in the severity of the most extreme flood

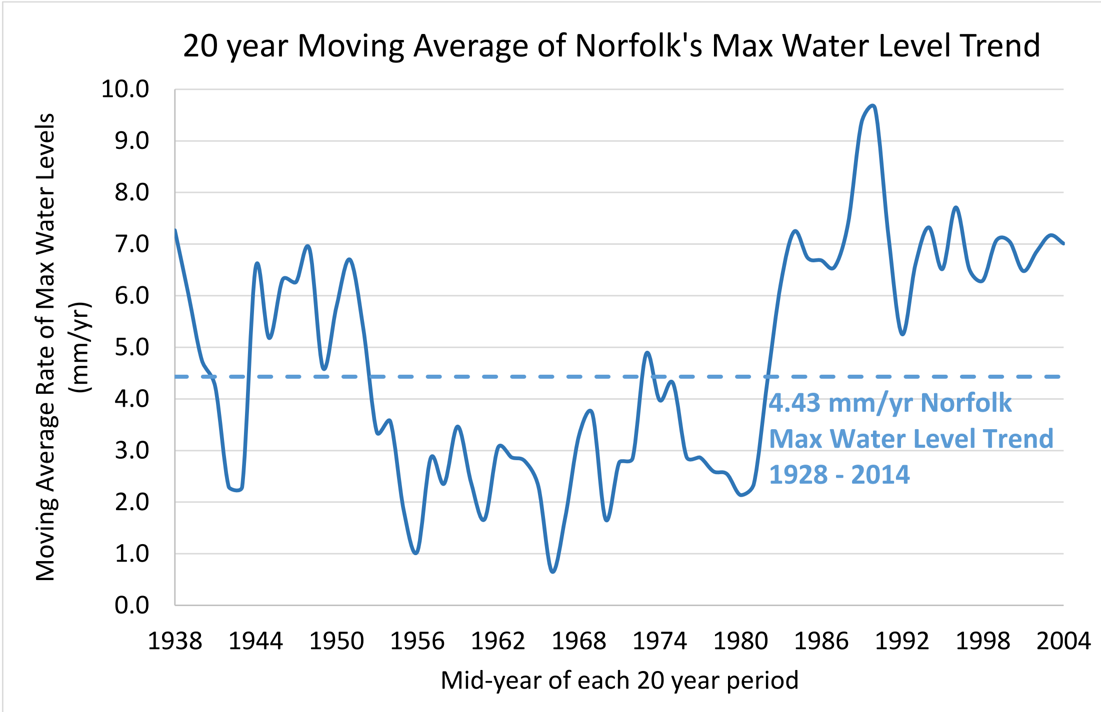


Figure 31: Moving 20 year average of Maximum Water Level trend
(Source: Norfolk monthly maximum water level data from NOAA, Sewells Point, VA, Station #8638610)

events in the Norfolk dataset. The increase in water level associated with these flood events is due to the rise in Local Mean Sea Level, not due to an increase in the severity of the flood events themselves. The magnitude of the dataset of MFE is not increasing.

The same probability distribution fitting method, which was used to analyze the monthly mean water level data, was applied to the Maximum Water Level and Maximum Flood Event data sets. The Norfolk monthly Maximum Water Level dataset from 1928-2014, a sampling of 1027 data points, was input into @RISK's "best fit" analysis. The data is well suited to both Weibull and Normal distributions, with μ=1.126 m (3.69 ft) and σ=0.244 m (0.801 ft) (Figure 32).

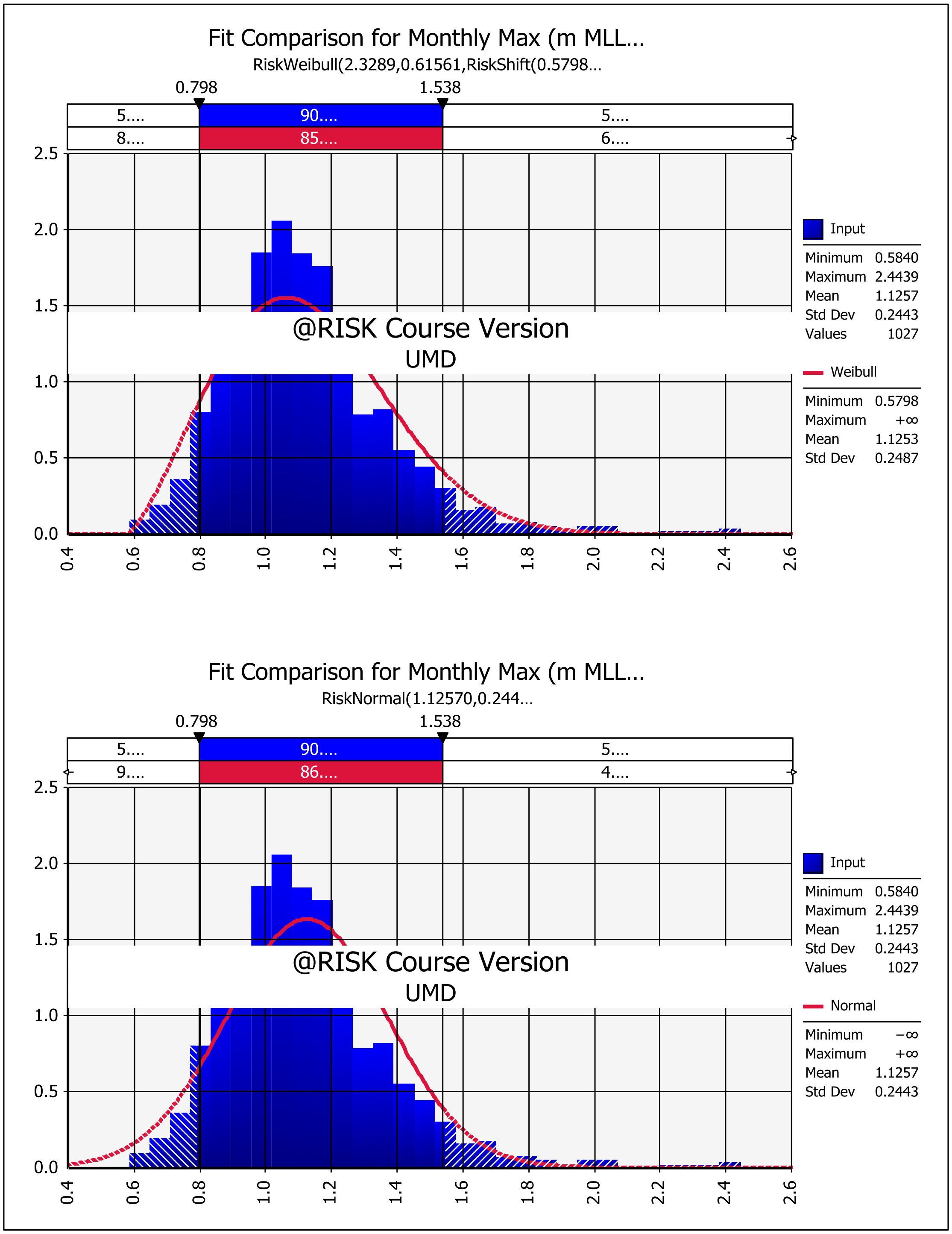


Figure 32: Fitting monthly Max Water Level data to Weibull and normal distributions with @RISK
(Source: Norfolk monthly maximum water level data from NOAA, Sewells Point, VA, Station #8638610)

Are Coastal Flood Events Increasing in Severity or Frequency?

The mainstream news media, including National Geographic magazine and PBS, has led the general public to believe that the severity and frequency of coastal flood events has increased over time (PBS NewsHour 2013; Roach 2007). Data suggests that this is not the case in Norfolk. Severity of flood events, as measured by the Maximum Water Level with respect to the Mean Sea Level trend at Naval Station Norfolk, is not increasing. In fact, this residual shows a slightly decreasing trend. Coastal flood events seem to be more intense only because of the increasing trend of the Mean Sea Level. Flood events are starting from a higher baseline than they were 50 years ago. Coastal flood events are more frequent due to Global Sea Level Rise, not due to a higher frequency of storms.

This phenomenon is not present only at Norfolk. A similar analysis was conducted for six other locations with naval stations on the U.S. East Coast (Table 4). These locations all showed a similar trend as that at Norfolk, with an increasing Mean Sea Level trend. The Max Flood Events at each locale exhibited a flat slope over time, once the data was detrended for the increasing Mean Sea Level.

Table 4: Tidal gauge water level trends at U.S. East Coast naval bases

Location	Date Range		# Data Pts	MWL Change (mm/yr)	MSL Change (mm/yr)	MFE Chang (mm/yr)
Key West, FL	1913	2013	1130	2.44	2.34	0.0912
Fernandina Beach, FL	1897	2013	830	2.27	2.00	0.2616
Charleston, SC	1921	2013	1107	3.54	3.12	0.4159
Solomon's Island, MD	1937	2013	884	3.49	3.71	-0.2160
Newport, RI	1930	2013	831	2.65	2.73	-0.0739
New London, CT	1938	2013	873	1.968	2.57	-0.4448

(Source: Data adapted from NOAA)

Determining Magnitude of Maximum Flood Events

Just as the previous sections presented equations for calculating the Local Mean Sea Level in a future year, a similar process can be used to predict local extreme flood events. To predict Local Maximum Water Levels in the future, the 2008 local mean water level is used as a starting point, to which is added the experts' sea level rise projection for a given future date, plus the mean of the annual Maximum Flood Event (MFE) height for that location (Figure 33). The Local Maximum Water Level (LMWL) in Norfolk in any future year, n, is calculated with the following equation:

$$LMWL_{year\ n} = LMSL_{2008} + \Delta_{annual\ GSLR} * (years\ since\ 2008) + LMFE_{annual} \quad (38)$$

In order to predict the Local Maximum Water Level (LMWL) in a given year, the annual mean and standard deviation of the historic Maximum Flood Event (residual) at that location is used. For Norfolk from 1928 to 2014, a dataset of the monthly Maximum Flood Event for has a mean of 0.803 meters and a standard deviation of 0.182 meters. The annual LMFE data follows a similar, flat slope trend as the monthly data (lower panel of Figure 30). However, as expected because only the most extreme events each year are included, the annual mean and standard deviation are higher than that of the monthly data. The annual LMFE mean is 1.238 meters and the standard deviation is 0.254 meters.

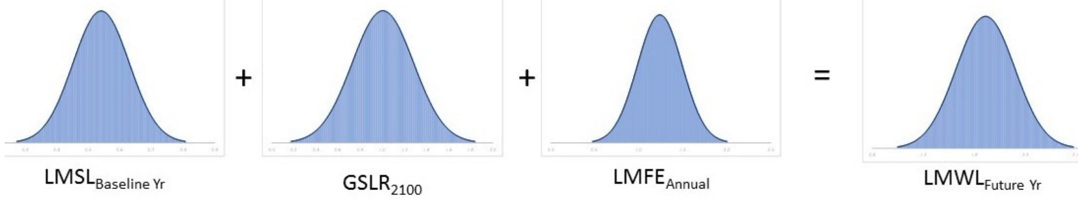


Figure 33: Predicting future Maximum Water Levels by combining normal distributions

It is more appropriate to use the annual LMFE in predicting future flood events for three main reasons. First, it will predict the most extreme and, thus, the most costly event each year. Second, due to the slow speed at which repairs are typically funded and made to flood damaged infrastructure, it is unlikely that repairs would be completed before the rare circumstance of more than one extreme flood event per year. Additionally, the regular seasonal variation of the water level data due to changes in water temperature, ocean currents, salinity, and wind patterns is smoothed with the use of the annual mean and standard deviation, as opposed to using the monthly mean and standard deviation.

Using the values previously calculated for the mean water level in 2008 (Equation 22), the average annual sea level rise (Equation 19), and the annual Maximum Flood Event relative to MSL for Norfolk yields:

$$LMWL_{year\ n} = 0.490m + 0.01092\frac{m}{yr} * (n - 2008) + 1.238m \tag{39}$$

Determining Standard Deviation of Maximum Flood Events

Using the Central Limit Theorem, the standard deviation for the flood extreme for any year is calculated by taking the square root of the sum of the variances of the three predicted water level datasets for that year. The three variances which will be summed are the experts' Global Sea Level Rise projections, the local mean water level trends, and the historic annual maximum flood events.

The variance of the annual maximum flood events for Naval Station Norfolk was calculated by squaring the standard deviation of the historic data:

$$\sigma^2_{LMFE} = (0.254\ m)^2 = 0.0646\ m^2 \tag{40}$$

The standard deviation for the predicted Local Maximum Water Level (LMWL) in a given year, *n*, is calculated by taking the square root of the sum of the variance of the predicted local mean water levels, the variance of the Global Sea Level Rise projection, and the variance of the annual maximum flood event data:

$$\sigma_{LMWL,year\ n} = \sqrt{[\sigma^2_{LMSL} + (Percent\ of\ total\ yrs\ passed) * \sigma^2_{GSLR-2100} + \sigma^2_{LMFE}]} \tag{41}$$

Values were previously calculated for the standard deviation of the local mean water level projections (Equation 15) and the variance of the predicted sea level rise to 2100 (Equation 16). The variance of the annual maximum flood events was calculated by squaring the standard deviation of the historic data (Equation 40). Substituting each of these values into Equation 41 gives the following Norfolk result:

$$\sigma_{LMWL,year\ n} = \sqrt{\left[0.00789\ m^2 + \frac{(n-2008)}{92\ yrs} * 0.0769\ m^2 + 0.0646\ m^2\right]} \tag{42}$$

Combined Results of Local Flood Events and Standard Deviation

Equations from the previous two sections can be used to predict future local flood events and their standard deviations. For example, in 2020 the mean Local Maximum Water Level is calculated as:

$$LMWL_{year\ n} = 0.490m + 0.01092\frac{m}{yr} * (n - 2008) + \ 1.238m \tag{39}$$

$$LMWL_{n=2020} = 0.490m + 0.01092\frac{m}{yr} * (2020 - 2008) + \ 1.238m \tag{43}$$

$$LMWL_{n=2020} = 1.860\ m \tag{44}$$

The standard deviation can be similarly calculated:

$$\sigma_{LMWL,year\ n} = \sqrt{[0.00789\ m^2 + \frac{(n - 2008)}{92\ yrs} * 0.0769\ m^2 + 0.0646\ m^2]} \tag{42}$$

$$\sigma_{LMWL,n=2020} = \sqrt{[0.00789\ m^2 + \frac{(2020 - 2008)}{92\ yrs} * 0.0769\ m^2 + 0.0646\ m^2]} \tag{45}$$

$$\sigma_{LMWL,n=2020} = 0.2872\ m \tag{46}$$

For the sample years of 2020, 2046, 2086, and 2100, calculations of LMFE and σ_{LMFE} are shown in Table 5. These tabulated results are based on inputs of Global Sea Level Rise projections, local mean water level data, and local maximum water level data in order to predict the local maximum flood events in the future. In a given year, the Maximum Water Level is predicted as a normal distribution with the mean and standard deviation calculated as explained above. Using this data for future means and standard deviations of maximum flood events at Naval Station Norfolk, one can determine the probability of exceeding critical flood levels at vital locations in the future. Based on the probabilities, decision makers can make more informed decisions about which assets require preventive measures.

Table 5: Local Maximum Water Level and standard deviation predictions for a given year at Norfolk

Year	LMWL (m MLLW)	σ_{LMWL} (m MLLW)
2020	1.860	0.2872
2046	2.144	0.3228
2086	2.580	0.3710
2100	2.733	0.3865

Using the methods described in this chapter, Figure 34 was created to display the predicted local Maximum Flood levels at Naval Station Norfolk from 2015 until 2100. Uncertainty bands of plus or minus 1σ are shown as dashed lines, which is inclusive of 16% - 84% of the predicted values. The observed annual mean and annual max water levels are also shown on the chart for reference.

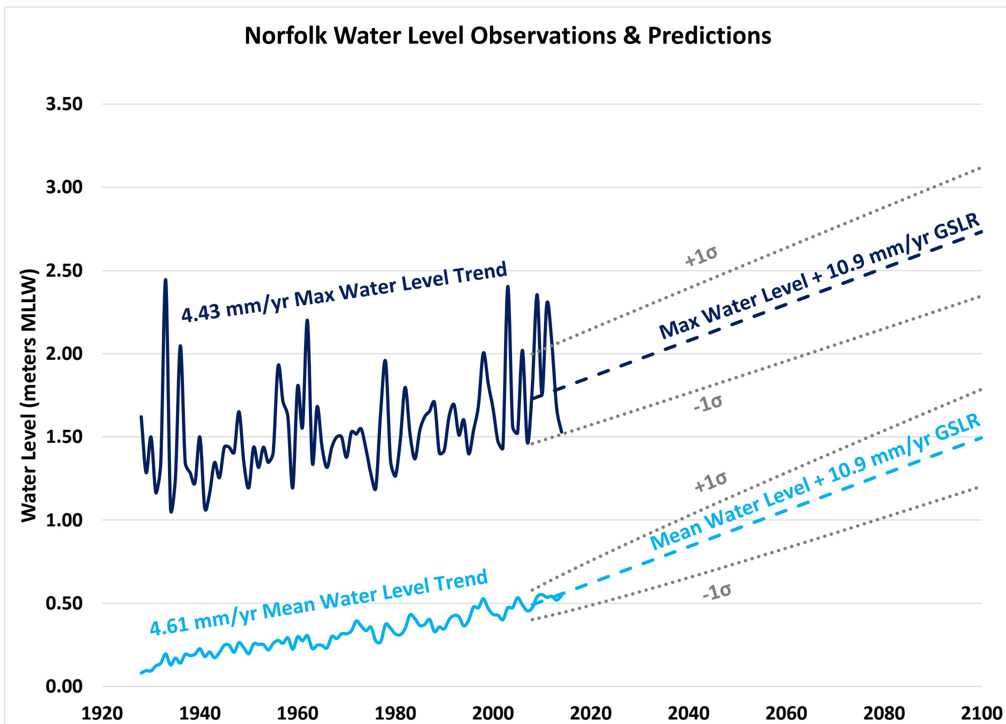


Figure 34: Predictions of Norfolk's Max Water Level using aggregated expert opinions
(Source: Adapted from NOAA water level data, Sewells Point, VA, Station #8638610)

Chapter 7: Application of Depth Damage Curves

Depth damage curves are used by the U.S. Army Corps of Engineers (USACE) and the Federal Emergency Management Agency (FEMA) to estimate the cost of flood damage to structures. These publicly accessible depth damage estimates, when combined with the probabilistic modeling presented in the previous chapters, can be used to estimate the costs of flood inundation on vulnerable assets. By applying the depth damage curves which are most applicable to the region, type of flooding, and the type of building affected, it is possible to achieve a realistic approximation of the asset's potential flood damage costs (Figure 35).

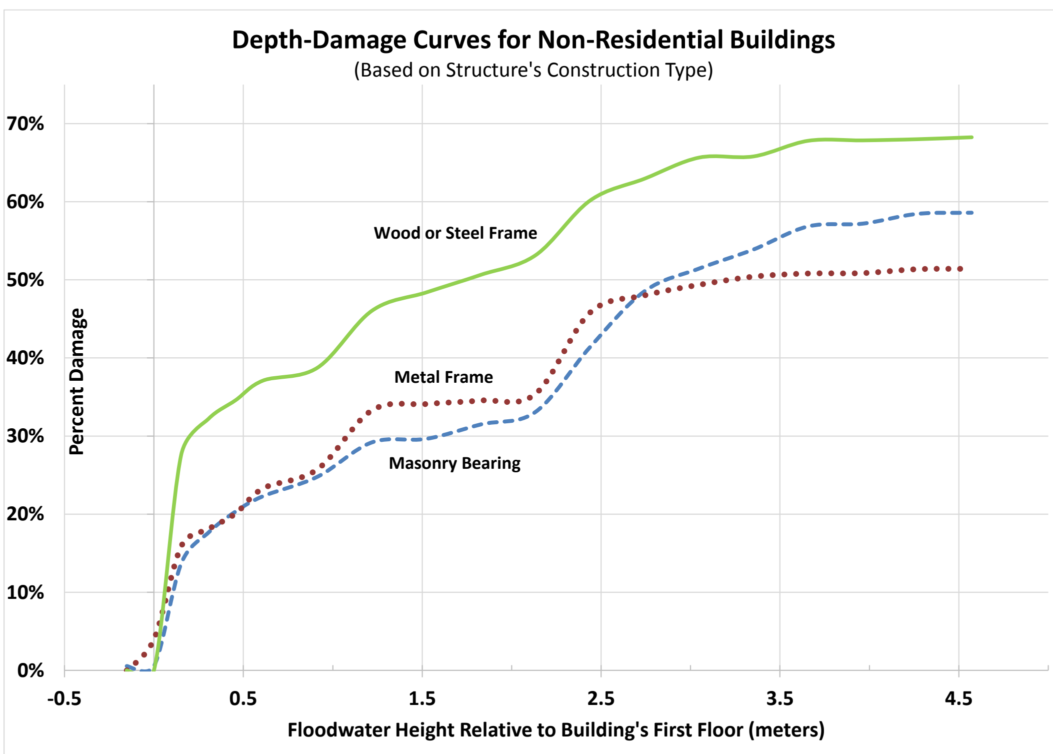


Figure 35: Example of depth damage curves used to predict floodwater damage in structures
(Source: Data adapted from U.S. Army Corps of Engineers 2006b)

Depth damage curves (DDC), also called depth damage functions, relate the height of floodwater in the building to a percentage of the structure's damage. Often this damage is expressed in terms of a percentage of the building's replacement value. The damage cost of the building's contents is typically approximated either as a percentage of the structure's damage cost, or as a percentage of the building's total content value. Plotting the depth damage function illustrates that damage occurs quickly at lower flood levels with a gradual decrease in the damage rate as the floodwaters rise. This relationship is not linear, hence the name depth damage curves. Depth damage curves take into account the structure's construction type, usage type, locale, type of flooding (freshwater or saltwater), duration of flood inundation, and first floor elevation in order to give an output of percentage of damage costs sustained by the structure.

History and Use of Depth Damage Curves

The basic methodology for depth damage curves was introduced by Dr. Gilbert F. White, in his 1945 thesis called the "Human Adjustment to Floods." He recommended quantifying the cost of flood damage in relation to either the flood inundation time or water level height (White 1945). He also introduced the idea of the estimated flood damage cost being characterized as a percentage of the total property value. As the "Father of Floodplain Management," White was instrumental in the creation of the first government subsidized flood insurance, the National Flood Insurance Program (NFIP) created in 1968 (Knowles and Kunreuther 2014).

The earliest nationwide generic residential depth damage curves were created by the Federal Insurance Administration (FIA) for the NFIP in 1970. These curves were constructed using historic floodwater damage costs collected by the U.S. Army Corps of Engineers (U.S. Army Corps of Engineers 1992). FIA, which is now called the Federal Insurance and Mitigation Administration (FIMA), manages the federal government's NFIP, setting the rates for government provided flood insurance premiums. The 1970 generic depth damage curves were adjusted in 1973 with actual data from NFIP insurance claims (U.S. Army Corps of Engineers 1996). The original 1970 and the validated 1973 FIA depth damage curves remain the basis of national depth damage curves utilized today. These generic depth damage curves are updated annually by FIMA for the purpose of reviewing flood insurance premium rates. Additionally, each USACE regional district has the option of conducting local surveys to construct their own regional depth damage curves.

In the last two decades, the USACE has established new national generic depth damage curves for residential buildings. These new curves, still based on the original 1970

FIA depth damage functions, use actual flood damage losses and include the damage costs to the structure's contents within the depth damage functions (U.S. Army Corps of Engineers 2000). Residential buildings are the first surveyed in a flood damage recovery event, since relocating affected families is a public safety and health priority in these situations. The flood damage data from these surveys is used to update the local depth damage curves for residential properties. While depth damage curves for residential buildings have been updated often, high-quality data for non-residential buildings does not exist on a national level.

However, residential buildings are a small percentage of the structures on a military installation, and the updated residential depth damage data is not applicable to a base's main infrastructure. In order to properly apply depth damage curves to military bases, a study specific to military installations is needed in order to more accurately represent the damage costs of flood events on a military base. Because of the expense and needed circumstances associated with conducting a survey of flood damage costs, few USACE district offices have developed non-residential depth damage curves for their regions. None have conducted extensive studies specifically documenting flood damages to a military installation.

The three sets of non-residential depth damage curves which were evaluated for use in this report were those developed in response to Hurricane Sandy, Tropical Storm Agnes, and Hurricane Katrina. After Hurricane Sandy in 2012, the North Atlantic Coast Comprehensive Study (NACCS) was released by the USACE. The report compares the depth damage curves created by an expert panel with the surveys of actual flood damage from the hurricane (U.S. Army Corps of Engineers 2015a). In 1972, Tropical Agnes caused a 12 meter high flood in Wilkes-Barre, Pennsylvania, leading the Baltimore District of USACE to compile a flood damage survey of the Wyoming Valley area (U.S. Army Corps of Engineers 1996). After Hurricane Katrina, a comprehensive study of residential and non-residential flood damage costs was conducted by the New Orleans District of USACE (U.S. Army Corps of Engineers 2006b). Of these three studies, the post-Katrina study is most appropriate for analyzing the potential effects of SLR in Norfolk.

Depth Damage Curve Development

For the post-Hurricane Sandy study, new depth damage curves were developed which include commercial buildings and urban high rises, in addition to the usual residential depth damage curves. The damage functions for commercial buildings were divided into two categories: engineered and pre/non-engineered. The typical commercial pre/non-engineered building surveyed was a one-story, high bay, steel-frame building. The commercial engineered building category consisted mainly of two-story buildings without basements.

Of 169 physical damage surveys conducted by USACE staff in New York and New Jersey, 70 were for non-residential buildings (U.S. Army Corps of Engineers 2015a). However, only ten of these were of the engineered commercial type. The survey data for each classification of building type and use was compared with the depth damage curves developed by an expert panel to illustrate estimated damage versus actual (Figure 36).

