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THESIS

**NUMERICALLY MODELING FLOODING
SUSCEPTIBILITY OF THE UNITED
STATES NAVAL ACADEMY**

by

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**NUMERICALLY MODELING FLOODING SUSCEPTIBILITY
OF THE UNITED STATES NAVAL ACADEMY**

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

Urban flooding affects many of the world's low-lying, coastal cities today. Whether induced by prolonged periods of rainfall, storm surge, or river overtopping, these issues pose as a hazard to human life as well as a source of damage to urban infrastructure. The United States Naval Academy is one location that is especially impacted by urban flooding. Due to glacial isostatic adjustment and reclaimed soil consolidation, this area experiences subsidence as well as the effects of sea level rise, which make it susceptible to urban flooding. As the frequency of these flooding events increases, there is an increasing need for an accurate forecasting model of urban flooding on and around the Naval Academy. This study aimed to examine the potential effects that future sea level rise will have on the Naval Academy. Delft3D FM was used to create a numerical model of the Severn River, which was then used to simulate environmental conditions during an October 2021 flooding event. Various parameters were altered to test model sensitivities and calibration was conducted with the use of qualitative and quantitative data from the event. These conditions were defined as a baseline extreme flooding event and were used to gauge the increase in inundation under three different sea level rise scenarios. In each scenario, the model showed significant increases in total inundated area by the year 2100 when subjected to conditions similar to the October 2021 flooding event.

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LIST OF ACRONYMS AND ABBREVIATIONS

AHPS	Advanced Hydrologic Prediction Service
ASL	absolute sea level rise
CORS	continuously operating reference stations
DEM	digital elevation model
GUI	graphical user interface
IPCC	Intergovernmental Panel on Climate Change
MLLW	mean lower low water
MSL	mean sea level
NAD83	North American Datum of 1983
NAVD88	North American Vertical datum of 1988
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PSU	practical salinity unit
RSL	relative sea level rise
SLARC	Sea Level Rise Advisory Council
SLR	sea level rise
USNA	United States Naval Academy
WLA	water level anomalies

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I. MOTIVATION

It is projected that 68% of the world's population will live in urban environments by the year 2050 [1]. In the United States alone, this trend is clearly exemplified by the United States' National Oceanic and Atmospheric Administration's (NOAA) National Coastal Population Report, which states that nearly 40% of the total population inhabits less than 10% of the country's total land mass [2]. According to this report, these areas of high population densities typically tend to be located in coastal regions. Specifically in the contiguous United States, population densities are approximately five times greater in counties bordering coastlines. These coastal cities are all threatened by rising sea levels and increasingly severe weather patterns, which makes urban flooding a particularly pertinent topic. Despite this issue, the global trend towards urbanization drives further urban development, which decreases permeable surfaces and ultimately exacerbates the issue at hand. All of this considered, the ability to assess coastal vulnerabilities and project future inundations is of the utmost importance.

Coastal flooding vulnerabilities can be identified and quantified through different means but in most cases, mean sea level rise (SLR) is ultimately the driving force to blame [3]. Despite the fact that climate change is a globally occurring process, SLR is dynamic with an array of locally dependent variables. Simply assessing eustatic SLR fails to properly identify vulnerabilities along specific coasts, which are multi-function systems dependent on urban development, erosion rates, regional currents, atmospheric conditions, and local changes in landmass elevation. As a result, coastal vulnerability must be assessed on a basis specific to the location of interest. Indicators, indices, GIS, and model-based methods can all be integrated with existing localized datasets to forward project inundation relative to current conditions [4]. Once identified and quantified, localized coastal vulnerability can be used to guide the development of coastline resiliency plans to ultimately mitigate projected effects. Coastal resiliency can be achieved through a variety of means that range from better management of existing environmental resources to the development of protective infrastructure. In all cases, however, the process must begin with a foundational, localized understanding of the stresses that future conditions will bring.

Coastline resiliency is not only of great importance to the general population, but also to the Department of Defense and even more specifically, to the Navy and Marine Corps. According to one 2016 report from the Union of Concerned Scientists, an approximate sea level rise of 0.915 m (3 feet) would threaten 128 Department of Defense Installations with 43% of these belonging to the Department of the Navy. These installations have a cumulative evaluation of roughly \$100 billion [5]. One of such installations that is particularly threatened by urban flooding is the United States Naval Academy (USNA), which is one of the highest-ranked public institutions in the nation, a National Historic Landmark, and the primary source of United States Naval Officer accession [6]. Located in the Chesapeake Bay along the Severn River, USNA experiences multiple flooding events on an annual basis that range in severity from minor nuisance flooding to complete disruption of normal operation [5].

This study recognized the importance of the development of flood susceptibility forecasting models for the Department of the Navy and accordingly sought to provide such a tool. Specifically, it did so by setting up a hydrodynamic numerical model to simulate past and potential future flooding events at USNA. The model was set up and calibrated for the fourth highest water level event on record for the city of Annapolis, which occurred in October 2021. This event, referred to as the “Oktober Flut,” significantly hindered military operations at USNA and temporarily halted the local economy of Annapolis, MD [7]. Numerical as well as observational datasets from this event were used to calibrate and define a baseline set of conditions, which in turn allowed for the simulation of future flooding under varying local SLR projections. This study is the first one to use process-based numerical simulations to forecast USNA’s repeated flooding events. The results presented here can inform flooding vulnerabilities and resiliency plans for USNA as well as the future modeling of other military installations threatened by urban flooding and sea level rise.

II. INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), mean sea level (MSL) rise between 1901 and 2010 was observed to be approximately 1.7 ± 0.2 mm/yr, which equates to a cumulative sea level rise of 0.17 to 0.21 m [8]. 75% of this observed increase can be attributed to a rise in glacial melt coupled with the thermal expansion of the oceans. Narrowing this timeframe down to specifically focus on the years between 1993 and 2010, the MSL rise rate was 3.4 ± 0.4 mm/yr. The IPCC has further concluded that this eustatic rate is likely to increase to 8 to 16 mm/yr by the year 2100 [8].

A. REGION OF FOCUS: THE CHESAPEAKE BAY

NOAA maintains the National Geodetic Survey (NGS), which is a network of Continuously Operating Reference Stations (CORS). These stations detail localized vertical shifts of the Earth's crust throughout the United States, from which trendlines yield linearized annual rates of subsidence or rebound. These rates, when combined with satellite-based, localized rates of absolute sea level rise (ASL), result in rates of regional relative sea level rise (RSL) [9]. In the United States, land along the East and Gulf Coasts experiences high rates of subsidence, which results in RSL rise rates at these locations well above the global rate of MSL rise. This rate of subsidence tends to be larger between the Northeast and mid-Atlantic sections of the U.S. Coastline, where land is currently subsiding at a rate of <0.8 mm/yr in Maine, which increase to approximately 1.7 mm/yr in the region of the Delaware Bay before decreasing to <0.9 mm/yr in the Carolinas [9]. Recent studies have identified the mid-Atlantic as a “hot spot” for relatively high rates of linearized RSL rise as well as a region where RSL rise is likely accelerating [10], [11], [12]. This suggests that typically reported RSL rates are a conservative gauge of future inundation.

In the Chesapeake Bay, NOAA maintains nine different water level stations, which have been operating continuously for up to 107 years in the case of the Baltimore, MD station (1903-2003). These records show that RSL trends vary spatially throughout the bay but in each case, records show consistently positive RSL trends (rising water levels), which

are largely caused by consistently negative land movement (subsidence). In one study conducted by the Virginia Institute of Marine Science, the analysis of these same Chesapeake Bay water level stations in conjunction with satellite-based data determined a Chesapeake Bay regional ASL rise of 1.8 mm/yr (1976-2007), which falls below the global rise in MSL during this period [9]. Despite this finding, the study states that regional RSL rates spanned from 3.1 to 5.8 mm/yr, which suggests that 53% of the observed sea level rise in the region of the Chesapeake Bay can be attributed to local land subsidence.

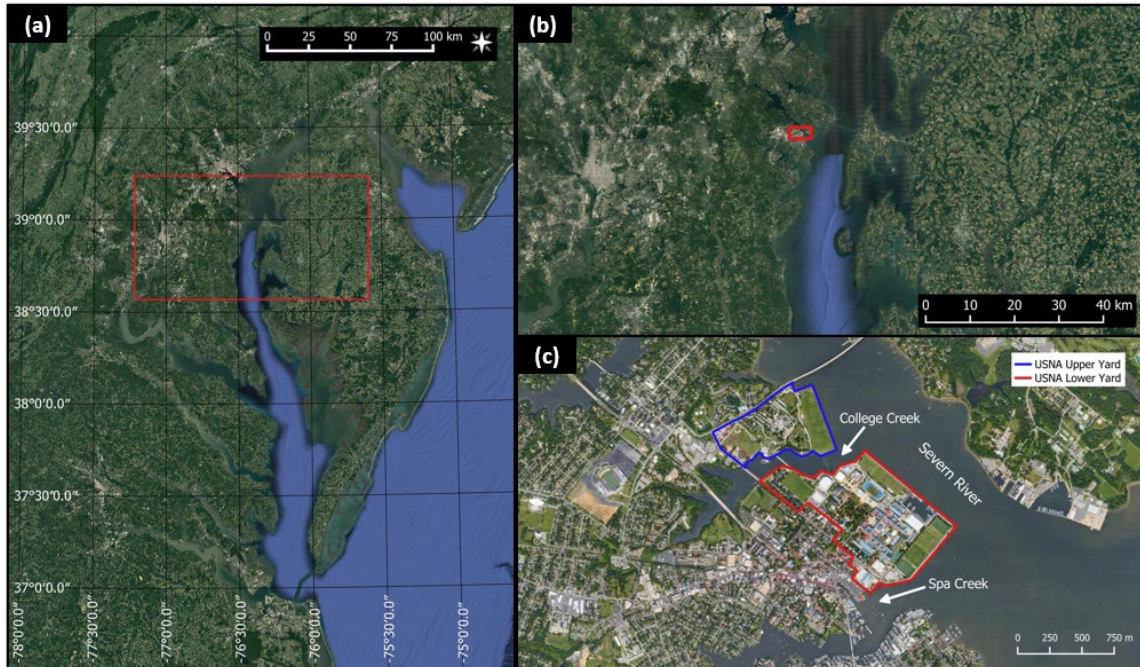
B. STUDY SITE: THE UNITED STATES NAVAL ACADEMY

One of the Department of Defense's most valuable—and most threatened—assets along the Chesapeake Bay is USNA. USNA is located on the northeastern edge of the city of Annapolis, Maryland (Figure 1). Annapolis sits on the south side of the Severn River, which is one of the western tributaries of the upper Chesapeake Bay (~12 km in length). The Severn River drains a watershed with an area of approximately 210 km² and while it does receive runoff inputs from several small creeks and streams, circulation of the Severn is primarily dependent on the tidally driven exchange of water with the upper Chesapeake Bay [13]. Between the years 1937 and 1999, localized CORS data revealed that Annapolis had a localized subsidence rate of -3.05 ± 1.74 mm/year with an ASL rise of 0.48 ± 1.74 mm/year [14]. These rates lead to a local RSL rise of 3.53 ± 0.13 mm/year. This RSL rate was further confirmed by research done by Zervas (2009), which calculated a RSL rise for Annapolis of 3.44 ± 0.23 mm/yr with a 95% confidence level between the years 1928 and 2006 [15].

The National Weather Service (NWS) defines different flood categories based on the severity of the flood's effects. For the purposes of this study, a generic "Minor Flood Stage" is the vertical height above a particular datum where water levels will result in shallow flooding of the most vulnerable locations along a shoreline with a low threat to property damage (0.3–0.6 m of inundation). This degree of inundation is also sometimes referred to as "nuisance flooding," as it may be caused by high tidal water levels or atmospheric conditions that are not related to extreme events like hurricanes. A "Moderate Flood Stage" is defined as the vertical water level height where widespread inundation is

observed with elevated threat of property damage (0.6–1.0 m of inundation), while a “Major Flood Stage” is defined as the vertical elevation above which severe flooding is observed with a significant threat to both property and life (1–1.5 m of inundation) [16]. Specifically pertaining to the Severn River, these thresholds have been defined as 0.56 m, 0.77 m, and 1.29 m for Minor, Moderate, and Major flood stages, respectively [17]. These elevations are referenced to the North American Vertical Datum of 1988 (NAVD88). From the 1990s to the 2000s, the cumulative number of hours that Annapolis tidal gauges have read water levels above the Minor Flood Stage threshold has nearly doubled. This cumulative time has again more than doubled between the 2000s and 2010s [13]. This relationship further supports the notion of accelerating RSL rise in the Annapolis/Chesapeake Bay region.

