FUGRO CONSULTANTS, INC.

LAFAYETTE RIVER TIDAL PROTECTION ALTERNATIVES EVALUATION

City of Norfolk
City-wide Coastal Flooding Contract
Work Order No. 7

Prepared for:
CITY OF NORFOLK
DEPARTMENT OF PUBLIC WORKS

January 2016
Fugro Project No. 04.8113009

January 20, 2016
Project No. 04.81130009

City of Norfolk
Department of Public Works
City Hall Building, Suite 700
Norfolk, Virginia 23510

Attention: Mr. John M. White, Director, Storm Water Division

Subject: Lafayette River Tidal Protection Alternatives Evaluation, City of Norfolk, City-wide Coastal Flooding Project, Work Order No. 7

Dear Mr. White:

Enclosed is Fugro Consultants', Inc. (Fugro) report documenting our Lafayette River Tidal Protection Alternatives Evaluation. This report was authorized by Work Order No. 7, dated April 24, 2013 of the City-wide Coastal Flooding contract (City of Norfolk Contract 13062). This report provides our evaluation of tidal protection alternatives for the Lafayette River watershed. Our report provides a description of various tidal protection alternatives, locations, and potential synergies with other infrastructure projects. This report also summarizes the screening for the various options relative to their technical merit, flexibility, and projected costs. The report also includes consideration of several different criteria for flood mitigation in terms of severity of storm and potential future sea level rise.

The work, as documented herein, builds on the tide gauge measurements of water levels within the City and the development of a GIS-based mapping capability to translate those measurements to flood depth predictions for various tide levels, as measured at Sewells Point. The results of those measurements and their implications were provided in Fugro's July 2010 *Preliminary Coastal Flooding Evaluation and Implications for Flood Defense Design* report (Fugro, 2010), which provides the starting point for the current evaluation and study. In addition to the technical considerations of flood mitigation alternatives, as discussed herein, the information from this study (and the broader City-wide Coastal Flooding study) also is directly relevant for various planning studies and emergency response preparations within the Lafayette River watershed of the City.

On behalf of the project team, we thank you for the opportunity to be of service to the citizens of Norfolk.

Sincerely,

Kevin R. Smith
Associate Engineering Geologist

Crystal Cox, P.E.
Senior Engineer

Dave Sackett, P.G.
Vice President, Fugro Consultants, Inc.

Copies Submitted: Five (5)

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

The City of Norfolk (City) is surrounded by several different bodies of water and their many tributaries. Because the City is low-lying, nearly all portions of the City are below elevation +15 feet and drainage gradients are limited. Thus, a significant percentage of the City is susceptible to flooding from high tides, nor'easters, hurricanes, and other storm events. The flooding ranges from nuisance flooding to severe, albeit less frequent, flooding from hurricanes and major nor'easters. The frequency, extent and duration of flooding has been documented to be increasing due to both natural factors and man-induced conditions

In recognition of those considerations, the City initiated a City-wide Coastal Flooding Evaluation in 2008. The information from the City-wide Coastal Flooding study is considered relevant for not only developing design criteria and designs of public works improvements but also provides important information for various planning studies and emergency response plans within the City.

The initial phase of the City-wide Coastal Flooding program included conducting a series of tasks intended to help the City programmatically: anticipate flooding scenarios, prioritize problem areas, define design criteria, and develop objectives for various remediation flood defense improvements. The activities envisioned by the program recognized that: 1) the ability to predict flooding and water depths is only as accurate as the data used to develop those predictions and 2) the availability of tidal records within and surrounding the City has historically been limited to the data provided by three (3) long-term tide gauges at Sewells Point, Money Point, and the Chesapeake Bay Bridge Tunnel. Thus, the initial work orders for the Contract included the deployment of tide gauges to measure water levels and provide a basis for predicting tides throughout the City relative to those at Sewells Point and the development of a GIS-based mapping capability to translate those measurements to predict flood depths for various tide levels, as measured at Sewells Point.

Evaluations of coastal flooding susceptibility within the City and implications for the design of future flood defense improvements were described in the Fugro report *Preliminary Coastal Flooding Evaluation And Implications For Flood Defense Design*, dated July 2010. That report: 1) provided a historical and regional perspective of tidal flooding, 2) summarized and evaluated the initial measurements and implications obtained from additional tide gauge deployment, 3) presented relationships between tidal water levels and storm return period, 4) discussed implications of future sea level rise, and 5) provided maps of predicted water depths within the City for various combinations of storm return period and future sea level rise. The report also described the implication of those findings relative to: 1) establishing flood design criteria, 2) developing flood mitigation strategies, 3) potential flood defense options, 4) public policy opportunities and 5) criteria for prioritizing flood mitigation areas and projects.

A second phase of the City-wide Coastal Flooding Contract began the evaluations of mitigation options for specific watersheds and locations within the City. The Lafayette River watershed was defined to be one of those areas for evaluation. The objectives and priorities for flood improvements to the Lafayette River watershed will depend on technical considerations, as described herein, that define flood risk (frequency, severity, and extent of flooding) and flood hazards. These technical factors together with the many societal factors that define the consequences (and their acceptability, or not) of flooding, along with the costs of flood mitigation measures must all be considered and evaluated when defining and prioritizing flood mitigation approach and priorities.

There are many ways to reduce the risk, severity, and consequences of flooding. Those approaches can be broadly divided into several categories, such as: 1) drainage and water conveyance system improvements, 2) elevation of the ground surface and structures, 3) construction of barriers to prevent flooding, 4) impoundment and storage of flood waters, 5) adaptive land use to accommodate flooding, and 6) public policy actions. Due to the size of the river mouth opening, anticipated complexities associated with constructing a tidal barrier in this watershed, and anticipated costs with such a tidal barrier, this study focuses on identifying a preferred crossing location and key attributes (e.g. relationship between flood barrier opening size and effect on tidal flushing and circulation) for a flood barrier system.

The present report documents the specific nature of coastal flooding and associated damage estimates and conceptual level evaluation of tidal barrier alternatives in regards to the Lafayette River watershed.

1.2 EVALUATION OF CONCEPTUAL FLOOD MITIGATION OPTIONS FOR THE LAFAYETTE RIVER

The Lafayette River watershed (Figure 1-1) which covers 8,700 acres and is one of Norfolk's largest watersheds, includes Old Dominion University's Campus as well as the Colonial Place, Lambert's Point, Larchmont, and Lochhaven neighborhoods. It also contains local landmarks located along the shoreline like the Virginia Zoological Park and the Hermitage Museum. Important transportation routes susceptible to flooding are also located in the watershed that provide access to the world's largest naval base Naval Station Norfolk, Port of Virginia's Norfolk International Terminals (NIT), Norfolk General Hospital, Eastern Virginia Medical School, Children's Hospital of the Kings Daughters, and Depaul Medical Center. The Lafayette River drains to the Elizabeth River, which is directly connected through Hampton Roads to the Chesapeake Bay. Inundation by rising waters in the bay combined with high tides and coastal storm surge events are the main sources of flooding within the Lafayette River watershed. A project overview plan is shown in Figure 1-2.

Flooding in the Lafayette River area is frequent; and varies from nuisance flooding to significant damage caused by high water. Flooding is caused by the combined effects of high tides, storm surge and heavy precipitation. The effects of these high tides (coastal flooding) are expected to worsen over time as mean sea level rises. In addition, the effects of sea level rise will be compounded by regional and local ground subsidence, themselves resulting from events in geologic time, and ongoing settlement of localized, man-made fill.

This study discusses potential storm protection controls, notably a storm surge barrier floodwall installed at or near the mouth of the Lafayette River.

This study demonstrates that infrastructure improvements consisting of a flood wall – with a gate to be closed during coastal surge events – can mitigate coastal flooding including much of the worst effects of extreme extra-tidal events from hurricanes and nor'easters. These improvements are technically feasible and are expected to have public support and favorable benefit to cost (B/C) ratios.

1.3 ALTERNATIVE CROSSINGS EVALUATED

This study began by including up to 7 different crossing options (A through G) for different levels of effect and flood protection (Figure 1-3) for the Lafayette River watershed. Based on overall damage reduction, critical facilities protected, and cost, two alignments (A and B) for the proposed flood barrier were deemed the best options. Crossing Option A is located at the mouth of the Lafayette River and Option B is located along the Hampton Boulevard Bridge.

This study also considered potential synergistic opportunities that would create infrastructure that could serve multiple purposes (e.g. flood protection and a new transportation pathway). Based on discussions with the Hampton Roads Transit Authority it was determined that a light rail route which would extend service from the Norfolk General Hospital area north to ODU and the Navy Base via a water crossing between Lamberts Point and the NIT Terminal would not be desirable. HRTA indicated that it would not be acceptable for rail service to be interrupted by gate openings to allow vessel traffic to pass into/out of the river opening. Therefore, a bridge would need to be constructed high enough to allow sail boats to pass beneath it and horizontal and vertical grade change restrictions would make it very difficult to design and costly to construct such a structure that would also have significant viewshed impacts. Additionally, HRTA did not anticipate that the potential ridership would economically justify the extension of light rail through this corridor. Alternatively, a heavy rail haul corridor that connects Norfolk Southern's coal terminal to a rail line north of Lafayette River would provide an alternative haul route if one of the rail lines was inaccessible due to flooding or other reasons.

A flood barrier crossing at the Hampton Boulevard Bridge (Option B) would have the shorter water crossing. However, the overland portion of this crossing would have potentially significant utility relocation issues, impacts to traffic for a wall section constructed along Hampton Boulevard, and/or restrict homeowner's access to the street if a wall is constructed along the western side of Hampton Boulevard. Another potential aspect that may make this option undesirable is that a barrier crossing at Hampton Boulevard Bridge would not provide protection to large number of people in the watershed located outside the barrier (e.g. Larchmont and Lochhaven neighborhoods).

A flood barrier crossing between Lamberts Point and NIT terminal would protect the largest percentage of properties and facilities of the alignments considered in this study. However, the crossing represents the longest water crossing option of the alignments considered. The barrier would require openings to permit tidal flushing and a gate to provide vessel access. Soft, weak ground conditions would make a mixed earthen fill and hard structure (e.g. for tidal and navigation gates) very challenging to prohibitive to construct due to anticipated settlements that the earthen fill would likely experience.

For the two down-selected crossing location options A (mouth of Lafayette River) and B (Hampton Boulevard Bridge), this study conducted preliminary hydraulic and hydrodynamic analyses to evaluate the impact of varying levels of storm events and tidal flushing of a wall and gate structure at the Lafayette River mouth and at the Hampton Boulevard Bridge crossings.

Three different configurations of hydraulic transparency (96% solid wall, 46% solid wall, and 17% solid wall) were considered for crossings A and B which comprise a total of six alternatives (See Section 8.0). These screening-level simulations indicate that depending on the percent transparency of the proposed flood structure during open conditions, the tidal flushing and normal flow of the watershed could be affected. The model simulation indicates that the storm surge barrier with approximately equal parts solid wall (46%) and radial/lift gate openings (54%) was not likely to be a prohibitive barrier to the normal tidal flushing and range even in the most upstream reaches of the Lafayette River. Also, the proposed structure could impact subaqueous bottomlands and potentially limited wetland areas along the shoreline area. This study has not evaluated potential environmental impacts that would preclude the implementation of the preferred option described in this study, however, further environmental assessment of the chosen alternative will be required.

2.0 INTRODUCTION AND BACKGROUND

2.1 PROJECT BACKGROUND

The City of Norfolk (City) is surrounded by many different bodies of water including the Chesapeake Bay, the Hampton Roads harbor, the Elizabeth and Lafayette Rivers and their many tributaries as well as several small lakes. Because the City is located in a low-lying physiographic region, drainage gradients are limited and nearly all portions of the City are below elevation (El.) +15 feet. Thus, a significant percentage of the City is susceptible to flooding from high tides, nor'easters, hurricanes, and other storm events. The intensity of flooding ranges from nuisance flooding, typically associated with high tides, to severe, albeit less frequent, flooding from hurricanes and major nor'easters.

In recent years, the City has recognized an increased need to address coastal flooding problems. In 1992 the City created the Environmental Storm Water Fund as a dedicated source of funding for water quality and quantity improvements. Historically, the City has addressed flood mitigation through stand-alone, small to intermediate-sized capital improvement projects. Today, remaining flood mitigation projects are numerous, complex, and may require considerably larger capital improvement budgets. Like all municipalities in the region, the ability to fund flood mitigation and flood defense improvements constrains implementation of such projects.

In addition, relative sea level in the local area is rising (at a current projected rate of 1.45 feet per 100 years (NOAA, 2010a). Assuming that this trend continues (or increases), both nuisance flooding and flooding from storm events will increase. This will further increase the need to address the issue of coastal flooding on a both project-specific and a holistic, watershed-scale basis.