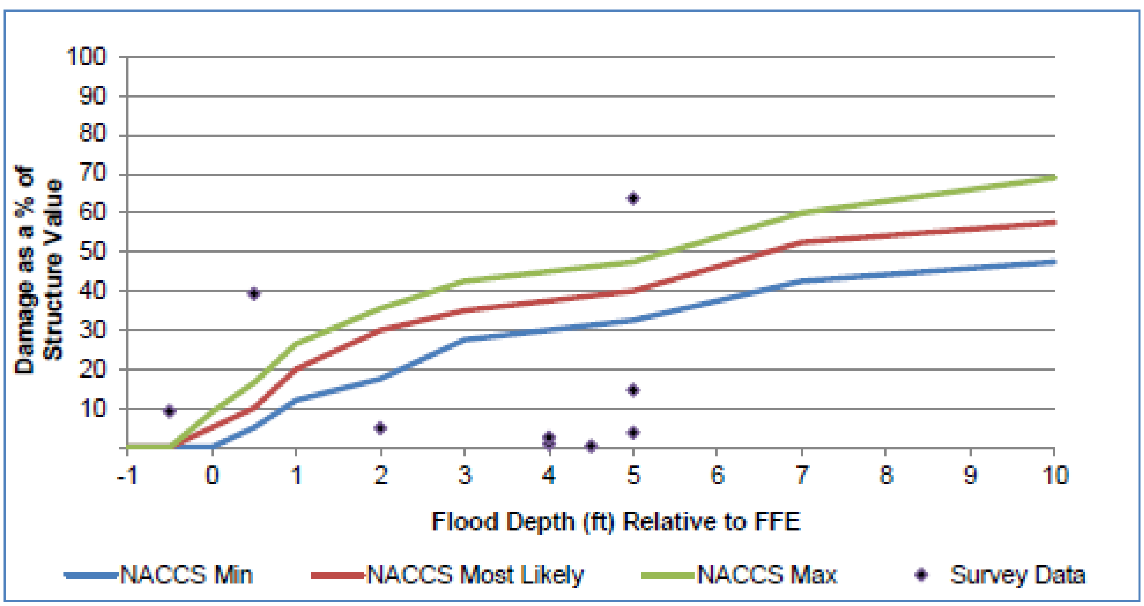


Figure 36: Comparison of 10 physical damage surveys to expert panel min, most likely and max depth-damage curves for engineered commercial type buildings in New York and New Jersey, post-Sandy
(Source: U.S. Army Corps of Engineers 2015a)

The comparison showed that for the majority of the commercial-engineered buildings surveyed, the actual damage was less than 20% of the total structural value, and the expert panel's estimates were significantly higher than the actual damage. The depth damage curve predictions did not correlate well to the survey data, at least in part due to the limited number of samples for this type of building. Only 10 of the 169 physical damage surveys were of the engineered commercial building variety. This type of building construction and use is most similar to the majority of buildings on military installations. Had the survey results had been more accurate, this data might have been useful for calculating the economic costs of sea level rise on military bases. However, due to its inaccuracies and small sample size, it was not deemed reliable enough for this analysis of the economics of sea level rise.

Another major study implementing depth damage curves is the 1996 Pennsylvania study performed by the USACE Baltimore District using flood damage survey data from Tropical Storm Agnes in 1972. This study focuses on depth damage functions in a freshwater, riverine flooding environment (U.S. Army Corps of Engineers 1996). The report develops equations for generic non-residential depth damage curves. However, because the sample size of the commercial buildings surveyed is so small, the report recommends that these depth damage curves are not applicable to other regions. Since naval installations are usually situated in coastal locations with saltwater flooding, this study's depth damage curves are not applicable to most Navy bases.

Post-Katrina Study of Depth Damage Curves

The 2006 New Orleans survey of eight parishes surrounding Donaldsonville, Louisiana outlines both freshwater riverine flooding and saltwater coastal flooding for short (one day or less) and long durations (one week) (U.S. Army Corps of Engineers 2006b). Norfolk's combination of freshwater and saltwater flooding most closely resembles that of the New Orleans dataset. Thus, the post-Katrina depth damage curves will be applied in this study for the purposes of predicting flood damage costs for the case study of Naval Station Norfolk (Table 6).

Table 6: Generic depth damage curves for 1 & 2-story non-residential buildings, based on building construction type

		Percent Damaged for Average Duration (3.5 days) Salt Water Flooding		
Max Flood Depth (ft)	Max Flood Depth (m)	Metal Frame	Masonry Bearing	Wood or Steel Frame
<-0.5	<-0.15	0.0%	0.0%	0.0%
-0.5	-0.15	0.0%	0.6%	0.0%
0.0	0.00	4.0%	0.6%	0.0%
0.5	0.15	15.9%	13.7%	27.6%
1.0	0.30	18.1%	17.7%	32.2%
1.5	0.46	20.1%	20.4%	34.6%
2.0	0.61	23.3%	22.3%	37.1%
3.0	0.91	25.8%	24.8%	38.8%
4.0	1.22	33.3%	29.2%	46.1%
5.0	1.52	34.1%	29.7%	48.4%
6.0	1.83	34.6%	31.5%	50.7%
7.0	2.13	35.4%	33.1%	53.2%
8.0	2.44	45.8%	41.4%	60.2%
9.0	2.74	48.0%	48.6%	63.0%
10.0	3.05	49.4%	51.5%	65.7%
11.0	3.35	50.4%	53.9%	65.8%
12.0	3.66	50.8%	56.9%	67.8%
13.0	3.96	50.9%	57.2%	67.9%
14.0	4.27	51.4%	58.5%	68.0%
15.0	4.57	51.4%	58.6%	68.3%

(Source: Data adapted from U.S. Army Corps of Engineers 2006b)

The 2006 New Orleans study compiled data from a variety of sources including local insurance adjustors, construction professionals, restoration contractors, home owners, and business owners. The study assumes the main structure of a building will withstand the flood, while the building's contents and its mechanical, electrical and architectural finishes will be damaged. If the damage cost is more than 50% of the replacement value, then the building will be considered a total loss. This total loss classification changes to 90% damage in the case of a historic building. The building's damage is expressed as a percentage of the building's replacement value, while the damage to the contents is expressed as a percentage of the structure's damage. In the study, all non-residential structures are assumed to have no basement (U.S. Army Corps of Engineers 2006b).

Because of the percentage-based, generic-type analysis from the New Orleans District, these depth damage curves can be applied in Norfolk, Virginia, even though property values are different in the two locales. These are the best non-residential depth damage curves publicly available and have been used by other researchers for their economic analysis (NOAA 2013). For analyzing different locations and a variety of building types, it is recommended to use region-specific and building type-specific depth damage curves, which best represent the type of flood damage commonly seen in that area.

Applying Depth Damage Curves to Naval Station Norfolk

When applying the New Orleans depth damage curves to Naval Station Norfolk, it became apparent that the damage functions developed for residential homes and commercial businesses did not directly apply to common military infrastructure. Much of the mission critical infrastructure on a military base is not accounted for among the generic depth damage curves created by USACE. For example, there are not depth damage curves for horizontal infrastructure such as piers, bulkheads, jetties, roads, parking lots, and runways. This is most likely due to the lack of insurance claims related to flood damages of these types of expensive infrastructure, which are typically publicly maintained assets.

Historic flood damage data for expensive and mission critical infrastructure is not well documented. Damage costs related to coastal flooding were requested from the Naval Facilities Engineering Command (NAVFAC) and the Naval History and Heritage Command. However, these expenditures were not tracked separately by either organization. Rather, they were grouped with emergency repair funds or maintenance allocations.

Searching for civilian studies of flood damage costs to horizontal infrastructure, the author only found two studies regarding pavement and none concerning airport runways. The first pavement study, performed after Hurricane Katrina, was not helpful for predicting flood damage costs. In the study, the road conditions prior to the storm were unavailable for comparing to the damaged roads (Zhang et al. 2008). Thus, the level of damage caused specifically by hurricane flooding could not be determined. The second pavement report was performed in the United Kingdom, and while thorough in its engineering analysis, did not provide an economic study of pavement damage due to flooding (Jacobs 2011).

While preparing depth damage curves for specific military installations would be one solution, it is not cost-effective. It would be more useful to develop generic depth damage curves for large-scale infrastructure. These curves could be used for commercial, military, and public property flood damage predictions.

For this study, the depth damage curves developed in 2006 based on the New Orleans area survey were adapted to the Norfolk area. The classifications used for the nonresidential structure's construction type include: wood or steel frame, concrete frame, and masonry (Table 7). Because base housing at Norfolk is privatized and not solely owned by the Department of Defense, residential depth damage curves are not needed. Only non-residential curves are needed to analyze Naval Station Norfolk.

Table 7: Classification of structures by construction type

Construction Type
Metal
Masonry
Wood or Steel

(Source: U.S. Army Corps of Engineers 2006b)

Applying Content to Structure Value Ratio

To account for the damage of the structure's contents, a Content-to-Structure Value Ratio (CSVR) is applied to the result of the depth damage curve function, in keeping with the technique used in the New Orleans study.

$$Damage\ to\ Contents = CSVR * Damage\ to\ Structure \tag{47}$$

The New Orleans study uses eight different occupancy types to classify the contents based on the building's use. These occupancy types are: eating/recreation, groceries/gas stations, multi-family residences, professional businesses, public or semi-public, repairs and home use, retail and personal, and warehouse and contractor services.

The occupancy types used for determining the CSVR in the New Orleans District study do not directly reflect the types of buildings on a military installation. This research adapted these building use types to conform to structures commonly found on a military base. The occupancy classifications used in this case study of Naval Station Norfolk include: barracks, office space, repair facility, utilities, warehouse, and no contents (Table 8). The no contents type is used for infrastructure such as a runway or roadway, since they do not house any contents and would not require a CSVR calculation.

Table 8: Classification of structures based on use type

CSVR Category	CSVR References	CSVR Multiplier
Barracks	Multi-family	0.14
Office Space	Professional	0.43
Repair Facility	Repair	1.22
Utilities	Repair	1.22
Warehouse	Warehouse	0.85
NO CONTENTS	N/A	0

(Source: Data adapted from U.S. Army Corps of Engineers 2006b)

Gathering Data for Assets on Military Installations

The military maintains a real property database, which classifies all property owned by the Department of Defense. The database contains specific data elements for each property, including square footage, facility classification, and Plant Replacement Value (PRV). PRV is the dataset which this research will use to calculate a structure's flood damage costs, based on its depth damage percentage. PRV is the total cost to replace the asset using current construction costs (Department of Defense 2011).

This research uses data directly from the NAVFAC iNFADS database for Naval Station Norfolk. The data elements of Facility Name and Plant Replacement Value are obtained from iNFADS. In addition, three more data elements are required to be input for each asset: (1) construction type, (2) asset use, and (3) first floor elevation above a given datum. The construction type and asset use classifications are needed to select the corresponding depth damage relationship. They are not included in the iNFADS real property database. In order to estimate damages using depth damage curves, the elevation of the first floor of the structure above a datum also needs to be specified. This elevation is not included in the iNFADS database, but it is usually available in a GIS database or on building plans. In order to use the method that will be outlined in this research, local personnel must gather and input these three data points for each asset to be analyzed.

Determining Expected Monetary Value of Future Flood Damage

Once an asset's construction type and use have been determined, the appropriate depth damage curve for that asset can be identified. Next, the height of the asset's first floor elevation is compared to the Maximum Water Level (MWL) projection for a future year. Using the asset's depth damage curve, a probability and monetary impact can be calculated for each height of potential flooding in a given year. These probabilities and costs are combined to give an Expected Monetary Value (EMV) of the cost of flooding for any time period. This process of using depth damage curves and floodwater height projections to predict EMV is outlined in detail in the next chapter of this report.

Chapter 8: Expected Monetary Value Analysis for Navy Assets

Decision trees are visual models which have been used over the past fifty years to evaluate risk, especially in cases that involve uncertainty. The combination of probability and either a monetary payoff or loss within a decision tree creates an Expected Monetary Value (EMV). Expected Monetary Value is not the actual monetary payoff or loss received, but it is in an indicator of the monetary risk involved in the decision. Decision trees help managers make decisions under uncertainty by clarifying "the choices, risks, objectives, monetary gains, and information needs involved in an investment problem" (Magee 1964). Decision trees can provide results in qualitative or quantitative formats.

For example, a qualitative decision tree can be created to illustrate whether to hold a graduation party inside or outside, with a chance of rain in the forecast (Figure 37). The decision maker will assess the situation and make a choice based on the probability of rain

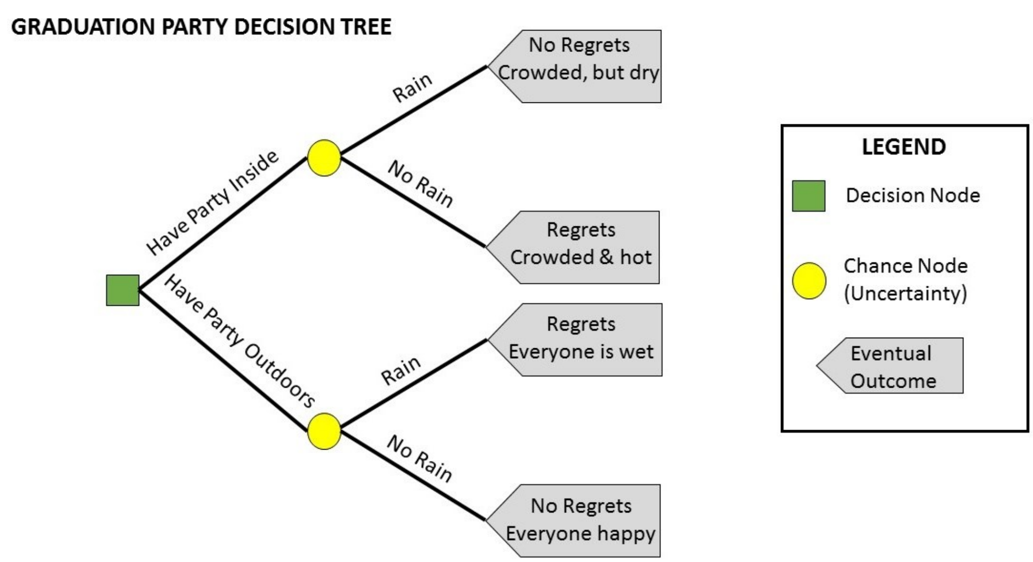


Figure 37: Example of a qualitative decision tree
(Source: Adapted from Magee 1964)

and the best possible outcome. The decision node illustrates the choices available to the planner, and the chance nodes show the possible outcomes. Reading left to right, from the decision node to the eventual outcomes, the outcomes are dependent on the chain of events. Both the decision made (indoors or outdoors) and the chance (rain or no rain) affect each outcome.

Adding financial information and probabilistic values to the decision tree produces a quantitative result, often called Expected Monetary Value (EMV) or Expected Value. Expected Monetary Value illustrates the relative economic value (or cost savings) of a series of inter-related events. EMV does not represent the exact expenditures related to a one-time decision, but it shows which investment alternative provides the highest likelihood of financial gain or least cost (Magee 1964). This type of analysis will be used to show the possible economic impacts due to sea level rise on naval installations.

Quantitative Decision Tree Analysis

As shown in the previous section, a decision tree builds from left to right, with the choices (Decision Nodes) indicated by boxes and the potential options coming off of the boxes as branches of the tree. Uncertainties (Chance Nodes) are indicated by circles, with the potential outcomes coming off the circles as more branches. Each potential outcome has an associated probability and monetary outcome. This eventual monetary outcome of a given path is written at the end of the path, on the tree's "leaves." The probability of occurrence of each branch originating from a Chance Node is written under the respective branch. The sum of all probabilities of branches originating from any Chance Node equals 1, or 100%.

Expected Monetary Value is calculated for each chance node by summing the probability multiplied by the monetary outcome for each branch (Equation 48). EMV for the node is typically written in a box over the chance node. To make a decision of least economic risk, the decision maker chooses the path from the Decision Nodes to the Chance Nodes that lead to the most advantageous EMVs.

$$EMV = \sum_{i=0}^{n} P(Future\ Event)_i * (Monetary\ Outcome\ of\ Future\ Event)_i \qquad (48)$$

Decision tree analysis is well suited for decisions about sea level rise adaptation measures, as they involve both probability and monetary outcomes related to the Chance Node. The Chance Node incorporates the probabilities, and associated damage costs, related to potential Maximum Water Levels of flooding in future years.

This chapter will analyze one hypothetical asset aboard Naval Station Norfolk in a future year as an example. However, the same approach can be used to analyze all facilities on a military installation and highlight which are the most vulnerable and cost-effective to protect. Due to the sensitive nature of identifying vulnerabilities aboard a military base, the example facility is not described in detail, but will be called Asset #2.

Using Depth Damage Curves to Find Monetary Outcomes

The depth damage curves discussed in the previous chapter are used to estimate the cost of damage which a building may incur due to different flood heights. This monetary outcome can be combined with the probability of future flood events to predict an Expected Monetary Value of possible flood damage.

In order to utilize the correct information from the depth damage curves used in this study, specific information about the asset is needed. The asset-specific data needed is: (1) the height of the first floor height above a selected datum, (2) the current replacement value, (3) the construction type, and (4) the building's use. For example, Asset #2 is an office building with a first floor elevation of 3.02 meters above MLLW, a $30,000,000 replacement cost, and built with masonry construction (Figure 38).

Using the correct datum for the building's finished first floor elevation is critical. Construction projects can be built too low or too high when the datum is confused. A

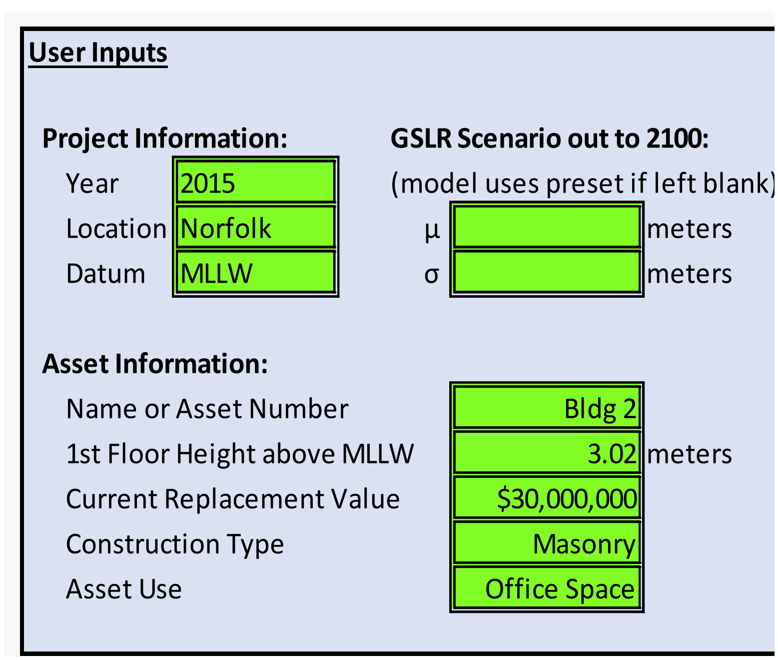


Figure 38: Asset information needed for using depth damage curves

datum is a reference point used for taking elevation measurements from. Two different datums are commonly used in coastal construction, MLLW and NAVD88. The datum typically used by coastal engineers and NOAA's National Ocean Service is Mean Lower Low Water (MLLW), which is the average of the daily lower low water level at a specific tidal gauge over a 19 year period called the National Tidal Datum Epoch (NTDE). NOAA is currently using the 1983-2001 NTDE. The North American Vertical Datum of 1988 (NAVD88), a set of fixed reference points in North America, is most often used by civil engineers in building plans. MLLW varies per location, while NAVD88 is the same reference plane at every location in the United States. Military installations also use a station datum (STND) which is a locally managed datum commonly used for elevation measurements.

The building's Plant Replacement Value (PRV) from the Navy's iNFADS database is the cost, in constant dollars, to completely replace the asset and achieve the same functionality (Department of Defense 2003). Constant dollars, which do not account for inflation, are used in the calculation of investment decisions for federal government assets (Office of Management and Budget 1992). PRV is used, along with depth damage curves, for calculating flood damage as a percentage of the building's total value. The building's construction type determines which depth damage curve is used for the analysis: either metal, masonry, steel, or wood framing.

For example, for Asset #2, since the building is masonry construction, the depth damage values for masonry are selected from Table 6. For example, for a flood water level between 0.15 meters (0.5 ft) and 0.30 meters (1 ft) inside Asset #2, the DDC% for masonry construction of 17.7% is used. The DDC% chosen is that of the top end of the flood range, in order to be more conservative than when using the bottom of the range. With a flood of 0.2 meters (0.66 ft), the DDC% of 17.7%, which corresponds to 0.30 meters (1 ft) of flooding is chosen. Ideally the DDC would be expressed as a continuous polynomial function in order to return a discrete value for every flood depth. Without this detail, the most conservative option is to use the DDC% corresponding to the top of the flood range and slightly overestimate the damage cost.

The Content to Structure Value Ratio (CSVR) is assigned based on what the facility is used for: barracks, office space, repair facility, utilities, or warehouse. Because it is an office building, the CSVR multiplier used is 0.43, as shown in Table 8.

Table 9 summarizes the asset's information and the DDC% and CSVR that apply to its analysis.

Table 9: Masonry depth damage curve for Asset #2 analysis

Name or Asset Number	Bldg 2
1st Floor Height above MLLW (m)	3.02
Current Replacement Value	$30,000,000
Construction Type	Masonry
Asset Use, CSVR= 0.43	Office Space

Flood Range Inside Bldg (ft)	Flood Range Inside Bldg (m)	DDC% for Masonry
<-0.5 ft	< -0.15 m	0.00%
-0.5 to 0.0 ft	-0.15 to 0 m	0.55%
0.0 to 0.5 ft	0 to 0.15 m	13.7%
0.5 to 1.0 ft	0.15 to 0.3 m	17.7%
1.0 to 1.5 ft	0.3 to 0.46 m	20.4%
1.5 to 2.0 ft	0.46 to 0.61 m	22.3%
2.0 to 3.0 ft	0.61 to 0.91 m	24.8%
3.0 to 4.0 ft	0.91 to 1.22 m	29.2%
4.0 to 5.0 ft	1.22 to 1.52 m	29.7%
5.0 to 6.0 ft	1.52 to 1.83 m	31.5%
6.0 to 7.0 ft	1.83 to 2.13 m	33.1%
7.0 to 8.0 ft	2.13 to 2.44 m	41.4%
8.0 to 9.0 ft	2.44 to 2.74 m	48.6%
9.0 to 10.0 ft	2.74 to 3.05m	51.5%
10.0 to 11.0 ft	3.05 to 3.35 m	53.9%
11.0 to 12.0 ft	3.35 to 3.66 m	56.9%
12.0 to 13.0 ft	3.66 to 3.96 m	57.2%
13.0 to 14.0 ft	3.96 to 4.27 m	58.5%
> 14.0 ft	> 4.27 m	58.6%

(Source: DDC% adapted from U.S. Army Corps of Engineers 2006b)

Estimating Monetary Outcome Based on Flood Heights

A depth damage percentage (DDC%) is associated with each flood water level from -0.15 m to 4.57 m (-0.5 ft to 15 ft), relative to the finished first floor of the building. The Estimated Damage Cost (EDC) to the structure, including its contents, is calculated using the structure's Plant Replacement Value (PRV):

$$Estimated\ Damage\ Cost\ (EDC) = (DDC\% * PRV) + ((DDC\% * PRV) * CSVR) \quad (49)$$

$$Estimated\ Damage\ Cost\ (EDC) = (DDC\% * PRV) * (1 + CSVR) \quad (50)$$

Using Equation (50), the Estimated Damage Cost of the structure (monetary outcome) and its contents can be calculated for each corresponding floodwater height range inside a building of a certain construction type and use category. For example, Asset #2's Estimated Damage Cost for a flood in the range between 0.15 meters and 0.30 meters within the building would be:

$$EDC_{\ 0.15m-0.3\ m\ flood, Asset\ \#2} = (17.7\% * \$30{,}000{,}000) * (1 + 0.43) \quad (51)$$

$$EDC_{\ 0.15m-0.3\ m\ flood, Asset\ \#2} = \$7{,}570{,}000 \quad (52)$$

Table 10 shows the Estimated Damage Cost for Asset #2 for each of the potential flood ranges specified in the Depth Damage Curves. The Estimated Damage Cost for each flood range indicates the estimated cost to repair the asset, if flooding with a Maximum Water Level in that range were to occur.

Table 10: Estimated Damage Cost (EDC) for Asset #2

Name or Asset Number	Bldg 2
1st Floor Height above MLLW (m)	3.02
Current Replacement Value	$30,000,000
Construction Type	Masonry
Asset Use, CSVR= 0.43	Office Space

Flood Range Inside Bldg (ft)	Flood Range Inside Bldg (m)	DDC% for Masonry	Estimated Damage Cost (EDC)
<-0.5 ft	< -0.15 m	0.00%	$ -
-0.5 to 0.0 ft	-0.15 to 0 m	0.55%	$ 235,950
0.0 to 0.5 ft	0 to 0.15 m	13.7%	$ 5,877,300
0.5 to 1.0 ft	0.15 to 0.3 m	17.7%	$ 7,571,850
1.0 to 1.5 ft	0.3 to 0.46 m	20.4%	$ 8,730,150
1.5 to 2.0 ft	0.46 to 0.61 m	22.3%	$ 9,566,700
2.0 to 3.0 ft	0.61 to 0.91 m	24.8%	$ 10,639,200
3.0 to 4.0 ft	0.91 to 1.22 m	29.2%	$ 12,526,800
4.0 to 5.0 ft	1.22 to 1.52 m	29.7%	$ 12,719,850
5.0 to 6.0 ft	1.52 to 1.83 m	31.5%	$ 13,513,500
6.0 to 7.0 ft	1.83 to 2.13 m	33.1%	$ 14,199,900
7.0 to 8.0 ft	2.13 to 2.44 m	41.4%	$ 17,760,600
8.0 to 9.0 ft	2.44 to 2.74 m	48.6%	$ 20,827,950
9.0 to 10.0 ft	2.74 to 3.05m	51.5%	$ 22,072,050
10.0 to 11.0 ft	3.05 to 3.35 m	53.9%	$ 23,123,100
11.0 to 12.0 ft	3.35 to 3.66 m	56.9%	$ 24,388,650
12.0 to 13.0 ft	3.66 to 3.96 m	57.2%	$ 24,538,800
13.0 to 14.0 ft	3.96 to 4.27 m	58.5%	$ 25,075,050
> 14.0 ft	> 4.27 m	58.6%	$ 25,139,400

(Source: DDC% adapted from U.S. Army Corps of Engineers 2006b)

Assessing the Probability of Flooding

Once the correct depth damage curve has been selected, the building's first floor height is compared to the Maximum Water Level (MWL) predicted in a given year at that location. The MWL calculations were detailed previously in Chapter 6. The elevation of the finished first floor of the building is compared to the mean of the normal distribution of the Maximum Water Level flood projection. From this, the probability is calculated of the MWL reaching each of the floodwater ranges set by the depth damage curve.