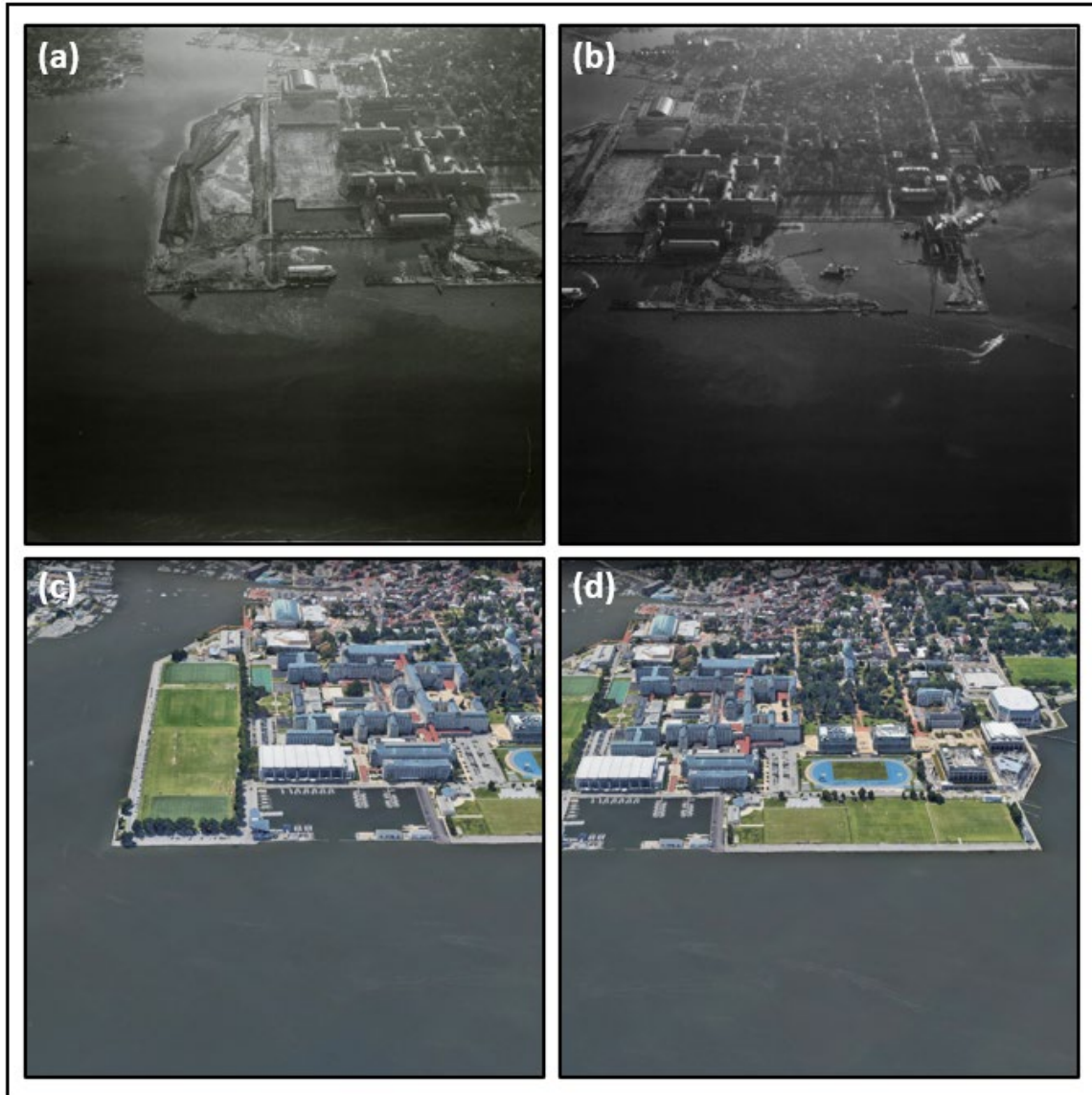
Typically, “nuisance flooding” is considered to cause relatively minor impacts. These minor tidal impacts, however, can amount to significant urban disruption when paired with localized rainfall or wind-driven local increases in sea level. Annapolis is particularly susceptible to these wind-driven storm surge events due to its orientation relative to prevailing wind directions. As visible in Figure 1, Annapolis and the southern-facing side of USNA experiences over 12 km of unobstructed fetch to its southeast. As highlighted in a 2022 *Earth Interactions* journal article, sustained winds with duration as small as three hours out of the northeast, east, southeast, and south directly correlate to significant local water level increases [13]. Conversely, sustained winds out of the northwest or north lead to significantly decreased local water levels.



Location of USNA relative to the Chesapeake Bay with increasing zoom through panels (a)-(c). (c) USNA consists of an “Upper” and “Lower” Yard, which are separated by College Creek. The Yard property lines are shown in blue and red.

Figure 1. United States Naval Academy and the Chesapeake Bay

The United States Naval Academy was first established in 1845. At this point in history, the campus—known as “The Yard”—was solely comprised of the former Fort Severn, which amounted to a total of 14 buildings over only 0.05 km² of land [18]. Since this time, The Yard has grown to over 1.3 km² with over 200 buildings. Much of this dramatic expansion was possible through land acquisition as well as land reclamation [18]. These land reclamation efforts were primarily focused on expanding outward into the bordering Severn River and the entrance of Spa Creek (Figure 1). The 1958 layout of USNA as well as its present view are shown in the aerial images of Figure 2. USNA’s expansion through land reclamation is clearly visible in panels (a) and (b) of this figure.



(a) 1958 view of the Yard bordering the entrance to Spa Creek, (b) 1958 view of the Yard bordering the Severn River and College Creek, (c) and (d) similar perspectives of the modern day layout of the Yard. The in-progress land reclamation efforts are clearly captured in the 1958 images.

Figure 2. Aerial views of USNA: 1958 versus present

Since 1958, USNA's reclaimed portions of land have experienced 65 years of soil compaction coupled with the localized subsidence of the Earth's crust. Today, this results in much of the heavily developed, mission-critical components of the Yard being built on low-lying land with extreme susceptibility to flooding—likely to a far greater extent than the surrounding city of Annapolis. Today, five of USNA's outermost roads experience

flooding with regular frequency, which are highlighted in Figure 3. Two of these five roads (McNair and Ramsey) sit at elevations below the Minor Flood Stage threshold [7]. Given the currently accelerating rates of Annapolis RSL rise, the Minor Flood Stage threshold will likely be surpassed on a daily basis by the year 2050 for the lowest of these roads (Ramsey Road) [19]. In the occurrence of even a Minor Flood Stage, all or some of these roads will close, which blocks faculty access to crucial academic buildings and drastically limits parking capacity. USNA experiences instances of this nuisance flooding at a rate of 30–40 times per year, which defines this issue as not just an anomaly, but rather a challenge that demands further attention [19].



Figure 3. USNA roads at heightened risk of flooding

While nuisance flooding in Annapolis is caused by common tidally driven water levels in conjunction with the right wind forcing, extreme water levels approaching the

Major Flood Stage threshold are typically caused by one of two meteorological events: tropical or extratropical cyclones [7], [19]. In the case of the tropical cyclone, water level anomalies (WLA), which are any observed water level above the tidally predicted value, occur due to warm-core, low pressure systems with strong, low-level winds. These systems can come in the form of hurricanes, tropical storms, or tropical depressions and are often associated with intense rainfall. Typically, these systems are fast-moving and result in flooding with a duration of no more than a few tidal cycles [7]. One example of such flooding is the September 2003 flooding event associated with Hurricane Isabel, which caused the Navy over \$120M in damage and required recovery efforts that lasted over a year [19]. In the case of extratropical cyclones, flooding is caused by slower moving low pressure systems with clearly defined frontal boundaries. In the Northeast, these systems typically come in the form of nor'easters and lead to flooding with a much longer duration when compared to tropical cyclone events. One example of this type of flooding is the Ash Wednesday Storm of 1962 [7], [17].

The ranking of these Annapolis extreme high-water events is maintained by NOAA and is available through both the NOAA hourly water level height data record [20] as well as the NOAA NWS Advanced Hydrologic Prediction Service (AHPS) Historic Crests data [17]. These records span nearly continuously from 1928 to present day for Annapolis station 8575512 [20]. These two sources reflect similar top 10 water levels but contain a discrepancy with one ranking. According to NOAA's water level height record, the October 2021 flooding event is associated with the third highest recorded water level on record with an elevation of 1.25 m relative to NAVD88. The AHPS listing verifies this height but lists the event as causing the fourth highest recorded water level. The discrepancy between the two is caused by the omission of 1933 Chesapeake-Potomac Hurricane from the NOAA hourly data rankings. This 1933 storm had a recorded maximum water level of 1.645 m above NAVD88, which places it third in the AHPS rankings. While this event and the associated extreme water levels are affirmed by the NOAA hourly water level data inventory, the official NOAA listing of the top 10 maximum water levels for the Annapolis station does not include the Chesapeake-Potomac Hurricane [20]. The remaining top 10 AHPS events, however, align with the NOAA hourly data listing with

the offset of one place. Assuming the AHPS ranking to be a more inclusive representation of the Annapolis water level record, the top five flooding events are listed and detailed in Table 1. The AHPS ranking lists water levels in feet with respect to Mean Lower Low Water (MLLW). The values reflected in Table 1 were converted to metric units and adjusted relative to NAVD88, which was done so with reference to NOAA’s tidal datum listing for Annapolis, MD station 875512 (local MLLW offset of -0.235 m with respect to NAVD88) [21]. The water level associated with the Oktober Flut—from which much of this study has been referenced—is highlighted in yellow. It is important to note that this event led to the only water level in the top five on record that was not caused by a tropical cyclone or its aftermath [7].

Table 1. Summation of historic Annapolis high water levels

Date	Rank	Causation	Maximum Water Level (m above NAVD88)	NWS Flood Stage Reached
19SEP2003	1	Hurricane Isabel	1.95	Major
23AUG1933	2	Chesapeake-Potomac Hurricane	1.65	Major
13AUG1955	3	Hurricane Connie	1.28	Moderate
30OCT2021	4	Wind forcing from extratropical storm system	1.26	Moderate
07SEP1996	5	Hurricane Fran	1.24	Moderate

C. RESEARCH OBJECTIVE

In July of 2019, a report was delivered to the Superintendent of USNA by the United States Naval Academy Sea Level Rise Advisory Council (SLARC) [19]. The report was titled “Initial Analysis and Recommendation to Prepare for the 21st Century Sea Level Rise and Storm Tides.” The report highlights the heightened need to direct further attention to the increasing occurrences of nuisance flooding at USNA. Given the available data on RSL rise, increasing severity of meteorological events, and design lifespans of currently implemented flooding mitigation efforts on the Yard, the SLARC concluded that future

resiliency efforts will be necessary to defend USNA from nuisance flooding originating both from the river side as well as the city side perimeters. The report recommends that these resiliency projects generally include raised seawalls, fortified walls, stormwater discharge pumps, elevated roadways, backflow preventers at stormwater drainage points, and nature-based solutions such as living shorelines [19]. Additionally, it concludes that future conditions may force the relocation of access points onto the Yard to higher elevations as well as a complete reconstruction of the current stormwater system.

Despite their exhaustive assessment of USNA's coastal vulnerabilities, the SLARC recognizes the ongoing and ever-changing nature of the study of SLR and calls for the periodic reassessment of current conditions at approximately five-year intervals. This allows for the reprioritization of short-term projects and maintains a long-term plan of action that is reactive to new data availability and updated study results. Ultimately, the SLARC recommends that this "long term vision for sea level rise adaptation on the Yard" extend through at least 2100 [19]. In accordance with the SLARC's recommendation, USNA must have the ability to integrate coastal data as it becomes available into existing plans. This ideally calls for a coastal resiliency plan that is dynamic in nature with design requirements that are subject to change alongside the often-unpredictable changes in the climate. Such an adaptive plan requires adaptive toolsets to continually reassess coastal vulnerabilities, which are then in turn used as additional inputs to coastal resiliency plans.

