FUGRO ATLANTIC

PRELIMINARY COASTAL FLOODING EVALUATION AND IMPLICATIONS FOR FLOOD DEFENSE DESIGN

City of Norfolk
City-Wide Coastal Flooding Contract
Work Order No. 3, Tasks 4 & 5

Prepared for:
CITY OF NORFOLK
DEPARTMENT OF PUBLIC WORKS

July 2010
Fugro Project No. 3627.003

FUGRO ATLANTIC

350 World Trade Center
Norfolk, Virginia 23510
Tel: (757) 625-3350

July 16, 2010
Project No. 3627.003

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

Attention: Mr. John White, Director, Stormwater Division

Subject: **Preliminary Coastal Flooding Evaluation and Implications for Flood Defense Design, City of Norfolk, City-Wide Coastal Flooding Project, Work Order No. 3, Tasks 4 & 5**

Dear Mr. White:

Enclosed is Fugro Atlantic's report documenting Tasks 4 and 5 of Work Order #3 of the City-Wide Coastal Flooding contract (City of Norfolk Contract 1125). This report provides our preliminary evaluation of coastal flooding susceptibility within the City and its implications for the design of future flood defense mitigation. A draft of this report was provided to the City on June 17, 2010; the City's comments have been considered in the revisions to the report.

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 measurements of tide heights within the City's waters are unique, in that no comparable data are available elsewhere within Hampton Roads. 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 is directly relevant for various planning studies and emergency response preparations within 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
Senior Engineering Geologist and Project Manager

Thomas W. McNeilan, P.E.
Vice President, Fugro Atlantic

Fugro Atlantic is the Norfolk-based, U.S. east coast operating group of Fugro N.V., an international engineering and survey firm with headquarters in Leidschendam, The Netherlands. Fugro N.V. was founded in 1962, has been publically traded on the Amsterdam stock exchange (AMX) since 1992, and has been a member of the stock exchange's MidKap Index since 2003. Fugro is the world's leading service provider of: 1) data relating to the earth's surface and sub-surface and 2) engineering and geological consulting services relative to the design and construction of infrastructure, energy, and development along the coastline and in the low lands around the globe. Fugro Atlantic's primary market focuses are: coastal infrastructure and industry; flood inundation and flood defense; and offshore energy development.

The Fugro team for the City-wide coastal flooding contract includes Moffatt & Nichol, a consulting engineering firm, whose core focus is the coastal, estuarine, and riverine environment. Moffatt & Nichol, established in 1945, is the oldest consulting firm in the country in this specialized discipline. The American Society of Civil Engineers' Harbor and Coastal Engineering award is named after Moffatt & Nichol's founders.

The City-Wide Coastal Flooding contract studies and this report have been prepared by the Fugro Atlantic team that includes:

- Mr. Kevin Smith, the senior engineering geologist and GIS services manager with Fugro Atlantic is the Project Manager for the City-wide Coastal Flooding Contract,
- Mr. Thomas McNeilan, the general manager of Fugro Atlantic is Fugro's principal-in-charge and lead engineer for the contract,
- Mr. Kyle Spencer and Mr. Dan Shaffer, GIS analysts on Fugro Atlantic's staff have developed the GIS-based mapping and prepared the predictive maps for the contract,
- Mr. Johnny Martin, senior coastal engineer with Moffatt & Nichol has supervised Moffatt & Nichol's hydrological analyses efforts,
- Dr. Paul Tschirky and Ms. Maura Boswell, coastal engineers with Moffatt & Nichol have assisted Mr. Martin, and
- Ms. Rosemary Smith, senior oceanographer with Fugro Geos, has provided the data analyses and interpretation of the tide gauge data.

Kevin Smith, Johnny Martin, and Tom McNeilan are the primary authors of this report.

CONTENTS

TABLES (Presented Within the Text)

FIGURES (Presented Following the Text)

MAPS (Included in Pockets at End of Report)

EXECUTIVE SUMMARY

The City of Norfolk (City) is surrounded by several different bodies of water and their many tributaries. Because the City is located on a low-lying physiographic region, 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, such as occurred in November 2009.

In recent years, the City has recognized an increased need to address coastal flooding problems. Thus in 2008, the City began to develop a City-wide evaluation to: anticipate flooding scenarios, help prioritize problem areas, define design criteria, and develop objectives for various remediation flood defense improvements. The November 2009 Nor'easter has both: 1) reinforced the City's decision to proactively evaluate coastal flooding and 2) elevated the City's needs and priorities for flood defense mitigation. In addition, the short but intense local storm over the Broad Creek area in August 2009 caused local flooding and damage. While the flooding and damage during that storm were significant, they were much less than would have occurred if that storm had coincided with peak rather than low tide conditions.

In addition, relative sea level in the Hampton Roads region is rising (at a current projected rate of 1.46 feet per 100 years[1]). Thus, both nuisance flooding and flooding from storm events will increase in the future, which will likely further increase the City's need to address the issue of coastal flooding.

The City's City-wide Coastal Flooding contract was initiated by installing tide gauges to measure water levels and provide a basis for predicting tides throughout the City relative to those at Sewells Point. Sewells Point, which has the longest history of tidal measurements, is the reference location used to communicate predicted tide levels to the City, the media, and to the population in general. The contract also includes 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. The measurements of tide heights within the City's waters are unique, in that no comparable data are available elsewhere within Hampton Roads.

This report provides 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.

The report presents return periods and water level relationships for the current sea level and after 0.5-foot of future sea level rise. The comparison suggests that a sea level rise of 0.5 feet will increase the frequency of events that produce a specific water level at Sewells Point.

[1] "Mean Sea Level Trend, 8638610 Sewells Point, Virginia." NOAA Tides & Currents. http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8638610

Mapping presented herein also shows that the area inundated will be significantly increased for any particular return period event after a 0.5-ft sea level rise.

The flood inundation maps included in this report were developed to be used for prioritizing, planning, and designing flood mitigation improvements. They also provide important information that can be used for emergency planning and response, and redevelopment planning.

When evaluating and using the information presented herein, 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 and natural processes 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.

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.

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.

The report concludes with synopses of various types of flood mitigation approaches and considerations that should be incorporated when prioritizing areas for flood defense improvements.

INTRODUCTION AND BACKGROUND

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 +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, such as occurred in November 2009.

In recent years, the City has recognized an increased need to address coastal flooding problems. 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[1]). 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 both project-specific and a holistic basis.

The November 2009 Nor'easter has both: 1) reinforced the City's decision to proactively evaluate coastal flooding and 2) elevated the City's needs and priorities for flood defense mitigation. In addition, the short but intense local storm over the Broad Creek area in August 2009 caused local flooding and damage. While the flooding and damage during that storm were significant, they were much less than would have occurred if that storm had coincided with peak rather than low tide conditions.

Study Background

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 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 Atlantic (and its sub-consultant Moffatt & Nichol) was initiated in 2008 in recognition of the City's

[1] "Mean Sea Level Trend, 8638610 Sewells Point, Virginia." NOAA Tides & Currents. http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8638610

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 used to apply the knowledge gained from the tidal measurements for anticipating and predicting flooding, prioritizing flood projects, and developing flood remediation measures.

Authorization

Work Order No. 3 for the City-Wide Coastal Flooding Study was issued by the City on August 29, 2008. The Tasks associated with Work Order No. 3 include: Task 4 - Simplified Coastal (and Upland) Flooding Analyses, which was to apply the information developed during the initial year of tidal measurement, and Task 5 – Criteria for Prioritizing and Designing Flood Mitigation Projects, which was to set the stage for defining future flood mitigation projects. This report documents the efforts for those two tasks.

TIDE GAUGE PROGRAM SYNOPSIS

The Fugro and Moffatt & Nichol recommendations for the implementation of the tide gauge measurement program were provided in previous Technical Notes (TNs):

- Tide Gauge Location Recommendations (TN: Work Order No. 1, Task 2, dated October 1, 2008; authored by Moffatt & Nichol) and
- Tide Gauge System Recommendations (TN: Work Order No. 1, Task 3, dated October 1, 2008; authored by Fugro).

Based on those two documents, the City requested that Fugro procure, install, and maintain the tide gauges and to download, process, and document the tide gauge data for one year. The tide gauge program was ultimately defined to include as many as: 4 permanent gauges (to be turned over to the City after one years use) and 3 temporary gauges to be installed and monitored for 3 months. The City's work order for this program was issued February 26, 2009.

Five gauges were installed in May 2009 at the locations shown on Figure 1. The gauge locations are:

- Little Creek - Recreation Center (P12RC),
- Lafayette River - Haven Creek Boat Ramp (P13HC),
- Lafayette River - Wayne Creek at Tidewater Drive Bridge (P13TW),
- Downtown Pump Station on Main Branch of Elizabeth River (P13PS), and

- Broad Creek at Virginia Beach Blvd. (P13VB).

Access arrangements to install the other two gauges were terminated by the City.

The gauges were downloaded at quarterly intervals and three quarterly reports have been delivered by Fugro for the periods: 1) May through August 2009, 2) September through November 2009, 3) November 2009 through February 2010, and 4) March through June 2010. The quarterly reports for the first 3 quarters have been delivered and the final report for the 4th quarter of data is in preparation. The turn-over of four gauges to the City will occur in July 2010.

After discussion among the City, Fugro, and Moffatt Nichol, it was mutually agreed that the two gauges previously installed in the Lafayette River drainage would be removed and replaced by one gauge to be installed at a new location (Figure 1) in that watershed. The new gauge was installed in July 2010. To provide overlap among the three gauges locations, all three gauges will be maintained for a period of 3 month(s), and then the two existing gauges will be removed.

TIDE GAUGE DATA EVALUATION

Oceanographic and Rainfall Events during the Data Collection Period

During the first 9 months that the City gauges have been in place there have been a number of meteorological events of consequence. These events in their sequence of importance were:

- **The Veterans Day, November Nor'easter** that caused the fourth highest tide levels measured in Norfolk since the installation of the Sewells Point tide gauge in 1927. This event, which extended over four days (November 11 through November 14, 2010), included more than three days where tides were more than 2 feet above normal, 32 hours where the water elevation was above El. +4 feet (re: NAVD88), four consecutive high tides that were above about El. +5 feet, and peak tides above El. +6 feet. Although the peak water levels during the event were slightly less than during Hurricane Isabel in 2003, the repeated cycles of elevated water through the duration of the event produced equal, if not more, wide-spread flooding than did Hurricane Isabel.
- **August 22, 2009 Storm**. A localized, intense storm on the afternoon of August 22, 2009 was centered over the Broad Creek watershed and included more than 5 inches of rainfall. The rainfall runoff elevated the water level in Broad Creek by 1 to 2 feet (and to a lesser extent at other gauges) for about 4 hours. Flooding in the Broad Creek watershed was locally severe. It was fortunate that the August storm occurred during the trough of the tidal cycle; otherwise flooding would have been significantly more severe and wide spread.
- **The June/July 2009, East Coast Sea Level Anomaly** was measured in the City gauges. The regional phenomena (NOAA, 2009) lasted for several weeks and during the peak of the anomaly, tides were more than 1/2 foot above normal throughout the City. Minor flooding occurred during the portion of the event that coincided with higher spring tides.

- **Other Nor'easter Events.** Various other Nor'easter conditions produced elevated water levels and sometimes localized flooding in Norfolk throughout the year. The most noticeable of these events occurred December 19, 2009 and February 6, 2010.

The tide gauge data measured over the last year are considered to provide a unique picture of the propagation of flood waters from Chesapeake Bay and the main stems of the Elizabeth River into the various drainages within the City. The data set is unique in that no comparable data have previously been recorded within the Hampton Roads region. The data document water levels at the five gauge locations that 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. Elsewhere, water levels above Sewells Point are interpreted to generally range from 0.3 to 0.6 feet above that at Sewells Point. The elevated water level (as compared to Sewells Point) throughout most of the City has important implications for flood defense design criteria and flood defense performance.

Vertical Datum

There are various different vertical datum that are often used as references for land surface elevation and tide levels. For example, tide levels are commonly referenced to mean high water, mean sea level, and mean lower low water. However, sea water level is not static, but rather changes with time (and is widely interpreted to be rising in recent time). The land surface is often defined relative to any of those water level datum or to other defined survey datum. Unless noted otherwise, elevations cited in this report are referenced to NAVD88 datum. This datum has been used because it is not affected by changes in sea level nor does it vary due to ground subsidence or settlement.

Comparison of Measured Tides at City Gauges Relative to Tides at Sewells Point

Statistical evaluation of the tides at each gauge has been conducted for the 9 months of data from gauge installation through February, 2010. As directed by the City, our evaluation of the tide gauge data and its implications has been accelerated to author this report prior to the availability of the final 4^{th} quarter tide gauge data.

Figure 2 through 6 present the peak water levels during each tidal cycle for each gauge plotted versus the peak water level during the same tidal cycle at Sewells Point. Linear regression analyses were performed for the following three cases:

1. y = mx + b,
2. y = 1x +b, and
3. y = mx
   where:
   y = tide level at gauge of interest and
   x = tide level at Sewells Point

The analyses for the entire data set and for various subsets of the data (e.g., using only data for tides greater than a certain value, and average water levels) indicate that the relationship based on the assumption that y = x + b provide a reasonable and practically applicable basis for evaluation of the differences in water levels at the tide gauges relative to those at Sewells Point. The calculated mean offset of each gauge relative to Sewells Point is as follows:

- Little Creek (Recreation Center - 0.1 feet below Sewells Point,
- Lafayette River (Haven Creek) - 1.2 feet above Sewells Point,
- Lafayette River (Tidewater Drive Bridge) - 0.6 feet above Sewells Point,
- Downtown Pump Station - 0.5 feet above Sewells Point, and
- Broad Creek (Virginia Beach Blvd) - 0.3 feet above Sewells Point.

Further examination of the data shows that most of the data within approximately 95% confidence level is banded within +/- 0.5 feet of the gauge relationships noted above. This variability with respect to the Sewells Point observed data is likely due to localized influences on water levels such as wind driven setup (varies with wind direction and location), localized storm water discharge effects, and local geometric amplifications. The local geometric amplifications in an embayment or cove can be seen with the Haven Creek tide data that are generally about 0.5 to 0.6 feet higher than the Tidewater Drive Bridge tide gauge, which is located along the same main conveyance (Lafayette River). This would suggest that for flood planning purposes an additional 0.5 feet should be added to the water levels predicted by the tide gauge relationships in areas of the watershed that consist of a narrow embayment or cove similar to that at Haven Creek.

A summary of the water level comparisons is provided in Table 1. The proposed adjustment factors for each of the gauges are relatively consistent for all comparisons.

Table 1. Summary of Statistical Water Level Relationship Comparisons

Tide Gauge	Average Water Level, feet	Difference compared to Sewells Point, feet	Adjustment Factor from Statistical Analyses	Standard Error of Statistical Analyses
Sewells Point	0.3	--	--	--
Recreation Center	0.3	-0.1	-0.1	0.172
Havens Creek	1.5	1.2	1.2	0.120
Tidewater Bridge	0.9	0.5	0.6	0.402
Downtown Pump Station	0.8	0.4	0.5	0.192
Broad Creek	0.6	0.2	0.3	0.241

Notes: Statistical analyses are shown on Figures 2 through 6.
All values have been rounded to the nearest tenth of a foot.
All elevations are re: NAVD88.

Figure 7 shows the water levels observed at the tide gauge locations during the November 2009 Nor'easter. There is some variability with the peaks during the November 2009 Nor'easter since these are single values during an extreme storm water level event. When the second highest peak during the storm is examined the relationships are closer.

The relationships of the peak tides at these locations relative to Sewells Point are summarized in Table 2.

Table 2 - Tide Gauge Measurements during November 2009 Nor'easter

Tide Gauge	Average Water Level, feet	Difference compared to Sewells Point, feet	Peak Water Level, feet	Difference compared to Sewells Point, feet	Secondary Peak Water Level, feet	Difference compared to Sewells Point, feet
Sewells Point	2.2	--	6.0	--	5.7	--
Havens Creek	3.4	1.2	6.8	0.7	6.6	0.9
Tidewater Bridge	2.6	0.4	6.6	0.6	6.3	0.6
Downtown Pump Station	2.6	0.4	6.8	0.7	6.1	0.4
Broad Creek	2.4	0.2	6.3	0.3	6.0	0.3

Notes: All elevations are re: NAVD88 datum.
All values have been rounded to the nearest tenth of a foot.
Nor'easter measurements from 11/11/09 – 11/16/09.
Recreation Center tide gauge not included; due to vandalism the gauge malfunctioned during nor'easter.

We note that even during the November Nor'easter, which recorded some of the highest historical water levels at Sewells Point, the general relationships and trends seen in the statistical comparisons from the 9 months of measured tide gauge data remain applicable.

WATER LEVEL ELEVATIONS AND RETURN PERIODS

The long-term data set provided by the Sewells Point tide gauge was analyzed using extremal 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 shown on Figure 8, and the water levels for various return periods are listed in the following table.

Table 3. Tide Elevations at Sewells Point for various Return Periods (based on current sea level elevation)

Return Period, years	Water Level at Sewells Point, feet (re: NAVD88 datum)
MHHW	1.2
2	3.8
5	4.6
10	5.2
25	6.0
50	6.6
100	7.2

HISTORIC AND REGIONAL PERSPECTIVE

The Hampton Roads region has always been subject to flooding. It is illustrative that the region was for many years known as the Virginia Tidewater (i.e., a region whose land was by nature linked to tidal waters [and tidal conditions]). The earliest known records of the area from the 17th century refer to violent storms and wide-spread flooding. The history of flooding in the City is indicative of the regional conditions. Figures 9 and 10 compare photographs of early 20th century flooding with that which occurred during the recent 2003 Hurricane Isabel passage and the November 2009 Nor'easter.

The largest tides measured since the installation of the Sewells Point tide gauge in 1927 have been, in descending sequence:

- The August 1933 Hurricane,
- Hurricane Isabel in September 2003,
- The Ash Wednesday Storm of March 1962,
- The Veterans Day Nor'easter of November 2009,
- The September 1936 Hurricane, and
- The September 1933 Hurricane.

The August 1933 hurricane produced a tide level that was more than 1 foot above any of the other storms, while the maximum tides at Sewells Point of the next four storms were all within a range of 0.2 feet. The maximum tide produced by the September 1933 hurricane was somewhat more than 0.5 feet below that from the recent November nor'easter. Since 1998, five storms (four nor'easters and one hurricane) have created tides that were within 1 to 2 feet of the tides from the recent November nor'easter.

