Rahway River Basin, New Jersey
Coastal Storm Risk Management Feasibility Study

Appendix B
Economics

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1 INTRODUCTION

This economic appendix accompanies the Rahway River Basin, New Jersey Coastal Storm Risk Management Feasibility Study Final Report. U.S Army Corps of Engineers (USACE) New York District has prepared this report to document the economic analysis in the optimization of the tentatively selected plan for the Rahway River Basin, New Jersey Coastal Storm Risk Management Feasibility Study. In what follows, the reader is encouraged to observe a distinction between the tentatively selected plan and the recommended plan. The tentatively selected plan was identified in the 2017 draft report following the economic analysis of 6 alternatives: 1, 2, 3a, 3b, 4, and 4a. The tentatively selected plan was identified as Alternative 4a. Alternative 4a includes non-structural treatments and Levee Segment D. During optimization, Alternative 4a was refined, the levee became part floodwall[1], and the alternative was evaluated at three sizes: small, medium, and large. The medium-sized Alternative 4a was found to have the highest net national economic development benefits and has been therefore identified as the recommended plan.

The analytic structure used to identify the tentatively selected plan is largely maintained in optimization. Departures from this structure in optimization and the coinciding identification of the recommended plan are noted and explained. The procedures and results of the economic flood damage analysis for the identification of the tentatively selected plan and recommended plan are detailed. The economic analysis used to identify the tentatively selected plan and the recommended plan includes the development of stage-damage relationships and annual damages over a 50-year analysis period. The period of analysis was updated during optimization to years 2029 through 2079. Damage assessment over this period includes inundation damages to structures, contents, and vehicles.

Flood damage calculations were performed using Version 1.4.2 of the Hydrologic Engineering Center's Flood Damage Analysis computer program. This program applies Monte Carlo simulation to calculate expected damage values while explicitly accounting for variability in the input data. For optimization of the tentatively selected plan, HEC-FDA models were built for with- and without-project conditions for the optimization plans at 10-year intervals over the period of analysis to appropriately capture the convex nature of sea level rise[2]. The economic analysis for optimization reflects updates to the dollar-denominated data to October 2019 price levels and amortization over the period of analysis has been updated to the fiscal year 2019 project evaluation and formulation rate (discount rate) of 2.75% in accordance with EGM 20-01 (USACE, 2019b)[3].

Over the course of the study's development, there have been two updates to the period of analysis.

The initial period of analysis was 2021 to 2071. This period of analysis was updated to 2023 to 2073 after a delay in the study following the discovery of contaminated soil at the footprint of the levee. Following district quality control review of cost engineering in December 2019, it was determined that the construction schedule would be longer than originally identified. Construction was estimated to begin in September 2024 and to be completed in December 2028. The 52-month construction duration reflects the extent of the nonstructural plan. The completion of construction in December 2028 suggests the new base year of 2029. The 50-year period of analysis has subsequently been revised to 2029 to 2079.

The recommended plan consists of the relocation of about 106 linear feet of observation deck and 2,200 linear feet of bike path, and the replacement of elements such as manholes, fire hydrants, utility poles, etc. related to the road raising of Englehard Ave. It also consists of the construction of 2,520 linear feet of levees and 1,968 linear of floodwalls as well as nonstructural treatments of 96 residential properties and 4 commercial properties[4]. The productivity rates for each construction task are extracted from the MCACES, Second Generation (MII). The construction tasks are imported into P6 for sequencing. It is assumed per engineering judgment that the relocation task will start right after mobilization followed by the construction of levees and floodwalls. However the nonstructural treatment will start right after mobilization and work concurrent with the relocation as well as the construction of levees and floodwalls. The treatment of the nonstructural elements are on the critical path using 2 crews. Average duration for each treatment using one crew is about 28 days, which brings the construction schedule to 52 months with time considered for punchlist. The construction of the levee/floodwall will be completed by January 2028 and the construction of the nonstructural treatments will be completed by December 2028. The midpoint of construction is May 2026.

A risk-informed decision was made to assume that the analysis that was completed for a period of analysis of 2023 to 2073 and described henceforth sufficiently approximates the analysis for a period of analysis of 2029 to 2079. This assumption is founded on the only time-dependent input to the location of the period of analysis for the purpose of the economics: water surface elevations. Conditional on the intermediate and high relative sea level scenarios, the water surface elevations for the various flood events are slightly higher, the farther into the future that the period of analysis takes place. However, it is expected that the water surface elevations that were calculated for 2023 to 2073 approximate the water surface elevations for 2029 to 2079 within an acceptable margin of error. This acceptable margin of error may result in some benefits being left on the table because slightly higher water levels and the coinciding reductions in flood risk are not being captured. Additionally, nonstructural treatments would be completed at the structure level throughout the duration construction which means that pre-base year benefits would be realized but not captured. The margin of error also means slightly higher residual risk than quantified for the reaches that do not have any proposed coastal storm risk management measures.

The analysis begins with the motivation for the economic analysis and the structure upon which this analysis is based. Section 2 describes the study area. Section 3 describes the coastal storm risk problem in the study area and details the history of flooding in the study area. Section 4 describes the flood damage analysis methods. Section 5 contains information about the calculation of the without-project future conditions and the extent of expected annual damages if no project is built. Section 6 contains the results of the economic analysis of the alternatives that were evaluated in the identification of the tentatively selected plan from the draft report of 2017. Section 7 presents details of the tentatively selected plan from the draft report of 2017. Section 8 introduces the variables over which the tentatively selected plan was optimized. Section 9 presents the results of the economic analysis of optimization and the identification of the recommended plan. Section 10 contains information on residual risk and project performance of the three optimization plans under the three relative sea level change scenarios. Finally, Section 11 contains a life safety assessment as it relates to the recommended plan.

2 Description of Study Area

2.1 Location and Setting

The study area is the tidally-influenced lower portion of the Rahway River Basin, located in northeastern New Jersey. The study area has been mapped in Figure 1. The 1% and .2% annual chance of exceedance floodplains are represented by the areas shaded in grey, the area impacted by Hurricane Sandy is overlaid with the area shaded in red, and finally the tidal-influenced portion of the Rahway River is in cross-hatched yellow. Observe that the Rahway River Basin lies within the metropolitan area of Greater New York City and occupies approximately 15 percent of Essex County, 35 percent of Union County, and 10 percent of Middlesex County. The basin is 83.3 square miles (53,300 acres) in area and is roughly crescent-shaped. The greatest width of the basin is approximately 10 miles in the east-west direction from the City of Linden to the City of Plainfield. The greatest length is approximately 18 miles in a north–south direction from West Orange to Metuchen. The tidal influence on the Rahway River extends roughly 5 miles from the Arthur

Kill into the City of Rahway. The Rahway River consists of the mainstem Rahway River and four branches. The West Branch flows south from Verona through South Mountain Reservation and downtown Millburn. The East Branch originates in West Orange and Montclair and travels through South Orange and Maplewood. These two branches converge near Route 78 in Springfield to form the Rahway River which flows through the municipalities of Springfield, Union, Cranford and Clark. The Rahway River then travels through Rahway, entering from Clark at Rahway River Park. The river receives the waters of Robinsons Branch at Elizabeth Avenue between West Grand Avenue and West Main Street and the waters of the South Branch at East Hazelwood Avenue and Leesville Avenue. Finally the river leaves Rahway to enter the city limits of Linden and Carteret before flowing into the Arthur Kill.

The study area is developed and contains residential and commercial structures within the floodplain. The area is suburban and urban with little available open space and lies within the 10th Congressional District, which is represented by Donald Payne Jr. (D-NJ). The local commercial and industrial facilities in the area represent an important regional commercial resource. The study area encompasses portions of the Cities of Linden and Rahway in Union County and the Borough of Carteret and Woodbridge Township in Middlesex County. The tidal influence on the Rahway River extends roughly five miles from the Arthur Kill into the City of Rahway. The City of Rahway is located in southern Union County, New Jersey. According to the United States Census Bureau, Rahway has a total area of 4.028 square miles. Of this area, 3.897 square miles is land and 0.131 square miles (3.26%) is water. Rahway is bordered to the northwest by Clark, the northeast by Linden and to the south by Woodbridge Township in Middlesex County. Woodbridge Township has a total area of 24.507 square miles, including 23.213 square miles of land and 1.294 square miles of water (5.28%). The City of Linden has a total area of 11.407 square miles, including 10.675 square miles of land and 0.732 square miles of water (6.42%). The Borough of Carteret has a total area of 5.000 square miles, including 4.418 square miles of land and 0.582 square miles of water (11.65%). Rahway has a median household income of $60,374 and a per capita income of $29, 939 (U.S. Census Bureau, 2015). The 2010 U.S. Census listed the Rahway City's population as 27,346. 5.9% of the population is under age 5 and 13.5% of the population is 65 years or older (U.S. Census Bureau, 2010). The racial makeup of Rahway is 52.3% white, 30.9% black, 23.5% Hispanic, and 4.3% Asian (U.S. Census Bureau, 2010).

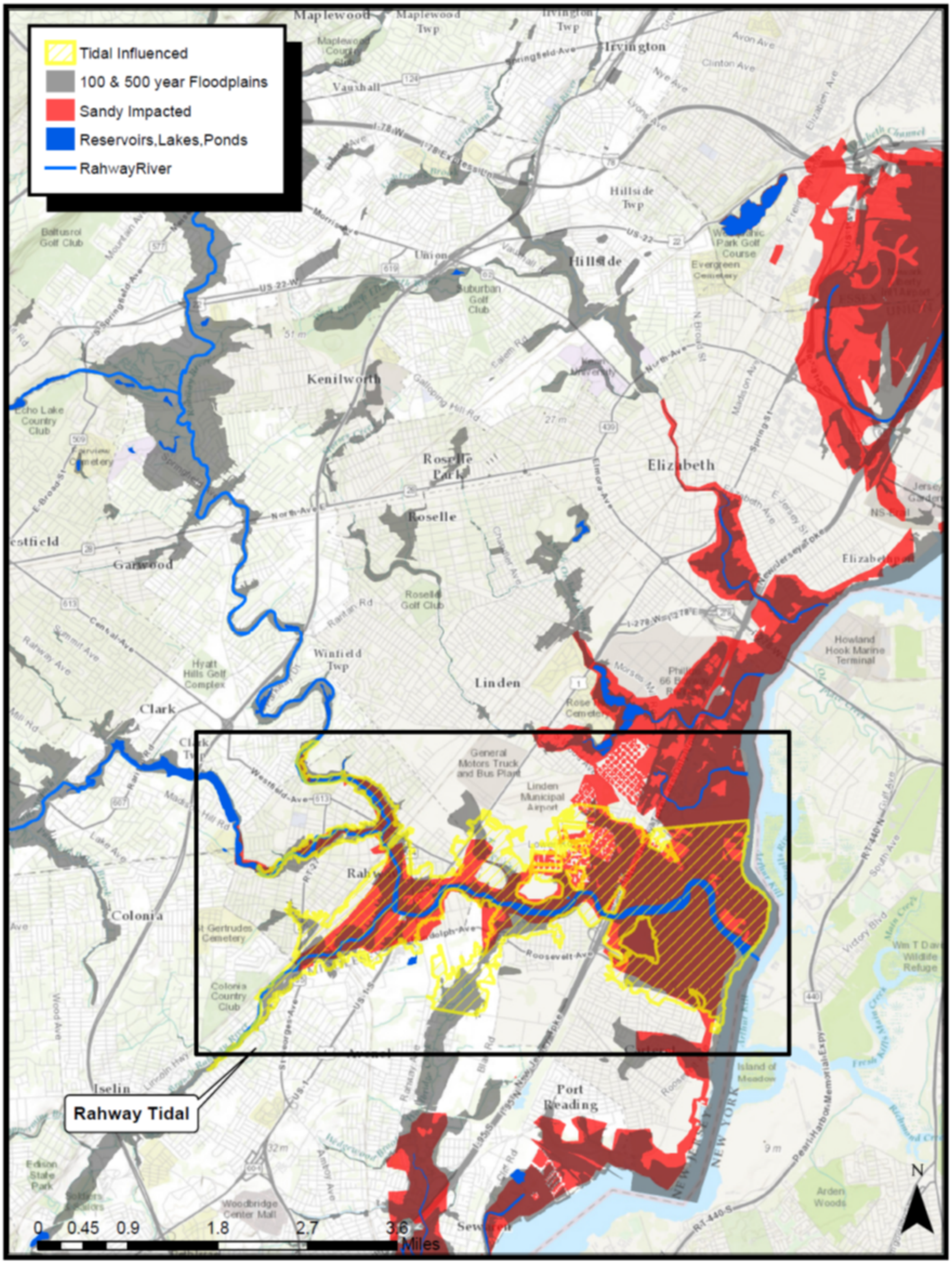


Figure 1: Rahway River Basin Study Area

3 Problem Identification

The primary problem encountered in the study area is tidal flooding with elevated water levels associated with coastal storm surge on the Rahway River and tributaries within the study area.

3.1 Storm history

3.1.1 Hurricane Sandy: October 22–29 2012

Hurricane Sandy initially formed as a tropical depression in the southwestern Caribbean. Sandy weakened somewhat and then made landfall as a post-tropical cyclone near Brigantine, New Jersey with 80.6 mph maximum sustained winds. The extensive size of Hurricane Sandy set the conditions for generating the record-setting storm surges that inundated the New Jersey and New York coastlines. The highest storm surge measured by a National Ocean Service tide gauge in New Jersey was 8.57 feet above normal tide levels at the northern end of Sandy Hook in the Gateway National Recreation Area. Since the station failed and stopped reporting during the storm, it is likely that the actual storm surge was higher. Farther south, the National Ocean Service tide gauges in Atlantic City and Cape May measured storm surges of 5.82 feet and 5.16 feet, respectively. The inundations that occurred along the coast due to the storm tide are organized in Table 1 and are expressed in height above ground level.

Table 1: Observed Inundation during Hurrican Sandy

Counties	Height above Ground Level
Monmouth and Middlesex	4 to 9 feet
Union and Hudson	3 to 7 feet
Essex and Bergen	2 to 4 feet
Ocean	3 to 5 feet
Atlantic, Burlington, and Cape May	2 to 4 feet

The highest storm surge occurred in areas that border lower New York Bay, Raritan Bay, and the Raritan River. The highest high-water mark measured by the U.S. Geological Survey was 8.9 feet above ground level at the U.S. Coast Guard Station on Sandy Hook. This high-water mark is consistent with the data from the nearby National Ocean Service tide gauge, which reported 8.01 feet above mean higher high water before it failed. Elsewhere, a high-water mark of 7.9 feet above ground level was measured in Keyport on the southern side of Raritan Bay and a mark of 7.7 feet was measured in Sayreville near the Raritan River. As storm surge from Sandy was pushed into New York and Raritan Bays, seawater surge occurred within the Hudson River and the coastal waterways and wetlands of northeastern New Jersey, including Newark Bay, the Passaic and Hackensack Rivers, Kill Van Kull, and Arthur Kill. Significant inundations occurred along the Hudson River in Weehawken, Hoboken, and Jersey City, where many high-water marks indicated that inundations were between 4 and 6.5 feet above ground level. Inundations of 4 to 6 feet were also measured across Newark Bay in Elizabeth and the area around Newark Liberty International Airport.

Discussions between USACE and the Middlesex Office of Emergency Management (OEM) revealed that municipalities within the lower portion of the Rahway River Basin and general area suffered tidally-induced flood damages from Sandy. It is estimated that Hurricane Sandy caused tens of millions of dollars of damage in the study area. The City of Rahway sustained an estimated $35 million in damages with approximately $15 million of it to city property and another $20 million to private property. Damages included costly repairs to the existing USACE levee pump stations. Damages for the Borough of Carteret are estimated at $53.1 million. Woodbridge Township suffered damages estimated at $7 million with 200 structures damaged, including 40 destroyed. The PSE&G power plant in Woodbridge was destroyed. The Blue Acres Program with the New Jersey Department of Environmental Protection is in the process of buying out 221 structures in Woodbridge (as of March 2020)[5]. No deaths associated with Hurricane Sandy have been identified within the study area.

Hurricane Sandy resulted in extensive impacts to critical infrastructure and the economy in the study area and surrounding communities. New Jersey Transit was shut down in its entirety. PATH light rail services were also shut down. Starting 1 November 2012, New Jersey Transit restored bus service on 68 bus routes in northern and central New Jersey and 18 bus routes in southern New Jersey, providing service over the entire routes with no detours or truncations. Partial service was scheduled to be restored on 58 bus routes in northern and central New Jersey and 17 routes in southern New Jersey, to operate with detours or truncations due to the impact from Hurricane Sandy. These service disruptions made commutes to work challenging for many citizens in and around the study area.

The hurricane not only halted the public transportation system, but lead to many road closures in and around the study area. The Garden State Parkway was closed approximately 130 miles from Exit 129 in Woodbridge Township to Cape May. The New Jersey Turnpike's Hudson County Extension was closed between Exit 14 (Newark Airport/I-78/Routes 1 & 9) and the Holland Tunnel, speed restrictions of 45mph were in place below Exit 12 (Carteret/Rahway), and the turnpike was closed farther south[6]. Additionally, there were multiple closures along Route 35 and Route 9 preventing the flow of traffic along these highways[7].

More than 8 million people were without power in New Jersey as stations flooded and trees fell on power lines (Huffpost, 2013). Governor Christie said on the morning of 30 October 2012 that some 2.4 million households in the state were without power. As of the morning of 2 November 2012, 1.6 million customers were still without power, down from 2.7 million. As of 3 November 2012, 31 percent of homes and businesses in the state did not have electricity (E Caroom, 2012).

Hurricane Sandy also threatened the environment due to the spread of pollutants and contaminants. In addition to the threat of contaminants from the Superfund sites, there were an estimated 630 storm-related oil spills in New York City. New Jersey, on the other hand, took the worst blow regarding oil contamination after a significant diesel fuel spill at the Motiva Refinery into the 10-mile-long, 600-foot wide tidal strait separating New Jersey from New York's Staten Island, known as Arthur Kill which is connected to the Rahway River. According to New Jersey environmental officials, the AP reported 336,000 gallons of diesel fuel spilled into the Arthur Kill waterway after a storage tank ruptured from the storm surge. The resulting damaging environmental implications resulting from the spill could leave a lasting scar on the sensitive salt marshes in the waterway, which are important wildlife habitats and nursery areas for fish. According to NOAA, there was a threat of large fish kills due to low oxygen levels in the water resulting from the bio-degradation of the oil (J Blaszak, 2012).

In the aftermath of the hurricane and its damage to the petroleum facilities, many gas stations were closed and people lined up for hours to get gasoline. According to American Automobile Association on 2 November 2012, about 60% of the gas stations in New Jersey were closed. On the night of 2 November 2012, Governor Christie took action to prevent a fuel shortage and ease the problem of extended wait times and lines at gas stations by signing Executive Order 108, declaring a limited state of energy emergency with regard to the supply of motor fuel and implementing odd-even rationing for gasoline purchases in 12 New Jersey counties. Gas price dropped after the storm, despite the closure of some refineries. Oil prices initially fell, since there was temporarily less demand from closed refineries.

3.1.2 Tropical Cyclone Irene: August 27–28 2011

Irene made its United States landfall near Little Egg Inlet, New Jersey on Sunday, August 28, 2011 as a hurricane with maximum sustained winds of 75 mph. At this point Irene had weakened to a tropical storm. Tropical Storm Irene produced about 3 to 13 inches of rain on the watersheds within the New York District's civil works boundaries in northern New Jersey and southern New York in about a 16 hour period between Saturday, August 27 and Sunday, August 28. Tropical Storm Irene rainfall total for the Rahway River basin was about 10 inches. Irene generated a storm surge of 4 to 6 feet along the New Jersey coast and a surge of 3 to 6 feet in the New York City and Long Island areas.

3.1.3 Other Storm Events

Tropical storms, nor'easters, hurricanes, and various other storms caused tidal inundation and damage in recent decades. These include:

- Storm of Apr 15–16 2007
- Tropical Storm Floyd on Sep 15–16 1999
- Storm of Oct 19 1996
- Northeaster Storm of Dec 11–12 1992
- Halloween Nor'easter of Oct 31 1991
- Hurricane Gloria on Sep 27 1985
- Coastal Storm of Mar 29–30 1984
- Tropical Storm Doria Aug 26–28 1971
- Coastal Storm of Mar 6–8 1962
- Hurricane of 12 Sep 1960 (Donna)
- Storm of Nov 6–7 1953
- Storm of Nov 25 1950
- Hurricane of Sep 14 1944

4 Methods

Simulation of flood damage in the future with- and without-project conditions is executed with Hydrologic Engineering Center Flood Damage Analysis (HEC-FDA) software. This software is a numerical integrator that incorporates hydrologic and economic data to evaluate the justification of proposed flood risk management plans. The software implements Monte Carlo simulation over a range of flood events and calculates expected damage specifically accounting for variability in the hydrologic and economic inputs. An end product is expected annual damage, which can be thought of as the average of the flood damage over the simulations run for that analysis year and plan. For optimization based on the water surfce elevation data, there are six analysis years: 2023, 2033, 2043, 2053, 2063, and 2073. These analysis years are used to approximate the non-linear curve of expected annual damage as a function of sea level rise[8]. Three sizes of the tentatively selected plan are evaluated for optimization: small, medium, and large, and these plans are evaluated with respect to the without-project condition. All plans and the without-project condition are evaluated at the three USACE relative sea level change scenarios: low, intermediate, and high[9].

Three key hydrologic inputs are used in the HEC-FDA analysis: water surface profiles, exceedance probability functions, and levee specifications. The water surface profiles represent the relationship between 8 flood events and the expected water surface elevation (stage-probability curves). The current analysis uses stage-probability curves that have been generated using two-dimensional hydrologic modeling. This means that storm surges coming up the river and riverine flows pushing down the river are considered simultaneously for a given location, resulting in a joint probability that the stage should exceed some elevation. Exceedance probability functions are closely related to the stage-curves because they plot the same relationship however include uncertainty bands. Finally, the proposed and existing levee specifications are entered into the model using the top of levee elevation. Interior/exterior relationships nor geotechnical failure are not considered[10]. For a more in-depth discussion on these inputs, please see the hydrology and hydraulic appendices.

The economic data organizes information about what is available to be damaged and the extent of the vulnerability to damage. Structures are organized by damage categories and within damage categories by occupancy types. Specific occupancy types are assigned depth-percent damage functions, which describe a relationship between the depth of flooding and the expected damage as a percent of a structure's depreciated replacement value. A structure inventory contains information on the structures in the .2% annual chance of exceedance floodplain together with the specifications on how vulnerable the structures are to flooding and the depreciated structure replacement value. Vulnerability to flooding is recorded using the ground stage, foundation height, and beginning damage depth. For a more in-depth discussion of the economic inputs, please continue reading onto the next section.

Counterfactual analysis with respect to expected flood damage is carried out by comparing with- and without-project conditions. In the with-project condition, everything is identical to the without-project condition except for the proposed coastal storm risk measures so that the reduction in flood damage can be attributed to the measures. In the with-project condition where a levee is a proposed measure, a levee is included as part of the with-project flood damage analysis but not the without-project analysis. The inclusion of the levee truncates the damage exceedance functions up to the elevation of the levee. In other words, if a levee is 14.2 feet NAVD88 high, then the structures in the damage reach where the proposed levee would be located would not experience damages until the water surface elevation goes beyond 14.2 feet NAVD88.

Nonstructural measures are implemented using modifications in the structure inventory. A non-structural alternative is one in which the physical mechanism and extent of flooding is largely unchanged (no riverine structures are constructed or modified to substantially constrain, impede or redirect floodwater) but the existing buildings within the floodplain are instead adapted or the regulatory framework that governs new development is modified to reduce the damage incurred during flood events. For this study, only nonstructural measures that directly affect existing buildings have been incorporated into the analysis.

The frequency and extent of the flooding by which the set of structures was chosen for nonstructural treatment does imply high-frequency flooding. In the future without-project condition, it might be assumed that homeowners mitigate against the flood risk by investing in one or more nonstructural treatments. Since Hurricane Sandy, many property owners have self-mitigated if they had the means or were successful in obtaining assistance from a local program like NJ Blue Acres. However, many properties remain at risk and are likely to stay that way because these property owners lack the resources to self-mitigate.

The nonstructural analysis considered 10 different treatment measures for application which can be described under the following broad categories[11]:

- Elevation: The structure is physically raised so that the main floor of the structure is at or above the specified design protection level.
- Dry Floodproof: All openings are sealed or fitted with removable watertight barriers and the exterior walls are treated to make them waterproof to the design protection level.
- Wet Floodproof: Treatments include the vacating or filling of basements, removal of utilities, and the provision of equivalent facilities above the design protection level. Wet floodproofing also includes a number of minor treatments such as the raising of exterior air conditioning units and the provision of louvers in crawlspace walls to allow the equalization of hydrostatic pressure. This treatment is generally applied to structures with a main floor elevation already

above the design protection level but that still incur significant damages due to the presence of basements and vulnerable utilities.

- Buyouts: Buyouts pertain to structure acquisition, relocation, and/or permanent evacuation of the floodplain.

The design protection level for this analysis was based on the water surface elevation with a 1% annual chance of being equaled or exceeded (the "100-year flood"), plus 1 foot. This height is used for elevations and floodproofing. While nonstructural measures reduce the risk of damage to individual structures and their contents, they are assumed not to reduce damages to exterior items such as vehicles and landscaping. It should also be noted that for elevations and wet floodproofing, some residual structure damage can still occur below the design level of protection following the implementation of the nonstructural measures.

The nonstructural actions were implemented in the HEC-FDA analysis by creating individual modules in HEC-FDA to model the proposed nonstructural actions versus without the actions, and by revising the structure inventory to reflect the proposed structure attributes. Following USACE Flood Risk Management Planning Center of Expertise guidance, individual modules were created for the group of structures receiving floodproofing and for the group of structures being elevated. These modules contained duplicated structures with the revised structure attributes. A without-project module was created to include the same structures before the attributes are revised in addition to the structures that would be bought out. The base module contains all structures that would not receive any nonstructural action. In the without-project condition, the base and without-project modules are run together; in the with-project condition, the base, floodproofing, and raising modules are run together. In this way, with-project nonstructural actions can be compared to the without-project structure attributes.

The structure attributes are modified for duplicated structures to model the effect of a nonstructural action on expected flood damage. The first floor elevation was modified for structures that would be elevated to the stage associated with the water surface elevation with a 1% annual chance of being equaled or exceeded plus 1 foot for the year 2073. In addition, for structures that are elevated and that previously had basements, the depth-damage relationship is modified to reflect the proposed basement filling. The beginning damage elevation is modified for structures that receive wet or dry floodproofing to reflect a change in the depth-damage curve where damages do not occur until, for example, three feet above the first floor, after which point the usual damage percentages at each depth continue. Finally, structures that are proposed to be bought out are assigned to a specific module that is used to remove the structures from the structure inventory for the with-project analysis for comparison of expected damages relative to the without-project conditions. This method for implementing nonstructural actions in HEC-FDA is used for all alternatives with nonstructural measures proposed and in optimization[12].