The objective of this research was to develop such a tool in the form of a numerical model that can be calibrated to existing datasets and output quantifiable metrics to assess future inundation under a variety of different SLR scenarios. The ability to conveniently model a wide range of potential outcomes is crucial for the development of a coastal resiliency plan that will be inherently dynamic in nature.

D. FLOOD SIMULATION WITH USE OF NUMERICAL MODELS

Flooding hydraulics have successfully been modeled with implementation of both 1D and 2D models with programs such as HEC-RAS, LISFLOOD-FP, TELEMAC-2D, and Delft3D Flexible Mesh. HEC-RAS was used to iteratively solve the 2D diffusive wave equations to simulate flooding from the Mamore River in Bolivia [22]. This study showed

adequate performance when comparing simulation inundation outputs with satellite imagery of the event. HEC-RAS has also been successfully used to create a 1D model to predict flooding extent on the River Severn in the United Kingdom [23]. In this study, HEC-RAS was used to solve the full shallow water equations and predicted inundated area well when calibrated to inundation data from past events. LISFLOOD-FP was used to model the entire $\sim 500,000 \text{ km}^2$ Ohio River Basin and produced good results with more than 95% of remotely sensed inundation being captured by the model output during the simulation of a particular flooding event. TELEMAC-2D was used to simulate nuisance flooding in an urban environment with a variety of different building layouts [24]. Past studies comparing inundation data output with both TELEMAC-2D and HEC-RAS-based models showed comparable results between the two programs [23].

Delft3D Flexible Mesh (FM) Suite has been used to model urban flooding in the Jingnan District of Shanghai, which typically is triggered by torrential rainfall events [25]. In this study, Delft3D FM was used to create inundation mapping for five theoretical rainfall events with return periods of one, three, five, 10, and 50 years. The model was initially calibrated using data from three historic rainfall events. In order to assess the city's urban drainage system, SOBEK was integrated into the model to simulate the city's sewer system. Results were compared from simulation runs with and without the inclusion of drainage system modeling and showed a 45% decrease in maximum inundation depth with the inclusion of the sewage system. While uncertainties were introduced to the model due to simplifications of the input data, the study concluded that Delft3D FM is a viable tool for the modeling of urban flooding.

III. METHODOLOGY

Based on Delft3D FM's past success with simulating nuisance urban flooding, it was taken to be the software of choice for this particular study and resulting model. The Delft3D FM Suite is comprised of several different modules integrated into a common interface, which has recommended uses that include the hydrodynamic modeling of flow, waves, water quality, and ecology [26].

A. NUMERICAL MODEL: DELFT3D FLEXIBLE MESH

One of the modules included in Delft3D FM is D-Flow Flexible Mesh. D-Flow FM is the successor of Deltares' previously released Delft-3D FLOW. The primary difference between the two software is an improved graphical user interface (GUI) and the introduction of unstructured grids. The added irregular grid capability allows for the use of triangular, quadrilateral, pentagonal, and hexagonal elements, which improves modeling flexibility and allows for local refinement of mesh resolution with relative ease. D-Flow FM allows for the use of multi-dimensional grids (1D, 2D, and 3D), but 1D and 3D functionalities are currently under development and have not yet been released [26].

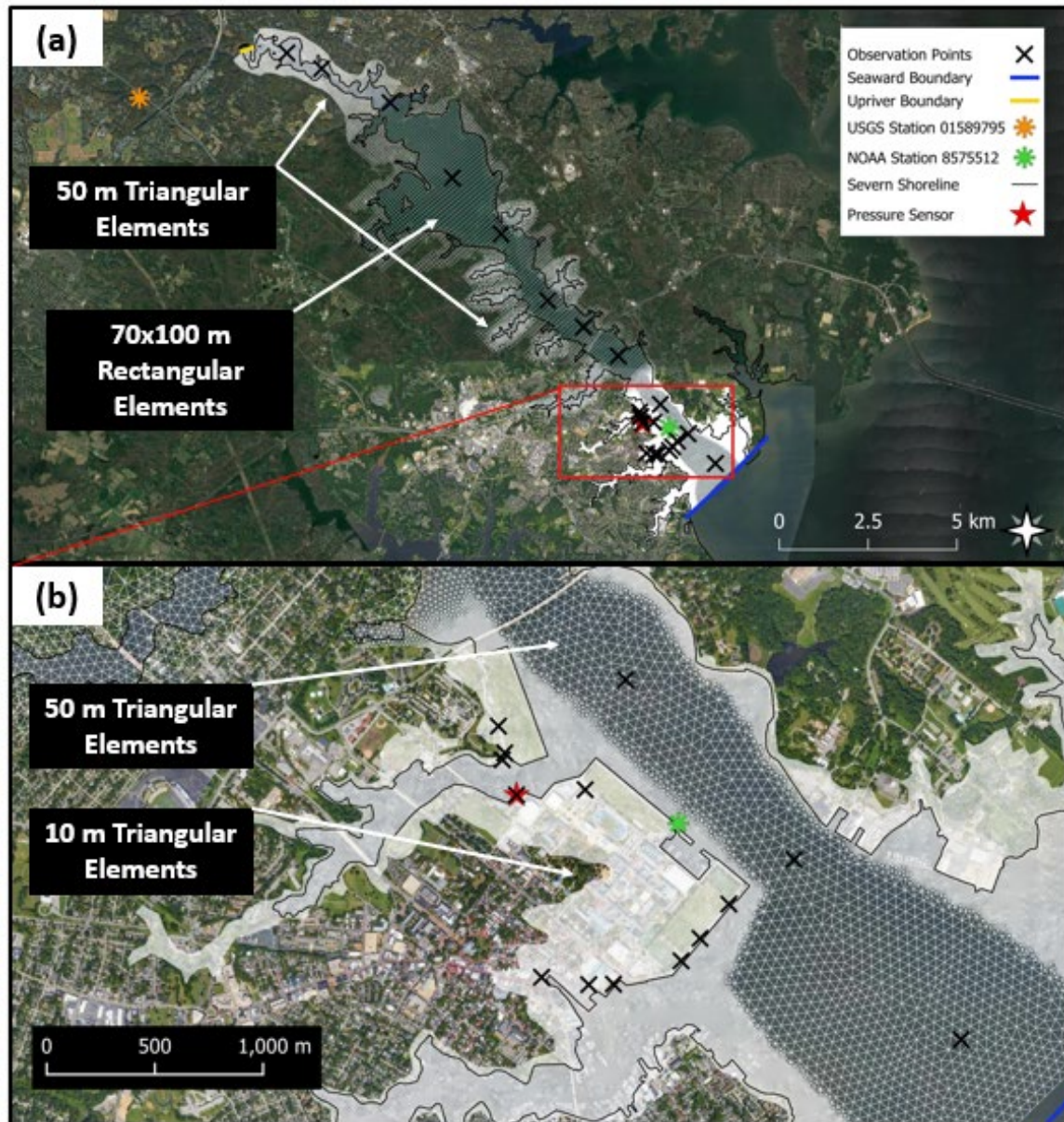
2D functionality in D-Flow FM solves the depth-averaged shallow water equations, which are derived from the full 3D Navier Stokes Equations [26]. A 2D unstructured grid spans the horizontal plane, while the vertical plane uses either the σ coordinate system introduced by N.A. Phillips in 1957 [27] or the traditional cartesian z coordinate system to perform depth-averaging calculations [26]. For fluids that are vertically homogenous and for flows of which the horizontal extent is much larger than the intended vertical scale, these depth-averaging methods provide an adequate method to model the hydrodynamics of "shallow seas, coastal areas, estuaries, lagoons, rivers and lakes" with minimal computational time requirements relative to the full modeling of 3D unsteady flow [26].

D-Flow FM iteratively solves the Navier Stokes equations for incompressible free surface flow under the shallow water and the Boussinesq assumptions for turbulent flow [26]. Vertical accelerations are neglected in the vertical momentum equation, which reduces it to the hydrostatic pressure equation. This reduces the depth-averaged system of

equations into a continuity equation and x and y component momentum equations, which renders the model as quasi-three-dimensional. Delft 3D FM allows for boundary forcing through any combination of water levels, discharges, velocities, Riemann invariants, or Neumann gradients [26], [28]. Initial conditions include both an initial water level as well as salinity with the latter being more of interest in circulation-type simulations [26].

B. MODEL DEVELOPMENT FOR THE SEVERN RIVER AND USNA

In order to create the model in Delft3D FM, multiple databases were consulted to first simulate the physical bathymetric and topographic conditions of USNA as well as the surrounding Severn River. The hydrodynamic grid consists of both regular and irregular components. The seaward boundary extends 3 km across the river from Greenbury Point, while the upriver boundary is located approximately 18 km to the northwest into the Severn's headwaters and is 300 m in length. Along the edges of the River, the grid extends inland until the surrounding topography reaches a height of 5 m. In areas with a steep vertical gradient, higher elevations of up to 47 m were captured. The grid covers the entire length of the Severn River up until its confluence with the Chesapeake, while also extending inland enough to capture the effects of any extreme flooding event that one could reasonably expect. The entire extent of the 2D grid is shown in Figure 4. The figure additionally shows model observation points, boundaries, forcing data sources, and varied Delft3D FM grid resolution.



(a) Delft3D FM grid overview (b) zoomed-in view of USNA. A black line details the Severn River land boundary that was referenced throughout the hydrodynamic model creation. Different areas of the grid may appear solid in color due to an increase in resolution.

Figure 4. Delft3D FM grid extent

The grid has a base resolution of 100 m, which is primarily seen in the grid sections further upriver. The regular grid transitions into irregular triangular elements in the vicinity of the grid's furthest reaches upriver, the Severn's tributaries, and UNSA. The irregular

elements that comprise the upriver and tributary grids have a resolution of approximately 50 m, while the grid covering USNA has a resolution of 10 m, which gradually decreases outwards towards the center of the river to an irregular resolution of 50 m. These varied resolutions are shown in Figure 4.

To achieve this grid with varied features, a uniform curvilinear grid with resolution of 70x100 m was first iteratively created using RGFGRID, which is a module of Delft3D FM that is responsible for the software's generation of curvilinear and unstructured grids [26]. This initial grid was generated from a set of splines following the curvature of the Severn. To create these splines, a land boundary file (.ldb) of the Severn River was created. Shapefiles (.shp) of the Chesapeake's shoreline were obtained from the state of Maryland's ArcGIS Online database [29]. These files were reprojected into the MD State Plane using QGIS. These reprojected shapefiles were then trimmed and used to create a Severn River land boundary file using Deltares' QUICKPLOT, which is a MATLAB-based results visualization program from an older Deltares software release simply named Delft3D [30].

The uniform curvilinear grid was then cut in the vicinity of the Severn's headwaters, the tributaries, and USNA. Irregular grids were independently created in each of these regions of interest and then nodes were merged with the main body of the initial grid. In order to optimize grid performance, orthogonality was monitored—especially in the regions of transitioning resolution. “Orthogonality is defined as the cosine of the angle ϕ between a flowlink and a netlink” [26]. Deltares defines a flowlink as the line segment connecting the circumcenters of two adjacent grid cells, while a netlink is defined as the edge of each cell. Given Deltares' criteria for orthogonality, the optimal value for this metric is 0.0 for a ϕ of 90°, but Deltares recommends an absolute ceiling on the value at 0.5 [26]. The maximum value of orthogonality in this particular grid was 0.195, with the vast majority of the grid exhibiting an orthogonality of 0.0. With orthogonality remaining below the upper threshold of 0.5, the grid's various regions of transitioning resolution did not pose as a source of potential instability in the results. The final iteration of the model's grid was comprised of 74,022 elements with 139,832 nodes with a total area of approximately 44 km².

Bathymetric and topographic data for the model was taken from three primary sources. LIDAR data from NOAA's 2019 Digital Elevation Models (DEMs) was taken from NOAA's National Geodetic Survey and used to define the topography of the grid [31]. A relatively coarse sampling of the Severn from a 2017 NOAA survey was used to define the majority of the model's bathymetry. The 2017 survey was a compilation of three historical hydrographic surveys titled HO8860 (1965), HO8874 (1966), and HO8859 (1965) [32], [33], [34]. Additional bathymetric data with a much finer resolution from a preliminary 2021 NOAA survey was used to define the riverbed in the vicinity of USNA [35]. From these three data sources, all values were converted to the appropriate transverse and vertical references and a composite topobathy sample file was created. Delft3D FM requires negative bathymetry values and positive topography values. The composite dataset was inverted accordingly with negative values indicating meters below NAVD88 and positive values indicating meters above NAVD88. Values were then projected onto individual grid nodes using a triangulation interpolation method [26]. The grid's resultant z-coordinate values are shown as a contour plot in Figure 5 (measurements are m relative to NAVD88). An additional view of the project's bathymetry is shown in Figure 6 with adjusted zoom and scaling to highlight slight variations in the topography of USNA.