As the region has been developed over the last four centuries, human activities have altered the landscape. While human activities have not altered the occurrence of storms, those activities have both reduced and increased the severity of flooding. For example, filling and land reclamation have elevated former wet lands, but have also narrowed the natural channels and waterways. Development of the City and the region has reduced the natural infiltration of rainfall into the ground and increased both the speed and magnitude of runoff. The region's susceptibility to flooding also has increased over the past centuries due to the natural processes of sea level rise and regional subsidence as well as more local settlement due to land reclamation.

In summary, the Hampton Roads region has always been susceptible to coastal flooding from tides and storm events. Both man's activities and natural processes 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.

FUTURE POTENTIAL SEA LEVEL RISE CONSIDERATIONS

The analyses shown on Figure 8 (and predicted flood levels shown on the Maps, described subsequently) are in reference to the current sea level elevation.

Consideration of potential future sea level rise (and/or future regional subsidence or more local ground settlement) is not part of the current analyses. While the prediction of future sea level rise is a contentious subject of considerable scientific debate, 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 recent rate of sea level rise at Sewells Point (relative sea level rise is considered to be the combined effects of sea level rise and subsidence) is 1.46 feet/century. To evaluate how a continuation of that rate of sea level rise will affect flooding in the City, we:

- Assumed a future 0.5-foot rise in sea level (if the rate of 1.46 feet/century continues this will equal the sea level in 35 years; i.e. 2045) and
- Recomputed the return period associated with various tide elevations at Sewells Point.

The return periods associated with different tide elevations at Sewells Point are summarized in the Table 4.

Table 4. Predicted Flood Levels and Return Periods, Current Sea Level Elevation and after 0.5-Foot Increase in Relative Sea Level

Sewells Point Tide Elevation, feet re: NAVD88	Approximate Return Period, years	
	based on Current Sea Level	after 0.5-foot rise in Sea Level
+5	8	5
+6	25	15
+7	80	50

Examination of the data in the proceeding table implies that continuation of current rate of sea level rise will increase the probability of seeing a particular flood water elevation by about 50% by 2045. This implies that the size of storm that can produce a specific flood water level will be less in the future than at the present. 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.

As noted, the consideration of possible future higher sea level is not included in the predictive flood maps presented subsequently.

PREDICTED WATER DEPTHS THROUGHOUT THE CITY

Implications and Use of the City Tide Gauge Data

As described above, the tide gauge data have been reviewed and used to estimate differences between average tide levels in each of the major watersheds (see Figure 11) within the City. Our interpretation of the average difference between the tide levels throughout the City and those at Sewells Point were listed in Table 1. Those differences do not include the effects of wind-forced surge nor localized storm water discharges or rainfall/runoff effects and are exclusive of cove effects in small coves.

Mapping Basis

Predicted flood depths have been determined by comparing ground surface elevations (based on City digital elevation model) to the predicted mean tide elevations within various City watersheds (i.e., drainage basins) for various tide elevations (re: NAVD88 Datum) at Sewells Point. Differences in predicted tide elevations throughout the City relative to those at Sewells Point are based on statistical analyses of nine months of tidal measurements from the five City tide gauges. In watersheds where tidal measurements are not available, we applied the adjustment factor from the nearest tide gauge.

We have chosen to present our predictions based on Sewells Point tides rather than specific return periods for two reasons: 1) the predictions based on tide elevations are more direct, whereas the predictions based on return period require other analyses steps that could reduce the accuracy of the predictions, and 2) the predictions based on elevation can be converted to consider and account for various assumptions relative to future sea level rise more directly than can predictions based on return period.

Inland areas flooded by backflow through the storm water system during coastal flooding events were screened using the rim elevation data in the City's existing storm water data files. We note that in some areas there is uncertainty in the accuracy of the rim elevations within the files used to develop this map. Verification of rim elevations via surveying (which was not a component of the current study) may be required to evaluate backflow potential. Since, the predictive flood maps have not been screened to account for locations where engineering controls such as flap valves that may prevent backflow. Therefore this screening level effort should be considered to be preliminary. In addition, in the downtown area, the predicted flood depths ignore the presence of the downtown flood wall, which provides a barrier to coastal flooding in that area.

The resulting maps are presented on Maps 1 through 5. A key to the areas covered by each chart is provided on Figure 12.

The predicted flood depths, shown on Maps 1 through 5, are based on the mean of the statistical analyses of the relationship between each City tide gauge and the tide measurements at Sewells Point. As discussed, variability about the predicted relationship occurs due to wind, wind direction, rainfall, storm water system discharge, and other factors. A 95% confidence that includes the effects of winds and rain can be obtained by adding about 0.5 feet to the predictor as shown by the predicted water depth contours.

Predicted Tidal Flooding for Various Tide Elevations at Sewells Point

Maps 1 through 5 show the predicted flood depths (in 1-foot increments) associated with the various tide elevations (re: NAVD88) at Sewells Point. Water depths in one-foot increments are shown by the palate of colors. The maps include a key to show how the different colors convert to water depth for tides of El. +5, +6, +7, and +8 feet (re: NAVD88) at Sewells Point. As shown in the key, the palette of green and blue colors is indexed to a Sewells Point tide at Elevation +6 feet (re NAVD88 datum). The maps also show the additional areas that would be flooded during El. +7- and +8-foot tides at Sewells Point by the yellow and orange bands that represent the additional inundated areas associated with those higher tide elevations.

Also shown in the legend on each chart are the return periods (based on current sea level conditions and after a future 0.5-foot rise in sea level) associated with each tide elevation at Sewells Point.

As noted above the predicted water depths as shown on Maps 1 through 5 are based on mean of the statistical analyses of the relationship between each City tide gauge and the tide measurements at Sewells Point. A 95% confidence that includes the effects of winds and rain can be obtained by adding about 0.5 feet to the predictor as shown by the predicted water depth contours.

Likewise, the mapped water depths on Maps 1 through 5 do not include cove effects that can occur in small narrow tributaries (such as Haven Creek). The Havens Creek tide gauge documents that local cove effects in such tributary areas can be approximated by adding 0.5 feet to the mapped flood depths.

Correlation of Flooding Areas and Pre-Development Morphology

It is not surprising that the flood prone areas within the City generally correlate to areas that were originally (prior to man's development) either: submerged, marsh and swamp, or other low-lying geomorphology. Figure 13 reproduces a1682 map of *Norfolk towne.* The map shows the shoreline and initial development of what is now the Norfolk downtown and Harbor Park area. This map is useful in that in addition to the shoreline and developed areas as they existed in the late 17th century, it also differentiates low-land and upland areas. The 1682 map has been geo-referenced and the current City shoreline and the alignments of major streets and roads have been overlain onto the early map. As can be seen, much of the downtown and adjacent area to the east is "filled land" that was originally submerged or low-lands.

Figure 14 shows the flood depth predictions (extracted from Map 4) for the area shown on Figure 13. The scale and areas covered by Figures 13 and14 are identical. We note that the flood depths shown in the downtown area on Figure 14 are the flood depths that would occur if there was no downtown floodwall. On Figure 14, we have added the shoreline and edge of swampy, low-land areas from the 1682 map to the current map of the area. Not surprisingly, the areas and depth of predicted flooding directly correlate to filled areas – i.e. the areas that were originally river-bottom and low-lands prior to development. This correlation is common throughout the City.

Use of Flood Depth Maps for Other Purposes

The predicted flood depths shown on Maps 1 through 5 are intended for use in the evaluation, planning and design of public works flood mitigation projects. The maps also provide meaningful data for planning and emergency response. For those other types of uses, we recommend that the maps be modified to include the potential additional flood depths associated with 1) wind, wind direction, rainfall, storm water system discharge, and other similar factors and 2) cove effects.

IMPLICATIONS FOR FLOOD DESIGN CRITERIA

Given the above findings, it is prudent for the City to update its design criteria for sizing storm water system infrastructure to account for these increased water levels. Table 5 provides our recommendations for the appropriate tailwater elevations, based on the statistical relations described previously, for different return periods in the various watersheds within the City.

Table 5. Tailwater Elevations
Based on Calculated Relationship to Sewells Point Tides

Location	Tailwater Elevations, feet (re: NAVD88) for Various Return Periods (years)						
	MHHW	2	5	10	25	50	100
Sewells Point	1.2	3.8	4.6	5.2	6.0	6.6	7.2
Watershed 4	1.1	3.7	4.5	5.1	5.9	6.5	7.1
Watershed 5	1.8	4.4	5.2	5.8	6.6	7.2	7.8
Watersheds 7 & 9	1.5	4.1	4.9	5.5	6.3	6.9	7.5
Watershed 8	1.7	4.3	5.1	5.7	6.5	7.1	7.7

The tailwater elevations in Table 5 are based on the gauge relationships within the watersheds in which they are located (with the exception of the Haven Creek tide gauge, which is interpreted to include amplification effects [cove effects] within enclosed bays). That is, for Watershed 4, we used the Recreation Center tide gauge relationship, for Watershed 5, we used the Tidewater Drive Bridge tide gauge relationship, for Watersheds 7 and 9, we used the Virginia Beach Blvd tide gauge relationship, and for Watershed 8, we used the Downtown Pump Station tide gauge relationship.

For designs that are meant to account for the effects of local winds, rainfall, storm water discharge effects, etc., we recommend that 0.5 feet be added to the tailwater elevations shown in Table 5. The tailwater elevations, inclusive of the 0.5-foot to account for the effects of local winds, rainfall, storm water discharge effects, and recommended for design are shown in Table 6.

Table 6. Recommended Tailwater Elevations
Based on Calculated Relationship to Sewells Point Tides and Ancillary Effects (Winds, Localized Runoff, etc.)

Location	Tailwater Elevations, feet (re: NAVD88) for Various Return Periods (years)						
	MHHW	2	5	10	25	50	100
Sewells Point	1.7	4.3	5.1	5.7	6.5	7.1	7.7
Watershed 4	1.6	4.2	5.0	5.6	6.4	7.0	7.6
Watershed 5	2.3	4.9	5.7	6.3	7.1	7.7	8.3
Watersheds 7 & 9	2.0	4.6	5.4	6.0	6.8	7.4	8.0
Watershed 8	2.2	4.8	5.6	6.2	7.0	7.6	8.2

*Note It is recommended to add an additional 0.5 feet in small embayment/cove such as Haven Creek site.

In narrow embayments or coves (similar to Haven Creek) an additional 0.5 feet should be added to the tailwater elevations shown in Table 6 to account for local cove effects.

FLOOD MITIGATION STRATEGIES

Mitigation Strategies and Approaches

Mitigating flood hazards 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 (and their acceptability, or not), 4) an evaluation of alternatives, and 5) the development and implementation of a mitigation and risk management plans.

The flood hazard and risk 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, 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,
- Adaptive land use to accommodate flooding, and
- Public policy.

Often mitigation approaches include more than one of the above strategies. The following lists a number of types of flood mitigation elements.

- Drainage and conveyance improvements:
  - Channelization or improved flood conveyance (stream channel improvements) and
  - Storm drainage system improvements;
- Elevation of the ground surface and/or structures;
- Barriers to flooding:
  - Earthen berms and levees,
  - Floodwalls,

  - Tidegates and barriers, and
  - Dams;
- Impoundment and storage:
  - Permanent detention and storage ponds or reservoirs and
  - Temporary use of land;
- Adaptive land use:
  - Wetlands, dunes, beach nourishment, and floodplain protected areas,
  - Setbacks and buffer areas, and
  - Land acquisition and set aside;
- Public policy:
  - Local building and construction code modifications,
  - Zoning and land use restrictions,
  - Education, and
  - Flood warning systems, modeling, and forecasting.

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

A brief discussion of the various types of flood mitigation options follows. Figures 15 through 23 provide examples of many of the different potential elements of flood mitigation.

Drainage and Conveyance Improvements

Improvements in stream channels and the channel of water through preferred flow paths can help reduce the rise of floodwaters and speed their recession. The more water that can be quickly conveyed, the lower the flood level within the given area. Conveyance improvements may include debris clearing control programs, increased capacity of storm water drainage systems, channel widening, or stream realignment. Figure 15 provides several examples of flood conveyance improvements.

Elevation of the Ground Surface and/or Structures

In low-lying areas, it is sometimes possible to raise the ground elevation so that the ground surface is higher than the storm tide elevations. Raising the ground elevation, however, can produce different secondary consequences for the various infrastructure and the conveyance of rainfall runoff.

Elevating buildings above flood levels is another approach that can be used for individual properties. Floodwaters flow under the building causing little or no damage to the structure or its contents. If floods are of long duration, this is potentially an unsafe approach since access is unsafe during flood conditions. If septic systems are present, the potential for water quality and public health risks are also an important consideration. Figure 16 illustrates the concept of structure elevation.

Flood Barriers

Flood barriers may include small earthen berms, protective sand dunes, larger levees, or concrete (or steel) floodwalls. All of these are designed to keep floodwaters out of a low lying area. Earthen levees have side slopes that require land for their footprint; the width of the footprint is dependent on the height of the levee.

For flood barriers to be effective it is necessary to surround the entire area to be protected without gaps, or for the barrier to tie into topography that is above the flood elevation. To be effective, the flood barrier must be able to withstand the forces associated with the floodwaters and waves.

In addition, care must taken to ensure adequate drainage measures are provided within the contained area so that the rain associated with tide and storm events does not flood the interior. Larger barriers tend to have high initial costs and require long term monitoring and maintenance. Failure of large flood barriers can be catastrophic with large areas flooded rapidly.

Temporary dams or flood barriers also can be used to block or redirect flows during flood events. Flood gates or inflatable dams have been successfully used for this purpose.

Figures 17 through 21 show examples of: small levees and walls, larger levees and walls, gates, pump stations, and temporary flood barriers.

Impoundment and Flood Storage

A different approach to flood mitigation is to attempt to store floodwaters in selected areas during floods and then release the stored water, in a controlled manner, after the flood. By storing and then releasing, it is possible to accommodate the floods without impacting the downstream areas. Approaches may include storm water detention ponds to trap runoff from impervious surfaces, construction of dams along rivers and creeks to regulate the downstream flow, and the use of wetlands as storage areas. These approaches typically require considerable land areas. Parks and golf courses are sometimes used for storing excess flood waters. Figure 22 shows several examples of impoundment and flood storage areas.

Adaptive Land Use

Adaptive land use usually involves the purchase of property and the removal (demolition or relocation) of structures in flood prone areas and designating the land as undevelopable. Often such areas are then used flood water detention and storage. The undeveloped green space also aids in buffering the adjacent area. This approach offers a long-term solution that removes the structure from the path of the flood. Adaptive land use is typically limited to areas that are frequently flooded, where floods are deep and/or of long duration, or where flooding is associated with high and dangerous flood water velocities. Maintaining wetlands, beaches, and dunes as buffers is one method of adaptive land use. Figure 23 illustrates this concept as applied to coastal dunes.

Public Policy

Building and Construction Codes. Local building codes can be used to help improve performance of structures subjected to flood waters. For example, standards can be set with respect to foundations or floor elevations to survive temporary flooding. Another example is dry water proofing, which is an approach that requires all portions of structures below specified flood elevations to be sealed or made impervious to water. This approach is generally only appropriate for buildings subject to less than 3 feet of flooding. This approach has the obvious disadvantage in that the structure and contents still remain within the flood path.

Land Use Plans and Zoning. Zoning rules, land use plans, and coastal zone management can be used to prevent construction or restrict the types of development (building size, density, use, open space preservation, etc.) within flood prone areas and to direct future development with regard to relative sea level rise risks. While these plans do not prevent flooding in flood prone areas, they can reduce the damage and risk.

Education. Flood mitigation strategies can include public information and outreach with respect to flooding risks, flood preparedness, access routes, flood protection information, funding support of mitigation measures, and least impact development techniques.

Flood Warning Systems. Part of an overall flood mitigation strategy may be flood warning and/or numerical simulation forecasting systems to alert both responsible City staff and the public of potential flooding events and their location and severity. Although this communication does not prevent flooding or long term damage, it can reduce safety risk and provide opportunity to re-locate valuables. The water level monitoring gauge stations can provide the basis for developing such a system.

Relative Costs of Various Approaches

The costs of various flood mitigation approaches are project specific and require detailed evaluation. Nevertheless relative comparison of the different types of approaches is possible. Tables 7 and 8 provide generalized comparisons of the relative capital and operational-maintenance costs associated with the different approaches.

Table 7. Relative Capital Investment Costs for Different Categories of Flood Mitigation Improvements

	Relative Cost		
	Low	**Medium**	**High**
Drainage & Conveyance Improvements	XXXXX	XXXXXXXXXX	XXXXX
Elevation of Ground or Structures	XXXXX	XXXXXXXXXX	XXXXXXXXXX
Flood Barrier Structures		XXXXX	XXXXXXXXXX
Impoundments and Storage	XXXXX	XXXXXXXXXX	
Adaptive Land Use	XXXXXXXXXX		
Public Policy	XXXXX	XXXXXXXXXX	XXXXX

Table 8. Relative Operational and Maintenance Costs for Different Categories of Flood Mitigation Improvements

	Relative Cost		
	Low	Medium	High
Drainage & Conveyance Improvements	XXXXX	XXXXXXXXXX	
Elevation of Ground or Structures	XXXXXXXXXX		
Flood Barrier Structures		XXXXXXXXXX	XXXXXXXXXX
Impoundments and Storage	XXXXX	XXXXX	
Adaptive Land Use	XXXXXXXXXX		
Public Policy	XXXXXXXXXX		

POTENTIAL FLOOD DEFENSE OPTIONS FOR THE CITY OF NORFOLK

Given the variability of conditions within the City of Norfolk, a wide range of flood mitigation projects and strategies will be required to provide meaningful relief. It should be noted that the first decision that will need to be made to assess potential options will be to define the appropriate return period of the flooding to be mitigated by the project. In some areas, a 100-yr return period flood may be mitigated with minor infrastructure improvements, while in other areas, significant projects will be required to mitigate a 2-yr return period flood. These decisions will have to be made on a case-by-case basis. The following discussion lists (in increasing order of existing coastal flood severity) the types of projects and their potential areas of applicability. General programmatic options and recommendations are included at the end of this section.

Storm Water Drainage System Improvements to Mitigate Localized Flooding (Flooding Depths Up to 2 Feet)

Where the current flooding behavior can be characterized as nuisance flooding, adequate relief may be achieved by installing storm water system drainage improvements (either additional parallel systems or upgraded systems). In many areas of the City, the current infrastructure is undersized for the amount of development. This factor coupled with higher tailwater conditions, impedes upland floodwaters from exiting the storm water systems in a timely manner. The installation of larger pipes with inline check valves, sized for an appropriate tailwater condition, should reduce flood depths and durations to more acceptable levels.