Extreme storm events, such as the November 2009 Nor'easter have: 1) reinforced the City's decision to proactively evaluate coastal flooding and 2) elevated the City's needs and priorities for flood defense mitigation. Moreover, events such as Superstorm Sandy in 2012 reinforce that the US East Coast is susceptible to major storm events, and if not mitigated appropriately, can be devastating. It is well documented that flood mitigation dollars investigated before a storm are approximately 1/10 of the amount that it costs to recover and restore after a major storm event.

2.2 CITY-WIDE COASTAL FLOODING PROGRAM

2.2.1 Previous Phases

In 2008, the City began to develop a City-wide evaluation to: anticipate flooding scenarios, help prioritize problem areas, develop design criteria and define objectives for various remediation flood defense improvements. The City-wide flood evaluation was recognized to require a phased and iterative approach to be conducted over several years. The initial efforts of the City-wide coastal flooding contract included the procurement, installation, and monitoring of tide gauges at five locations within the City to define local variations of the tide levels relative to those at Sewells Point, which has the longest history of tidal measurements in the Hampton Roads region. The Sewells Point tide measurements are also the reference that has been and is used to communicate predicted tide levels to the City, the media, and to the population in general.

The City of Norfolk's (City) City-wide Coastal Flooding (Contract 11254) with Fugro Consultants, Inc. (and its sub-consultant Moffatt & Nichol) was initiated in 2008 in recognition of the City's increasing susceptibility to flooding. Of concern were the impacts due to both: 1) the recurring combinations of various tidal and meteorological conditions and 2) potential large nor'easter and tropical events.

The program of activities envisioned by the Contract recognized that: 1) the ability to predict flooding and water depths is only as accurate as the data used to develop those predictions and 2) the availability of tidal records within and surrounding the City has historically been limited to the data provided by three (3) long-term tidal gauges at Sewells Point, Money Point, and the Chesapeake Bay Bridge Tunnel. Thus, three (inter-related) work orders issued by the City included: Work Order No. 1- development of a program for installing and monitoring tide gauges, Work Order No. 4 - the installation of those tide gauges, and Work Order No. 3 - the development of a GIS-based model to be subsequently used to apply the knowledge gained from the tidal measurements for anticipating and predicting flooding, prioritizing flood projects, and developing flood remediation measures.

The results of these studies and activities were documented in Fugro's July 2010 *Preliminary Coastal Flooding Evaluation and Implications for Flood Defense Design* report (Fugro, 2010).

2.2.2 Current Phase

With the culmination of the initial evaluation's work order, the focus of the City-wide Coastal Flooding contract has evolved to focus on: 1) flood mitigation alternative evaluations/concept development for different areas of the City and 2) prioritizing projects for different areas and approaches within and throughout the City. This current report provides the alternatives evaluation of a flood barrier concept for the Lafayette River watershed. The location of this drainage basin within the City is shown on Figure 1-1. Figure 2-1 shows the extent of the drainage basin and Figure 2-2 shows the area at the outlet of the basin.

2.3 AUTHORIZATION

Work Order No. 7 for the City-Wide Coastal Flooding Study was issued by the City on April 24, 2013. The intent of this current work order is to provide an evaluation of flood barrier crossing alternatives for that can be used by the City for evaluation, budgeting and project development scheduling. The Fugro team's work scope included the following activities:

- Task A - Site characterization tasks,
- Task B – Hydrological/hydraulic analyses, and
- Task C – Evaluation of flood barrier alignment alternatives,
- Task D - Summary report.

As per the City's request, our alternatives evaluations will consider two levels of flood protection, specified as follows:

- A 100-year design, as required for a FEMA certified floodwall, and
- A 10-year design event.

2.4 INCORPORATED DOCUMENTS

The following external documents are incorporated into this report by reference:

The report *Preliminary Coastal Flooding Evaluation and Implications for Flood Defense Design*, dated July 2010, described preliminary evaluations of coastal flooding susceptibility within the City and its implications for the design of future flood defense improvements. Design water levels for the Lafayette River area and other project areas are based on measurements and analysis presented in this report, hereinafter referred to as the Preliminary Flooding Evaluation.

3.0 LIST OF ACRONYMS

3.1 LIST OF ACRONYMS

- FEMA = Federal Emergency Management Agency
- FIRM = Flood Insurance Rate Map
- FIS = Flood Insurance Study
- SWL = Still Water Level, as determined in effective FEMA FIS
- BFE = Base Flood Elevation, as determined in effective FEMA FIRM and FIS
- FB = freeboard
- SLR = Sea Level Rise
- SP = Sewells Point
- LF = linear feet, e.g. to describe the running length of a floodwall
- % a.c. = percent annual chance of exceedance; terminology used by FEMA to describe exceedance frequency, e.g. 100-year “return period” has 1% annual chance
- 100-year Return Period (RP) = 1% annual chance of occurrence
- 50-year Return Period (RP) = 2% annual chance of occurrence
- 25-year Return Period (RP) = 4% annual chance of occurrence
- 10-year Return Period (RP) = 10% annual chance of occurrence
- 5-year Return Period (RP) = 20% annual chance of occurrence
- 2-year Return Period (RP) = 50% annual chance of occurrence
- 1-year Return Period (RP) = 100% annual chance of occurrence

4.0 THE LAFAYETTE RIVER WATERSHED LOCATION AND DESCRIPTION

4.1 WATERSHED DESCRIPTION AND RECEIVING WATER BODY

The Lafayette River watershed is located in the west-central portion of the City of Norfolk (Figure 1-1). The watershed includes 26,624 parcels within the 8,787 acres of land in the watershed. Approximately 81,000 residents of the City live within the drainage basin (as defined by the City's Planning Department). Since a logical barrier crossing option from NIT to Lambert Point is an option considered in this study, the area between approximately Hampton Boulevard, Norfolk Southern rail lines and the shoreline along Lafayette/Elizabeth River confluence are also included in this study (Figure 1-2).

The Lafayette River is the receiving body of water which subsequently feeds into the Chesapeake Bay. Both bodies of water are tidally influenced and subject to storm surges.

4.2 TOPOGRAPHY AND BATHYMETRY

4.2.1 Topography

The topography of the Lafayette River watershed is generally flat and below elevation (El.) +14 feet NAVD88. Figure 4-1 presents the topography from a 2009 LiDAR-based survey conducted by Pictometry, Inc under contract to the City of Norfolk. Elevation ranges are color coded by 1 foot intervals on Figure 4-1. A statistical summary of the ground surface elevation is provided in Table 4-1 and also presented in Figure 4-2. Approximately 23 percent of the study area lies below El. +8 feet NAVD88. The eastern portions of the watershed's ground surface slopes gently to the west, the northern portion slopes to the south, and the southern portion slopes gently to the north into the Lafayette River. For reference, the maximum 100-year return period (1% annual chance) still water elevation in the watershed is given as +8.8 ft NAVD88 in the August 2014 effective FEMA Flood Insurance Study for the project area.

The watershed is made up of several surface drainage systems that trend west and northwest. Low lying areas are present along the entire interior Lafayette River shoreline area. Ground surface slope varies throughout the watershed.

Table 4-1: Summary of Watershed Topography

Elevation (ft, NAVD88)	Number of Acres	Cumulative Number of Acres	Percent of Watershed	Cumulative Percent
Lower than 3	381	381	4.3%	4.3%
3 to 4	151	532	1.7%	6.1%
4 to 5	203	735	2.3%	8.4%
5 to 6	299	1,035	3.4%	11.8%
6 to 7	404	1,438	4.6%	16.4%
7 to 8	553	1,991	6.3%	22.7%

Elevation (ft, NAVD88)	Number of Acres	Cumulative Number of Acres	Percent of Watershed	Cumulative Percent
8 to 9	747	2,738	8.5%	31.2%
9 to 10	1,030	3,769	11.8%	43.0%
10 to 11	1,460	5,228	16.7%	59.7%
11 to 12	1,422	6,650	16.2%	75.9%
12 to 13	1,053	7,703	12.0%	87.9%
13 to 14	690	8,393	7.9%	95.8%
14 to 15	219	8,612	2.5%	98.3%
15 to 40	151	8,764	1.7%	100.0%

4.2.2 Bathymetry

The bathymetry of the Lafayette River is markedly shallow until reaching the mouth of the river where deeper navigation channels and shipping berths are maintained for the NIT shipping terminal and the deeper channel of the Elizabeth River. Modern bathymetric data were not available for the mouth of the Lafayette River. Therefore, during May 2013, Fugro conducted a regional hydrographic survey of the mouth of the Lafayette River. Bathymetric data were collected using an R2Sonic 2024 multibeam echosounder along regional survey lines. Figure 4-3 presents the multibeam data collected in 2013 that were combined with NOAA and USACE bathymetric data to create an integrated set of bathymetric data.

Bathymetric elevation in the surveyed area range from El. -2 feet to -62 feet NAVD88 (Figure 4-3). In the area between the NIT Terminal and Lamberts Point, where one of the conceptual alignment crossings is located, the riverbottom is relatively flat and water depth is less than 10 feet with the exception of 2 deeper areas associated with Lafayette River Navigation Channel and a trench depression inferred to be related to Dominion's power cable crossing.

Water depths in the Lafayette River Navigation Channel are approximately 10 to 12 feet deep. Another notable feature observed in the bathymetry near the river mouth is a trench scar related to the burial of Dominion's high voltage submarine transmission cable (Figure 4-3).

Water depth in the berths in front of the NIT terminal and Norfolk Southern Rail Terminal have been dredged to about 55 feet. A flood barrier crossing that connects to the Norfolk Southern Terminal at Lamberts Point would have to cross the deep dredge cut where the water depth increases from 16 to 55 feet over approximately a 900-foot horizontal distance.

The multibeam data also reveal mound-like features (inset in Figure 4-3) that are approximately 2 to 4 feet high and 50 to 75 feet in diameter that may be related to oyster beds. Pock-mark features likely related to gas/fluid escape and/or barge spuds are also common in the area west of where the conceptual flood barrier crossing is located.

4.3 LAND USE

The number of acres and percent of the watershed with the following land use classification (as defined by the City's Planning Department) is summarized in Table 4.2. Figure 4-4 presents a map of the land use in the Lafayette River watershed. Table 4-2 indicates that the land use in the watershed is primarily low density residential. All together the low, medium, and high density residential comprised approximately 49 percent of the land use in the watershed. Roadways comprise the next second largest amount of land use. Open space/recreational represents the third largest land use in the watershed, with smaller percentages of commercial, industrial, institutional, and vacant land uses.

Table 4-2: Lafayette River Watershed Land Use Classifications

Usage	Number of Acres	Percent of Watershed
Low Density Residential	3524	40.2%
Medium Density Residential	423	4.8%
High Density Residential	335	3.8%
Commercial	416	4.8%
Institutional	572	6.5%
Open Space/Recreational	793	9.1%
Transportation/Utility	48	0.5%
Industrial	359	4.1%
Mixed Use	14	0.2%
Vacant	274	3.1%
Roadways	2,000	22.8%

Note: The land usage statistics represent only the area of land within the watershed and do not include the Lafayette River body of water.

4.4 BASIN RIM DESCRIPTION

The perimeter of the watershed is about 139,200 feet (26.4 miles). The northern perimeter is delineated approximately by Little Creek Road on the north. The eastern perimeter is located approximately along North Military Highway, Interstate-64, and Azalea Garden Road. The southern rim of the watershed roughly follows the CSX Norfolk Southern rail-line. The western rim of the watershed crosses the Larchmont area (approximately along Hampton Boulevard), and the outlet of the watershed has been defined in this study as a line crossing the river from Larchmont to Norfolk International Terminal (NIT).

Depending on the level of flood protection (i.e., the water level elevation at the basin outlet), there will be a number of areas along the basin rim that will be lower than the elevation of the flood protection at the basin outlet. The number of locations along the basin rim and the length of the segments below different threshold elevations are summarized as in Table 4.3 and Figure

4-5. Refer to Table 5-1 for corresponding return-periods (e.g. 100-year, 50-year, etc.) that correspond to water levels listed in Table 4-3.

Table 4-3: Low Ground Surface Conditions along Watershed Perimeter

Elevation (ft, NAVD88)	Length of Perimeter (Feet)
Less than 2.2[a]	2,132
Less than 4.2 [a]	2,515
Less than 4.8	2,639
Less than 6.2	2,684
Less than 7.0	3,448
Less than 7.6	3,448
Less than 8.2	7,246

[a] Rim elevation occurs along the western shoreline perimeter near Larchmont; an interior drainage (white dashed line shown in Figure 4-5 is at a higher elevation)

Perimeter lengths of the watershed with elevations below a given elevation increase as elevations increase (Table 4-3) Depending on the elevation selected, additional floodwalls, berms, or road raising would be needed, and the additional required lengths for alternate protection scenarios can range from 100 to over 2,000 feet.