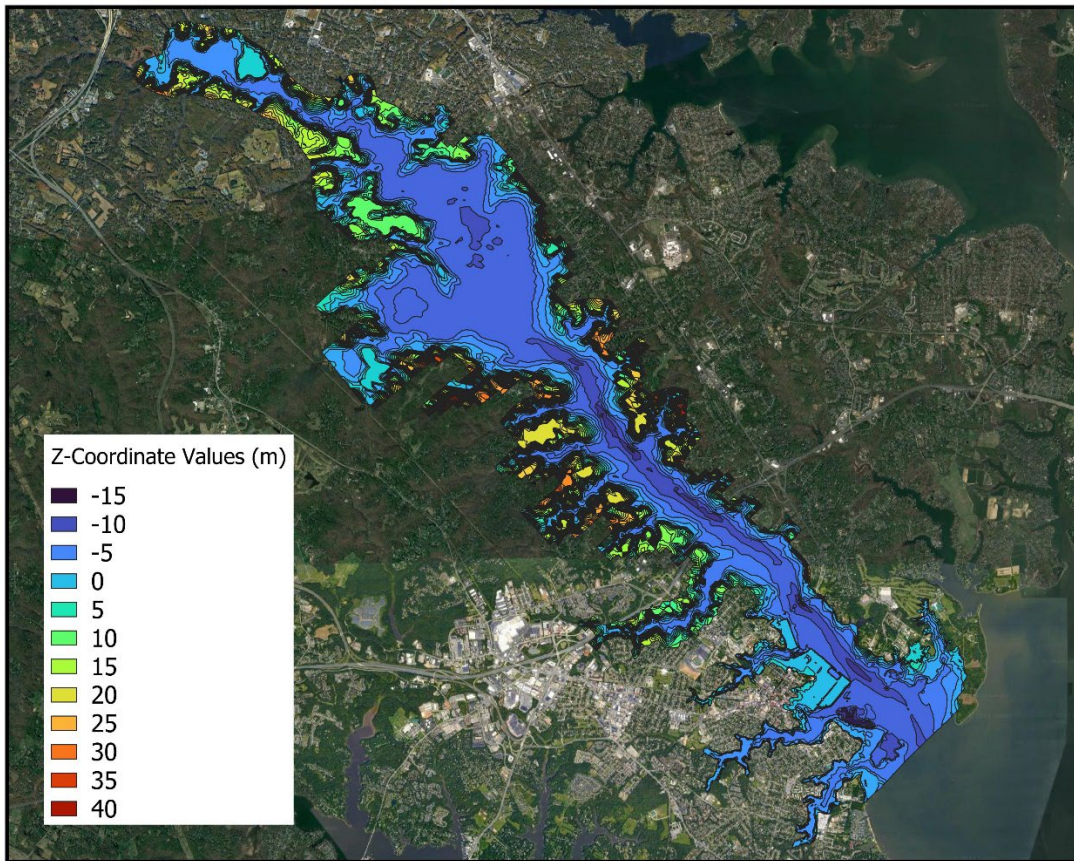


Figure 5. Delft3D FM topography and bathymetry for the entirety of the Severn River and surrounding shorelines

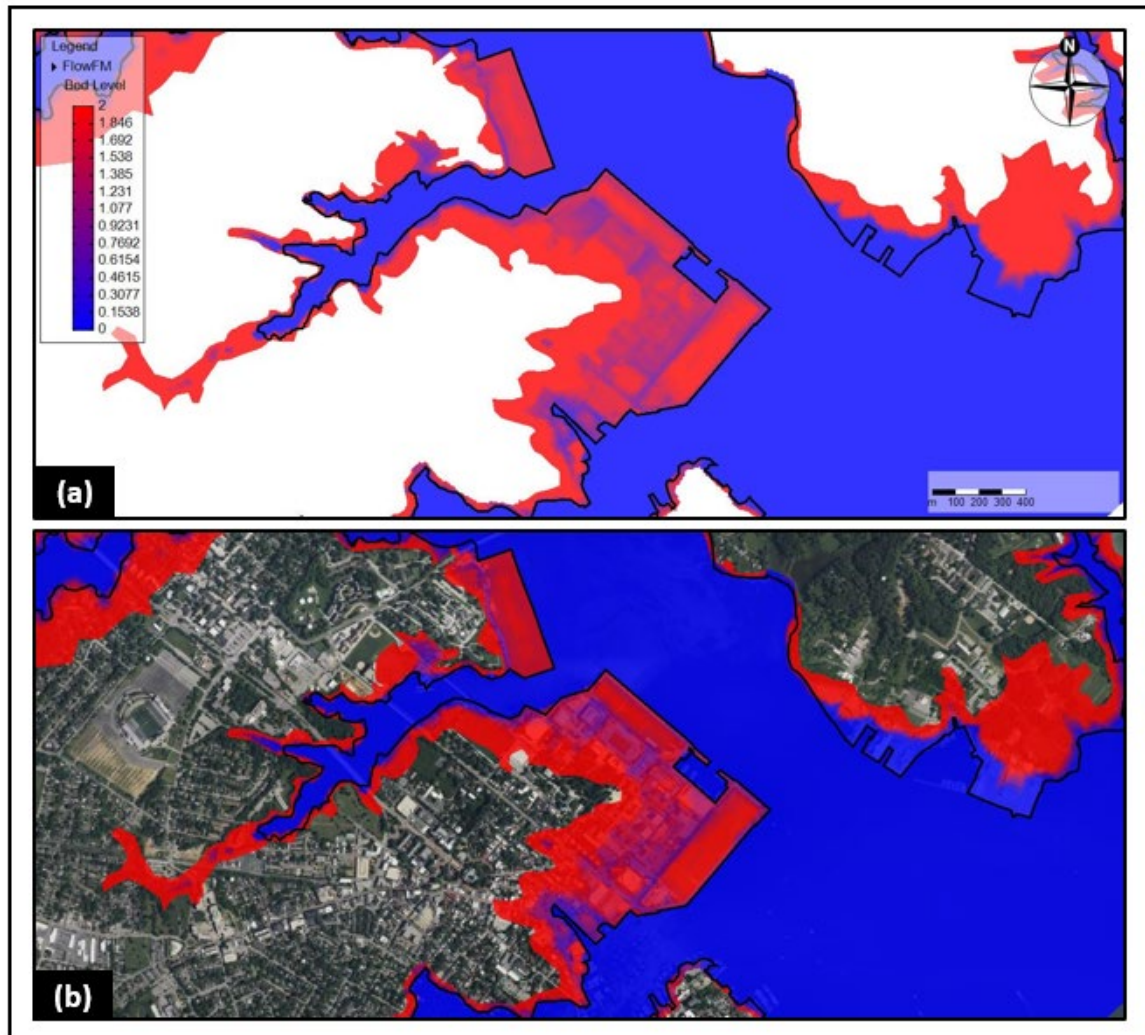
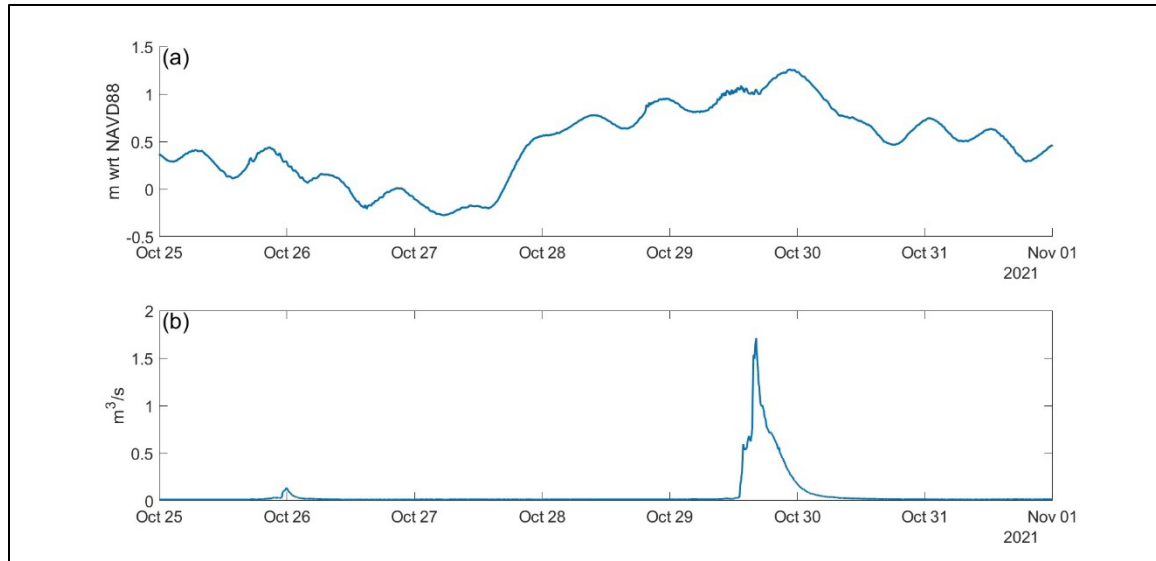


Figure 6. Topography at USNA with and without satellite underlay

Model forcing signals were collected from various online databases. The baseline flooding event for this study is the Oktober Flut of 2021. The model was forced with time-varying water level and river discharge recorded during this event (see Figure 7). Water level data (m, with respect to NAVD88) taken from NOAA Station 8575512 (shown in Figure 4) was used to force the model's seaward boundary, while discharge data (m^3/s) from United States Geological Survey (USGS) Station 01589795 (shown in Figure 4) was used to force the model's upriver boundary. The model's timeframe spanned from 25OCT21 00:00:00 to 01NOV21 00:00:00. Forcing datasets spanned this entire timeframe and were input to the model in metric units. The model was normalized to Eastern Standard

Time (EST) and all datasets were adjusted accordingly. All vertical elevations used in the model were referenced to NAVD88, while all horizontal coordinates were referenced to the North American Datum of 1983 (NAD83) Maryland State Plane (EPSG 6487). All data was converted with respect to these temporal and spatial references prior to its inclusion in the model.



(a) Verified water levels at NOAA Station 8575512, (b) Verified river discharge at USGS Station 01589795.

Figure 7. October 2021 flood environmental data

The model utilized 0.0 m as the initial water level as well as the default fluid density of 1000 kg/m^3 . Tide generating forces, salinity, secondary flows, wave action, as well as bed level morphology were disabled. A Manning equation roughness model was used to impart the effects of friction with a free-slip wall condition on all wetted surfaces [26]. A $k-\varepsilon$ turbulence model was additionally implemented. A summation of model parameters is shown in Table 2.

Table 2. Model parameters

Model Parameter	Value
Angle of Latitude	38 (degrees)
Angle of Longitude	76 (degrees)
Start Time	25OCT21 00:00:00
Stop Time	01NOV21 00:00:00
History File Output Interval	5 (mins)
Map File Output Interval	20 (mins)
Density	1000 (kg/m ³)
Initial Water Level	0 (m)
Uniform Horizontal Eddy Viscosity	0.1 (m ² /s)
Uniform Horizontal Eddy Diffusivity	0.1 (m ² /s)
Smagorinsky Factor	0.2
Conveyance 2D Type	R=HU
Turbulence Model	k- ϵ
Roughness Formulation	Manning's Roughness Coefficient

C. DATASETS FOR MODEL EVALUATION

Model calibration datasets were obtained from a previously conducted study of the event and its published findings titled “The Oktober Flut: An anomalous extreme high-water event in Annapolis, MD, USA, October 2021” [7]. While carrying out this study, a HOBO U20 Water Level Logger was deployed in College Creek (see Figure 4) from 0718 28OCT21 to 2254 05NOV21. This duration adequately captured the peak of the high-water event. The pressure logger recorded absolute pressure and temperature every five minutes. In the original study involving the sensor, atmospheric pressure data was taken from Station 8575512 and the signal was subtracted from the sensor’s absolute pressure signal. A constant salinity of 10 Practical Salinity Units (PSU) was assumed, which is a typical composition value in the Severn. Using a variable temperature read from recorded data, water density was calculated at each recording interval and used to calculate pressure assuming hydrostatic equilibrium [7].