5 WITHOUT-PROJECT FUTURE CONDITIONS

Without-project flood damages were modeled in HEC-FDA for the years 2029 and 2079 for the optimization analysis[13]. Without-project flood damages are presented in detail at the USACE relative sea level change intermediate scenario. Note that the optimization plans relative to future without-project conditions are evaluated under all three relative sea level change scenarios. See Sections 8-11 for the analysis with respect to the three relative sea level change scenarios.

The intermediate scenario at the Bergen Point gauge suggests that sea level rise in the study area will accelerate over time. The sea level is expected to increase on average 0.0244 feet per year so that the sea level increases 1.22 feet over the 50-year period of analysis in the intermediate scenario, exacerbating the frequency and severity of flooding in the future (USACE, 2019).

In the future without-project condition, tidal inundation in the study area is expected to increase over time in direct relation to the assumed rate in relative sea level change. Tidal inundation together with river inflows have been jointly evaluated for the analysis years to estimate the flood magnitude for a series of 8 flood events. For more information, please see the hydraulic appendix.

5.1 DELINEATION OF DAMAGE REACHES

In order to conduct economic damage analysis for the without-project condition and alternative plans, the study area has been separated into five streams containing a total of 27 damage reaches, as depicted in Table 2. A map of the stream boundaries of the damage reaches is contained in Figure 2. Streams, reach locations and the upstream and downstream limits of the reaches in the HEC-FDA model were selected to be consistent with the hydrologic/hydraulic modeling and were mostly located at the location of bridges, existing levees, and alternative hydraulic structures such as new levees and floodwalls, so that the effects of these features could be evaluated in detail. Damage reach index locations were used to assign stage-probability and stage-damage functions with uncertainty data for plan evaluations for a given damage reach. Index locations were identified as the half-way point between the beginning and ending stations of a damage reach.

Table 2: Rahway Coastal Storm Risk Management Damage Reaches

Stream	Damage Reach	Bank	Downstream Station	Upstream Station
Carteret & Woodbridge	A-CW-4-L	Left	20876.51	23622.28
	B-CW-4-R	Right	23243.43	23622.28
	C-CW-2-L	Left	19201.06	19883.70
	D-CW-2-R	Right	14731.32	17565.28
	U-CW-1B-L	Left	10548.64	19201.06
	U-CW-1B-R	Right	10548.64	14731.00
	U-CW-1-L	Left	5.52	10548.64
	U-CW-1-R	Right	5.52	10548.64
	U-CW-3-L	Left	19883.70	20876.51
	U-CW-3-R	Right	17565.28	23243.43
Millburn-Clark	A-MB-1-L	Left	28472.74	29222.75
	A-MB-1-R	Right	28472.74	29222.75
	A-MB-2-L	Left	29222.75	30056.00
	A-MB-2-R	Right	29222.75	30056.00
Rahway	A-RR-1-L	Left	24509.34	27042.00
	A-RR-2-L	Left	27042.00	27392.85
	CH-RR-3-L	Left	27392.85	28188.89
	CH-RR-3-R	Right	27392.85	28188.89
	E-RR-1-R	Right	24509.34	27042.00
	N-RR-2-R	Right	27042.00	27392.85
Robinsons Branch	A-RB-L	Left	175.45	8840.25
	A-RB-R	Right	175.45	8840.25
South Branch	B-SB-2-R	Right	872.00	2283.30
	E-SB-1-L	Left	210.79	2499.70
	U-SB-1-R	Right	210.80	872.00
	U-SB-2-L	Left	2499.70	11400.90
	U-SB-3-R	Right	2283.30	11400.90

5.2 Structure Inventory

A database of residential and nonresidential structures in the study area was compiled for the modeling of flood damages. The structure inventory consists of structures that reside in the 500-year floodplain in the relative sea level change low scenario. The structure inventory will not adjust according to the relative sea level change scenario[14]. The structure inventory data was generated through analysis of Geographic Information System (GIS) data, county assessor data, and street-level imagery available through Google Earth®. Street-level imagery was examined for each structure in the inventory to obtain structure type, condition, exterior construction, main floor elevation, low opening elevation, number of garages, and the presence of a basement. StreetView is sufficient to determine if a structure has a basement either through visible basement windows or doors or if a neighboring building that appears to be in the same method, time period, and style has visible basement windows or doors. If basement windows or doors cannot be seen through either method, the default was to assume no basement. Information from Streetview yields information comparable to a field survey. Structure ground elevations were obtained from a digital elevation model of the study area. Beginning damage depth elevations were obtained from Streetview population survey, representing the elevation at which flood waters enter structures with basements above the basement floor, typically through a basement window.

Each structure (or distinct use type where several distinct structure uses occur within a single building) was assigned a unique structure identification number following the identification of all structures for inventory using GIS mapping. GIS also was used to determine each structure's footprint size, main floor area, and to assign each structure to its proper river station cross section. The final structure inventory contains the information listed below[15].

- Structure ID Number
- Exterior Construction
- Map Number
- Quality of Construction
- Type of structure
- Current Condition
- Use of structure
- Ground Elevation
- Building Footprint Area
- Foundation Height
- Number of Stories
- Location of Low Openings
- Basement Type
- Assigned Reach
- Number of Garages
- Notes/Description (as required)

Table 3 shows the quantity of structures in each of the 27 damage reaches, with subtotals for each type of structure category. Structures built after 1991 are broken out pursuant to Section 308 of the Water Resources Development Act of 1990 (P.L. 101-640). This regulation stipulates the following:

> "The Secretary shall not include in the benefit base for justifying Federal flood damage reduction projects
>
> (1)(A) any new or substantially improved structure (other than a structure necessary for conducting a water-dependent activity) built in the 100-year flood plain with a first floor elevation less than the 100 -year flood elevation after July 1, 1991; or
>
> (B) in the case of a county substantially located within the 100-year flood plain, any new or substantially improved structure (other than a structure necessary for conducting a water-dependent activity) built in the 10-year flood plain after July 1, 1991; and
>
> (2) any structure which becomes located in the 100-year flood plain with a first floor elevation less than the 100-year flood elevation or in the 10 -year flood plain, as the case may be, by virtue of constrictions placed in the flood plain after July 1, 1991."

After examination of the structures via Google Earth in aerial and street view, it was concluded that the structures are not necessary for conducting a water-dependent activity, and the 195 structures were excluded from further analysis.

The values of the different categories of structures in each of the damage reaches have been organized in Table 4. As shown in the table, the inventory valuation (depreciated replacement value as of October 2019) totals over $1.8 billion, with a total residential (non-apartment) valuation of over $446 million[16]. Observe that depreciated structure replacement value reflects the depreciated replacement cost of the structure and does not include the value of the land on which the structure resides. The structure values were based on a sister study, Rahway River Flood Risk Management Project, which contains structure values that were calculated through RSMeans and Marshall and Swift. Tax assessor data was used to determine a multiplier for Rahway Flood Risk Management structure values for a calibration specific to Rahway Tidal. Tax assessor data was also used to corroborate structure characteristics including residential/non-residential, condition, and age.

Table 5 provides a general summary of the proportions of structures found in each damage category type and their average depreciated structure replacement values. Observe that the largest proportion (65%) of structures are residential despite accounting for 20% of the inventory's depreciated structure replacement value. Conversely, commercial structures account for 33% of the number

Table 3: Structure Inventory: Type and Quantity of Structures per Damage Reach

Stream	Reach	Apartment	Commercial	Residential	Built after 1991	Total
Carteret &	A-CW-4-L		7	15	6	28
Woodbridge	B-CW-4-R		14		1	15
	C-CW-2-L		18	91	7	116
	D-CW-2-R		35	162	6	203
	U-CW-1B-L		125	119	44	288
	U-CW-1B-R			32		32
	U-CW-1-L		101		75	176
	U-CW-1-R	1	235	131	28	395
	U-CW-3-L		5	2		7
	U-CW-3-R		38	48		86
Millburn-Clark	A-MB-1-L		5	4		9
	A-MB-1-R	1	2	14		17
	A-MB-2-L	1	3	105	1	110
	A-MB-2-R	3	1	17		21
Robinson's	A-RB-L	8	11	81		100
Branch	A-RB-R	3	9	63		75
Rahway	A-RR-1-L	5	12	156	13	186
	A-RR-2-L		10	59	1	70
	CH-RR-3-L		2	4		6
	CH-RR-3-R	1	2	10		13
	E-RR-1-R	6	22	118	1	147
	N-RR-2-R	1	5			7
	B-SB-2-R	1	4	14		19
	E-SB-1-L		14	174	6	194
	U-SB-1-R		1			1
	U-SB-2-L		54	45	5	104
	U-SB-3-R	5	23	26		54
Total		36	758	1,490	195	2,479

Table 4: Structure Inventory: Type and Value of Structures per Damage Reach

Stream	Reach	Apartment	Commercial	Residential	Built after 1991	Total
Carteret & Woodbridge	A-CW-4-L		128,313	3,782	1,449	133,544
	B-CW-4-R		13,833		16,785	30,619
	C-CW-2-L		48,403	20,074	1,863	70,340
	D-CW-2-R		152,936	21,438	1,903	176,277
	U-CW-1B-L		92,002	24,154	15,047	131,204
	U-CW-1B-R			5,232		5,232
	U-CW-1-L		83,796			83,796
	U-CW-1-R	1,505	67,304	27,749	41,617	138,176
	U-CW-3-L		81,292	468		81,760
	U-CW-3-R		111,488	13,842		125,330
Millburn-Clark	A-MB-1-L		21,456	1,250		22,706
	A-MB-1-R	2,619	1,996	4,104		8,720
	A-MB-2-L	513	1,488	23,107	391	25,499
	A-MB-2-R	25,171	3,729	4,138		33,039
Robinson's Branch	A-RB-L	14,837	10,040	23,950		48,827
	A-RB-R	3,809	7,178	17,553		28,540
Rahway	A-RR-1-L	2,524	23,993	36,280	23,961	86,758
	A-RR-2-L		2,544	24,397	1,509	28,450
	CH-RR-3-L		6,587	2,470		9,057
	CH-RR-3-R	2,072	1,239	3,004		6,314
	E-RR-1-R	101,597	82,759	39,097	158	223,612
	N-RR-2-R	3,290	107,153		585	111,027
South Branch	B-SB-2-R	836	3,948	3,077		7,861
	E-SB-1-L		8,227	39,667	1,755	47,894
	U-SB-1-R		343			343
	U-SB-2-L		92,094	8,975	4,040	105,109
	U-SB-3-R	6,787	45,006	10,488		62,281
Total		165,561	1,199,147	358,296	111,064	1,834,068

Price level October 2019, Values in Thousands

of structures, though the value of those structures is 70% of the inventory's depreciated structure replacement value.

Table 5: Proportion of Structures by Damage Category

Damage Category	Average Value	Sum Value	Percent Value	Quantity	Percent Quantity
Apartment	4,599	165,561	10%	36	2%
Commercial	1,582	1,199,147	70%	758	33%
Residential	240	358,296	20%	1,490	65%
Total	6,421	1,723,005	100%	2,284	100%

Price level October 2019, Values in Thousands

5.2.1 Motor Vehicle Inventory

The HEC-FDA inventory includes estimates of the quantities and values of privately-owned motor vehicles that are likely to be exposed to flood risk. These estimates are based on the average number of vehicles per household in the study area, the average replacement value of these vehicles, and an estimate of the evacuation rate or rate at which residents move at least one car to higher ground given warning of the risk of flooding. The higher of the evacuation rate or rate at which residents move at least one car to higher ground is chosen to result with a lower, more conservative estimate of the number of cars that remain in the floodplain exposed to flood damage. EGM 09-04 presents a method for estimating the risk-weighted replacement value of the average number of vehicles at a residential structure (USACE, 2009) in the implementation of flood damage analysis. Following this method, the risk-weighted replacement value of the average number of vehicles per household in the study area is calculated according to Equation 1:

$$R = \phi V N, \tag{1}$$

where R represents the risk weighted replacement value of automobiles per household, ϕ represents the share of automobiles exposed to flood inundation, V represents the average replacement value of an automobile, and N represents the average number of automobiles per household.

The 2013–2017 American Community Survey 5-Year Estimates contain data on household size by vehicles available, which was used to estimate the average quantity of vehicles per household. Over the years 2013–2017 in Middlesex and Union Counties, there was on average 1.70 cars available per household (U.S. Census Bureau, 2017). This average quantity of cars per household is assigned to single and multi-family residences in the structure inventory. Automobiles are not assigned to commercial structures, but are assigned to structures that were built after 1991.

The average replacement value of the vehicles in these counties is assessed using Edmunds 2018 Q3 Used Car Report. Edmunds reports that the average value of a used car adjusted to FY2020 price levels is $20,490 (Edmunds, 2018). This means that it would require on average $34,833 to replace the vehicles available at each household in the study area.

Experience from Superstorm Sandy and other devastating tropical storms shows that evacuation rates tend to be low despite advanced warning. Brown et al. (2016) analyze the results of an NYC Department of Health and Mental Hygiene survey evidence of the mental health needs of adult residents in South Brooklyn, the Rockaways, and Staten Island shortly after Sandy. Respondents self-reported whether they evacuated before, during, or after the storm. Of the 420 surveyed residents, 24% responded that they evacuated before the storm, 11% during, and 14% after the storm (Brown et al., 2016). It is not reported how many of the residents who stayed did not move at least one vehicle to higher ground. Economic Guidance Memorandum, 09-04, Generic Depth-Damage Relationships for Vehicles contains an expected rate of moving at least one vehicle to higher ground for different periods of warning time. The survey evidence shows that 11.9% of respondents did not move their vehicles to higher ground when the warning was greater than 12 hours (USACE, 2009). It is therefore assumed that 11.9% of vehicles remain exposed to flood risk. While this proportion of vehicles may be low relative to estimated evacuation rates, assuming the lower rate imposes potentially less bias upon the analysis. The average value of the vehicles exposed to flood risk per household in the event of a coastal storm is then $4,145[17].

The flood damage analysis in HEC-FDA makes use of depth-damage functions that give a relationship between the depth of flooding above ground and the damage as a percent of depreciated replacement structure value caused by flood inundation with anticipated variability in percent damage. Depth-damage functions are specified for five different vehicle classes: sedans, pickups, SUVs, sports cars, and mini vans. Without the detailed information of what class of car is available to be damaged at each structure, the most common class of car is used for informing the use of the depth-damage function. According to data reported by Santander Consumer USA, the most popular vehicle class in the USA in 2018 was the SUV (Macesich, 2019). It follows that the SUV depth-damage function is used in the flood damage analysis. The last component of this exercise is calculating the number of housing units in each reach to which the risk-weighted average vehicle value per household is assigned. The total number of housing units was estimated by assuming that each residential structure contained a single unit. The number of units in an apartment building was derived by dividing the building's total square footage by 1,200[18].

A summary of the HEC-FDA inventory's distribution and value of vehicles by damage reach is shown in Table 6. Observe that the quantity of motor vehicle correlates with the quantity of structures and damage category of structures in a reach. For example, there is 1 structure in reach B-CW-4-R which is an apartment built after 1991. This structure has 32 residences with an estimated 54.4 automobiles at the structure. The replacement value of these vehicles is $1,115,000. The replacement value of the vehicles expected to be exposed to flood inundation having not been moved to higher ground is $133,000.

Table 6: Distribution of Motor Vehicles in Study Area

Stream	Reach	Structures with Autos	Auto Quantity	Sum Value	Risk-Weighted Value†
Carteret & Woodbridge	A-CW-4-L	21	22	766	91
	B-CW-4-R	1	32	1,115	133
	C-CW-2-L	97	99	3,448	410
	D-CW-2-R	168	168	5,852	696
	U-CW-1B-L	129	131	4,563	543
	U-CW-1B-R	32	32	1,115	133
	U-CW-1-R	159	250	8,709	1,036
	U-CW-3-L	2	2	70	8
	U-CW-3-R	48	54	1,881	224
Millburn-Clark	A-MB-1-L	4	4	139	17
	A-MB-1-R	15	30	1,045	124
	A-MB-2-L	107	114	3,971	473
	A-MB-2-R	20	81	2,822	336
Robinson's Branch	A-RB-L	89	141	4,912	584
	A-RB-R	66	86	2,996	356
Rahway	A-RR-1-L	175	207	7,210	858
	A-RR-2-L	60	67	2,334	278
	CH-RR-3-L	4	4	139	17
	CH-RR-3-R	11	19	662	79
	E-RR-1-R	123	200	6,967	829
South Branch	B-SB-2-R	15	18	627	75
	E-SB-1-L	180	199	6,932	825
	U-SB-2-L	45	45	1,567	187
	U-SB-3-R	31	64	2,230	265
Total		1,602	2,069	72,070	8,576

† Value adjusted for the probability that vehicles will be removed by owners prior to a flood event.

October 2019 Price Level, Values in thousands

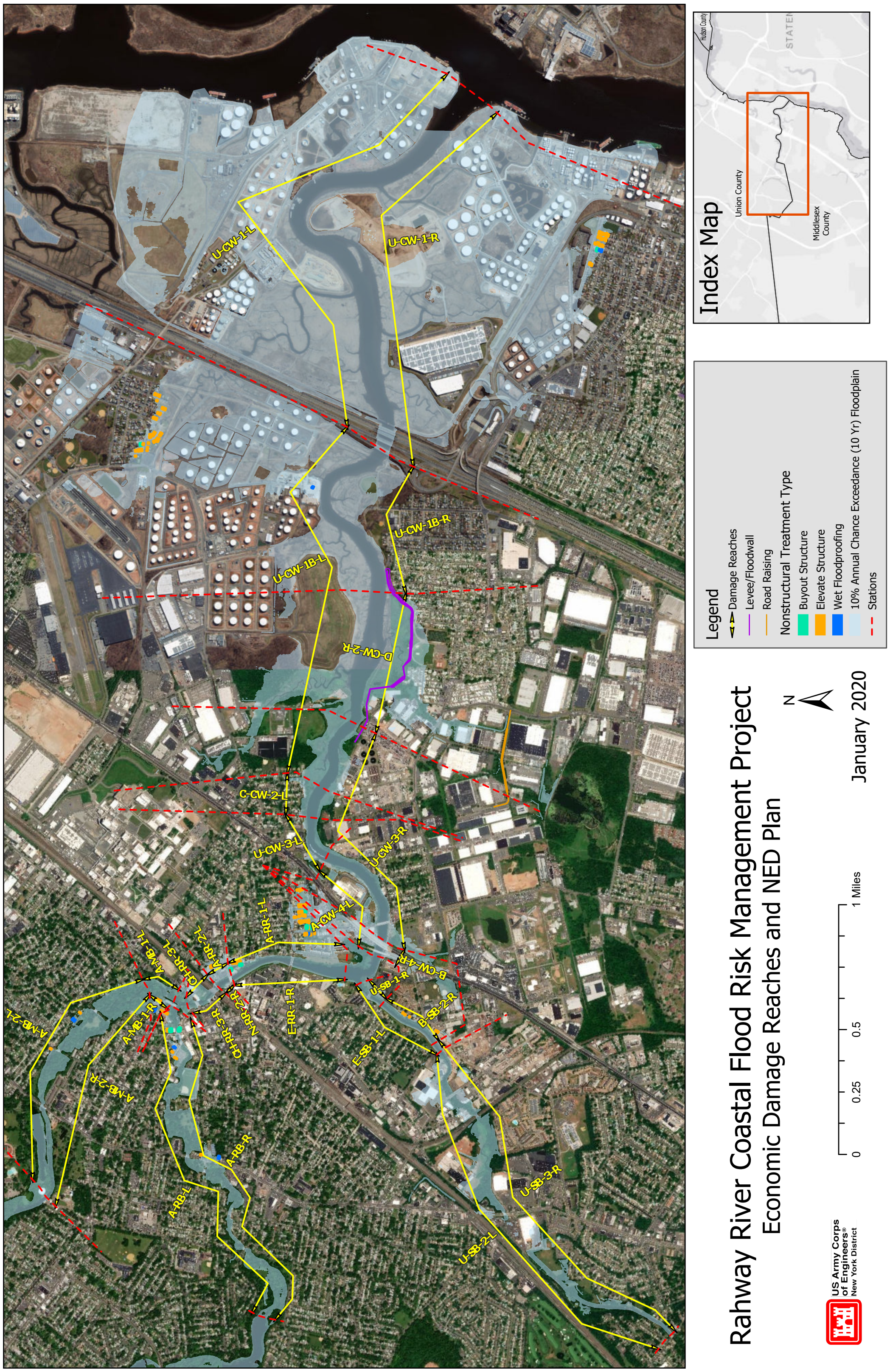


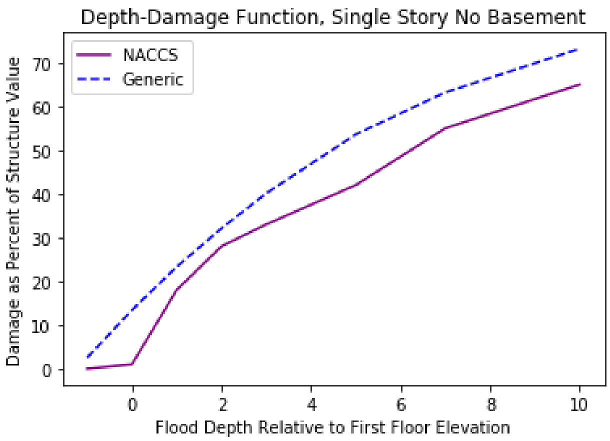
Figure 2: Damage Reaches

5.2.2 Inundation Damage Categories

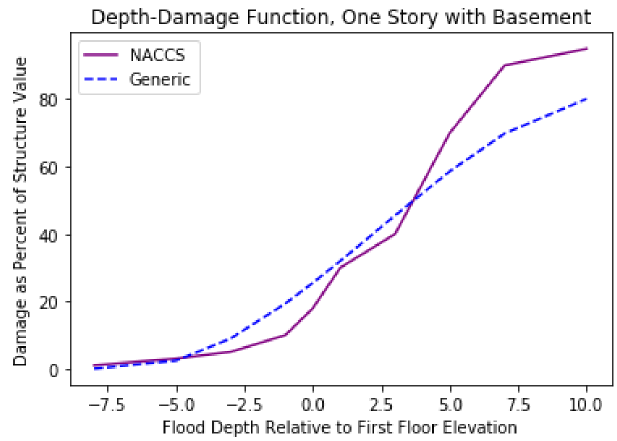
The computation of annual flood damages in this analysis is based on the application of depth-damage functions to the structures in the study area to compute the expected damage incurred by structures and their contents during flood events of different probability of occurrence. The depth-damage relationship expresses how much damage is expected as a percent of structure value (depreciated structure replacement value) at various flood depths relative to the main floor of a structure. For optimization, the depth-damage relationships for structures and contents are modeled using the North Atlantic Coast Comprehensive Study (NACCS) functions (USACE, 2015b). U.S. Army Corps or Engineers generic depth-damage functions were used for automobiles (SUVs)[19].

Observe that the depth-damage relationships that were used in the identification of the tentatively selected plan do not apply to the optimization analysis as they have been updated for full compliance with Engineering Regulation 1105-2-101 (USACE, 2017)[20]. With the full range of the NACCS depth-damage functions applied to the entire structure inventory, the full scope of uncertainty is modeled as stipulated in ER 1105-2-101. A triangular distribution captures the variability in depth-percent damage. These functions have also been used because they are modeled specifically for the North Atlantic Coast and have depth-damage relationships for commercial and apartment buildings. This comprehensive set of depth damage functions encompasses all relationships contained within the Rahway River Basin, New Jersey Coastal Storm Risk Management Feasibility Study structure inventory, except for automobiles. The depth-damage functions for autos are modeled using depth-damage relationships based on Economic Guidance Memorandum 09-04, Generic Depth-Damage Relationships for Vehicles (USACE, 2009).

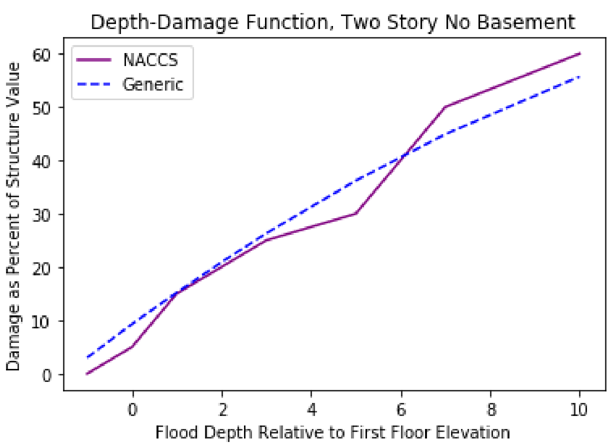
The NACCS depth-damage relationships were produced through expert elicitation. The damage functions are based on experts' knowledge of the North Atlantic Coastal region in which the Rahway Tidal study area resides. The damage functions are anticipated to be predictive of the damages that would be incurred in future coastal events in the without-project condition, and are used to improve analyses of economic justification of the coastal storm risk management alternatives evaluated for the study. These damage relationships have valid application for this study given that the NACCS depth-damage relationships were developed for the study area and greater North Atlantic Coastal region, for coastal storms, and represent physical damages. Importantly, these damage relationships are presented in triangular distributions to account for uncertainty in building construction and are therefore compliant with Engineering Regulation 1105-2-101. Separate NACCS depth-damage relationships have been created for inundation, erosion, and wave impacts, and only the inundation damage relationships were used for the study.