A shoreline comparison over the last 117 years (1894 to 2011) is shown on Figure 4-6. Receding land and reclamation areas are both shown along the river banks.

4.5 SITE CONDITIONS AT BASIN OUTLET

The basin outlet represents the mouth of the Lafayette River, where the river outlets into the Elizabeth River. This location in the hydraulic and hydrodynamic model used in this study spans the river between Tanner Point and Boush's Bluff (Figure 2-2).

4.6 NAVIGATION REQUIREMENTS

The Lafayette River accommodates a significant amount of recreational vessel traffic and limited commercial crabbing. A vessel navigation channel maintained to El. -8.5 feet MLLW and 100 feet wide (according to a NOAA nautical chart) extends approximately 7,000 feet upstream from the mouth of the river to the vicinity of the Norfolk Yacht Club. Also, recreational boats gain access to the waterway at the Haven Creek boat ramp which is located in the Lafayette River and Old Dominion University Sailing Center located near the Lambert's Point Golf Course.

Flood barrier considerations include maintaining boating access to the Lafayette River. A barrier across the mouth of the Lafayette River that would accommodate rail access would need to maintain sail boat access to by either implementing a movable rail bridge or a bridge with adequate clearance for sail masts.

4.7 SUBSURFACE GEOTECHNICAL CONDITIONS

Subsurface conditions in the Lafayette River area are generally understood to include weak, compressible materials that can be several tens to more than a hundred feet thick and are underlain by stronger, more competent materials (Yorktown formation). Structures founded on the weak, compressible soils can experience significant settlement. Heavily loaded structures in this region are commonly built on piled foundations that are embedded in the more competent layers (e.g. Yorktown formation) (Figures 4-7 through 4-8). However, the depth to the competent layer is often highly variable due to fluvial erosion during the last major sea level lowstand (approximately 18,000 to 12,000 years ago [ka]). The thick, weak, compressible soils with a variable thickness make understanding the site's geologic conditions a critical component to project planning and design and those conditions can make certain aspects of the flood barrier foundation system design and construction complex and costly. In particular, mixed foundation systems that use a combination of piled systems to support hard structures and earthen systems constructed on the weak, compressible soils (such as those used for causeways) can lead to complexities of how those two components interact and make such a system prohibitively expensive.

To develop a preliminary understanding of the subsurface conditions in the study area, Fugro conducted a preliminary seismic survey and reviewed available geotechnical and seismic data that were synthesized by the project team. The seismic survey was conducted at the mouth of the Lafayette River along the vessel tracklines in Figure 4-9. The seismic data were collected using a Chirp sub-bottom profiler that imaged to a depth of 20 to 60 feet. Figure 4-10 presents an interpretation of a Chirp seismic record collected during the survey. The Chirp data were integrated with Fugro's proprietary seismic data collected using a boomer, multi-channel seismic reflection survey data that imaged to a depth of over 300 feet.

Limited geotechnical data are available in the study area. Primary sources of information were 1967 boring logs from existing Hampton Boulevard Bridge design plans and a variety of borings at the NIT terminal and Lamberts Point. (Figures 4-7 and 4-8). We also reviewed a comprehensive suite of geotechnical data collected for and used in the design of the Craney Island Eastward Expansion project in relatively close proximity to the planned flood barrier (where Fugro is the lead geotechnical consultant and Moffatt & Nichol are the lead designer). Stratigraphic relationships were then interpreted and presented on Figures 4-7 (Hampton Boulevard Bridge) and Figure 4-8 (NIT Terminal and Norfolk Southern Railyard) which is also the basin outlet for the Lafayette River watershed.

Using the available geotechnical data combined with seismic data (Chirp and boomer), the elevation for the top of the Yorktown formation was defined (Figure 4-9). The elevation of the top of the Yorktown formation varies by as much as 75 feet near the mouth of the Lafayette River. Near the NIT Terminal the top of the Yorktown is at approximately El. -100 feet MLLW. On the southern end of the Lafayette River outlet, near Lambert's Point, the top of the Yorktown is at approximately El. -65 feet MLLW.

4.7.1 Geology and Subsurface Stratigraphy

Based on the information reviewed, the subsurface stratigraphy is generally comprised of three stratigraphic units at the Hampton Boulevard Bridge and NIT-Lamberts Point barrier alignments. In descending sequence, the units are artificial fill, Quaternary age alluvium, Pliocene age Yorktown Formation. The artificial fill represents the embankment and fill materials placed along the shoreline. Exploration logs suggest the material is primarily sand soils with various amounts debris (e.g. brick, gravel, etc.). The artificial fill ranges from about 8 to 20 feet thick. Artificial fill does not appear to be of appreciable thickness in the Lafayette River channel.

Quaternary age alluvium generally underlies the artificial fill. The alluvium is primarily comprised of soft, fine grained silt and clay generally referred to as Norfolk Clays. Locally, sandy layers up to 10 feet thick may be present (e.g. beneath the NIT terminal). The thickness of the soft fine-grained sediments encountered by the explorations, range from 40 to 110 feet. The base of this unit likely represents an erosional surface and ranges in elevation from El. -40 to -110 feet. Due to the low strength and high variability in thickness, understanding the engineering properties and thickness of this unit may be critical to future foundation designs in this area.

Pliocene age Yorktown formation sediments underlie the fine-grained alluvium. The Yorktown formation is generally comprised of marine silty sands. Regionally, this unit is commonly the end-bearing strata for many piled foundations. As discussed in the previous section, the elevation of the interface between this unit and the overlying soft alluvium (Figures 4-7 through 4-9) can vary significantly in the basin outlet area and will likely play an important role in foundation designs.

4.7.2 Foundation Considerations

The soft compressible soils comprising the Quaternary age Norfolk Clay layer are limited in their ability to support loads. Typically, shallow foundations bearing in this layer can only support light loads without experiencing excessive settlement. Therefore, it is common for foundations supporting moderate or greater loads to be founded on piles that are embedded in the deeper Yorktown formation. Figure 4-9 presents the elevation of the top of the Yorktown formation interpreted based on seismic reflection and geotechnical data.

5.0 COASTAL FLOODING: TIDE- / SURGE-DRIVEN TAILWATER ELEVATIONS

5.1 PREVIOUS INTERPRETIVE REPORT AND STUDY IMPLICATIONS

The *Preliminary Coastal Flooding Evaluation and Implications for Flood Defense Design* report (Fugro, 2010) provided our preliminary evaluations of coastal flooding susceptibility within the City and its implications for the design of future flood defense improvements. The information from the City-wide Coastal Flooding study is considered relevant for not only developing design criteria and designs of public works improvements but also provides important information for various planning studies and emergency response plans within the City.

5.2 TIDES AND SURGE-DRIVEN WATER LEVEL ELEVATIONS

The Lafayette River watershed drains to the Elizabeth River, which is directly connected through Hampton Roads to the Chesapeake Bay. Inundation by rising waters in the Bay in high tide and coastal storm surge events is a primary source of flooding in the Lafayette River. Long-term measured water levels, supplemented with shorter periods of record from gauges at points around the City, were used in developing extreme event water levels to apply in flooding evaluations, analysis of alternative flood mitigation approaches, and preliminary design of structural and hydraulic elements of the preferred alternative.

5.2.1 Long-term Measured Water Levels at Sewells Point

The most relevant long-term tide gauge to this project site is NOAA #8638610 at Sewells Point. This data set was analyzed using extreme-value statistical methods to estimate water level return periods. Daily maximum measured water levels are available for this location since the original gauge deployment in 1928. The historical data were adjusted to account for historical sea level rise and peak storm water levels were extracted for the statistical analysis. The results of those analyses, which show the relationship of water level (adjusted to the current elevation of sea level) versus return period, are listed in the following table and shown in Figure 5-1.

Table 5-1: Tide Elevations at Sewells Point for Various Return Periods

Return Period (years)	Water Level at Sewells Point (ft, NAVD88)
MHHW	1.2
1	3.2
2	3.8
5	4.6
10	5.2
25	6.0
50	6.6
100	7.2

Previous work orders under this contract (see Incorporated Documents) included the installation of five tide gauges within various watersheds. These gauges have provided quantitative data to measure and predict tides throughout the City relative to those at Sewells Point which – having the longest history of tidal measurements in the area – is the reference location used to communicate predicted tide levels. The approximately 1.5 years of measured tide data at the newly installed gauges include both the normal day-in variations of tidal and meteorological conditions as well as several unusual extreme conditions. During this period, the tide gauges captured the November 2009 nor'easter that produced the fourth highest recorded water level at the Sewells Point tide gauge, since it was established in 1928.

5.2.2 Short-term Water Level Measurements in Other Parts of the City

The 2009 - 2012 tide gauge data provide a unique picture of the propagation of flood waters from the Chesapeake Bay and the main stems of the Elizabeth River into the various water bodies within the City. Measured water levels at the five gauge locations vary from less than 0.1 foot below the water level at Sewells Point to localized water levels nearly 1.5 feet above Sewells Point in the small Haven's Creek cove. At other gauge locations, water levels are interpreted to generally range from 0.3 to 0.6 feet above that at Sewells Point. The elevated water levels (as compared to Sewells Point) throughout most of the City have important implications for flood defense design criteria and flood defense performance.

The tide gauges at Tidewater Drive Bridge, Colonial Place and the Haven Creek Boat Ramp are located within the Lafayette River watershed. The statistical analyses of the measurements at these gauges relative to those at Sewells Point indicated that the peak and low water levels at this location are on average 0.6 foot above those at Sewells Point.

The differences of the tide level offset between the local tide gauge and Sewells Point can be due to many local factors, such as wind driven setup (which varies with wind direction and location), localized storm water discharge effects, and local geometric amplifications the effects of wind direction and local geometric amplification (e.g., cove effects). For design applications it is appropriate to consider those temporal variations between the local tide and those at Sewells Point. A 1.1 foot increase in tailwater elevations, above the base Sewells Point value, is recommended for the Lafayette River watershed to account for temporal, local effects.

5.3 CONSIDERATION OF FUTURE SEA LEVEL RISE

Prediction of the rate of potential future sea level rise (and/or future regional subsidence or more local ground settlement) is not part of the current analyses. However, it is appropriate to recognize that if sea level rise continues or accelerates it will increase the frequency and severity of flooding events. Thus, it is appropriate to acknowledge how the potential for future sea level rise may increase flooding within the City.

Published data and evaluations (NOAA, 2010) interpret that the recently determined rate of relative sea level rise at Sewells Point is 1.46 feet/century. To evaluate how a continuation of that rate of sea level rise will affect flooding in the City, the return periods associated with various tide elevations at Sewells Point have been computed assuming a 0.5 foot and a 1.0 foot rise in future sea level. At the NOAA estimated rate of 1.46 feet/century, these rises correspond approximately to the years 2045 and 2080, respectively.

USACE and IPCC have prepared reports that include sea level change curves based on research (USACE, 2011 and IPCC, 2014). USACE recently evaluated tide gauges in the Hampton Roads area and interpreted the contribution of land subsidence to relative sea level rise.

Figure 5-2 presents three curves for Sewells Point based on USACE guidance documents (USACE, 2011). The USACE curves were based on IPCC (2009) eustatic sea level change curves.

In 2014, the IPCC released a new set of curves based on new research. Figure 5-2 presents relative sea level rise curves based on the IPCC (2014) information and USACE (2011) land subsidence rates. The comparison of the USACE and IPCC curves in Figure 5-2 indicate the range in the projected sea level rate for the IPCC is less than the USACE information which are based on the previous generation of RCP curves. The range is sea level rise projected in 2040 based on the IPCC curves is approximately 0.2 foot.

The return periods associated with varying tide elevations at Sewells Point – and their modification based on discreet values of future sea level rise – are summarized in Table 5.2 and Figure 5-3.

Table 5-2: Predicted Storm Surge Levels and Return Periods, Current Sea Level Elevation and after 0.5- and 1.0-Foot Increases in Relative Sea Level

Sewells Point Tide Elevation, (ft, NAVD88)	Approximate Return Period (years)		
	Based on Current Sea Level	After 0.5-foot rise in Sea Level (est. 2045)	After 1.0-foot rise in Sea Level (est. 2080)
+5	8	5	2.5
+6	25	15	8
+7	80	50	25

Table 5.2 implies that continuation of the current rate of sea level rise will double the probability of exceeding a particular coastal flood elevation in any given year by about 2045. Put another way, the implication is that in a future with sea level rise, a less severe storm will be able to produce a specific total flood water level. Figure 5-2 illustrates the implications future sea level rise has on the flood water levels for various storm return periods. In addition to increasing the frequency of a specific flood event, future sea level rise also will increase the area of flooding for a specific size storm event.