The height of the pressure logger was determined relative to NAVD88 with respect to the 2019 DEM elevation value at the location at which it was deployed [31]. These DEMs report a vertical accuracy of +/- 0.064 m at a 95% confidence level [31], while the

sensor itself reports an accuracy of ± 0.5 cm [7], which leads to a cumulative error bounding of ± 0.069 m on the pressure logger water level signal. The resultant water level signal obtained from the pressure logger allowed for the numerical calibration of the model. The Oktober Flut study also provided this research with a set of 10 timestamped photographs detailing flooding and its aftermath at various points on the Yard between 1113 29OCT21 and 1000 21NOV21. These images allowed for a qualitative calibration of the model.

To validate the model using these available datasets, 10 observation points were placed at the coordinates of each flooding image as well as one at the coordinates at which the pressure logger was deployed. “Observation points” are a user-defined feature in Delft 3D FM that allow for the monitoring of computational results at specific locations. An additional 11 observation points were added at mid-channel along the entire length of the Severn. These observation points are additionally shown in Figure 4. Water level signal outputs from typically submerged observation points were used to calibrate the propagation of the model’s water level forcing signal (quantitative calibration), while the outputs from the typically dry observation points were used to detect and determine the extent of the simulated Yard-wide flooding (qualitative calibration).

IV. RESULTS

Following the creation of the model, sensitivity analyses were first conducted to determine optimal parameter configurations. Following this, the model went through a quantitative as well as qualitative calibration with use of data from a previously conducted study on the October 2021 flooding event [7]. Once the model was properly calibrated to the past event, it was then used to project how an event of similar magnitude would inundate the Yard under a variety of different SLR scenarios.

A. MODEL SENSITIVITY ANALYSIS

To best simulate the actual outcome of the October 2021 flooding event, time step and Manning coefficient were varied across multiple simulations to evaluate the sensitivity of the model to numerical and physical parameters.

1. Time Step

Since the unsteady form of the equations was used, a sensitivity analysis with timestep was initially conducted. Delft3D FM allows for the implementation of either a fixed or adaptive timestep [26]. To implement an adaptive timestep, a maximum Courant number must be specified, from which the timestep is calculated using the Courant-Friedrichs-Lewy (CFL) condition. The user is able to specify the Courant number CFL, but given an explicit horizontal advection scheme, this value must be smaller than 1. The default value for the software is set to 0.7 [28]. The timestep is then iteratively calculated for each element by the computational kernel in accordance with the Courant restriction (Equation 1) [28].

$$CFL = u \frac{\Delta t}{\Delta x} \quad (1)$$

where u is the convection velocity, Δt is the time step and Δx is the local mesh size. The user additionally defines an “initial time step” as well as a “maximum timestep,” from which the timestep calculation is bounded. The maximum timestep is the upper allowable limit for the computational timestep. If the timestep calculated by the computational kernel

is greater than this value, the timestep will be capped by the user-specified maximum timestep. Conversely, if the calculated time step is smaller than the user specified maximum time step, the timestep will be capped by the Courant-restricted value. The initial timestep is the value that the model uses when no data is initially available for an automatic calculation [26]. The adaptive timestep calculation cannot be explicitly disabled, but by setting the Courant number to a sufficiently high value, the computational timestep remains fixed at whatever the user defines as the maximum time step [26]. The timestep was ultimately varied to decrease computational time while maintaining satisfactory results. To test this threshold, the week-long October flood simulation was run with various fixed and adaptive timesteps. These timestep settings are summarized in Table 3 with the resultant simulation run times as well as the actual average timestep as reflected by the output.

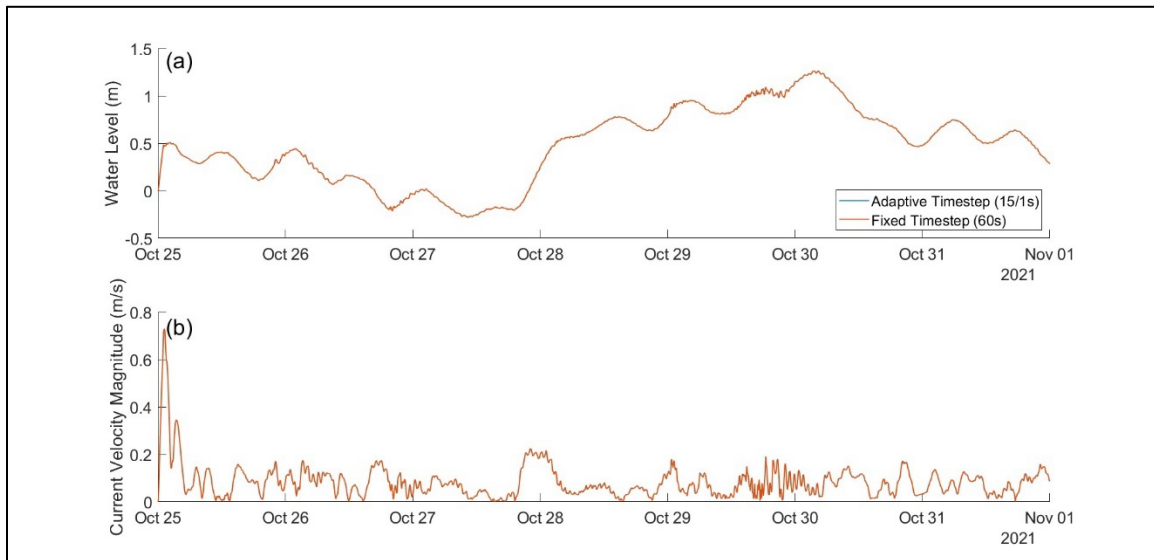
Table 3. Model time step sensitivity analysis summary

Maximum Time Step (s)	Initial Time Step (s)	Courant Number	Run Time (hrs)	Actual Average Timestep
15	1	0.7	4.60	11.17
30	1	0.7	3.74	11.80
10	10	1.0	3.88	9.68
15	15	1.0	3.72	13.15
30	30	1.0	3.55	16.08
60	60	1.0	2.38	16.08

Timestep input settings are shown along with the corresponding run times. Additionally, shown is the actual average timestep of each run. To implement a fixed timestep, the Courant number was set to 1. These fixed timestep runs are highlighted in yellow.

As a fixed timestep was increased above 15 seconds, computational timestep defaulted to the automatic Courant-limited calculation, which is shown by the convergence of the actual average timestep to 16.08 seconds regardless of increasing input parameters. For the 10 and 15 second fixed timestep runs, as well as for the two adaptive timesteps tested, model output showed minimal variation. Figure 8 shows water levels and current velocities for two different timestep input configurations at an observation point located mid-channel across from USNA. The 60s timestep was the shortest simulation in terms of

computational time, while the 15/1s timestep was the longest. While not initially apparent, each subplot of Figure 8 shows two different signals, both of which are nearly identical. There is no visible change in results between the two timestep configurations shown. All additional configurations tested also yielded identical results.



(a) Water level and (b) current results from a simulation with a maximum/initial timestep of 15/1s as well as a fixed timestep of 60s.

Figure 8. Water level and current velocities across different timesteps

Due to the convergence of results across all time steps tested and an automatically Courant-limited timestep of no greater than 16.08 seconds, a baseline timestep was decided upon to decrease computational time. An adaptive timestep with a maximum timestep of 30 seconds and an initial timestep of 1 second was determined to be the timestep for all future simulations.

2. Manning Coefficient

Delft3D FM allows for the implementation of a Manning roughness formulation, which calculates a C_{2D} velocity coefficient using Equation 2 [26].

$$C_{2D} = \frac{\sqrt[6]{R}}{n} \quad (2)$$

Where R is hydraulic radius and n is the Manning coefficient. Delft3D FM recommends a default Manning roughness coefficient of 0.023, which falls between the recommended values for open flow through a clean earthen channel (0.022) and a gravelly earthen channel (0.025) [36]. The Severn riverbed is made up of mainly sand and mud, which makes the default Manning coefficient of 0.023 a reasonable choice for this particular model [37]. To confirm this assumption, the Manning coefficient was increased well beyond the recommended value over two additional simulations and the outputs were examined. Water level signals from the furthest upriver observation point (17 km upriver from seaward boundary and where signal lag was expected to be largest) were plotted over the original forcing signal and evaluated for maximum signal lag (see Figure 4 for observation point location). Results from this analysis are shown in Figure 9. A similar analysis was done with data from the pressure sensor observation point (see Figure 4).

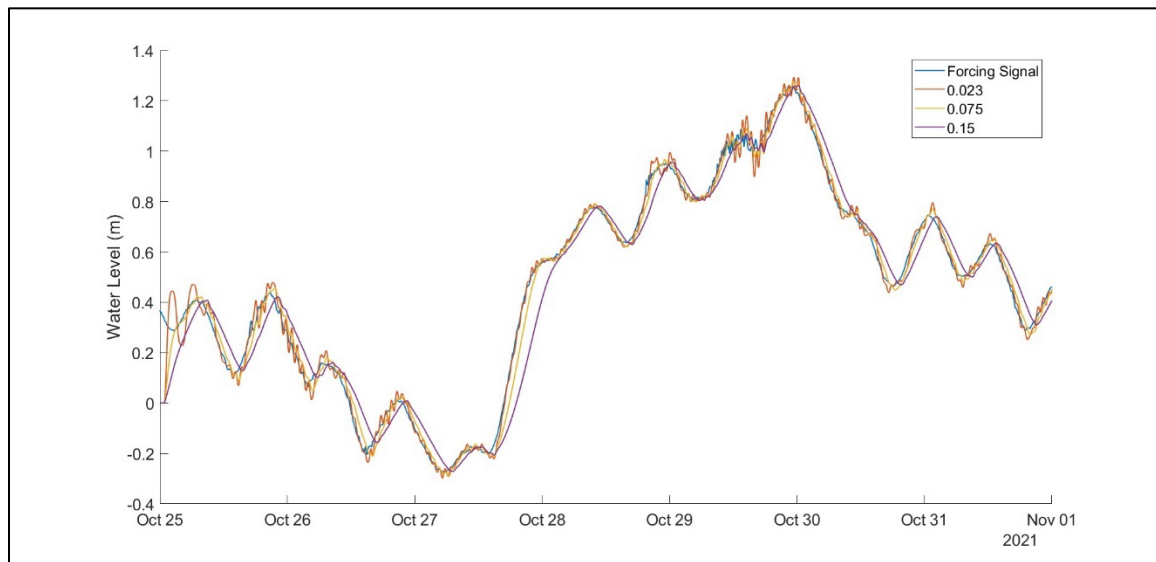


Figure 9. Upriver water levels over varied Manning coefficients

Increasing the Manning roughness coefficient proved to effectively slow the propagation of the forcing signal through the model domain, which increases lag in signal with increased distance upriver. The increased coefficient also smoothed small oscillations in the output signal. Despite the fact that these results could be considered realistic, there

are no data sources from further upriver to definitively confirm appropriate signal lag upriver of USNA. Changes to the Manning coefficient did not lead to any significant changes in simulated water levels at the pressure sensor calibration point (see Figure 4), which is likely due to its relatively close proximity to the seaward boundary. For this reason, the default roughness coefficient of 0.023 was used in all future simulations. A summary of all Manning coefficients tested is listed in Table 4.