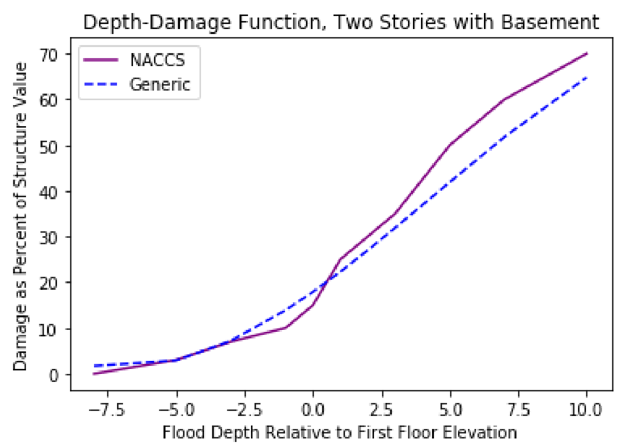
(a) One Story, No Basement



(b) One Story, With Basement



(c) Two Story, No Basement



(d) Two Story, With Basement

Figure 3: Depth Damage Functions: NACCS vs USACE Generic

Generic depth-damage relationships were also been developed for use in and are commonly used for U.S. Army Corps of Engineers flood risk management studies (USACE, 2003, 2000a). Examples of the generic depth-damage functions as compared to the NACCS depth-damage functions are plotted in Figure 3. The depth-damage functions for single-story residential structures are plotted in the first row of charts and depth-damage functions for two-story residential structures are plotted in the second row. In the first column of charts are damage relationships for structures that do not have basements and damage relationships for structures with basements are plotted in the second column. Observe that the two sets of depth-damage functions track each other, and that the NACCS functions tend to predict higher percent damage at higher flood depths. The NACCS depth-damage function does predict more than 30 percentage points higher damage for 7 feet of flood inundation relative to the first floor elevation in the case of one story structures with basements as in Figure 3(b). This faster acceleration observed with the NACCS relationships reflects coastal flood inundation. There are also larger uncertainty bands with the NACCS damage relationships and this reflects a greater understanding of the effects of mold on structures.

Separate damage relationships are used for estimating the flood damage that would occur to a structure and that would occur to the contents within a structure. As discussed above, the relationship estimates damage as a percent of depreciated structure replacement value. A content-to-structure value ratio is used to quantify the value of the damage that would occur to the contents within a structure. A separate content depth-damage relationship is used to reflect the different rate at which the contents within a structure are damaged. The values used for the content-to-structure value ratios that relate the content depth-damage relationship to the depreciated structure replacement value were updated in optimization to ratios that are informed by survey evidence.

The content-to-structure value ratios used in optimization economics are presented in Table 7. These content-to-structure ratios have been updated from those used in the identification of the tentatively selected plan[21]. Different content-to-structure value ratios are used for four different residential structure types, for commercial structures, and for apartments. The residential ratios are sourced from Table 6-4 of EM 1110-2-1619 (USACE, 1996). The residential ratios range from 40.2% to 44.1%. It is reported in USACE (1996) that the variability in the residential content-to-structure value ratio is log-normally distributed. However, a normal distribution had to be assumed due to the technical limitations of the computing software. The commercial and apartment ratios are sourced from Table 42 of USACE (2006). This source of content-to-structure ratios is applicable to this study because the USACE (2006) study is a coastal study with similar structures in the study area. The commercial content-to-structure value ratio represents the average of the ratios over the principle commercial categories reported in USACE (2006), excluding apartments. The content-to-structure value ratio has been aggregated over the various commercial structure uses because the specific structure use is not information that is currently available in the structure inventory. As a result, all commercial structures have been assigned an average of the content-to-structure value ratios. Variability is then captured using the sample standard deviation of the content-to-structure value ratios of the different uses of commercial structures in Table 42 from USACE (2006). A normal distribution has also been assumed for the commercial content-to-structure value ratio as the normal distribution is the closest to the t-distribution. Apartments were broken out of the sample and from Table 42 in USACE (2006) because apartments are broken out and modeled as a separate damage category in the Rahway Tidal structure inventory. In the apartments case, a triangular distribution was assumed reflecting the smaller number of survey responses specific to apartments in USACE (2006).

Table 7: Content-to-Structure Value Ratios

Structure Category	Mean	Standard Deviation	
One Story, No Basement	.434	.25	
One Story, With Basement	.435	.217	
Two Story, No Basement	.402	.259	
Two Story, With Basement	.441	.248	
Commercial	1.32	.687	
	Min	Most Likely	Max
Apartment	.08	.14	.2

Source: USACE (1996), USACE (2006)

5.2.3 Existing Levees

Two existing levees are included under without-project and all alternative conditions:

- The Rahway existing levee is located on the right descending bank between the beginning (downstream) Station of 24509.34 and ending (upstream) Station of 27042. The levee has a top elevation of 12.6 feet in terms of the North American Vertical Datum of 1988 (NAVD88). This stationing corresponds to the HEC-FDA damage reach named E-RR-1-R.
- The South Branch existing levee is located on the left descending bank between the beginning (downstream) Station of 210.79 and ending (upstream) Station of 2499.697. The levee has a top elevation of 12.6 feet NAVD88. This stationing corresponds to the HEC-FDA damage reach named E-SB-1-L.

The existing levees can be seen in Figure 11. The existing levees form the existing Rahway levee drawn in maroon in the figure. The existing levee is modeled as two separate levees in HEC-FDA as the levee lies on streams and in damage reaches that are modeled separately.

5.2.4 Risk and Uncertainty Parameters

This study has been conducted in accordance with Engineering Manual 1110-2-1619, Risk-Based Analysis for Flood Damage Reduction Studies, which requires that the inputs to the damage estimation computations are explicitly subjected to probabilistic analyses (USACE, 1996). The economic analysis of the plans for optimization used the Hydrologic Engineering Center's Flood Damage Analysis computer program HEC-FDA version 1.4.2[22]. HEC-FDA applies Monte Carlo simulation techniques to calculate expected damage values while explicitly accounting for variability in the input data.

Variability was incorporated into the following components of the flood damage calculations:

- Stage-frequency functions
- Stage-damage functions
- Structure first floor elevation
- Structure depreciated replacement value
- Content-to-structure value ratios
- Vehicle replacement values
- Depth-damage functions

Variability associated with the stage-frequency relationship was applied in HEC-FDA using equivalent record lengths. For this analysis, equivalent record lengths of 75 years were used to generate uncertainty bands for all reaches and conditions. The equivalent record length was calibrated to reflect the range in the NACCS uncertainty bands.

Variability associated with the main floor elevation of single-family (and similar two-family) residential structures was applied using a normal distribution with a standard deviation of 0.6 feet, in accordance with the guidance in Table 6-5 of EM 1110-2-1619 for inventories compiled by visual survey and topographic mapping with two-foot contour intervals (USACE, 1996). This variability is assigned to reflect the potential for measurement error in the recorded first floor elevations[23].

The depreciated structure replacement value is subject to variability that is assumed to be characterized by a normal probability distribution with a coefficient of variation of 10% for all structures. The 10% coefficient of variation is a reasonably conservative estimate as it represents the range in depreciation over a 50-year range of structure age according to RSMeans. This coefficient reflects error in the measurement of the depreciated structure replacement value by applying differences in depreciation rates to the structures. Data on the variability in the content-to-structure ratios for optimization is organized in Table 7[24]. The last paragraph of Section 5.2.2 describes the method for quantifying error in the content-to-structure value ratios. These variability statistics follow Engineering Manual 1110-2-1619, Table 6-4 (USACE, 1996).

For optimization, a triangular distribution was used to model variation in expected damages. The triangular distribution of the NACCS depth-damage functions is informed by the variability in the most significant determinants of structure vulnerability to flood damage. This variability reflects the unknown true construction composition of each individual structure, among other determinants[25]. For example, a residential structure may be in good condition, constructed of masonry, and relatively new, resulting in below average damages. Conversely, a residential structure may be in poor condition, constructed of a wood frame, and relatively old, resulting in above average damages. These construction characteristics are unknown and are therefore expected to be determinants of flood damage error for a specific class of structures. For more information, see USACE (2015b).

5.2.5 Without-project Expected Annual Damages

Average annual flood inundation damages were calculated for the without-project base year (2029) and the future condition (2079)[26]. Equivalent annual damages were calculated for a 50-year period of analysis using the 2020 fiscal year USACE project evaluation and formulation rate (discount rate) of 2.75% in accordance with EGM 20-01 (USACE, 2019b). The economic analysis for optimization is presented using October 2019 price levels.

The future without-project condition damages under the methods, assumptions, parameters set for the optimization economics are presented in Table 8. Among other things, these damages are calculated using the NACCS depth-damage functions and the USACE relative sea level change intermediate scenario for water surface elevations. These values have been calculated at 10-year intervals, interpolated, and amortized in a spread sheet external from HEC-FDA to better capture the non-linearity between sea level rise and inundation damages. The total equivalent annual damage in the future without-project condition across all damage categories has been calculated to be $46,480,000. A large share of the equivalent annual damages are generated by commercial structures in the study area, which have been calculated to experience $35,706,000 in equivalent annual damages.

Table 8: Future Without-project Condition Damages by Damage Category and Stream

Stream	Residential	Apartment	Auto	Commercial	Total
Carteret & Woodbridge	2,461	0	105	22,806	25,372
Millburn-Clark	756	472	36	505	1,769
Rahway	1,819	3,256	77	7,719	12,871
Robinsons Branch	734	225	18	546	1,523
South Branch	793	0	21	4,130	4,944
Total	6,563	3,954	257	35,706	46,480

Project evaluation and formulation rate (discount rate) of 2.75% in accordance with EGM 20-01
Price level October 2019, Values in Thousands

Table 9: Quantity of Damaged Structures by Flood Event

Damage Category	Annual Chance of Exceedance						
	0.5	0.2	0.1	0.04	0.02	0.01	0.005
Residential	76	231	565	971	1165	1395	1419
Apartment	2	7	11	18	21	27	31
Commercial	45	99	192	266	305	342	350
Total	123	337	768	1255	1491	1764	1800

2073 future-without project conditions

Table 9 contains the quantity of structures organized by annual chance of exceedance flood event. It is estimated that 123 structures experience repetitive damage as measured by positive annual damages in the 2073 future without-project condition at the intermediate relative sea level change scenario. These 123 structures represent approximately 6% of the structure inventory. Non-structural measures have been recommended for 61 of these structures, and 7 of the structures reside behind the recommended levee. There are two clusters of structures that experience repetitive damages. There are 18 structures on Madison, Arthur, and Parkway streets in Linden, and 25 structures on Lafayette, Essex, Bridge, Elizabeth, Grand, Irving, and Main streets in Rahway. Many of these structures are included in the non-structural portion of the recommended plan. The structures for which no coastal storm risk management measures have been proposed and that experience repetitive flooding may be assumed to be hardened in the future with- and without-project conditions. Hardening measures may include applying sealants to cracks in foundations, installing sump pumps, pointing downspouts away from a structure, placing sandbags in front of exposed gaps, or using bricks to limit pooling. These hardening measures are important actions for reducing residual risk now and in the future. It should be observed however that these hardening measures are too granular to be captured by the modeling implemented with the Hydrologic Engineering Center Flood Damage Anaylsis software.

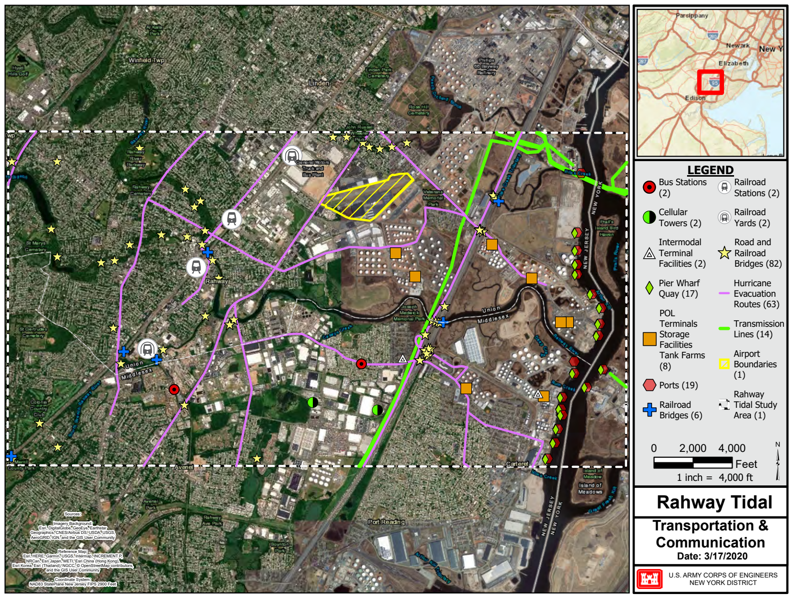
5.3 CRITICAL INFRASTRUCTURE

There is substantial critical infrastructure in the study area, a portion of which is included in the structure inventory. None of the critical infrastructure in the structure inventory correspond to the coastal storm risk management measures proposed in the recommended plan. Table 10 contains a list of the type and number of critical infrastructure and emergency operations structures in the study area. Table 66 contains the maximum inundation depths at the critical infrastructure in the structure inventory within each damage reach.

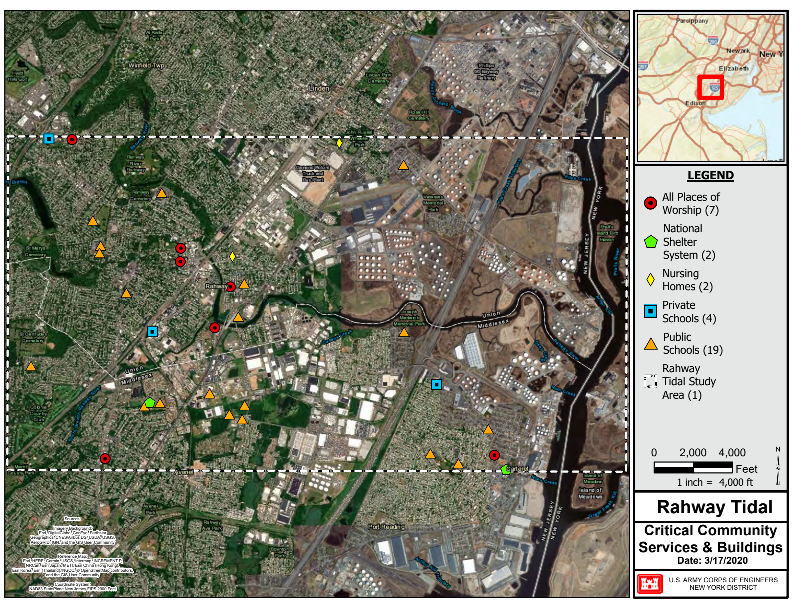
Table 10: Critical Infrastructure in Study Area

Transportation and Communication	Quantity	Resources and Infrastructure	Quantity
Bus Stations	2	Dam Points	1
Cellular Towers	2	Electric Generating Units	18
Intermodal Terminal Facilities	2	Electric Power Generating Plants	5
Pier Wharf Quay	17	Gas Stations	21
POL Terminals & Facilities	8	Natural Gas Compressor Stations	2
Ports	19	Natural Gas Receipt and Delivery	5
Railroad Bridges	6	Oil and Natural Gas Interconnects	2
Railroad Stations	2	Petroleum Pumping Stations	2
Railroad Yards	2	Substations	5
Road and Railroad Bridges	82	Oil and Natural Gas Pipelines	1,056
Hurricane Evacuation Routes	63	Railroads	162
Transmission Lines	14	Wastewater Treatment Plants	2
Airport Boundaries	1		
Community Services and Buildings	**Quantity**	**Emergency Services**	**Quantity**
All Places of Worship	7	Emergency Medical Service	8
National Shelter System	2	Fire Stations	6
Nursing Homes	2	Hospitals	3
Private Schools	4	Law Enforcement Location	3
Public Schools	19	Pharmacies	14
		Urgent Care Facilities	2

In the future without-project condition, the critical infrastructure identified in Table 10 remains exposed to the coastal storm risk that is described in Section 5.2.5. Tables 4 and 5 contain maps of the critical infrastructure that is tabulated in Table 10. The critical infrastructure is mapped by 4 groups: transportation and communication, community services and buildings, resources and infrastructure, and emergency services. A comparison of the extent of the 10-year flood in 2 with the maps of the critical infrastructure demonstrates that much of the infrastructure experiences coastal storm risk.

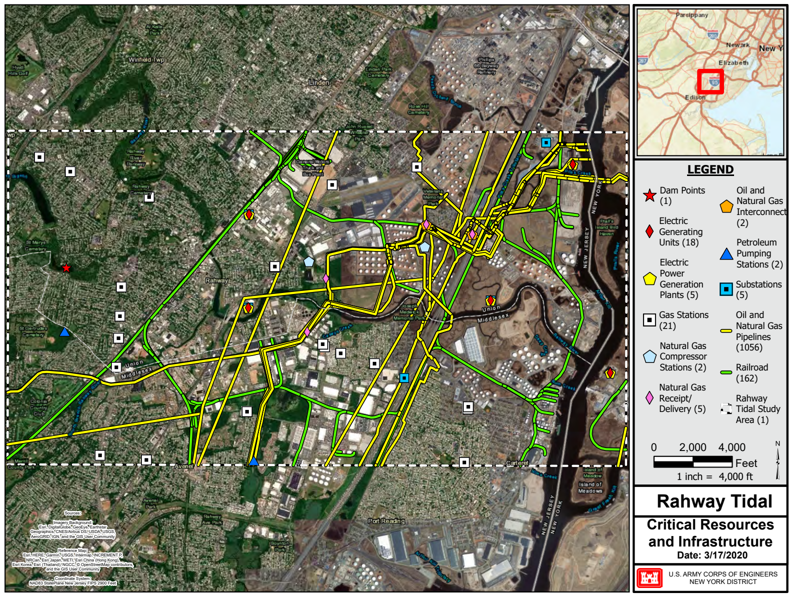


(a) Transportation and Communication

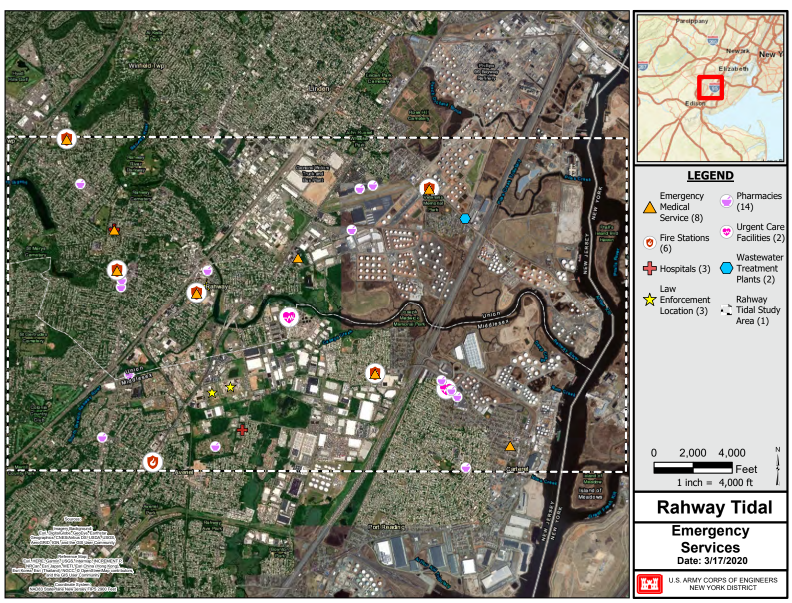


(b) Community Service and Buildings

Figure 4: Study Area Critical Infrastructure



(a) Resources and Infrastructure



(b) Emergency Services

Figure 5: Study Area Critical Infrastructure

Observe that petroleum facilities as outlined in yellow in Figure 2-3 make up a substantial share of the study area. These petroleum facilities are located at the mouth of the Rahway River along the Arthur Kill for the purpose of ease of transportation. This location for these petroleum facilities, also known as tank farms, also means that the facilities are at considerable risk of damage from coastal storms. Damages from Hurricane Sandy to the Kinder Morgan facility alone totaled $69 million. It has been reported to the U.S. Army Corps of Engineers New York District by various terminal operators that the damage included tanks slipping off of their foundations. Oil was also lost into the Arthur Kill, damaging the environment. The terminal facility operators have plans for hardening the facilities which they expect would reduce damages to similar storms in the future by 20%[27]. These facilities nonetheless remain exposed to the damaging effects of coastal storms.

6 Evaluation of Alternatives

This section describes results of the economic analysis of the alternatives that were evaluated for identifying a tentatively selected plan as part of the 2017 draft report. We present the information in this section for reference as to the identification of Alternative 4a as the tentatively selected plan. The parameters and data used in the evaluation of the alternatives for the 2017 draft report and subsequent identification of the tentatively selected plan have not been updated to reflect changes made during optimization nor the current price level and discount rate. Please also observe that the pre-optimization tentatively selected plan Alternative 4a as described in this section is slightly different than the post-optimization recommended plan. This change is the result of refinements that occurred during optimization. For the economic analysis the optimization and the description of the recommended plan, please see Sections 8 – 11.

Five alternatives were evaluated for the Rahway River Basin, New Jersey Coastal Storm Risk Management Feasibility Study. Alternatives 1 and 2 are comprised entirely of structural measures, which include channel work, levees, floodwalls, and tide gates. Alternatives 3A and 3B are comprised of nonstructural measures, which include dry flood proofing (e.g., sealing basement windows on residential properties), wet flood proofing, elevation (raising buildings), and pump replacements[28]. Alternative 3A includes nonstructural treatments for structures located within the 10% chance of annual exceedance floodplain, and Alternative 3B includes nonstructural treatments for structures located within the 2% chance of annual exceedance floodplain. Alternative 4 is comprised of a combination of structural and non-structural measures. Alternative 4a uses the same composition of Alternative 4, excluding the ringwalls. Ringwalls were considered part of non-structural for this phase, but no longer fall into that category according to Planning Bulletin 2016-01 (USACE, 2015a). Ringwalls are not part of the recommended plan.

6.1 Organization of Economic Reaches

Six economic reaches were defined for the analysis of alternatives in the identification of the tentatively selected plan. The economic reaches consist of a combination of damage reaches defined in Table 2. Observe that each damage reach has been assigned to an economic reach. The listing of economic reaches and their associated damage reaches is provided Table 11.

6.2 Alternative 1: Floodwalls and Levees with Channel Modification

Alternative 1 consists of a combination of 4 levee/floodwall segments, 2 closure gates, interior drainage structures, and channel modification. Figure 6 contains a map of the proposed elements in Alternative 1. This alternative, at present conditions, is likely to have a 1 percent chance of annual exceedance in the protected areas. The design height of the levees and floodwalls is at elevation 12.6 feet NAVD88, consistent with existing levees in the study area.

6.2.1 Levee and Floodwall Segments

Alternative 1 is separated into levee/floodwall segments A through D, which correspond to the economic reaches defined in Section 5.1 of this appendix.

SEGMENT A

Segment A includes floodwalls along both banks of the Rahway River that begin just upstream of Rahway River Station 27932.85. The right bank floodwall continues downstream to tie-in at a bridge raising and road raising at Rahway River Station 27107.37. The left bank floodwall continues downstream to Rahway River Station 26210.85 where it ties in to Essex Street, requiring the road to be raised by approximately 1.5 feet for a distance of approximately 150 feet. The Rahway River left bank floodwall resumes its course just downstream of Rahway River Station 25887.58, and ties to high ground at the recently modified East Milton Avenue Bridge. A left bank

Table 11: Organization of Economic Reaches

Economic Reach	Subcategory	Damage Reach	Damage Reach Stream
Reach A	No Levee	A-CW-4-L	Carteret & Woodbridge
	No Levee	A-RR-1-L	Rahway River
	No Levee	A-RR-2-L	Rahway River
	No Levee	N-RR-2-R	Rahway River
	Existing Levee	E-RR-1-R	Rahway River
	No Levee	A-MB-1-L	Millburn-Clark
	No Levee	A-MB-1-R	Millburn-Clark
	No Levee	A-MB-2-L	Millburn-Clark
	No Levee	A-MB-2-R	Millburn-Clark
	No Levee	CH-RR-3-L	Rahway River
	No Levee	CH-RR-3-R	Rahway River
	No Levee	A-RB-L	Robinsons Branch
	No Levee	A-RB-R	Robinsons Branch
Reach B	No Levee	B-CW-4-R	Carteret & Woodbridge
	No Levee	B-SB-2-R	South Branch
Reach C	No Levee	C-CW-2-L	Carteret & Woodbridge
Reach D	TSP Levee	D-CW-2-R	Carteret & Woodbridge
Reach E	Existing Levee	E-SB-1-L	South Branch
Reach U	No Levee	U-CW-1B-L	Carteret & Woodbridge
	No Levee	U-CW-1B-R	Carteret & Woodbridge
	No Levee	U-CW-1-L	Carteret & Woodbridge
	No Levee	U-CW-1-R	Carteret & Woodbridge
	No Levee	U-CW-3-L	Carteret & Woodbridge
	No Levee	U-CW-3-R	Carteret & Woodbridge
	No Levee	U-SB-1-R	South Branch
	No Levee	U-SB-2-L	South Branch
	No Levee	U-SB-3-R	South Branch

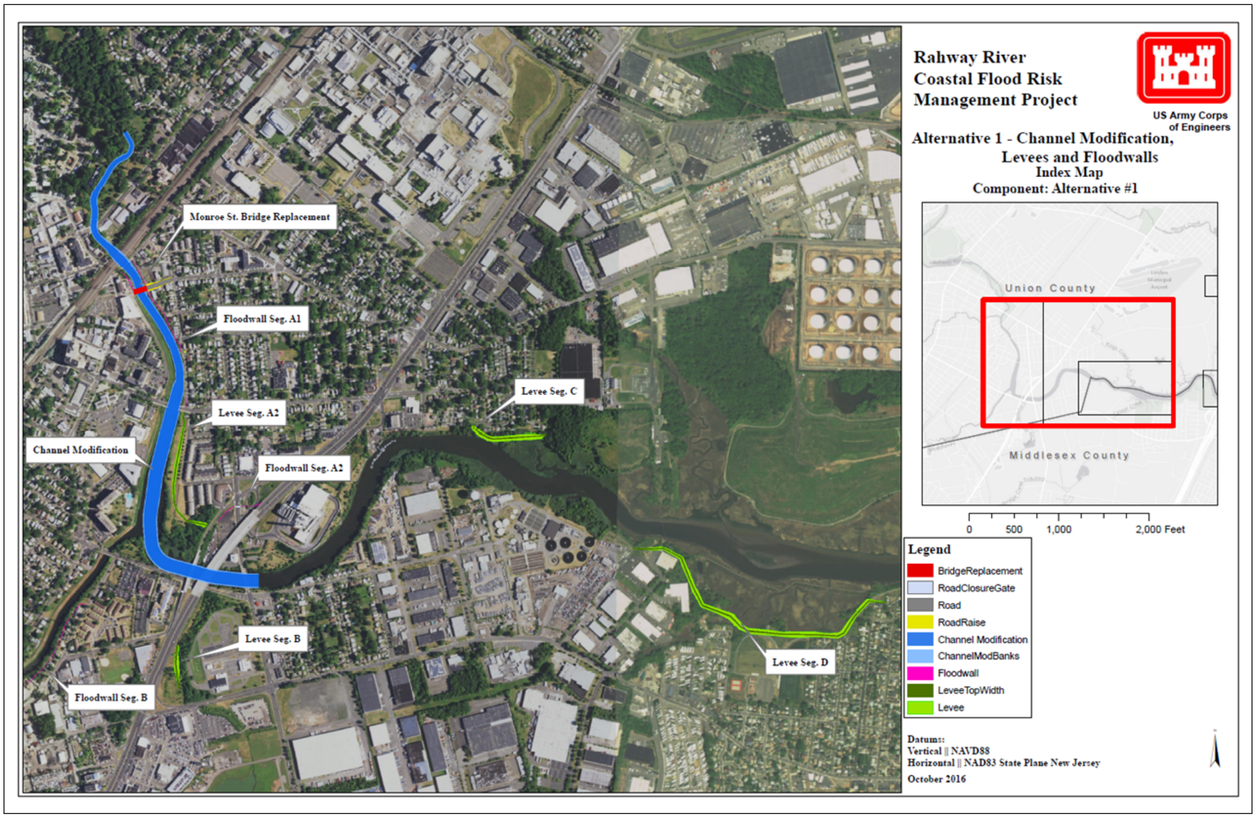


Figure 6: Alternative 1 Plan Overview

levee section starts downstream of the bridge, and continues downstream for approximately 1,510 feet until it ties into high ground just downstream of the Rahway River / South Branch confluence. The flood risk mitigation area for Segment A ends with a floodwall approximately 580 feet long located between the Route 1 exit and Route 1 itself. Segment A also includes a 6,450 foot long channel modification in order to mitigate for the impact of bank encroachments caused by existing levees in the Rahway River and the additional encroachments that would be incurred by Segment A levees and floodwalls. The upstream and downstream ends of channel modification are: 500 ft. upstream of W. Grand Avenue Bridge upstream of the confluence with Robinson's Branch and approximately 100 ft. downstream of Lawrence Street Bridge downstream of the confluence with the South Branch, respectively.