This approach can be cost effective in resolving the most frequently occurring flooding issues that produce small flooding depths over a wide area. The storm water system drainage improvements also can be an important part of larger scale flood mitigation measures. However, it must be realized that resizing existing storm water drainage systems can be problematic especially where existing pipes are buried within older infrastructure. Nonetheless, storm water drainage improvements help reduce flooding by conveying floodwaters out of localized areas more readily.

Elevation of Existing Ground Surface to Mitigate Localized Flooding (Flooding Depths Up to 2 Feet)

Where current flooding can be characterized as nuisance flooding, adequate relief also may be achieved by minor fill projects to raise the level of the ground surface. Areas along the shoreline that suffer mainly from river flooding may experience adequate relief by raising the elevation of the existing ground. In some areas, limited increases in ground surface elevation can prevent floodwaters caused by elevated tides from entering selected sites. It is expected that these types of improvements will only be practical or feasible in localized areas where existing flooding depths are less than 1 to 2 feet.

Small Floodwalls or Earthen Levees to Protect against Neighborhood-Scale Flooding (Flooding Depths up to 3 to 4 Feet)

Based on the analyses completed to date, it is likely that installation of small floodwalls or earthen levees may be a viable option within some areas of the City. These types of solutions are envisioned to require walls or earthen levees that are no more than 3 to 4 feet high. The failure of this height wall or levee has only limited risk to the loss of human life.

This mitigation approach will be most economical and beneficial in areas where the surrounding topography is higher so that the floodwall or levee length is relatively short. It is important to note that before these systems are installed, analysis of the storm water drainage system should be completed to verify that the floodwall does not serve as an impediment to the interior drainage. It is likely that some improvement of the storm water drainage systems behind floodwalls and levees may be required in concert with small wall or levee projects.

This scale of project often can be relatively unobtrusive when combined with appropriate landscaping. However, while these types of systems may be preferable in many locations, it should be noted that some ongoing maintenance may be required given the size of the structures and their vulnerability to wave attack.

Elevation of Structures or Buyout of Home Owners in Local Areas of High Flooding (Flood Depths above 3 to 4 Feet)

In local areas, where flood depths are above 3 to 4 feet, elevating existing structures may be the most feasible solution. Alternately, where the flooding is limited to just a few properties, it may be more cost effective to buyout the homeowners of the subject properties. This option may be difficult to implement, but FEMA funding for these options may be available and make them more practicable.

The advantage of these options is that once completed, limited maintenance is required. Special care and coordination with the property owners is required so that aesthetics and neighborhood character are maintained. The potential for contentious negotiations (especially with the buyout option) must be recognized. Thus, these options may be a last resort when no other options are feasible.

Major Capital Improvements in Areas where Flood Depths Could Exceed 4 to 5 feet

Where large areas are subject to chronic nuisance flooding and the potential for deep flood waters during extreme events could be wide spread, larger capital improvement projects may be required. These projects likely will include some combination of flood walls or levees, tide gates, and/or pump structures. These projects can be most easily and readily implemented where the drainage outlet from the flood prone area is relatively narrow.

The advantage of these systems is that they can be designed to provide the necessary level of flood protection. Various system components can be included to provide redundancy and additional flood protection. However, major capital improvements usually require significant budget. Also, maintenance is required to protect the value and effectiveness of the system. The complex inner workings of these systems and their interactions must be considered, as failures during large events can cause significant damage.

Temporary Barriers (such as Inflatable Dams, etc.)

There may be special situations where other types of flood mitigation systems may be prudent or preferable to those listed above. For example, inflatable, bladder dams may be an option where recreational and aesthetic needs will not allow construction of a floodwall that would disconnect people from the shoreline. It is expected that these specialized, high maintenance systems will only be used in limited applications due to ongoing costs and susceptibility to failure.

Beach and Shoreline Projects

Along the coastal shoreline of the City, ongoing beach and dune maintenance and improvements provides flood protection from storm surges.

PUBLIC POLICY OPPORTUNITIES

In addition to the infrastructure options listed above, public policy updates may be appropriate. The tide data collected for this project enhances the understanding and appreciation of flooding risks in the City. That knowledge provides the opportunity to implement a monitoring and flood warning system that can provide opportunities to develop education and planning tools for the purpose of reducing the consequences of future flooding.

Given the strong statistical relationships found between the tide gauges, it is feasible to implement a real-time monitoring and flood warning system that indexes predicted water levels throughout the City to the predicted water level at Sewells Point. Also the long-term gauges could be linked by telemetry to the internet to provide real-time confirmation of flood levels within the City.

These concepts can be extended further by contracting a meteorological organization to provide forecasts and nowcasts for Sewells Point water levels in advance of and during flood events. Those predicted water levels can then be used to refine the predicted flooding maps, and then distribute them to emergency planning and 1st responder groups within the City. Having predictive flood maps will be useful for planning and executing emergency response actions in advance of and during events and will allow 1st responders to anticipate the likely extent and location of areas of inundation, potential access restrictions, and appropriate evacuation routes.

The system could be further developed to disseminate information to the public on a real-time or near real-time basis using the internet, reverse 911, *Norfolk Alert*, the media, or other processes. This information would allow citizens to move themselves and their belongings to higher elevations (second floors, etc.) to limit the potential damage. In addition to maps, 3D graphics such as shown on Figure 24 can be used to disseminate predicted flood depths.

The findings from this study also can be used by the planning department within the City. Building codes should be strengthened to the appropriate levels within the flood-prone areas based on expected flooding frequency and flood depths. Land use planning should also use this mapping to define optimal location of schools, public safety (fire and police stations), and emergency shelters. Long-term planning can use the information to evaluate the need and opportunities for area-wide improvements that may reduce future flooding. For example, Figure 14 illustrates the risk and severity of flooding in the proposed Park Place redevelopment area and at the proposed intermodal transportation center at Harbor Park.

CRITERIA FOR PRIORITIZING PROJECTS

The predictive maps provided in this report are intended to allow the City to assess the frequency and extent of coastal flooding. The extent of the areas together with the value of infrastructure, and disruption of City traffic and services provides input for defining flood defense mitigation priorities. Site-specific and broader region flood mitigation strategies should use the predictive flood maps to evaluate the risk of flooding and potential damage.

The first step in developing a plan for project prioritization and implementation was to identify the coastal flooding risks through mapping and correlation to water level measurement data. These technical steps define the risks of flooding and flood hazard.

The next steps will be for the City to define various societal factors. Those evaluations then define the consequences of flooding.

When the flood risk, hazard evaluation, and flood consequences evaluations are combined they provide the basis for defining and prioritizing flood mitigation improvements. Setting goals and priorities for flood mitigation options throughout the City will require an iterative and collaborative dialogue among City officials, engineers, and the public so that the chosen steps can be implemented.

In concert with flood risk and flood consequences, cost considerations are the third major input to flood mitigation strategies and priorities. Cost considerations include cost of doing nothing (i.e., the costs of sustaining flood damage), initial project cost, long-term project (operational and maintenance) costs, and society and economic loss (or gain) associated with the flood mitigation. Economic losses or gains can include costs associated with the economic value of the land, transportation access and transportation costs, environmental consequences (both positive and negative), etc.

Areas where simple storm water system drainage improvements and slight land elevation modifications can be made are logical areas to prioritize for improvement. These storm water system drainage improvements are likely necessary even with larger flood mitigation measures to insure proper drainage of the areas contained within larger floodwall systems.

Given the variety of coastal flooding exposures ranging from open coastal areas to low relief creek embayments, a variety of flood mitigation approaches are likely to be used in the City. Since there is no likely single stand-alone strategy, the phasing and integration of the various strategies will be important to consider.

Some suggested criteria for prioritizing projects are:

- Technical Considerations (i.e., risk of and hazard associated with flooding):
  - Frequency of flooding (relative elevation of ground and infrastructure to flood levels),
  - Extent and depth of flooding,
  - Potential for damage (current land use, property value, and tax revenue),
  - Availability of land, and
  - Evaluation of mitigation concepts;
- Societal Factors (i.e., consequence of flooding):
  - Population density,
  - Building density,
  - Political, social/historical, and economic justice considerations,
  - Potential disruptions and safety risks including transportation impacts, and
  - Affect on land ownership and land use;
- Cost factors:
  - Costs of sustaining flood damage,
  - Capital investment costs,
  - Long-term operational and maintenance costs, and
  - Potential State or Federal funding participation; and
- Other factors:
  - Environmental consequences,
  - Ease of permitting,
  - Collateral losses or synergistic benefits,
  - Potential for cost-effective mitigation measure, and
  - Protection of priority sites (historic, public, etc.).

Flood mitigation projects can be assessed by examining their relative importance to the above listed criteria. A scoring sheet, developed during a working session of key stakeholders, is a common tool to select and prioritize project that have the greatest possible "buy in."

The project evaluation, scoring sheet approach may include the following sequence of steps:

- Goal/Category – define flood prevention, property protection, public information, flood mitigation factors and considerations;
- Criteria – evaluate the considerations semi-quantitatively by assigned points for the various factors and considerations (e.g. High = 5, Medium = 3, Low =1);

- Summary the score; and
- Rank the priority of the various projects being considered.

CONCLUDING COMMENTS

The expected range of flooding levels within the City is within the range of conventional flood mitigation alternatives. The final solution for any given area or location will depend on the return period selected for design (i.e., level of protection) as well as the local site conditions (topography, subsurface conditions, etc.) and available funds.

The City (as do all municipalities) currently faces dwindling budgets while still facing public expectations that projects and improvements be implemented. Based on the information available and the current economic climate, the City should look for projects that will be cost-effective but still provide meaningful relief to the greatest number of residential and commercial properties.

It will be advantageous if these projects are located in areas where the coastal flooding enters the subject area through a more defined channel or bridge so that the required flood mitigation infrastructure may be minimized compared to the area affected. While completing infrastructure projects to provide flooding relief should be given priority, the information gleaned from this study should also be used to develop a real-time monitoring and early warning system to provide citizens and first responders the tools needed to limit flood damages and protect life and property.

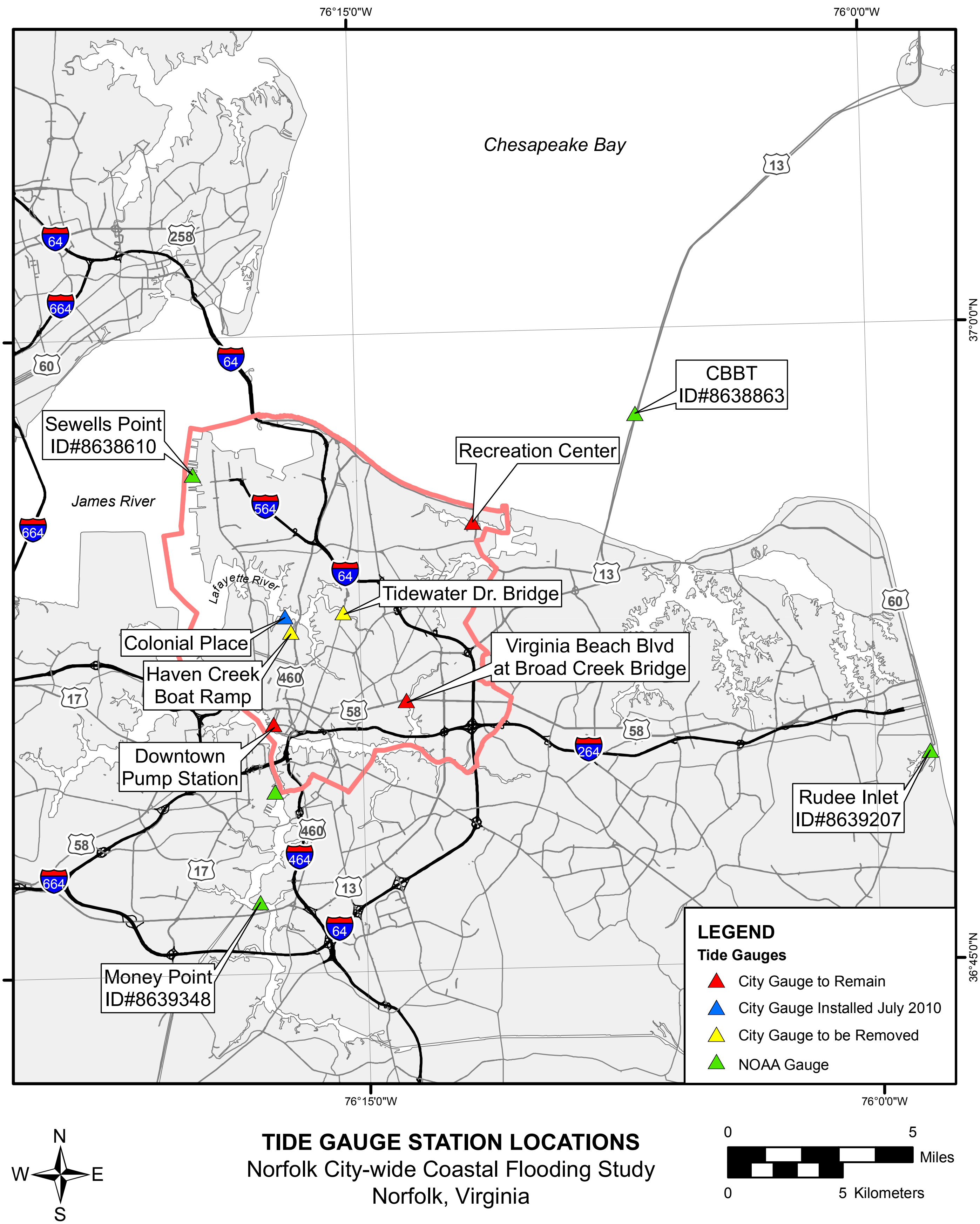
The City will be prudent to implement this study and its findings in ongoing and future planning efforts (land use planning, siting of City facilities, etc.) to reduce the consequences of future storm events and provide adequate facilities when future flood events occur.

REFERENCES

NOAA (2010), http://co-ops.nos.noaa.gov/sltrends/sltrends_station.shtml?stnid=8638610 Sewells Point, VA

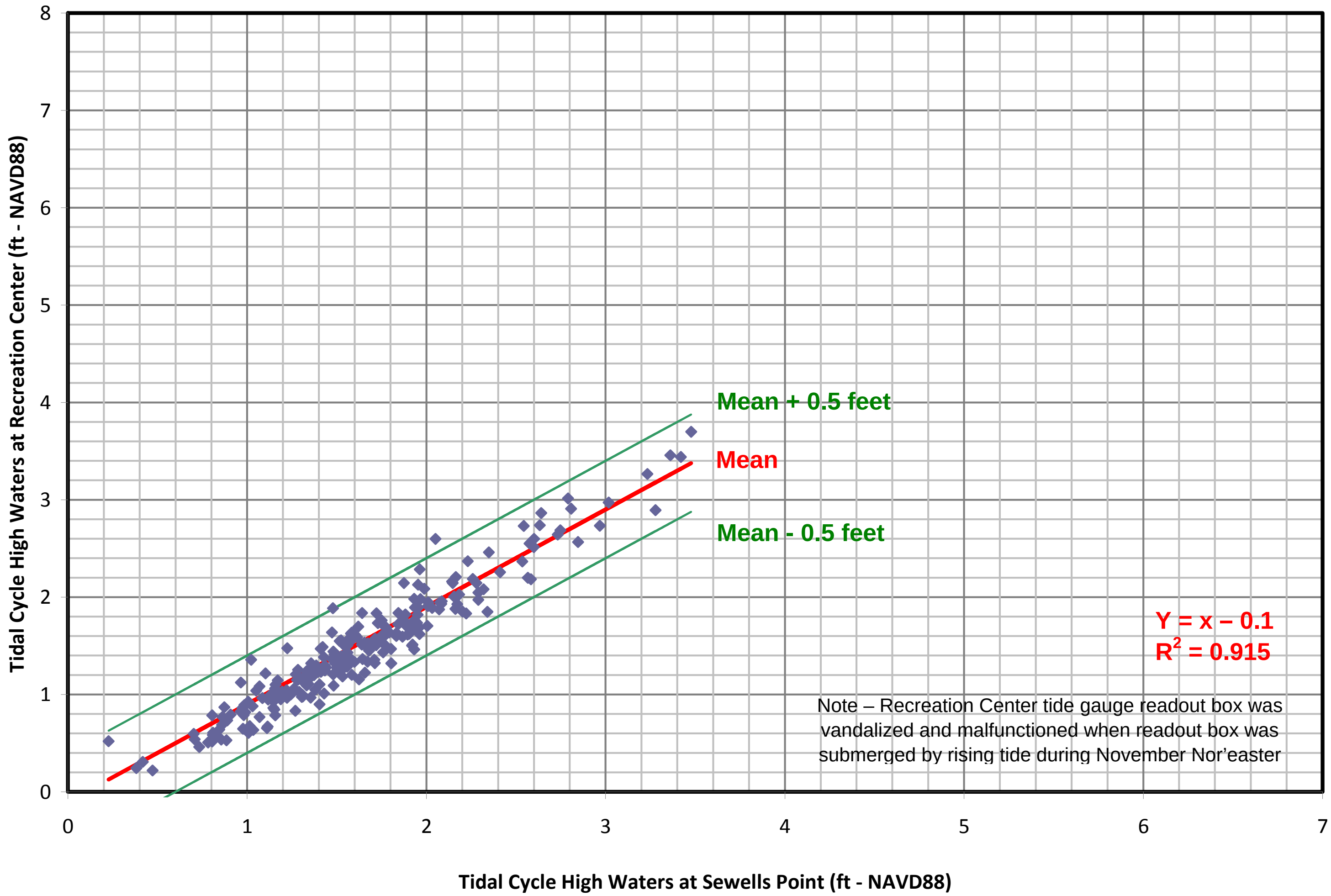
NOAA (2009), "Elevated East Coast Sea Level Anomaly: June - July 2009," NOAA Technical Report NOS CO-OPS 051, August.