Table 4. Manning coefficient sensitivity analysis summary

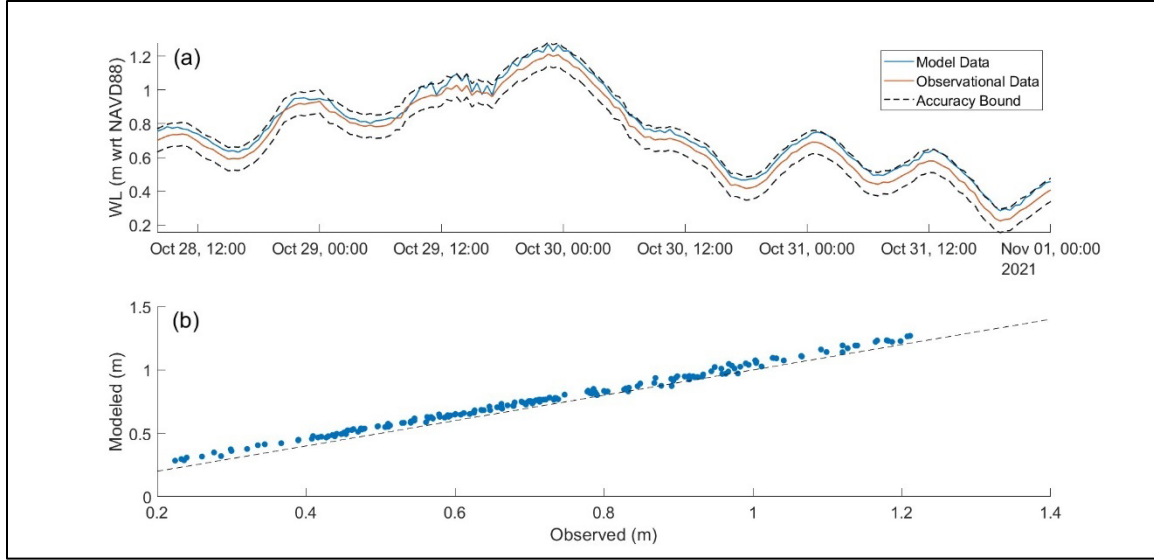
Manning Coefficient	Recommended Surface Material [36]	Maximum Signal Lag
0.023	Clean-Gravelly Earthen Channel	55 mins
0.075	Floodplains with Heavy Brush	1 hr 25 mins
0.15	Floodplains with Trees	3 hr 30 mins

Runs with three different Manning coefficients are shown with the baseline value of 0.023 being highlighted in yellow. The recommended surface material corresponding to each value is shown. Additionally, shown is the maximum signal lag between the forcing signal and the simulated water level output at the furthest upriver observation point (see Figure 4).

B. MODEL CALIBRATION

Model calibration consisted of two parts: a numerical data quantitative calibration and an observational data qualitative calibration. Quantitative calibration capability stemmed from the pressure logger data that was placed in College Creek during the October flooding event. The pressure logger water level signal was compared to model output from an observation point at the location that the logger was deployed (see Figure 4).

The pressure logger read data from 28OCT to 06NOV, while the model simulated 25OCT to 01NOV. Each of these timeframes captured the peak extent of the flood. The overlay between the model output and the pressure logger data is shown in Figure 10 with the appropriate error bounding of ± 0.069 m (see Chapter III, Section C) around the observational water level signal.



(a) Model and observed water level signal. The accuracy bound of ± 0.069 m is represented by the dotted lines. (b) model output versus observed values. Model output values are plotted over observational values with a line to represent perfect agreement of values.

Figure 10. Quantitative calibration

Figure 10 illustrates a general alignment between simulated water levels and observed water level at the actual location of the pressure logger (see Figure 4). Specifically, 85.9% of the model output fell within the expected accuracy bound for the pressure logger. Model data consistently fell slightly above the observational values with a maximum difference of 0.07 m. Root mean square deviation (RMSD) as well as mean absolute error (MAE) were calculated using Equations 3 and 4, where x is the model-predicted value, $\hat{x}$ is the actual observed value, and N is the total number of data points. In this case, the pressure logger sampled water levels at a six-minute interval, while the model output was recorded at a five-minute interval. Accordingly, Equations 3 and 4 were used with a sample size of 177 data points at 30-minute intervals. The RMSD and MAE were calculated as 0.0489 m and 0.0460 m, respectively.

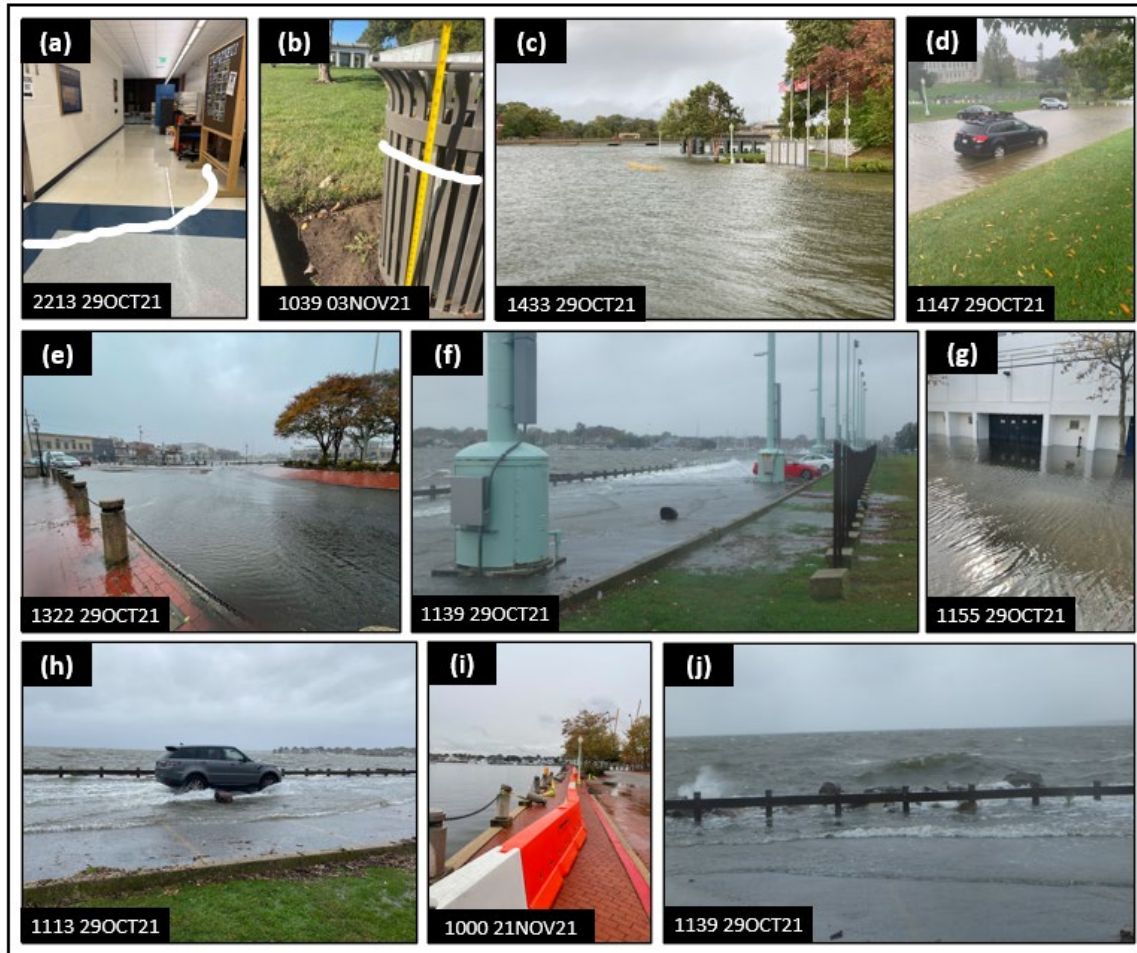
$$RMSD = \sqrt{\frac{\sum_{i=1}^N (x_i - \hat{x}_i)^2}{N}} \quad (3)$$

$$MAE = \frac{\sum_{i=1}^N |x_i - \hat{x}_i|}{N} \quad (4)$$

In addition to quantitatively calibrating the model with water levels, a qualitative calibration was performed using a set of 10 timestamped images from the previous Oktober Flut study that documented USNA flooding and its effects at different points throughout the October 2021 flooding event [7]. Each of these images is shown in Figure 11. Of the 10 photos, eight document locations actively flooded during the event, while two show flooding aftermath. Synthetic observation points were placed within the model domain at the locations at which each of these images were taken and the presence or absence of flooding was checked at each location in the simulated output.

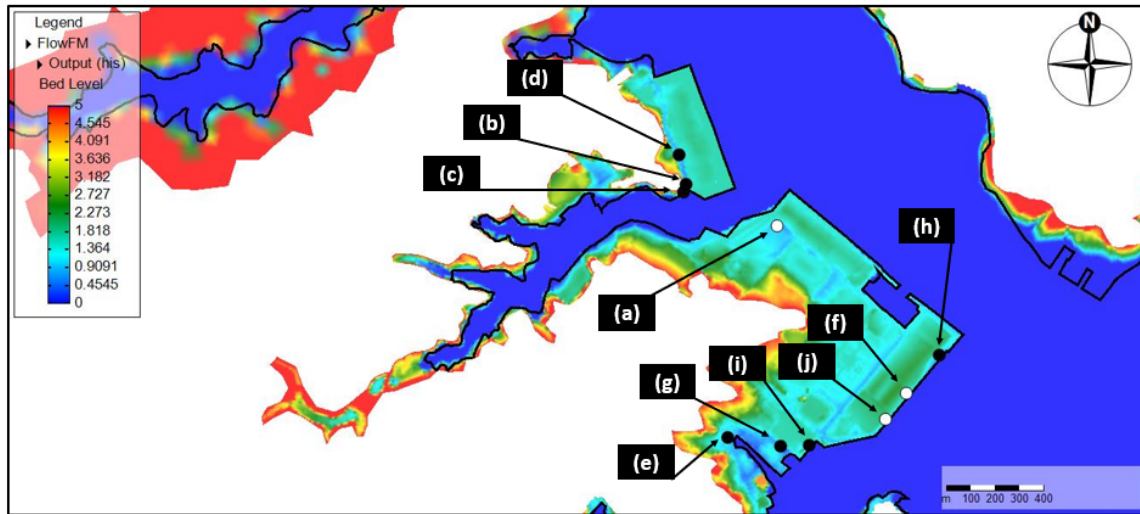
Delft3D FM utilizes triangular interpolation across the entire model domain when assigning bed level values at grid nodes. When this qualitative assessment was initially conducted, the model overestimated flooding on the perimeter of the yard as linear interpolation of bed level does not accurately simulate the many vertical seawalls that make up USNA's border with the Severn River. Later iterations of the model used an updated depth file that utilized piecewise triangular interpolation along these vertical land/water interfaces in order to simulate a near-vertical bed level gradient. In this sense, the effects of vertical seawalls were better captured.

Figure 12 illustrates each observation point and whether or not the model output indicated flooding during the simulated weeklong period. Each of the ten observation points were located at areas that did see significant flooding during the October 2021 flooding event. Each of these ten locations correspond to one of the ten images shown in Figure 11, which either document flooding during the event itself or its aftermath.



(a), (c)-(h), and (j) show flooding during the October 2021 flooding event. (b) and (i) show flooding effects with (b) showing a residual waterline on a trashcan, and (i) showing damaged infrastructure. Waterlines are highlighted in (a) and (b) with a white line. Photograph Source: [38].

Figure 11. Qualitative calibration image dataset



Qualitative calibration model output. Bed level is plotted with an adjusted scaling of continuous shades to show small topographical changes. Each circle represents the location of an observation point. A filled circle represents the presence of flooding in the output, while an unfilled circle indicates that the observation point remained dry throughout the simulation.

Figure 12. Qualitative calibration

Seven out of the ten observation points showed the expected flooding in the output. Out of the eight images with timestamps during the simulation period (showing flooding versus flooding aftermath), five of the corresponding observation points showed flooding that corresponded with the specific image timestamp. Of the three locations that showed a complete absence of flooding, two of these are located on Turner Joy Rd, which runs along the southwest perimeter of USNA (see Figure 3). This road experiences the greatest unobstructed fetch of anywhere on the Yard. As a result, flooding along this road is usually due to wave action, which this model does not account for. Further discussion of this topic is presented in Chapter V.

C. FUTURE PROJECTIONS FOR EXTREME FLOODING EVENTS

NOAA maintains regional data on RSL rise and uses this data to make a series of regional projections that amount to six different SLR scenarios, which range from a “Low” scenario to an “Extreme” scenario [39]. These scenarios forecast from present day out to 2100 and are bounded by a 0.3 m global MSL rise for the Low scenario all the way to a 2.5 m global MSL rise with the Extreme scenario. The Low scenario stems from a linear

extrapolation of MSL rates from the early 1990s while the Extreme scenario stems from an “extreme ice-sheet melt/discharge scenario” [39]. The resulting RSL projections for the Low through High scenarios are shown for Annapolis Station 8575512 in Figure 13.