SEGMENT B

Segment B consists of a combination of a levee and a floodwall. The floodwall would be located on the right bank of South Branch just downstream of South Branch Station 2283.30, and continuing downstream for approximately 5,700 feet toward South Branch Station 872.0. A levee serves as a flood risk mitigation measure from Carteret & Woodbridge overland flow, and is located near the intersection of Randolph Avenue and Edgar Road.

SEGMENT C

Segment C includes a levee on the left bank of the Carteret & Woodbridge River beginning about 200 feet downstream of Carteret & Woodbridge Station 19883.37, and ending about 350 feet upstream of Carteret & Woodbridge Station 19201.06. The levee is 890 feet long with an average height above ground of approximately 7.5 feet, and levee is located on the left bank of the Rahway River, approximately one mile downstream of the confluence with the South Branch.

SEGMENT D

Segment D includes a 3,360 linear feet of levee on the right bank of the Carteret & Woodbridge River. The levee begins about 100 feet downstream of Carteret & Woodbridge Station 19883.37 and ends about 150 feet downstream of Carteret & Woodbridge Station 14731.32. The average levee height is approximately 7.5 feet above ground level.

6.2.2 Residual Damages and Benefits

Using HEC-FDA, average annual damages were calculated for the base year and future years with Alternative 1 in place. Equivalent annual damages were calculated for the 50-year period of analysis using the 2017 fiscal year USACE project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01 (USACE, 2016). The expected damages are presented in October 2016 price levels. A summary of equivalent annual damages and flood damage reduction benefits by damage reach for Alternative 1 is presented in Table 12, and a summary of equivalent annual damages and flood damage reduction benefits by economic reach for Alternative 1 is presented in Table 13.

6.2.3 Cost Estimate

A summary of the costs and benefits for Alternative 1 is presented in Table 14. Operations and maintenance in Table 14 and all following tables is calculated at .5% of total construction cost based on historical data. Interest during construction for Alternative 1 is based on a 72-month con-

Table 12: Damages and Benefits for Alternative 1 by Damage Reach

Stream	Damage Reach	Without-project Damages	With Alternative 1 Damages	Damage Reduction Benefits	Residual Risk
Carteret & Woodbridge	A-CW-4-L	623,500	155,000	468,500	25%
	B-CW-4-R	147,600	108,200	39,400	73%
	C-CW-2-L	213,900	168,900	45,000	79%
	D-CW-2-R	3,312,300	968,700	2,343,600	29%
	U-CW-1B-L	950,400	950,700	-300	100%
	U-CW-1B-R	9,300	9,200	100	99%
	U-CW-1-L	872,700	872,700	0	100%
	U-CW-1-R	3,001,000	2,980,000	21,000	99%
	U-CW-3-L	49,800	48,300	1,500	97%
	U-CW-3-R	481,600	478,100	3,500	99%
Millburn-Clark	A-MB-1-L	33,100	17,200	15,900	52%
	A-MB-1-R	532,500	434,600	97,900	82%
	A-MB-2-L	204,200	170,100	34,100	83%
	A-MB-2-R	15,000	11,500	3,500	77%
Rahway	A-RR-1-L	2,126,800	279,600	1,847,200	13%
	A-RR-2-L	265,100	49,500	215,600	19%
	CH-RR-3-L	669,900	542,000	127,900	81%
	CH-RR-3-R	15,000	13,700	1,300	91%
	E-RR-1-R	588,600	586,700	1,900	100%
	N-RR-2-R	169,800	175,300	-5,500	103%
Robinson's Branch	A-RB-L	673,900	606,300	67,600	90%
	A-RB-R	381,600	363,600	18,000	95%
South Branch	B-SB-2-R	61,300	38,300	23,000	62%
	E-SB-1-L	194,500	192,300	2,200	99%
	U-SB-1-R	8,200	7,800	400	95%
	U-SB-2-L	1,107,500	952,600	154,900	86%
	U-SB-3-R	817,500	759,600	57,900	93%
Total		17,526,500	11,940,300	5,586,200	68%

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01

Price level October 2016

Table 13: Alternative 1 Average Annual Damages and Benefits

Economic Reach	Subcategory	Without-project Damages	With Alternative 1 Damages	Damage Reduction Benefits	Reach Benefits	Residual Risk
Reach A	Alt 1 Levee	3,185,200	659,300	2,525,800	2,893,900	21%
	Existing Levee	588,600	586,700	1,900		100%
	No Levee	2,525,300	2,159,000	366,200		85%
Reach B	Alt 1 Levee	208,800	146,500	62,400	62,400	70%
Reach C	Alt 1 Levee	213,900	168,900	45,000	45,000	79%
Reach D	Alt 1 Levee	3,312,300	968,700	2,343,600	2,343,600	29%
Reach E	Existing Levee	194,500	192,300	2,200	2,200	99%
Reach U	No Levee	7,297,900	7,059,000	239,000	239,000	97%
Total		17,526,500	11,940,300	5,586,200	5,586,200	68%

Project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01
Price level October 2016

struction schedule at the 2017 fiscal year USACE project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01 (USACE, 2016).

Table 14: Alternative 1 Average Annual Benefits, Costs, and Net NED Benefits

First Cost	106,506,651
Interest During Construction	6,911,507
Total Investment Cost	113,418,157
Annual Investment Cost	4,304,001
Annual O&M Cost	456,695
Total Annual Cost	4,760,697
Annual Benefits	5,586,200
Net Benefits	825,500
BCR	1.2

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01
Price level October 2016

6.2.4 Project Performance

The annual exceedance probabilities and the long-term risk of exceeding the levees proposed in Alternative 1 have been organized in Table 15. Levee assurance, otherwise known as conditional non-exceedance probability, for each levee in Alternative 1 has been organized in Table 16. The expected annual exceedance probabilities range between 1% and 2% for all levee segments. The levee segments pass the 1% event with assurance between 34.05% and 53.76% assurance.

Table 15: Alternative 1 Annual Exceedance Probability

Segment	AEP Mean	LTEP 10 Years	LTEP 30 Years	LTEP 50 years
Levee A1	0.0137	0.1286	0.3382	0.4974
Levee A2	0.0181	0.1672	0.4224	0.5994
Floodwall A2	0.0162	0.151	0.388	0.5588
Levee B	0.0161	0.1498	0.3854	0.5557
Floodwall B	0.0166	0.1544	0.3953	0.5676
Levee C	0.0159	0.1483	0.3821	0.5517
Comparable Probability				
Fire Damage	.003†			
Earthquake	.023‡			

† Average 2002–2010 based on home structure fires National Fire Protection Association and U.S. Census housing unit data. ‡Dombroski (2005)
AEP: Annual Exceedance Probability, LTEP: Long-term Exceedance Probability

Table 16: Alternative 1 Assurance

Segment	Assurance at Flood Event 10%	4%	2%	1%	0.40%	0.20%
Levee A1	0.9997	0.9501	0.7282	0.5376	0.2318	0.0763
Levee A2	0.9996	0.915	35992	0.351	0.1135	0.0334
Floodwall A2	0.9997	0.9749	0.6626	0.3405	0.0841	0.0174
Levee B	0.9997	0.9632	0.6654	0.3757	0.1049	0.0248
Floodwall B	0.9997	0.9422	0.6451	0.3879	0.1291	0.04
Levee C	0.9997	0.978	0.6719	0.3555	0.0872	0.018

6.3 Alternative 2: Tidal Surge Barrier

The main feature of Alternative 2 is a surge barrier consisting of tide gates and a pumping station at the New Jersey Turnpike Bridge. Figure 7 contains a map of the proposed tidal surge barrier in Alternative 2.

Figure 7: Alternative 2 Plan Overview

A surge barrier is a specific type of floodgate designed to prevent a storm surge from flooding the area behind the barrier up to a specified design height. The barrier would be upstream of the bridge (west of the Turnpike), spanning across the width of the river from Carteret to Linden. Additional channel modification, levees and floodwalls in Carteret and Linden, and closure structures complete the plan. This alternative is likely to have a 1% chance of annual exceedance. The surge barrier is located approximately 775 feet upstream of the New Jersey Turnpike with a design elevation of 13 feet NAVD88. The surge barrier includes:

- Six tainter gates allowing navigable passage

- A pumping station with four pumps at a total capacity of 2.7 million gallons per minute
- Levee tie-ins to high ground (the turnpike) on the left and right banks
- Channel modification at the surge barrier for a length of approximately 2,000 feet

Gates will be open during normal tide conditions and fluvial events. During tidal events, the gates will close during a rising tide as long as the headwater (landside) has a lower water surface elevation than the tailwater (ocean-side). Levees on the left and right banks of the surge barrier will tie into the New Jersey Turnpike. The alternative also includes approximately 2,000 feet of channel modifications.

6.3.1 Residual Damages and Benefits

Using HEC-FDA, average annual damages were calculated for the base year and future years with Alternative 2 in place, and equivalent annual damages were calculated for the 50-year period of analysis, using the 2017 fiscal year USACE project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01 (USACE, 2016). A summary of equivalent annual damages and flood damage reduction benefits by damage reach for Alternative 2 is presented in Table 17, and a summary of equivalent annual damages and flood damage reduction benefits by economic reach for Alternative 2 is presented in Table 18. The economic analysis for Alternative 2 is presented at October 2016 price level.

6.3.2 Cost Estimate

A summary of the costs and benefits for Alternative 2 is presented in Table 19. Interest during construction for Alternative 2 is based on a 96-month construction schedule at the 2017 fiscal year USACE project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01 (USACE, 2016).

Table 17: Damages and Benefits for Alternative 2 by Damage Reach

Stream	Damage Reach	Without-project Damages	With Alternative 2 Damages	Damage Reduction Benefits	Residual Risk
Carteret & Woodbridge	A-CW-4-L	623,500	300,800	322,700	48%
	B-CW-4-R	147,600	81,000	66,600	55%
	C-CW-2-L	213,900	150,600	63,300	70%
	D-CW-2-R	3,312,300	1,311,800	2,000,500	40%
	U-CW-1B-L	950,400	436,100	514,300	46%
	U-CW-1B-R	9,300	8,400	900	90%
	U-CW-1-L	872,700	869,500	3,200	100%
	U-CW-1-R	3,001,000	2,998,800	2,200	100%
	U-CW-3-L	49,800	67,700	-17,900	136%
	U-CW-3-R	481,600	286,300	195,300	59%
Millburn-Clark	A-MB-1-L	33,100	32,800	300	99%
	A-MB-1-R	532,500	280,400	252,100	53%
	A-MB-2-L	204,200	179,900	24,300	88%
	A-MB-2-R	15,000	14,600	400	97%
Rahway	A-RR-1-L	2,126,800	824,700	1,302,100	39%
	A-RR-2-L	265,100	128,300	136,800	48%
	CH-RR-3-L	669,900	326,500	343,400	49%
	CH-RR-3-R	15,000	13,200	1,800	88%
	E-RR-1-R	588,600	361,500	227,100	61%
	N-RR-2-R	169,800	166,900	2,900	98%
Robinson's Branch	A-RB-L	673,900	588,700	85,200	87%
	A-RB-R	381,600	376,800	4,800	99%
South Branch	B-SB-2-R	61,300	35,300	26,000	58%
	E-SB-1-L	194,500	106,800	87,700	55%
	U-SB-1-R	8,200	4,200	4,000	51%
	U-SB-2-L	1,107,500	639,100	468,400	58%
	U-SB-3-R	817,500	590,800	226,700	72%
Total		17,526,500	11,181,100	6,345,400	64%

Project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01

Price level October 2016

Table 18: Alternative 2 Average Annual Damages and Benefits

Economic Reach	Subcategory	Without-project Damages	With Alternative 2 Damages	Damage Reduction Benefits	Reach Benefits	Residual Risk
Reach A	No Levee	3,185,200	1,420,700	1,764,500	2,703,900	45%
	Existing Levee	588,600	361,500	227,100		61%
	No Levee	2,525,300	1,812,800	712,300		72%
Reach B	No Levee	208,800	116,200	92,600	92,600	56%
Reach C	No Levee	213,900	150,600	63,300	63,300	70%
Reach D	No Levee	3,312,300	1,311,800	2,000,500	2,000,500	40%
Reach E	Existing Levee	194,500	106,800	87,700	87,700	55%
Reach U	No Levee	7,297,900	5,900,900	1,397,100	1,397,100	81%
Total		17,526,500	11,181,100	6,345,400	6,345,400	64%

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01
Price level October 2016

Table 19: Alternative 2 Average Annual Benefits, Costs, and Net NED Benefits

First Cost	988,808,637
Interest During Construction	119,775,589
Total Investment Cost	1,108,584,226
Annual Investment Cost	42,068,650
Annual O&M Cost	4,943,657
Total Annual Cost	47,012,307
Annual Benefits	6,345,400
Net Benefits	-40,666,907
BCR	0.1

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01
Price level October 2016

6.4 Alternative 3A: Nonstructural Treatment (10% Annual Chance Exceedance Floodplain)

Under Alternative 3A, nonstructural treatments were applied to structures located within the study area 10% chance of annual exceedance floodplain using a spreadsheet matrix that considered physical characteristics including building configuration, usage, footprint size, foundation type, and existing main floor elevation to select the most appropriate/feasible treatment for each structure and estimate the treatment cost.

The design protection level for this analysis was based on the 2071 water surface elevation with a 1% annual chance of being equaled or exceeded (the "100-year flood"), plus 1 foot. This height is used for elevations and floodproofing. While nonstructural measures reduce the risk of damage to individual structures and their contents, they are assumed not to reduce damages to exterior items such as vehicles and landscaping. It should also be noted that for elevations and wet floodproofing, some residual structure damage can still occur below the design level of protection following the implementation of the nonstructural measures. The structures identified for nonstructural treatments under Alternative 3A are summarized in Table 20.

Table 20: Nonstructural Measures Applied to Structures in the 10% ACE Floodplain

Damage Reduction Measure	Residential	Nonresidential	Total
Dry Flood Proofing		2	2
Elevate Structure	136	4	140
Ringwall Around Structure	35	69	104
Wet Flood Proofing	3	4	7
Total	174	79	253

6.4.1 Residual Damages and Benefits

Using HEC-FDA, average annual damages were calculated for the base year and future years with Alternative 3A in place, and Equivalent Annual Damages were calculated for the 50-year period of analysis, using the 2017 fiscal year USACE project evaluation and formulation rate (discount rate of 2.875% in accordance with EGM 17-01 (USACE, 2016). The economic analysis for Alternative 3a is presented at October 2016 price level.

ANALYSIS PROCEDURES FOR RINGWALLS

With-project damages for structures located behind ringwalls were calculated by changing the above-first floor elevation at which damages begin for each structure relative to the assigned ringwall height. For example, structure 5312 has a ground elevation of 9.34, a foundation height of 0.5 feet (first floor elevation 9.84 feet NAVD88), and is located behind a ringwall will have a top elevation of 14.4 feet NAVD88. Under with-project conditions, the "begin damage" elevation for structure 5312 is set to 4.56 (14.4 – (9.34 + 0.5)) to simulate a floodwall with an elevation of 4.56 feet above first floor. FDA output for the analysis of Structure 5312 (analysis year 2071 static data – no R&U parameters) is provided below in Table 21.

As shown in the table generated from HEC-FDA output, without-project damages begin when the ground-level of Structure 5312, as flooding encroaches on the structure's foundation (located -0.5 feet below the main floor). With a ringwall in place, damages begin to accrue when the height of the ringwall is exceeded – 4.56 feet above the main floor elevation. Note that with-ringwall 4 damages for the 250 year event and the 500 year event are identical to without-project damages for those analysis years and frequency events – proving that the approach for simulating a levee is valid.

A summary of equivalent annual damages and flood damage reduction benefits by damage reach for Alternative 3A is presented in Table 22, and a summary of equivalent annual damages and flood damage reduction benefits by economic reach for Alternative 3A is presented in Table 23.

Table 21: Structure 5312 Floodwall Simulation for With-ringwall Damage Estimate

Event	Stage	First Floor Depth	Without-project Damages	With-ringwall Damages
2 Yr	8.75	-1.09	0	0
5 Yr	9.98	0.14	54	0
10 Yr	10.68	0.84	279	0
25 Yr	11.48	1.64	515	0
50 Yr	12.43	2.59	744	0
100 Yr	13.39	3.55	946	0
250 Yr	14.71	4.87	1,237	1,237
500 Yr	16.42	6.58	1,392	1,392

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01
Price level October 2016, Values in thousands

Table 22: Damages and Benefits for Alternative 3a by Damage Reach

Stream	Damage Reach	Without-project Damages	With Alternative 3a Damages	Damage Reduction Benefits	Residual Risk
Carteret & Woodbridge	A-CW-4-L	623,500	179,800	443,700	29%
	B-CW-4-R	147,600	147,600	0	100%
	C-CW-2-L	213,900	205,400	8,500	96%
	D-CW-2-R	3,312,300	1,018,500	2,293,800	31%
	U-CW-1B-L	950,400	374,900	575,500	39%
	U-CW-1B-R	9,300	9,300	0	100%
	U-CW-1-L	872,700	747,000	125,700	86%
	U-CW-1-R	3,001,000	2,318,800	682,200	77%
	U-CW-3-L	49,800	49,800	0	100%
	U-CW-3-R	481,600	240,000	241,600	50%
Millburn-Clark	A-MB-1-L	33,100	33,100	0	100%
	A-MB-1-R	532,500	56,300	476,200	11%
	A-MB-2-L	204,200	159,100	45,100	78%
	A-MB-2-R	15,000	15,000	0	100%
Rahway	A-RR-1-L	2,126,800	291,800	1,835,000	14%
	A-RR-2-L	265,100	63,800	201,300	24%
	CH-RR-3-L	669,900	83,100	586,800	12%
	CH-RR-3-R	15,000	15,000	0	100%
	E-RR-1-R	588,600	416,000	172,600	71%
	N-RR-2-R	169,800	169,800	0	100%
Robinson’s Branch	A-RB-L	673,900	353,200	320,700	52%
	A-RB-R	381,600	263,700	117,900	69%
South Branch	B-SB-2-R	61,300	53,900	7,400	88%
	E-SB-1-L	194,500	138,400	56,100	71%
	U-SB-1-R	8,200	8,200	0	100%
	U-SB-2-L	1,107,500	912,200	195,300	82%
	U-SB-3-R	817,500	525,300	292,200	64%
Total		17,526,500	8,849,000	8,677,500	50%

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01

Price level October 2016

Table 23: Alternative 3a Average Annual Damages and Benefits

Economic Reach	Subcategory	Without-project Damages	With Alternative 3a Damages	Damage Reduction Benefits	Reach Benefits	Residual Risk
Reach A	No Levee	3,185,200	705,100	2,480,000	4,199,300	22%
	Existing Levee	588,600	416,000	172,600		71%
	No Levee	2,525,300	978,600	1,546,700		39%
Reach B	No Levee	208,800	201,400	7,400	7,400	96%
Reach C	No Levee	213,900	205,400	8,500	8,500	96%
Reach D	No Levee	3,312,300	1,018,500	2,293,800	2,293,800	31%
Reach E	Existing Levee	194,500	138,400	56,100	56,100	71%
Reach U	No Levee	7,297,900	5,185,500	2,112,500	2,112,500	71%
Total		17,526,500	8,849,000	8,677,500	8,677,500	50%

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01
Price level October 2016

6.4.2 Cost Estimate

A summary of the costs and benefits for Alternative 3A is presented in Table 24. Interest during construction for Alternative 3A is based on a 24-month construction schedule at the 2017 fiscal year USACE project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01 (USACE, 2016).

Table 24: Alternative 3a Average Annual Benefits, Costs, and Net NED Benefits

First Cost	623,323,356
Interest During Construction	10,290,951
Total Investment Cost	633,614,307
Annual Investment Cost	24,044,450
Annual O&M Cost	2,875,748
Total Annual Cost	26,920,198
Annual Benefits	8,677,500
Net Benefits	-18,242,698
BCR	0.3

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01
Price level October 2016

6.5 Alternative 3B: Nonstructural Treatment (2% Annual Chance Exceedance Floodplain)

Under Alternative 3B, nonstructural treatments were applied to structures located within the study area 2% annual chance of exceedance floodplain using a spreadsheet matrix which considered physical characteristics including building configuration, usage, footprint size, foundation type, and existing main floor elevation in order to select and cost the most appropriate/feasible treatment for each structure. The methodology and assumptions used to assign nonstructural treatments to individual structures under Alternative 3B were identical to those for Alternative 3A, though the structure population used for the analysis of Alternative 3B was comprised of 581 structures. The structures identified for nonstructural treatments are summarized in Table 25.

Table 25: Nonstructural Measures Applied to Structures in the 2% ACE Floodplain

Damage Reduction Measure	Residential	Nonresidential	Total
Dry Flood Proofing	11	37	48
Elevate Structure	287	5	292
Ringwall Around Structure	76	110	186
Wet Flood Proofing	51	4	55
Total	425	156	581

6.5.1 Residual Damages and Benefits

Using HEC-FDA, Average Annual Damages were calculated for the base year and future years with Alternative 3B in place, and Equivalent Annual Damages were calculated for the 50-year period of analysis, using the 2017 fiscal year USACE project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01 (USACE, 2016). A summary of equivalent annual damages and flood damage reduction benefits by damage reach for Alternative 3B is presented in Table 26, and a summary of equivalent annual damages and flood damage reduction benefits by economic reach for Alternative 3B is presented in Table 27. The economic analysis for Alternative 3B is presented at October 2016 price level.

Table 26: Damages and Benefits for Alternative 3b by Damage Reach

Stream	Damage Reach	Without-project Damages	With Alternative 3b Damages	Damage Reduction Benefits	Residual Risk
Carteret	A-CW-4-L	623,500	131,500	492,000	21%
	B-CW-4-R	147,600	147,600	0	100%
	C-CW-2-L	213,900	156,100	57,800	73%
	D-CW-2-R	3,312,300	851,100	2,461,200	26%
	U-CW-1B-L	950,400	326,300	624,100	34%
	U-CW-1B-R	9,300	9,300	0	100%
	U-CW-1-L	872,700	657,500	215,200	75%
	U-CW-1-R	3,001,000	2,293,300	707,700	76%
	U-CW-3-L	49,800	49,800	0	100%
	U-CW-3-R	481,600	219,800	261,800	46%
Millburn-Clark	A-MB-1-L	33,100	30,500	2,600	92%
	A-MB-1-R	532,500	54,100	478,400	10%
	A-MB-2-L	204,200	92,600	111,600	45%
	A-MB-2-R	15,000	13,300	1,700	89%
Rahway	A-RR-1-L	2,126,800	207,400	1,919,400	10%
	A-RR-2-L	265,100	41,900	223,200	16%
	CH-RR-3-L	669,900	64,600	605,300	10%
	CH-RR-3-R	15,000	15,000	0	100%
	E-RR-1-R	588,600	394,100	194,500	67%
	N-RR-2-R	169,800	169,800	0	100%
Robinsons Branch	A-RB-L	673,900	333,500	340,400	49%
	A-RB-R	381,600	177,400	204,200	46%
South Branch	B-SB-2-R	61,300	35,600	25,700	58%
	E-SB-1-L	194,500	124,400	70,100	64%
	U-SB-1-R	8,200	8,200	0	100%
	U-SB-2-L	1,107,500	885,200	222,300	80%
	U-SB-3-R	817,500	350,400	467,100	43%
Total		17,526,500	7,840,000	9,686,500	45%

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01

Price Level October 2016

Table 27: Alternative 3b Average Annual Damages and Benefits

Economic Reach	Subcategory	Without-project Damages	With Alternative 3b Damages	Damage Reduction Benefits	Reach Benefits	Residual Risk
Reach A	No Levee	3,185,200	550,500	2,634,600	4,573,300	17%
	Existing Levee	588,600	394,100	194,500		67%
	No Levee	2,525,300	780,900	1,744,200		31%
Reach B	No Levee	208,800	183,200	25,700	25,700	88%
Reach C	No Levee	213,900	156,100	57,800	57,800	73%
Reach D	No Levee	3,312,300	851,100	2,461,200	2,461,200	26%
Reach E	Existing Levee	194,500	124,400	70,100	70,100	64%
Reach U	No Levee	7,297,900	4,799,700	2,498,200	2,498,200	66%
Total		17,526,500	7,840,000	9,686,500	9,686,500	45%

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01
Price level October 2016

6.5.2 Cost Estimate

A summary of the costs and benefits for Alternative 3B is presented in Table 24. Interest during construction for Alternative 3B is based on a 24-month construction schedule at the 2017 fiscal year USACE project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01 (USACE, 2016).