5.4 COASTAL TAILWATER ELEVATIONS FOR THE LAFAYETTE RIVER WATERSHED

Historically, the tailwater elevation for drainage improvements in the City has been based on various water elevations (e.g., mean high water, mean low water, etc.) at Sewells Point. The measurement of water levels using tide gauges throughout the City (Fugro, 2012) has shown that water levels in the various drainage basins within the City are typically elevated over the measurements at Sewells Point. In addition, consideration of sea level rise here-to-before has not been considered in the design of storm water drainage and flood mitigation improvements. The following table documents how those effects have been accounted for in the current storm water and flood mitigation alternatives evaluation.

The following approach was taken to evaluate tailwater elevations for further study and design at the Lafayette River watershed. Starting with extreme total water level values determined from Sewells Point gauge data, a basin offset was added based on the findings of the May 2012 report as discussed above. Second, an additional offset was added to account for wind setup and/or cove setup effects. Finally, a 1.0 foot allowance for future sea level rise was considered. The 1.0 ft allowance for sea level rise is based on a continuation of the rate of sea level rise as documented over the last decade and a structure designed to last 50 to 60 years (NOAA, 2010a). The incremental and cumulative offsets for the Lafayette River watershed are indicated in Table 5-3.

Table 5-3: Tailwater Correction from Sewells Point and Allowance for Sea Level Rise at the Lafayette River Watershed

Consideration	Offset Relative to Sewells Point (ft)	
	Incremental	Cumulative
Basin Offset	0.6	0.6
Wind Direction and/or Cove Offset	0.5	1.1
Allowance for Future Sea Level Rise	1.0	2.1

The 1-ft allowance for sea level rise is based on a continuation of the rate of sea level rise as documented over the last decade and a structure designed to last 50 to 60 years (NOAA, 2010a).

The storm water system's ability to discharge precipitation runoff through the existing outfalls is hindered during high tides and surge events by the elevated tailwater. Figure 5-4 illustrates the tailwater phenomena and the implications it has on storm water drainage systems. Table 5-4 below details the recurrence interval tailwater elevations at Sewells Point and the resulting design tailwater elevations for the Lafayette River watershed (Fugro, 2010), based on Sewells Point water levels plus the basin offset and wind direction / cove offset from Table 5-3.

Table 5-4: Tailwater Elevations at Sewells Point and the Lafayette River Watershed

Return Period (years)	Sewells Point Water Level (ft, NAVD88)	Lafayette River Watershed Design Tailwater Elevation (ft, NAVD88)
MHHW	1.2	2.3
1	3.2	4.3
2	3.8	4.9
5	4.6	5.7
10	5.2	6.3
25	6.0	7.1
50	6.6	7.7
100	7.2	8.3

It was decided to conduct the hydrologic and hydraulic modeling studies without inclusion of future sea level rise, so that focus could be placed on determining the overall costs to meet the desired level of protection for present flooding levels.

6.0 COASTAL FLOODING: PRECIPITATION HYDROLOGY AND HYDRAULICS

Coastal flooding events with high tailwater elevations in the Lafayette River are likely to be associated with intense and/or prolonged rainfall events occurring over the Lafayette River watershed. Any engineered solution for mitigating coastal flooding in the Lafayette River watershed must account for this interaction between the storm water system and the elevated water surface (tailwater) in the receiving waters.

An extensive set of hydrologic and hydraulic analyses and model simulations have been conducted, characterizing flooding due to joint precipitation and elevated tailwater events. These analyses are summarized below for the watershed's existing condition.

6.1 RAINFALL AND PRECIPITATION

The synthetic 24-hour Soil Conservation Service (SCS) Type II rainfall distribution was used to generate rainfall-runoff hydrographs for the evaluation of design alternatives. The Type II distribution represents the most intense short duration rainfall (NRCS, 1986). The design rainfall duration-frequency depths were derived from precipitation frequency estimates published by the National Oceanic and Atmospheric Administration (NOAA) for the Norfolk International Airport (NOAA, 2004 - nearest station). These 24-hour rainfall amounts are listed in Table 6-1 below.

Table 6-1: NOAA Return Frequency Rainfall Accumulation for Norfolk International Airport

Average Recurrence Interval (ARI) (years)	24-hr Precipitation Frequency Estimate (inches)
1	2.93
2	3.57
5	4.62
10	5.51
25	6.82
50	7.96
100	9.21

6.2 ELEVATION OF PROTECTION

The coastal flood evaluation includes the consideration of three different levels of flood risk:

- a 100-year return period event, as required for a FEMA certified floodwall, and

- a 10-year return period event.

6.2.1 10-Year and 100-Year Return Periods

As noted, the water level elevations at Sewells Point that are associated with the 100-year and 10-year return periods are elevation +7.2 and +5.2 feet NAVD88, respectively. Those water levels at Sewells Point correspond to design water elevations in the Lafayette River watershed equal to elevation +8.3 and +6.3 feet NAVD88.

An additional +1.0 ft or more may ultimately be added to these elevations to account for uncertainty associated with the rate of future sea level rise. Adjustments to required barrier heights and extents may be made during the conceptual design of engineered solutions, but these adjustments are unlikely to significantly influence the hydrologic and hydraulic analyses underpinning the evaluation of conceptual alternatives.

6.2.2 Summary

The protection associated with an elevation +8.3-ft NAVD88 is approximately equivalent to a 100-year return period design based on current sea level. After a future 1-foot sea level rise (approximately year 2080), the +8.3-ft crest elevation corresponds to approximately a 31-year return period event.

The protection associated with an elevation +6.3-ft NAVD88 is approximately equivalent to a 10-year return period design based on current sea level. After a future 1-foot sea level rise (approximately year 2080), the +6.3-ft crest elevation corresponds to approximately a 3-year return period event.

6.3 DESIGN COMBINATIONS OF COASTAL WATER ELEVATION AND PRECIPITATION

Based on alternatives that may be considered for mitigation of coastal flooding, the project team determined that a fixed matrix of tailwater vs. precipitation would be utilized in the study. The simulation matrix includes individual simulations of six different rainfall conditions with (1) tailwater of mean higher high water (MHHW) tide and separately with (2) coincident return period tailwater and rainfall events (e.g., 2-year return period rainfall with 2-year return period coastal tailwater). These scenarios would serve to bracket the expected range of conditions that the proposed alternatives would likely be subjected to during a flood mitigation project's design life. The combinations of tailwater elevation and precipitation shown in Table 6.2 have been considered in the existing conditions hydrologic and hydraulic analyses.

Table 6-2: Design Combinations of Tailwater and Precipitation

Design Case	24-hr Design Storm Precipitation (in)	Tailwater Elevation (ft, NAVD88)
2yr RP rainfall, MHHW tide	3.57	+2.3
2yr RP rainfall, MHHW tide	3.57	+2.3
100yr RP rainfall, MHHW tide	9.21	+2.3
2yr RP rainfall, 2yr RP coastal surge	3.57	+4.9
10yr RP rainfall, 10yr RP coastal surge	5.51	+6.3

Design Case	24-hr Design Storm Precipitation (in)	Tailwater Elevation (ft, NAVD88)
100yr RP rainfall, 100yr RP coastal surge	9.21	+8.3

6.4 EXISTING SYSTEM HYDROLOGIC/HYDRAULIC EVALUATION

6.4.1 Selection of Model: XPSWMM

The XP-SWMM software package utilizes the EPA Stormwater Management Model version 5 (SWMM 5) one-dimensional (1-D) analytical engine for running rainfall-runoff simulations for single event or long-term simulations of runoff quantity and quality. XP-SWMM simulates runoff from subcatchment areas and routes it through systems of pipes, channels, pumps, and storage devices.

XP-SWMM also incorporates a two-dimensional (2-D) analytical module for the routing of surface flood flows, based on the TUFLOW program developed by WBM Oceanics Australia and The University of Queensland. TUFLOW is specifically oriented towards establishing the flow patterns in coastal waters, estuaries, rivers, floodplains and urban areas where the flow patterns are essentially 2-D in nature and would be difficult to appropriately represent using a 1-D model. A powerful feature of TUFLOW is its ability to dynamically link to the 1-D network of the XP-SWMM engine. In XP-SWMM, the user sets up a model as a combination of 1-D storm-drain network domains linked to 2-D domains, i.e. the 2-D and 1-D domains are linked to form one model.

6.4.2 Development of Model Inputs

The pipe network for the storm water collection system was modeled using the unsteady state 1-D XP-SWMM's link node modeling module. The 2-D surface model grid, representing street flooding, is linked to the nodes of the 1-D model (representing inlets). Runoff from the hydrologic portion of the simulation enters the 1-D hydraulic model within the pipe system. Storm water that surcharges from the pipe system then becomes surface flow in the 2-D model. The rate at which 2-D surface flow is recaptured by the pipe system is restricted by a maximum inlet capacity, based on the equation:

$$Q\ (cfs) = coefficient \times grid\ cell\ depth\ (ft)\ \hat{}\ exponent$$

The default parameters in XP-SWMM were applied, with the coefficient = 13.385, and the exponent = 0.5. Between the depths of 0ft - 2ft, this approximates an inlet area of roughly 3 sq.ft.

The primary inputs to the XP-SWMM model for this study include:

- Rainfall: time series of rainfall,
- Subcatchment Data: area, overland flow, % slope, % impervious, curve number,
- Junction Data: inverts, depth, ponded area,
- Conduit Data: shape, size, length, roughness, inverts, loss coefficients,
- Outfall-inverts, tide gate, tidal boundary condition,
- Building footprints within the Lafayette River watershed, and
- Topographic Data as a Digital Elevation Model (DEM).

The sources of data used for each of these categories of input are described below.

6.4.3 Rainfall Data

The precipitation frequency depths for the project were based on the published NOAA Atlas 14 values for Norfolk International Airport (NOAA, 2004), applied over the NRCS (formerly SCS) Type-II 24-hour rainfall distribution (USDA, 1986).

6.4.4 Subcatchments

The Lafayette River drainage area was divided into 4,939 smaller subcatchments based on the Light Detection And Ranging (LiDAR) topographic data collected by the City of Norfolk in 2009. Each subcatchment was analyzed to determine input parameters for XP-SWMM. Percent imperviousness and curve number were estimated from USGS data sets representing land use and imperviousness provided by the City. Percent slope was estimated from topography. Other model inputs for subcatchments were simply left as the default values.

6.4.5 Junctions

Junctions represent the point where runoff enters the storm water pipe network in each subcatchment. Junction locations, invert elevations, and rim elevations were derived from the stormdrain database provided by the City. The topography and stormwater junction rim elevations were examined to eliminate erroneous data points.

6.4.6 Conduits

The storm water infrastructure network present in each subcatchment was simplified in XP-SWMM by using one or two stormwater pipes per subcatchment. Conduit sizes and geometries were derived from the stormdrain database provided by the City.

6.4.7 Outfalls

The Lafayette River waterbody was included in the model as part of the 2-D hydrodynamic grid. Therefore, the outfalls that drain water from the watershed into Lafayette River were set up as 1-D nodes with their inverts linked to the 2-D grid. The inverts of the outfalls were determined from the stormdrain database provided by the City (Figure 6-1). The boundary conditions for the model simulations were set as a fixed water surface elevation on the edge of the 2-D model grid at the -Hampton Boulevard Bridge, where the Lafayette River outlets to the Chesapeake Bay. The boundary condition water surface elevation was based on recurrence interval tailwater elevations in Table 5.4.

6.4.8 Buildings

The building footprints were entered into the XP-SWMM model to act as ineffective flow area in the 2-D surface flow calculations. The buildings were derived from the database of GIS information provided by the City.

6.4.9 Topographic Data

In 2009, Pictometry, Inc., under contract to the City of Norfolk, performed a LiDAR survey which provided topographic data at a 3-ft by 3-ft horizontal resolution. Those survey data provide the basis for the 20-ft x 20-ft grid size DEM that was used in the XP-SWMM model for Lafayette River.

6.4.10 Model Calibration

Detailed calibration data was not available for the Lafayette River watershed. However, the XP-SWMM model results reasonably matched the patterns and depths of flooding in the area as noted by City stormwater staff and were determined to be acceptable.

6.4.11 Existing System Flooding During Various Storm Events

Storm events of various return intervals were run in the XP-SWMM model to evaluate the behavior of the Lafayette River watershed under existing conditions. Design storms were developed for 2, 10 and 100-year return periods, 24-hr duration rainfall events were based on Norfolk International Airport precipitation frequency estimates (downloaded from NOAA). This report includes only results for the 10-year and 100-year return period design storms will be presented.