FIGURES



TIDE GAUGE STATION LOCATIONS
Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

FIGURE 1



COMPARISON OF TIDE GAUGE MEASUREMENTS AND SEWELLS POINT

Little Creek – Recreation Center (P12RC)

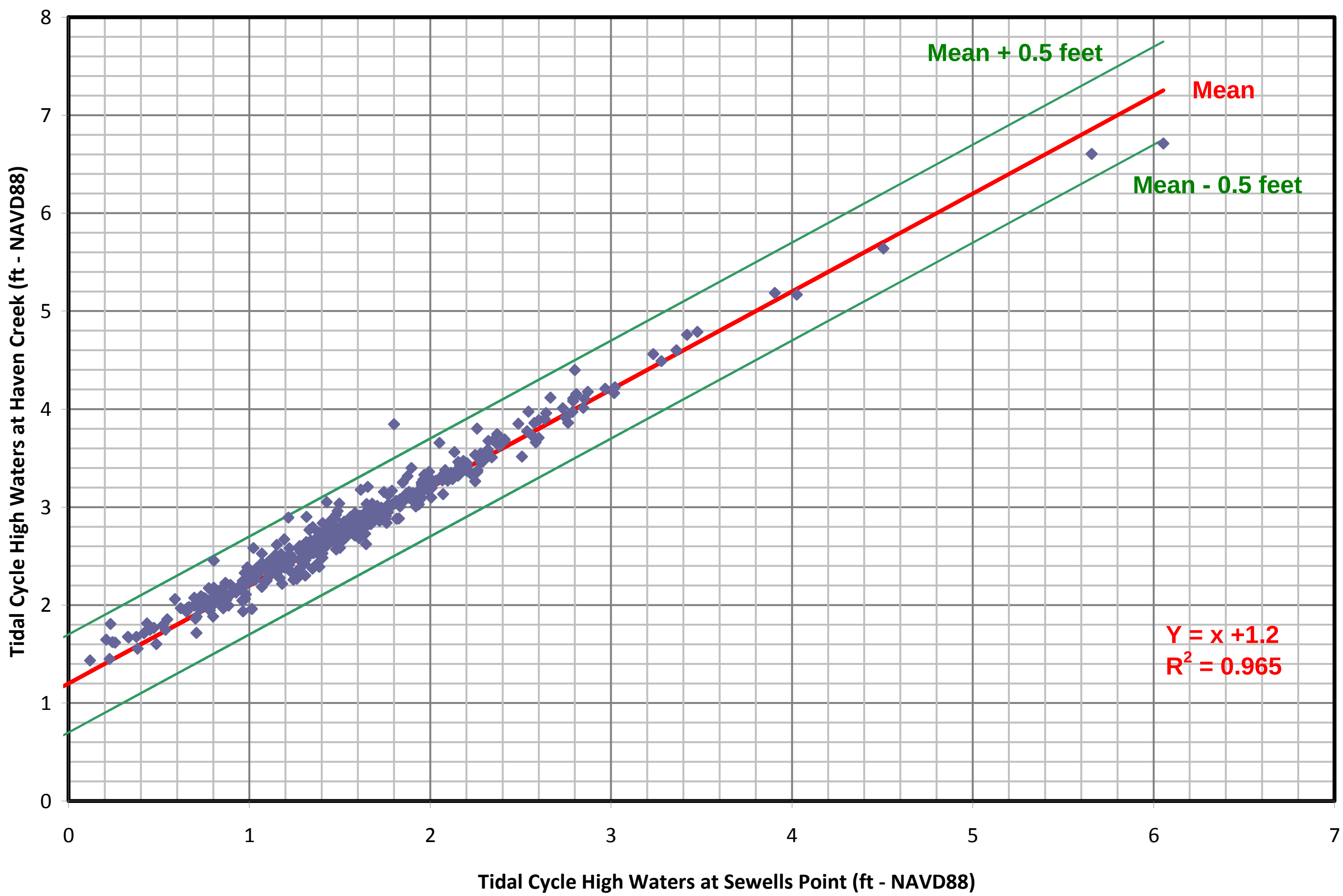
Norfolk City-wide Coastal Flooding Study

Norfolk, Virginia

FIGURE 2

N:\PROJECTS\3627_CITY_NORFOLK\3627-003 PH1 FLOOD\EVALUATION\OUTPUTS\FINAL COASTAL FLOODING STUDY\DOC FROM XLS JEF\FIG 3.DOC

City of Norfolk, Department of Public Works
Project No. 3627.003



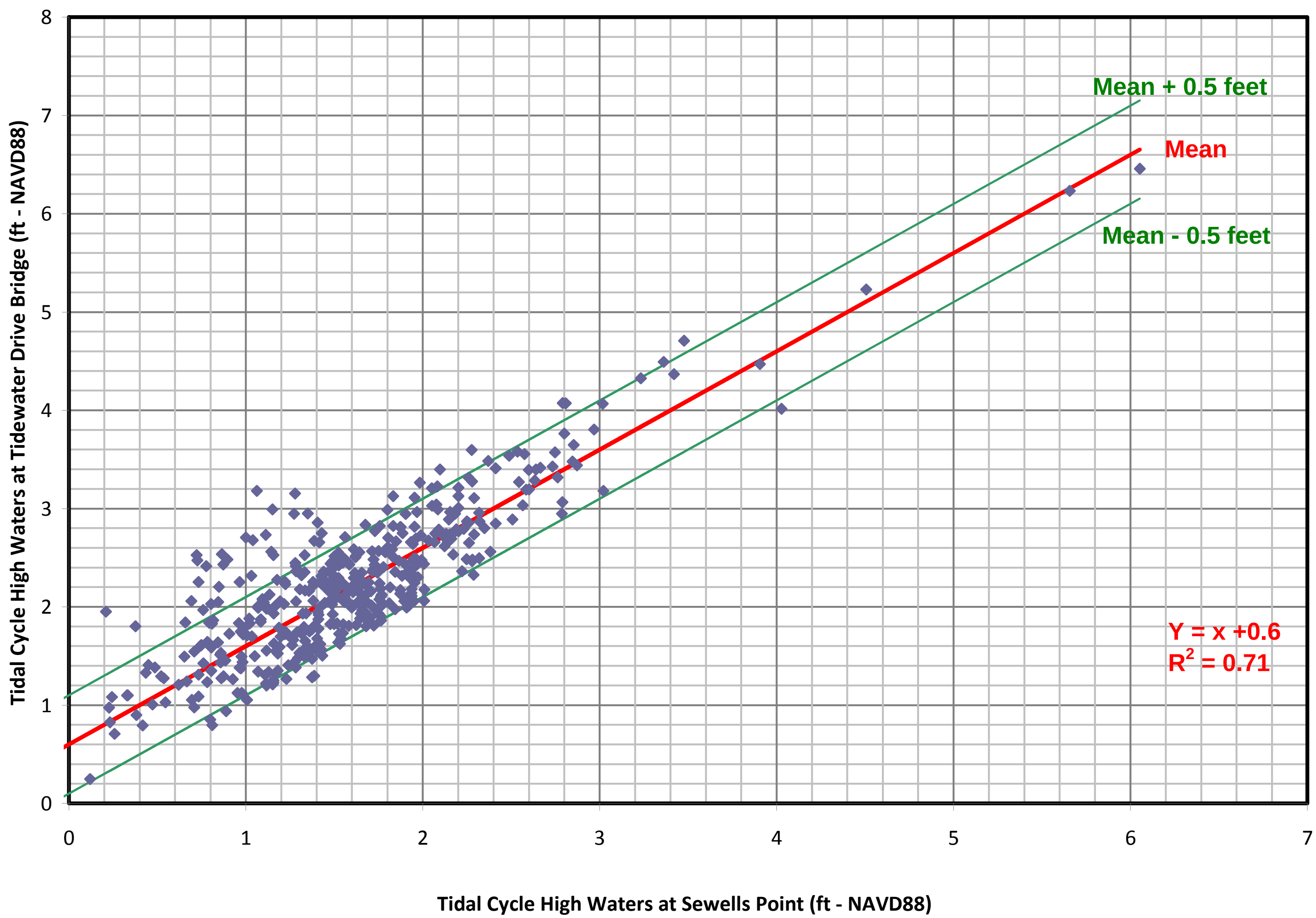
COMPARISON OF TIDE GAUGE MEASUREMENTS AND SEWELLS POINT

Lafayette River – Haven Creek Boat Ramp (P13HC)

Norfolk City-wide Coastal Flooding Study

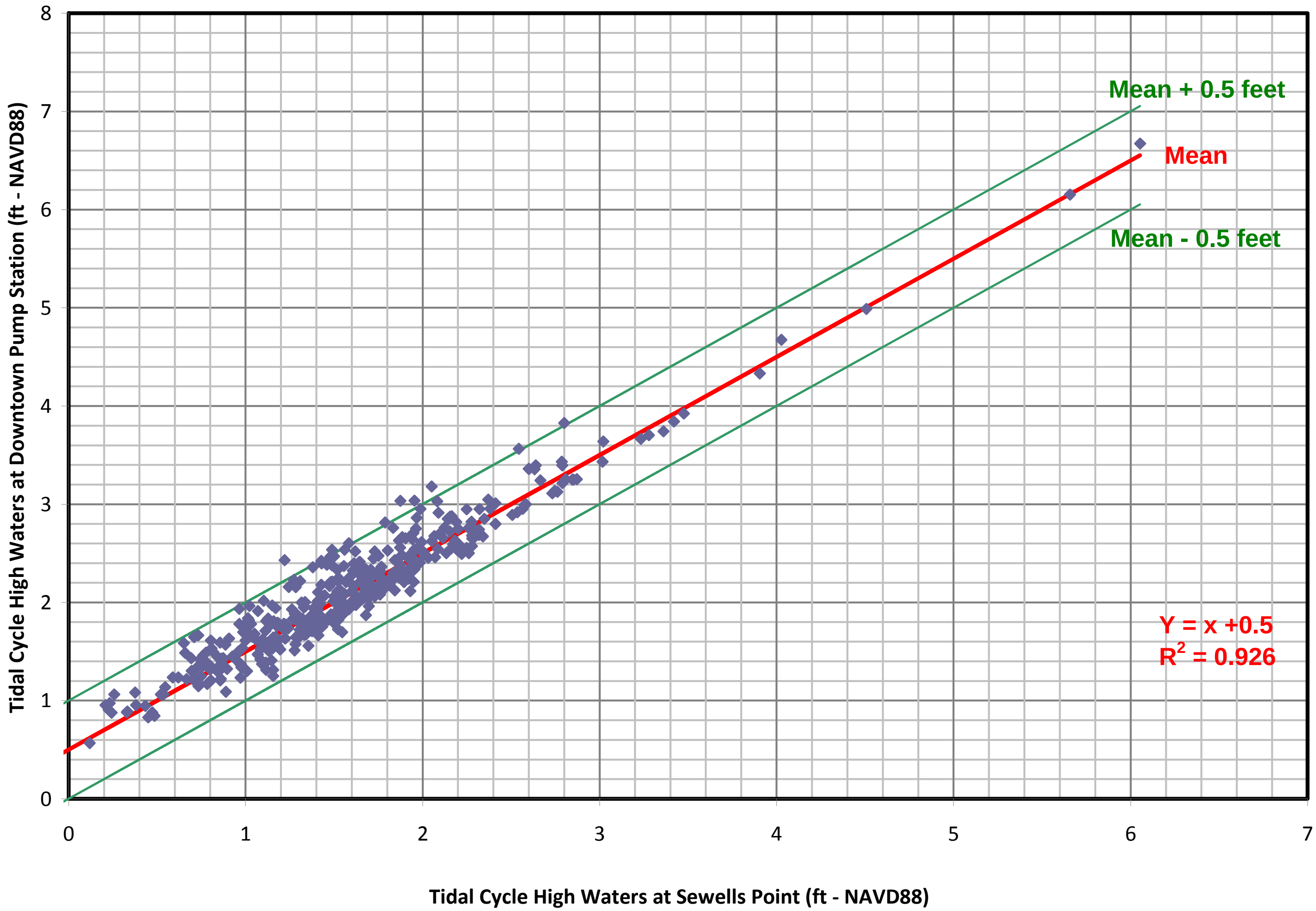
Norfolk, Virginia

FIGURE 3



COMPARISON OF TIDE GAUGE MEASUREMENTS AND SEWELLS POINT
Lafayette River – Wayne Creek at Tidewater Drive Bridge (P13TW)
Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

FIGURE 4



COMPARISON OF TIDE GAUGE MEASUREMENTS AND SEWELLS POINT

Downtown Pump Station on Main Branch of Elizabeth River (P13PS)

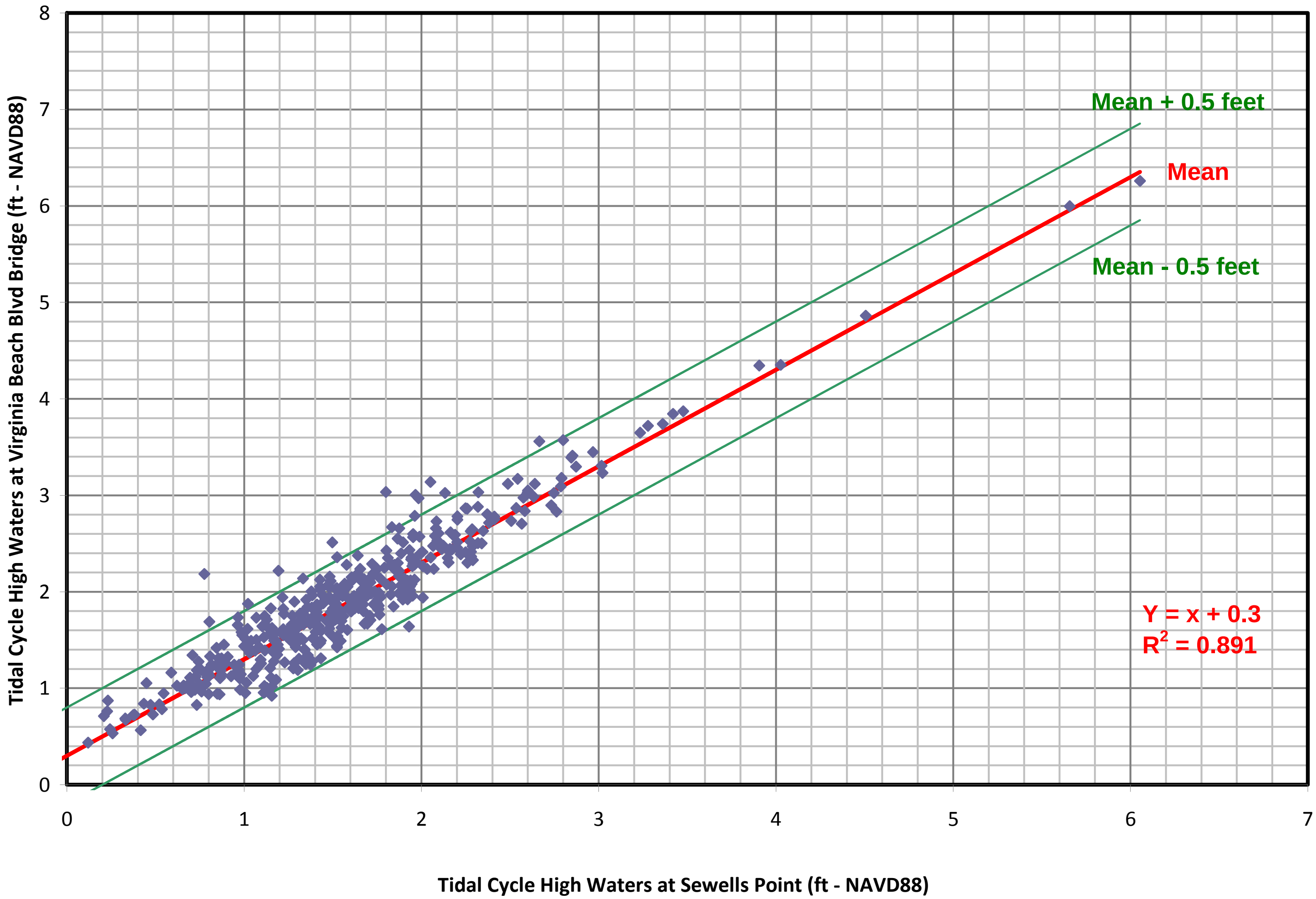
Norfolk City-wide Coastal Flooding Study

Norfolk, Virginia

FIGURE 5

City of Norfolk, Department of Public Works
Project No. 3627.003

N:\PROJECTS\3627_CITY_NORFOLK\3627-003 PH1 FLOODEVALUATION\OUTPUTS\FINAL COASTAL FLOODING STUDY\DOC FROM XLS JEF\FIG 5.DOC



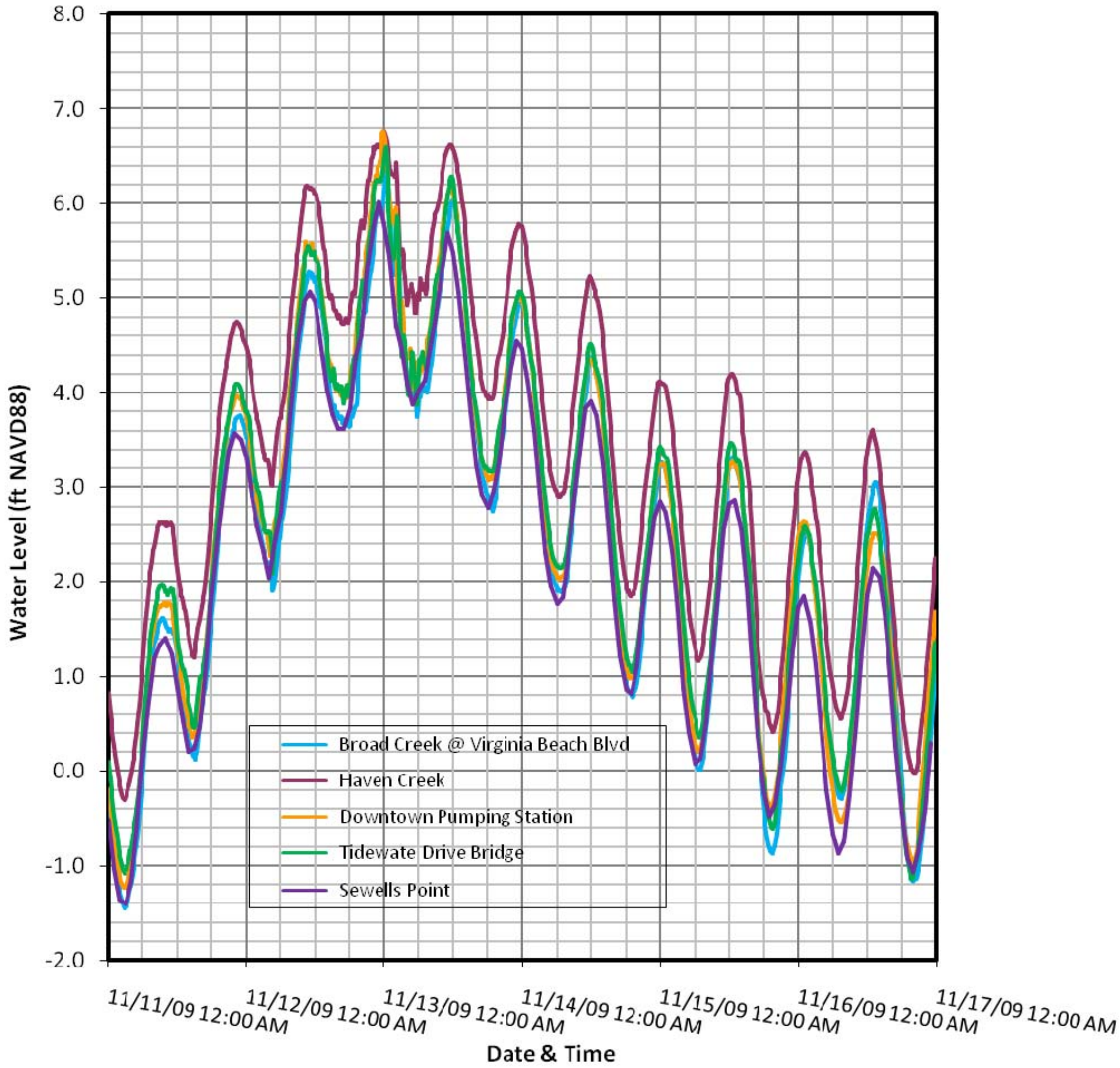
COMPARISON OF TIDE GAUGE MEASUREMENTS AND SEWELLS POINT

Broad Creek at Virginia Beach Blvd. (P13VB)