To calculate the probability of specific floodwater heights inside the building, several different calculations are required. The water level height needed to reach each specific flood range in the depth damage curves is calculated by adding these ranges to the building's first floor elevation (Equation 53).

$$Water\ Level\ for\ h\ meters\ of\ flooding = Bldg's\ 1st\ Floor\ Elevation + h \qquad (53)$$

$$Water\ Level\ for\ 0.3\ meters\ of\ flooding_{Asset\ \#2} = 3.02\ m + 0.305\ m \qquad (54)$$

For example, to calculate the water level height which would correspond to 0.305 m (1.0 ft) of flooding above the finished first floor of Asset #2, 0.305 m (1.0 ft) is added to the building's elevation of 3.02 meters above MLLW, indicating that 3.33 meters of flooding is required for the building to flood 0.305 meters, or one foot.

To determine the probability of the Maximum Water Level height reaching 3.33 meters in a given year, the normal distribution density function, f(z), is used to find the area under the curve for the LMWL normal distribution. In the year 2046, the predicted Local Maximum Water Level (LMWL) is described as a normal distribution with μ=2.14

m and σ=0.323 m (Table 5). The F(z) function is used to determine the probability of occurrence of a specific water level height.

$$z = \frac{(Water\ Level\ Flood\ Height - \mu_{LMWL})}{\sigma_{LMWL}} \tag{55}$$

The z term indicates the standard normal variate, defined as the number of standard deviations away from the mean that the water level flood height is. For example, for a normal distribution, a z value of 1.0 yields an area under the f(z) curve of 0.34. This indicates that 34% of values are between the mean and one standard deviation. If the z value is positive, the probability is added to 0.50, which is the area under the curve up to the mean. If the z value is negative, the probability is subtracted from 0.50.

The result for this example of 3.33 meters of flood water is:

$$z = \frac{(3.33\ m - 2.14\ m)}{0.323\ m} = 3.66 \tag{56}$$

For the Norfolk Asset #2 example, the z value was 3.66 for a flood height of 0.305 meters (1.0 ft). This means that, in order to achieve 0.305 meters of flooding in Asset #2 in the year 2046, the Maximum Water Level that year must be 3.66 standard deviations higher than the expected MWL in 2046. Using a normal distribution z-table or the =NORMDIST function in Excel with the standard normal variate, a z value of 3.66 yields a probability of 99.987%. This percentage is the probability that the maximum floodwater height in a given year will be less than 3.33 meters (Figure 39). Therefore, the probability of the building flooding more than 0.305 meters is very remote, 0.013%.

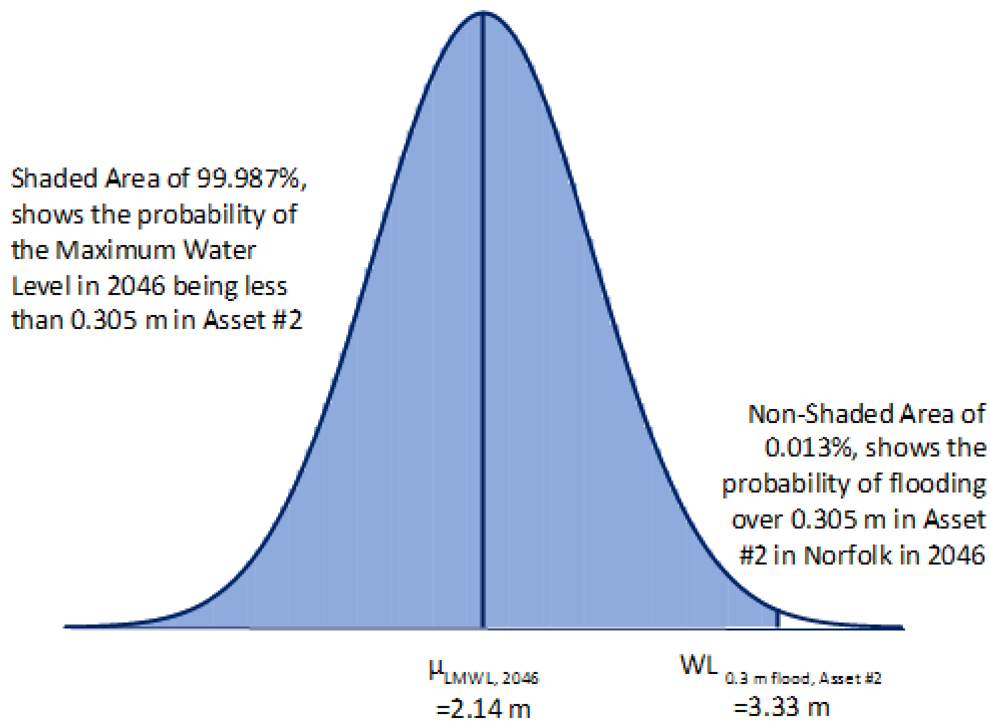


Figure 39: Normal probability distribution for Asset #2 with a 0.305 m flood in the year 2046

To apply the depth damage curve and EMV analysis, it is necessary to calculate the probability that the floodwater height inside the building will be within the ranges specified in the depth damage curve table. For Asset #2, the probability of the floodwater height being less than 0.15 meters (0.5 ft) inside the building, a water level height of 3.17 meters, would be 99.928%. The cumulative area under the curve up to a 0.305 meter flood is 99.987%. The cumulative area under the curve up to a 0.15 meter flood is 99.928%. To determine the probability of flooding the building at a range between 0.15 meters and 0.30 meters, the probability of floodwater (FW) inside the building at 0.15 meters is subtracted from the probability of floodwater at 0.305 meters.

$$P(0.15m < FW < 0.3m) = P(FW < 0.3m) - P(FW < 0.15m) \qquad (57)$$

For the example of Asset #2 in 2046, the probability that the maximum floodwater will be in the range from 0.15 meters to 0.305 meters is:

$$P(0.15m < FW < 0.3m) = 99.987\% - 99.928\% = 0.059\% \quad (58)$$

Following this same approach, the probability of the maximum flood height for each of the depth damage curve ranges are calculated. The sum of all the probabilities associated with different flood height ranges in each year equals 100%.

Table 11 summarizes the probability of flooding for Asset #2 in 2046, for each of the DDC flood ranges.

Table 11: Probability of annual Maximum Water Level within each flood range

Name or Asset Number	Bldg 2		PREDICTED ANNUAL MWL (m MLLW)	PREDICTED ANNUAL STD DEV OF MWL (m MLLW)
1st Floor Height above MLLW (m)	3.02			
Current Replacement Value	$30,000,000			
Construction Type	Masonry	FUTURE YEAR		
Asset Use, CSVR=0.43	Office Space	2046	2.1436	0.3228

Flood Range Inside Bldg (ft)	Flood Range Inside Bldg (m)	DDC% for Masonry	Estimated Damage Cost (EDC)	Probability of Annual MWL in Flood Range
<-0.5 ft	< -0.15 m	0.00%	$ -	98.7544%
-0.5 to 0.0 ft	-0.15 to 0 m	0.55%	$ 235,950	0.9141%
0.0 to 0.5 ft	0 to 0.15 m	13.7%	$ 5,877,300	0.2596%
0.5 to 1.0 ft	0.15 to 0.3 m	17.7%	$ 7,571,850	0.0592%
1.0 to 1.5 ft	0.3 to 0.46 m	20.4%	$ 8,730,150	0.0109%
1.5 to 2.0 ft	0.46 to 0.61 m	22.3%	$ 9,566,700	0.0016%
2.0 to 3.0 ft	0.61 to 0.91 m	24.8%	$ 10,639,200	0.0002%
3.0 to 4.0 ft	0.91 to 1.22 m	29.2%	$ 12,526,800	0.0000%
4.0 to 5.0 ft	1.22 to 1.52 m	29.7%	$ 12,719,850	0.0000%
5.0 to 6.0 ft	1.52 to 1.83 m	31.5%	$ 13,513,500	0.0000%
6.0 to 7.0 ft	1.83 to 2.13 m	33.1%	$ 14,199,900	0.0000%
7.0 to 8.0 ft	2.13 to 2.44 m	41.4%	$ 17,760,600	0.0000%
8.0 to 9.0 ft	2.44 to 2.74 m	48.6%	$ 20,827,950	0.0000%
9.0 to 10.0 ft	2.74 to 3.05m	51.5%	$ 22,072,050	0.0000%
10.0 to 11.0 ft	3.05 to 3.35 m	53.9%	$ 23,123,100	0.0000%
11.0 to 12.0 ft	3.35 to 3.66 m	56.9%	$ 24,388,650	0.0000%
12.0 to 13.0 ft	3.66 to 3.96 m	57.2%	$ 24,538,800	0.0000%
13.0 to 14.0 ft	3.96 to 4.27 m	58.5%	$ 25,075,050	0.0000%
> 14.0 ft	> 4.27 m	58.6%	$ 25,139,400	0.0000%

(Source: DDC% adapted from U.S. Army Corps of Engineers 2006b)

Calculating Economic Risk for an Asset

Once the probability and associated damage cost for each flood range have been determined, the Expected Monetary Value (EMV) of flooding costs in that year can be calculated. EMV equals the sum of the probabilities times the damage cost for each flood range *k*. The Expected Monetary Value for the selected year is calculated using Equation (48).

$$EMV = \sum_{k=0}^{K} P(Floodwater\ Height)_k * Estimated\ Damage\ Cost_k \qquad (48)$$

where *k* represents the specified range of floodwater (FW) height inside the building and *K* is the highest floodwater height for which Estimated Damage Costs (EDC) are determined.

EMV represents the average expected cost of damage due to flooding in that year. The true cost may be higher or it may be lower. In most years, the damage cost will be lower than EMV. However, in some years, damage costs will be significantly higher than EMV.

For Asset #2 in 2046, the EMV of each flood range is calculated by multiplying the probability of flooding within each range by the damage cost due to flooding in that range. For example, using the results from Equation (52) for the probability of flooding in the range from 0.15 meters to 0.3 meters and Equation (58) for the Estimated Damage Cost of a 0.3 meter flood of Asset #2, the EMV can be determined for that specific flood range:

$$EMV_{0.15m-0.3m} = P(0.15m < FW < 0.3m) * (EDC\ _{0.15m-0.3m\ flood,Asset\ \#2}) \qquad (59)$$

$$EMV_{0.15m-0.3m} = 0.059\% * \$7{,}570{,}000 \qquad (60)$$

$$EMV_{0.15m-0.3m} = \$4{,}480 \quad (61)$$

Table 12 summarizes the EMV associated with flood damage of Asset #2 in 2046, for each of the DDC flood ranges. The Total Expected Monetary Value is the sum of the EMV's for all flood ranges from -0.15 meters (-0.5 ft) to 4.57 meters (15 ft) during a given year. The Total EMV for Asset #2 in the year 2046 is $23,000 of flood damage costs. This

Table 12: Expected Monetary Value of flood damage in the year 2046 for Asset #2

Name or Asset Number	Bldg 2		PREDICTED ANNUAL MWL (m MLLW)	PREDICTED ANNUAL STD DEV OF MWL (m MLLW)
1st Floor Height above MLLW (m)	3.02			
Current Replacement Value	$30,000,000			
Construction Type	Masonry	FUTURE YEAR		
Asset Use, CSVR=0.43	Office Space	2046	2.1436	0.3228

Flood Range Inside Bldg (ft)	Flood Range Inside Bldg (m)	DDC% for Masonry	Estimated Damage Cost (EDC)	Probability of Annual MWL in Flood Range, P(FW)	Annual P(FW)*EDC in Flood Range
<-0.5 ft	< -0.15 m	0.00%	$ -	98.7544%	$ -
-0.5 to 0.0 ft	-0.15 to 0 m	0.55%	$ 235,950	0.9141%	$ 2,157
0.0 to 0.5 ft	0 to 0.15 m	13.7%	$ 5,877,300	0.2596%	$ 15,260
0.5 to 1.0 ft	0.15 to 0.3 m	17.7%	$ 7,571,850	0.0592%	$ 4,485
1.0 to 1.5 ft	0.3 to 0.46 m	20.4%	$ 8,730,150	0.0109%	$ 948
1.5 to 2.0 ft	0.46 to 0.61 m	22.3%	$ 9,566,700	0.0016%	$ 153
2.0 to 3.0 ft	0.61 to 0.91 m	24.8%	$ 10,639,200	0.0002%	$ 22
3.0 to 4.0 ft	0.91 to 1.22 m	29.2%	$ 12,526,800	0.0000%	$ 0.18
4.0 to 5.0 ft	1.22 to 1.52 m	29.7%	$ 12,719,850	0.0000%	$ 0.0005
5.0 to 6.0 ft	1.52 to 1.83 m	31.5%	$ 13,513,500	0.0000%	$ 0.0000007
6.0 to 7.0 ft	1.83 to 2.13 m	33.1%	$ 14,199,900	0.0000%	$ -
7.0 to 8.0 ft	2.13 to 2.44 m	41.4%	$ 17,760,600	0.0000%	$ -
8.0 to 9.0 ft	2.44 to 2.74 m	48.6%	$ 20,827,950	0.0000%	$ -
9.0 to 10.0 ft	2.74 to 3.05m	51.5%	$ 22,072,050	0.0000%	$ -
10.0 to 11.0 ft	3.05 to 3.35 m	53.9%	$ 23,123,100	0.0000%	$ -
11.0 to 12.0 ft	3.35 to 3.66 m	56.9%	$ 24,388,650	0.0000%	$ -
12.0 to 13.0 ft	3.66 to 3.96 m	57.2%	$ 24,538,800	0.0000%	$ -
13.0 to 14.0 ft	3.96 to 4.27 m	58.5%	$ 25,075,050	0.0000%	$ -
> 14.0 ft	> 4.27 m	58.6%	$ 25,139,400	0.0000%	$ -
				Annual EMV $_{Asset \#2,\ 2046}$ =	**$ 23,025**

(Source: DDC% adapted from U.S. Army Corps of Engineers 2006b)

means that, if no action is taken to protect Asset #2 before then, Navy decision makers should budget over $23,000 for fixing flood damages occurring in the year 2046. If flood damage does not occur, this money should be set aside and added to a similar account budgeted for the following year to pay for flood damage. It is highly likely (P = 98.75%) that no flood damage will occur in 2046. However, there is a slight chance (P = 1.25%) that significant damage will occur. Annualized, these damage costs equal $23,000.

The EMV result is most useful when comparing this projected flood damage cost to an adaptation alternative in future years, such as wet floodproofing the entire building (Figure 40). If the annualized cost to floodproof the building is $100,000, then it doesn't make sense to undertake this costly adaptation measure in 2046 when the EMV is only $23,000. However, if the aggregated experts' estimate of GSLR by 2100 as discussed in Chapter 4, is accurate, then by 2086 the building's annual EMV will have increased to $847,000. This is due to the climbing sea level and higher Local Maximum Water Levels in 2086. By this point, the EMV of the "Do Nothing," or unprotected "no adaptation,"

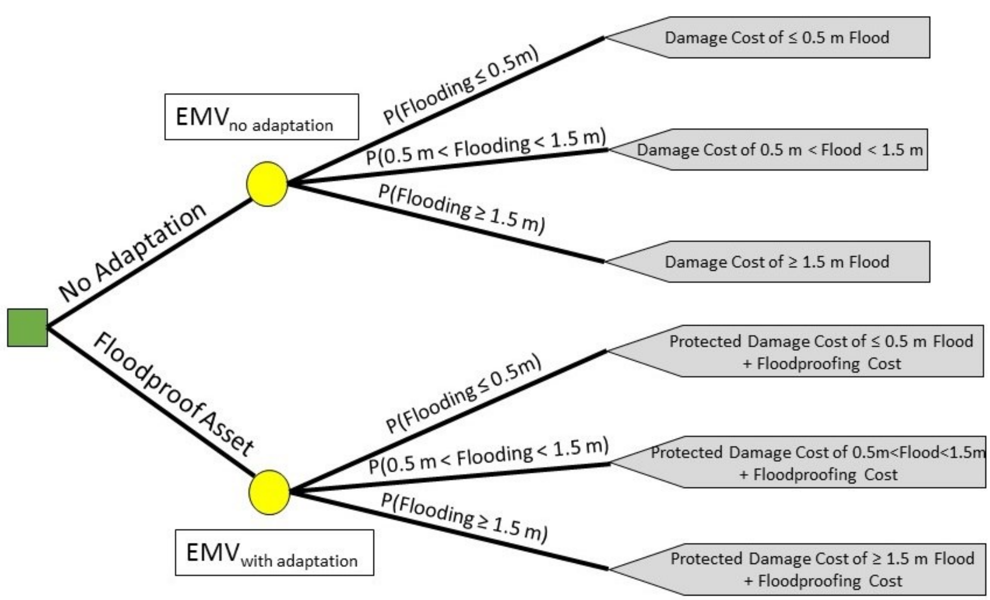


Figure 40: Simplified decision tree comparing future flood damage costs to the cost of floodproofing

option is far greater than the annualized cost to floodproof the building, and it makes economic sense to take this action. There is a tipping point at some year between 2046 and 2086 where the decision to floodproof has changed.

The utility of this method as a decision making tool is evident when the annual EMV for an asset is calculated for all years up to and including the year 2100 and compared to the annualized costs of various preventive measures. This decision-making methods will be discussed further in Chapter 9.

Chapter 9: Implementing Sea Level Adaptation (ISLA)

Tying all of the previous chapters together, the goal of this chapter is to provide a sea level rise decision tool that helps Navy facility managers make educated decisions about how to adapt to increased flood events. By combining Chapter 4's Global Sea Level Rise projections and Chapter 5's analysis of Local Sea Level Rise, Maximum Water Level projections in future years were calculated, as detailed in Chapter 6. Chapter 7 added Depth Damage Curves, and Chapter 8 incorporated decision tree methodology to calculate Expected Monetary Value for flood damage costs in future years. This chapter introduces Implementing Sea Level Adaptation (ISLA), a decision tool which compares the annual EMV of future flood damage cost to the annual cost of implementing adaptation measures.

Because sea level rise is a slow-moving threat and budgets are limited, the big question is "How does a planner know which adaptation measure to implement when?" Chapter 3 introduced a variety of options for protecting a structure from flood damage, ranging from floodproofing to relocation. Deciding which of these options makes the most economic sense, and at what time in the future, is the goal of this approach.

For Asset #2, one of the least expensive options for floodproofing the building is a temporary flood barrier. Temporary flood barriers are used across entrances for dry floodproofing a structure when a flood is impending. These flood barriers can be installed across a doorway to a building, access path through a levee, vehicular entrance, roadway, or any other entry point through a structure. The advantage of temporary flood barriers, such as the metal flood shield shown in Figure 41, is that they are fully removable when not in use. In order for the temporary flood barrier to be effective, the rest of the structure

Figure 41: Example of an aluminum flood shield deployed to protect a business
(Source: FEMA)

also needs to be impermeable to water. Masonry type construction is the most ideal to easily waterproof.

Since Asset #2 is a slab-on-grade masonry building which was sealed with a waterproof membrane to prevent groundwater seepage, a temporary flood barrier is a viable option for flood protection. For this building, low-cost flood shields can be installed up to 0.61 meters (2 feet) high above the finished first floor. If the flood shields were required to be higher than 0.61 meters, they would need to be built of a stronger material than a single sheet of aluminum in order to withstand the hydrostatic pressure due to a flood.

The cost to design, build and maintain the temporary flood barriers for all of the building's entrances for Asset #2 in the present year, 2015, is $50,000. This cost is input into ISLA as Net Present Value (NPV), which takes into account the adaptation measure's total cost over its design life, brought back to the present year using a given interest rate. The equation used to calculate Net Present Value is:

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} \tag{62}$$

where C_t is the adaptation measure's cost in year t, i is the interest rate, and n is the design life of the adaptation.

NPV for this example includes the initial investment for the flood barriers as well as the life-cycle costs of future maintenance and operations. Maintenance costs associated with temporary flood barriers include regular inspection and replacing of waterproof gaskets, as well as corrosion inspections of the associated mounting hardware. Operational costs consist of the labor required to deploy and remove the flood barriers in the event of a forecast flood. Both the maintenance and operational costs are relative to the number of future flood events.

The cost to floodproof the building is quite low because the exterior walls of Asset #2 were previously waterproofed during its construction. Thus, the only costs incurred to floodproof the building are for the temporary flood barrier and its attachment hardware. For structures that do not have waterproofed walls, or non-masonry construction which cannot be easily waterproofed, the cost of implementing similar temporary flood protection is significantly higher.

Calculating Future Cost of an Adaptation Measure

To use Decision Tree methods for determining if an adaptation measure is economically advantageous, a comparison of EMV's for each choice is required. The EMV calculated in the last chapter represents the "Do Nothing" option for Asset #2. The EMV of implementing the temporary flood barrier for this example can be calculated by combining the adaptation's annual life-cycle cost with the annual Expected Damage Cost (EDC) due to flooding. With the temporary flood barrier installed and providing enhanced protection for the structure, the annual EDC must be recalculated using the height of the adaptation measure.

As previously stated, the NPV of temporary flood barriers for Asset #2 in 2015 was $50,000. This cost is given in constant dollars, also called real dollars, which do not account for inflation. Constant dollars are used for federal government investment decisions due to the uncertainty in the inflation rate and the constant purchasing power of the real dollar approach (Office of Management and Budget 1992). The inflation-free interest rate, or the real interest rate, is used for constant dollar analysis.

The annual cost of the adaptation measure in a future year is found by using the general amortization equation:

$$A = P\frac{i\,(1+i)^n}{(1+i)^n - 1} \tag{63}$$

where A is the annual cost, P is the Net Present Value, i is the interest rate, and n is the design life. The remaining design life, n, of Asset #2 may not be the same n as the design life of the adaptation measure. To avoid confusion between unequal design lives, the

Capitalized Cost equation is used. The Capitalized Cost equation is Equation (63) with *n* equal to infinity. This yields the simplified equation:

$$A = P * i \tag{64}$$

where *A* is the amortized annual cost, *P* is the net present value and *i* is the interest rate.

A sensitivity analysis was conducted comparing the results of Equation (63) and Equation (64). Both equations converged to the same solution at *n* = 65 years when *i* was between 4% - 10%. Coincidentally, the average physical life of NAVFAC structures is estimated at 67 years (NAVFAC 2013). Even though estimating the design life at infinity for these structures is unrealistic, using the simplified Capitalized Cost equation provides an approximated annual cost for economic comparison.

Since this is a study of military facilities, *i* is the social discount rate, which is the interest rate applied to government projects. This inflation-free interest rate is input into ISLA by the user, and can be easily updated to achieve a sensitivity analysis of the investment at different interest rates. However, it is recommended to use a discount rate of 7% when comparing the benefits and costs of public investments (Office of Management and Budget 1992).

The Annual Capitalized Cost (ACC) of implementing temporary flood barriers for Asset #2 at Norfolk using *i* = 7% is:

$$ACC_n = \$50{,}000 * 7\% \tag{65}$$

$$ACC_n = \$3{,}500 \tag{66}$$

This means that an annual cost of $3,500 will be incurred if temporary flood barriers are built in any year after 2015.

Determining EMV with an Adaptation Measure Implemented

After the Annualized Capital Cost of an adaptation measure has been determined, one more calculation is necessary for comparison with the annual EMV of the "Do Nothing" option. For Asset #2, once the temporary flood barriers are installed and operational, they will protect against a flood that is less than 0.61 meters relative to the first floor of the building. Therefore, a new annual EMV of flood damage, with the protective flood barrier installed, must be calculated. The same calculations are used as in Chapter 8. However, damage will not occur unless flood waters exceed the protection height of the adaptation measure. For Asset #2 with temporary flood barriers deployed, this means that the building will not incur damage from flood heights below 3.63 meters (3.02 meters building height + 0.61 meters of flood barrier protection). When the floodwater height exceeds the protected height, damage will be the same as that of an unprotected asset, since flood waters will pour over the barrier and inundate the structure up to the flood height.

For Asset #2 in 2046, the vast majority of expected damage was due to floodwaters less than 0.61 meters inside the structure (see Table 12 in Chapter 8). Thus, by implementing the 0.61 meters temporary flood barriers before 2046, only the highest and least likely of floods (P=0.0023%) would remain a threat. The annual Estimated Damage Cost (EDC) with the temporary flood barriers implemented in the year 2046 for Asset #2 is calculated to be $175. This is significantly smaller than the annual EMV of the "Do Nothing" option in the same year which was $23,000.

To calculate the total annual EMV with adaptation, the new Estimated Damage Cost with the temporary flood barriers are combined with the annualized cost of the implemented adaptation measure. Annual EMV with adaptation will then be compared to the annual EMV without adaptation:

$$EMV_{w/\ adaptation} = \sum_{k=0}^{K} P(FW)_k * (EDC)_k + ACC \tag{67}$$

$$EMV_{w/\ adaptation,\ \ Asset\ \#2,\ \ 2046} = \$175 + \$3{,}500 \tag{68}$$

$$EMV_{w/\ adaptation,\ \ Asset\ \#2,\ \ 2046} = \$3{,}675 \tag{69}$$

where *EMV* is Expected Monetary Value, *P(FW)* is the probability of flooding inside the structure to a specified height range *k*, *EDC* is the Estimated Damage Cost due to flooding to the specified height range *k*, and *ACC* is the Annualized Capital Cost to implement the adaptation measure in a given year.

Table 13 shows how the annual EMV for Asset #2 with the temporary flood barriers employed compares to the annual EMV without any adaptation measures.