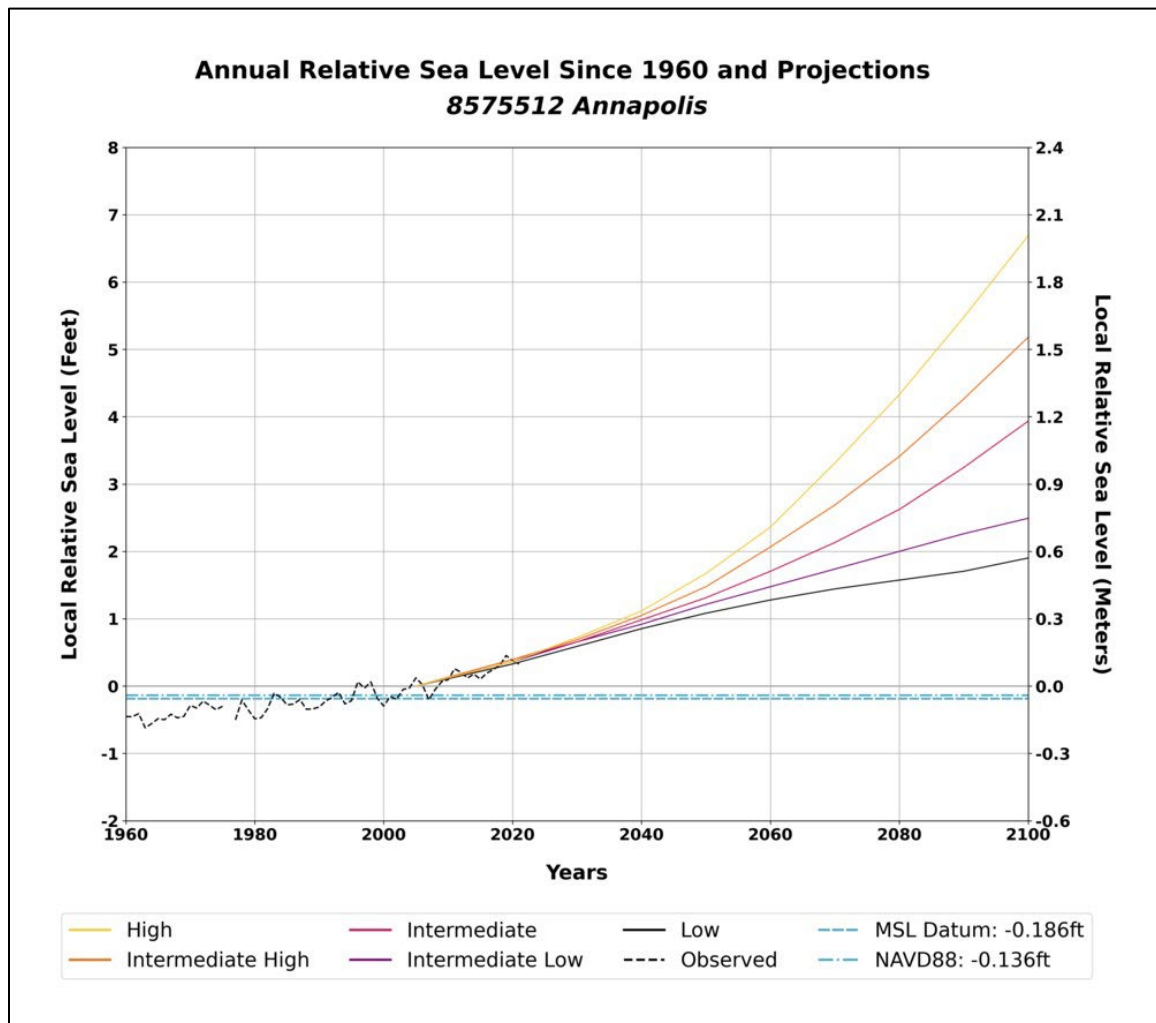


Figure 13. Annapolis sea level rise scenarios. Source: [40].

For the purposes of this study, RSL rise scenarios out to the year 2100 were of interest, which was determined in accordance with the SLARC’s recommendation to the Superintendent concerning USNA’s adaptive plan to combat SLR [19]. A plot digitizer was used to determine the projected RSL rise between 2021 and 2100 for the Low,

Intermediate, and High scenarios. The resulting RSL rise values normalized to 2021 Annapolis MSL are shown in Table 5.

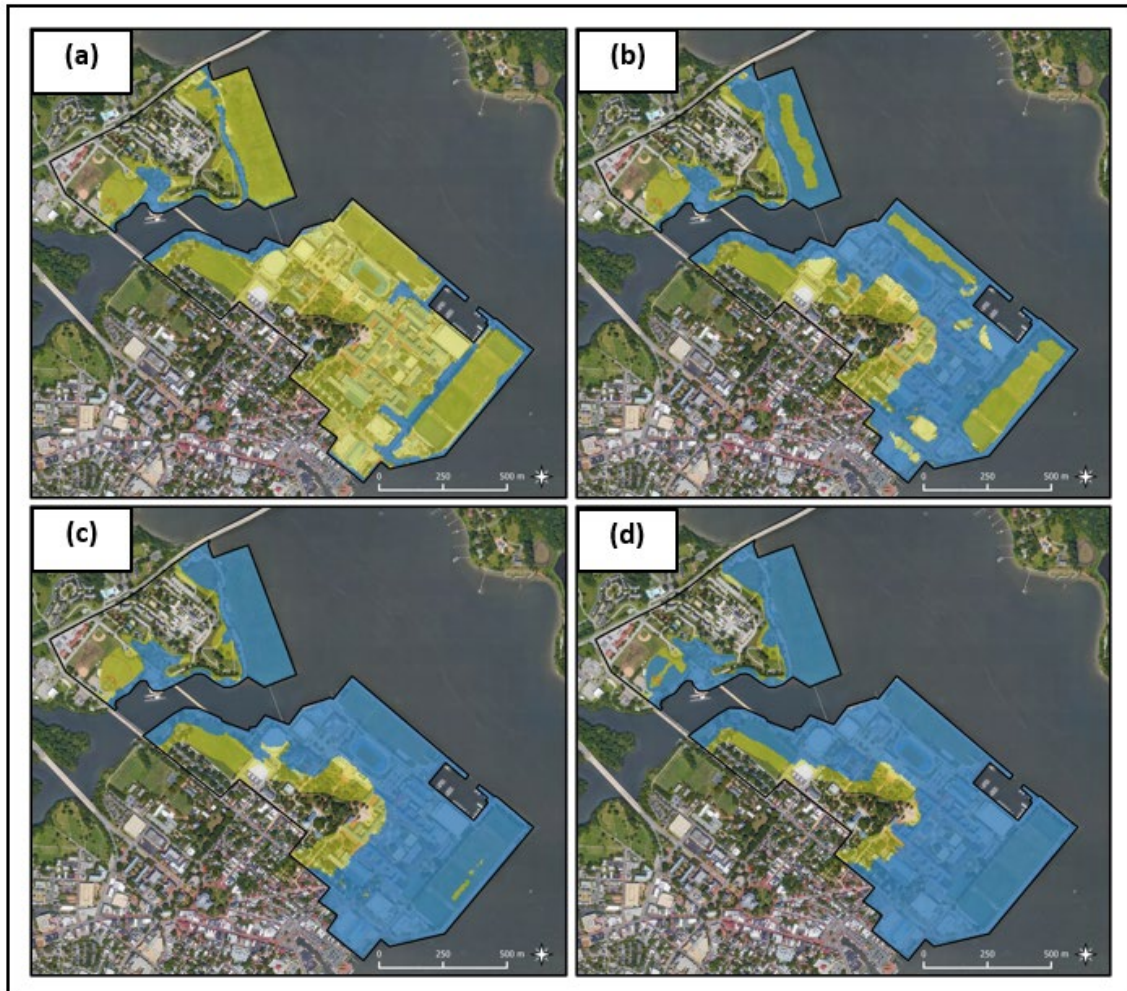
Table 5. 2100 Annapolis RSL rise scenarios

Scenario	Relative Sea Level Rise
Low	+0.473 m
Intermediate	+1.088 m
High	+1.927 m

To identify the possible flooding extent at USNA during year 2100, Low, Intermediate, and High relative sea level rise scenarios were simulated by adding 0.473, 1.088, and 1.927 m, respectively, to the October 2021 water level forcing signal. During the October 2021 flooding event, a maximum recorded water level of 1.258 m relative to NAVD88 occurred on 30OCT21 at 03:36:00 [21]. This maximum water level categorizes the October Flood under the Moderate Flood Stage ($0.77 \text{ m NAVD88} < 1.258 \text{ m} < 1.29 \text{ m NAVD88}$) as defined by the NWS [16]. With reference to the October Flood and in accordance with Table 5, the Baseline (2021 conditions), Low, Intermediate, and High test cases were forced by water level signals with a peak height of 1.258 m, 1.731 m, 2.346 m, and 3.185 m, respectively (relative to NAVD88). This means that under all RSL rise scenarios tested, an event of similar magnitude to the October flood would lead to water levels well above 1.29 m by the year 2100, which surpasses the Major Flood Stage [16].

The model outputs from each of these three test cases were compared to the Baseline October 2021 test case using inundation mapping, in which the total flooded area of the Yard was spatially plotted and calculated at 03:40:00 on 30OCT21. This time corresponds to the closest model output to the peak of the event given a 20-minute output interval. Model outputs were initially reviewed using Delft3D QUICKPLOT and later analyzed using MATLAB and QGIS. The resulting inundation maps from these analyses are shown compositely in Figure 14. The shaded regions overlaid on the satellite map represent the extent of the Delft 3D FM grid. Blue regions represent flooded areas, while tan regions represent dry areas within the model domain. Simulation outputs were trimmed

to specifically detail USNA property. Individual inundation maps for each test case are further shown in the Appendix.



(a) Baseline scenario (October 2021 flooding event) (b) Low scenario (+0.473 m RSL rise), (c) Intermediate scenario (+1.088 m RSL rise), (d) High scenario (+1.927 m RSL rise). A black outline represents the Upper and Lower property of the Yard.

Figure 14. Simulated inundation maps: Baseline, Low, Intermediate, and High scenarios

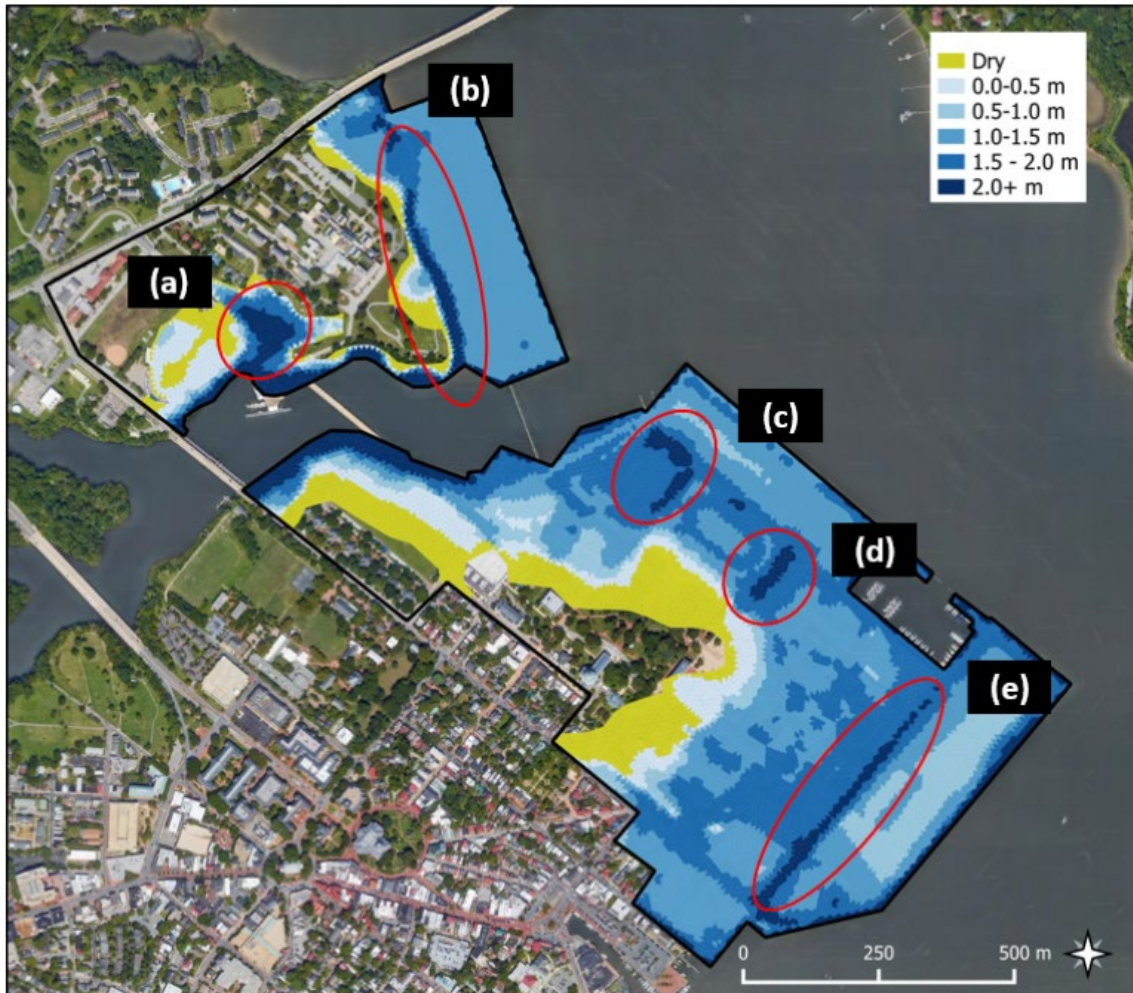
While determining the total flooded area of the Yard, the Upper and Lower Yard were considered to calculate total area of interest (Figure 1). Using the two polygons outlined in Figure 14, the total USNA area of interest was taken to be 846,584 m², or ~0.85

km². A flooded cell was taken to be one containing a water depth of anything greater than 0.0 m. The cumulative flooded areas from each inundation map are shown in Table 6.