Norfolk City-wide Coastal Flooding Study

Norfolk, Virginia

FIGURE 6



TIDE GAUGE MEASUREMENTS DURING NOVEMBER 2009 NOR'EASTER

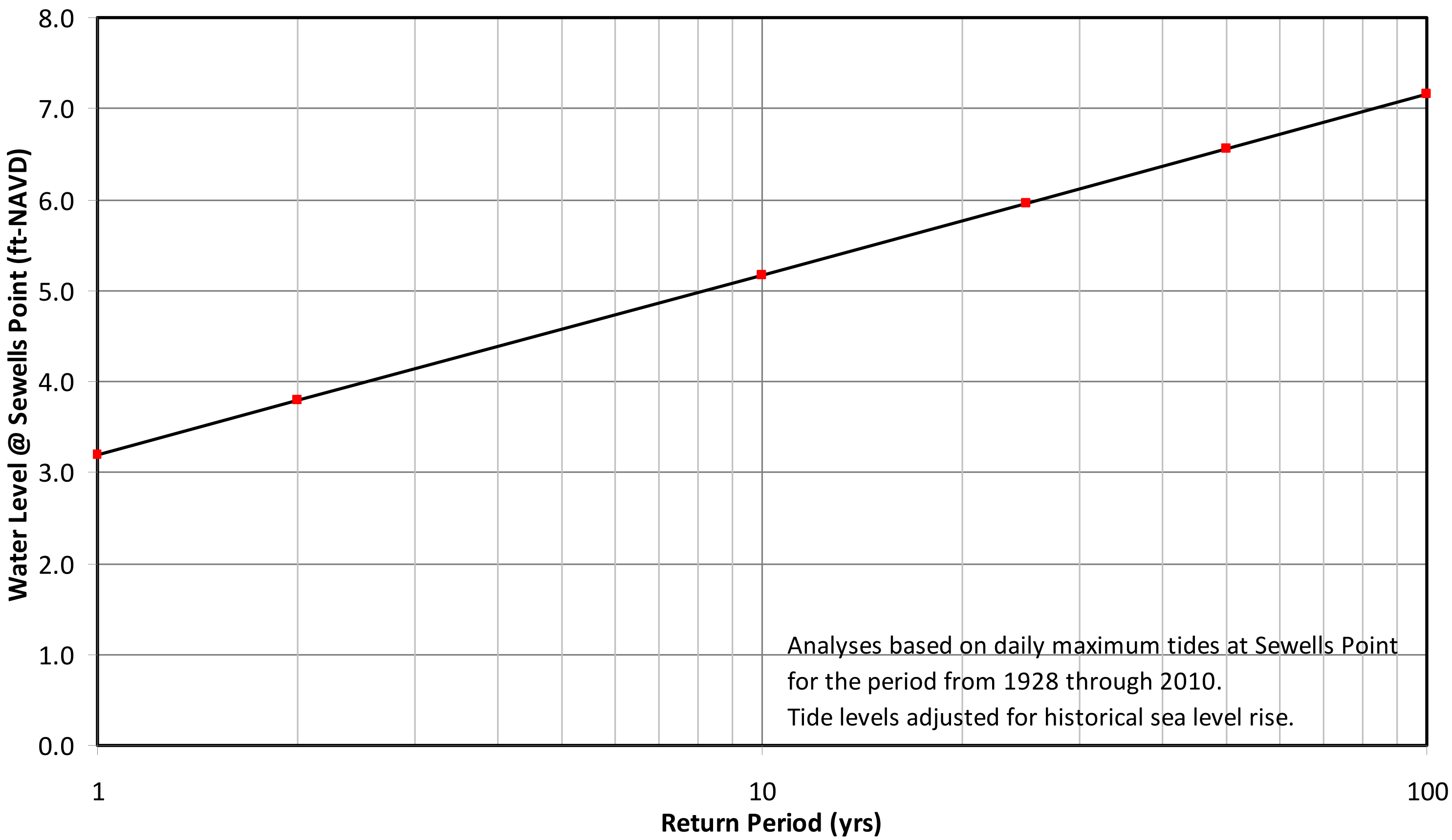
Norfolk City-wide Coastal Flooding Study

Norfolk, Virginia

FIGURE 7

City of Norfolk, Department of Public Works
Project No. 3627.003

N:\PROJECTS\3627_CITY_NORFOLK\3627-003 PH1 FLOODEVALUATION\OUTPUTS\FINAL COASTAL FLOODING STUDY\DOC FROM XLS JEF\FIG 7.DOC



RETURN PERIOD ANALYSES FOR SEWELLS POINT

Norfolk City-wide Coastal Flooding Study

Norfolk, Virginia

FIGURE 8

City of Norfolk, Department of Public Works

Project No. 3627.003

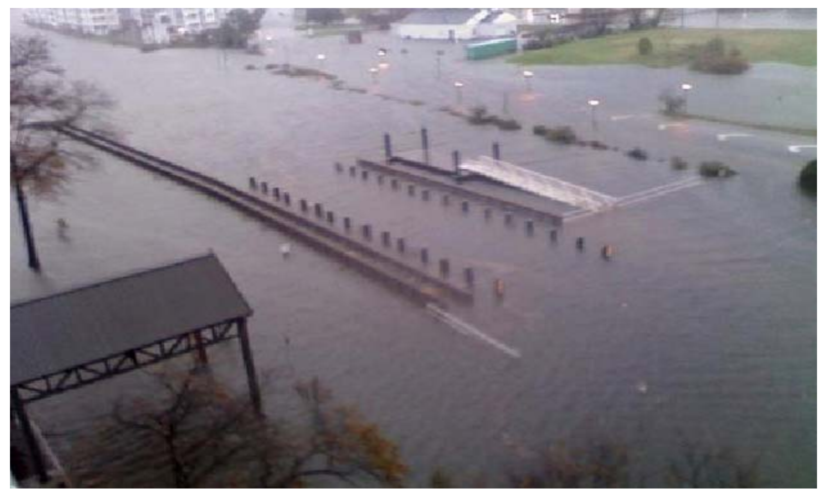
N:\PROJECTS\3627_CITY_NORFOLK\3627-003 PH1 FLOODEVALUATION\OUTPUTS\FINAL COASTAL FLOODING STUDY\DOC FROM XLS JEF\FIG 8.DOC

Southeastern Gale, April 1915 (above) and August 1933 Hurricane (below)

FLOOD EVENT PHOTOS
Historic Events
Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

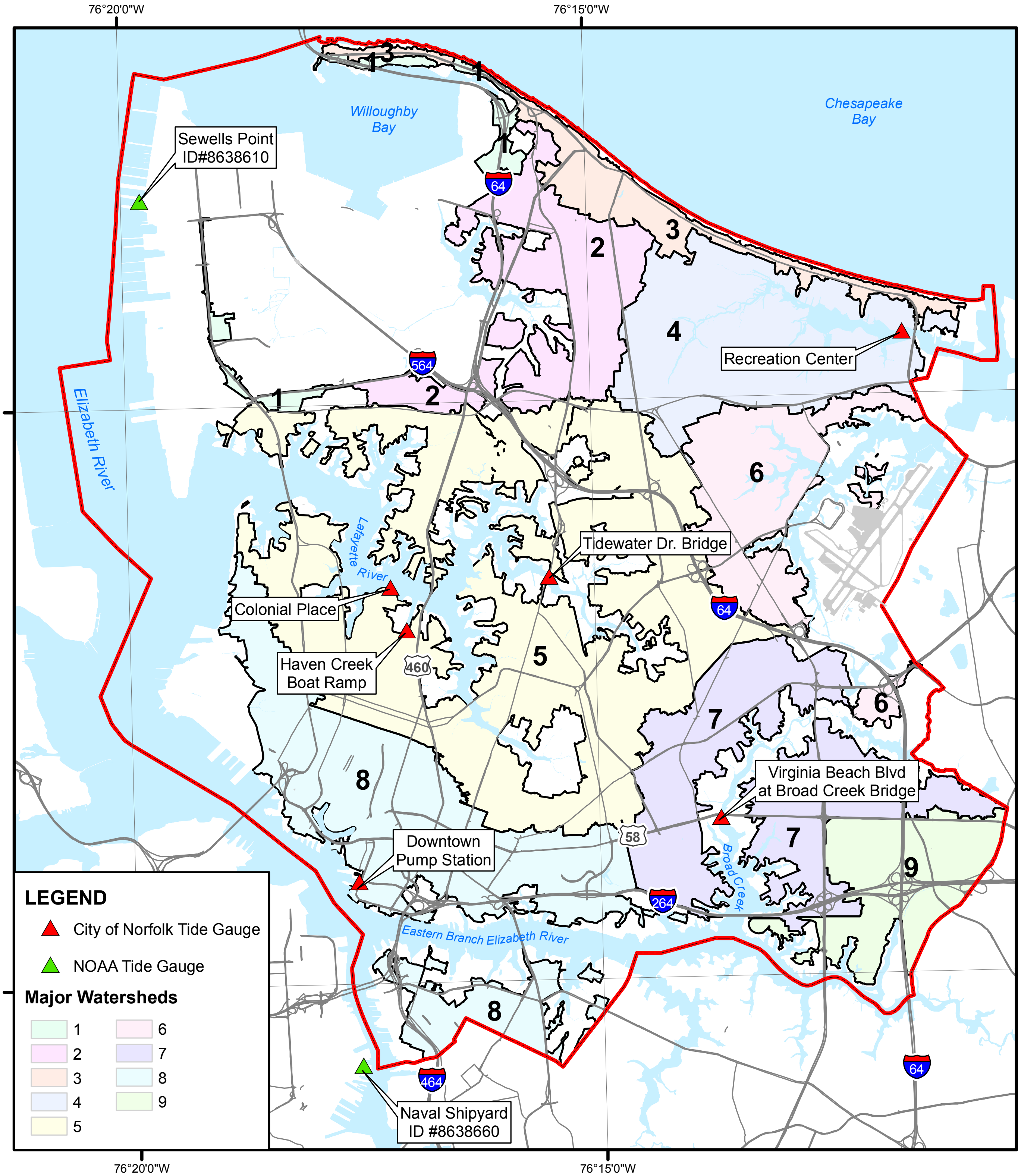
FIGURE 9

Hurricane Isabel, September 2003 (above) and 2009 November Nor'easter (below)



FLOOD EVENT PHOTOS
Recent Events
Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

FIGURE 10

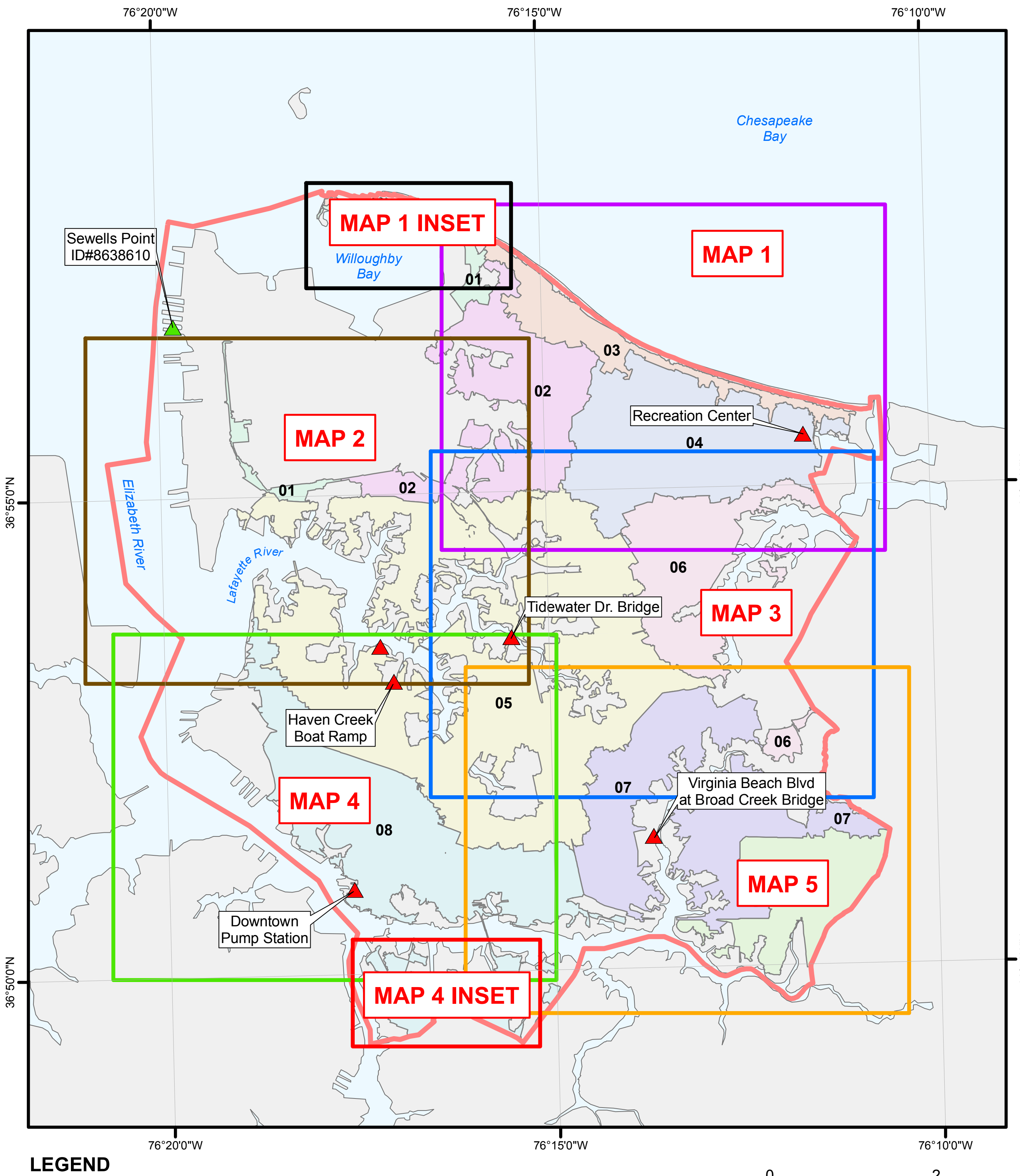


MAJOR WATERSHEDS
Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

FIGURE 11

N:\Projects\3627_City_Norfolk\3627-003_Ph1_FloodEvaluation\Outputs\Final_Coastal_Flooding_Study\MXD\Fig-11_Watersheds.mxd, 08/20/10, kspencer

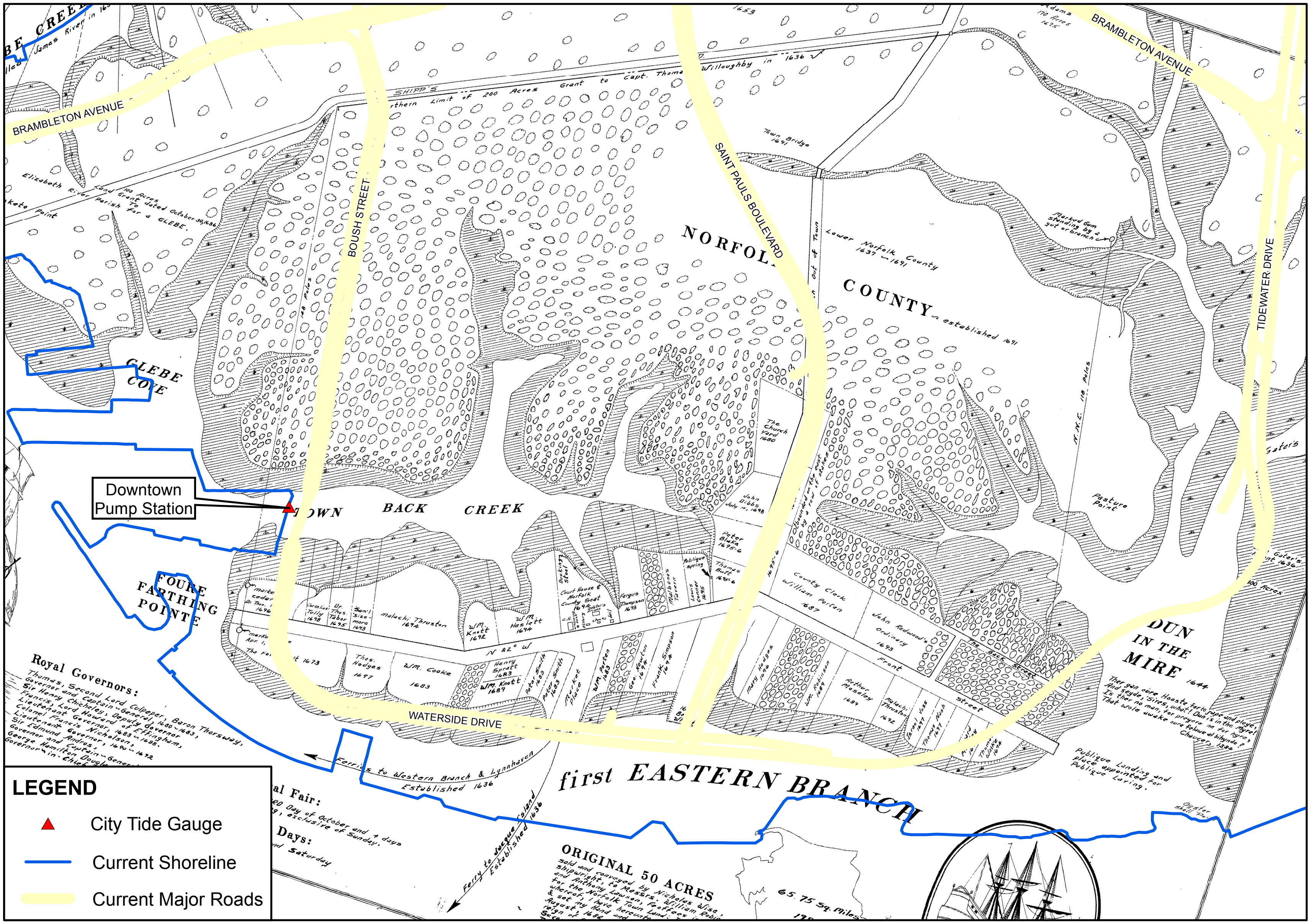
City of Norfolk, Department of Public Works
Project No. 3627.003