Table 13: Annual EMV with adaptation measure implemented in future years

Year Built	EMV without adaptation	Future Cost of Prev Measure	Annualized Capital Cost of Prev Measure	SUM {P(FW)*EDC} with adaptation	EMV with adaptation
2015	$58	$50,000	$3,500	$0	$3,500
2016	$76	$50,000	$3,500	$0	$3,500
2017	$98	$50,000	$3,500	$0	$3,500
2018	$127	$50,000	$3,500	$0	$3,500
2019	$163	$50,000	$3,500	$0	$3,500
2020	$208	$50,000	$3,500	$0	$3,500
…	…	…	…	…	…
2044	$17,518	$50,000	$3,500	$112	$3,612
2045	$20,113	$50,000	$3,500	$140	$3,640
2046	$23,025	$50,000	$3,500	$175	$3,675

Determining Annual Savings and Tipping Point of Adaptation Decisions

Once the new annual EMV with protection is calculated, the Annual Savings for the adaptation measure can be determined for each year. The Annual Savings is the difference between the annual EMV with no adaptation measures and the annual EMV with adaptation.

$$Annual\ Savings = EMV_{without\ adaptation} - EMV_{with\ adaptation} \tag{70}$$

The highlighted row in Table 14, year 2034, shows the Tipping Point for Asset #2 with temporary flood barriers implemented. The Tipping Point is the year where the

Table 14: Comparing annual savings of EMV with and without adaptation measures implemented

Year Built	EMV without adaptation	Future Cost of Prev Measure	Annualized Capital Cost of Prev Measure	SUM {P(FW)*EDC} with adaptation	EMV with adaptation	Annual Savings of EMV's
2015	$58	$50,000	$3,500	$0	$3,500	-$3,442
2016	$76	$50,000	$3,500	$0	$3,500	-$3,424
2017	$98	$50,000	$3,500	$0	$3,500	-$3,402
2018	$127	$50,000	$3,500	$0	$3,500	-$3,373
2019	$163	$50,000	$3,500	$0	$3,500	-$3,337
2020	$208	$50,000	$3,500	$0	$3,500	-$3,292
...	...	...	...	...	...	...
2031	$2,140	$50,000	$3,500	$4	$3,504	-$1,364
2032	$2,573	$50,000	$3,500	$5	$3,505	-$932
2033	$3,080	$50,000	$3,500	$7	$3,507	-$426
2034	$3,674	$50,000	$3,500	$9	$3,509	$165
2035	$4,364	$50,000	$3,500	$12	$3,512	$853
...	...	...	...	...	...	...
2041	$11,361	$50,000	$3,500	$55	$3,555	$7,806
2042	$13,167	$50,000	$3,500	$70	$3,570	$9,597
2043	$15,211	$50,000	$3,500	$89	$3,589	$11,622
2044	$17,518	$50,000	$3,500	$112	$3,612	$13,906
2045	$20,113	$50,000	$3,500	$140	$3,640	$16,473
2046	$23,025	$50,000	$3,500	$175	$3,675	$19,350

adaptation measure becomes more economical than not having protection against flood damage. This is where the Annual Savings switches from being a negative number to a positive number (Figure 42). However, to be more conservative and prevent future flood damage, ISLA recommends to implement the preventive measure the year prior, in 2033.

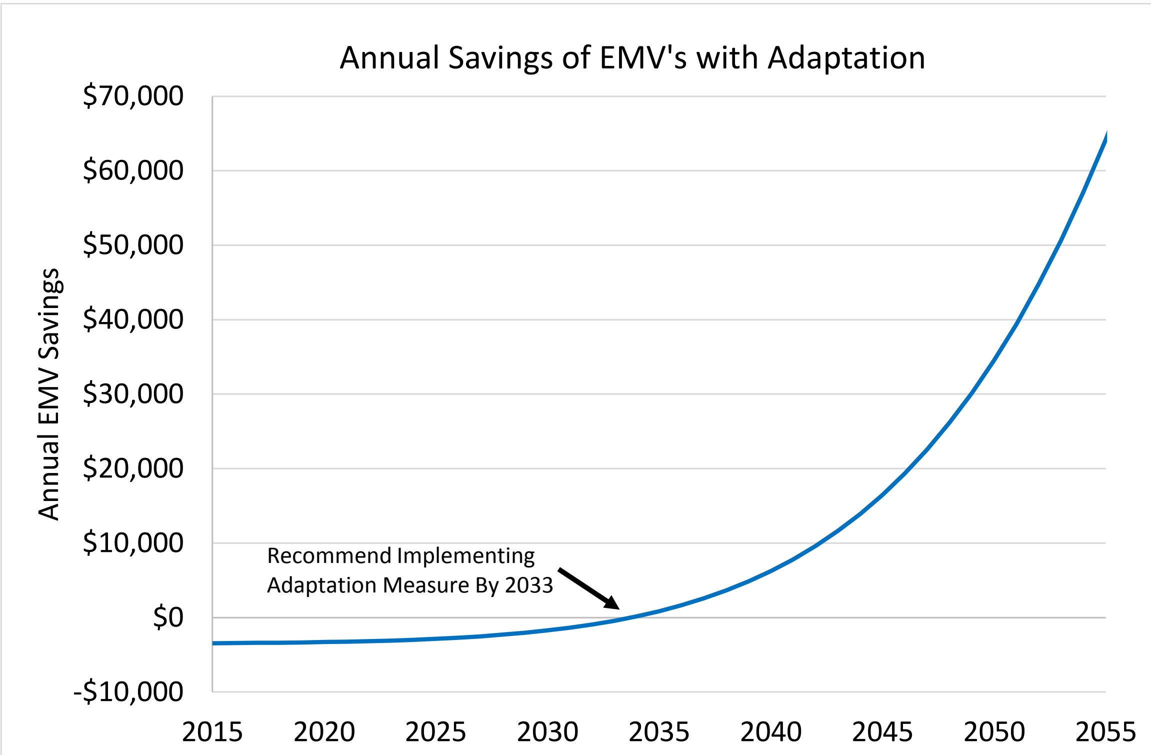


Figure 42: Annual Savings due to implementing temporary flood barrier adaptation measure

If a Tipping Point never occurs for a particular adaptation measure, meaning the annual savings remain negative until 2100, then the implementation of a preventive measure is not recommended. This instance occurs when the cost to implement this measure is so much greater than the threat of flood damage that it is not cost effective. Conversely, if the Annual Savings indicates a positive number in the current year, then it is recommended to implement the preventive measure as soon as possible, due to the cost savings immediately provided in case of a flood.

Figure 43 illustrates the comparison of the Annual Expected Monetary Values with and without the implementation of the temporary flood barrier adaptation. The Tipping Point is shown at 2033, as it was in Figure 42.

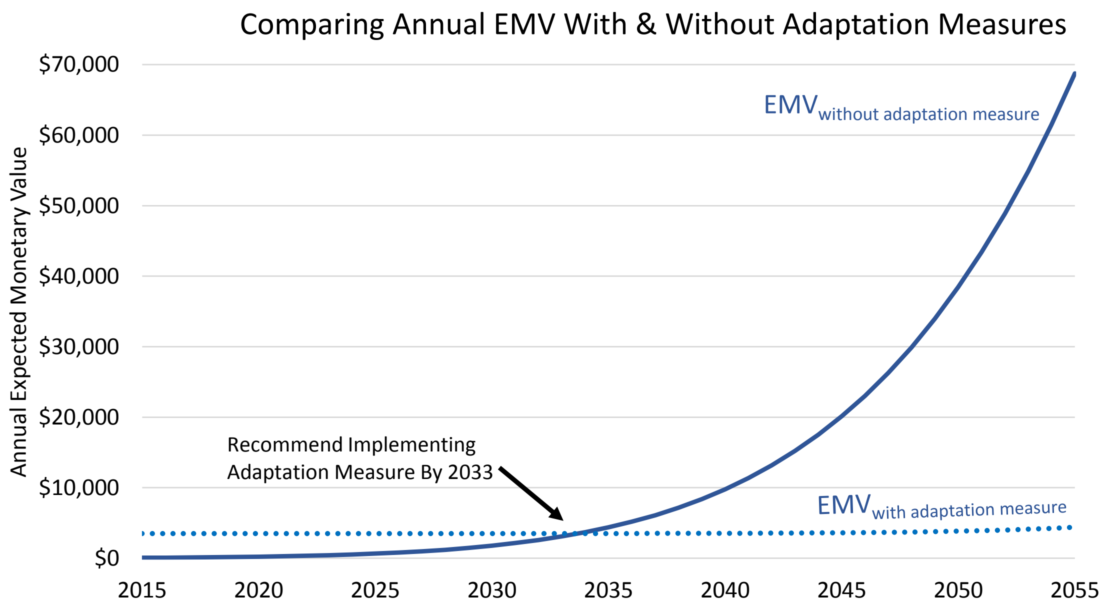


Figure 43: EMV Comparison indicating when to implement a chosen adaptation measure

Sensitivity Analysis of ISLA

ISLA provides the ability to easily compare the output given a variety of input parameters. Using the case study of Asset #2 and Preventive Measure A previously introduced, a sensitivity analysis was conducted to find the effects of varying the annual interest rate and the GSLR variance. Other input parameters can be varied as required by the user to meet their specific decision making needs.

The results of varying the annual interest rate are shown in Table 15, with the year 2060 EMV's shown as a comparison baseline. As the annual interest rate increases from 0 to 7 percent, the recommendation for when to implement Preventive Measure A is delayed. With ISLA's Constant Dollar analysis, the annual interest rate is only used in Equation (64) for calculating the Capitalized Cost of the preventive measure in the future, and thus does not have a significant impact.

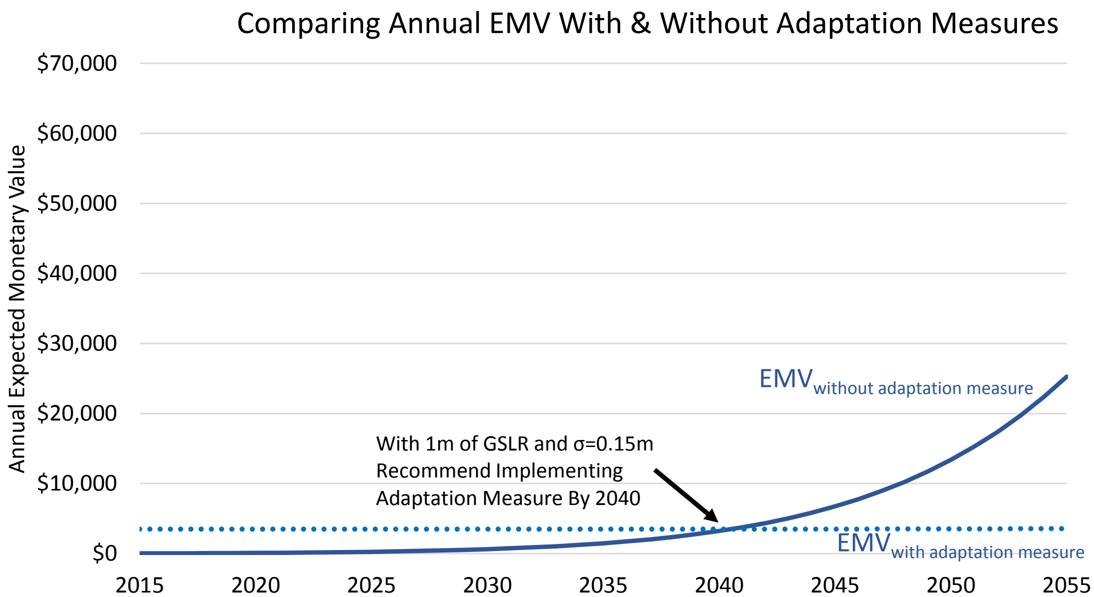
Table 15: Sensitivity analysis with varied annual interest rate

Annual Interest Rate	Year Recommended to Implement A	2060 EMV_{do} nothing option	2060 EMV_{with} Prev Measure A
0.0%	2015	$116,000	$2,600
0.5%	2020	$116,000	$2,800
1.0%	2023	$116,000	$3,100
1.5%	2025	$116,000	$3,300
2.0%	2028	$116,000	$3,600
2.5%	2029	$116,000	$3,800
3.0%	2029	$116,000	$4,000
3.5%	2029	$116,000	$4,300
4.0%	2030	$116,000	$4,600
4.5%	2031	$116,000	$4,800
5.0%	2031	$116,000	$5,000
5.5%	2032	$116,000	$5,300
6.0%	2033	$116,000	$5,600
6.5%	2033	$116,000	$5,800
7.0%	2033	$116,000	$6,000

Another parameter analyzed was the standard deviation of the Global Sea Level Rise Estimate. In Chapter 4, the aggregated GSLR projection by the year 2100 for use in this study was determined to be a mean of 1.0 meters and a standard deviation of 0.277 meters. Fixing the mean at 1.0 meters and varying the standard deviation had an interesting result. Table 16 shows the results of this investigation, with the year 2060 EMV's used again as a comparison baseline. As the standard deviation of the GSLR estimate increases, the recommendation of when to implement Preventive Measure A moves earlier. This is because the probability of future flooding increases with higher standard deviations. With more flood damage projected to occur sooner, the EMV curve for the "Do Nothing" option becomes more vertical earlier and intercepts the EMV curve for Preventive Measure A at an earlier year (Figure 44).

Table 16: Sensitivity analysis with varied standard deviation of GSLR estimate to 2100

Standard Deviation	Year Recommended to Implement A	2060 $EMV_{do\ nothing\ option}$	2060 $EMV_{with\ Prev\ Measure\ A}$
0	2044	$25,000	$3,500
0.05	2044	$27,000	$3,600
0.10	2042	$34,000	$3,600
0.15	2040	$46,000	$3,800
0.20	2037	$65,000	$4,100
0.25	2035	$95,000	$5,100
0.277	2033	$116,000	$6,000
0.30	2032	$136,000	$7,300
0.35	2030	$191,000	$12,000
0.40	2027	$258,000	$21,000
0.45	2025	$338,000	$35,000
0.50	2023	$429,000	$57,000



(a) Above shows the result of σ=0.15m, (b) below, shows the result of σ=0.40m

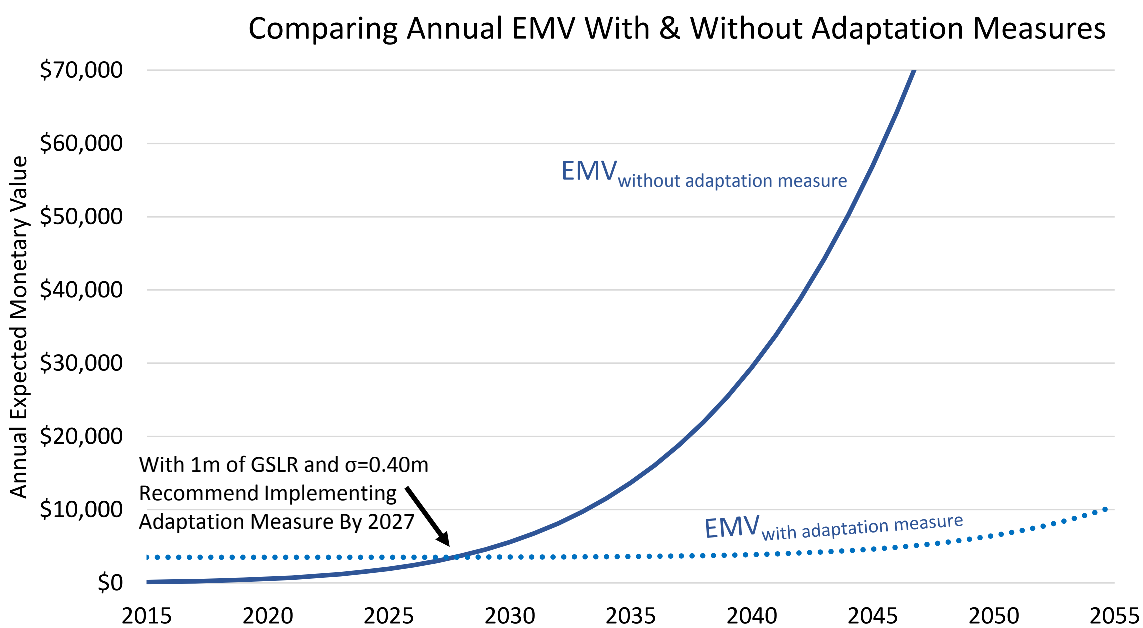


Figure 44: Sensitivity analysis illustrated graphically to show the effect of changing the standard deviation of the GSLR estimate

Another way to utilize ISLA to further study the economic impact of implementing preventive measures is to analyze the IPCC's 2013 scenarios. Discussed in Chapters 2 and 4 of this study, the IPCC's 2013 report used four different scenarios, called Representative Concentration Pathways, or RCP's. The RCP's represent possible climate futures due to greenhouse gas emissions, and are numbered based on their associated radiative forcing by the year 2100 (IPCC 2013). One of the results of these possible climate futures is global sea level rise. The scenarios increase in severity from RCP 2.6, representing a low emissions scenario to RCP 8.5, which assumes very high emissions.

ISLA was used to conduct a sensitivity analysis of these four scenarios. Their associated GSLR means and standard deviations were input in ISLA's user dashboard to achieve the simple analysis of this variety of GSLR projections. None of the IPCC scenarios reach as high a future sea level as the 1.0 meter estimate from Chapter 4. Thus ISLA's output for the IPCC RCP scenarios recommends delaying implementation of preventive measures for much longer than the previous example in this chapter. The sensitivity analysis, with the year 2060 EMV's as a comparison baseline are illustrated in Table 17.

Table 17: Sensitivity analysis of IPCC GSLR estimates by 2100

IPCC RCP Scenario	Min GSLR Estimate by 2100 (m)	Max GSLR Estimate by 2100 (m)	Year Recommended to Implement A	2060 EMV_{do} nothing option	2060 EMV_{with} Prev Measure A
2.6	0.28	0.61	2082	$720	$3,500
4.5	0.36	0.71	2067	$1,500	$3,500
6.0	0.38	0.73	2065	$1,800	$3,500
8.5	0.52	0.98	2051	$8,900	$3,500

Comparison of Integrating Expected Costs over Time

An alternative method for comparing the cost of adaptation measures is integration over time of all associated costs. This technique is different from that previously presented because it sums the annual expected costs over an extended period of time, instead of looking at single-year snapshots of these costs, to inform the decision. This approach is used for traditional economic analysis of the life-cycle costs of civil works projects. However, the integration method is not appropriate for comparing multiple alternatives with unequal service lives. A detailed discussion of this integration method, its application to this problem, and a sensitivity analysis of economic study periods is included in Appendix B of this paper.

Selecting Between Alternate Adaptation Measures

In order to better illustrate the decision maker's Tipping Point with the annual EMV comparison, the ISLA decision tool allows for the comparison of up to three different flood preventive measures of the user's choosing. ISLA's User Dashboard with these options is shown in Figure 45. Two other adaptation measures for protecting Asset #2 are compared to the temporary flood barrier previously discussed. These options are a 1.52 meter barrier flood wall surrounding the building, with a Net Present Value of $300,000, and a 3.05 meter flood wall with an NPV of $600,000.

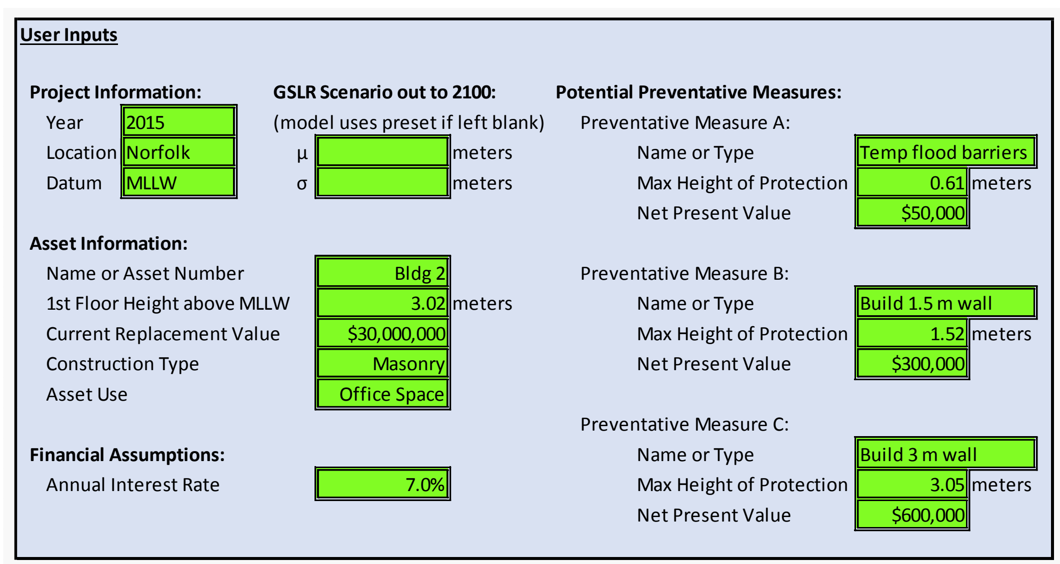


Figure 45: Screenshot of ISLA's User Dashboard in Microsoft Excel, user inputs shown in green

ISLA provides recommendations in the format of both a table and a chart, to aid the decision maker in deciding which adaptations are most economically advantageous in the future. Because Asset #2 has a relatively high elevation (building height of 3.02 meters), the vast majority of current day flood scenarios do not even reach the building. However, as the Mean Sea Level rises, the same levels of flooding gradually begin to threaten the building. By 2033, the sea level will have risen enough that the relatively inexpensive option of implementing 0.61 meter temporary flood barriers provides an annual savings. Yet it will not be until the years 2045 and 2050, as shown in Figure 46, that sea level will have risen enough to make the significantly more expensive 1.52 meter and 3.05 meter flood wall options become economically attractive. Thus, the recommendation for protecting Asset #2 would be to implement the 0.61 meter temporary flood barriers no later than the year 2033.

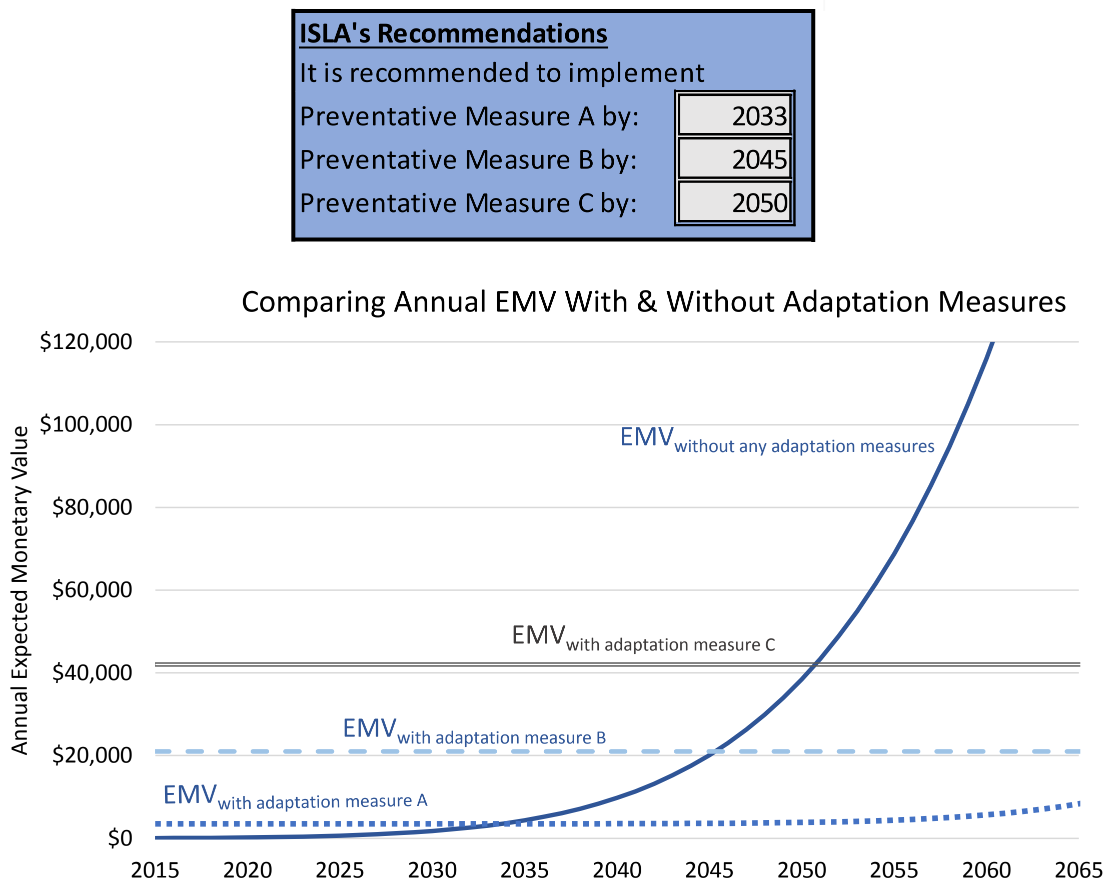


Figure 46: ISLA's Output screen, showing the recommended years to implement adaptation

Note in Figure 47 that the EMV curves for the 0.61 meter temporary flood barrier, called Preventive Measure A, and the 1.52 meter barrier wall, Preventive Measure B, intersect in the year 2073. This indicates that, after that date, the 1.52 meter wall has a lower EMV and becomes a more economically advantageous choice. Beyond that point, decision makers may choose to implement the next level of preventive measure.

In the case of Asset #2, if the intersection of the two EMV curves had been closer to Preventive Measure A's suggested implementation date of 2033, the decision maker might have chosen to implement the 1.5 meter wall instead of the 0.61 meter temporary flood barriers. This option would protect the asset further into the future and avoid the costs of investing in two different adaptation measures during the building's service life. However, for the EMV values shown in Figure 46, forty years separate the recommended implementation date for the temporary flood barriers from the date when the 1.52 meter wall becomes economically more advantageous. Thus, the recommendation for Asset #2 would be to implement the first option of the 0.61 meter temporary flood barriers by 2033.