6.4.12 MHHW Tailwater

The design rainfall events were simulated in the existing condition XP-SWMM model using a boundary condition water level equal to MHHW where Lafayette River outlets to the Elizabeth River near the NIT. MHHW for Lafayette River was determined to be +1.6-ft NAVD88 (Moffatt and Nichol, 2010). Model results for the 10-year and 100-year return period design rainfall events with a MHHW tailwater condition are presented in Figure 6-2 and Figure 6-3, respectively**.** Figures 6-2 and 6-3 show water levels throughout the City under the design storm criteria given. Model result statistics for each simulation are presented in Table 6-3 below.

6.4.13 Storm Surge Tailwater

The five design rainfall events were also simulated in the existing condition XP-SWMM model using the corresponding return period coastal surge-driven tailwater elevation as the outlet boundary condition. The recurrence interval storm surge levels used in the modeling are presented in Table 5-4. Model results for the joint 10-year return period rainfall and storm surge and the joint 100-year return period rainfall and storm surge are presented in Figure 6-4 and Figure 6-5, respectively. Figures 6-4 and 6-5 show water levels throughout the City under the design storm criteria given. Model results for each design storm scenario are presented in Table 6.3.

We also simulated the extent of flooding from 10-year and 100-year coastal storm surges without coincident rainfall. We note that the elevated tailwater associated with tidal surge has the most significant impact on the extent and depth of interior flooding. The duration of flooding is also increased with higher tailwater (as the tailwater elevation increases, the gradient decreases, and it takes longer for the storm water system to move the ponded rainfall runoff.) This effect is greatest for the longer return periods (lower-probability, larger storms). Nonetheless, it is also apparent from the existing conditions modeling that the interior drainage system also is a serious constraint. The existing storm water conveyance system appears to be able to carry a ~10-year return period, 24hr duration design rainfall with the tailwater at MHHW.

Table 6-3: Existing Condition XP-SWMM Model Results

Lafayette River Scenario	Total Storm Runoff Volume (ac-ft)	Max Flood Volume (ac-ft)	Max Flooded Area (ac)	[1]Max Flooded Area (%)	Average of Max Flood Depth (ft)	Average Duration of Flooding (hrs)
2yr RP rainfall, MHHW tide	1,607	390	492	5.6%	0.79	1.3
10yr RP rainfall, MHHW tide	2,908	867	990	11.3%	0.88	1.6
100yr RP rainfall, MHHW tide	5,503	1,651	1,672	19.0%	0.99	2.3
2yr RP rainfall, 2yr RP coastal surge	1,607	848	763	8.7%	1.11	2.8
10yr RP rainfall, 10yr RP coastal surge	2,908	2,209	1,596	18.2%	1.38	4.4
100yr RP rainfall, 100yr RP coastal surge	5,503	5,496	3,015	34.3%	1.82	7.6

[1]Maximum flooded area as percent (%) of watershed area above MHHW.
Excluded 240 acres land below MHHW
Total area land = 8,887 acres

7.0 EXISTING CONDITION ESTIMATES OF DAMAGE COSTS

7.1 METHODOLOGY

Flood damage estimates, in terms of monetary costs, were assessed for a range of flooding scenarios under existing conditions and for many of the flood mitigation alternatives, to aid in selection of a preferred design alternative. The initial analysis focused on direct damage to structures and contents of private and public buildings. The purpose of this analysis is to estimate the economic damages associated with future flood events in the Lafayette River watershed, under existing infrastructure conditions, as a basis for performing a benefit-cost comparison of flood damage mitigation alternatives. It is noted that future damage estimates can be further refined by incorporating additional factors such as vehicle damage, displacement costs, emergency response and management costs, and damage reductions resulting from responses to flood warnings.

Structure and contents flood damage assessments were based on predicted flood water depth above the first floor in a structure and the value of the structure. Damage estimates were calculated based on a percentage of the building value where the percentage is a function of the flood water depth. This Depth-Damage Function (DDF) generally increases as the flood water depth increases. DDFs have been developed for various types of buildings by the United States Army Corps of Engineers (USACE), and are published in the "Catalog of Residential Depth-Damage Functions" (USACE 1992), USACE's EGM 01-03 (USACE, 2000) and EGM 04-01 (USACE, 2003). This study used a building inventory file developed by the project team with assistance from the City, output flooding extend and depth results from the hydrologic/hydraulic modeling analyses, high-resolution LiDAR topography data, and flood water DDF curves. A GIS-based routine was developed to calculate and compile the damage estimates for the various flooding scenarios and mitigation alternatives.

Damage assessments were conducted for all 4 of the existing condition scenarios evaluated in XP-SWMM. This section of the report describes the procedure and inputs utilized and presents the results of the damage assessment estimates for existing conditions. Detailed outputs are included in Appendix D.

7.1.1 Building Inventory Methodology

A GIS file of the building footprints was developed for this study and was used to define the spatial locations of buildings in the Lafayette River watershed. The project team coordinated with the City to update building footprints based on 2009 aerial photography. Approximately 37,000 buildings were identified within the Lafayette River watershed for use in the damage assessments.

The buildings were then classified by type using the updated building footprints. The building type was used to determine which DDF would be used for damage estimates. The building type was based primarily on information provided by the City's assessor's office. The information was further refined using high-resolution aerial photographs and site reconnaissance conducted during the study. Building classifications are summarized in Table 7-1.

Table 7-1: Typical Building Classifications

Primary Type	Sub-type	Sub-type	Comment
Residential			Dwelling
	1-Story		
	2-Story		Includes 2 or more stories
	Split-Level		
		Basement	
		No Basement	
Accessory			Detached garage, shed, etc.
Auto Supply			
Clothing			
Department Store			
Grocery Store			
Lodging			Hotel, motel, etc.
Single Story Office			
Multiple Story Office			
Restaurant			
School			
Service Station			

7.1.2 Building Values

Building values were assigned to the buildings based on information provided by the City's assessor's office. Where available, the City's 2010 assessed values were used. In some cases, assessment values were not available and had to be estimated based on similar structures and usage type.

7.1.3 First Floor Elevations

In order to estimate the flood depth at a building, first floor elevations (FFE) were developed. FFE derived from surveyed results were not available for most buildings. Therefore, FFE were developed for using the following procedure. For buildings outside of the 100-year flood zone or were constructed during in 1979 or earlier, we used the 2009 LiDAR data to estimate the FFE. If a building did not have a crawl space (as defined in the assessor's database), we assumed the FFE is 0.5 feet above the ground surface. This assumes an offset for a 6-inch ground slab. If the building has a crawl space, then the offset for the ground surface was assumed based on reconnaissance work conducted during the study. During the study, reconnaissance through the watershed was conducted to estimate and assign the FFE where crawl space height data was incomplete in the database.

If buildings were inside the 100-year flood zone and constructed after 1979, FFE were assigned based on 100-year flood elevation + 1 foot (e.g. 7.3 ft [NAVD88] + 1 ft = 8.3 feet). In August of 1979 the City of Norfolk entered the National Flood Insurance Program (NFIP). Therefore, per the NFIP, buildings constructed within 100-yr flood zones are required to be 1 foot above the 100-year flood elevation.

7.1.4 Depth Damage Functions - Structures and Contents

A depth-damage function is a mathematical relationship between the depth of flood water above or below the first floor of a building and the amount of damage that can be attributed to that water. The depth damage functions used in this study for residential and non-residential buildings estimate the damage based on a function of the flood water depth at the building and a percentage of the building value. Depth damage functions have been developed for various building types based on statistical studies. Figure 7-1 illustrates the DDF concept and how it relates to FFE. The depth damage curves published by the USACE (1992, 2000, 2003), as described above, were used in this study. The guidance documents provide a "mean" percentage and a "standard deviation" percentage to use when estimating damage from various flood water depths.

7.1.5 Damage Assessment Estimates

The GIS-based damage assessment tool, developed for this study, reads the flood water body outputs from the modeling simulations and estimates the flood water depth for each building based on the building's FFE and flood model output. Structure and content damages were estimated using the flood water depth and respective DDFs. The predicted damage for structure and contents assessments for existing conditions are provided in Table 7-2. The distribution of estimated damages for the 10-year rainfall with MHHW tailwater and the 100-year rainfall with MHHW tailwater are presented in Figures 7-2 and 7-3 and respectively. The distribution of estimated damages for 10-year rainfall with 10-year coastal surge and the 100-year rainfall with 100-year coastal surge are presented in Figures 7-4 and 7-5.

Table 7-2: Existing Condition Structure and Contents Flood Damage Estimates

Lafayette River Scenario	Number of Buildings Impacted	Structural Damage[a] ($, millions)	Contents Damage[a] ($, millions)	Total Damage[a] ($, millions)
10yr RP rainfall, MHHW tide	1,260	36.2 (0.15)	19.9 (0.08)	56.2 (0.2)
100yr RP rainfall, MHHW tide	2,219	54.9 (0.14)	31.1 (0.075)	86.0 (0.21)
10yr RP rainfall, 10yr RP coastal surge	2,164	61.0 (0.25)	35.8 (0.14)	96.8 (0.39)
100yr RP rainfall, 100yr RP coastal surge	6,181	174.9 (0.27)	103.6 (0.159)	278.5 (0.43)

[a] Number in parentheses represents one standard deviation based on recommended depth damage function (DDF) percentage.

Summaries of flood damage estimates by building type are provided in Figures 7-6 and 7-7 for 10-yr rainfall and 100-yr rainfall events.

8.0 DEVELOPMENT OF FLOOD DAMAGE MITIGATION ALTERNATIVE CONCEPTS

8.1 INTRODUCTION

There are many ways to mitigate the risk, severity, and consequences of flooding. Those approaches can be broadly divided into several categories, such as: 1) drainage and water conveyance system improvements, 2) elevation of the ground surface and structures, 3) construction of barriers to prevent flooding, 4) impoundment and storage of flood waters, 5) adaptive land use to accommodate flooding, 6) relocation and/or abandonment and 7) public policy actions.

The objectives and priorities for flood improvements will depend on technical considerations, as described herein, that define flood risk (frequency, severity, and extent of flooding) and flood hazards. These technical factors together with the many societal factors that define the consequences (and their acceptability, or not) of flooding, and the costs of flood mitigation measures all must be considered and evaluated when defining and prioritizing flood mitigation approach and priorities.

It is important to recognize that the Hampton Roads region has always been subject to flooding. As the region has been developed over the last four centuries, man's activities have altered the landscape. Both human activities (e.g., land filling and changes to runoff patterns) and natural processes (e.g., sea level rise and ground subsidence) have altered the severity and extent of flooding that occurs during any particular event. As the region has been developed, the changes in the land surface have altered the patterns, extent, and severity of flooding - these changes have been ongoing for four centuries.

8.2 FLOOD MITIGATION/DEFENSE STRATEGIES AND OPTIONS

The development of a flood mitigation/defense project requires a sequence of steps; namely: 1) the identification of the flooding hazards, 2) an assessment of the flooding risks, 3) the evaluation of the consequences of flooding, 4) the degree to which those consequences can be accepted or tolerated, 5) an evaluation of mitigation alternatives, and 6) the development and implementation of mitigation and risk management plans.

The nature and risk of flood hazards are defined by technical considerations, such as the predicted:

- Depth of the flooding,
- Size and location of the flooded region, and
- Recurrence intervals or frequency of flooding.

The consequences of flooding are dependent on the potential for loss of life or injury, population and population density, economic losses, disruption of City services, access, and other societal factors. Together the risks and consequences provide the formative information for defining flood mitigation objectives and priorities.

Flood mitigation involves either preventing the flood waters from entering an area, moving the flood waters from the area at a sufficient rate to mitigate consequences, and/or adapting the area to accommodate the flood. These strategies can include both structural and non-structural measures. Different types of flood mitigation strategies can be grouped by the following categories of objectives:

- Drainage or conveyance system improvement,
- Elevation of ground surface or structures above flood elevation,
- Barriers to prevent flooding,
- Impoundment and storage of flood waters,
- Relocation and/or abandonment,
- Adaptive land use to accommodate flooding, and
- Public policy.

Mitigation approaches often include more than one of the above strategies, through combinations of flood mitigation elements such as the following:

- Drainage and conveyance improvements
    - Channelization or improved flood conveyance (stream channel improvements)
    - Storm drainage system improvements
- Elevation of the ground surface and/or structures
- Barriers to flooding
    - Earthen berms and levees
    - Floodwalls
    - Tide-gates and barriers
- Impoundment and storage
    - Permanent detention and storage ponds or reservoirs
    - Temporary use of land
- Adaptive land use
    - Wetlands, dunes, beach nourishment, and floodplain protected areas
    - Setbacks and buffer areas
    - Land acquisition/relocation and set aside/abandonment
- Public policy
    - Local building and construction code modifications
    - Zoning and land use restrictions
    - Education
    - Flood warning systems, modeling, and forecasting

Although some flood mitigation strategies listed are more commonly thought of as approaches to control flooding from precipitation and rainfall runoff, they can also be components of coastal flooding defense. This is because extreme tides are associated with meteorological events that often produce large amounts of rainfall. For this reason, the design of any barriers to coastal flooding must also be designed to accommodate impounded rainfall and storm water runoff from the area behind the flood barrier. Thus, conventional upland storm water improvements and storage options can and should be components of flood mitigation strategies for mitigating coastal flooding.