MAP EXTENTS
Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

FIGURE 12

N:\Projects\3627_City_Norfolk\3627-003_Ph1_FloodEvaluation\Outputs\Final_Coastal_Flooding_Study\MXD\Fig-12_Chart_Extents.mxd, 08/20/10, kspencer



N
W E
S

0 600
Feet

PRE-DEVELOPMENT MORPHOLOGY
Downtown and Harbor Park Area
Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

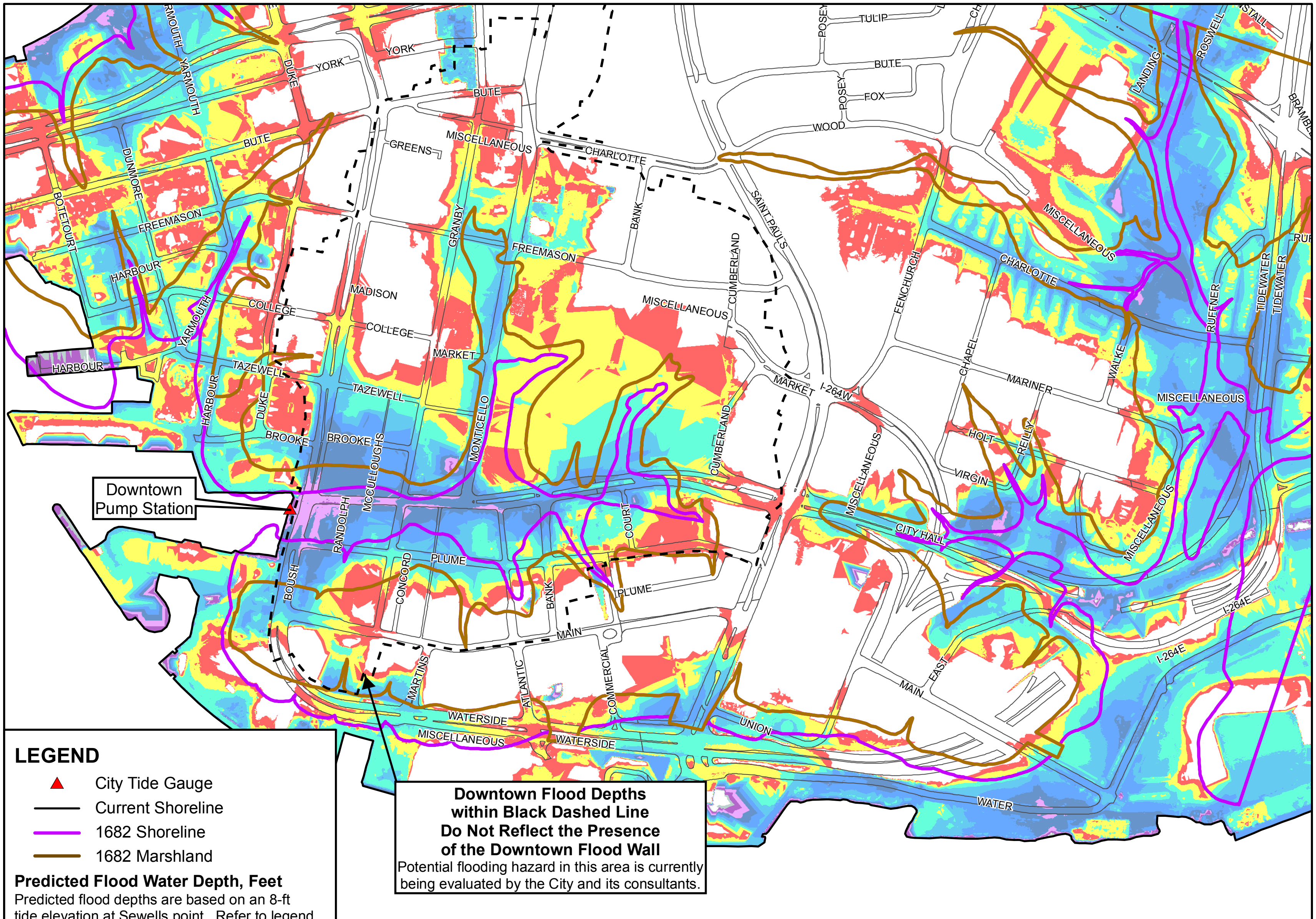
Brown, L. and Franklin G. "Norfolk Town" [map]. Bureau of Surveys, Norfolk, Virginia, 1682.

City of Norfolk, Department of Public Works
Project No. 3627.003

FUGRO

FIGURE 13

N:\Projects\3627_City_Norfolk\3627-003_Ph1_FloodEvaluation\Outputs\Final_Coastal_Flooding_Study\MXD\Fig-14_Historical_with_FloodMap.mxd, 08/17/10, kspencer



LEGEND

- ▲ City Tide Gauge
- Current Shoreline
- 1682 Shoreline
- 1682 Marshland

Predicted Flood Water Depth, Feet

Predicted flood depths are based on an 8-ft tide elevation at Sewells point. Refer to legend on maps for additional information.

- 0.0 - 1.0
- 1.1 - 2.0
- 2.1 - 3.0
- 3.1 - 4.0
- 4.1 - 5.0
- 5.1 - 6.0
- 6.1 - 7.0
- 7.1 - 8.0
- > 8 .0

PREDICTED FLOOD DEPTHS
Downtown and Harbor Park Area
Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

N W E S

0 600 Feet

City of Norfolk, Department of Public Works
Project No. 3627.003

FUGRO

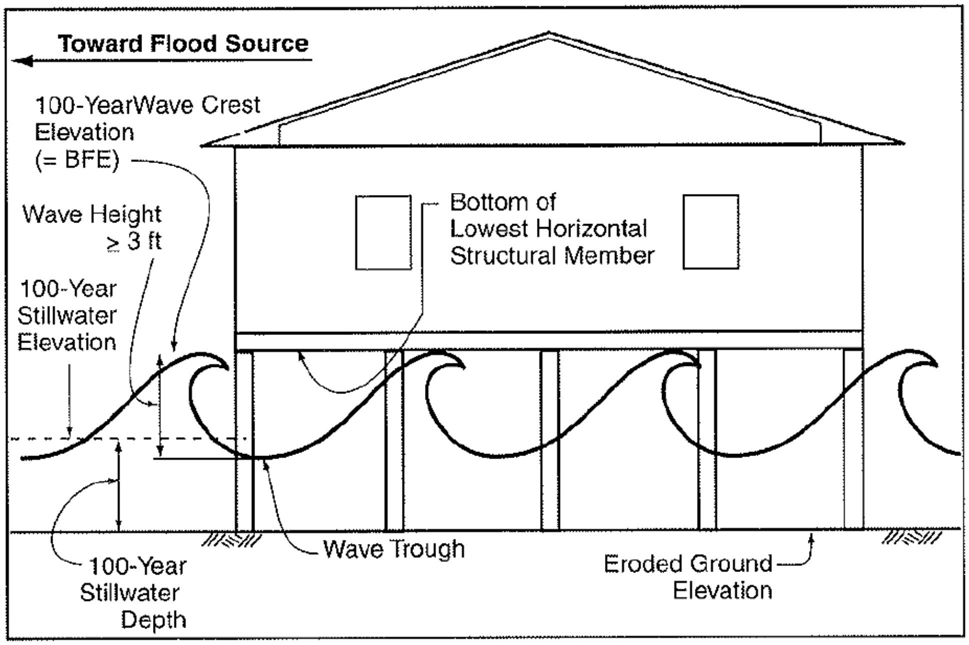
FIGURE 14

Open Channel Improvement Project, Raleigh, North Carolina

Existing Open Channel, Rocky Mount, North Carolina

FLOOD MITIGATION CONCEPTS
Channelization Improvements
Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

FIGURE 15



Elevation of structures
above base flood

FLOOD MITIGATION CONCEPTS
Elevation of Structures
Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

Earthen Levee – New Orleans

Floodwall – New Orleans

FLOOD MITIGATION CONCEPTS
Flood Levees And Flood Walls
Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

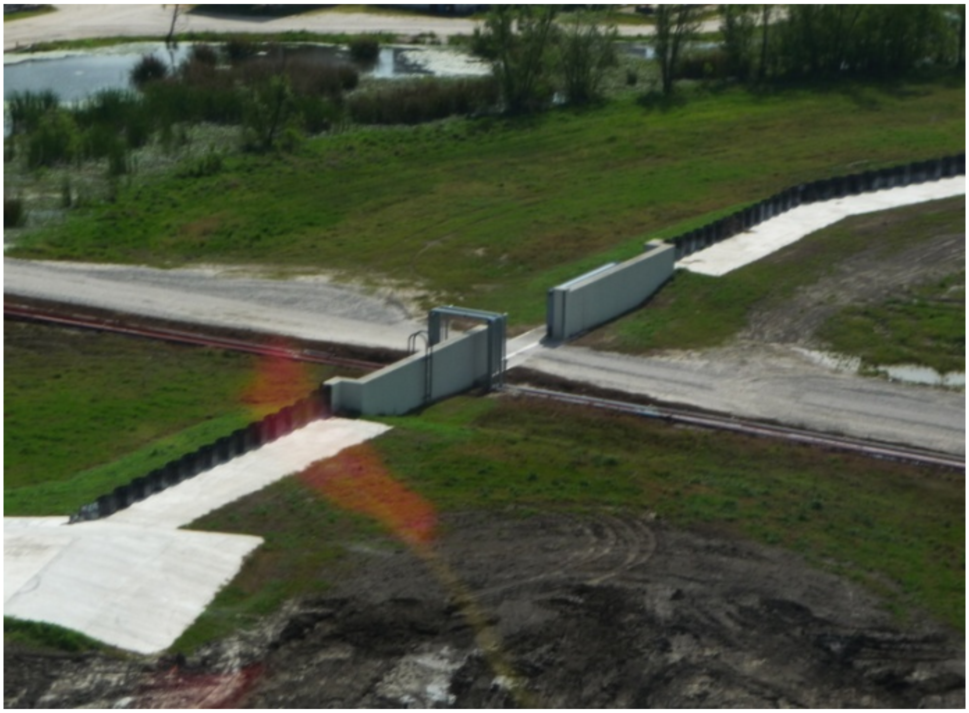
Regional earthen levee, part of coastal defense system
The Netherlands

City of Norfolk,
Downtown Flood Wall

FLOOD MITIGATION CONCEPTS
Flood Levees And Flood Walls
Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

FIGURE 18

Flood gate within existing flood wall, St. Charles Parish, Louisiana



Large flood gate, part of Maasland Barrier regional flood defense structures protecting Rotterdam Harbour

FLOOD MITIGATION CONCEPTS
Gates in Flood Levees and Flood Walls
Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

FIGURE 19

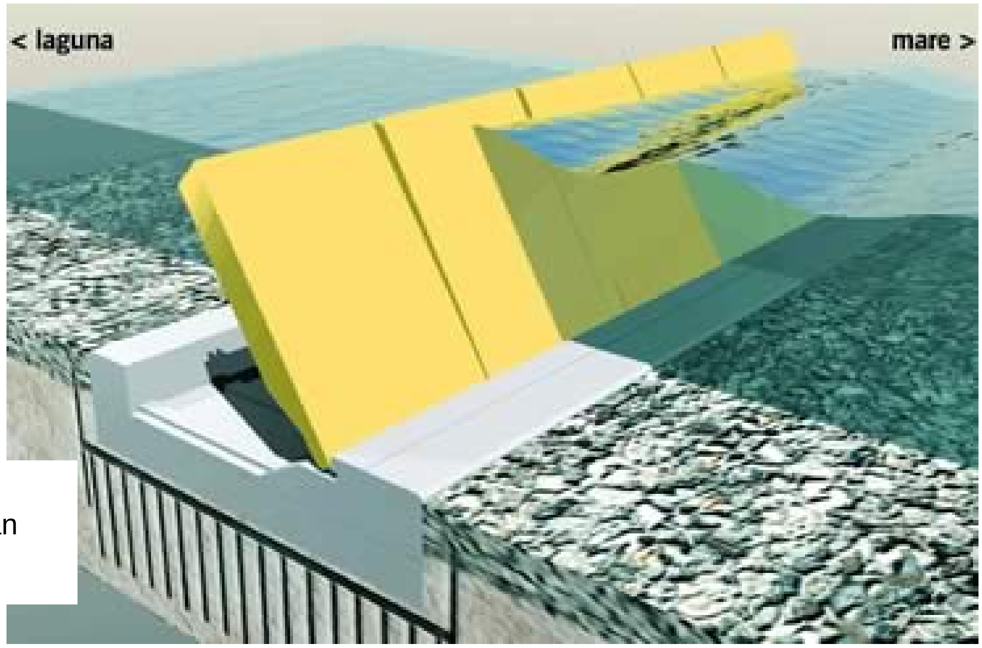
City of Norfolk, Pump Station, exterior and pumps

FLOOD MITIGATION CONCEPTS

Pump Stations

Norfolk City-wide Coastal Flooding Study

Norfolk, Virginia



Temporary flood wall, concept plan for Venice, Italy

Inflatable Dam, Lafourche Parish, Louisiana

FLOOD MITIGATION CONCEPTS

Temporary Barrier Structures

Norfolk City-wide Coastal Flooding Study

Norfolk, Virginia

Ponding of flood waters in in-stream storage impoundment area, Charlotte, North Carolina

Ponding of flood waters in off-stream storage impoundment area, Sacramento Delta, California

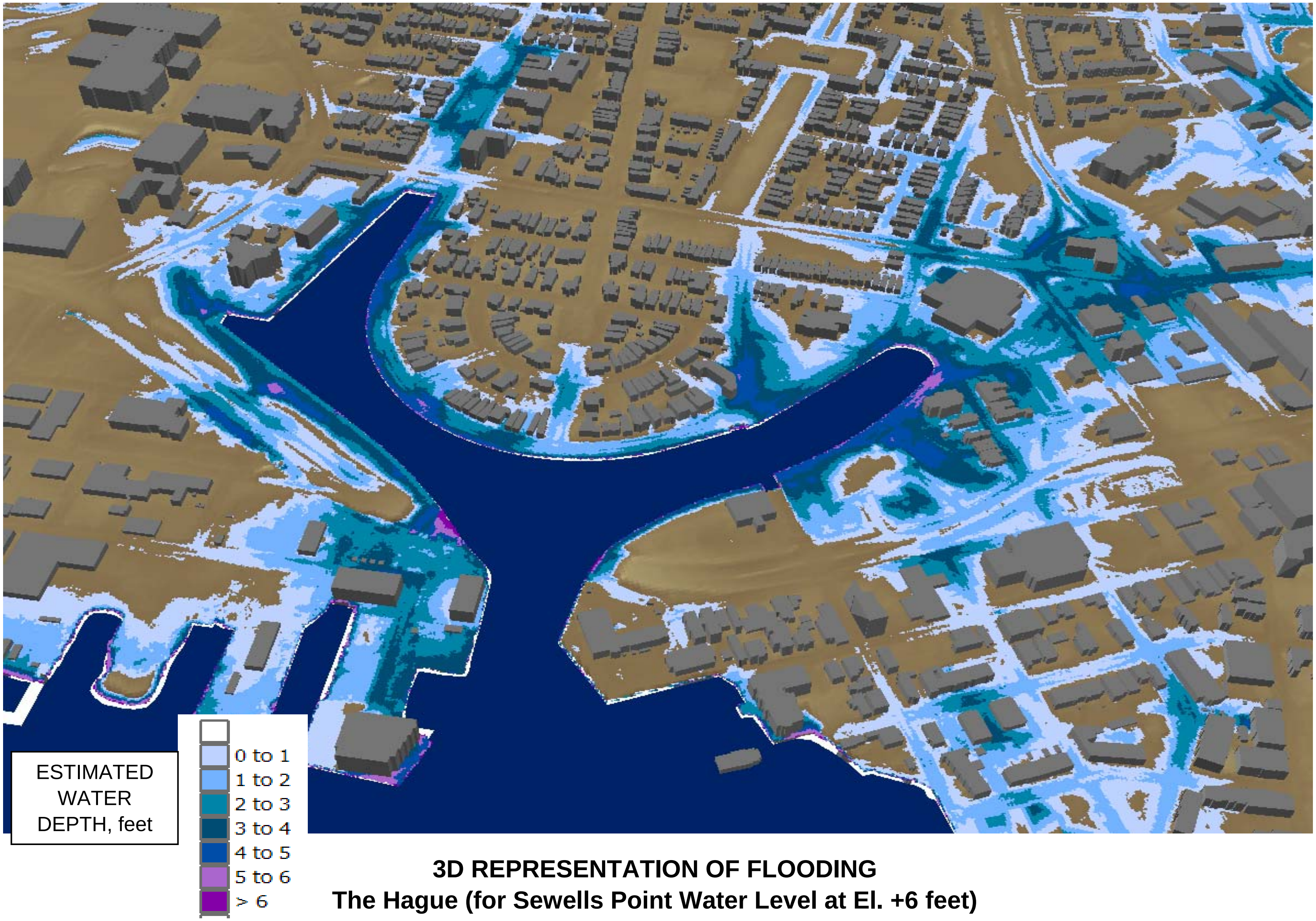
FLOOD MITIGATION CONCEPTS
Impoundment & Flood Storage
Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

FIGURE 22

Beach front property with eroded coastal dune is subject to flooding, East Ocean View, Norfolk

Beach front property after beach is widened and dune is stabilized, East Ocean View, Norfolk