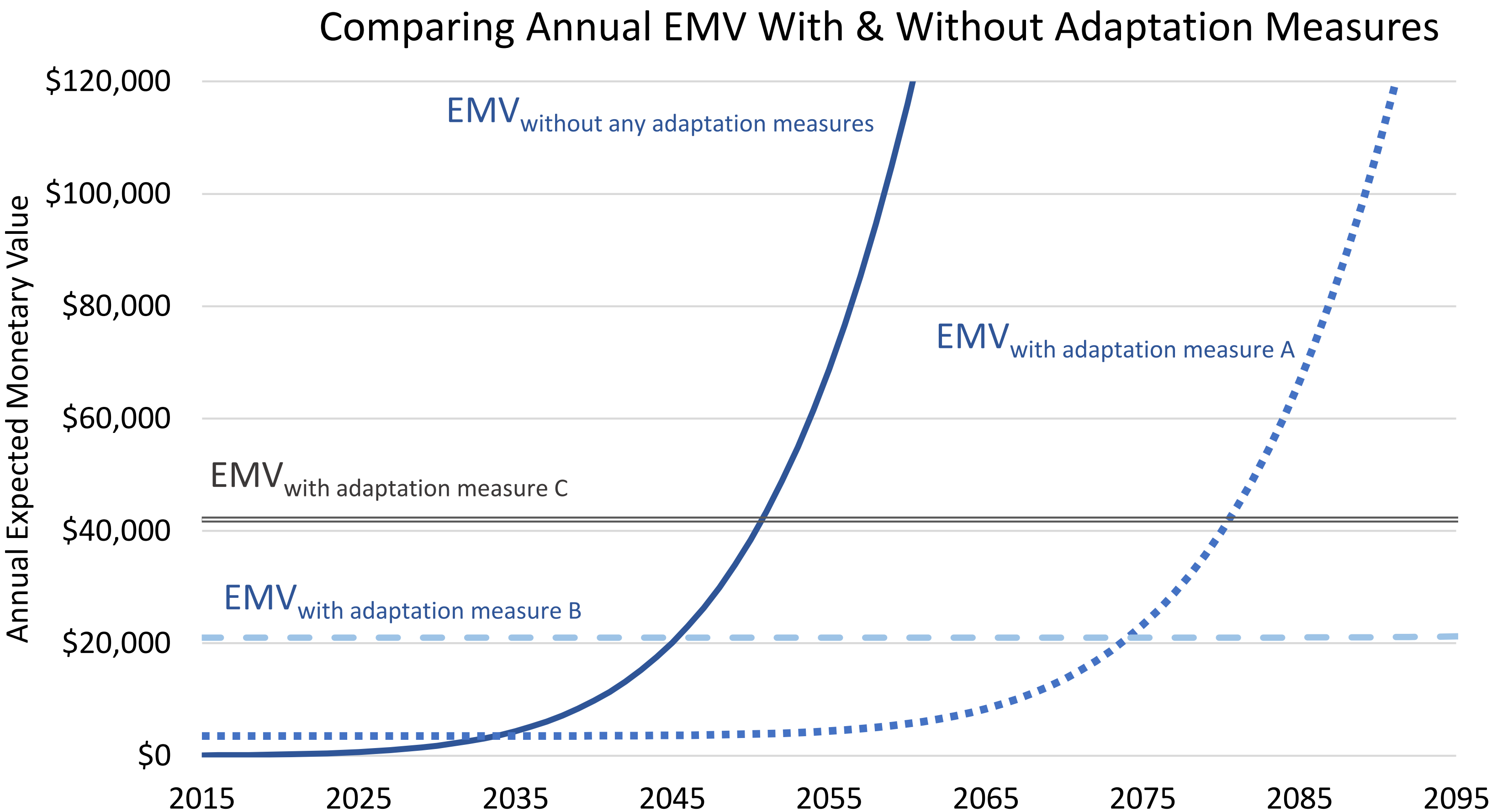


Figure 47: Annual EMV comparison indicating when to implement various adaptation measures

Chapter 10: Conclusion & Recommendations for Future Work

ISLA incorporates a unique method for analyzing the implementation of adaptation measures to combat sea level rise. It is innovative in its use of decision tree theory to combine the probability of future flood events with the estimated cost of flood damage. This economic valuation, using Expected Monetary Value, allows for comparison of a variety of adaptation measures over time. The comparative measure of future flood damage with and without adaptation allows the decision maker to determine what future year it would be most cost-effective to implement a chosen adaptation solution (Figure 48).

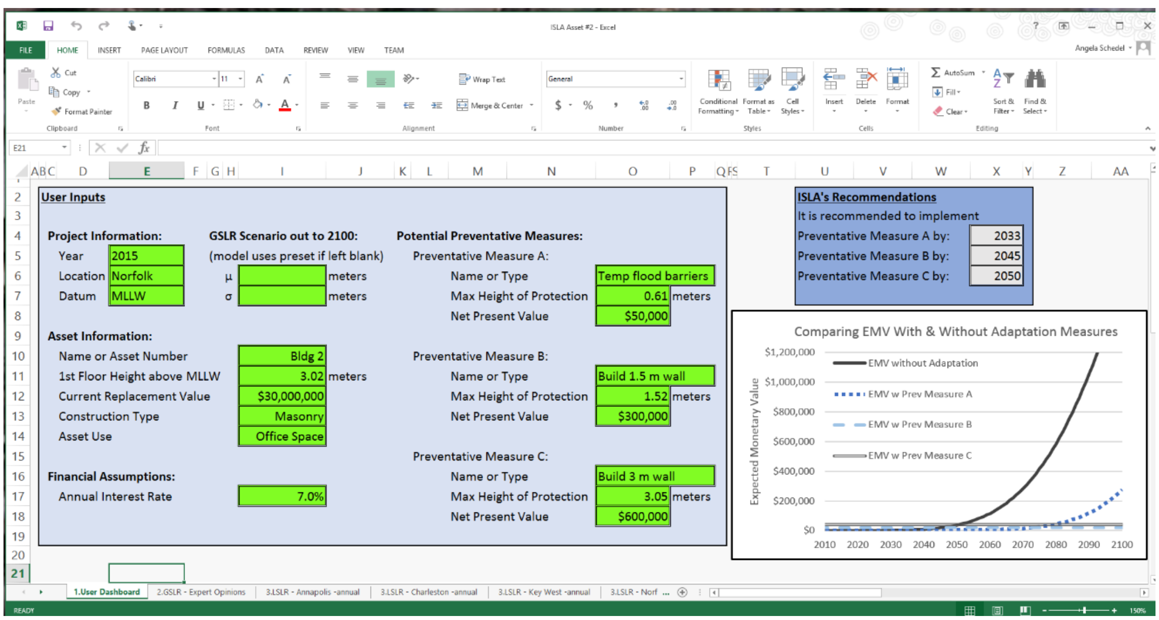


Figure 48: Screenshot of Complete ISLA User Dashboard in Microsoft Excel

Unique Contributions of this Research

The analysis presented here fills many of the gaps which exist in current sea level rise adaptation studies. The methodology links the contributions of the academic community with practicing civil engineers who lack solid information about sea level rise trends in their region. The ISLA tool provides an easy-to-use interface which quickly communicates its results in a straightforward graphic presentation. This tool informs engineers and planners about the potential economic consequences of future sea level rise, helping them to make the most economically advantageous decision for adaptation.

In addition to providing answers for engineers and planners about future sea level rise adaptation options, ISLA incorporates several new techniques for interpreting sea level rise projections and tidal gauge data. The conglomeration of Global Sea Level Rise research into a singular GSLR projection combines the expert opinions presented in eleven different GSLR studies. Equally weighting each GSLR projection to the year 2100 and combining them using the Central Limit Theorem is a novel approach to aggregating numerous expert opinions. However, if an ISLA user wants to experiment with a different GSLR scenario than the one calculated, the User Dashboard accommodates this input.

Another original idea presented in this research is the use of a historical Maximum Flood Event (MFE) for extreme flood forecasting. The Maximum Flood Event is calculated from tidal gauge data by detrending the Maximum Water Level (MWL) with respect to the Mean Sea Level (MSL). For the seven U.S. East Coast tidal gauge stations surveyed, all showed a flat slope for the MFE trend, but an increasing MSL trend. The flat slope of the residual illustrated that the severity of flood events, as measured by the maximum water level with respect to the Mean Sea Level trend, is not increasing. Coastal flood events seem to be more intense only because of the increasing trend of the Mean Sea Level. Flood events are starting from a higher baseline than they were 50 years ago. Coastal flood events are more frequent and more severe due to Global Sea Level Rise.

The strategy used to predict future flood events for use in the ISLA tool is also a new contribution. Modeling the different components of Local Sea Level Rise as normal distributions then combining them into one normal distribution is a unique approach. The three LSLR components which were used to calculate the Local Maximum Water Level (LMWL) in future years were the Global Sea Level Rise forecast to the year 2100, the Local Mean Sea Level in a baseline year, and the annual Local Maximum Flood Event. The mean and standard deviation of the Local Maximum Water Level in a future year was calculated by merging these values. This LMWL normal distribution provided the probability of flood occurrence in future years with respect to GSLR and local water level trends, which is unique to this research.

One of the most innovative strategies introduced in this research is the employment of Decision Tree methodology and Expected Monetary Value (EMV) to forecast the economic effects of sea level rise. EMV represents the average expected cost of damage due to flooding in a future year. EMV is calculated by summing the product of the probability of occurrence of a range of floodwater heights combined with the Estimated Damage Cost for the associated floodwater heights. ISLA allows the user to compare the EMV of an unprotected vulnerable asset with the EMV's of multiple different adaptation measures which protect the asset to chosen flood heights. By plotting these EMV's over time, ISLA illustrates which adaptation measure is the best economic choice. ISLA's result, which compares the annual costs savings of the EMV without adaptation to the EMV's with adaptation, also shows the user when the best year is to employ this measure.

No other economic analysis of Global Sea Level Rise which is currently in use by planners tells the user **when** to implement an adaptation measure. ISLA provides a unique and easy-to-use practical application for stakeholders who desire to know when, where and how to best implement adaptation measures to protect against sea level rise and future flood events. The economic perspective which this study employs to recommend adaptation decisions is unique within the body of sea level research, civil engineering, and adaptation planning.

Future Use of this Research

This research, while limited in scope to naval installations, is applicable to any military installation. The ISLA decision making tool could be used by military planners for sea level rise adaptation decisions. The Naval Facilities Engineering Command at the U.S. Naval Academy Public Works Department has already expressed an interest in using ISLA's application to justify funding sea level rise adaptation efforts. ISLA has undergone several modifications at the recommendation of USNA's Director of Facilities Management.

Besides its use for military installations, ISLA is also applicable to civilian assets. The user inputs are generic enough that vulnerable civilian assets can be analyzed and recommendations for when to implement adaptation measures can be suggested. City planners or facility managers of large organizations could use ISLA to help them make economic decisions for adapting to future sea level rise.

ISLA is designed to accept newer tidal gauge data when it becomes available in the future. Inputting the water level data will update the Local Sea Level Rise trends and the Maximum Water Level projections for that location accordingly. Other types of critical data which may be updated, such as new Depth Damage Curves or Global Sea Level Rise projections, can also be added. ISLA's interface is flexible enough to easily handle the input and analysis of this updated data.

Even though this paper only demonstrates the analysis of naval installations on the U.S. East Coast, ISLA is not limited to this region. Any location around the globe which has historical tidal gauge data can be input into this tool. This approach has uses beyond just that of U.S. naval installations on the East Coast.

Future Work: Suggested Improvements to ISLA

The method developed in this paper focuses on examining one asset at a time. However, it is often desired to analyze an entire portfolio of assets and potential adaptation measures that could protect more than one asset. Changes to ISLA could allow for easier analysis of numerous assets simultaneously. Ideally, with extensive alteration, ISLA could provide the asset management cost of adapting to sea level rise over an entire naval installation, hospital complex, college campus, metropolitan area, or floodplain. Using the EMV of flood damage for an entire portfolio of structures and infrastructure, large scale adaptation measures could be examined. For a macro-example, analyzing all of the flood-prone areas of the Chesapeake Bay would permit the evaluation of the cost effectiveness of a storm surge barrier across the 24-mile long mouth of the Chesapeake Bay. While this is an extreme example, it is similar to the analysis used in the UK to demonstrate the economic value of investing in a new Thames River Barrier.

Additionally, instead of asking the user to provide the Net Present Value (NPV) of each adaptation measure, the User Dashboard could ask for the initial capital investment and the annual operating and maintenance costs. Net Present Value could then be calculated by ISLA for each adaptation option. This would ease the burden on the user for having to pre-calculate NPV or understand the equations involved in this.

ISLA was designed within Microsoft Excel, in order to provide accessibility to a wider range of stakeholders. MATLAB was investigated for use in incorporating this decision-making tool. However, due to the expense of the MATLAB software and its limited availability to the general public, it was decided to use Microsoft Excel. If a more robust analysis tool was desired, ISLA could be converted to MATLAB, but this would limit the number of potential users.

Future Work: Better GSLR Estimates and Site-Specific DDC

One component of this research that will likely undergo changes is in the estimates of future sea level rise. As time passes and more data becomes available, Global Sea Level Rise estimates will undoubtedly be revised and updated. Because of this, ISLA was modified to permit the user to input which GSLR scenario they prefer to use. Additionally, within the "GSLR – Expert Opinions" page of ISLA is the ability to add more accurate and updated GSLR estimates as they become available in the future. Adding more expert opinions of GSLR projections helps hone the normal distribution created in Chapter 4, by increasing the sample size of experts. As with most probability theory, the Central Limit Theorem provides a more precise estimate and smaller variance with a larger sample size.

Perhaps the greatest weakness in the method of this research, and an area for significant future work, is the lack of detailed depth damage curves and Content to Structure Value Ratios for military-specific infrastructure. Generic DDC and CSVR for non-residential buildings are limited to commercial facilities, such as restaurants, grocery stores, apartments and other revenue-producing ventures. Neither the DDC nor the CSVR used in this analysis are ideal for estimating potential flood damage costs of military installations. The non-residential DDC used in ISLA were limited to one or two story commercial buildings. DDC for the typical multi-story (3 to 5 stories) office buildings found on military installations were not available.

Specialized depth damage curves need to be developed for large horizontal infrastructure such as runways, piers, breakwaters, and jetties. This infrastructure is common to almost every naval base and is vulnerable to flood damage in coastal storms.

New military-specific DDC would allow a more accurate picture of the base's economic burden due to sea level rise.

Additionally, this research only estimates flood damage costs due to inundation. It does not take into account other common causes of coastal storm flood damage, which include waves and erosion due to waves. DDC which incorporate these other modes of flood damage for military infrastructure are recommended to be developed.

However, creating new DDC is not inexpensive or quick. The process requires extensive study of past flood damage, as well as a panel of experts who are familiar with construction specific to the region studied. Despite the cost involved, a site-specific depth damage curve study is an investment that can prevent excessive expenditures due to future flood damage of vulnerable assets such as the pier shown in Figure 49.

Figure 49: The author and family on a pier with a ship at Naval Station Norfolk
(Note the vulnerable utilities close to water level, which are highlighted in the background.)

Future Work: Other Considerations

This study only assesses the economic aspect of flood damage to buildings and infrastructure on the base. It does not attempt to estimate the loss of operational capability. For example, if the roads are flooded between the fuel storage tanks and the runway or aircraft hangars, then no aircraft can be refueled. Without the ability to fuel the aircraft, these assets are not available to conduct operations and thus become victims of the flood event, even though the ground the aircraft is on may be dry. Similarly, if a central communications building or a main power supply is out of service due to a flood, it limits the ability of ships and aircraft to get underway to perform their missions.

These operational concerns were the subject of a Department of Defense (DOD) study which quantified the risks of flood inundation at NS Norfolk in terms of military operational capabilities (Burks-Copes et al. 2014). Future work could be conducted by combining the analysis in the DOD report with this research to achieve a more comprehensive economic result.

Another area for future study is to examine the potential economic losses on the general populace in the Norfolk area. The U.S. Navy is the largest employer in the Norfolk region. This study did not examine the interruption of work or loss of jobs due to future floods. If relocation of facilities on the base was determined to be the best financial option for avoiding future flood damage, it is possible that these commands could be relocated to a different military base in another locale. While the building in question would escape potential floods, the employees that work there may lose their jobs due to the move.

One avenue not explored by this research is the potential economic result of implementing non-structural measures. Financial instruments such as catastrophe bonds and flood insurance can be used to buy down the risk of future floods. While naval installations are not optimal candidates for government-subsidized flood insurance, other non-structural flood protection may be possible.

Finally, the age and condition of the buildings examined in this study were not evaluated as part of this analysis. Future work is recommended for deciding how to best capture this information as part of the economic analysis of preventing flood damage. At a certain age and condition, it is not worth investing in adaption measures to protect the building from flooding. In this case, it would be more economical to demolish the building and construct a new one on higher ground or with improved floodproofing. Adding a building "end date" to this economic analysis would prevent spending money to protect a structure which is obsolete.

Appendix A: ISLA Worksheet Screenshots

This appendix contains screenshots of each of ISLA's worksheet pages in Microsoft Excel 2013. ISLA is the Implementing Sea Level Adaptations decision tool that is the practical application of this research.

Explanations regarding the purpose and functionality of each worksheet follow each screenshot. The remainder of Appendix A following this page will be presented in Landscape format in order to better represent the entire screenshot.

1. User Dashboard

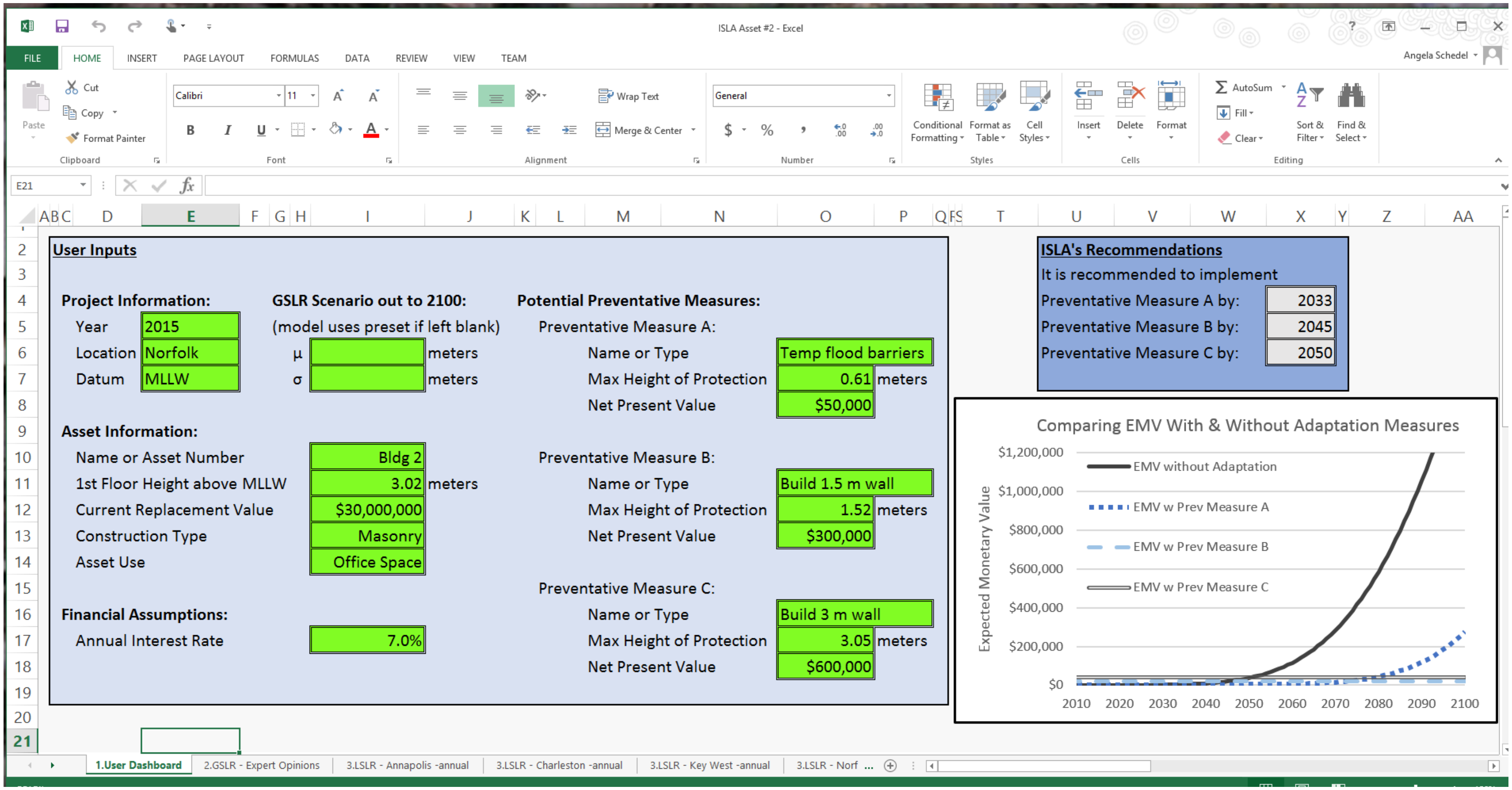


Figure 50: User Dashboard Worksheet. User input cells are coded in green. ISLA's output is the table and chart on the right.

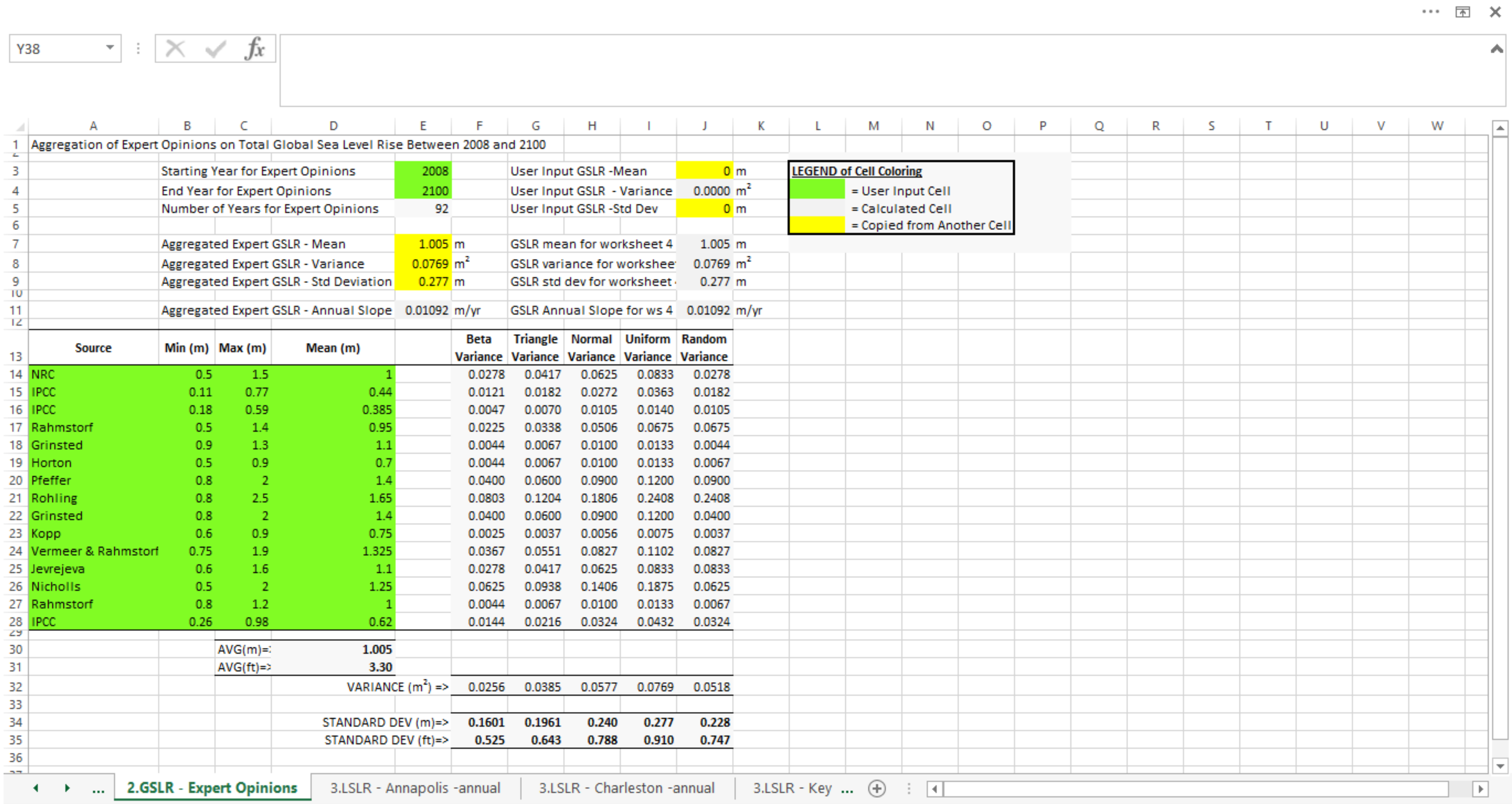
The function of the area inside the light grey box on the left side of this worksheet is to allow the user to input information. The green colored cells are those which the user can modify. None of the green cells have formulas since they are only input cells. Excel's Data Validation function is used to limit the input of the user to the range of options which ISLA can analyze. For example, cell I11 (1^{st} Floor Height above the selected datum) only allows numerical entries less than 10 meters, while cell I12 (Current Replacement Value) only allows positive integers to be entered.

The cells in Table 18 have special formatting which links to corresponding drop-down lists in the Appendix: Drop-Down Lists worksheet (Figure 59). For example, cell E7 (Datum) permits the user to select only one of two choices, MLLW or NAVD88.

Table 18: User Dashboard cells with special formatting

Cell	**Drop-Down List Title**
E5	Year
E6	Location
E7	Datum
I13	Construction Type
I14	Asset Use
I17	Annual Interest Rate
O7	Max Height of Protection (m)
O12	Max Height of Protection (m)
O17	Max Height of Protection (m)

2.GSLR - Expert Opinions



Y38

	A	B	C	D	E	F	G	H	I	J	K
1	Aggregation of Expert Opinions on Total Global Sea Level Rise Between 2008 and 2100										
3		Starting Year for Expert Opinions			2008		User Input GSLR -Mean			0	m
4		End Year for Expert Opinions			2100		User Input GSLR - Variance			0.0000	m^2
5		Number of Years for Expert Opinions			92		User Input GSLR -Std Dev			0	m
7		Aggregated Expert GSLR - Mean			1.005	m	GSLR mean for worksheet 4			1.005	m
8		Aggregated Expert GSLR - Variance			0.0769	m^2	GSLR variance for workshee			0.0769	m^2
9		Aggregated Expert GSLR - Std Deviation			0.277	m	GSLR std dev for worksheet			0.277	m
11		Aggregated Expert GSLR - Annual Slope			0.01092	m/yr	GSLR Annual Slope for ws 4			0.01092	m/yr

LEGEND of Cell Coloring
= User Input Cell
= Calculated Cell
= Copied from Another Cell

	Source	Min (m)	Max (m)	Mean (m)		Beta Variance	Triangle Variance	Normal Variance	Uniform Variance	Random Variance
14	NRC	0.5	1.5	1		0.0278	0.0417	0.0625	0.0833	0.0278
15	IPCC	0.11	0.77	0.44		0.0121	0.0182	0.0272	0.0363	0.0182
16	IPCC	0.18	0.59	0.385		0.0047	0.0070	0.0105	0.0140	0.0105
17	Rahmstorf	0.5	1.4	0.95		0.0225	0.0338	0.0506	0.0675	0.0675
18	Grinsted	0.9	1.3	1.1		0.0044	0.0067	0.0100	0.0133	0.0044
19	Horton	0.5	0.9	0.7		0.0044	0.0067	0.0100	0.0133	0.0067
20	Pfeffer	0.8	2	1.4		0.0400	0.0600	0.0900	0.1200	0.0900
21	Rohling	0.8	2.5	1.65		0.0803	0.1204	0.1806	0.2408	0.2408
22	Grinsted	0.8	2	1.4		0.0400	0.0600	0.0900	0.1200	0.0400
23	Kopp	0.6	0.9	0.75		0.0025	0.0037	0.0056	0.0075	0.0037
24	Vermeer & Rahmstorf	0.75	1.9	1.325		0.0367	0.0551	0.0827	0.1102	0.0827
25	Jevrejeva	0.6	1.6	1.1		0.0278	0.0417	0.0625	0.0833	0.0833
26	Nicholls	0.5	2	1.25		0.0625	0.0938	0.1406	0.1875	0.0625
27	Rahmstorf	0.8	1.2	1		0.0044	0.0067	0.0100	0.0133	0.0067
28	IPCC	0.26	0.98	0.62		0.0144	0.0216	0.0324	0.0432	0.0324
30			AVG(m)=:	1.005						
31			AVG(ft)=:	3.30						
32				VARIANCE (m^2) =>		0.0256	0.0385	0.0577	0.0769	0.0518
34				STANDARD DEV (m)=>		0.1601	0.1961	0.240	0.277	0.228
35				STANDARD DEV (ft)=>		0.525	0.643	0.788	0.910	0.747

2.GSLR - Expert Opinions | 3.LSLR - Annapolis -annual | 3.LSLR - Charleston -annual | 3.LSLR - Key ...