A further overview of the different approaches and their applicability is provided in Fugro (2010).

8.3 FLOOD DAMAGE MITIGATION OPTIONS ELIMINATED

Prior to defining the alternate flood mitigation/defense options for evaluation, it was possible to eliminate some approaches due to obvious lack of technical feasibility or other intrinsic factors associated with the approach. Table 8-1 illustrates how the initial screening process was used to eliminate the approaches described below.

Table 8-1: Flood Mitigation Alternatives Feasibility Assessment

Flood Mitigation Alternative Options	Options Deemed Technically/ Economically Unfeasible	Potentially Feasible Options	Feasibility Explanation
Drainage & Conveyance Improvements			
Channelization			Lack of land availability
Storm Drainage Improvements			Based on Benefit/Cost Analysis
Elevation of Ground Surface			
Building Elevation			Historical Buildings/Expensive
Grade Raise			Based on Benefit/Cost Analysis
Flood Barriers			
Earthen Berms & Levees			Based on Benefit/Cost Analysis
Floodwalls			Based on Benefit/Cost Analysis
Dams			Based on Benefit/Cost Analysis
Temporary Dams			Based on Benefit/Cost Analysis
Tidegates			Based on Benefit/Cost Analysis
Pump Stations			Based on Benefit/Cost Analysis
Impoundment & Storage			
Permanent Retention Ponds			Lack of land availability
Temporary Use of Land			Lack of land availability
Adaptive Land Use			
Wetlands			Lack of land availability
Beach Nourishment			Lack of land availability
Protected Floodplain Areas			Lack of land availability
Setbacks & Buffers			Lack of land availability
Land Acquisition & Set Aside			Potentially very expensive
Public Policy			
Building Codes			Protect newly built structures
Zoning & Land Use			Limit structures in flood-prone areas
Education			Enhance understanding of flood risks
Warning Systems			Attempt to limit potential damage

8.4 FLOOD BARRIER ALIGNMENT OPTIONS SELECTED FOR EVALUATION

Based on the preliminary evaluation, it was determined that storm surge barriers could be used to aid in mitigating coastal flooding within the Lafayette River watershed.

The first phase of this study evaluated seven potential barrier crossings locations in the Lafayette River watershed. The barrier crossing locations are denoted as “A” through “G” and were selected based on:

- Locations where a barrier may provide protection to a sub-basin within the watershed,
- Water crossing is narrow (with the exception of alignment A), and
- Tie-in points at the shoreline areas are accessible and could be tied into high ground elevations to minimize floodwall lengths.

Figure 1-3 and Chart 1 present the locations of the alignments. Chart 1 also presents profile views along the alignments, shoreline locations, 100-year, and 10-year return period water levels. The alignments were evaluated based on anticipated cost and benefit through reduction in flood damages and flooding impacts to the City. A metric used to approximate barrier cost was developed using the area of the wall for the overland and overwater sections of the wall. Flood barrier cost studies have found that there is a reasonably good relationship between the area (length x height) of the barrier and its cost. Areas of flood barriers were calculated using the project GIS database. Topography from the 2009 LiDAR survey was used to calculate overland wall areas and bathymetry from various data sources (e.g. Fugro 2013 hydrographic survey, NOAA, and USACE) were used to model the riverbottom elevation and calculate overwater wall areas. A wall section unit cost was then used to develop a cost score based the area of the barrier. We refer to this metric as a “score” rather than a “cost” since this does not represent a true opinion of probably cost. Table 8-2 presents a summary of the cost scores for the various alignments.

Alignment benefits were evaluated based on potential reduction in flood damages and reduction in flooding impacts to the watershed. Flood damages (to contents and structures as described in Section 7) were estimated based on the coincident 100-yr surge and 100-yr precipitation simulation. We note a flood barrier would not mitigate all flooding during a storm event since some flooding would likely be related to precipitation and the storm water system’s inability to convey water and mitigate flooding. However, our H&H analyses indicate that storm surge is primary source of flooding in this watershed during significant storm events. Table 8-2 presents the potential reduction in flooding damages if a barrier mitigated all flooding during the event.

An alignment score was then calculated by dividing the potential flood damage reduction by the total floodwall cost score. Alignment A (NIT-Lamberts Point) ranked the highest and Alignments B (Hampton Blvd Bridge) and E (Granby Street Bridge) ranked second highest. Alignments A and B were deemed to provide the most benefit to the watershed in terms of mitigating flooding impacts to (refer to Figure:

- Economy/commerce by preserving access to NIT and Navy Base,

- Maintaining access to critical facilities including the Norfolk General Hospital, EVMS, CHKD, and Depaul Medical Center, and
- Providing flood protection to ODU, the largest number of citizens, and heritage sites.

Based on this information, Alignments A and B were selected to evaluate further.

Table 8-2a: Flood Barrier Alignments Evaluated

Barrier Alignment	Location	Acres Protected (ac)	Percent of Watershed Protected	Buildings Protected	Property Value ($)	Population Protected	Overland Distance to + 10 Elevation (ft)	River Crossing Distance (ft)
A	NIT-Lamberts Point	10,773	100	13,162	7,200,000,000	81,000	165	6,700
B	Hampton Blvd Bridge	9,310	86	12,050	6,200,000,000	75,000	11,533	1,650
C	Jamestown Crescent-Talbot Park	8,132	75	11,013	5,300,000,000	67,000	10,323	3,800
D	Knitting Mill Creek-Riverpoint	7,583	70	5,739	4,800,000,000	62,000	10,450	1,600
E	Granby Street Bridge	6,531	61	4,921	3,800,000,000	52,000	11,594	850
F	Willow Wood Drive Bridge (Wayne Creek)	4,216	39	3,378	2,500,000,000	33,000	10,910	900
G	Riverview-Rosso Ct/Veaux Loop	2,314	21	1,543	1,300,000,000	19,000	8,297	700

Table 8-2b: Flood Barrier Alignments Evaluated

Barrier Alignment	"OLFW Average Exposed Height (ft) (Typical Range of Exposed Wall Height, ft)	OWFW Max Exposed Height (ft)	OWFW Average Exposed Height (ft)	Overland Floodwall Cost Score*	Overwater Floodwall Cost Score*	Total Floodwall Cost Score	Flood Damages Prevented for Combined 100yr tidal + 100yr precip ($)	Alignment Score
				OLC	OWC	TFCS = OLC + OWC	FDP	= FCP / TFCS
A	2 (1 to 4)	22	18	500,000	16,800,000	17,300,000	370,000,000	21
B	2.9 (2 to 6)	30	21	8,400,000	11,300,000	19,700,000	320,000,000	16
C	2.2 (1 to 6)	22	16	5,300,000	19,900,000	25,200,000	270,000,000	11
D	4.0 (2 to 7)	22	18	11,200,000	8,300,000	19,500,000	240,000,000	12
E	1.5 (2 to 3)	26	18	3,800,000	4,800,000	8,600,000	140,000,000	16
F	2.0 (1 to 3)	14	13	4,300,000	3,800,000	8,100,000	90,000,000	11
G	1.7 (1 to 3)	16	14	4,200,000	3,200,000	7,400,000	50,000,000	7

OLFW = Overland Floodwall
OWFW = Overwater Floodwall
* = Based on Wall Area (square feet) Exposed Above Ground/Riverbottom
Refer to Chart 1 for wall alignment profiles

8.5 ALTERNATIVES SELECTED FOR FURTHER EVALUATION

8.5.1 Flood Barrier Conceptual Overview

A storm surge barrier across the Lafayette River at crossing locations A or B would be approximately 7,000 feet or 1,700 feet long overwater, respectively (Table 8-2a). The barrier could take various forms across its length. Portions of the barrier could be solid walls or causeway sections that would block flow completely during both normal daily and infrequent storm conditions. Portions of the barrier could be comprised of a series of controllable gates (such as radial gates or lift gates). These would be open during typical tidal conditions, and the gate sections would provide hydraulic transparency to the daily tidal flow exchange between the exterior and interior (protected) sides of the barrier. Some local flow restrictions would be associated with the gate sections due to supporting piers, gate sills, etc.

Figure 8-1 shows a typical cross-section of a solid barrier wall that could comprise portions of the overall storm surge barrier length. The conceptual section consists of a combination of 48-inch diameter by 0.75-inch thick steel pipe piles spaced approximately 10 feet on center, connected by steel sheet piles over the gap between pipe piles. Required pipe pile lengths are expected to range from approximately 80 to 120 feet based on existing geophysical and geotechnical data reviewed during this study shown in Figures 4-7 through 4-11 and data available from the Craney Island Eastward Expansion (CIEE) construction. At this conceptual level of design, the sheet piles are considered to extend to the same depth as the pipe piles.

In a standalone surge barrier, concrete batter piles would provide required additional structural resistance to overturning. If the barrier is structurally integrated with a transportation structure, such as a rail trestle, the batter piles may not be required.

Gates for Tidal Flow Exchange (Non-Navigable or Limited Navigable)

Controllable gates would be provided between the solid wall sections, and the gates would be normally open to allow for tidal exchange of water between the Lafayette River and the Elizabeth River. All but one of the gates would be non-navigable; the navigable gate is discussed in a later section below. Initial concepts for the non-navigable gate sections of the barrier include radial gates or vertical lifting gates. These gate types have been used successfully in several locations, and historical cost data is available for estimating construction costs.

In order to give a sense of how these types of gates would be applicable to a Lafayette River storm surge barrier, an example of a constructed storm surge barrier on the Ems River in Germany is presented. Figures 8-2a and 8-2b present photographs of the existing Ems storm surge barrier constructed between 1998 and 2002, which includes three different gate types:

a) a rotary segment gate navigable by large vessels, e.g. the “main shipping fairway arch”,

b) a radial segment gate navigable only by small vessels, e.g. the “inland navigation arch”, and

c) several non-navigable lift gates.

The main shipping fairway gate (a) is normally stored underwater in a rotated-down position, below shipping depths. It has an opening approximately 197 feet (60 meters) wide, a normal pool water depth of approximately 30 feet (9 meters), and no overhead elements that would restrict vessel height.

Figure 8-2b shows a closer view of the three kinds of gates in the Ems barrier, including from left to right: a lifting gate (c); the main shipping rotary gate (a); the inland navigation radial gate (b); and a lifting gate (c). The inland navigation gate (b) is normally stored in a rotated-up position as shown in the photo in Figure 8-2b, and smaller vessels are able to navigate the span. In the Ems barrier, it has an opening approximately 164 feet (50 meters) wide, a normal pool water depth of approximately 23 feet (7 meters), and an air gap of approximately 24 feet (7.4 meters).

A radial gate such as this would not provide the required vertical clearance needed for sailboat navigation through a storm surge barrier on the Lafayette River. However, non-navigable radial gates would be appropriate for allowing tidal exchange through the barrier. Radial gates have been used in coastal and inland waterways for many decades, and the design and operation requirements are well understood.

Vertical lift gates would be an alternative to radial gates in a Lafayette River barrier. Lift gates flank the navigable gates in the Ems barrier example (Figure 8-2b, upper image); a view of the lift gates from river water level is shown in Figure 8-2b (lower image). In the Ems example, the gates rise only a few feet above normal water level in the barrier's open configuration, and depths to the gates' sills vary between 16 to 23 feet (5 to 7 meters).

The primary differences between radial or lift gates shown here for the Ems barrier and those within a Lafayette River barrier are related to the water depths to the gate sills. These would be much less in the Lafayette River barrier than those reported for the Ems barrier gates. Non-navigable sill elevations in the Lafayette River barrier are expected to follow existing river bed elevations between -3 and -5 feet NAVD88, for water depths ranging between 1.5 and 6 feet during normal tides. The height of the steel gate face for a Lafayette River barrier would be approximately 16 feet – to achieve a design crest elevation of +12 feet NAVD88 – significantly less than the Ems barrier lift gate height of approximately 33 (10 meters).

For the present conceptual evaluation of storm surge barrier alignments and practical considerations, radial gates and lifting gates are considered equivalent from cost, aesthetic, environmental and other aspects for providing the non-navigable open segments of the barrier. More detailed comparisons of costs and other aspects would be considered when making a firm decision on gate types at a later design stage.