Table 6. Inundation map data summary for an event like the October 2021 flood (Baseline) and the same event under three sea level rise scenarios.

Scenario	Flooded Area (m ²)	Flooded Area (%)
Baseline	131,671	12.03
Low	513,356	46.90
Intermediate	677,808	61.92
High	749,080	68.43

Inundation depths were analyzed spatially throughout the Yard and different regions most at risk of flooding were identified based on maximum inundation depth. Five areas, all coinciding with roadways, were identified on the Yard that consistently showed the greatest flooding depth. These five areas were: a) the intersection of Bowyer and Ramsay Road, b) Ramsay Road on the western side of Hospital Point field, c) the northeast side of Rickover Hall, d) the Midshipman store parking lot, and e) Brownson Rd. These five areas are shown in Figure 15 over a contoured inundation plot for the High RSL rise scenario. Additionally, seen in Figure 15 is the fact that greater inundation depths along USNA's perimeter can be particularly seen on the sections of the Yard bordering College Creek.



(a) Bowyer and Ramsay Road, (b) Ramsay Road on the western side of Hospital Point field, (c) the northeast side of Rickover Hall, (d) the Midshipman store parking lot, and (e) Brownson Rd. Inundation depths are shown for the High RSL rise simulation.

Figure 15. USNA areas of heightened risk

In the case of the High SLR rise scenario, each of these five areas of concern showed a maximum inundation depth of greater than 2 m. According to the NWS, such inundation depths would be considered a significant threat to both property and life [16]. Table 7 summarizes the maximum observed flooding depth at each of the five areas of heightened risk for each of the four scenarios tested.

Table 7. Summary of maximum observed inundation depths during an event like the October 2021 flood

Location	Baseline Scenario (m)	Low Scenario (m)	Intermediate Scenario (m)	High Scenario (m)
(a) Bowyer and Ramsay	0.653	1.13	1.75	2.58
(b) Ramsay (Hospital Point Field)	0.432	0.907	1.53	2.35
(c) NE side of Rickover Hall	0.0	0.945	1.55	2.37
(d) Midstore Parking Lot	0.134	0.676	1.29	2.12
(e) Brownson	0.421	0.749	1.36	2.20

Under all future RSL rise projections, maximum inundation depths were seen at the intersection of Boyer and Ramsay. Following this location in order of largest to smallest was the northeast side of Rickover Hall, Ramsay Road along Hospital Point, Brownson Road, and finally the Midshipman store parking lot. This ordering of maximum observed depths was consistent with the exception of the Baseline test case, which failed to predict flooding along the northeast side of Rickover Hall. Aside from this omission, the ordering remains the same. Further discussion of this is presented in Chapter V.

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V. DISCUSSION

This study was effective in using past flooding events to calibrate a hydrodynamic model of the Severn River and USNA, which then was used to simulate future flooding events of similar magnitudes under a variety of different RSL rise projections for the Annapolis area. Without additional considerations other than SLR, however, the resultant model only provides a conservative representation of USNA flooding by the year 2100.

A. MODEL LIMITATIONS

Future iterations of the model could be of increased value with the addition of any combination of considerations made for rainfall, groundwater intrusion, urban drainage systems, and waves. All of these additional processes have dynamic impacts that can exacerbate flooding events beyond just what is caused by SLR and water levels from the Severn River.

The absence of wave-driven flooding considerations can be seen in the qualitative calibration of the model. Observation points (f) and (j) (see Figure 12) failed to show any flooding during the simulated Baseline simulation of the October 2021 flood. In actuality, these locations experienced some of the more severe flooding effects seen on the Yard, which is clearly visible in the corresponding images (f) and (j) of Figure 11 [7]. Also visible in these images, however, is a disorganized sea state and whitecaps, which suggests that wind-driven waves are the primary mechanism of flooding along USNA's southeastern perimeter. This is especially visible in image (j) of Figure 11, which captures a wave actively breaking over the riprap that lines this section of the Yard. As discussed in Chapter II, Section B, Turner Joy Road and the southeastern perimeter of the Yard experiences 12 km of unobstructed fetch, which extends across the Chesapeake Bay to Kent Island (see Figure 1 and 3). Turner Joy Road sits at approximately 1.6 m above NAVD88, which places it at a much higher elevation than other points on the Yard that regularly experience flooding [31]. Even so, the area can flood during any storm with sustained winds out of the northeast, east, southeast, or south [13], [7]. Given the fact that this model only captures the effects of tidally and wind-driven surge flooding (i.e., neglecting flooding from waves

and from drainage systems), the inundation extent along USNA's southeastern perimeter caused by the October flood is not fully captured in the baseline simulation (Figure 12). If this study were to be repeated with wave considerations enabled, it is likely that USNA's top five areas of heightened risk would need to be reclassified to include Turney Joy Road.

The absence of urban drainage system considerations can also be seen in the qualitative calibration of the model. Of the three observation points that failed to show any flooding, one was located at Rickover Hall (see location (a) of Figure 11 and 12). Observation point (a) is located at one of the lower points on the Yard with an elevation of approximately 0.85 m above NAVD88 and is in a region vulnerable to nuisance flooding, which is reflected by image (a) of Figure 11. As seen in this image, flooding can lead to water in the building itself in the more extreme cases. Due to this region's relatively low elevation, flooding is often caused by inadequate rainfall drainage and backflow through stormwater infrastructure along the perimeter of the building [19]. As seen in Figure 6, the northeast side of Rickover Hall occupies a region of low elevation but is surrounded by areas of relatively higher elevation. Due to the model's absence of the drainage system, the Baseline simulation failed to identify this region of the Yard as a flooded area. Even so, all projections under the three RSL rise test cases for 2100 identified this area as one of heightened risk. This is due to the area surrounding Rickover Hall being overtopped by increased static water levels. This relationship is shown in Table 7, which shows Rickover Hall remaining dry during the Baseline test case, but then showing the second largest inundation depth of anywhere on the Yard in all three future projections. Depending on the actual performance of future urban drainage systems outside of Rickover Hall, nuisance flooding in this area could either increase or decrease. In any case, future models would benefit from the added consideration of such systems.

One additionally beneficial improvement to the study would be an inland expansion of the grid. The grid was expanded inland from the Severn River to a minimum vertical elevation of 5 m with respect to NAVD88. The October 2021 flood had a maximum recorded water level of 1.258 m relative to NAVD88. Under the High RSL rise scenario, an event with a similar magnitude would translate to a maximum water level of 3.185 m, which leaves a small margin between maximum possible inundation depth and the furthest

inland extents of some areas of the grid. This small margin is illustrated in the High RSL rise scenario inundation map in Figure 15, which shows minimal dry grid elements in select areas between the edge of the simulated flooding and the edge of the computational grid. An extended grid would be especially pertinent in the modeling of flooding events with more severe magnitudes than the October flood. For perspective, in 2003 Hurricane Isabel led to a maximum recorded water level of 1.95 m at USNA [21]. Under the High RSL rise projection between 2003 and 2100, such an event would lead to water levels in excess of 3.95 m relative to NAVD88 [40]. Extending the grid inland with a slightly higher elevation threshold would greatly improve the model's ability to simulate extreme flooding events without much of a cost in terms of computational requirements.

B. OTHER FUTURE CONSIDERATIONS

Further model enhancement would greatly benefit from the deployment of additional pressure sensors at different points along the Severn River. This would provide additional datasets for use in the model's quantitative calibration at different sites. In this study, observational data obtained from the October 2021 pressure sensor deployment was collected with relatively close proximity to Station 8575512, which was the source of the model's forcing data. Additional water level datasets from further upriver would lead to a more comprehensive Manning coefficient calibration, which would improve signal propagation and the reliability of inundation projection throughout the entire computational domain. In the case of this study, however, the area of interest was specifically limited to USNA. Given USNA's proximity to the seaward boundary, a large signal lag between forcing signal and the area of interest was not anticipated, which validates these results without a more thorough friction calibration.

The results of this study clearly highlight the need for the development of a coastal resiliency plan that accounts for the likely severe effects of future nuisance flooding at USNA. Successful SLR adaptation for USNA out to the year 2100 will likely require drastic changes to infrastructure. While raised seawalls may prevent floodwater entrance along the Yard's border with College Creek and the Severn, adaptations may additionally require the installment of breakwaters to dissipate wave energy along USNA's southeastern

border with Spa Creek. Additional improvements to infrastructure will likely also include an improvement of stormwater drainage systems on the Yard. In future iterations of this research, this model could be used to gauge the effectiveness of these potential adaptations. Under all RSL rise scenarios, USNA demonstrates extreme vulnerability to the rising water levels around Annapolis, MD.

VI. CONCLUSIONS

The ultimate objective of this study was to develop a numerical model to simulate past and future flooding of USNA. Such a model was desirable as it could be calibrated to existing datasets from past flooding events and then used to simulate future flooding under a variety of different SLR scenarios. Variability of outcome is inherent in the study of localized RSL rise and its effects. This makes the planning of future flood mitigation efforts an especially difficult task, which calls for the ability to conveniently model future inundation under newly updated assumptions. This study was successful in creating a model with these capabilities.

Specifically, the study showed that USNA's sensitivity to SLR could be accurately modeled using an irregular grid of varied resolution, a water level forcing signal originating at a seaward boundary, and a baseline set of model parameters. Once set up, the model was successfully calibrated both quantitatively as well as qualitatively to simulate the observed effects of the October 2021 flooding event. The model showed reasonable alignment with the observed flooding of the Yard during this event with the exception of Turney Joy Road and Rickover Hall, which experienced flooding due to wind driven waves and faulty stormwater drainage. The model did, however, prove to be reliable in predicting flooding due to tidally or wind-driven extreme water levels.

In the case of a flooding event with similar magnitude to the October 2021 flood, the model predicted significant increases in total inundated area under all RSL rise scenarios for the year 2100. Even under the Low scenario, which used a quasi-linear extrapolation under current rates of RSL rise, the Yard saw a 34.87% increase in flooded area by 2100 with flooding depths frequently approaching 1 m. These metrics represent a conservative estimate of SLR applied with an already conservative model configuration. Under the Intermediate and High scenarios, total inundated area further increased by 49.89% and 56.4%, respectively. Under all scenarios, the model showed five particular areas of the Yard to be most at risk of nuisance flooding: These five areas were: a) the intersection of Bowyer and Ramsay Road, b) Ramsay Road on the western side of Hospital

Point field, c) the northeast side of Rickover Hall, d) the Midshipman store parking lot, and e) Brownson Rd.

APPENDIX. INUNDATION MAPS



Figure 16. Baseline scenario inundation map



Figure 17. Low scenario inundation map



Figure 18. Intermediate scenario inundation map



Figure 19. High scenario inundation map

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