Figure 51: GSLR - Expert Opinions Worksheet

This worksheet summarizes Chapter 4, which is the aggregation of expert Global Sea Level Rise projections in the year 2100. Green cells indicate user input, yellow cells indicate this cell was copied from another cell, and grey cells are calculated by Excel.

The most often cited expert opinions of GSLR projections from Table 1 are represented in the worksheet. The projections only contained minimum and maximum values, thus the mean value was calculated as the point halfway between the two. The mean values were averaged to find the mean of the mean for the GSLR projections to the year 2100. The variances were calculated using Equations (5) through (8), then each type of variance was averaged at the bottom of its corresponding column. The uniform distribution had the largest variance and was selected as the most conservative of the types of probability distributions.

The GSLR projection's mean, variance, and standard deviation were copied into the upper half of the worksheet. The annual GSLR slope was calculated using Equation (18). Because ISLA allows the user to input a GSLR estimate in the terms of a uniform distribution's mean and standard deviation, this input is copied from the User Dashboard worksheet into the cells on the right side of the upper half of the worksheet. If these cells have values in them, the User Input values are copied into the cells below for use in Worksheet 4. If the User Input cells are blank, then the aggregated expert GSLR estimate is used for Worksheet 4.

3. LSLR – Selected Location – annual

W98

Locale	Start Yr	End Yr	units	Datum	Baseline Yr		Δ NAVD88 - MLLW
Norfolk	1928	2014	m	MLLW	2008	NAVD88	MLLW
8638610		Ht above STND=>		1.336		1.827	0.491

Monthly	Max	Mean	Residual
SLOPE (m/mo)	0.000369	0.000384	-0.000014
Y-INTERCEPT	0.9308	0.1192	0.8099

Predicted Value of Mean Tide Height (m) in Baseline Year (datum dependent)	0.4901
Predicted Value of Max Tide Height (m) in Baseline Year (datum dependent)	1.7286
Predicted Value of Residual (m) in Baseline Year (datum dependent)	1.2385
$\sigma^2_{\text{Fit of monthly mean dataset}}$	0.00789

Annual	MAX	MEAN	RESIDUAL
VARIANCE	0.0841	0.0146	0.0646
SLOPE(m/yr)	0.0048	0.0046	0.0002

$\sigma^2_{\text{Fit of annualized mean dataset}}$	0.001278

MONTHLY DATA

Index Number (x)	Month	Year	Monthly Max (m MLLW)	Monthly Mean (m MLLW)	Residual (m) (Max-Mean)		Predicted MSL from Best Fit Line	$(MSL_{actual} - MSL_{predicted})^2$
1	1	1928	0.584	-0.111	0.695		0.1196	0.0532
2	2	1928	0.676	-0.004	0.680		0.1200	0.0154
3	3	1928	0.676	0.051	0.625		0.1204	0.0048
4	4	1928	0.889	0.039	0.850		0.1207	0.0067
5	5	1928	1.072	0.173	0.899		0.1211	0.0027
6	6	1928	0.798	0.100	0.698		0.1215	0.0005
7	7	1928	0.645	0.081	0.564		0.1218	0.0017
8	8	1928	0.676	0.158	0.518		0.1222	0.0013
9	9	1928	1.621	0.282	1.339		0.1226	0.0254
10	10	1928	1.133	0.139	0.994		0.1229	0.0003

ANNUALIZED DATA

YEAR	ANNUAL MAX (m)	ANNUAL MEAN AVG (m)	RESIDUAL (m) Max-Mean		Predicted MSL from Best Fit Line	$(MSL_{actual} - MSL_{predicted})^2$
1928	1.621	0.0806	1.5403		0.1223	0.0017
1929	1.285	0.0950	1.1900		0.1269	0.0010
1930	1.499	0.0932	1.4058		0.1315	0.0015
1931	1.163	0.1241	1.0391		0.1361	0.0001
1932	1.346	0.1393	1.2067		0.1407	0.0000
1933	2.444	0.1957	2.2482		0.1453	0.0025
1934	1.072	0.1287	0.9433		0.1499	0.0004
1935	1.255	0.1705	1.0844		0.1545	0.0003
1936	2.047	0.1403	1.9067		0.1591	0.0004
1937	1.346	0.1928	1.1532		0.1637	0.0008

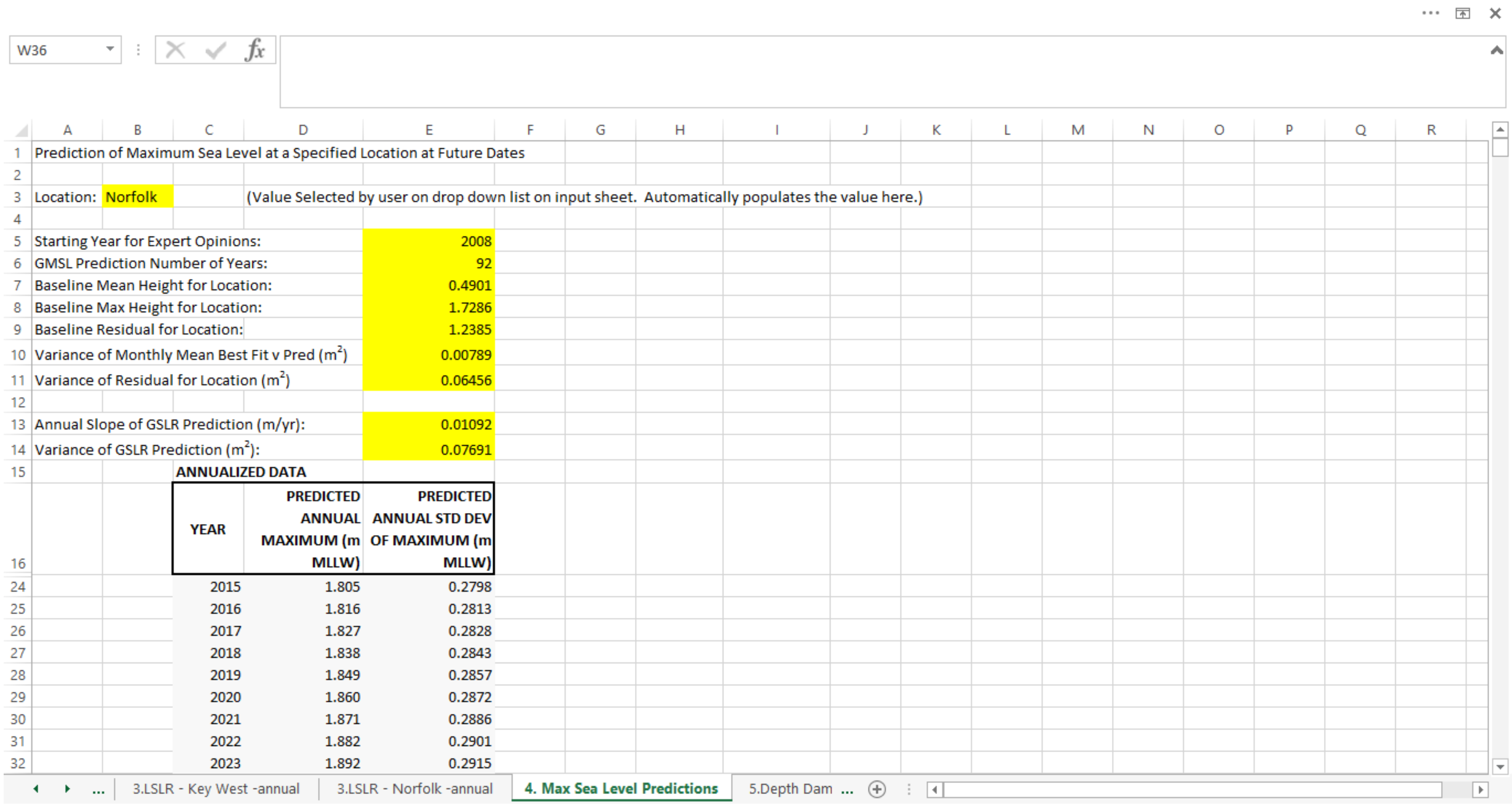
3.LSLR - Charleston -annual | 3.LSLR - Key West -annual | **3.LSLR - Norfolk -annual** | 4. Max Sea Le ...

Figure 52: Local Sea Level Rise trend worksheet using historic water level data for chosen location

This worksheet calculates the Local Sea Level Rise trend for a chosen location, using historic tidal gauge data. The worksheet summarizes the calculations in Chapter 5, and include a few from Chapter 6. The monthly water level data is converted to annual on the right side of the worksheet, and the annual slope for Mean Sea Level, Maximum Water Level, and the Maximum Flood Event (or Residual) are calculated above their respective columns. Because ISLA allows the user to select between the MLLW and NAVD88 datum, the Predicted Values of the Mean, Max, and Residual in the Baseline Year are dependent on the datum selected. These Predicted Values are calculated using a variation of Equation (16).

ISLA has the capacity to use water level data for numerous locations. At the current iteration, it is loaded with data for Annapolis, Charleston, Key West and Norfolk. These locations were chosen to test ISLA's functionality in different regions, and also because their rates of LSLR differ.

4. Max Sea Level Projections


Prediction of Maximum Sea Level at a Specified Location at Future Dates

Location: Norfolk (Value Selected by user on drop down list on input sheet. Automatically populates the value here.)

Starting Year for Expert Opinions:	2008
GMSL Prediction Number of Years:	92
Baseline Mean Height for Location:	0.4901
Baseline Max Height for Location:	1.7286
Baseline Residual for Location:	1.2385
Variance of Monthly Mean Best Fit v Pred (m^2)	0.00789
Variance of Residual for Location (m^2)	0.06456
Annual Slope of GSLR Prediction (m/yr):	0.01092
Variance of GSLR Prediction (m^2):	0.07691

ANNUALIZED DATA

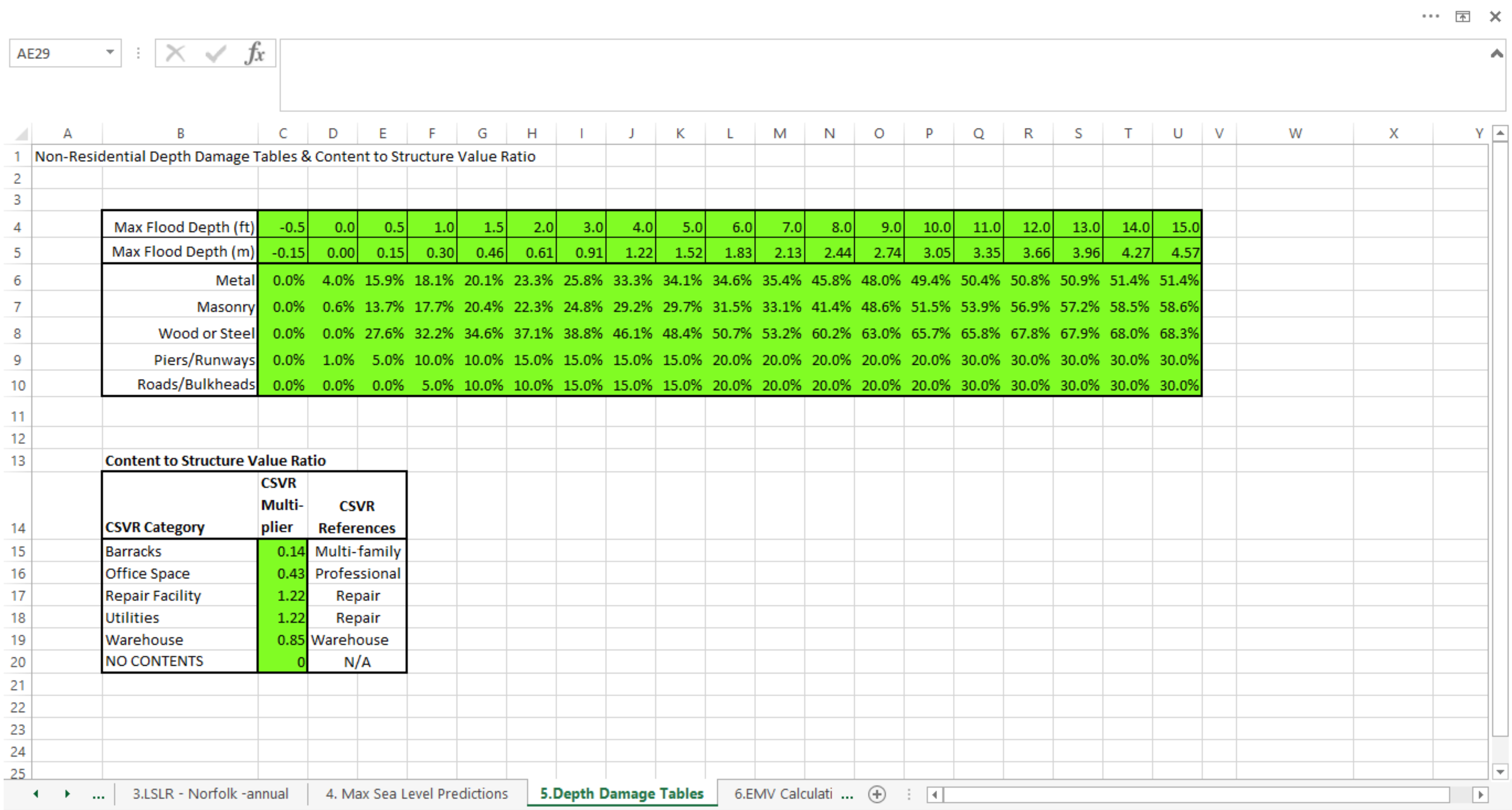
YEAR	PREDICTED ANNUAL MAXIMUM (m MLLW)	PREDICTED ANNUAL STD DEV OF MAXIMUM (m MLLW)
2015	1.805	0.2798
2016	1.816	0.2813
2017	1.827	0.2828
2018	1.838	0.2843
2019	1.849	0.2857
2020	1.860	0.2872
2021	1.871	0.2886
2022	1.882	0.2901
2023	1.892	0.2915

Figure 53: Max Sea Level Predictions Worksheet in future years at a chosen location

This worksheet takes the data from the previous two worksheets and predicts Maximum Water Levels in future years. The methods used for this worksheet is summarized in Chapter 6, where it is explained how the future Maximum Sea Level is estimated as a normal distribution with a predicted mean and standard deviation.

The predicted annual Maximum Water Level in a future year is calculated using Equation (38), which combines the Global Sea Level Rise projection to the year 2100, the Local Mean Sea Level in a baseline year, and the annual Local Maximum Flood Event. The mean and standard deviation of the Local Maximum Water Level in a future year was calculated by merging these values. This LMWL normal distribution provided the probability of flood occurrence in future years with respect to GSLR and local water level trends. The predicted Annual Standard Deviation in a future year is calculated with Equation (41).

5. Depth Damage Tables



Non-Residential Depth Damage Tables & Content to Structure Value Ratio

Max Flood Depth (ft)	-0.5	0.0	0.5	1.0	1.5	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0
Max Flood Depth (m)	-0.15	0.00	0.15	0.30	0.46	0.61	0.91	1.22	1.52	1.83	2.13	2.44	2.74	3.05	3.35	3.66	3.96	4.27	4.57
Metal	0.0%	4.0%	15.9%	18.1%	20.1%	23.3%	25.8%	33.3%	34.1%	34.6%	35.4%	45.8%	48.0%	49.4%	50.4%	50.8%	50.9%	51.4%	51.4%
Masonry	0.0%	0.6%	13.7%	17.7%	20.4%	22.3%	24.8%	29.2%	29.7%	31.5%	33.1%	41.4%	48.6%	51.5%	53.9%	56.9%	57.2%	58.5%	58.6%
Wood or Steel	0.0%	0.0%	27.6%	32.2%	34.6%	37.1%	38.8%	46.1%	48.4%	50.7%	53.2%	60.2%	63.0%	65.7%	65.8%	67.8%	67.9%	68.0%	68.3%
Piers/Runways	0.0%	1.0%	5.0%	10.0%	10.0%	15.0%	15.0%	15.0%	15.0%	20.0%	20.0%	20.0%	20.0%	20.0%	30.0%	30.0%	30.0%	30.0%	30.0%
Roads/Bulkheads	0.0%	0.0%	0.0%	5.0%	10.0%	10.0%	15.0%	15.0%	15.0%	20.0%	20.0%	20.0%	20.0%	20.0%	30.0%	30.0%	30.0%	30.0%	30.0%

Content to Structure Value Ratio

CSVR Category	CSVR Multi-plier	CSVR References
Barracks	0.14	Multi-family
Office Space	0.43	Professional
Repair Facility	1.22	Repair
Utilities	1.22	Repair
Warehouse	0.85	Warehouse
NO CONTENTS	0	N/A

Figure 54: Depth damage curves, used by ISLA for flood damage cost calculations

This worksheet shows the non-residential Depth Damage Curves and Content to Structure Value ratio used as look-up tables by ISLA. The description of these and the selection of this generic DDC and CSVR are detailed in Chapter 7. If updated DDC or CSVR in a similar format become available, these can be amended easily.

6. EMV Calculations

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
4	Asset Information:																					
5		1st Floor Height above			3.02	m	Percent Damaged for Each Maximum Flood Height Range (m) in Relation to Asset Height and Construction Type															
6		Current Replacement Value			$30,000,000		-0.15	0.00	0.15	0.30	0.46	0.61	0.91	1.22	1.52	1.83	2.13	2.44	2.74	3.05	3.35	3.66
7		Construction Type			Masonry		0.0%	0.6%	13.7%	17.7%	20.4%	22.3%	24.8%	29.2%	29.7%	31.5%	33.1%	41.4%	48.6%	51.5%	53.9%	56.9%
8		Asset Use			Office Space																	
9		CSVR for Damage			43%																	
10							Probability of Occurrence for Each Maximum Flood Height Range (m) in Relation to Asset Height															
11			Year	PREDICTED ANNUAL MAXIMUM (m MLLW)	PREDICTED ANNUAL STD DEV OF MAXIMUM (m MLLW)	EMV_{annual} total	-0.15	0.00	0.15	0.30	0.46	0.61	0.91	1.22	1.52	1.83	2.13	2.44	2.74	3.05	3.35	3.66
19			2015	1.8051	0.2798	$ 58	99.99%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20			2016	1.8160	0.2813	$ 76	99.99%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
21			2017	1.8269	0.2828	$ 98	99.99%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
22			2018	1.8378	0.2843	$ 127	99.99%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
23			2019	1.8487	0.2857	$ 163	99.98%	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
24			2020	1.8597	0.2872	$ 208	99.98%	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
25			2021	1.8706	0.2886	$ 264	99.97%	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
26			2022	1.8815	0.2901	$ 332	99.97%	0.03%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
27			2023	1.8924	0.2915	$ 417	99.96%	0.04%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
28			2024	1.9033	0.2930	$ 520	99.95%	0.04%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
29			2025	1.9143	0.2944	$ 646	99.94%	0.05%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
30			2026	1.9252	0.2958	$ 798	99.93%	0.06%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
31			2027	1.9361	0.2972	$ 981	99.91%	0.07%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
32			2028	1.9470	0.2986	$ 1,200	99.90%	0.09%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
33			2029	1.9579	0.3000	$ 1,461	99.88%	0.10%	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
34			2030	1.9689	0.3014	$ 1,772	99.86%	0.12%	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

B12 | 4. Max Sea Level Predictions | 5.Depth Damage Tables | 6.EMV Calculations | 7.Prev Measure EMV

Figure 55: EMV Calculations Worksheet for a chosen asset

This worksheet combines the results of the Max Sea Level Projections Worksheet with the Depth Damage Curves and CSVR from the previous worksheet. The probability of occurrence of each year's Maximum Water Level attaining a height relative to the floodwater ranges listed in the Depth Damage Curves is calculated using Excel's NORMDIST function. This function has the same result as using Equations (53) and (55).

The associated damage percentages to the structure are then calculated given a certain depth of flood water in the asset in a future year. The Estimated Damage Costs for that specific asset are calculated using Equation (50). Annual Expected Monetary Value of flood damage in future years for the chosen asset is the result of this worksheet. EMV is calculated using Equation (48) to combine the floodwater probabilities with the Estimated Damage Costs. The methods used in this worksheet are summarized in Chapter 8.

7. Preventive Measure ∑[P(FW) EDC]*

AR144

∑P(FW)*EDC Calculations Given a Specific Asset, Locale, and Preventative Measure Height

Asset Information:

1st Floor Height above	3.02	m
Current Replacement Value	$30,000,000	
Construction Type	Masonry	
Asset Use	Office Space	
CSVR for Damage	43%	

Percent Damaged for Each Maximum Flood Height Range (m) in Relation to Asset Height and Construction Type

-0.15	0.00	0.15	0.30	0.46	0.61	0.91	1.22	1.52	1.83	2.13	2.44	2.74	3.05	3.35	3.66
0.0%	0.6%	13.7%	17.7%	20.4%	22.3%	24.8%	29.2%	29.7%	31.5%	33.1%	41.4%	48.6%	51.5%	53.9%	56.9%

Annual EMV of Damages with Preventative Measures Implemented to a Specific Height (m)

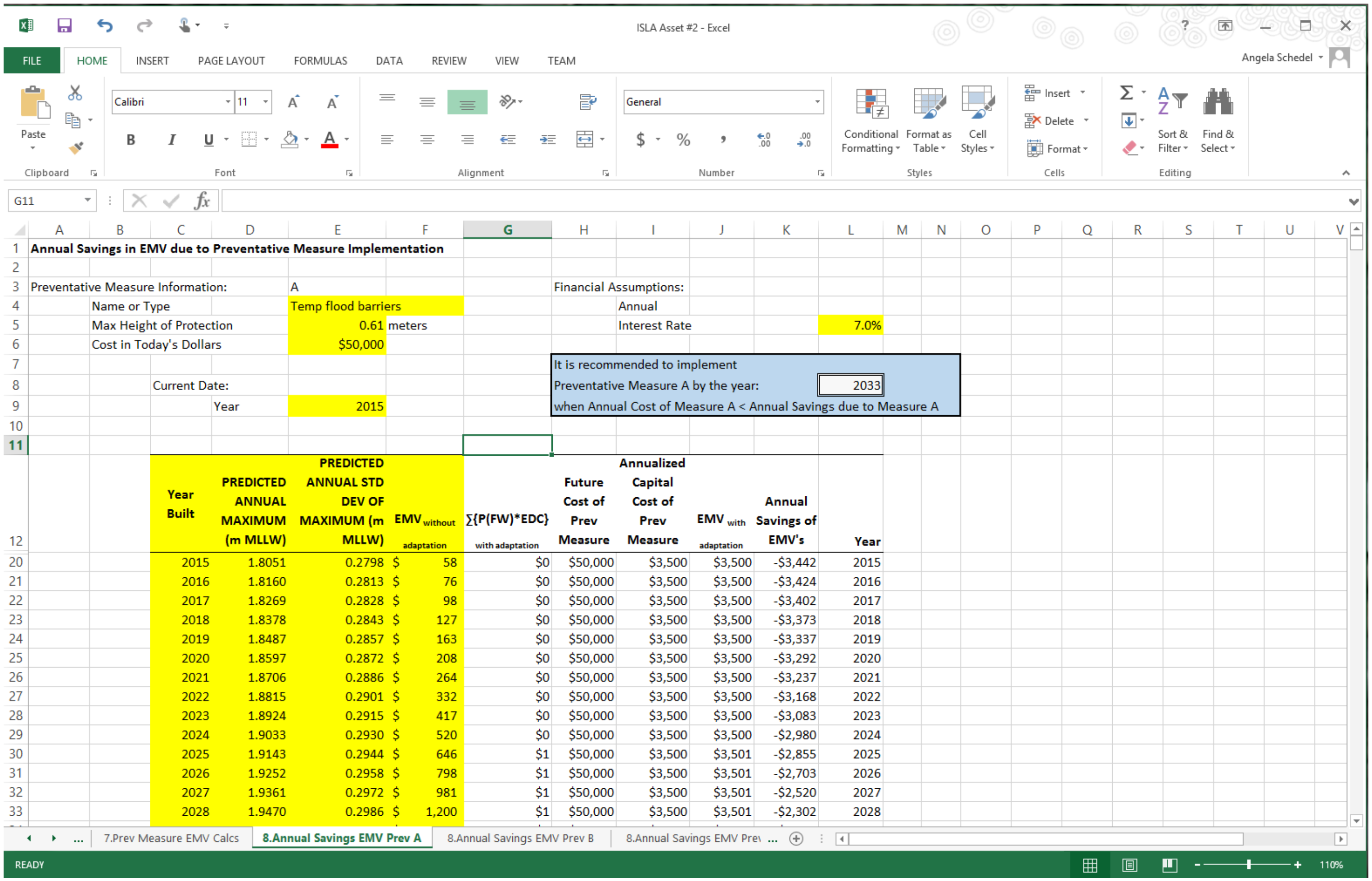
Year	PREDICTED ANNUAL MAXIMUM (m MLLW)	PREDICTED ANNUAL STD DEV OF MAXIMUM (m MLLW)	-0.15	0.00	0.15	0.30	0.46	0.61	0.91	1.22	1.52	1.83	2.13	2.44	2.74	3.05	3.35	3.66
2015	1.8051	0.2798	$58	$58	$42	$4	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2016	1.8160	0.2813	$76	$76	$56	$5	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2017	1.8269	0.2828	$98	$98	$74	$7	$1	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2018	1.8378	0.2843	$127	$127	$96	$10	$1	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2019	1.8487	0.2857	$163	$163	$125	$14	$1	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2020	1.8597	0.2872	$208	$208	$161	$19	$1	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2021	1.8706	0.2886	$264	$264	$206	$25	$2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2022	1.8815	0.2901	$332	$332	$263	$33	$3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2023	1.8924	0.2915	$417	$417	$333	$43	$4	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2024	1.9033	0.2930	$520	$520	$419	$57	$5	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2025	1.9143	0.2944	$646	$646	$524	$74	$7	$1	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2026	1.9252	0.2958	$798	$798	$653	$95	$10	$1	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2027	1.9361	0.2972	$981	$981	$809	$122	$13	$1	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0

5.Depth Damage Tables | 6.EMV Calculations | 7.Prev Measure P(FW)EDC | 8.Annual Savings EMV

Figure 56: ∑[P(FW)*EDC] calculations for preventive measures

The calculations in this worksheet use the results of the previous worksheet, except the estimated annual flood damage cost is now calculated based on specific heights of implemented adaptation measures. The estimated annual flood damage cost with adaptation will be added to the annual cost to implement the adaptation in the next worksheet.