<u>Primary Navigable Gate Segment</u>

In the present conceptual arrangement of a barrier at the Lafayette River mouth, navigation would be allowed through a single opening 300 feet wide centered on the existing navigation channel shown on NOAA chart #12245. It is envisioned that a horizontal sector gate would be provided for closure of the navigation channel during storm surge events. Examples of such a gate are the existing structures in storm surge barrier at Seabrook (Figure 8-3 upper image) and on the Harvey Canal (Figure 8-3 lower image), both in New Orleans, LA. Compartments or "islands" are required to either side of the navigation channel to allow for the sector gate controls and housing of the sector gate components when open, and training walls would be provided on either side of the gate to promote safe navigation of the gate.

Horizontal sector gates are an appropriate gate type for the navigable span of a Lafayette River storm surge barrier. As a concept, horizontal sector gates allow for a wide range of design opening widths – from 90 feet at Seabrook, New Orleans to 1,200 feet in the Maeslant barrier in Rotterdam, Netherlands. They do not require any overhead structural elements and thus do not limit the above-water dimension of vessels passing through the gate. The sill elevation would be at least as deep as the presently charted navigation channel bed El. -8 feet NAVD88.

8.5.2 Alternatives

For the purposes of this high-level evaluation of issues affecting the feasibility and cost of a storm surge barrier, three different combinations of solid wall sections and controllable gate sections have been considered. These alternatives are shown as six options listed in Table 8-3. Alternatives 1 through 6 differ from each other in the relative degree of openness, or transparency (the ability for the daily tidal exchange to continue as normal), to tidal flows due to differences in extents of solid wall segments compared to radial or lift gate segments. In these examples, the solid wall segments are assumed to include some form of relatively small gate to allow some tidal exchange, but these would be much less hydraulically transparent than the proposed radial or lift gates. A conceptual solid wall section of the proposed storm surge barrier wall is shown on Figure 8-1. Plans for each alternative location are shown on Figures 8-4 through 8-6.

Table 8-3: Flood Barrier Alternatives Evaluated

Alternative	Alignment Crossing Location	Protection Type	Hydraulic Transparency
1	A (NIT-Lamberts Point)	Storm Surge Barrier Wall	96% solid wall/earthen structure (Least Hydraulic Transparency)
2	B (Hampton Blvd)	Storm Surge Barrier Wall	46% solid wall/earthen structure (More Hydraulic Transparency)
3	A (NIT-Lamberts Point)	Storm Surge Barrier Wall	17% solid wall/earthen structure (Most Hydraulic Transparency)
4	B (Hampton Blvd)	Storm Surge Barrier Wall	96% solid wall/earthen structure (Least Hydraulic Transparency)
5	A (NIT-Lamberts Point)	Storm Surge Barrier Wall	46% solid wall/earthen structure (More Hydraulic Transparency)
6	B (Hampton Blvd)	Storm Surge Barrier Wall	17% solid wall/earthen structure (Most Hydraulic Transparency)

Alternatives 1, 2 and 3 include a storm surge barrier wall placed at the mouth of the Lafayette River as shown in Figure 1-3. The barrier at the mouth of the river would be approximately 1.5 miles long and would span from Lamberts Points to NIT. This barrier alternative is 100 percent marine-based. Advantages of this alternative include the protection of the entire Lafayette River watershed including the outlying neighborhoods of Larchmont, Edgewater and Lochhaven and an opportunity for synergistic design that could include a heavy rail line located between Lamberts Point and NIT. Disadvantages of this alternative include the overall length and cost of the protective wall, increased navigational concerns for the yacht club and recreational boaters and an increase in environmental concerns related to subaqueous bottomlands impacts and tidal flushing.

Alternatives 4, 5 and 6 include a storm surge barrier wall placed along the alignment of the Hampton Boulevard Bridge as shown in Figure 1-3. This barrier alternative is marine-based and land-based. This alternative would include approximately 0.3 miles of marine-based protection consisting of a storm surge barrier wall located along the existing alignment of the Hampton Boulevard Bridge along with land-based tide gates and related storm protection devices spanning a distance of approximately 0.3 miles north and 1.5 miles south of the Hampton Boulevard Bridge. Advantages of this alternative include less marine-based construction, no navigation concern for the yacht club, a reduction in environmental concern in the areas of subaqueous bottomlands impacts and tidal flushing and a slightly reduced cost. Disadvantages of this alternative include not providing protection to majority of the neighborhoods of Larchmont, Edgewater and Lochhaven, construction that may cause traffic interruptions along Hampton Boulevard and a reduction in synergistic design possibilities.

8.5.3 Alternatives 1 and 4 (Least Hydraulically Transparent)

Alternatives 1 and 4 would include a storm surge barrier at either the Lafayette River mouth or at the Hampton Boulevard Bridge. This barrier would be the least hydraulically transparent and would consist of 96 percent solid wall or earthen barrier across the Lafayette River. The daily tidal exchanges would flow through the navigation area through sluice gates embedded in the solid barrier at regular intervals. These alternatives can be seen in Figure 8-4.

8.5.4 Alternatives 2 and 5 (More Hydraulically Transparent)

Alternatives 2 and 5 consist of a more hydraulically transparent barrier. These two options feature alternating segments of solid wall and radial/lift gates along the length of the flood barrier. The radial/lift gates would comprise approximately 50% of the barrier length, while 46% would be solid wall or earthen abutment. Navigation would follow through a sector gate at the original navigational channel location. Daily tidal exchanges would occur as normal through the navigational sector gates and radial/lift gates. No sluice gates would be provided in the solid barrier sections. These alternatives can be seen in Figure 8-5.

8.5.5 Alternatives 3 and 6 (Most Hydraulically Transparent)

Alternatives 3 and 6 would consist of the most hydraulically transparent options at either Hampton Boulevard or the Lafayette River mouth. In this scenario, 83% of the length of the barrier would consist of controllable radial or lift gates, with solid walls or earthen abutments at the barrier-land interface and on the navigational gate islands. Daily tidal exchange would be allowed through the open navigational channel and through the lifting gates. No sluice gates would be provided through the solid barrier sections. These alternatives can be seen in Figure 8-6.

EVALUATION OF CONCEPTUAL ALTERNATIVES

9.1 HYDROLOGIC / HYDRAULIC MODELING EVALUATIONS

Six alternatives were considered in order to reduce flooding of the Lafayette River watershed during storm events. For the first three alternatives, storm surge barriers of varying hydraulic transparency were placed in the model at the outlet of the Lafayette River into the Elizabeth River. For alternatives 4-6 barriers of varying hydraulic transparency were placed at Hampton Boulevard. The hydrologic and hydraulic evaluation of these alternatives was performed to answer the following questions:

- Are pumps needed to convey stormwater runoff accumulating in the protected area behind the barrier, when the barrier is closed during a coastal storm?
- What are the likely effects of a storm surge barrier on water levels, discharges, and flow patterns within the Lafayette River during typical tidal conditions?

These questions were addressed by extending the XPSWMM models developed for prior phases of the Lafayette River coastal flooding study. The XPSWMM model extent is shown within the red outlined area on Figure 9-1. Simulations of typical tidal flow in the river are based on a downstream boundary condition derived from measured tide data at Sewells Point (NOAA #8638610).

The time period April 15 to 22, 2011 was simulated as representing a typical range of tidal variations that coincided with measured water level data from City-operated tide gauges at Tidewater Drive Bridge and at Colonial Place (Figure 9-1). The initial model simulation produced tidal amplitudes and phases similar to those measured at the tide gauge locations. The model was calibrated by varying Manning's roughness globally to achieve the best match at both Colonial Place and Tidewater Drive Bridge.

The model simulated discharges in the river at the river mouth barrier alignment and at a Hampton Blvd. bridge alignment. Peak ebb and flood discharges are shown in Table 9-1. The calibrated model was then used to address the primary questions regarding the need for pumps and the impacts of a storm surge barrier on tidal hydraulics in the Lafayette River system.

Table 9-1: Lafayette River Tidal Flow Rates from Model Simulation

Location	Peak Flood Tide Discharge, cubic feet / second (cfs)	Peak Ebb Tide Discharge, cubic feet / second (cfs)
Lafayette River mouth at confluence with Elizabeth River	15,000 to 21,000	14,000 to 19,000
Lafayette River at Hampton Boulevard Bridge	9,000 to 12,000	7,000 to 11,000

9.1.1 Pump Effectiveness During Flooding

The need for pumps was evaluated by simulating the 1% annual chance (100-year return period) joint rainfall with MHHW tailwater conditions in the XPSWMM model, for a scenario with a closed storm surge barrier across the Lafayette River mouth. A 24-hour duration rainfall depth of 9.21 inches was input to the model using a NRCS Type II rainfall distribution. The XPSWMM model indicated that the presence of the closed barrier at the river mouth would result in an average water surface elevation of +5.1 feet NAVD88 in the river and along its shorelines. This is an increase of approximately 2.6 feet over the no-barrier (existing conditions) XPSWMM simulation. However, it is expected that the storm surge barrier would be closed only when the predicted surge-driven water levels are sufficiently high that they would begin to cause flooding with or without coincident rainfall. The closed barrier would prevent the coastal flooding from the storm surge component, and the residual flooding from precipitation behind the barrier would be less than the combined storm surge plus precipitation flooding. Therefore, the barrier alone would reduce flood depths and durations in the design events.

Based on these results, it does not appear that an array of high-capacity pumps will be needed at the storm barrier, in order for the barrier to be effective in providing flood mitigation at design storm levels. Some residual flooding would still occur behind the closed barrier in a 1% annual chance rainfall event.

9.1.2 Change in Tidal Water Levels and Flows

The effects on tidal flows and water levels were simulated in the XPSWMM model for a storm surge barrier equivalent to Alternative 2 (above). The navigable and non-navigable gates were simulated as hydraulic structures (gates) with specified sill elevations, opening heights and widths, and friction and expansion / contraction coefficients.

The impacts on flow are primarily driven by the barrier's reduction of the width and cross-sectional area available for conveying river flow. The degree of flow area reduction depends on the mix of solid barrier segments and normally-open gate segments comprising the barrier. This reduction in tidal flow potential would also affect the daily tidal range, particularly in the most upstream reaches of the river.

The model simulation indicated that the storm surge barrier with approximately equal parts solid wall (46%) and radial/lift gate openings (54%) was not likely to be a prohibitive barrier to the normal tidal flushing and range even in the most upstream reaches of the Lafayette River.

9.2 FLOOD DAMAGE REDUCTION ESTIMATES

Flood damage estimates were assessed for the flood mitigation alternatives previously described. The procedures followed to estimate the flood damages were exactly the same as used to determine the existing condition damages. The estimated damage results for coincident events are summarized in Table 9-2.

Table 9-2: Estimated Flood Damage Reductions

Lafayette River Scenario	Number of Buildings Impacted	Structural Damage[a] ($, millions)	Contents Damage[a] ($, millions)	Total Damage[a] ($, millions)
10yr RP rainfall, MHHW tide	1,260	36.2 (0.15)	19.9 (0.08)	56.2 (0.2)
100yr RP rainfall, MHHW tide	2,219	54.9 (0.14)	31.1 (0.075)	86.0 (0.21)
10yr RP rainfall, 10yr RP coastal surge	2,164	61.0 (0.25)	35.8 (0.14)	96.8 (0.39)
100yr RP rainfall, 100yr RP coastal surge	6,181	174.9 (0.27)	103.6 (0.159)	278.5 (0.43)
100yr (MHHW Tailwater) Storm with Barrier 1 (River Mouth)	3,651 (-41%)	74.3 (-58%)	42.8 (-59%)	117.1 (-58%)
100yr (MHHW Tailwater) Storm with Barrier 2 (Hampton Blvd.)	4,447 (-28%)	101.8 (-42%)	59.8 (-42%)	161.6 (-42%)

[a] Number in parentheses represents one standard deviation based on recommended depth damage function (DDF) percentage

9.3 GENERALIZED ENVIRONMENTAL IMPACTS

The construction and operation of a storm surge barrier across the Lafayette River would have the potential to impact the river environment in several different ways. A detailed discussion of each type of impact and the degree that each barrier option would have on the Lafayette River environment is beyond the scope of the present study. An overview of the literature relative to the environmental impacts of similar storm surge barriers on tidal estuaries in other areas is provided, and parallels are drawn to identify likely categories of impacts for the Lafayette River.

In general, a storm surge barrier would have the potential to affect tidal hydraulics (flows and water levels) and water quality parameters such as temperature, dissolved oxygen, nutrient concentrations, etc. Also, the proposed structure could impact subaqueous bottomlands and potentially limited wetland areas along the shoreline area. This study has not identified potential environmental impacts that would preclude the implementation of the preferred option described in this study, however, further environmental assessment of the chosen alternative is recommended.