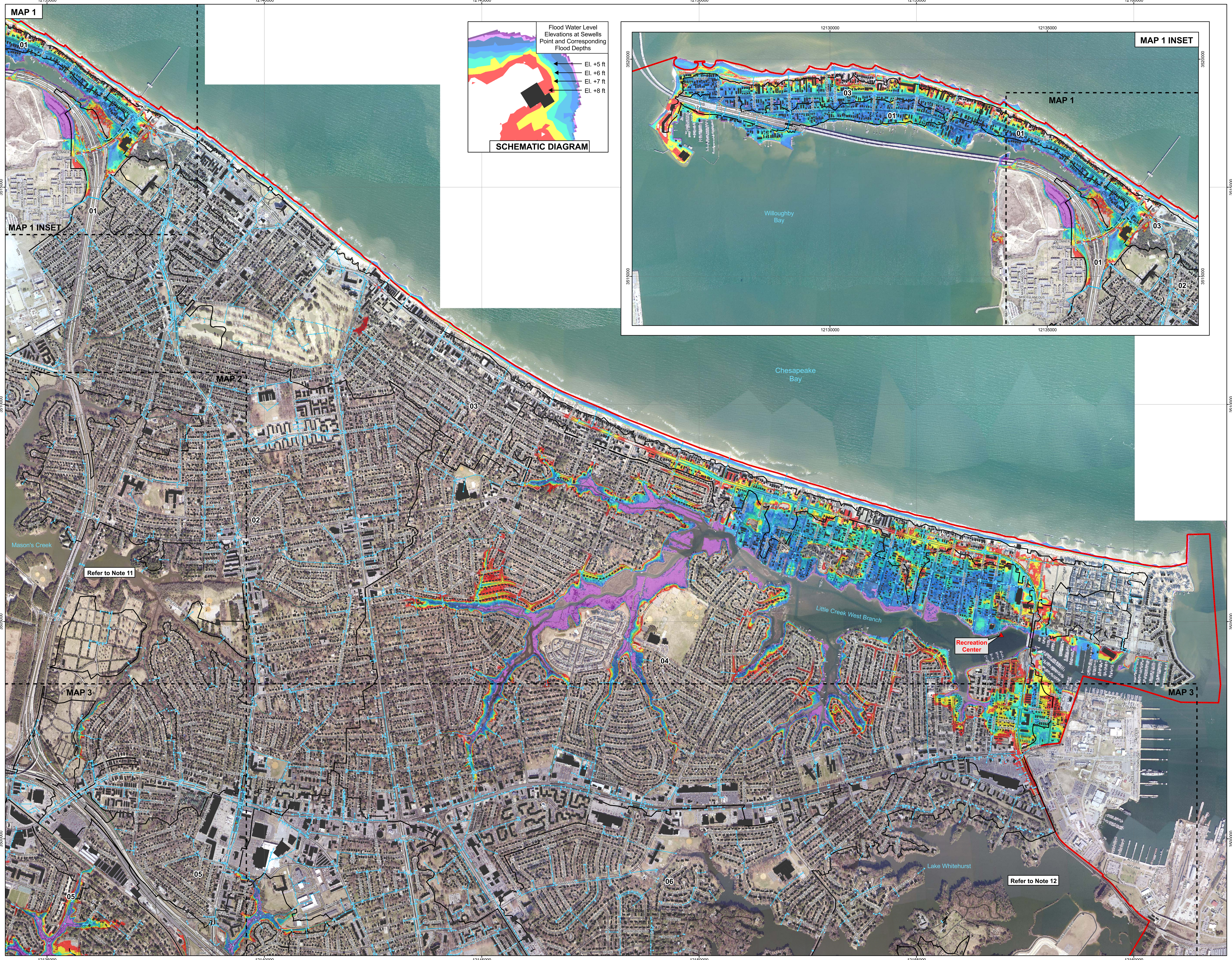
FLOOD MITIGATION CONCEPTS
Coastal Dune Stabilization
Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia



3D REPRESENTATION OF FLOODING
The Hague (for Sewells Point Water Level at El. +6 feet)
Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

FIGURE 24

MAPS



LEGEND

- City of Norfolk Tide Gauge
- NOAA Tide Gauge
- Storm Water Structure
- Storm Water Pipe
- Storm Water Ditch
- Road
- Building
- 01 Major Watershed
- City of Norfolk Limits

Predicted Flood Water Depth, Feet

	+5	+6	+7	+8
(red)	--	--	--	0.0 - 1.0
(yellow)	--	--	0.0 - 1.0	1.1 - 2.0
(green)	--	0.0 - 1.0	1.1 - 2.0	2.1 - 3.0
(light blue)	0.0 - 1.0	1.1 - 2.0	2.1 - 3.0	3.1 - 4.0
(blue)	1.1 - 2.0	2.1 - 3.0	3.1 - 4.0	4.1 - 5.0
(dark blue)	2.1 - 3.0	3.1 - 4.0	4.1 - 5.0	5.1 - 6.0
(light purple)	3.1 - 4.0	4.1 - 5.0	5.1 - 6.0	6.1 - 7.0
(purple)	4.1 - 5.0	5.1 - 6.0	6.1 - 7.0	7.1 - 8.0
(dark purple)	> 5.0	> 6.0	> 7.0	> 8 .0
Approximate Return Period, Years				
Based on Current Sea Level	8 yr	25 yr	80 yr	250 yr
After 0.5 ft Rise In Sea Level	5 yr	15 yr	50 yr	150 yr

← Flood Water Elevation (Feet, NAVD88) at Sewells Point

Increasing Depth of Flood Water ↓

NOTES:

1. Mapped flood depths at 1-foot increments (refer to legend) associated with an El. +6 foot tide at Sewells Point are shown by the palette of green and blue contours.
2. The yellow and orange bands show the additional areas that would be inundated by higher water levels associated with Sewells Point tides at El. +7 and +8 feet, respectively.
3. The area inundated for an El. +4 foot tide at Sewells Point can be approximated by subtracting the 1-foot contour from the mapped inundation area for an El. +5 foot water level at Sewells Point. Refer to schematic diagram in map.
4. Predicted flood depths have been determined by comparing ground surface elevations (based on the City's digital elevation model DEM) and predicted mean tide elevations within various City watersheds for various tide elevations (re: NAVD88 Datum) at Sewells Point.
5. Differences in predicted tide elevations, within City watersheds, relative to Sewells Point are based on statistical analyses of 9 months of tidal measurements from 5 City tide gauges.
6. In watersheds where tidal measurements are available, the differences between measured tides and Sewells Point are based on the tide gauge data; in watersheds where no tide gauge data are available, we have used the tide data from the nearest gauge.
7. The predicted flood depths are based on the mean of the statistical analyses of the relationship between each City gauge and Sewells Point. As discussed in the report, variability about the mean occurs due to wind, wind direction, rainfall, stormwater system discharge and other factors. A 95% confidence that includes the effects of winds and rain can be obtained by adding about 0.5 feet to the mean as shown by the predicted water depth contours.
8. The mapped water depths do not include cove effects that can occur in small narrow tributaries such as Haven Creek. Local cove effects in such tributary areas with aspect ratios similar to Haven Creek can be approximated by adding 0.5 feet to the mapped flood depths.
9. City Stormwater infrastructure are shown for pictorial purposes. The flood depth predictions do not consider efficiencies or deficiencies of the system.
10. The predicted flood levels in the downtown area ignore the presence of the Downtown Floodwall.
11. Predicted coastal flooding is not mapped in the Mason's Creek watershed, as the outlet for that watershed includes a tide gate.
12. Predicted coastal flooding is not mapped in the Lake Whitehurst watershed, as the watershed is isolated from coastal water surges.
13. Inland areas flooded by backflow through the stormwater system during coastal flooding events were screened using the rim elevation data in the City's existing stormwater data files. Verification of rim elevations was not part of the scope of this project. There is uncertainty in the accuracy of the rim elevations within the files used to develop this map. Verification of rim elevations via surveying may be required to evaluate backflow potential. Additionally, mapped flooded areas do not include the presence of engineering controls such as flap valves that may prevent backflow. Therefore this screening level effort should be considered to be preliminary.

DATA SOURCES:

1. City digital elevation model (DEM) generated from 2009 LiDAR survey conducted by Pictometry, Inc. under contract to the City of Norfolk.
2. City 2009 aerial photograph mosaic provided by the City of Norfolk GIS Department.
3. City watershed boundaries provided by the City of Norfolk GIS Deptartment.
4. City stormwater drainage system provided by the City of Norfolk GIS Deptartment.

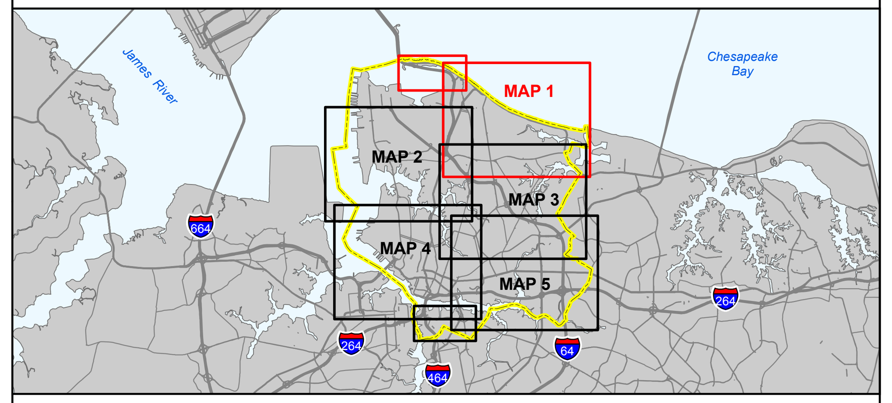
This document may only be used for the purpose for which it was commissioned and in accordance with the terms of engagement for that commission. Unauthorized use of this document in any form whatsoever is prohibited.

GEODETIC INFORMATION

SPHEROID:	GRS 1980
SEMI-MAJOR AXIS:	6,378,137.000
SEMI-MINOR AXIS:	6,356,752.314
INVERSE FLATTENING:	298.25722101
ECCENTRICITY^2:	0.006694380
PROJECTION:	LAMBERT CONFORMAL CONIC
ZONE:	VIRGINIA SOUTH
LONGITUDE OF ORIGIN:	36.3°
FALSE EASTING:	11,482,916
FALSE NORTHING:	3,280,833

N W E S

Coordinate Grid: Virginia State Plane South, NAD83, Feet



FUGRO ATLANTIC
World Trade Center, Suite 350
101 West Main Street
Norfolk, Virginia 23510
Tel: (757) 625-3350,
Fax: (757) 625-3352
www.fugroatlantic.com

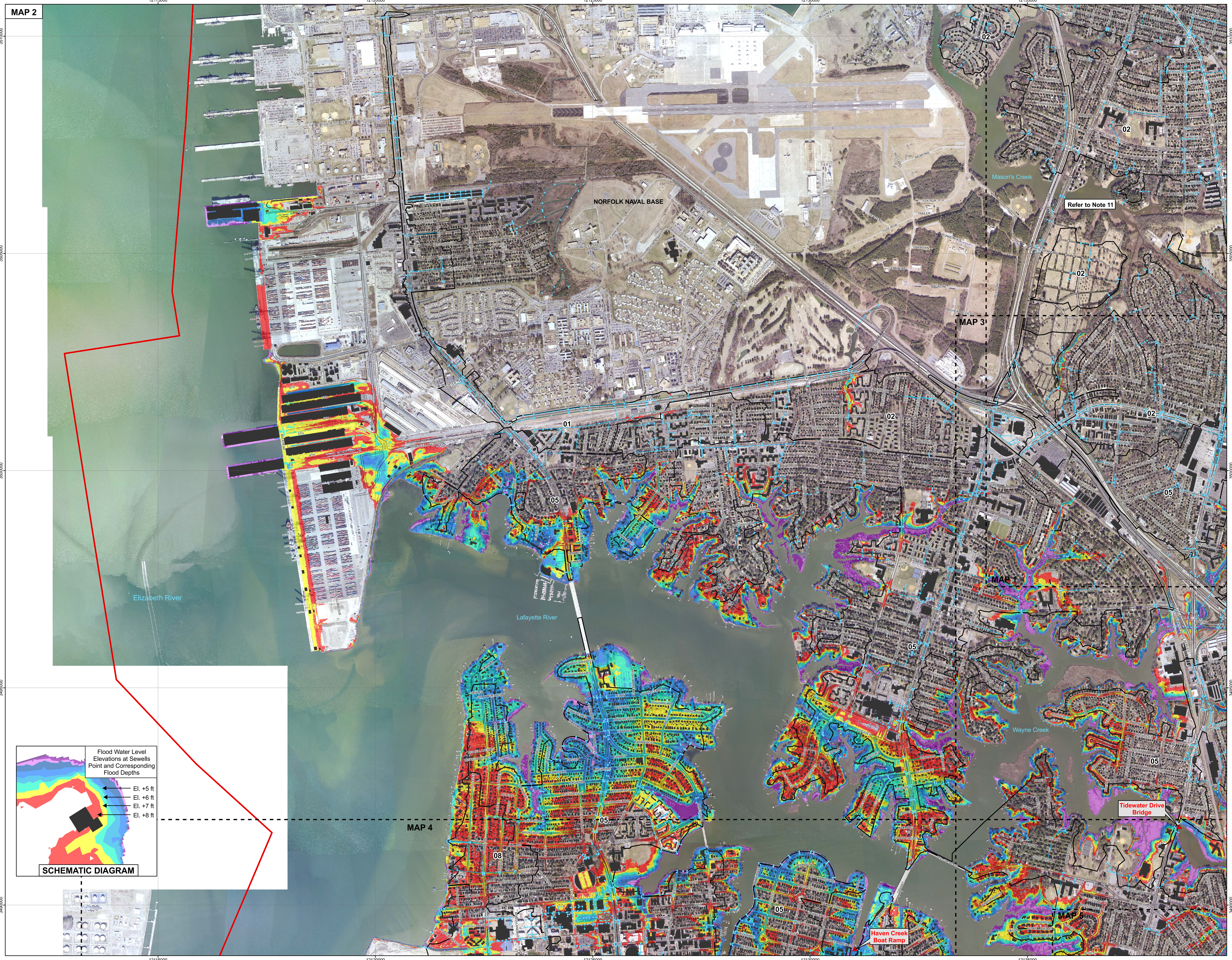
PREDICTED COASTAL FLOODING ASSOCIATED WITH VARIOUS SEWELLS POINT TIDE ELEVATIONS

Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

0 1,000 2,000 3,000 Feet

NO:	DATE:	DESCRIPTION:	DRAWN:	CHKD:	APPR:
1	June 2010	Coastal Flooding Study Draft Report	KWS	KRS	KRS
2	July 2010	Coastal Flooding Study Final Report	KWS	KRS	KRS
3					

JOB NUMBER: 3627.003 MAP NO.: 1



LEGEND

- City of Norfolk Tide Gauge
- NOAA Tide Gauge
- Storm Water Structure
- Storm Water Pipe
- Storm Water Ditch
- Road
- Building
- 01 Major Watershed
- City of Norfolk Limits

Predicted Flood Water Depth, Feet

	+5	+6	+7	+8
(red)	--	--	--	0.0 - 1.0
(yellow)	--	--	0.0 - 1.0	1.1 - 2.0
(aqua)	--	0.0 - 1.0	1.1 - 2.0	2.1 - 3.0
(light blue)	0.0 - 1.0	1.1 - 2.0	2.1 - 3.0	3.1 - 4.0
(blue)	1.1 - 2.0	2.1 - 3.0	3.1 - 4.0	4.1 - 5.0
(steel blue)	2.1 - 3.0	3.1 - 4.0	4.1 - 5.0	5.1 - 6.0
(pink)	3.1 - 4.0	4.1 - 5.0	5.1 - 6.0	6.1 - 7.0
(violet)	4.1 - 5.0	5.1 - 6.0	6.1 - 7.0	7.1 - 8.0
(purple)	> 5.0	> 6.0	> 7.0	> 8 .0
Approximate Return Period, Years				
Based on Current Sea Level	8 yr	25 yr	80 yr	250 yr
After 0.5 ft Rise In Sea Level	5 yr	15 yr	50 yr	150 yr

← Flood Water Elevation (Feet, NAVD88) at Sewells Point

↓ Increasing Depth of Flood Water

NOTES:

1. Mapped flood depths at 1-foot increments (refer to legend) associated with an El. +6 foot tide at Sewells Point are shown by the palette of green and blue contours.
2. The yellow and orange bands show the additional areas that would be inundated by higher water levels associated with Sewells Point tides at El. +7 and +8 feet, respectively.
3. The area inundated for an El. +4 foot tide at Sewells Point can be approximated by subtracting the 1-foot contour from the mapped inundation area for an El. +5 foot water level at Sewells Point. Refer to schematic diagram in map.
4. Predicted flood depths have been determined by comparing ground surface elevations (based on the City's digital elevation model DEM) and predicted mean tide elevations within various City watersheds for various tide elevations (re: NAVD88 Datum) at Sewells Point.
5. Differences in predicted tide elevations, within City watersheds, relative to Sewells Point are based on statistical analyses of 9 months of tidal measurements from 5 City tide gauges.
6. In watersheds where tidal measurements are available, the differences between measured tides and Sewells Point are based on the tide gauge data; in watersheds where no tide gauge data are available, we have used the tide data from the nearest gauge.
7. The predicted flood depths are based on the mean of the statistical analyses of the relationship between each City gauge and Sewells Point. As discussed in the report, variability about the mean occurs due to wind, wind direction, rainfall, stormwater system discharge and other factors. A 95% confidence that includes the effects of winds and rain can be obtained by adding about 0.5 feet to the mean as shown by the predicted water depth contours.
8. The mapped water depths do not include cove effects that can occur in small narrow tributaries such as Haven Creek. Local cove effects in such tributary areas with aspect ratios similar to Haven Creek can be approximated by adding 0.5 feet to the mapped flood depths.
9. City Stormwater infrastructure are shown for pictorial purposes. The flood depth predictions do not consider efficiencies or deficiencies of the system.
10. The predicted flood levels in the downtown area ignore the presence of the Downtown Floodwall.
11. Predicted coastal flooding is not mapped in the Mason's Creek watershed, as the outlet for that watershed includes a tide gate.
12. Predicted coastal flooding is not mapped in the Lake Whitehurst watershed, as the watershed is isolated from coastal water surges.
13. Inland areas flooded by backflow through the stormwater system during coastal flooding events were screened using the rim elevation data in the City's existing stormwater data files. Verification of rim elevations was not part of the scope of this project. There is uncertainty in the accuracy of the rim elevations within the files used to develop this map. Verification of rim elevations via surveying may be required to evaluate backflow potential. Additionally, mapped flooded areas do not include the presence of engineering controls such as flap valves that may prevent backflow. Therefore this screening level effort should be considered to be preliminary.