8. Annual Savings EMV Preventive Measures



ISLA Asset #2 - Excel

Annual Savings in EMV due to Preventative Measure Implementation

Preventative Measure Information: A

Name or Type: Temp flood barriers
Max Height of Protection: 0.61 meters
Cost in Today's Dollars: $50,000

Current Date:
Year: 2015

Financial Assumptions:
Annual Interest Rate: 7.0%

It is recommended to implement
Preventative Measure A by the year: 2033
when Annual Cost of Measure A < Annual Savings due to Measure A

Year Built	PREDICTED ANNUAL MAXIMUM (m MLLW)	PREDICTED ANNUAL STD DEV OF MAXIMUM (m MLLW)	$EMV_{without\ adaptation}$	∑{P(FW)*EDC} with adaptation	Future Cost of Prev Measure	Annualized Capital Cost of Prev Measure	$EMV_{with\ adaptation}$	Annual Savings of EMV's	Year
2015	1.8051	0.2798	$ 58	$0	$50,000	$3,500	$3,500	-$3,442	2015
2016	1.8160	0.2813	$ 76	$0	$50,000	$3,500	$3,500	-$3,424	2016
2017	1.8269	0.2828	$ 98	$0	$50,000	$3,500	$3,500	-$3,402	2017
2018	1.8378	0.2843	$ 127	$0	$50,000	$3,500	$3,500	-$3,373	2018
2019	1.8487	0.2857	$ 163	$0	$50,000	$3,500	$3,500	-$3,337	2019
2020	1.8597	0.2872	$ 208	$0	$50,000	$3,500	$3,500	-$3,292	2020
2021	1.8706	0.2886	$ 264	$0	$50,000	$3,500	$3,500	-$3,237	2021
2022	1.8815	0.2901	$ 332	$0	$50,000	$3,500	$3,500	-$3,168	2022
2023	1.8924	0.2915	$ 417	$0	$50,000	$3,500	$3,500	-$3,083	2023
2024	1.9033	0.2930	$ 520	$0	$50,000	$3,500	$3,500	-$2,980	2024
2025	1.9143	0.2944	$ 646	$1	$50,000	$3,500	$3,501	-$2,855	2025
2026	1.9252	0.2958	$ 798	$1	$50,000	$3,500	$3,501	-$2,703	2026
2027	1.9361	0.2972	$ 981	$1	$50,000	$3,500	$3,501	-$2,520	2027
2028	1.9470	0.2986	$ 1,200	$1	$50,000	$3,500	$3,501	-$2,302	2028

7.Prev Measure EMV Calcs | 8.Annual Savings EMV Prev A | 8.Annual Savings EMV Prev B | 8.Annual Savings EMV Prev ...

Figure 57: Annual Savings due to Preventive Measures Worksheet

This worksheet calculates the annual costs savings in EMV's with and without implementing a selected adaptation measure. The Annual Capitalized Cost of the adaptation measure is calculated for future years using Equations (64) through (66). The new EMV with the adaptation measure implemented is calculated with Equations (67) through (69) and compared to the EMV without adaptation which was calculated in worksheet 6. EMV Calculations. The Annual Savings determined by comparing the EMV's uses Equation (70). The calculations in this worksheet are summarized in Chapter 9.

9. Output – Comparison Chart

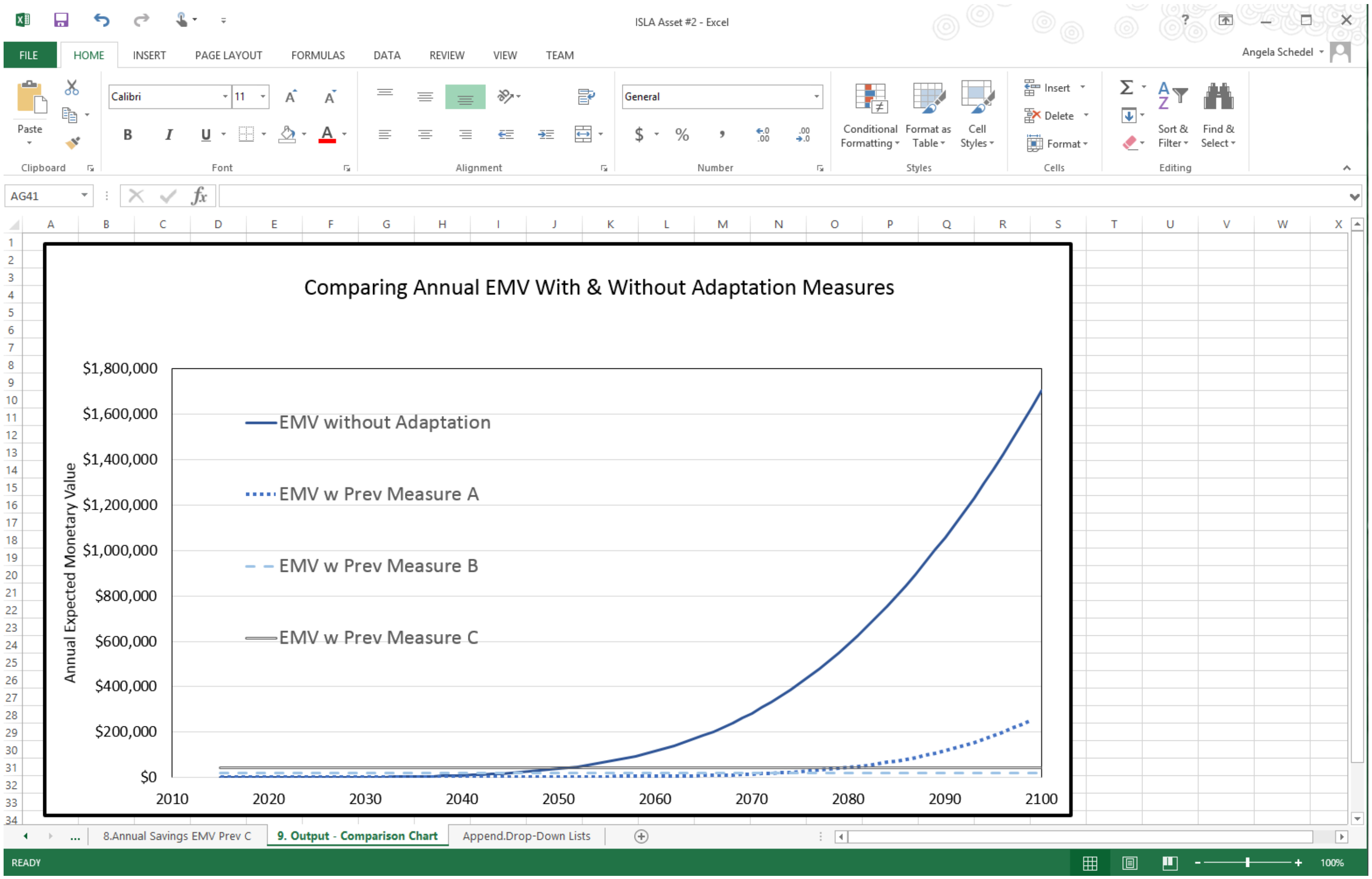
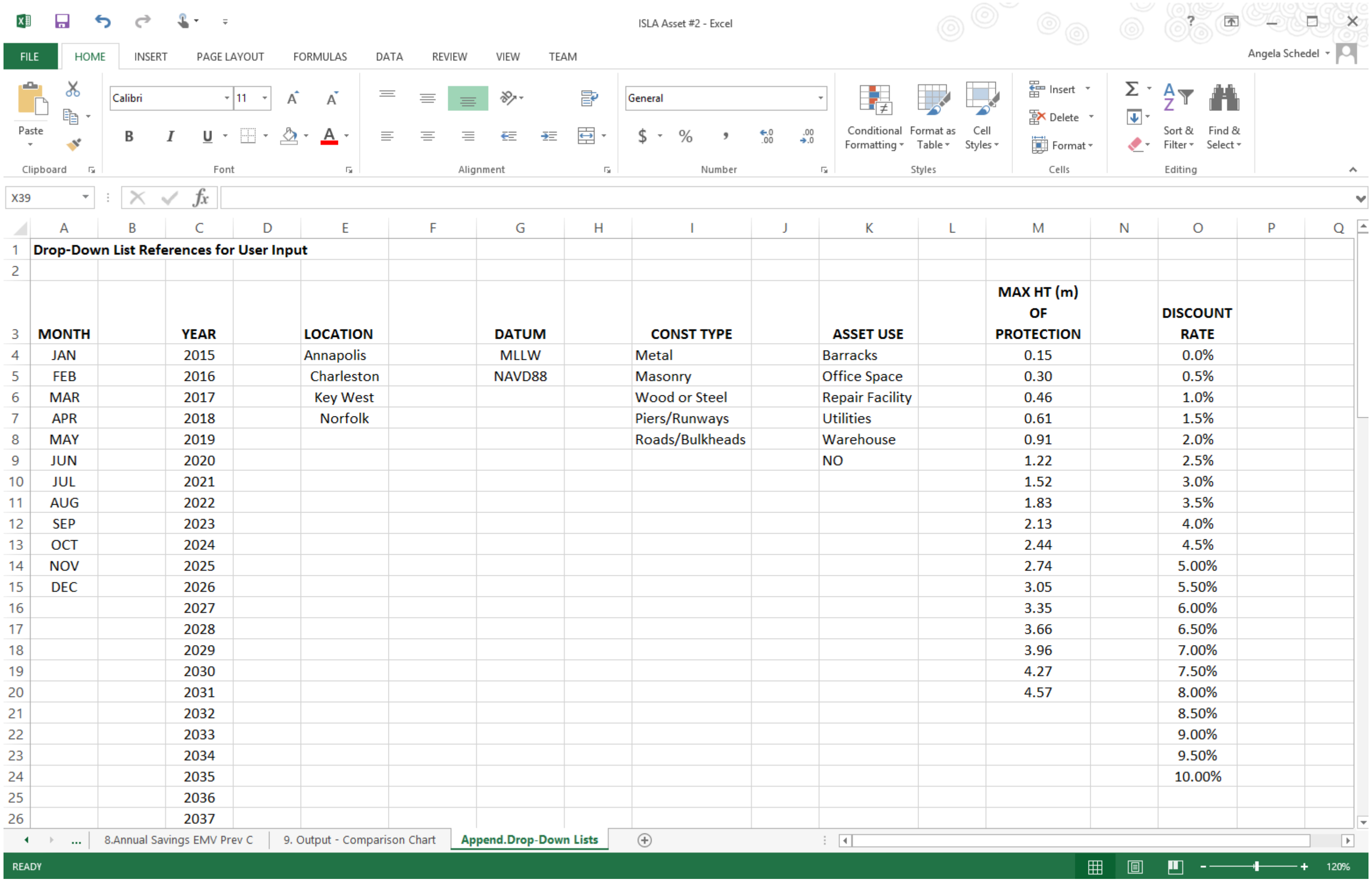


Figure 58: ISLA's output – graphical chart comparing multiple adaptation measures

This worksheet repeats the functioning chart shown on the first User Dashboard screen, which illustrates the comparison of the EMV's without adaptation measures and with adaptation measures. The chart is repeated here to allow the user to view a larger version which allows for better fidelity when comparing adaptation measures which may have intersecting lines.

Append. Drop-Down List



Drop-Down List References for User Input

MONTH	YEAR	LOCATION	DATUM	CONST TYPE	ASSET USE	MAX HT (m) OF PROTECTION	DISCOUNT RATE
JAN	2015	Annapolis	MLLW	Metal	Barracks	0.15	0.0%
FEB	2016	Charleston	NAVD88	Masonry	Office Space	0.30	0.5%
MAR	2017	Key West		Wood or Steel	Repair Facility	0.46	1.0%
APR	2018	Norfolk		Piers/Runways	Utilities	0.61	1.5%
MAY	2019			Roads/Bulkheads	Warehouse	0.91	2.0%
JUN	2020				NO	1.22	2.5%
JUL	2021					1.52	3.0%
AUG	2022					1.83	3.5%
SEP	2023					2.13	4.0%
OCT	2024					2.44	4.5%
NOV	2025					2.74	5.00%
DEC	2026					3.05	5.50%
	2027					3.35	6.00%
	2028					3.66	6.50%
	2029					3.96	7.00%
	2030					4.27	7.50%
	2031					4.57	8.00%
	2032						8.50%
	2033						9.00%
	2034						9.50%
	2035						10.00%
	2036						
	2037						

Figure 59: Appendix for ISLA, showing drop-down lists referenced by cells in the User Dashboard worksheet

This worksheet is the appendix for ISLA. It is used as a reference for the cells on the User Dashboard which have special formatting for drop-down lists. Drop-down lists are useful for this tool, because they limit the choices the user can input to those selections which ISLA can interpret. Limiting the choice of inputs to those in this appendix also helps keep ISLA's calculation time to a minimum. These drop-down lists can be easily modified if a wider range of choices is desired.

Appendix B: Present Value Integration Method

By integrating all of the annual benefits and costs over time, a decision whether it is economically reasonable to build a chosen flood protection measure can be determined. However, due to the increasing nature of Global Sea Level Rise over time, the implementation decision is better informed using the annual cost comparison previously presented. A sensitivity analysis that compares these two methods is presented within this appendix.

When summing the annual benefits and costs of an adaptation measure over time, the costs must be compared at an equal time horizon. This horizon can be either the Future Value (FV) of all of the associated costs, or the Present Value (PV). The example presented here will use PV in the current year, 2015. The cash flow diagrams to be compared show all of the annual costs of implementing an adaptation measure versus the estimated damage associated with the "Do Nothing" option.

Financial assumptions made in this economic model are:

1. The money required for the initial cost of building the adaptation measure is not currently in the decision maker's bank account. Therefore, there is no return on investment in the early years if the decision is made to delay building the adaptation measure.
2. The money has to be borrowed. Since the example is a government project, federal treasury bonds will have to be sold to obtain the money.
3. The interest rate for the treasury bonds is set by the Office of Management and Budget. For 2015, the annual discount rate is 3.4% for the 30-year treasury bond

(Office of Management and Budget 2015). However, it is recommended to use 7% as the discount rate for benefit to cost comparisons for federal projects (Office of Management and Budget 1992).

4. An annual inflation rate of 2% (Office of Management and Budget 2015) will be applied to the initial cost for future year comparison.
5. The money borrowed via treasury bonds will be paid back in annual installments of principal and interest (amortized).

The economic study period, for which the cost comparison is evaluated, can be varied based on the decision maker's preference. In some cases, the economic study period may be equivalent to the design life of the adaptation measure. For example, if the adaptation measure being evaluated is a 0.5 meter flood protection wall, the design life, and hence the economic study period, might be as large as 100 years for a masonry-built structure. Alternatively, the economic study period could also be equivalent to the remaining physical life of the asset to be protected. For example, suppose the structure being evaluated for adaptation was constructed in 1960 with a design life of 50 years, but renovated in 1990 to extend the design life another 50 years. In 2015, the building would have a remaining physical life of 25 years. The cash flow diagrams in Figure 60 shown illustrate this type of an analysis, with a start year, T_0, of 2015 and an economic study period, N, of 25 years.

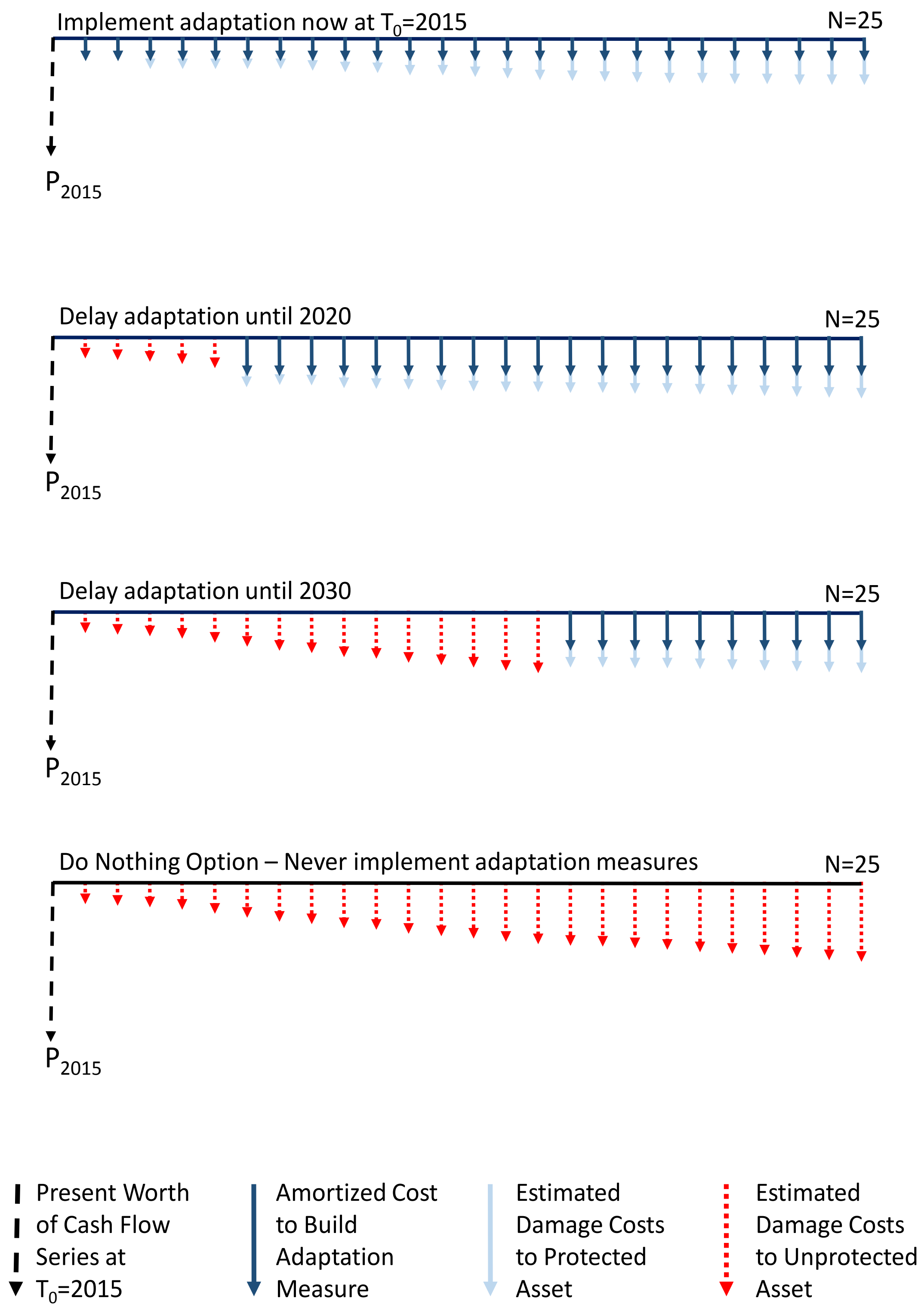


Figure 60: Cash flow diagrams comparing the present worth of delaying protection for an asset

The equations used to analyze annual benefits and costs over time from the cash flow diagrams, taking into consideration the time value of money, are detailed here. The costs in each future year, n, of the economic study period, N, are brought back to present value:

$$P = F\ (1 + i)^{-n} \tag{71}$$

where P is the present value of a future cash flow, F. This future cash flow occurs in time n, and is analyzed with a given interest rate, i. The present value (P) of a series of future cash flows is expressed as:

$$P = \sum_{n=0}^{N} \frac{A_n}{(1 + i)^n} \tag{72}$$

where P is the present value of the future cash flows, n is the future year, A_n is the annual cash flow in a future year n, i is the interest rate, and N is the economic study period (Park 2013).

The "Do Nothing" option, also called the "without adaptation" option, illustrates the annual Expected Monetary Value of flood damage costs without any adaptation measures implemented. The present value of these expected cash flows can be expressed as:

$$P_{without\ adaptation} = \sum_{n=T_0}^{T_0+N} \frac{EMV_{without\ adaptation_n}}{(1 + R)^n} \tag{73}$$

where the terms have the same meaning as in Equation (72) above, with the addition of four new terms. *EMV* is Expected Monetary Value, as described and calculated in Chapter 8, T_0 is the starting year of the economic analysis, R is the discount rate used for economic analysis of federal projects, and N is the chosen economic study period.

The present value of the “Do Nothing” option is compared to the future Estimated Damage Costs (EDC) and future costs to build the adaptation measure over time. The present value of the “with adaptation” option is:

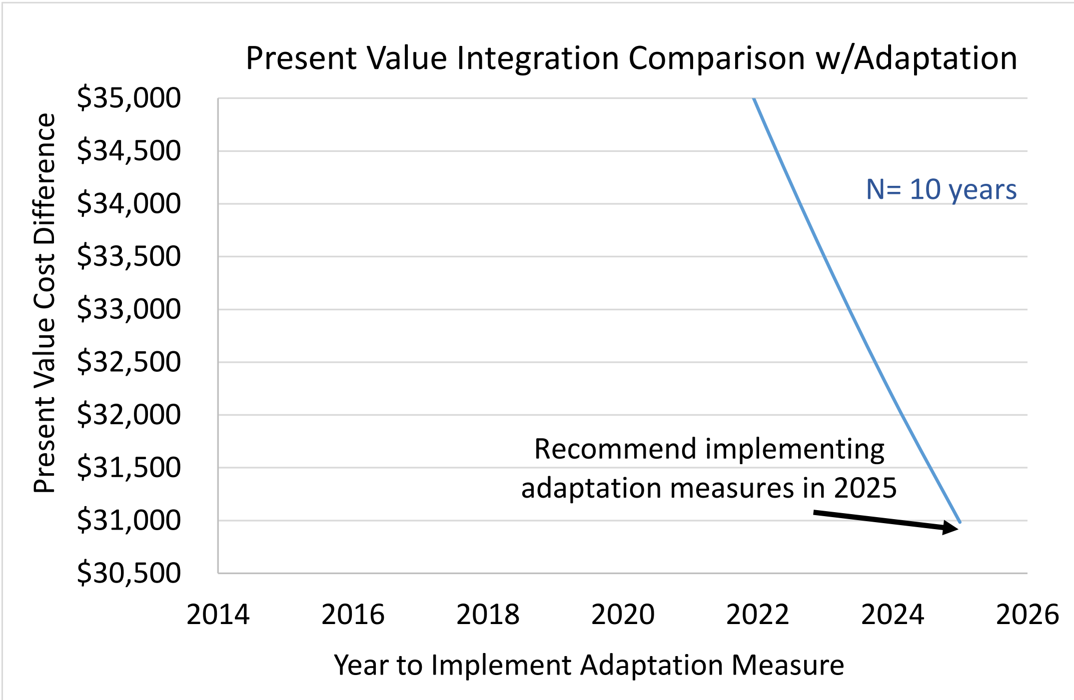
$$P_{with\ adaptation} = \sum_{n=T_0}^{T_0+N} \frac{\left[\sum P(FW) * EDC_{with\ adaptation}\right]_n + ACC_n}{(1+R)^n} \qquad (74)$$

where *P(FW)* is the probability of flooding inside the structure to a specified height, *EDC* is the Estimated Damage Cost due to flooding to the specified height, and ACC_n is the Annualized Capital Cost to implement the adaptation measure in year *n*.

Cost comparison of Equation (74) to Equation (73) yields a result of when to best implement a chosen adaptation measure. This is similar to the comparison analysis of annual costs, as done in the previous section. Therefore, Equation (70) can be adapted:

$$Present\ Worth\ Cost\ Savings = P_{without\ adaptation} - P_{with\ adaptation} \qquad (75)$$

The Tipping Point is the year the adaptation measure becomes more economical than not having protection against flood damage. This is where the Present Worth Cost Savings no longer decreases, but starts increasing over time. The year where the cost savings is at the lowest point on the curve is the year it is recommended to implement the adaptation measure (Figure 61).