A study of the impacts of the Oosterschelde (Eastern Scheldt) storm surge barrier in the Netherlands noted that the barrier had decreased the area of the tidal flow cross-section by approximately 80 percent (Pater, 2012). This had the effect of reducing the tidal range, reducing the tidal prism and thus reducing overall flow velocities inside the estuary. The study's modeling components indicated that the Oosterschelde barrier reduced the tidal water level range by 10 to 20 percent compared to without-barrier conditions. As a result, sediment transport patterns and estuary morphology was altered by channels filling in with sediment. Also, the increased local flow velocities at the barrier structures resulting in increased sediment transport and deepening of flow channels through the gates.

A modeling study of the potential effects of storm surge barriers on Galveston Bay in Texas found that a 40 to 60 percent flow area reduction at the largest pass (Bolivar Roads Inlet) would likely reduce the bay's interior tidal range and tidal prism by 20 to 30 percent (Ruijs, 2011).

Storm surge barriers have been constructed or are in construction around the world, including in the United States. Sizes of tidal openings also vary among barrier systems. Venice's MOSE (Modulo Sperimentale Elettromeccanico or Electromechanical Experimental Module) barrier represents one of the most open structures, but is also one of the most expensive to construct. When retracted, the MOSE barrier is below the seabed and does not construct tidal flows. For a barrier at the Lafayette River, size and number of the openings will require a balance between project cost, environmental impact, and preference of the owner.

9.4 VIEWSHED IMPACT

A storm surge barrier will have a visual impact on the landscape or viewshed. Figure 9-2 presents a viewshed perspective of a 6-foot tall person standing on the shoreline in Larchmont and looking to the southwest and northwest. In the viewshed model, a surge barrier with an El. +12 feet across the mouth of the Lafayette River was modeled. The perspective views in Figure 9-2 also include cranes at NIT terminal, containers stacked three and four containers high, Craney Island Dredged Material Management Area, and Lamberts Point. Early engagement during the project planning process with coastal residents whose viewsheds may be impacted by a barrier, will provide important feedback about project support or opposition.

9.5 POTENTIAL SYNERGISTIC OPTIONS WITH RAIL PROJECTS

This study also considered potential synergistic opportunities that would create infrastructure that could serve multiple purposes (e.g. flood protection and a new transportation pathway). The project team identified potential rail projects that would either extend light rail or a heavy haul rail that would connect the Norfolk Southern Coal Terminal and NIT Terminal and on to a rail line located on the northern side of the Lafayette River. A general trestle concept is shown on Figure 9-5. Figure 1-3 shows an alternate tie-in point to the Norfolk Southern Terminal.

Although the Lafayette River mouth crossing shown in Figures 1-3 and 8-2 tie into the area near Lambert's Point Golf Course, there could be a synergistic advantage to connecting with the Norfolk Southern Terminal to the south. By adding a heavy rail line to a surge barrier project, Norfolk Southern and the NIT Terminal to the north would gain an alternative route for transporting goods throughout the area. This alternate route would provide a secondary or redundant route to allow trains to operate if one of the rail lines was obstructed due to flooding or some other reason.

At an early stage of this study, the project team met with Hampton Roads Transit Authority (HRTA) to discuss the potential of creating a combined light rail and flood barrier system. Based on discussions with the Hampton Roads Transit Authority it was determined that a light rail route which would extend service from the Norfolk General Hospital area north to ODU and the Navy Base via a water crossing between Lamberts Point and the NIT Terminal would not be desirable. HRTA indicated that it would not be acceptable for rail service to be interrupted by gate openings to allow vessel traffic to pass into/out of the river opening. Therefore, a bridge would need to be constructed high enough to allow sail boats to pass beneath it and horizontal and vertical grade change restrictions would make it very difficult to design and costly to construct such a structure that would also have significant viewshed impacts. Additionally, HRTA did not anticipate that the potential ridership would economically justify the extension of light rail through this corridor.

9.6 TECHNICAL EVALUATION: ENGINEERING DESIGN REQUIREMENTS AND DRIVERS

9.6.1 Geotechnical Evaluation of Existing Soils

Based on our experience during the design and construction of Craney Island, the existing soil conditions at the crossing locations are expected be complex and challenging. As part of this study, we collected seismic data at the mouth of the Lafayette River and reviewed proprietary seismic data in our files and available geotechnical data. Both crossing locations (A and B) are anticipated to be comprised of soft, weak, and highly compressible soils approximately 50 to 110 feet thick. High load bearing structures will likely be founded on piles that embedded into the Yorktown formation (Figure 4-7 through 4-9). This may result in pile lengths on the order to 70 to 130 feet long.

Causeways constructed of earthen fill on the soft, compressible soils will be expected to settle. Depending on thickness of the fills, settlements for berms constructed to elevation +12 feet could experience settlement of 10 to 20 feet. Challenges are expected to be encountered where earthen fills are adjacent to hard structures founded on piles if settlement of the fills is not mitigated appropriately. Seismic data at the mouth of the Lafayette River reveal two large buried channels that have incised into the top of the Yorktown and created relief of about 50 and 15 feet, respectively, in the top of the Yorktown. This is expected to result in different magnitudes and rates of settlement or pile and sheet pile wall lengths.

9.6.2 Effective Wall Height

The effective wall height of the flood barrier was determined from results of the hydraulic and hydrologic analyses along with consideration of anticipated sea level rise and Federal Emergency Management Agency (FEMA) recommendations for flood protective structures. The anticipated 100-YR return period tailwater in the Lafayette River (due to the 100YR design storm) in the Lafayette River was determined to be +8.2 ft NAVD88. Sea level rise can be anticipated to contribute an additional 1.0 ft of water height as previously discussed for a 50 to 60 year design life structure. FEMA recommendations suggest an additional 1.0 ft of freeboard is used in determining effective flood barrier height. An additional 1.0 ft of freeboard (total 2.0 ft of freeboard) was included in the design effective flood barrier height determination to account for wave overtopping and wind effects. The total height of the storm surge barrier wall was determined to be +11.2 ft NAVD88 (+8.2 ft NAVD88 100-YR tailwater, 2.0 ft consideration for sea level rise and wave overtopping and 1.0 ft consideration for freeboard). A conceptual solid wall section of the storm surge barrier wall is shown in Figure 8.1.

9.6.3 Navigable Gate

Multiple types of navigable gate types were initially considered. Each have advantages and disadvantages relative to the needs of providing navigation access through a flood barrier across the Lafayette River. See Table 9.2 below for the strengths and limitations of each type.

Table 9.2: Navigational Gate Types

Gate Type	Example	Strengths	Limitations
Horizontal Sector (Figures 9-3 and 9-4)	Seabrook, New Orleans, LA IHNC (Lake Borgne), LA Ems River, Germany Maeslant (Rotterdam), Netherlands St. Petersburg, Russia	Reliable closure as surge forces arcs to seat against each other. Unlimited vertical clearance for boat traffic.	Requires storage area to either side of opening. Rotation track in bed, sediment/maintenance.
Vertical Sector	Thames Barrier, London, England	Unlimited vertical clearance for boat traffic.	Requires gate storage excavated into river bed.
Vertical Lifting	St. Petersburg, Russia Eastern Scheldt Barrier, Netherlands Ems River, Germany	Gate out of water when open: maintenance access and lower corrosion potential.	Requires maintenance, sediment removal on seat in river bed. Very high lifting height required for sail traffic.
Flap / Wicket	MOSE, Venice, Italy (proposed) Olmstead, Illinois River Seine, Andresy, France River Tees, Stockton on Tees, England	Very transparent to flow when open	Requires gate storage excavated into river bed.

Horizontal sector gates are an appropriate gate type for the navigable span of a Lafayette River storm surge barrier. As a concept, horizontal sector gates allow for a wide range of design opening widths – from 90 feet at Seabrook, New Orleans (Figure 9-3) to 1,200 feet in the Maeslant barrier in Rotterdam, Netherlands. They do not require any overhead structural elements and thus do not limit the above-water dimension of vessels passing through the gate. The sill elevation would be at least as deep as the presently charted navigation channel bed elevation of -8 feet NAVD88.

10.0 CONCEPTUAL LEVEL OPINION OF PROBABLE COSTS FOR FLOOD BARRIER SYSTEM

Opinions of probable cost were developed based on recent (last 10 years) historical cost data for projects in the Hampton Roads region and published costs for storm surge barriers constructed in the United States and European countries.

Table 10-1 presents the approximate costs of different alternatives for a storm surge barrier across the mouth of the Lafayette River between the NIT terminal and the Norfolk-Southern Railyard.

Table 10-1: Estimated Costs of Lafayette River Mouth Barriers

Alternative	Approximate Construction Cost ($US)
1 – Lafayette River Mouth Barrier 96% solid wall structure	$1.3 billion
2 – Lafayette River Mouth Barrier 46% solid wall structure	$1.4 billion
3 – Lafayette River Mouth Barrier 17% solid wall structure	$1.5 billion
4 – Hampton Blvd Bridge Barrier 96% solid wall structure	$870 million
5 – Hampton Blvd Bridge Barrier 46% solid wall structure	$930 million
6 – Hampton Blvd Bridge Barrier 17% solid wall structure	$1.0 billion

Based on the conceptual opinion of probable cost breakdowns, the tidal barrier options relative to the type of tide gate had a variance of approximately $10 million with the Steel Gate being the most cost-effective option and the Inflatable Dam being the most expensive.

The model simulation indicated that the storm surge barrier with approximately equal parts solid wall (46%) and radial/lift gate openings (54%) was not likely to be a prohibitive barrier to the normal tidal flushing and range even in the most upstream reaches of the Lafayette River.

11.0 CONCLUSIONS AND RECOMMENDATIONS

The Lafayette River area includes the Colonial Place and Larchmont residential/commercial communities, portions of the Lochhaven area, and also contains the Norfolk Yacht Club, NIT Terminal, and Lambert's Point. Over time some of the areas within the watershed that were underwater became reclaimed land. Apart from being an important recreational waterway, the confluence of the Lafayette River where it discharges into the Elizabeth River presents a significant obstacle for flood prevention.

Flooding in the Lafayette River area is frequent; and varies from nuisance flooding to events causing significant damage. Flooding is cause by the combined effects of high tides, storm surges and heavy precipitation. The effects of these high tides (coastal flooding) are expected to worsen over time as mean sea level rises. In addition, the effects of sea level rise will be compounded by regional and local ground subsidence, themselves resulting from events in geologic time, and ongoing settlement of localized, man-made fill.

The primary conclusions and recommendations from the current study include:

- Preliminary study shows the overall benefit for the residents and property in the Lafayette River watershed along with estimated cost indicate that a barrier at the mouth of the Lafayette River or along the Hampton Boulevard Bridge with approximately equal parts solid wall and open gates are effective flooding solutions with minimal environmental impact.
- Other options for dealing with flooding in the Lafayette River on a watershed scale, such as impoundment, adaptive land use or elevation increases proved unfeasible due to either lack of land availability or cost considerations. However, such options on a smaller scale (e.g. neighborhood) may provide benefit but were not considered in this study. The intent of this study is to identify larger scale flood barrier options.
- The delta costs for building the floodwall higher for sea level rise concerns would be on the order of 5-15% per foot. A final decision concerning what height should control should be made during the next design phase.
- Environmental factors including tidal flushing, normal flow of the watershed, and impacts to subaqueous bottomlands and limited wetlands need to be further evaluated in final design of the storm surge barrier wall. The screening level study model simulation indicated that the storm surge barrier with approximately equal parts solid wall (46%) and radial/lift gate openings (54%) was not likely to be a prohibitive barrier to the normal tidal flushing and range even in the most upstream reaches of the Lafayette River.

In summary, this study demonstrates that infrastructure improvements consisting of a flood wall with gate can mitigate coastal flooding including much of the worst effects of extreme extra-tidal events from hurricanes and nor'easters. Because the Lafayette River cove is large in comparison with the size of the watershed, its capacity to store storm water runoff is adequate. Thus, pumps are not anticipated to be required to pass the excess storm water inflow over the flood barrier. These improvements are technically feasible, and are expected to have public support and favorable benefit to cost (B/C) ratios.

12.0 LIMITATIONS

All documents have been prepared for the exclusive use of the City of Norfolk for the preliminary evaluation of flood mitigation options for the project location. The data, findings, and conclusions presented herein were prepared in accordance with generally accepted civil engineering practices of the project region.

In performing our professional services we have used generally accepted civil engineering principles and have applied that degree of care and skill ordinarily exercised, under similar circumstances, by reputable civil engineers currently practicing in this or similar localities. No other warranty, express or implied, is made as to the professional advice included in these documents.

13.0 REFERENCES

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