Table 28: Alternative 3b Average Annual Benefits, Costs, and Net NED Benefits

First Cost	973,143,314
Interest During Construction	104,626,626
Total Investment Cost	1,077,769,939
Annual Investment Cost	40,889,306
Annual OM Cost	4,495,920
Total Annual Cost	45,395,226
Annual Benefits	9,686,500
Net Benefits	-35,708,726
BCR	0.2

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01
Price level October 2016

6.6 Alternative 4: Levee Segment D & Nonstructural Treatment (10% Annual Chance Exceedance Floodplain)

Alternative 4 provides a combination of non-structural and structural measures. Figure 8 contains a map of the proposed elements in Alternative 4. The structural measure is Levee Segment D (a component of Alternative 1), located on the right bank of the Carteret & Woodbridge River between the beginning (downstream) Station of 14731.32 and ending (upstream) Station of 17565.28. The levee would be constructed with a top elevation of 12.6 feet NAVD88. This stationing corresponds to the HEC-FDA damage reach named D-CW-2-R, which includes a total of 197 structures and 291 residentially-owned automobiles. Non-structural treatments were developed for a total of 149 structures, as outlined in Table 29.

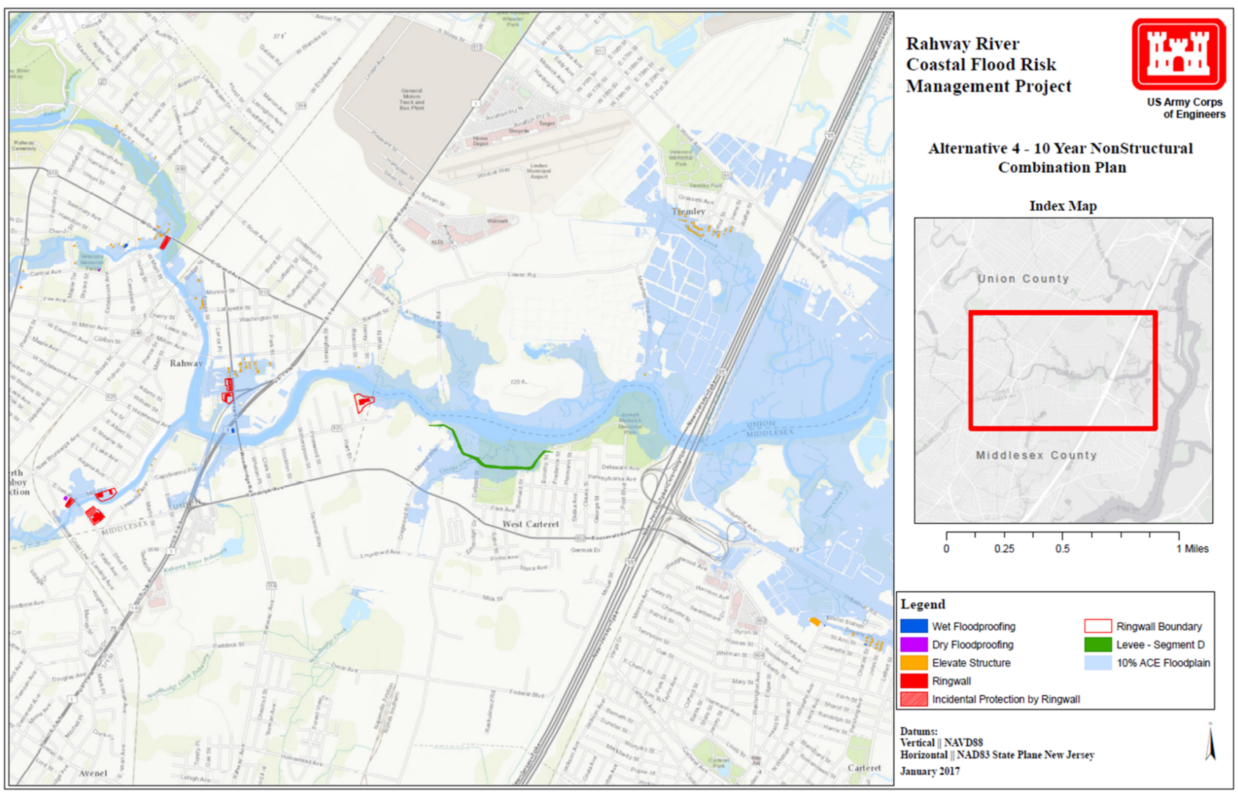


Figure 8: Alternative 4 Plan Overview

Table 29: Nonstructural Measures Applied — Alternative 4

Damage Reduction Measure	Residential	Nonresidential	Total
Dry Flood Proofing		2	2
Elevate Structure	124	6	130
Ringwall Around Structure		13	13
Wet Flood Proofing	1	3	4
Total	125	24	149

6.6.1 Residual Damages and Benefits

Using HEC-FDA, average annual damages were calculated for the base year and future years with Alternative 4 in place, and Equivalent Annual Damages were calculated for the 50-year period of analysis, using the 2017 fiscal year USACE project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01 (USACE, 2016). A summary of equivalent annual damages and flood damage reduction benefits by damage reach for Alternative 4 is presented in Table 30, and a summary of equivalent annual damages and flood damage reduction benefits by economic reach for Alternative 4 is presented in Table 31. The economic analysis for Alternative 4 is presented at October 2016 price level.

6.6.2 Cost Estimate

A summary of the costs and benefits for Alternative 4 is presented in Table 32. Interest during construction for Alternative 4 is based on a 96-month construction schedule at the 2017 fiscal year USACE project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01 (USACE, 2016).

6.6.3 Additional Ringwall Analyses for Plan Formulation Evaluations

Individual ringwall performance metrics were developed to aid in the refinement of Alternative 4. Alternative 4 calls for seven ringwalls to provide coastal storm risk reduction to a total of 13 structures, as outlined in Table 33 below.

To analyze the performance of the ringwalls, a separate HEC-FDA model was developed that analyzed only the 13 structures for which ringwalls were specified under Alternative 4. The results

Table 30: Damages and Benefits for Alternative 4 by Damage Reach

Stream	Damage Reach	Without-project Damages	With Alternative 4 Damages	Damage Reduction Benefits	Residual Risk
Carteret	A-CW-4-L	623,500	453,700	169,800	73%
	B-CW-4-R	147,600	147,600	0	100%
	C-CW-2-L	213,900	205,400	8,500	96%
	D-CW-2-R	3,312,300	962,000	2,350,300	29%
	U-CW-1B-L	950,400	379,400	571,000	40%
	U-CW-1B-R	9,300	9,300	0	100%
	U-CW-1-L	872,700	872,700	0	100%
	U-CW-1-R	3,001,000	2,352,200	648,800	78%
	U-CW-3-L	49,800	49,800	0	100%
	U-CW-3-R	481,600	239,900	241,700	50%
Millburn-Clark	A-MB-1-L	33,100	33,100	0	100%
	A-MB-1-R	532,500	264,300	268,200	50%
	A-MB-2-L	204,200	192,800	11,400	94%
	A-MB-2-R	15,000	15,000	0	100%
Rahway	A-RR-1-L	2,126,800	1,254,500	872,300	59%
	A-RR-2-L	265,100	219,200	45,900	83%
	CH-RR-3-L	669,900	669,900	0	100%
	CH-RR-3-R	15,000	15,000	0	100%
	E-RR-1-R	588,600	588,600	0	100%
	N-RR-2-R	169,800	169,800	0	100%
Robinsons Branch	A-RB-L	673,900	607,200	66,700	90%
	A-RB-R	381,600	342,200	39,400	90%
South Branch	B-SB-2-R	61,300	53,600	7,700	87%
	E-SB-1-L	194,500	194,500	0	100%
	U-SB-1-R	8,200	8,200	0	100%
	U-SB-2-L	1,107,500	915,600	191,900	83%
	U-SB-3-R	817,500	541,100	276,400	66%
Total		17,526,500	11,756,600	5,769,900	67%

Project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01

Price level October 2016

Table 31: Alternative 4 Average Annual Damages and Benefits

Economic Reach	Subcategory	Without-project Damages	With Alternative 4 Damages	Damage Reduction Benefits	Reach Benefits	Residual Risk
Reach A	No Levee	3,185,200	2,097,200	1,088,000	1,473,700	66%
	Existing Levee	588,600	588,600	0		100%
	No Levee	2,525,300	2,139,600	385,700		85%
Reach B	No Levee	208,800	201,200	7,700	7,700	96%
Reach C	No Levee	213,900	205,400	8,500		96%
Reach D	Alt 1 Levee	3,312,300	962,000	2,350,300	2,350,300	29%
Reach E	Existing Levee	194,500	194,500	0	0	100%
Reach U	No Levee	7,297,900	5,368,100	1,929,800	1,929,800	74%
Total		17,526,500	11,756,600	5,769,900	5,769,900	67%

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01
Price level October 2016

Table 32: Alternative 4 Average Annual Benefits, Costs, and Net NED Benefits

First Cost	180,535,678
Interest During Construction	11,041,013
Total Investment Cost	191,576,691
Annual Investment Cost	7,269,969
Annual OM Cost	466,278
Total Annual Cost	7,736,246
Annual Benefits	5,769,900
Net Benefits	-1,966,346
BCR	0.7

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01
Price level October 2016

Table 33: Alternative 4 Ringwalls

Ringwall Group	Structure	Elevation	Damage Reach
R001	5405	14.4	U-SB-3-R
R001	5406	14.4	U-SB-3-R
R002	5312	14.4	U-SB-2-L
R003	5381	14.4	U-SB-2-L
R003	5382	14.4	U-SB-2-L
R004	5751	14.4	U-CW-3-R
R005	1173	14.4	A-RR-1-L
R006	1175	14.4	A-RR-1-L
R006	1370	14.4	A-RR-1-L
R006	1371	14.4	A-RR-1-L
R006	1372	14.4	A-RR-1-L
R006	1373	14.4	A-RR-1-L
R007	5093	16	A-MB-1-R

of the model for the 13 structures are shown in Table 34.

Table 34: Ringwall Risk Reduction Performance Under Alternative 4

Damage Reach	Stream	Ringwall Group	Without-project Damages	Alternative 4 Damages	Alternative 4 Benefits	Residual Risk
U-SB-3-R	South	R001	397,200	122,900	274,300	31%
U-SB-2-L	South Branch	R002, R003	268,300	64,600	203,700	24%
U-CW-3-R	Carteret-Woodbridge	R004	254,300	9,600	244,700	4%
A-RR-1-L	Rahway River	R005, R006	574,300	40,100	534,200	7%
A-MB-1-R	Milburn-Clark	R007	132,100	7,200	124,900	5%
Total			1,626,200	244,400	1,381,800	15%

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01
Price level October 2016

Damage reaches in the HEC-FDA model were used to isolate the without-project and Alternative 4 (with ringwall) damages for the following Ringwall Groups:

- R001 (Damage Reach U-SB-3-R)
- R004 (Damage Reach U-CW-3-R)
- R007 (Damage Reach A-MB-1-R)

With- and without-project damages for structures within Ringwall Groups R002, R003, R005, and

R006 were isolated by developing additional separate HEC-FDA models that contain structures within:

- R002 (Structure Number 5312 evaluated)
- R005 (Structure Number 1173 evaluated)

As such, damages for Ringwall Group R003 were isolated by subtracting the results of Ringwall Group R002 (which includes 1 structure from damage reach U-SB-2-L) from the overall ringwall total for damage reach U-SB-2-L. Similarly, damages for Ringwall Group R006 were isolated by subtracting the results of Ringwall Group R005 (which includes ONE structure from damage reach A-RR-1-L) from the overall ringwall total for damage reach A-RR-1-L. Isolated damages under with- and without-project conditions are provided for each of the ringwall groups in Table 35.

Table 35: Individual Ringwall Risk Reduction Performance Under Alternative 4

Ringwall Group	Damage Reach	Stream	Without-project Damages	Alternative 4 Damages	Alternative 4 Benefits	Residual Risk
R001	U-SB-3-R	South	397,200	122,900	274,300	31%
R002	U-SB-2-L	South Branch	122,600	33,400	89,200	27%
R003	U-SB-2-L	South Branch	145,700	31,200	114,500	21%
R004	U-CW-3-R	Carteret-Woodbridge	254,300	9,600	244,700	4%
R005	A-RR-1-L	Rahway River	522,900	35,300	487,600	7%
R006	A-RR-1-L	Rahway River	51,400	4,800	46,600	9%
R007	A-MB-1-R	Millburn-Clark	132,100	7,200	124,900	5%
	Total		1,626,200	244,400	1,381,800	15%

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01
Price level October 2016

6.7 Alternative 4a: Levee Segment D & Nonstructural Treatment without Ringwalls (10% Annual Chance Exceedance Floodplain)

Alternative 4a provides a combination of non-structural and structural measures, similarly to Alternative 4. Figure 9 contains a map of the proposed structural flood risk management measure in Alternative 4a. The structural measure is Levee Segment D, as in Alternative 4. The levee would be constructed with a top elevation of 12.6 feet NAVD88. The difference between Alternative 4 and Alternative 4a is that the ringwalls have been removed in Alternative 4a. Ringwalls were considered part of the non-structural for this phase, but no longer fall into that category. Ringwalls are not part of the recommended plan. Non-structural treatments were developed for a total of 136 structures, as outlined in Table 36.

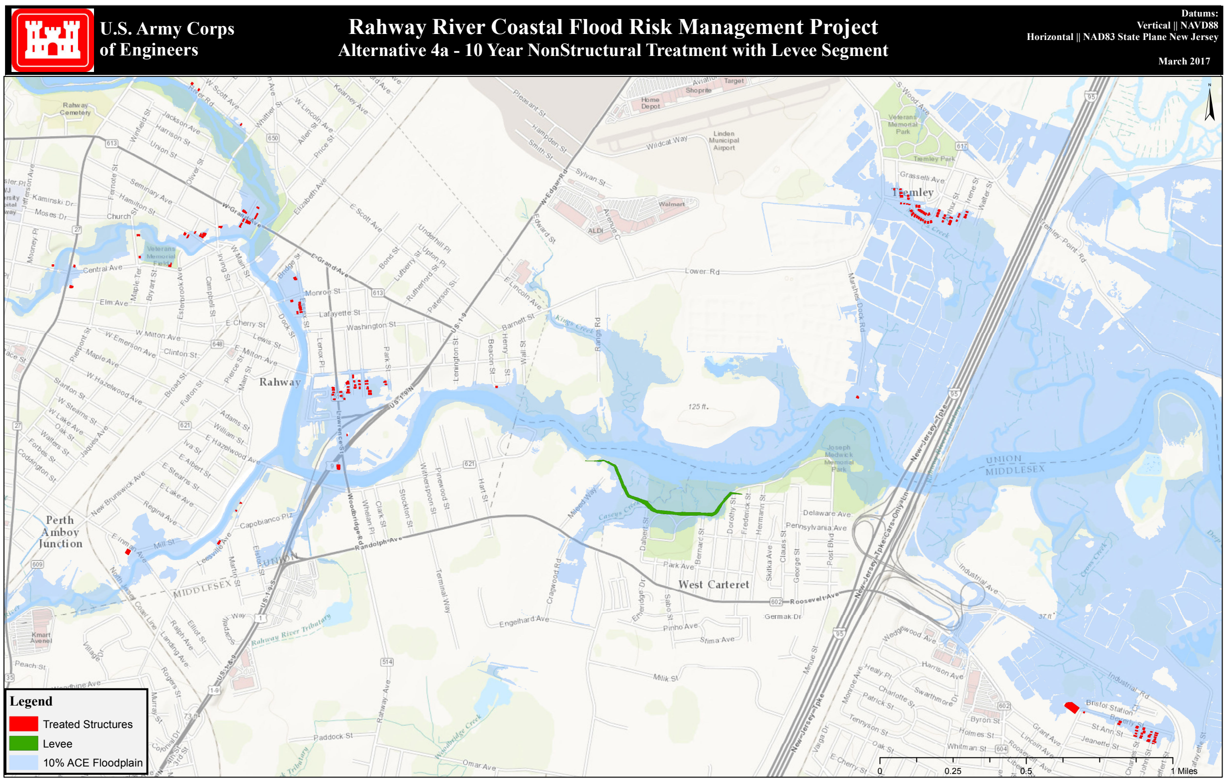


Figure 9: Alternative 4a/TSP Plan Overview

Table 36: Nonstructural Measures Applied — Alternative 4a

Damage Reduction Measure	Residential	Nonresidential	Total
Dry Flood Proofing		2	2
Elevate Structure	124	6	130
Wet Flood Proofing	1	3	4
Total	125	11	136

6.7.1 Residual Damages and Benefits

Using HEC-FDA, Average Annual Damages were calculated for the base year and future years with Alternative 4a in place, and Equivalent Annual Damages were calculated for the 50-year period of analysis, using the 2017 fiscal year USACE project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01 (USACE, 2016). A summary of equivalent annual damages and flood damage reduction benefits by damage reach for Alternative 4a is presented in Table 37, and a summary of equivalent annual damages and flood damage reduction benefits by economic reach for Alternative 4a is presented in Table 38. The economic analysis for Alternative 4a is presented at October 2016 price level.

6.7.2 Cost Estimate

A summary of the costs and for Alternative 4a is presented in Table 39. Interest during construction for Alternative 4 is based on a 96-month construction schedule at the 2017 fiscal year USACE project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01 (USACE, 2016).

7 Comparison of Alternatives

A summary of all damages, benefits, costs, and subsequent benefit-cost ratios for the two structural plans, two nonstructural plans, and two combination plans evaluated for the Rahway River Basin Coastal Storm Risk Management Study is presented in Table 40.

7.1 Tentatively Selected Plan: Alternative 4a

Alternative 4a was identified as the tentatively selected plan for the Rahway River Basin, New Jersey Coastal Storm Risk Management Feasibility Study.

Alternative 4a provides a combination of non-structural and structural measures. The non-structural and structural measures are separable, independent measures and are incrementally justified. The structural measure is Levee Segment D (a component of Alternative 1), located on the right bank of the Carteret & Woodbridge River between the beginning (downstream) Station of 14731.32 and ending (upstream) Station of 17565.28. The levee would be constructed with a top elevation of 12.6 ft. NAVD88. This stationing corresponds to the HEC-FDA damage reach named D-CW-2-R, which includes a total of 197 structures and 291 residentially-owned automobiles. Non-structural

Table 37: Damages and Benefits for Alternative 4a by Damage Reach

Stream	Damage Reach	Without-project Damages	With Alternative 4a Damages	Damage Reduction Benefits	Residual Risk
Carteret & Woodbridge	A-CW-4-L	623,500	453,700	169,800	73%
	B-CW-4-R	147,600	147,600	0	100%
	C-CW-2-L	213,900	205,400	8,500	96%
	D-CW-2-R	3,312,300	962,000	2,350,300	29%
	U-CW-1B-L	950,400	379,400	571,000	40%
	U-CW-1B-R	9,300	9,300	0	100%
	U-CW-1-L	872,700	872,700	0	100%
	U-CW-1-R	3,001,000	2,352,200	648,800	78%
	U-CW-3-L	49,800	49,800	0	100%
	U-CW-3-R	481,600	484,600	-3000	101%
Millburn-Clark	A-MB-1-L	33,100	33,100	0	100%
	A-MB-1-R	532,500	389,200	143,300	73%
	A-MB-2-L	204,200	192,800	11,400	94%
	A-MB-2-R	15,000	15,000	0	100%
Rahway	A-RR-1-L	2,126,800	1,788,700	338,100	84%
	A-RR-2-L	265,100	219,200	45,900	83%
	CH-RR-3-L	669,900	669,900	0	100%
	CH-RR-3-R	15,000	15,000	0	100%
	E-RR-1-R	588,600	588,600	0	100%
	N-RR-2-R	169,800	169,800	0	100%
Robinson's Branch	A-RB-L	673,900	607,200	66,700	90%
	A-RB-R	381,600	342,200	39,400	90%
South Branch	B-SB-2-R	61,300	53,600	7,700	87%
	E-SB-1-L	194,500	194,500	0	100%
	U-SB-1-R	8,200	8,200	0	100%
	U-SB-2-L	1,107,500	1,119,300	-11,800	101%
	U-SB-3-R	817,500	541,100	2,100	66%
Total	17,526,500	13,138,400	4,388,100		33%

Project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01

Price level October 2016

Table 38: Alternative 4a Average Annual Damages and Benefits

Economic Reach	Subcategory	Without-project Damages	With Alternative 4a Damages	Damage Reduction Benefits	Reach Benefits	Residual Risk
Reach A	No Levee	3,185,200	2,631,400	553,800		83%
	Existing Levee	588,600	588,600	0	814,600	100%
	No Levee	2,525,300	2,264,500	260,800		90%
Reach B	No Levee	208,800	201,200	7,700	7,700	96%
Reach C	No Levee	213,900	205,400	8,500	8,500	96%
Reach D	Alt 1 Levee	3,312,300	962,000	2,350,300	2,350,300	29%
Reach E	Existing Levee	194,500	194,500	0	0	100%
Reach U	No Levee	7,297,900	6,090,800	1,207,100	1,207,100	83%
Total		17,526,500	13,138,400	4,388,100	4,388,100	75%

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01
Price level October 2016

Table 39: Alternative 4a Average Annual Benefits, Costs, and Net NED Benefits

First Cost	65,502,480
Interest During Construction	3,215,681
Total Investment Cost	68,718,161
Annual Investment Cost	2,607,723
Annual OM Cost	47,610
Total Annual Cost	2,655,332
Annual Benefits	4,388,100
Net Benefits	1,732,768
BCR	1.7

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01
Price level October 2016

Table 40: Alternatives Summary and TSP Selection

Alternative	Inundation Damages Without Project	Inundation Damages With Project	Residual Risk	Annual Benefits	First Cost	Annual Cost	Net Benefits	BCR
1	17,526,500	11,940,300	68%	5,586,200	106,506,651	4,760,697	825,503	1.2
2	17,526,500	11,181,100	64%	6,345,400	988,808,637	47,012,307	-40,666,907	0.1
3a	17,526,500	8,849,000	50%	8,677,500	623,323,356	26,920,198	-18,242,698	0.3
3b	17,526,500	7,840,000	45%	9,686,500	973,143,314	45,395,226	-35,708,726	0
4	17,526,500	11,756,600	67%	5,769,900	180,535,678	7,736,246	-1,966,346	0.7
4a	17,526,500	13,138,400	75%	4,388,100	66,900,321	2,650,871	1,737,229	1.7

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01

Price level October 2016

treatments were developed for a total of 136 structures, as outlined in Table 36.

The benefit and costs for 4a are summarized in Table 41.

Table 41: TSP Costs and Benefits

	TSP
First Cost	66,900,321
Interest During Construction	1,598,186
Total Investment Cost	68,498,507
Annual Investment Cost	2,599,387
Annual O&M Cost	51,484
Total Annual Cost	2,650,871
Without-project Damages	17,526,500
With-project Damages	13,138,400
Annual Benefits	4,388,100
Net Benefits	1,737,229
BCR	1.7

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01
Price level October 2016

7.2 Project Performance and Risk Analysis

This study has been conducted in accordance with Engineering Regulation 1105-2-101, “Risk Analysis for Flood Damage Reduction Studies,” which requires that the risk analysis for a flood protection project quantifies the performance of all alternatives and evaluates the residual risk, including the consequences of the project’s capacity exceedance (USACE, 2017). Table 42 quantifies the performance of all alternatives in partial accordance with ER 1105-2-101.

Table 42: Expected and Probabilistic Values of Damage Reduced by Alternative

Alternative	Equivalent Annual Damages				Probability Damage Reduced Exceeds Indicated Values		
	Without Project	With Project	Residual Risk	Damage Reduced	75%	50%	25%
1	17,526,500	11,940,300	68%	5,586,200	3,837,100	5,409,000	7,201,600
2	17,526,500	11,181,100	64%	6,345,400	4,148,100	6,288,500	8,598,500
3a	17,526,500	8,849,000	50%	8,677,500	6,030,800	8,591,400	11,190,100
3b	17,526,500	7,840,000	45%	9,686,500	6,538,400	9,532,400	12,662,600
4	17,526,500	11,756,600	67%	5,769,900	4,265,800	5,799,800	7,222,800
4a	17,526,500	13,138,400	75%	4,388,100	3,567,300	4,485,900	5,266,100

ACE represents annual chance exceedance. Oct 2016 Price Level

Project evaluation and formulation rate (discount rate) 2.875% in accordance with EGM 17-01

8 Optimization Approach

This section introduces the economic analysis of the optimization step of the Rahway River Basin, New Jersey Coastal Storm Risk Management Feasibility Study Tentatively Selected Plan. Three sizes of the tentatively selected plan were evaluated over the period of analysis under the three different USACE relative sea level change scenarios. As such, relative sea level change played an important role in the optimization of the tentatively selected plan and identification of the recommended plan.

The height of the refined tentatively selected plan levee/floodwall and the scale and scope of the nonstructural actions proposed for optimization were varied in elevation in the different relative sea level change scenarios. The refined tentatively selected plan levee/floodwall from Alternative 4a was formulated with the assumption of the relative sea level change Low scenario and has a proposed elevation of 12.6 feet NAVD88. This means that in the formulation of the 12.6-foot tentatively selected plan levee/floodwall elevation height, it was assumed that the rate of sea level change would persist at its historical rate. The future without-project conditions for optimization have been presented with respect to the relative sea level change intermediate scenario. Despite this presentation, there is substantial uncertainty in the future rate of rate of sea level change. Further, because relative sea level change is an exogeneous variable, the future outcome for sea level change cannot be chosen. Therefore relative sea level change cannot serve as the choice variable in this optimization problem. The economic analysis thus is carried out for all relative sea level change scenarios to evaluate the performance of the proposed optimization alternatives under the three assumptions. In effect, this approach isolates the size of the selected plan as the choice variable in optimization and the differential plan size performance is evaluated under the varying conditions.

8.1 Optimization Alternatives

Three plans were proposed for optimization of the tentatively selected plan to identify a recommended plan. The plans are small, medium, and large. The small plan levee/floodwall is the levee as proposed in Alternative 4a and in the relative sea level change low scenario and is now part floodwall. This levee/floodwall has a top elevation of 12.6 feet. The medium plan levee/floodwall has a top elevation of 14.2 feet, and the large plan has a top elevation of 16 feet[29].

Each plan contains a set of proposed nonstructural actions for the structures contained within the

10% chance of annual exceedance floodplain as in the tentatively selected plan. The nonstructural actions in the small, medium, and large plans are optimized according to a design height of the 1% chance of annual exceedance water surface elevations in 2073 conditional on the relative sea level change Low, Medium, and High scenarios, plus one foot for water surface perturbations. The composition of the nonstructural plans is organized in Table 43. The number of structures that are proposed to receive nonstructural treatment are 105 in the small plan, 110 in the medium plan, and 146 in the large plan. Observe that the majority of the nonstructural actions in each plan are elevations, but buyouts take a more prominent role as the water surface elevations of the estimated flood events increase with higher relative sea level change scenarios. The non-structural and structural measures remain separable, incrementally-justified independent measures.