(a) above, shows the sensitivity analysis of N=10 years, (b) below, shows N=25 years

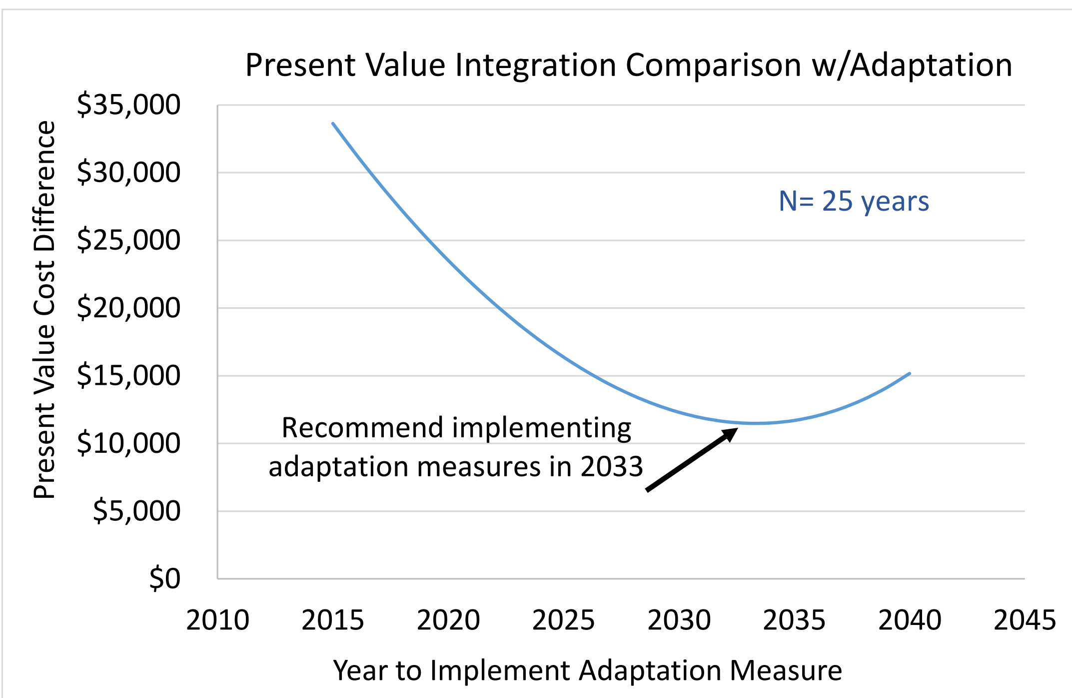
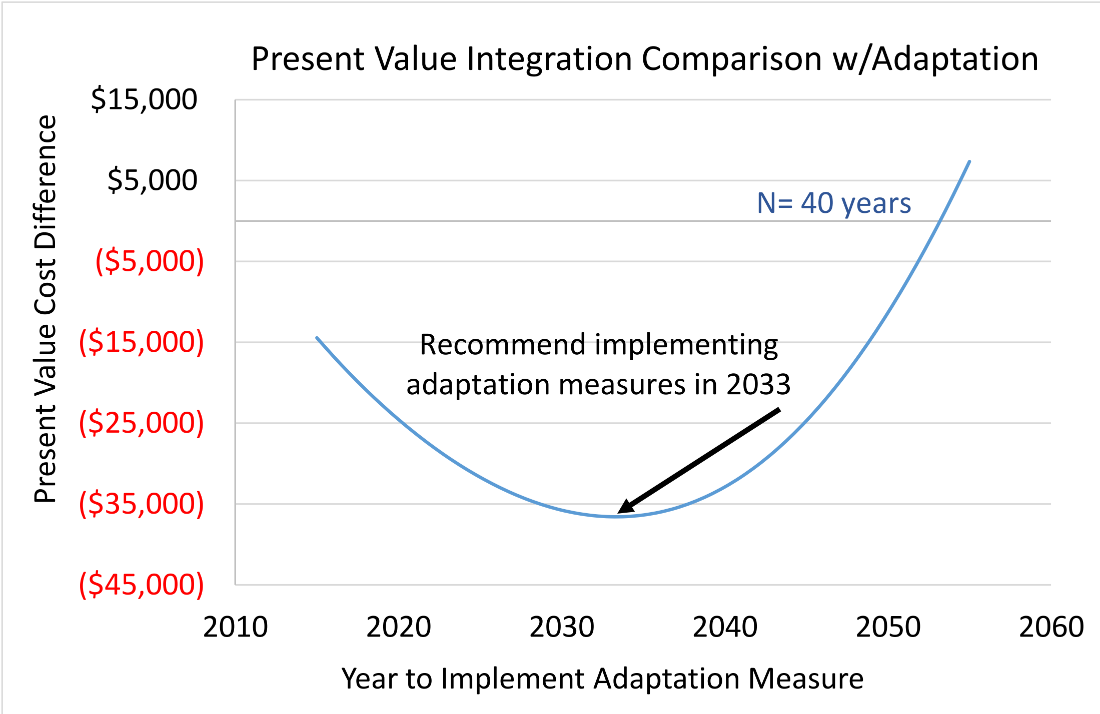


Figure 61: Present Worth integration over time method showing the recommended year to implement Preventive Measure A for Asset #2 at Norfolk

Sensitivity analysis was conducted using the present value integration over time method at R=7% for Asset #2 at Norfolk and Preventive Measure A. The economic study period, N was varied and analyzed at N=10 years, 25 years, 40 years and 50 years, with N representing the remaining physical life of the vulnerable asset. The sensitivity analysis suggested that the recommended year to implement the preventive measure via the integration over time method was the same as that result found with ISLA's annual EMV cost comparison (Figure 62). The recommended year found via the integration method was the same as ISLA's recommendation, but only at larger economic study periods.

The optimal economic study period will vary depending on the asset's location, remaining physical life, plant replacement value, first floor height above datum, and the decision maker's preference. In addition to economic study period, the implementation recommendation which results from the present value integration method is highly dependent on the interest rate used to calculate the present value of each cash flow series. As previously noted, a discount rate of 7% is recommended for the benefit to cost comparison of federal projects (Office of Management and Budget 1992). However, for a more realistic analysis, the actual discount rate could be used. The discount rate for civil works projects with an economic study period over 20 years is equivalent to the 30-year treasury bond rate. This rate is currently 3.4% when taking inflation into account, and 1.4% without inflation (Office of Management and Budget 2015). With the present value integration method, the recommendation of which year to implement an adaptation measure changes significantly if the interest rate used is 1.4% compared to 7%.



(a) above, shows the sensitivity analysis of N=40 years, (b) below, shows N=50 years

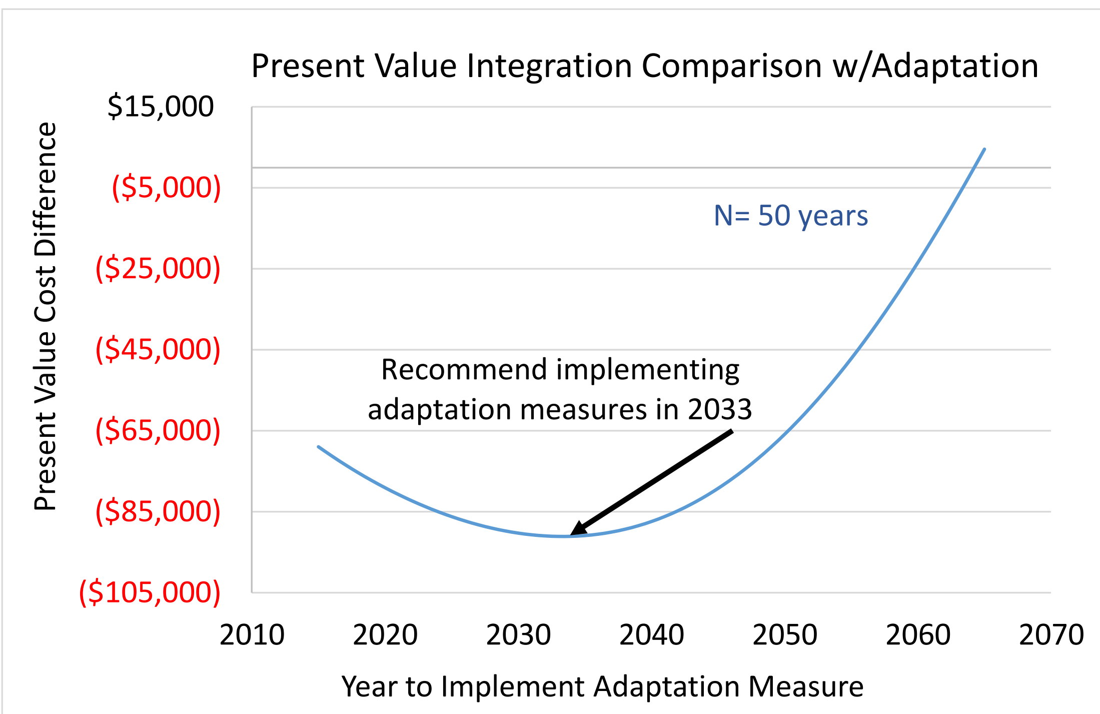


Figure 62: Present Worth integration over time method shows the recommended year to implement a preventive measure is the same as the annual EMV comparison method

Because of the variety of factors which can affect the present value integration method, the annual comparison of EMV’s detailed in Chapter 9 is a better method for determining economic feasibility. The annual EMV comparison redraws the decision tree in single-year snapshots and determines which year is recommended to implement an adaptation measure.

The annual EMV comparison method is also preferred because it allows for a greater range of buildings in a portfolio management situation. Since the optimal economic study period, *N*, varies depending on the building and the adaptation measure analyzed, it would be difficult to compare a variety of structures each with a different economic study period. For present worth analysis to be used as a comparison method, the cash flows must be compared over the same period. This would not be possible if analyzing multiple adaptation alternatives using integration. However, annual equivalent worth analysis is a comparison method used often by economists when alternatives compared do not have equal lives (Park 2013). In this case, the annual EMV analysis is superior to the present value integration method because it allows for the comparison of several different adaptation measures that may have different service lives.

Glossary

AMOC - Atlantic Meridional Overturning Current (or Circulation), a major ocean current which transports warm, salty water from the Tropics in a northbound flow, and cold, less salty water in southbound flow. The current acts as a heat exchanger between the Northern and Southern Hemispheres. Changes in the current's flow impact Local Sea Level Rise in adjacent coastal regions.

GIA- Glacial Isostatic Adjustment, the vertical movement of the Earth's crust in the 21st century as a result of the removal of glaciers that once covered portions of the Northern Hemisphere and compressed the land underneath due to their great size and weight

MLLW – Mean Lower Low Water, the average of the daily lower low water level observed over the 19 year period established as the National Tidal Datum Epoch

MSL – Mean Sea Level, the average of hourly water level observations during the 19 year period established as the National Tidal Datum Epoch

NAVD 88 – North American Vertical Datum of 1988, a set of fixed reference points used for calculating elevations on the earth's surface, not the same as Mean Sea Level

NTDE – National Tidal Datum Epoch, established by the National Ocean Service, a specific 19 year period in which water level observations are analyzed in order to obtain mean value for tidal datums, such as Mean Lower Low Water and Mean Sea Level

PRV- Plant Replacement Value, the cost of replacing an existing building or structure with today's dollars, while conforming to current building codes

RCP - Representative Concentration Pathways, IPCC term for a variety of scenarios in the 2013 report which take into account the severity of future greenhouse gas concentrations and the effects of specific quantities of gases

Bibliography

Allianz Group for World Wildlife Fund. 2006. *Climate Change and Insurance: An Agenda for Action in the United States*.

Annan, J. D., and J. C. Hargreaves. 2007. "Efficient Estimation and Ensemble Generation in Climate Modelling." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 365. (1857): 2077.

Bahr, David B., Mark Dyurgerov, and Mark F. Meier. 2009. "Sea-Level Rise from Glaciers and Ice Caps: A Lower Bound." *Geophysical Research Letters.* 36 (3).

Batten, B. K, P. Weberg, M. Mampara, and L. Xu. 2008. "Evaluation of Sea Level Rise for FEMA Flood Insurance Studies: Magnitude and Time-Frames of Relevance." *Proceedings of Solutions to Coastal Disasters 2008; Oahu, Hawaii*.

Beven, Jack, and Hugh Cobb. 2004. "NHC Tropical Cyclone Report, Hurricane Isabel." *National Hurricane Center*. January 16, 2004. http://www.nhc.noaa.gov/2003isabel.shtml.

Burks-Copes, Kelly A., E. Russo, S. Bourne, and M. Case. 2014. *Risk Quantification for Sustaining Coastal Military Installation Asset and Mission Capabilities*. RC-1701. Department of Defense Strategic Environmental Research and Development Program.

CCAR. 2013. Colorado Center for Astrodynamics Research: University of Colorado, Boulder. Reconstructed Sea Level Version 1. Dataset accessed 2014-03-10 at http://podaac.jpl.nasa.gov/dataset/RECON_SEA_LEVEL_OST_L4_V1

Church, J.A., Woodworth, P.L., Aarup, T, and Wilson, SW. 2010. *Understanding Sea-Level Rise and Variability.* Chichester: Wiley-Blackwell Publishing.

Clemen, Robert T., and Robert L. Winkler. 1999. "Combining Probability Distributions from Experts in Risk Analysis." *Risk Analysis.* 19 (2): 187–203.

Department of Defense. 2003. *Report of the Plant Replacement Value (PRV) Panel*. Office of the Deputy Under Secretary of Defense (Installations & Environment).

Department of Defense. 2011. *Base Structure Report Fiscal Year 2012 Baseline (A Summary of DoD's Real Property Inventory)*. Office of the Deputy Under Secretary of Defense (Installations & Environment).

Department of Defense. 2014. *Climate Change Adaptation Roadmap*. Office of the Deputy Under Secretary of Defense (Installations & Environment).

Engelhart, S.E., and Horton, B.P. 2012. *Holocene sea level database for the Atlantic Coast of the United States*. Quaternary Science Reviews. (54): 12-25.

FEMA. 2013. *Floodproofing Non-Residential Buildings*. Federal Emergency Management Agency. FEMA P-936.

FEMA. 2014. *Homeowner's Guide to Retrofitting: Six Ways to Protect Your Home From Flooding*. Federal Emergency Management Agency. FEMA P-312, 3rd Edition.

Goddard, Paul B., Jianjun Yin, Stephen M. Griffies, and Shaoqing Zhang. 2015. "An Extreme Event of Sea-Level Rise along the Northeast Coast of North America in 2009–2010." *Nature Communications.* 6 (February).

Grinsted, A., J. C. Moore, and S. Jevrejeva. 2008. "Observational Evidence for Volcanic Impact on Sea Level and the Global Water Cycle." *PNAS.* 104 (50): 19730–34.

Grinsted, A., J. C. Moore, and S. Jevrejeva. 2009. "Reconstructing Sea Level from Paleo and Projected Temperatures 200 to 2100 Ad." *Climate Dynamics.* 34 (4): 461–72.

Horton, Radley, Celine Herweijer, Cynthia Rosenzweig, Jiping Liu, Vivien Gornitz, and Alex C. Ruane. 2008. "Sea Level Rise Projections for Current Generation CGCMs Based on the Semi-Empirical Method." *Geophysical Research Letters.* 35 (2).

Houston, J. 2013. "Methodology for Combining Coastal Design-Flood Levels and Sea-Level Rise Projections." *Journal of Waterway, Port, Coastal, and Ocean Engineering.* 139 (5): 341–45.

Houston, J., and R. Dean. 2011. "Sea-Level Acceleration Based on US Tide Gauges and Extensions of Previous Global-Gauge Analyses."

IPCC. 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. (J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson, eds). Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis*. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds). Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.

IPCC. 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, eds*)*. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.

Jacobs. 2011. “The Effects of Inundation on Pavements.” Highways Agency Contractors Report. Ref No: 383 (1308) JCBS. Jacobs Engineering U.K. Limited.

Jevrejeva, S., A. Grinsted, J. C. Moore, and S. Holgate. 2006. “Nonlinear Trends and Multiyear Cycles in Sea Level Records.” *Journal of Geophysical Research.* 111 (September): 11.

Jevrejeva, S., J. C. Moore, and A. Grinsted. 2010. “How Will Sea Level Respond to Changes in Natural and Anthropogenic Forcings by 2100?” *Geophysical Research Letters.* 37 (April).

Jevrejeva, S., J.C. Moore, A. Grinsted, A.P. Matthews, and G. Spada. 2014. “Trends and Acceleration in Global and Regional Sea Levels since 1807.” *Global and Planetary Change.* 113 (February): 11–22.

Knowles, Scott G., and Howard C. Kunreuther. 2014. “Troubled Waters: The National Flood Insurance Program in Historical Perspective.” *Journal of Policy History*. 26 (3): 327-353.

Kopp, Robert E., Frederik J. Simons, Jerry X. Mitrovica, Adam C. Maloof, and Michael Oppenheimer. 2009. “Probabilistic Assessment of Sea Level during the Last Interglacial Stage.” *Nature.* 462 (7275): 863–U51.

Kriebel, David L., and Joseph D. Geiman. 2013. “A Coastal Flood Stage to Define Existing and Future Sea-Level Hazards.” *Journal of Coastal Research*. December, 1017–24.

Lorenzoni, Irene, Nick F. Pidgeon, and Robert E. O’Connor. 2005. “Dangerous Climate Change: The Role for Risk Research.” *Risk Analysis.* 25 (6): 1387–98.

Lowe, J.A., T.P. Howard, A. Pardaens, J. Tinker, J. Holt, S. Wakelin, G. Milne, J. Leake, J. Wolf, K. Horsburgh, T. Reeder, G. Jenkins, J. Ridley, S. Dye, S. Bradley. 2009. *UK Climate Predictions Science Report: Marine and Coastal Projections*. Met Office Hadley Centre, Exeter, UK.

Magee, John F. 1964. “Decision Trees for Decision Making.” *Harvard Business Review.* August 7.

Mainville, Andre and Michael R. Craymer. 2005. “Present-day tilting of the Great Lakes region based on water level gauges.” *Geological Society of America Bulletin*. 117 (7/8): 1070-1080.

Maryland Department of the Environment. 2012. *Groundwater Protection Program: Annual Report to the Maryland General Assembly.* Annapolis, MD.

Mays, Larry W. 2011. *Water Resources Engineering*. John Wiley & Sons, Inc: Hoboken, NJ.

McFarlane, Benjamin J. 2013. *Coastal Resiliency: Adapting to Climate Change in Hampton Roads*. PEP 13-08. Hampton Roads Planning District Commission.

Michael, J. A. 2007. “Episodic Flooding and the Cost of Sea-Level Rise.” *Ecological Economics.* 63 (1): 149–59.

Moore, J. C., S. Jevrejeva, and A. Grinsted. 2010. “Efficacy of Geoengineering to Limit 21st Century Sea-Level Rise.” *Proceedings of the National Academy of Sciences.* 107 (36): 15699–703.

Morano, Marc. 2013. “UN IPCC Report Exposed By Its Own Members as ‘a Pure Political Process’ -- ‘Scientific Truth Isn’t Negotiated in the Dead of Night behind Closed Doors’ -- Climate Depot Round Up.” *Climate Depot*. September 26. http://www.climatedepot.com/2013/09/26/

Morris, Peter A. 1983. “An Axiomatic Approach to Expert Resolution.” *Management Science.* 29 (1): 24–32.

National Research Council. 1987. *Responding to Changes in Sea Level: Engineering Implications*. Washington, D.C.: The National Academies Press.

National Research Council. 2010. *America’s Climate Choices: Panel on Advancing the Science of Climate Change*. Washington, D.C.: The National Academies Press.

NAVFAC. 2013. Economic Analysis Handbook. Naval Facilities Engineering Command. P-442.

Nicholls, Robert J, Natasha Marinova, Jason A Lowe, Sally Brown, Pier Vellinga, Diogo de Gusmão, Jochen Hinkel, and Richard S. J. Tol. 2011. “Sea-Level Rise and Its Possible Impacts given a ‘beyond 4°C World’ in the Twenty-First Century.” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences.* 369 (1934): 161–81.

NOAA. 2013. *What Will Adaptation Cost? An Economic Framework for Coastal Community Infrastructure*. Eastern Research Group, Inc. under contract for

National Oceanic and Atmospheric Administration Coastal Services Center.

NOAA. 2014. "Event History: Extratropical - Storm Surge and Coastal Inundation." National Oceanic and Atmospheric Administration. http://www.stormsurge.noaa.gov/event_history.html.

NOAA. 2015. Data from National Oceanic and Atmospheric Administration Tides & Currents website. Various tidal stations. http://www.tidesandcurrents.noaa.gov

Office of Management and Budget. 1992. "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs." Circular A-94. Transmittal Memo No. 64.

Office of Management and Budget. 2015. "2015 Discount Rates for OMB Circular A-94." Appendix C. Memorandum M-15-05.

Park, Chan S. 2013. *Fundamentals of Engineering Economics*. Third Edition. Pearson Education, Prentice Hall: Upper Saddle River, New Jersey.

Parris, A., P. Bromirksi, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, et al. 2012. "Global Sea Level Rise Scenarios for the US National Climate Assessment." NOAA Tech Memo OAR CPO-1.

PBS NewsHour. 2013. "Why the strongest storms are getting stronger." PBS NewsHour video. November 12, 2013. Transcript available at www.pbs.org/newshour

Pfeffer, W. T., J. T. Harper, and S. O'Neel. 2008. "Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise." *Science.* 321 (5894): 1340–43.

Rahmstorf, Stefan. 2007. "A Semi-Empirical Approach to Projecting Future Sea-Level Rise." *Science.* 315 (5810): 368–70.

Rahmstorf, Stefan. 2012. "Sea-Level Rise: Towards Understanding Local Vulnerability." *Environmental Research Letters.* 7 (2).

Rahmstorf, Stefan, and Martin Vermeer. 2011. "Discussion of: Houston, J.R. and Dean, R.G., 2011. Sea-Level Acceleration Based on U.S. Tide Gauges and Extensions of Previous Global-Gauge Analyses. Journal of Coastal Research, 27(3), 409–417." *Journal of Coastal Research.* 274 (July): 784–87.

Rick, UK, MT Boykoff, and RA Pielke Jr. 2011. "Effective Media Reporting of Sea Level Rise Projections: 1989–2009." *Environmental Research Letters.* 6.

Roach, John. 2007. "Hurricanes Have Doubled Due to Global Warming, Study Says." *National Geographic News.* www.news.nationalgeographic.com.

Rohling, E. J., K. Grant, M. Bolshaw, A. P. Roberts, M. Siddall, Ch. Hemleben, and M. Kucera. 2009. “Antarctic Temperature and Global Sea Level Closely Coupled over the Past Five Glacial Cycles.” *Nature Geoscience.* 2 (June): 500–504.

Sallenger, Asbury H., Kara S. Doran, and Peter A. Howd. 2012. “Hotspot of Accelerated Sea-Level Rise on the Atlantic Coast of North America.” *Nature Climate Change*. 2: 884-888.

Samuel, Peter. 2012. “Floodgate at Midtown Tunnel Norfolk VA Kept Sandy Closure to Less than Half a Day.” *TollRoadsNews*. November 20. http://tollroadsnews.com/news/floodgate-at-midtown-tunnel-norfolk-va-kept-sandy-closure-to-less-than-half-a-day.

Schultz, Mark. 2003. “Wasp Sailors Provide Disaster Relief from Hurricane Isabel.” October 1. http://www.navy.mil/submit/display.asp?story_id=9791.

Scott, Timothy W., Donald J.P. Swift, G. Richard Whittecar, and George A. Brook. 2010. “Glacioisostatic Influences on Virginia’s Late Pleistocene Coastal Plain Deposits.” *Geomorphology.* 116 (1–2): 175–88.

Sella, Giovanni F., Seth Stein, Timothy H. Dixon, Michael Craymer, Thomas S. James, Stephane Mazzotti, and Roy K. Dokka. 2007. “Observation of Glacial Isostatic Adjustment in ‘stable’ North America with GPS.” *Geophysical Research Letters.* 34 (January): 6.

Siddall, Mark, Thomas F. Stocker, and Peter U. Clark. 2009. “Constraints on Future Sea-Level Rise from Past Sea-Level Change.” *Nature Geoscience.* 2 (8): 571–75.

Stamey, B., H. Wang, and M. Koterba. 2007. “Predicting the next Storm Surge Flood.” *Sea Technology.* 48 (8): 10.

Titley, David, RADM. 2010. *The Navy’s Climate Change Interests*. Oceanographer of the Navy’s Office, U.S. Navy: Washington, D.C.

U.S. Army Corps of Engineers. 1992. “Catalog of Residential Depth-Damage Functions Used by the Army Corps of Engineers in Flood Damage Estimation.” IWR Report 92-R-3. U.S. Army Corps of Engineers, Institute for Water Resources.

U.S. Army Corps of Engineers. 1996. “Analysis of Nonresidential Content Value and Depth-Damage Data for Flood Damage Reduction Studies.” IWR 96-R-12. U.S. Army Corps of Engineers, Institute for Water Resources.

U.S. Army Corps of Engineers. 2000. “Economic Guidance Memorandum (EGM) 01-03, Generic Depth Damage Relationships.”

U.S. Army Corps of Engineers. 2006a. "Final Flood Damage Reduction Analysis for the United States Naval Academy." U.S. Army Corps of Engineers, Baltimore District.

U.S. Army Corps of Engineers. 2006b. "Depth-Damage Relationships for Structures, Contents and Vehicles and Content-To-Structure Value Ratios (CSVR) in Support of the Donaldsville to the Gulf, Louisiana Feasibility Study." U.S. Army Corps of Engineers, New Orleans District.

U.S. Army Corps of Engineers. 2009. "Water Resource Policies and Authorities Incorporating Sea-Level Change Considerations in Civil Works Programs." Circular No. 1165-2-211.

U.S. Army Corps of Engineers. 2011. "Sea Level Change Considerations for Civil Works Programs." Circular No. 1165-2-211.

U.S. Army Corps of Engineers. 2014. "Procedures to Evaluate Sea Level Change: Impacts, Responses, and Adaptation." Technical Letter ETL-1100-2-1.

U.S. Army Corps of Engineers. 2015a. "North Atlantic Coast Comprehensive Study: Resilient Adaptation to Increasing Risk." Final Report.

U.S. Army Corps of Engineers. 2015b. "Nonstructural Flood Damage Reduction Matrix." National Nonstructural / Flood Proofing Committee.

U.S. Geological Survey. 2003. "Ground Water in Freshwater-Saltwater Environments of the Atlantic Coast." Circular 1262. Paul Barlow. Reston, VA.

U.S. Geological Survey. 2013. "Land Subsidence and Relative Sea-Level Rise in the Southern Chesapeake Bay Region." Circular 1392. Jack Eggleston and Jason Pope. Reston, VA.

Vermeer, M., and S. Rahmstorf. 2009. "Global Sea Level Linked to Global Temperature." *Proceedings of the National Academy of Sciences.* 106 (December): 21527–32.

Virginia Department of Environmental Quality. 2014. "Virginia Water Quality Assessment 305(b)/303(d) Integrated Report."

White, G. F. 1945. "Human Adjustment to Flood," University of Chicago, Dep. of Geography, Research Paper, No. 29.

Zhang, Z., Z. Wu, M. Martinez, and K. Gaspard. 2008. "Pavement Structures Damage Caused by Hurricane Katrina Flooding." *Journal of Geotechnical and Geoenvironmental Engineering.* 134 (5): 633–43.