Table 43: Nonstructural Measures Applied — Optimization

Structure Category	Damage Reduction Measure	Small Plan	Medium Plan	Large Plan
Residential	Dry Flood Proofing			2
	Wet Flood Proofing	10	7	
	Elevate Structure	84	89	69
	Buyout	6	10	67
Nonresidential	Dry Flood Proofing			1
	Wet Flood Proofing	3	2	
	Elevate Structure	2	2	4
	Buyout			3
Total		105	110	146

8.2 Water Surface Elevation Data

Water surface elevations are required at 10-year intervals between the years of 2023 and 2073 to accurately model the expected damages as a function of relative sea level change[30]. The 10-year intervals are used to approximate the acceleration in sea level change over time. This exercise is important for modeling flood damage analysis using the Hydrologic Engineering Center-Flood Damage Analysis model. Typically, this model linearly interpolates the effects of any changes happening over time between analysis years, including sea level change. The linear interpolation biases models using the U.S. Army Corps of Engineers (USACE) relative sea level change intermediate and high scenarios because they demonstrate substantial acceleration in sea level change. The low/historical scenario is effectively linear and is sufficiently estimated within the Hydrologic Engineering Center-Flood Damage Analysis model.

A creative solution was required to come up with the necessary water surface elevation data subject to a set of constraints. Typically, hydrologists and hydraulic engineers work together using USACE-certified models and methods to develop all of the water surface profiles used in a feasibility study. Indeed, water surface profiles were generated for the years 2023 and 2073 in the conventional way. A complication arises in the requirement for joint probability stages to simultaneously account for the riverine and tidal influences over the range of flood events. Creating 4 additional sets of joint probability stages for analysis years 2033, 2043, 2053, and 2063 was understood to require far more time than permitted under PB 2014-01 SMART Planning $3 \times 3 \times 3$ Rules. A quicker, risk-informed solution was required pursuant to the PB 2014-01 SMART Planning $3 \times 3 \times 3$ Rules (USACE, 2014).

An additional constraint is found amongst the rate of sea level change over the cross sections represented by the study water surface profiles. For some cross sections, there is little to no relative sea level change between the 2023 water surface elevations and the water surface elevations calculated for the high scenario in 2073. For other cross sections, there is a very large difference. For example, at cross section 8751.454 in 2023, there is a .01 probability that the water surface elevation will exceed 21.75 feet NAVD88 and this same flood event is higher by four-hundredths of a foot in the high scenario in 2073 at 21.79 NAVD88. However, at cross section 16323.3, there is a .01 probability that the water surface elevation will exceed 14.81 feet NAVD88 in 2023, and this flood event increases to an elevation of 19.19 feet NAVD in 2073 in the high scenario. This vast discrepancy in rates of sea level change precludes a preferred method of taking the rate of sea level change for the stage-frequency curve at the mouth of the Rahway River and applying that same rate to all cross sections. Clearly, the rate of sea level change is not the same across cross sections thereby required a different method.

Facing the described challenges, a simple numerical algorithm was developed as a $3 \times 3 \times 3$ risk-informed solution to calculating water surface elevation data accurately for 7 cross sections, 9 flood events, and 3 relative sea level change scenarios. Importantly, the algorithm interpolated the necessary data using water surface elevation data that had previously been estimated using USACE-certified tools and methods. The interpolation is linear for the relative sea level change low scenario and non-linear for the relative sea level change intermediate and high scenarios. The functional form of the non-linearity is informed by USACE guidance and the way sea level is known to accelerate as a function of time. Engineering Regulation 1100-2-8162 describes the functional form of relative sea level change as a function of time in Appendix B. Paragraph B-4.c(2) explains that the change in relative sea level between two periods can be estimated using a linear and quadratic term in time. Equation 2 is the replication of the equation presented in the engineering regulation[31]:

$$E(t_2) - E(t_1) = .0017\,(t_2 - t_1) + b\left(t_2^2 - t_1^2\right) \tag{2}$$

where t_1 is the time between the project's construction date and 1992 and t_2 is the time between a future date at which one wants an estimate for sea level change and 1992. On the left-hand side, $E(t)$ represents relative sea level at that time period. The parametrization of Equation 2 represents the rate of global mean sea level change. The coefficient of the first term on the right-hand side of Equation 2 represents the historic rate of global mean sea level change at 1.7mm/year. The coefficient on the second term on the right-hand side of Equation 2 represents the rates of change (acceleration) above the historical rate of change. In the case of global mean sea level change, the coefficient b takes on two different values for the two higher rates of sea level change; 2.71E-5 for the USACE relative sea level change intermediate scenario and 1.13E-4 for the USACE high scenario.

Equation 2 as parametrized does not serve as an accurate representation of relative sea level change in the Rahway Tidal Basin. The rate of global mean sea level change is quicker than estimated for many cross sections among the Rahway River Basin. To best approximate the rate of relative sea level change at the cross sections throughout the study area at the various exceedance probabilities and rates of sea level change, Equation 2 was slightly modified:

$$E_{r,f,c}(t_2) - E_{r,f,c}(t_1) = a_{f,c}\,(t_2 - t_1) + b_{r,f,c}\left(t_2^2 - t_1^2\right) \tag{3}$$

where the relative sea level change on the left-hand side is estimated for sea level change scenario r, frequency f, and cross section c; and the coefficients $a_{f,c}$ and $b_{r,f,c}$ represent the linear and quadratic rate of change over time for sea level change scenario r, frequency f, and cross section c. These coefficients have been estimated using the 2023 and 2073 stage-frequency projections for each cross section and relative sea level change scenario. Please observe that the coefficients have been calculated for the change in sea level using the water surface profiles that were generated using USACE-certified tools and methods. Using estimates of the values of the coefficients, relative sea level change for 2033, 2043, 2053, and 2063 are projected resulting in the required set of water surface profiles.

The first step in identifying the coefficients is to calculate $a_{f,c}$, which is simply the average rate of sea level change over the period of analysis in the low scenario for a given frequency and cross section. This coefficient tells us how many feet per year the low/historical scenario predicts water surface elevations to increase into the future. With $a_{f,c}$ calculated, the only remaining unknown for the equations that represent relative sea level change between 2023 and 2073 is the coefficient $b_{r,f,c}$ which represents the acceleration in sea level beyond the low scenario that is predicted in intermediate and high scenarios. The left-hand side is the change in water surface elevations between 2023 and 2073. The other terms on the right-hand side represent the change in time $((2073-1992)-(2023-1992))$ and the change in time squared $((2073-1992)^2-(2023-1992)^2)$. The year 1992 is part of the calculation because this is the center of the current tidal epoch. With only one unknown, the equation is identified and a solution for the coefficient $b_{r,f,c}$ exists. The coefficients $a_{f,c}$ and $b_{r,f,c}$ are then used to interpolate the change in sea level from 2023 to 2033, from 2033 to 2043, so on and so forth.

The stage-frequency data projected for the intermediate scenario of relative sea level change at cross section 16323.9 is plotted in Figure 10 as an example. Observe the modest acceleration demonstrated over time for each of the exceedance probabilities. The projected data obtained from this method and plotted in Figure 10 is organized in Table 44. This and all other projected data will be used in the optimization step of the economic analysis for the Rahway River Basin, New Jersey Coastal Storm Risk Management Feasibility Study. The equation used to estimate the stage of cross section 16323.9 for the 1% annual chance of exceedance flood event is found to be:

$$E_{int,.01,16323.9}(t_2) = E_{int,.01,16323.9}(t_{2023}) + .0144(t_2 - t_{2023}) + .0002857(t_2^2 - t_{2023}^2) \tag{4}$$

where the coefficient $a = .0144$ and the coefficient $b = .0002857$. The water surface elevation for this event is expected to be 2.32 feet higher in 2073 than in 2023.

The Python script that was used to execute this risk-informed SMART-planning-inspired solution has been provided as an attachment to this appendix. Please review the Python script for a detailed step-by-step understanding of the method that was developed to interpolate the required water surface profiles.

9 Optimization: Economics

The small, medium, and large plans have been evaluated for expected damages reduced from the base year 2029 through the end of the period of analysis (2079)[32]. Each plan has been evaluated

Table 44: Rahway Stage-Frequency Data Intermediate RSLC XS 16323.9

	Frequency								
Year	0.002	0.005	0.010	0.020	0.040	0.100	0.200	0.500	0.990
2023	16.080000	15.510000	14.810000	12.860000	11.520000	9.980000	8.940000	6.800000	5.830000
2033	16.420286	15.921571	15.159714	13.454286	12.038143	10.546714	9.284857	7.129714	6.165571
2043	16.813429	16.406357	15.566571	14.116429	12.660214	11.228071	9.683286	7.511571	6.554357
2053	17.259429	16.964357	16.030571	14.846429	13.386214	12.024071	10.135286	7.945571	6.996357
2063	17.758286	17.595571	16.551714	15.644286	14.216143	12.934714	10.640857	8.431714	7.491571
2073	18.310000	18.300000	17.130000	16.510000	15.150000	13.960000	11.200000	8.970000	8.040000

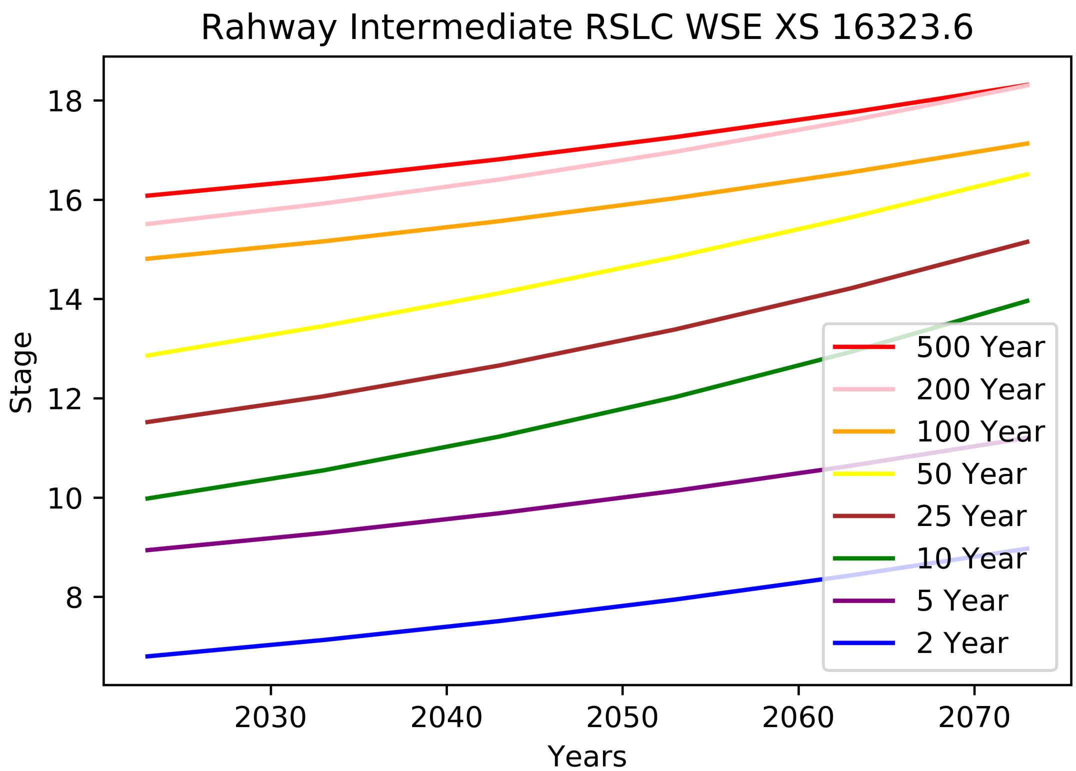


Figure 10: Stage-Frequency for Intermediate Scenario XS 16323.9

with respect to each of the three relative sea level change scenarios. The analysis for the relative sea level change low scenario is reasonably implemented in HEC-FDA as a single model for the 50-year period of analysis due to the linearity of the relative sea level change low projection. The three plans were evaluated at 10-year intervals in HEC-FDA for the relative sea level change intermediate and high scenarios to accurately capture the effect of acceleration in sea level rise on expected damages. The expected damages were then interpolated over the 10-year intervals and amortized over the 50-year period of analysis to arrive at expected annual damages with and without the project. The economics is performed with data at October 2019 price levels and using the fiscal year 2020 project evaluation and formulation rate (discount rate) of 2.75% in accordance with EGM 20-01 (USACE, 2019b). The price level has been updated for optimization using the USACE Civil Works Construction Cost Index System (USACE, 2019a).

9.1 Cost Engineering

This section summarizes and duplicates information available in the cost engineering appendix. The first cost breakdowns for the small, medium, and large plans are organized in Tables 46–48. The annualized costs are presented in Table 45.

Table 45: Annual Cost Rahway Tidal Optimization

Item	Small Plan	Medium Plan	Large Plan
First Cost	54,934,124	71,929,111	133,595,785
Interest During Construction	4,299,582	2,424,017	4,518,643
Total Investment Cost	59,233,706	74,353,017	138,114,428
Annualized Investment Cost	2,247,806	2,754,104	5,241,178
Annualized Operation & Maintenance Cost	231,990	231,990	476,406
Total Annual Cost	2,443,851	2,986,094	5,717,588

Project evaluation and formulation rate (discount rate) of 2.75% in accordance with EGM 20-01
Price level October 2019

Table 46: First Cost Small Plan

Account	Description	Subtotal	Contingency Percent	Contingency Cost	Total Cost
01	Total Lands and Damages	1,606,542	30%	481,963	2,088,505
06	Total Fish and Wildlife Facilities	1,984,198	17.47%	346,562	2,230,761
11	Total Levees and Floodwalls	7,840,942	27.39%	2,147,413	9,988,355
18	Total Cultural Resource Preservation	2,588,250	13.38%	346,359	2,934,609
19	Total Buildings, Grounds, and Utilities	17,532,740	36.63%	6,422,565	23,955,305
30	Planning, Engineering, and Design	7,888,168.03	25.28%	1,993,921	9,882,089
31	Construction Management	3,144,343.66	19.40%	610,158	3,754,502
Total Small Plan		42,585,184		12,348,940	54,934,124

Price level October 2019

Interest during construction for the small plan is based on a 64-month construction schedule at the 2020 fiscal year USACE project evaluation and formulation rate (discount rate) of 2.75% in accordance with EGM 20-01 (USACE, 2016). Likewise, interest during construction for the medium plan is based on a 52-month construction schedule and a 29-month construction schedule for the large plan. Pursuant to Planning Bulletin 2019-03, interest during construction for the nonstructural portion of the plan is based on the 1.5-month construction duration for the measures and structures.

The project first cost of the small plan is $54,934,124 and the total annual cost of the small plan is $2,443,851. The project first cost of the medium plan is $72,929,111 and the total annual cost of the medium plan is $2,986,094. The project first cost of the large plan is $133,595,785 and the total annual cost of the large plan is $5,717,588.

Table 47: First Cost Medium Plan

Account	Description	Subtotal	Contingency Percent	Contingency Cost	Total Cost
01	Total Lands and Damages	6,471,000	40.00%	2,589,000	9,060,000
06	Total Fish and Wildlife Facilities	2,157,000	35.00%	755,000	2,912,000
11	Total Levees and Floodwalls	17,178,000	35.00%	6,002,000	23,149,000
18	Total Cultural Resources Preservation	1,070,000	35.00%	375,000	1,445,000
19	Total Buildings, Grounds and Utilities	12,621,000	35.00%	4,417,000	17,038,000
30	Planning, Engineering and Design	8,592,000	35.00 %	3,007,000	11,600,000
31	Construction Management	3,609,000	35.00%	1,263,000	4,872,000
Total Medium Plan		53,041,000		18,888,000	71,929,000

Price level October 2019

Table 48: First Cost Large Plan

Account	Description	Subtotal	Contingency Percent	Contingency Cost	Total Cost
01	Total Lands and Damages	2,805,535	30.00%	841,600	3,647,195
06	Total Fish and Wildlife Facilities	3,500,306	17.47%	700,061	4,200,367
08	Total Roads, Railroads,and Bridges	1,501,524	38.15%	300,305	1,801,829
11	Total Levees and Floodwalls	16,118,811	27.39%	3,223,762	19,342,573
18	Total Cultural Resource Preservation	3,958,500	13.38%	791,700	4,750,200
19	Total Buildings, Grounds, and Utilities	54,322,415	36.63%	10,864,483	65,186,898
30	Planning, Engineering, and Design	20,551,772.63	25.28%	4,110,355	24,662,127
31	Construction Management	8,337,163	19.40%	1,667,433	10,004,596
Total Large Plan		111,096,027		22,499,759	133,595,785

Price level October 2019

9.2 Expected Annual Damages and Net Benefits

The expected annual damages and the probability distribution of the damages reduced are organized by relative sea level change scenario and plan in Table 49[33]. Without-project damages increase from $32,151,000 in the relative sea level change low scenario to $57,576,000 in the relative sea level change high scenario. Expected damages reduced (the difference in without- and with-project damages) are largest for the large plan levee/floodwall. The three right columns present the distribution of damages reduced in quartiles to ascertain the variability in the analysis. The large levee/floodwall consistently provides the highest level of expected flood risk reduction benefits. Please see Section 4 for a description of the method used for calculating with- and without-project damages.

Expected net benefits and the probability distribution of net benefits are organized in Table 50. Net benefits are calculated as the difference of expected annual costs from expected annual benefits. The plan with the highest expected annual net benefits can be identified as the national economic development plan. Observe that for the intermediate and high relative sea level change scenarios, the medium plan has the highest expected net benefits. Further, the medium plan has lower residual risk than the small plan in the relative sea level change low scenario and approximately the same

Table 49: Expected Annual Damage and Probability Distribution of Damages Reduced

		Expected Annual Damages		Damage Reduced	Damages Reduced with Specified Probability		
RSLC Scenario	Alternative	Without Alternative	With Alternative	Mean	0.75	0.5	0.25
Low	Small	32,151	27,482	4,669	3,973	4,708	5,403
	Medium	32,151	26,821	5,330	4,423	5,328	6,216
	Large	32,151	26,075	6,076	4,883	6,244	7,186
Intermediate	Small	46,480	40,326	6,154	5,420	6,204	6,803
	Medium	46,480	39,218	7,262	6,267	7,307	8,276
	Large	46,480	37,880	8,600	7,248	8,709	9,913
High	Small	57,576	50,335	7,241	6,490	7,293	8,017
	Medium	57,576	48,920	8,656	7,660	8,701	9,669
	Large	57,576	47,203	10,373	8,915	10,478	11,792

Project evaluation and formulation rate (discount rate) 2.75% in accordance with EGM 20-01

Price level October 2019, Values in Thousands

net benefits as the small plan in that scenario. Therefore the medium plan is the recommended plan and is expected to provide $4,276,000 in net national economic development benefits annually.

The probability distribution of net benefits is organized in the final three columns of Table 50. This probability distribution represents the variability of net benefits from low to high with costs held constant. Costs are held constant because the factors that result in the variability of damages reduced are not the same as the factors that result in the variability of costs. The small plan has the highest net benefits in the relative sea level change low scenario over the bottom half of the probability distribution. The large plan is not expected to have the highest benefits in the relative sea level change high scenario, but does pull ahead at the high end of the distribution of damages reduced.

Table 50: Expected Net Benefits and Probability Distribution of Net Benefits

		Expected Annual		Net Benefits	Net Benefits Exceeded with Specified Probability		
RSLC Scenario	Alternative	Benefits	Cost	Mean	0.75	0.5	0.25
Low	Small	4,669	2,383	2,286	1,590	2,325	3,020
	Medium	5,330	2,986	2,344	1,437	2,342	3,230
	Large	6,076	5,585	491	-702	659	1,601
Intermediate	Small	6,154	2,383	3,771	3,037	3,821	4,420
	Medium	7,262	2,986	4,276	3,281	4,321	5,290
	Large	8,600	5,585	3,015	1,663	3,124	4,328
High	Small	7,241	2,383	4,858	4,107	4,910	5,634
	Medium	8,656	2,986	5,670	4,674	5,715	6,683
	Large	10,373	5,585	4,788	3,330	4,893	6,207

Project evaluation and formulation rate (discount rate) 2.75% in accordance with EGM 20-01
Price level October 2019, Values in Thousands

The expected benefit-to-cost ratios (BCRs) and probability distribution of benefit-to-cost ratios for all plans and relative sea level change scenarios are organized in Table 51. The medium plan has a benefit-to-cost ratio of 2.4 in the intermediate scenario. As there is a 75% chance that the benefit-to-cost ratio is greater than 2.1 for the intermediate scenario, there is a much larger probability that the benefit-to-cost ratio is greater than 1.

Table 51: Expected Benefit-to-Cost Ratio (BCR) and Probability Distribution of BCR

			BCR Exceeded with Specified Probability		
RSLC Scenario	Alternative	Expected BCR	0.75	0.5	0.25
Low	Small	2	1.7	2	2.3
	Medium	1.7	1.4	1.7	2
	Large	1.1	0.9	1.1	1.3
Intermediate	Small	2.6	2.3	2.6	2.9
	Medium	2.4	2.1	2.4	2.7
	Large	1.5	1.3	1.6	1.8
High	Small	3	2.7	3.1	3.4
	Medium	2.8	2.5	2.8	3.2
	Large	1.9	1.6	1.9	2.1

Project evaluation and formulation rate (discount rate) of 2.75%
in accordance with EGM 20-01; Price level October 2019

9.3 Recommended Plan

The recommended plan is the medium plan, as demonstrated by the preceding economic analysis. The medium plan has a levee/floodwall in reach D-CW-2-R at an elevation of 14.2 feet NAVD88 and nonstructural actions proposed for 110 structures. The medium plan is expected to have the highest net benefits among all optimization alternatives of $4,276,000 and an expected benefit-to-cost ratio of 2.4. Pursuant to Engineering Regulation 1105-2-101, observe from Table 50 that it can be determined that the probability of economic justification of the recommended plan is far higher than 75%. A map of the recommended plan is contained in Figure 11.

The damage reduction benefits for the recommended plan are organized in Table 52. Observe that induced flooding is not an expected characteristic of the recommended plan. Residual risk ranges from 31% to 100%. There are 16 reaches that remain with 100% residual risk because no flood risk management measures are recommended in these reaches. The recommended levee/floodwall provides flood risk reduction to one reach and the nonstructural actions to 110 structures provide flood risk reduction in 9 other reaches.

The project performance of the recommended plan is presented in Table 53. The annual exceedance probability, long-term exceedance probability, and assurance by flood events are organized for the recommended plan by 10-year intervals. These statistics are provided for a representative plan reach, which is reach D-CW-2-R where the recommended levee/floodwall is located. The annual

Table 52: Recommended Plan Damage Reduction Benefits by Damage Reach

Stream	Damage Reach	Without-project Damages	With Medium Plan Damages	Damage Reduction Benefits	Residual Risk
Carteret & Woodbridge	A-CW-4-L	3,363	3,328	36	99%
	B-CW-4-R	566	566	-	100%
	C-CW-2-L	784	784	-	100%
	D-CW-2-R	7,046	2,207	4,840	31%
	U-CW-1B-L	1,426	788	638	55%
	U-CW-1B-R	25	25	-	100%
	U-CW-1-L	5,057	5,057	-	100%
	U-CW-1-R	3,082	2,753	329	89%
	U-CW-3-L	125	125	-	100%
	U-CW-3-R	3,898	3,898	-	100%
Millburn-Clark	A-MB-1-L	94	94	-	100%
	A-MB-1-R	914	789	126	86%
	A-MB-2-L	691	658	33	95%
	A-MB-2-R	71	71	-	100%
Rahway	A-RR-1-L	4,458	3,645	814	82%
	A-RR-2-L	854	744	110	87%
	CH-RR-3-L	1,463	1,463	-	100%
	CH-RR-3-R	55	55	-	100%
	E-RR-1-R	5,166	5,166	-	100%
	N-RR-2-R	877	877	-	100%
Robinson's Branch	A-RB-L	914	769	145	84%
	A-RB-R	609	454	155	75%
South Branch	B-SB-2-R	223	186	38	83%
	E-SB-1-L	827	827	-	100%
	U-SB-1-R	36	36	-	100%
	U-SB-2-L	2,690	2,690	-	100%
	U-SB-3-R	1,168	1,168	-	100%
Total		46,480	39,218	7,262	84%

Project evaluation and formulation rate (discount rate) 2.75% in accordance with EGM 20-01

Price Level October 2019, Values in Thousands

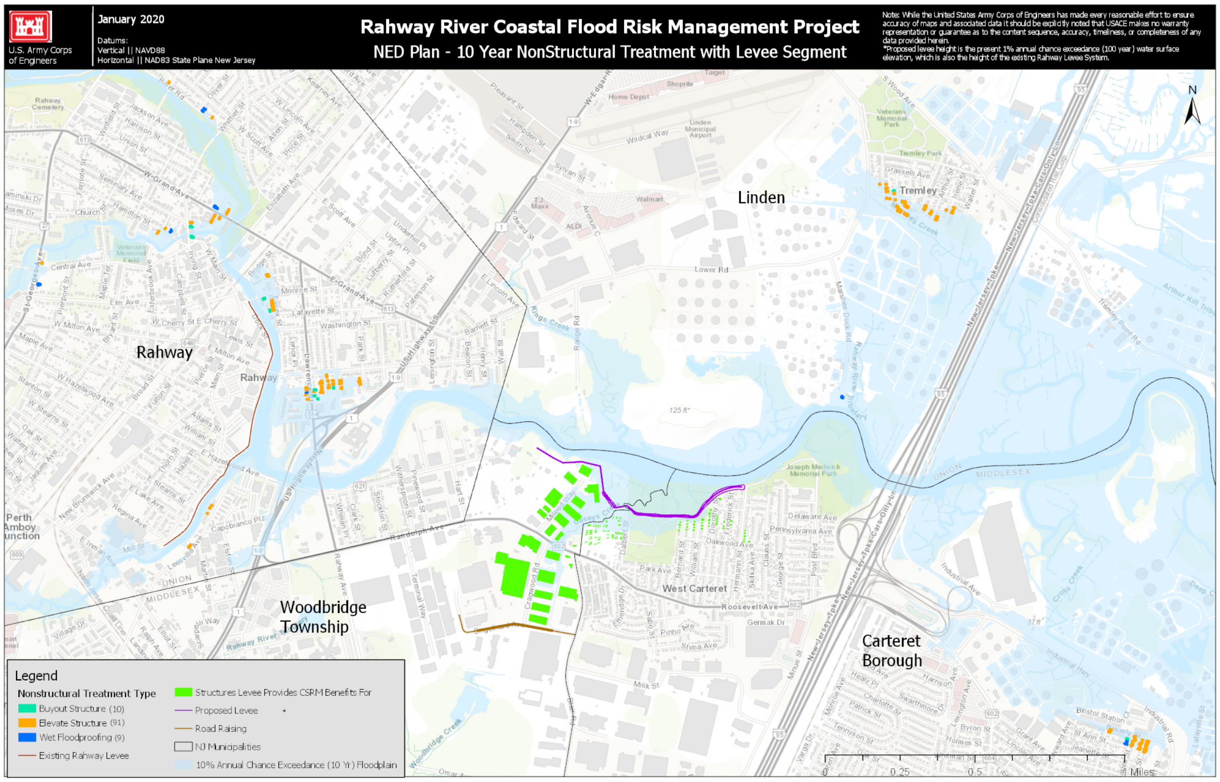


Figure 11: Recommended Plan

exceedance probability is the annual chance that the target stage will be exceeded. The target stage in the reach with a levee/floodwall is the elevation of the levee/floodwall. As such, the annual exceedance probability measures the chance that the water surface elevation will exceed the levee/floodwall elevation in any given year. In other words, this is the annual chance that the elevation of the river will exceed the levee/floodwall. This probability measures from just below 2% to just over 7%. The long-term exceedance probability measures the chance that the levee/floodwall elevation will be exceeded by the water elevation at least once in the stated period. At the beginning of the period of analysis, there is a nearly 13% chance that the levee/floodwall elevation will be exceeded by the river at least once in 10 years, and approximately a 50% chance of this happening at least once in 50 years. These probabilities increase to about 52% and 98%, respectively, by the end of the period of analysis. Finally, assurance is the probability of containing a specific exceedance probability event (e.g. 2% or 50-year flood) conditional on that event occurring. The recommended plan will pass the 2% event with 71% assurance at the beginning of the period of analysis and with 6% assurance at the end of the period of analysis.

Table 53: Recommended Plan Project Performance

Plan	Most Likely Future Year	AEP Median	AEP Expected	LTEP 10 Years	LTEP 30 Years	LTEP 50 years	Assurance by Event 10%	Assurance by Event 2%	Assurance by Event 1%	Assurance by Event 0.40%	Assurance by Event 0.20%
Medium Plan	2033	0.0134	0.0139	0.1307	0.3432	0.5037	0.9997	0.7116	0.3718	0.2285	0.1819
	2043	0.0167	0.0176	0.163	0.4137	0.5893	0.9997	0.5979	0.2775	0.1694	0.1344
	2053	0.0241	0.0264	0.2345	0.5514	0.7371	0.9997	0.431	0.1749	0.1084	0.0861
	2063	0.0452	0.0467	0.38	0.7617	0.9084	0.9877	0.1274	0.0802	0.0533	0.0433
	2073	0.0687	0.0715	0.5239	0.0891	0.9755	0.8682	0.0584	0.0004	0.0004	0.0004

AEP: Annual Exceedance Probability, LTEP: Long-term Exceedance Probability

9.3.1 Incremental Justification

Table 54: Recommended Plan Incremental Justification

Measure	Annual Benefits	Annual Costs	Net Benefits	BCR
Levee/Floodwall	4,840	1,794	3,046	2.7
Nonstructural	2,422	1,192	1,230	2.0
Total	7,262	2,986	4,276	2.4

Project evaluation and formulation rate (discount rate) 2.75% in accordance with EGM 20-01
Price Level October 2019, Values in Thousands

Pursuant to Engineering Regulation 1105-2-100, measures must be economically justified incrementally (USACE, 2000c). Table 54 contains the results of the incremental analysis according to the measures recommended. The levee/floodwall is expected to provide $2,415,000 in net national economic development benefits per year and has a benefit-to-cost ratio of 2.0. The nonstructural actions recommended are expected to provide $1,791,000 in net national economic development benefits per year and have a benefit-to-cost ratio of 3.8. Observe that both measures recommended are incrementally economically justified.

Incremental justification has also been evaluated with respect to the nonstructural plan by damage reach. Table 55 contains the results of the incremental analysis by damage reach. The first column of Table 55 contains the name of the damage reach, the next three columns contains the quantity of the specific nonstructural treatment, and the following columns display the benefit-cost analysis for that reach. Observe that 8 of the 10 reaches with nonstructural actions have positive net benefits and benefit-to-cost ratios above 1. There are two reaches with negative net benefits.

9.3.2 Critical Infrastructure

The critical infrastructure that resides behind the recommended levee/floodwall in reach D-CW-2-R would experience a reduction in coastal storm risk. There is substantial critical infrastructure behind the recommended levee/floodwall, as can be seen in Figures 4 and 5. The critical infrastructure that resides just south of the western half of Joseph Medwick Memorial Park is that which benefits from coastal storm risk reduction. A quantitative assessment of the reduction in coastal storm risk to this critical infrastructure has not been performed. It is important to observe the wealth of critical infrastructure that will experience the reduction in coastal storm risk. Randolph Avenue is hurricane evacuation route and resides behind the recommended levee/floodwall. Addi-

Table 55: Recommended Plan Incremental Justification

Reach	Floodproof	Elevations	Buyouts	Benefits	Costs	Net Benefits	BCR
A-CW-4-L	0	3	0	36	33	3	1.1
A-MB-1-R	1	3	0	126	43	82	2.9
A-MB-2-L	2	2	0	33	43	-10	0.8
A-RB-L	1	4	1	145	65	80	2.2
A-RB-R	1	1	1	155	33	122	4.8
A-RR-1-L	1	27	5	814	358	456	2.3
A-RR-2-L	0	2	1	110	33	77	3.4
B-SB-2-R	0	4	0	38	43	-6	0.9
U-CW-1B-L	1	27	1	638	314	324	2.0
U-CW-1-R	2	18	1	329	228	102	1.4
Total	9	91	10	2422	1192	1230	2.0

Project evaluation and formulation rate (discount rate) 2.75% in accordance with EGM 20-01
Price Level October 2019, Values in Thousands

tionally, there are oil and natural gas pipelines, a natural gas receipt/delivery facility, gas stations, and rail roads. There are no nonstructural measures recommended for critical infrastructure.

9.3.3 Nonstructural Participation Rate Sensitivity Analysis

A complete plan as stipulated in Planning Bulletin 2016-01 includes retaining the use of eminent domain, if necessary, for acquisition, relocation, and permanent evacuation of a floodplain (USACE, 2015a). However, all other nonstructural measures cannot be mandatory; therefore participation in floodproofing and elevation is voluntary. While the assumed rate of participation is 100%, the true participation rate is unknown. Participation rate uncertainty brings into question plan selection and the point at which benefits may no longer exceed costs for a potential project. Pursuant to Planning Bulletin 2019-03, sensitivity analysis of different nonstructural participation rates is required to communicate the inherent uncertainty of benefits exceeding the costs and plan selection (USACE, 2018).

Worst-case and best-case economic justification scenarios for 25%, 50% and 75% participation rates have been estimated using results from the HEC-FDA model. The worst-case scenario for the 25% participation rate reflects the participation of the 25% of structures that have the lowest average net national economic development benefits. The best-case scenario for the 25% participation rate reflects the participation of the 25% of structures that have the highest net national economic development benefits. Costs and benefits are estimated for each structure, and aggregated for the group of participating structures for sensitivity analysis.

Table 56 contains the results of the participation rate sensitivity analysis. Expected annual damage was approximated for each structure in the nonstructural plan for analysis year 2043. Expected annual damage was annualized using a multiplier representing a linear relationship between annual expected damage in 2043 and equivalent annual damage over the period of analysis. Average annual benefits are calculated as the difference in without- and with-project equivalent annual damage. Average cost of a nonstructural treatment is calculated as the average of the 019 account and the coincident 30 and 31 account charges from Table 47 over 110 structures, and this cost is annualized over the period of analysis with the appropriate interest during construction. Average annual net national economic development benefits are the difference of annual benefits and annual costs, and the benefit-to-cost ratio is the result of benefits divided by costs. In the worst case scenario with only the 25% of structures that have the lowest ranked net benefits, net benefits are -$111,000. In the best case scenario with only the 25% structures that have the highest ranked net benefits, net benefits are $823,000. Net benefits improve as the participation rate increases.

Table 56: Nonstructural Participation Rate Sensitivity Analysis

Participation Rate	Scenario	Annual Benefits	Annual Costs	Net Benefits	BCR
25%	Worst Case	160	271	-111	0.6
25%	Best Case	1094	271	823	4.0
50%	Worst Case	470	542	-72	0.9
50%	Best Case	1613	542	1071	3.0
75%	Worst Case	914	813	101	1.1
75%	Best Case	1965	813	1153	2.4

Project evaluation and formulation rate (discount rate) 2.75% in accordance with EGM 20-01
Price Level October 2019, Values in Thousands
Damages reduced calculated without risk

10 Optimization: Residual Risk and Project Performance

The estimated residual risk associated with each plan under each relative sea level change scenario is organized in Table 57. The residual risk of the medium plan is between 83% and 85%. The residual risk of the medium plan is lower than residual risk of the small plan which ranges between 85% and 87%.

Table 57: Optimization Plans Residual Risk

		Expected Annual Damage ($1000)		
RSLC Scenario	Alternative	Without Alternative	With Alternative	Residual Risk
Low	Small	32,151	27,482	85%
	Medium	32,151	26,821	83%
	Large	32,151	26,075	81%
Intermediate	Small	46,480	40,326	87%
	Medium	46,480	39,218	84%
	Large	46,480	37,880	81%
High	Small	57,576	50,335	87%
	Medium	57,576	48,920	85%
	Large	57,576	47,203	82%

Project evaluation and formulation rate (discount rate) of 2.75% in accordance with EGM 20-01
Price level October 2019, Values in Thousands

It is important to recognize that there exists residual risk that is not quantified. Among the factors contributing to residual risk that have not been quantified is the structure inventory boundary. The structure inventory boundary is defined by the .2% annual chance of exceedance floodplain at the relative sea level change low scenario. Moving from the relative sea level change low scenario to the relative sea level change intermediate and high scenarios, the projected inundation is higher meaning that the .2% annual chance of exceedance floodplain is larger. On average, the water levels in the relative sea level change high scenario are 1.2 feet higher than in the relative sea level change low scenario for the .2% annual chance of exceedance flood event in 2073. The difference in water levels between the two scenarios ranges from 0 feet up to 2.38 feet at cross section 16323.6. This could mean a meaningful expansion in the .2% annual chance of exceedance floodplain and larger residual risk.

Pursuant to Engineering Regulation 1105-2-101, transformed and transferred risk resulting from the project must be discussed. Elaborating on these risks, Engineering Regulation 1105-2-100 reads:

> “Transformed risk is a risk that emerges or increases as a result of mitigating another risk. A transferred risk relocates risk or increases risk from one region of the watershed to another region. The nature of the risk of flooding is different with a levee/floodwall versus without a levee/floodwall. A levee/floodwall reduces the likelihood that existing

> improved property will be flooded but can often encourage new development, which can lead to an overall increase in risk if not managed effectively through proper land use and building codes. A levee/floodwall may transform the flood risk from gradual and observable long before action is necessary to sudden and catastrophic."

The residual risk, including transformed and/or transferred, can also be characterized by the expected annual probability of the recommended measures being exceeded. These annual exceedance probabilities form part of the project performance statistics. The project performance by annual exceedance probability, long-term exceedance probability, and conditional non-exceedance is presented in Tables 58–63. This presentation is used to compare the project performance of the different size levee/floodwalls in each of the relative sea level change scenarios. To assist in the evaluation of the residual risk, the annual probability of fire damage and the annual probability of a significant earthquake in the New York, New Jersey, and Connecticut have been included in the annual exceedance probability tables.

Table 58: Annual Exceedance Probability RSLC Low

	AEP		LTEP	
Plan	Mean	10 Years	30 Years	50 years
Small	0.031	0.2701	0.6112	0.7929
Medium	0.015	0.1399	0.3636	0.5292
Large	0.0078	0.0751	0.2089	0.3233
Comparable Probability				
Fire Damage	.003†			
Earthquake	.023‡			

Performance for Reach D-CW-2-R, Location of TSP Levee for Optimization
† Average 2002–2010 based on home structure fires National Fire Protection Association and U.S. Census housing unit data. ‡Dombroski (2005)
AEP: Annual Exceedance Probability, LTEP: Long-term Exceedance Probability

Pursuant to Engineering Regulation 1105-2-101, assurance by a historic event must also be documented (USACE, 2017). Hurricane Sandy was approximately a 90-year event based on the NACCS stage frequency curve at Rahway River at Mouth Point ID 11659. In the relative sea level change low scenario, the recommended plan will pass a flood inundation event equivalent to Hurricane Sandy with assurance between 33.93% and 67.99%. In the relative sea level change intermediate scenario, the recommended plan will pass a flood inundation event equivalent to Hurricane Sandy with assurance between .04% and 71.16%. Finally, in the relative sea level change high scenario, the recommended plan will pass a flood inundation event equivalent to Hurricane Sandy

Table 59: Annual Exceedance Probability RSLC Intermediate

Plan	Most Likely Future Year	AEP Mean	LTEP 10 Years	LTEP 30 Years	LTEP 50 years
Small	2033	0.0264	0.235	0.5524	0.7381
	2043	0.0389	0.3273	0.6955	0.8622
	2053	0.0617	0.4709	0.8519	0.9586
	2063	0.0886	0.6047	0.9382	0.9903
	2073	0.1199	0.7213	0.9784	0.9983
Medium	2033	0.0139	0.1307	0.3432	0.5037
	2043	0.0176	0.163	0.4137	0.5893
	2053	0.0264	0.2345	0.5514	0.7371
	2063	0.0467	0.38	0.7617	0.9084
	2073	0.0715	0.5239	0.0891	0.9755
Large	2033	0.007	0.0675	0.189	0.2947
	2043	0.0084	0.0807	0.2231	0.3434
	2053	0.0107	0.1016	0.2749	0.4148
	2063	0.0155	0.1448	0.3746	0.5426
	2073	0.0317	0.2753	0.6194	0.8001
Comparable Probability					
Fire Damage		.003†			
Earthquake		.023‡			

Performance for Reach D-CW-2-R, Location of TSP Levee for Optimization

† Average 2002–2010 based on home structure fires National Fire Protection Association and U.S. Census housing unit data. ‡Dombroski (2005)

AEP: Annual Exceedance Probability, LTEP: Long-term Exceedance Probability

Table 60: Annual Exceedance Probability RSLC High

Plan	Most Likely Future Year	AEP Mean	LTEP 10 Years	LTEP 30 Years	LTEP 50 years
Small	2033	0.0412	0.3436	0.7171	0.8781
	2043	0.0434	0.3582	0.7357	0.8911
	2053	0.0899	0.6103	0.9408	0.991
	2063	0.1383	0.7742	0.9885	0.9994
	2073	0.1764	0.8494	0.9966	0.9999
Medium	2033	0.0146	0.137	0.3572	0.5212
	2043	0.0196	0.1797	0.4479	0.6285
	2053	0.0305	0.2665	0.6053	0.7876
	2063	0.0709	0.5209	0.89	0.9747
	2073	0.1263	0.7408	0.9826	0.9988
Large	2033	0.0073	0.0707	0.1975	0.3071
	2043	0.0094	0.0904	0.2475	0.3774
	2053	0.0133	0.1255	0.3312	0.4885
	2063	0.0213	0.194	0.4763	0.6598
	2073	0.0511	0.4083	0.7928	0.9275
Comparable Probability					
Fire Damage		.003†			
Earthquake		.023‡			

Performance for Reach D-CW-2-R, Location of TSP Levee for Optimization

† Average 2002–2010 based on home structure fires National Fire Protection Association and U.S. Census housing unit data. ‡Dombroski (2005)

AEP: Annual Exceedance Probability, LTEP: Long-term Exceedance Probability

with assurance between .18% and 68.55%.

Table 61: Assurance Relative Sea Level Change Low Scenario

	CNEP				
Plan	10%	2%	1%	0.40%	0.20%
Small	0.9997	0.3458	0.144	0.062	0.0427
Medium	0.9997	0.6799	0.3393	0.1866	0.1423
Large	0.9997	0.9238	0.6298	0.4416	0.3703

Performance for Reach D-CW-2-R, Location of TSP Levee for Optimization

Table 62: Assurance Relative Sea Level Change Intermediate Scenario

	Most Likely	CNEP				
Plan	Future Year	10%	2%	1%	0.40%	0.20%
Small	2033	0.9997	0.3979	0.1604	0.0798	0.0581
	2043	0.9958	0.2427	0.0993	0.0494	0.0352
	2053	0.9274	0.0498	0.0438	0.0227	0.0167
	2063	0.6632	0.0008	0.001	0.0008	0.0006
	2073	0.3176	0	0	0	0
Medium	2033	0.9997	0.7116	0.3718	0.2285	0.1819
	2043	0.9997	0.5979	0.2775	0.1694	0.1344
	2053	0.9997	0.431	0.1749	0.1084	0.0861
	2063	0.9877	0.1274	0.0802	0.0533	0.0433
	2073	0.8682	0.0584	0.0004	0.0004	0.0004
Large	2033	0.9997	0.9301	0.6672	0.5061	0.4399
	2043	0.9997	0.8925	0.5856	0.4394	0.3798
	2053	0.9997	0.8185	0.4727	0.353	0.3059
	2063	0.9997	0.6735	0.3233	0.2516	0.2212
	2073	0.9981	0.4004	0.1582	0.1412	0.1294

Performance for Reach D-CW-2-R, Location of TSP Levee for Optimization

Table 63: Assurance Relative Sea Level Change High Scenario

Plan	Most Likely Future Year	CNEP 10%	2%	1%	0.40%	0.20%
Small	2033	0.9855	0.2175	0.0707	0.0315	0.0198
	2043	0.9726	0.2069	0.0777	0.0358	0.0249
	2053	0.599	0.0474	0.0266	0.0131	0.0093
	2063	0.1022	0.0004	0.0011	0.0008	0.0005
	2073	0.0047	0	0	0	0
Medium	2033	0.9997	0.6855	0.3522	0.2124	0.1674
	2043	0.9997	0.5345	0.2369	0.1386	0.1073
	2053	0.9936	0.3295	0.122	0.0694	0.0531
	2063	0.7618	0.0878	0.0337	0.0199	0.0153
	2073	0.189	0.0022	0.0018	0.0014	0.001
Large	2033	0.9997	0.9191	0.6511	0.4876	0.4201
	2043	0.9997	0.8543	0.5432	0.3923	0.3342
	2053	0.9997	0.7225	0.3876	0.2726	0.229
	2063	0.9996	0.4889	0.2026	0.1463	0.1226
	2073	0.868	0.1746	0.0512	0.0422	0.0359

Performance for Reach D-CW-2-R, Location of TSP Levee for Optimization

11 LIFE SAFETY

The Rahway River Basin, New Jersey Coastal Storm Risk Management Feasibility Study recommended plan includes a levee/floodwall, and therefore must assess life safety and the qualification of the tolerable risk guidelines, according to Planning Bulletin 2019-04 (USACE, 2019c). Levee/floodwall risk which is sometimes considered as incremental risk is used to describe the additional risk imposed by non-performance of the levee/floodwall. The incremental risk may occur from one or more of 4 scenarios: 1) breach prior to overtopping, 2) overtopping with breach, 3) malfunction or improper operation of levee/floodwall system components, and 4) levee/floodwall overtopping without breach. This discussion is important because in the event of levee/floodwall non-performance, flood waters would inundate the community behind by the levee/floodwall which would pose a risk to life loss.

The scenario first considered in this analysis is the fourth scenario, levee/floodwall overtopping without breach. It has been assumed for exceedance probabilities and the concomitant water surface elevations beyond the 14.2-foot elevation of the recommended plan levee/floodwall that the water surface elevation inside the levee/floodwall immediately reaches the water surface elevation outside the levee/floodwall. This equilibrium of the interior and exterior water surface elevations represents the most extreme case of inundation of the community protected by the levee/floodwall. Such water surface elevations have been estimated to be the same with as without the levee/floodwall, indicating that the incremental risk in this scenario is null.

The residual risk attributed to the alternative scenarios, breach prior to overtopping, overtopping with breach, and malfunction or improper operation of levee/floodwall system components can be informed by the USACE Levee Portfolio Report (USACE, 2018). The Levee Safety Program has identified 5 different levels of risk for different levee conditions; very low, low, moderate, high, and very high. The level of risk is determined by, among other things, the size of the population experiencing flood risk reduction from the levee/floodwall, the levee/floodwall height, and the expected flood loading hazard. Low-risk levees typically reduce the risk of flooding to rural areas and are generally shorter in height. Low risk levees generally overtop more frequently than higher risk levees. Moderate-risk levees have over 1,000 people in the adjacent area receiving flood risk reduction and these levees have similar levee heights and flood loading hazards to that of very-high- and high-risk levees. The area behind the recommended plan levee/floodwall has 196 structures, and the recommended plan levee/floodwall has an average height of 10.2 feet at a 14.2-foot elevation NAVD88. The recommended plan levee/floodwall can therefore be assigned low to moderate risk.

Among all USACE moderate-risk levees, less than one-half were found to have performance failure modes that would likely result in a breach prior to overtopping. Embankment and foundation seepage and piping was found to be the most common likely failure mode of moderate-risk levees at 30% (USACE, 2018). Embankment erosion and closure system malfunction or improper operation are two major risk drivers that were found among 20% of moderate risk levees. The recommended plan levee/floodwall will be constructed pursuant to Engineering Manual 1110-2-1913 and other up-to-date engineering best practice, which reduces the probability of these risk drivers occurring (USACE, 2000b). The incremental risk attributed to scenarios 1–3 nonetheless is determined to be low to moderate.

Part of a qualitative life safety assessment includes statistical information on the hazard conditions in the study area. Such conditions are developed for the future without-project condition. The percentage of the population in the study area of 65 years or older is considered an important statistic in considering the population at risk. Demographic information is obtained from the U.S. Census Bureau's 2018 American Community Survey 5-year Estimates. Table 64 contains the total population, quantity of population 65 and older, and percent of population 65 and older for

Middlesex and Union counties. Observe that the average percent of the population that is 65 years or older is 14% throughout the study area.

Table 64: Population Older than 65 in Study Area

County	Total Population	Population Older than 65	Percent of Population Older than 65
Middlesex	553,066	76,895	14%
Union	826,698	117,814	14%
Total	1,379,764	194,709	14%

Source: U.S. Census Bureau ACS 2018 5-year Estimate

Other hazard conditions include the maximum inundation levels predicted in each of the study area damage reaches and the inundation levels at the critical infrastructure throughout the study area. The maximum inundation levels in terms of the maximum depth and stage for the 1% and .2% annual chance of exceedance events for each of the study area damage reaches have been organized in Table 65. Observe that the maximum inundation levels in terms of flood depth in the study area occur in reach A-CW-4-L at 13.48 feet NAVD88 for the 1% annual chance of exceedance event and 13.54 feet NAVD88 for the 2% annual chance of exceedance event.

There is substantial critical infrastructure throughout the study area. A sample of the critical infrastructure that experiences significant inundation is given in Table 66. There are many sewage and water treament plants, power plants, pump stations and substations, and power plants. The depth of the 1% annual chance of exceedance event ranges from 4.05 feet NAVD88 to 11.96 feet NAVD88.

Pursuant to Planning Bulletin 2019-04, the information gathered in the life safety assessment must be applied to the Tolerable Risk Guidelines framework (USACE, 2019c). Specifically, Tolerable Risk Guidelines 1 and 4 must be assessed. Tolerable Risk Guideline 1 requires an understanding of the risk. It must be considered whether society is willing to trade off with the risk associated with the levee/floodwall system to secure the benefits of living and working in the levee/floodwalled area. Tolerable Risk Guideline 1 requires assessing whether the risks are commensurate with the benefits. An evaluation of life safety risk, societal life risk, individual life risk, economic risk, and environmental risk should all play into the determination as to whether the risks are commensurate with the benefits of the levee/floodwall.

The assessment of the life safety risk, societal life risk, individual life risk, and economic risk are informed by the Life Risk Matrix (Figure 1) from PB 2019-04, reprinted here as Figure 12 (USACE, 2019c). Observe that life safety risks generally meet Tolerable Risk Guideline 1 when the

Table 65: Maximum Inundation Levels for Study Area Reaches

Stream	Reach	Depth 0.01	Stage 0.01	Depth 0.002	Stage 0.002
Carteret & Woodbridge	A-CW-4-L	13.48	18.15	13.54	18.21
	B-CW-4-R	7.45	18.15	7.52	18.21
	C-CW-2-L	8.47	17.90	8.62	18.04
	D-CW-2-R	10.97	17.75	11.19	17.93
	U-CW-1B-L	12.93	17.78	13.24	17.96
	U-CW-1B-R	4.14	17.51	4.40	17.77
	U-CW-1-L	9.86	17.28	10.33	17.61
	U-CW-1-R	10.14	17.24	10.64	17.58
	U-CW-3-L	11.57	17.97	11.68	18.08
	U-CW-3-R	11.96	18.12	12.11	18.19
Millburn-Clark	A-MB-1-L	5.96	18.59	6.25	19.21
	A-MB-1-R	10.48	18.59	10.68	19.21
	A-MB-2-L	8.64	21.38	10.23	25.25
	A-MB-2-R	5.60	21.39	7.19	25.26
Rahway	A-RB-L	10.33	20.77	10.58	21.58
	A-RB-R	9.50	20.77	9.74	21.58
	A-RR-1-L	11.97	18.20	12.05	18.35
	A-RR-2-L	11.09	18.21	11.24	18.38
	CH-RR-3-L	8.76	18.23	8.95	18.42
	CH-RR-3-R	4.57	18.23	4.75	18.43
	E-RR-1-R	11.12	18.20	11.26	18.35
	N-RR-2-R	4.75	18.21	4.90	18.37
South Branch	B-SB-2-R	8.04	17.32	9.10	18.31
	E-SB-1-L	11.51	17.32	12.57	18.31
	U-SB-1-R	6.18	17.16	7.33	18.31
	U-SB-2-L	8.68	17.75	9.61	18.30
	U-SB-3-R	8.12	18.14	8.98	18.30
Study Area		13.48	21.39	13.54	25.26

Without-project Condition, RSLC Intermediate, Analysis Year 2073

Table 66: Depth and Elevation of Flooding at Critical Infrastructure in Structure Inventory

Structure	Reach	Depth at .01	Stage at .01	Depth at .002	Stage at .002
Sewage Treatment	U-CW-3-R	11.96	17.86	12.11	18.01
Pump Station	E-RR-1-R	11.12	18.19	11.26	18.33
Sewage Treatment	U-CW-1-L	8.16	17.09	8.55	17.48
Substation	A-RR-2-L	5.66	18.21	5.82	18.37
Water Treatment	A-MB-2-L	4.74	21.38	8.61	25.25
Power Plant	A-CW-4-L	4.05	18.05	4.14	18.14

Without-project Condition, RSLC Intermediate, Analysis Year 2073 annual exceedance probability of life loss with respect to individual life and societal life are both below $1.E-04$. Typically a determination of the project's location on the life risk matrix would require separate quantitative modeling to identify the respective annual exceedance probabilities.

The effect of incremental risk of the proposed levee/floodwall on the annual exceedance probability of life loss can however be assessed without quantitative modeling. Recall that water levels are not predicted to be higher in the floodplain in the event of overtopping than they would have been without the levee/floodwall. This means that the effect of incremental risk with respect to levee/floodwall overtopping on the annual exceedance probability of life loss is null and that the proposed levee/floodwall generally meets Tolerable Risk Guideline 1. There are other modes of levee/floodwall failure that effect incremental risk and the project's ability to meet Tolerable Risk Guideline 1, such as levee/floodwall breach. However, this levee/floodwall will be built according to the latest USACE guidelines and regulations, minimizing this risk. As such, the perceivable effect of the incremental risk of the levee/floodwall on the annual exceedance probability of life loss suggests that the project meets Tolerable Risk Guideline 1.

Tolerable Risk Guideline 4 must also be assessed. Tolerable Risk Guideline 4 requires determination of cost-effective, socially acceptable, or environmentally acceptable ways to reduce risk from an individual or societal risk perspective. It should be considered whether appropriate actions have been taken to reduce risks, could any actions reasonably be taken that would reduce risks further, what would be the cost of reducing risk and how much would the risk be reduced, if the actions should be detailed in further study, and if there is demonstrated progress toward implementing risk reduction measures. An appropriate action that has been taken to reduce risks includes the adaptability in the design to sea level rise. As the levee/floodwall is expected to overtop frequently late in the period of analysis, it can be expected that this scenario of levee/floodwall non-performance would by exacerbated if the rate of sea level change accelerates. Designing the levee/floodwall to be adaptable allows for a more nimble response to changing sea levels. Other actions could be taken. For example, educational materials communicating the incremental risk could be prepared for the population behind the levee/floodwall. Minimizing transformed and transferred risk might also be considered by the local authorities once the levee/floodwall is constructed. Consideration could be put into whether it is useful to continue developing the area behind the levee/floodwall. These recommendations for other actions to reduce risks further are recommendations that are made to the local authorities for their consideration.

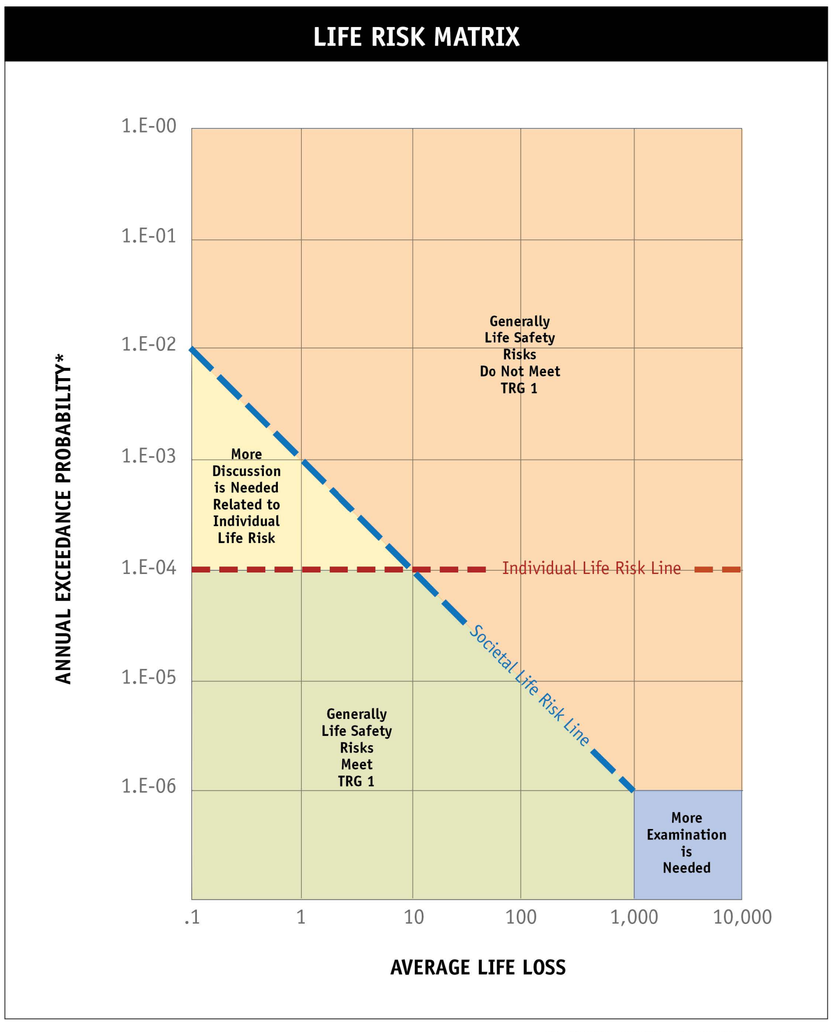


Figure 12: Life Risk Matrix

NOTES

[1]The refining of the levee to be part floodwall resulted from real estate constraints.

[2]HEC-FDA models were prepared for existing without-project conditions and for each alternative plan in the relative sea level change low scenario in the identification of the tentatively selected plan.

[3]Estimates of with- and without-project damages in the identification of the tentatively selected plan were based on October 2016 price levels and fiscal year 2017 project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01 and a 50-year period of analysis (USACE, 2016).

[4]10 additional properties are buyouts, which are counted under acquisition fees.

[5]The structure inventory used in the economic analysis leading to identification of the tentatively selected plan contained 2 Blue Acres-participating structures. These structures were removed from the structure inventory during optimization.

[6]Source: `https://www.nj.com/news/2012/10/hurricane_sandy_wreaks_continu.html`

[7]Source: `https://nj1015.com/nj-traffic-road-closures-flooding-and-more-in-sandys-aftermath/`

[8]This data was generated when the period of analysis was 2023 to 2073. The period of analysis has been changed to 2029 to 2079. A risk-informed assumption has been made that the data collected and analysis performed for the 2023 to 2073 period of analysis sufficiently approximates the 2029 to 2079 period of analysis.

[9]The methods described here also apply to analysis that took place in the identification of the tentatively selected plan, that was described in the 2017 draft report, and that can be found in Sections 7 and 8 of the current Economic Appendix. Please observe that in the identification of the tentatively selected plan, the analysis years were 2021 and 2071, and that the assumed rate of sea level change was the low scenario.

[10]Interior/exterior relationships and geotechnical failure are typically used for levees where there is considerable risk of levee failure in terms of overtopping or breach. This risk is not present for this levee as this levee would be built according to the U.S. Army Corps of Engineers guidelines and regulations. It is important to note that when no interior/exterior relationship is defined, the moment that the water surface elevation reaches the height of the levee, the water level in the floodplain is simulated to be simultaneously equal to the water level of the river. This worst-case scenario for levee overtopping is not what is expected for this levee nor what has been observed for levees in the area. Typically the levee continues to provide flood risk reduction even when the water level elevation is above the levee elevation. Analytically this results in benefits that are not quantified with respect to the proposed levee and damages overstated with respect to the existing levees.

[11]Ringwalls were considered in the identification of the tentatively selected plan. A ringwall is a structure (and in some cases, groups of closely adjacent structures) is encircled by a small floodwall constructed to the design protection elevation. According to Planning Bulletin 2016-01, barriers (ring floodwalls/ring berms) are no longer considered

nonstructural measures (USACE, 2015a). Ringwalls were at the time of the identification of the tentatively selected plan considered part of non-structural plan. Note that ringwalls no longer fall into the nonstructural category and that ringwalls are not part of the recommended plan.

[12]The height of a levee elevation is used for small ringwalls. Ringwalls were considered part of the non-structural in the identification of the tentatively selected plan, but no longer fall into that category. Ringwalls are not part of the recommended plan.

[13]Please observe that without-project flood damages were calculated for the without-project base year of 2023 and the future condition of 2073 using the coinciding water surface profiles. During the process of optimization, the period of analysis was updated to 2029 through 2079. A risk-informed decision was made to assume that the hydraulic and hydrologic data estimated and the economic analysis performed for the period of analysis of 2023 to 2073 sufficiently approximate the period of analysis of 2029 to 2079. Please also observe that in the identification of the tentatively selected plan, without-project flood damages were modeled in HEC-FDA for the years 2021 and 2071. The formulation took place in the draft report in FY2017 and was used for tentatively selected plan selection and subsequent analysis for optimization resulted in the recommended plan. The assumed rate of sea level rise for that stage of the analysis was the USACE relative sea level change low scenario. This means that it was assumed that sea levels will continue to increase into the future at the constant rate as observed over the historical record.

[14]The structure inventory not adjusting to reflect the 500-year floodplain in the relative sea level change intermediate and high scenarios results in additional additional damages and residual risk that is not quantified. It also means that there are benefits left on the table because in the relative sea level change intermediate and high scenarios, there are potentially more structures that benefit from flood risk management through Levee Segment D. In this way, the results presented in Section 9 for the relative sea level change intermediate and high scenarios are conservative estimates.

[15]There are instances where hardening is taking place in the future without-project condition. This hardening was included for the evaluation of the alternatives as it relates to the future with- and without-project conditions. In the process of updating the model structure for engineering regulatory compliance and as suggested and verified by agency technical review, we have abstracted from the quantification of the damage to the tanks in the future with- and without-project conditions. This abstraction in the optimization phase has no effect on plan selection.

[16]The depreciated replacement value was updated from October 2016 price level to October 2019 price level using the Civil Works Construction Cost Index System, Engineering Manual 1110-2-1304 (USACE, 2019a).

[17]Following Equation 1: $\$20,490 \times 1.7 \times 0.119 = \$4,145$

[18]The 1,200 square foot represents the 1,000 square feet for the assumed average apartment size plus an additional 200 square feet to account for hallways and other common areas.

[19]The primary source of depth-damage functions for the identification of the tentatively selected plan was the generic depth-damage functions for residential structures. The identification of the tentatively selected plan also used Passaic River Basin depth-damage functions.

[20]Damage functions for single-family residential structures without basements and two- or multi-family struc-

tures with similar physical characteristics were applied in accordance with Economic Guidance Memorandum 01-03, Generic Depth-Damage Relationships (USACE, 2000a). Damage functions for single-family residential structures with basements and two- or multi-family structures with similar physical characteristics were applied in accordance with Economic Guidance Memorandum 04-01, Generic Depth-Damage Relationships for Residential Structures with Basements (USACE, 2003). The primary source for depth-damage functions for non-residential structures were those developed by the U.S. Army Corps of Engineers for the Passaic River Basin as part of the Flood Protection Feasibility Study Main Stem Passaic River. The development of the damage functions is described in the Phase I - General Design Memorandum of the Passaic River Basin Flood Protection Feasibility Study (USACE, 1987). Passaic River Basin damage functions for non-residential structures, apartment buildings, and large multi-family structures were applied in accordance with previous experience with similar flood risk reduction projects in northern New Jersey. Direct depth-damage functions were used for petroleum facilities.

[21] In the identification of the tentatively selected plan, the content damage as a percent of structure value for increasing depths of flooding for structures using the generic depth-damage functions was entered following the concomitant content depth-damage functions presented in USACE (2003, 2000a). The content-to-structure value ratio for each occupancy type was entered as 100 percent so that the content depth-damage function is multiplied by the structure value as required. Passaic River Basin content depth-damage functions were implemented in HEC-FDA similarly. In addition to damage to structures and associated contents, the Passaic River Basin damage functions for non-residential structures incorporate a third (“other”) component for damage to features external to the main structure such as storage tanks for oil, storage yards, plant machinery, vehicles, and landscaping. Other damages are also evaluated by entering an other-to-structure value ratio of 100 in HEC-FDA so that the other depth-damage function was multiplied by the structure value.

[22] Estimates of annual flood damage were computed for the tentatively selected plan using version 1.4 of HEC-FDA.

[23] Variability in structure first floor elevations for non-residential and larger residential and apartment structures that were assigned Passaic River Basin damage functions in the identification of the tentatively selected plan is described as having a normal distribution and a standard deviation of error of 1 foot. These statistics are based on a comparison of first floor estimates made with GIS and the additional foundation heights for surveyed elevations obtained from samples of structures in previous studies. Survey and analysis was executed, collecting first floor elevations and randomly sampling from inventoried structures. The outcome of a statistical analysis conducted to estimate the variability associated with the estimation of the first floor elevation resulted in a standard deviation of 1 foot. Examples of previous studies with which the 1 foot standard deviation was concluded to be appropriate include the Carencro Flood Risk Reduction Feasibility Study and the Western Lake Erie Basin Blanchard River Watershed Study (USACE, 2011, 2015c). This information does not apply to the current optimization analysis

[24] In the identification of the tentatively selected plan, for the content-to-structure and other-to-structure value ratios were subjected to variability by assuming normal distributions with a coefficient of variation of 25% and 10% respectively. These parameters and other-to-structure value ratios were not used in optimization.

[25] Variability was quantified for the depth-damage functions in the identification of the tentatively selected plan using the standard deviation of damage presented in USACE (2003, 2000a).

[26]Please observe that average annual flood inundation damages were calculated for the without-project base year of 2023 and the future condition of 2073 using the coinciding water surface profiles. During the process of optimization, the period of analysis was updated to 2029 through 2079. A risk-informed decision was made to assume that the hydraulic and hydrologic data estimated and the economic analysis performed for the period of analysis of 2023 to 2073 sufficiently approximate the period of analysis of 2029 to 2079. Please also observe that in the identification of the tentatively selected plan, average annual damages were calculated for the without-project base year (2021) and the future condition (2071).This formulation took place in the draft report in FY2017 and was used for tentatively selected plan selection and subsequent analysis for optimization resulted in the recommended plan. Please see sections 8-11 for the analysis for optimization. Equivalent annual damages were calculated for the 50-year period of analysis using the 2017 fiscal year USACE project evaluation and formulation rate (discount rate) of 2.875% in accordance with EGM 17-01 (USACE, 2016). The economic analysis in the identification of the tentatively selected plan was evaluated and in presented using October 2016 price levels.

[27]During optimization, damage to the petroleum facilities was excluded from the estimates of the future with- or without-project condition damages. An engineering regulatory-compliant method for estimating the damage to petroleum facilities does not exist. Abstracting from the damage estimates to the petroleum facilities was suggested and verified by Agency Technical Review. The exclusion of the petroleum facilities from the with- and without-project condition damage estimates does not affect plan selection as it relates to optimization.

[28]According to Planning Bulletin 2016-01, barriers (ring floodwalls/ring berms) are no longer considered nonstructural measures (USACE, 2015a). Ringwalls were at the time of the identification of the tentatively selected plan considered part of non-structural plan. Note that ringwalls no longer fall into the nonstructural category and that ringwalls are not part of the recommended plan.

[29]The length of damage reach D-CW-2-R where the selected levee/floodwall is located was designed for the small 12.6-foot elevation levee/floodwall. As can be expected, the medium and large levee/floodwalls are longer than the small levee/floodwall and extend beyond the damage reach thereby providing flood risk management benefits to additional structures. However, the damages reaches were not re-defined for each levee/floodwall size which means that benefits are potentially left on the table. In this way, the results presented in Section 9 are conservative.

[30]Please observe that this data is being used to approximate the data that would have been estimated for the period of analysis of 2029 to 2079

[31]The referenced equation from Engineering Regulation 1100-2-8162 is Equation 3 (USACE, 2013)

[32]A risk-informed decision was made to assume that the analysis that was completed for a period of analysis of 2023 to 2073 sufficiently approximates the analysis for a period of analysis of 2029 to 2079. This assumption is founded on the only time-dependent input to the location of the period of analysis for the purpose of the economics: water surface elevations. Conditional on the intermediate and high relative sea level scenarios, the water surface elevations for the various flood events are slightly higher, the farther into the future that the period of analysis takes place. However, it is expected that the water surface elevations that were calculated for 2023 to 2073 approximate the water surface elevations for 2029 to 2079 within an acceptable margin of error. This acceptable margin of error may result in some benefits being left on the table because slightly higher water levels and the coinciding reductions

in flood risk are not being captured. Additionally, there would be nonstructural treatments being completed at the structure level throughout the duration of construction which means that pre-base year benefits would be realized and not captured. The margin of error also means slightly higher residual risk than quantified for the reaches that do not have any proposed coastal storm risk management measures.

[33]Damages to petroleum facilities do not form part of the recommended plan optimization. This does not affect plan selection in any way.

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12 ATTACHMENTS

12.1 RELATIVE SEA LEVEL CHANGE PYTHON SCRIPT

The following Python script was developed for interpolating water surface elevations between 2023 and 2073 for the years 2033, 2043, 2053, and 2063.

```
    # -*- coding: utf-8 -*-
"""
```

```
Calculation of Water Surface Elevations at 10-year Intervals
relative sea level change Low, Intermediate, and High Scenarios

This code uses water surface profiles at the end points of a period of analysis
and the functional form described in ER 1100-2-8162 to interpolate the water
surface profiles at 10-year intervals.

Beginning Year = 2023
End year = 2073
Data interpolated for 2033, 2043, 2053, and 2063

Created on Wed Oct  9 11:19:23 2019

@author: Richard J Nugent III, PhD
"""

import xlrd
import numpy as np
import pandas as pd
from matplotlib import pyplot

## Data ---------------------------------------------------------------
loc2043 = ('C://Users/username/Studies/Rahway/Engineering/H&H/charts_joint_probability_2043.xlsx')
loc2073 = ('C://Users/username/Studies/Rahway/Engineering/H&H/charts_joint_probability_2073.xlsx')


data_2043_16323 = pd.read_excel(loc2043, sheet_name = 'XS 16323.6', header = 1,
    usecols=4, index_col = 0, skiprows = 0, nrows = 9)
data_2073_16323 = pd.read_excel(loc2073, sheet_name = 'XS 16323.6', header = 1,
    usecols=4, index_col = 0, skiprows = 0, nrows = 9)
data_2043_4274 = pd.read_excel(loc2043, sheet_name = 'XS 4274.044', header = 1,
    usecols=4, index_col = 0, skiprows = 0, nrows = 9)
data_2073_4274 = pd.read_excel(loc2073, sheet_name = 'XS 4274.044', header = 1,
    usecols=4, index_col = 0, skiprows = 0, nrows = 9)
data_2043_25887 = pd.read_excel(loc2043, sheet_name = 'XS 25887.58', header = 1,
    usecols=4, index_col = 0, skiprows = 0, nrows = 9)
data_2073_25887= pd.read_excel(loc2073, sheet_name = 'XS 25887.58', header = 1,
    usecols=4, index_col = 0, skiprows = 0, nrows = 9)
data_2043_28188 = pd.read_excel(loc2043, sheet_name = 'XS 28188.9', header = 1,
    usecols=4, index_col = 0, skiprows = 0, nrows = 9)
data_2073_28188 = pd.read_excel(loc2073, sheet_name = 'XS 28188.9', header = 1,
    usecols=4, index_col = 0, skiprows = 0, nrows = 9)
data_2043_34903 = pd.read_excel(loc2043, sheet_name = 'XS 34903.35', header = 1,
    usecols=4, index_col = 0, skiprows = 0, nrows = 9)
data_2073_34903 = pd.read_excel(loc2073, sheet_name = 'XS 34903.35', header = 1,
    usecols=4, index_col = 0, skiprows = 0, nrows = 9)
data_2043_8751 = pd.read_excel(loc2043, sheet_name = 'XS 8751.545', header = 1,
    usecols=4, index_col = 0, skiprows = 0, nrows = 9)
data_2073_8751 = pd.read_excel(loc2073, sheet_name = 'XS 8751.545', header = 1,
    usecols=4, index_col = 0, skiprows = 0, nrows = 9)
data_2043_7871 = pd.read_excel(loc2043, sheet_name = 'XS 7871.026', header = 1,
```

```
    usecols=4, index_col = 0, skiprows = 0, nrows = 9)
data_2073_7871 = pd.read_excel(loc2073, sheet_name = 'XS 7871.026', header = 1,
    usecols=4, index_col = 0, skiprows = 0, nrows = 9)

xs_4274 = pd.merge(data_2043_4274, data_2073_4274, how = 'outer', left_index=True,
    right_index=True, sort=True)
xs_7871 = pd.merge(data_2043_7871, data_2073_7871, how = 'outer', left_index=True,
    right_index=True, sort=True)
xs_8751 = pd.merge(data_2043_8751, data_2073_8751, how = 'outer', left_index=True,
    right_index=True, sort=True)
xs_16323 = pd.merge(data_2043_16323, data_2073_16323, how = 'outer', left_index=True,
    right_index=True, sort=True)
xs_25887 = pd.merge(data_2043_25887, data_2073_25887, how = 'outer', left_index=True,
    right_index=True, sort=True)
xs_28188 = pd.merge(data_2043_28188, data_2073_28188, how = 'outer', left_index=True,
    right_index=True, sort=True)
xs_34903 =pd.merge(data_2043_34903, data_2073_34903, how = 'outer', left_index=True,
    right_index=True, sort=True)


## Parameters ------------------------------------------------------
x2023 = 2023-1992
x2033 = 2033-1992
x2043 = 2043-1992
x2053 = 2053-1992
x2063 = 2063-1992
x2073 = 2073-1992

x2023sq = x2023**2
x2033sq = x2033**2
x2043sq = x2043**2
x2053sq = x2053**2
x2063sq = x2063**2
x2073sq = x2073**2


# Calculation over the 7 cross sections -------------------------------------------


for df in (xs_4274, xs_7871, xs_8751, xs_16323, xs_25887, xs_28188, xs_34903):
    df['delta_y_low'] = df.iloc[:,5] - df.iloc[:,0]
    df['a_low'] = (df['delta_y_low'])/(x2073-x2023)

    df['delta_y_int'] = df.iloc[:,6] - df.iloc[:,0]
    df['b_int'] = (df['delta_y_int'])/(x2073sq-x2023sq)-
         df['a_low']*(x2073-x2023)/(x2073sq-x2023sq)

    df['delta_y_high'] = df.iloc[:,7] - df.iloc[:,0]
    df['b_high'] = (df['delta_y_high'])/(x2073sq-x2023sq)-
        df['a_low']*(x2073-x2023)/(x2073sq-x2023sq)
```

```
    df['y2033_low'] = df.iloc[:,0]+df['a_low']*(x2033-x2023)
    df['y2043_low'] = df['y2033_low']+df['a_low']*(x2043-x2033)
    df['y2053_low'] = df['y2043_low']+df['a_low']*(x2053-x2043)
    df['y2063_low'] = df['y2053_low']+df['a_low']*(x2063-x2053)

    df['y2033_int'] = df.iloc[:,0]+df['a_low']*(x2033-x2023)+df['b_int']*(x2033sq-x2023sq)
    df['y2043_int'] = df['y2033_int']+df['a_low']*(x2043-x2033)+df['b_int']*(x2043sq-x2033sq)
    df['y2053_int'] = df['y2043_int']+df['a_low']*(x2053-x2043)+df['b_int']*(x2053sq-x2043sq)
    df['y2063_int'] = df['y2053_int']+df['a_low']*(x2063-x2053)+df['b_int']*(x2063sq-x2053sq)

    df['y2033_high'] = df.iloc[:,0]+df['a_low']*(x2033-x2023)+df['b_high']*(x2033sq-x2023sq)
    df['y2043_high'] = df['y2033_high']+df['a_low']*(x2043-x2033)+df['b_high']*(x2043sq-x2033sq)
    df['y2053_high'] = df['y2043_high']+df['a_low']*(x2053-x2043)+df['b_high']*(x2053sq-x2043sq)
    df['y2063_high'] = df['y2053_high']+df['a_low']*(x2063-x2053)+df['b_high']*(x2063sq-x2053sq)

# Save Data ------------------------------------------------------------------------------

rahway_wse = pd.ExcelWriter('C://Users/username/Studies/Rahway/Engineering/H&H/
    rahway_wse_10yr_intervals.xlsx')
xs_4274.to_excel(rahway_wse, sheet_name = 'xs_4274')
xs_7871.to_excel(rahway_wse, sheet_name = 'xs_7871')
xs_8751.to_excel(rahway_wse, sheet_name = 'xs_8751')
xs_16323.to_excel(rahway_wse, sheet_name = 'xs_16323')
xs_25887.to_excel(rahway_wse, sheet_name = 'xs_25887')
xs_28188.to_excel(rahway_wse, sheet_name = 'xs_28188')
xs_34903.to_excel(rahway_wse, sheet_name = 'xs_34903')
rahway_wse.save()

# Export XS 16323 Intermediate to LaTeX

xs_16323['y2023'] = xs_16323.iloc[:,0]
xs_16323['y2073_int'] = xs_16323.iloc[:,6]
xs_16323_int = xs_16323[['y2023', 'y2033_int', 'y2043_int', 'y2053_int',
    'y2063_int', 'y2073_int']]
xs_16323_int = xs_16323_int.transpose()
xs_16323_int.to_latex()

xs_16323_int['year500'] = xs_16323_int.iloc[:,0]
xs_16323_int['year200'] = xs_16323_int.iloc[:,1]
xs_16323_int['year100'] = xs_16323_int.iloc[:,2]
xs_16323_int['year50'] = xs_16323_int.iloc[:,3]
xs_16323_int['year25'] = xs_16323_int.iloc[:,4]
xs_16323_int['year10'] = xs_16323_int.iloc[:,5]
xs_16323_int['year5'] = xs_16323_int.iloc[:,6]
xs_16323_int['year2'] = xs_16323_int.iloc[:,7]
xs_16323_int['year1'] = xs_16323_int.iloc[:,8]

idx = pd.Index([2023, 2033, 2043, 2053, 2063, 2073])
xs_16323_int = xs_16323_int.set_index([idx])
```

```
pyplot.figure(dpi=800)
pyplot.plot(xs_16323_int['year500'], label = '500 Year', color = 'red')
pyplot.plot(xs_16323_int['year200'], label = '200 Year', color = 'pink')
pyplot.plot(xs_16323_int['year100'], label = '100 Year', color = 'orange')
pyplot.plot(xs_16323_int['year50'], label = '50 Year', color = 'yellow')
pyplot.plot(xs_16323_int['year25'], label = '25 Year', color = 'brown')
pyplot.plot(xs_16323_int['year10'], label = '10 Year', color = 'green')
pyplot.plot(xs_16323_int['year5'], label = '5 Year', color = 'purple')
pyplot.plot(xs_16323_int['year2'], label = '2 Year', color = 'blue')
pyplot.title('Rahway Intermediate RSLC WSE XS 16323.6')
pyplot.ylabel('Stage')
pyplot.xlabel('Years')
pyplot.legend(loc = 'best')
pyplot.savefig('C://Users/username/Studies/Rahway/RSLC/xs_16323_plot')
```