DATA SOURCES:

1. City digital elevation model (DEM) generated from 2009 LiDAR survey conducted by Pictometry, Inc. under contract to the City of Norfolk.
2. City 2009 aerial photograph mosaic provided by the City of Norfolk GIS Department.
3. City watershed boundaries provided by the City of Norfolk GIS Deptartment.
4. City stormwater drainage system provided by the City of Norfolk GIS Deptartment.

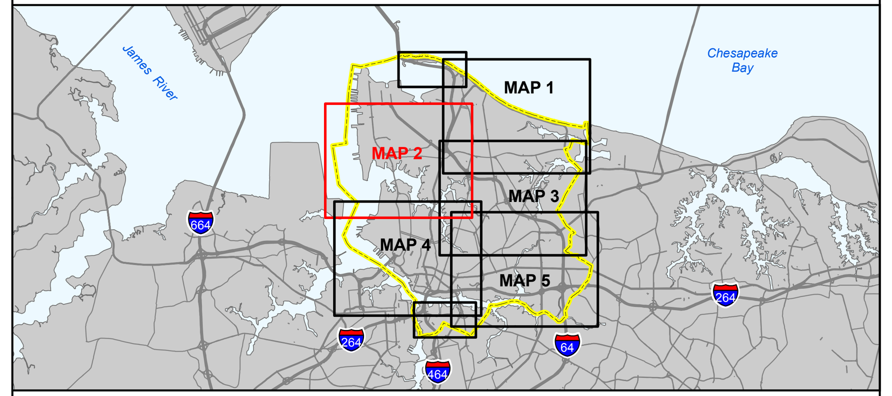
This document may only be used for the purpose for which it was commissioned and in accordance with the terms of engagement for that commission. Unauthorized use of this document in any form whatsoever is prohibited.

GEODETIC INFORMATION

SPHEROID:	GRS 1980
SEMI-MAJOR AXIS:	6,378,137.000
SEMI-MINOR AXIS:	6,356,752.314
INVERSE FLATTENING:	298.25722101
ECCENTRICITY^2:	0.006694380
PROJECTION:	LAMBERT CONFORMAL CONIC
ZONE:	VIRGINIA SOUTH
LONGITUDE OF ORIGIN:	36.3°
FALSE EASTING:	11,482,916
FALSE NORTHING:	3,280,833

N W E S

Coordinate Grid: Virginia State Plane South, NAD83, Feet



FUGRO ATLANTIC
World Trade Center, Suite 350
101 West Main Street
Norfolk, Virginia 23510
Tel: (757) 625-3350,
Fax: (757) 625-3352
www.fugroatlantic.com

PREDICTED COASTAL FLOODING ASSOCIATED WITH VARIOUS SEWELLS POINT TIDE ELEVATIONS

Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

0 1,000 2,000 3,000 Feet

NO:	DATE:	DESCRIPTION:	DRAWN:	CHKD:	APPR:
1	June 2010	Coastal Flooding Study Draft Report	KWS	KRS	KRS
2	July 2010	Coastal Flooding Study Final Report	KWS	KRS	KRS
3					

JOB NUMBER: 3627.003 MAP NO.: 2

LEGEND

- City of Norfolk Tide Gauge
- NOAA Tide Gauge
- Storm Water Structure
- Storm Water Pipe
- Storm Water Ditch
- Road
- Building
- 01 Major Watershed
- City of Norfolk Limits

Predicted Flood Water Depth, Feet

	+5	+6	+7	+8
(red)	--	--	--	0.0 - 1.0
(yellow)	--	--	0.0 - 1.0	1.1 - 2.0
(aqua)	--	0.0 - 1.0	1.1 - 2.0	2.1 - 3.0
(light blue)	0.0 - 1.0	1.1 - 2.0	2.1 - 3.0	3.1 - 4.0
(blue)	1.1 - 2.0	2.1 - 3.0	3.1 - 4.0	4.1 - 5.0
(steel blue)	2.1 - 3.0	3.1 - 4.0	4.1 - 5.0	5.1 - 6.0
(light purple)	3.1 - 4.0	4.1 - 5.0	5.1 - 6.0	6.1 - 7.0
(purple)	4.1 - 5.0	5.1 - 6.0	6.1 - 7.0	7.1 - 8.0
(dark purple)	> 5.0	> 6.0	> 7.0	> 8 .0
Approximate Return Period, Years				
Based on Current Sea Level	8 yr	25 yr	80 yr	250 yr
After 0.5 ft Rise In Sea Level	5 yr	15 yr	50 yr	150 yr

← Flood Water Elevation (Feet, NAVD88) at Sewells Point

Increasing Depth of Flood Water ↓

NOTES:

1. Mapped flood depths at 1-foot increments (refer to legend) associated with an El. +6 foot tide at Sewells Point are shown by the palette of green and blue contours.
2. The yellow and orange bands show the additional areas that would be inundated by higher water levels associated with Sewells Point tides at El. +7 and +8 feet, respectively.
3. The area inundated for an El. +4 foot tide at Sewells Point can be approximated by subtracting the 1-foot contour from the mapped inundation area for an El. +5 foot water level at Sewells Point. Refer to schematic diagram in map.
4. Predicted flood depths have been determined by comparing ground surface elevations (based on the City's digital elevation model DEM) and predicted mean tide elevations within various City watersheds for various tide elevations (re: NAVD88 Datum) at Sewells Point.
5. Differences in predicted tide elevations, within City watersheds, relative to Sewells Point are based on statistical analyses of 9 months of tidal measurements from 5 City tide gauges.
6. In watersheds where tidal measurements are available, the differences between measured tides and Sewells Point are based on the tide gauge data; in watersheds where no tide gauge data are available, we have used the tide data from the nearest gauge.
7. The predicted flood depths are based on the mean of the statistical analyses of the relationship between each City gauge and Sewells Point. As discussed in the report, variability about the mean occurs due to wind, wind direction, rainfall, stormwater system discharge and other factors. A 95% confidence that includes the effects of winds and rain can be obtained by adding about 0.5 feet to the mean as shown by the predicted water depth contours.
8. The mapped water depths do not include cove effects that can occur in small narrow tributaries such as Haven Creek. Local cove effects in such tributary areas with aspect ratios similar to Haven Creek can be approximated by adding 0.5 feet to the mapped flood depths.
9. City Stormwater infrastructure are shown for pictorial purposes. The flood depth predictions do not consider efficiencies or deficiencies of the system.
10. The predicted flood levels in the downtown area ignore the presence of the Downtown Floodwall.
11. Predicted coastal flooding is not mapped in the Mason's Creek watershed, as the outlet for that watershed includes a tide gate.
12. Predicted coastal flooding is not mapped in the Lake Whitehurst watershed, as the watershed is isolated from coastal water surges.
13. Inland areas flooded by backflow through the stormwater system during coastal flooding events were screened using the rim elevation data in the City's existing stormwater data files. Verification of rim elevations was not part of the scope of this project. There is uncertainty in the accuracy of the rim elevations within the files used to develop this map. Verification of rim elevations via surveying may be required to evaluate backflow potential. Additionally, mapped flooded areas do not include the presence of engineering controls such as flap valves that may prevent backflow. Therefore this screening level effort should be considered to be preliminary.

DATA SOURCES:

1. City digital elevation model (DEM) generated from 2009 LiDAR survey conducted by Pictometry, Inc. under contract to the City of Norfolk.
2. City 2009 aerial photograph mosaic provided by the City of Norfolk GIS Department.
3. City watershed boundaries provided by the City of Norfolk GIS Deptartment.
4. City stormwater drainage system provided by the City of Norfolk GIS Deptartment.

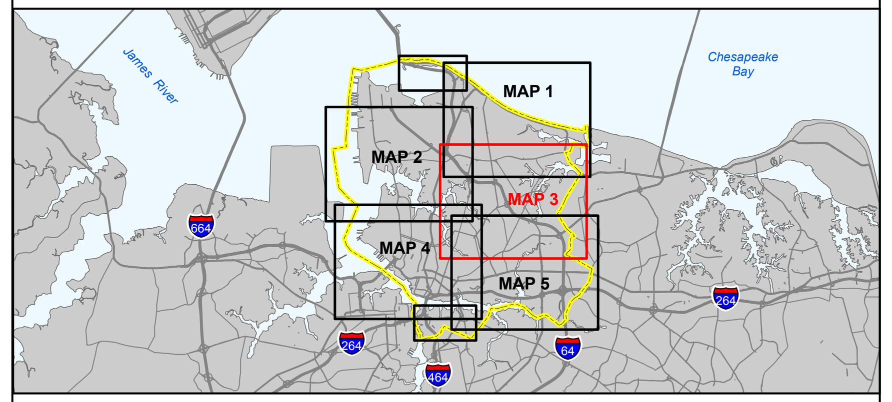
This document may only be used for the purpose for which it was commissioned and in accordance with the terms of engagement for that commission. Unauthorized use of this document in any form whatsoever is prohibited.

GEODETIC INFORMATION

SPHEROID:	GRS 1980
SEMI-MAJOR AXIS:	6,378,137.000
SEMI-MINOR AXIS:	6,356,752.314
INVERSE FLATTENING:	298.25722101
ECCENTRICITY^2:	0.006694380
PROJECTION:	LAMBERT CONFORMAL CONIC
ZONE:	VIRGINIA SOUTH
LONGITUDE OF ORIGIN:	36.3°
FALSE EASTING:	11,482,916
FALSE NORTHING:	3,280,833

N W E S

Coordinate Grid: Virginia State Plane South, NAD83, Feet



FUGRO ATLANTIC
World Trade Center, Suite 350
101 West Main Street
Norfolk, Virginia 23510
Tel: (757) 625-3350,
Fax: (757) 625-3352
www.fugroatlantic.com

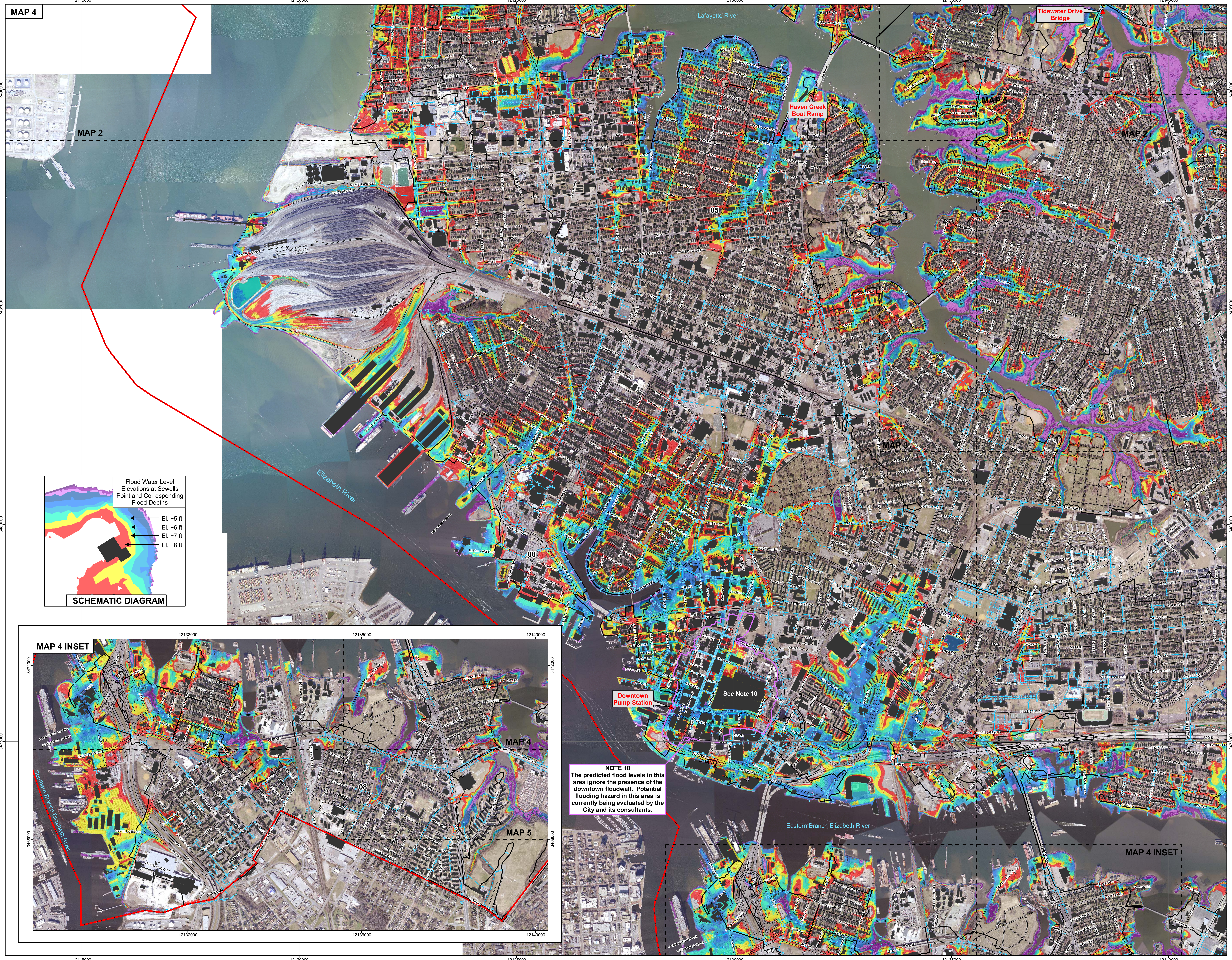
PREDICTED COASTAL FLOODING ASSOCIATED WITH VARIOUS SEWELLS POINT TIDE ELEVATIONS

Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

0 1,000 2,000 3,000 Feet

NO:	DATE:	DESCRIPTION:	DRAWN:	CHKD:	APPR:
1	June 2010	Coastal Flooding Study Draft Report	KWS	KRS	KRS
2	July 2010	Coastal Flooding Study Final Report	KWS	KRS	KRS
3					

JOB NUMBER: 3627.003 | MAP NO.: 3



LEGEND

- City of Norfolk Tide Gauge
- NOAA Tide Gauge
- Storm Water Structure
- Storm Water Pipe
- Storm Water Ditch
- Road
- Building
- 01 Major Watershed
- City of Norfolk Limits

Predicted Flood Water Depth, Feet

	+5	+6	+7	+8
(red)	--	--	--	0.0 - 1.0
(yellow)	--	--	0.0 - 1.0	1.1 - 2.0
(green)	--	0.0 - 1.0	1.1 - 2.0	2.1 - 3.0
(light blue)	0.0 - 1.0	1.1 - 2.0	2.1 - 3.0	3.1 - 4.0
(blue)	1.1 - 2.0	2.1 - 3.0	3.1 - 4.0	4.1 - 5.0
(dark blue)	2.1 - 3.0	3.1 - 4.0	4.1 - 5.0	5.1 - 6.0
(light purple)	3.1 - 4.0	4.1 - 5.0	5.1 - 6.0	6.1 - 7.0
(purple)	4.1 - 5.0	5.1 - 6.0	6.1 - 7.0	7.1 - 8.0
(dark purple)	> 5.0	> 6.0	> 7.0	> 8 .0
Approximate Return Period, Years				
Based on Current Sea Level	8 yr	25 yr	80 yr	250 yr
After 0.5 ft Rise In Sea Level	5 yr	15 yr	50 yr	150 yr

← Flood Water Elevation (Feet, NAVD88) at Sewells Point

↓ Increasing Depth of Flood Water

NOTES:

1. Mapped flood depths at 1-foot increments (refer to legend) associated with an El. +6 foot tide at Sewells Point are shown by the palette of green and blue contours.
2. The yellow and orange bands show the additional areas that would be inundated by higher water levels associated with Sewells Point tides at El. +7 and +8 feet, respectively.
3. The area inundated for an El. +4 foot tide at Sewells Point can be approximated by subtracting the 1-foot contour from the mapped inundation area for an El. +5 foot water level at Sewells Point. Refer to schematic diagram in map.
4. Predicted flood depths have been determined by comparing ground surface elevations (based on the City's digital elevation model DEM) and predicted mean tide elevations within various City watersheds for various tide elevations (re: NAVD88 Datum) at Sewells Point.
5. Differences in predicted tide elevations, within City watersheds, relative to Sewells Point are based on statistical analyses of 9 months of tidal measurements from 5 City tide gauges.
6. In watersheds where tidal measurements are available, the differences between measured tides and Sewells Point are based on the tide gauge data; in watersheds where no tide gauge data are available, we have used the tide data from the nearest gauge.
7. The predicted flood depths are based on the mean of the statistical analyses of the relationship between each City gauge and Sewells Point. As discussed in the report, variability about the mean occurs due to wind, wind direction, rainfall, stormwater system discharge and other factors. A 95% confidence that includes the effects of winds and rain can be obtained by adding about 0.5 feet to the mean as shown by the predicted water depth contours.
8. The mapped water depths do not include cove effects that can occur in small narrow tributaries such as Haven Creek. Local cove effects in such tributary areas with aspect ratios similar to Haven Creek can be approximated by adding 0.5 feet to the mapped flood depths.
9. City Stormwater infrastructure are shown for pictorial purposes. The flood depth predictions do not consider efficiencies or deficiencies of the system.
10. The predicted flood levels in the downtown area ignore the presence of the Downtown Floodwall.
11. Predicted coastal flooding is not mapped in the Mason's Creek watershed, as the outlet for that watershed includes a tide gate.
12. Predicted coastal flooding is not mapped in the Lake Whitehurst watershed, as the watershed is isolated from coastal water surges.
13. Inland areas flooded by backflow through the stormwater system during coastal flooding events were screened using the rim elevation data in the City's existing stormwater data files. Verification of rim elevations was not part of the scope of this project. There is uncertainty in the accuracy of the rim elevations within the files used to develop this map. Verification of rim elevations via surveying may be required to evaluate backflow potential. Additionally, mapped flooded areas do not include the presence of engineering controls such as flap valves that may prevent backflow. Therefore this screening level effort should be considered to be preliminary.

DATA SOURCES:

1. City digital elevation model (DEM) generated from 2009 LiDAR survey conducted by Pictometry, Inc. under contract to the City of Norfolk.
2. City 2009 aerial photograph mosaic provided by the City of Norfolk GIS Department.
3. City watershed boundaries provided by the City of Norfolk GIS Deptartment.
4. City stormwater drainage system provided by the City of Norfolk GIS Deptartment.

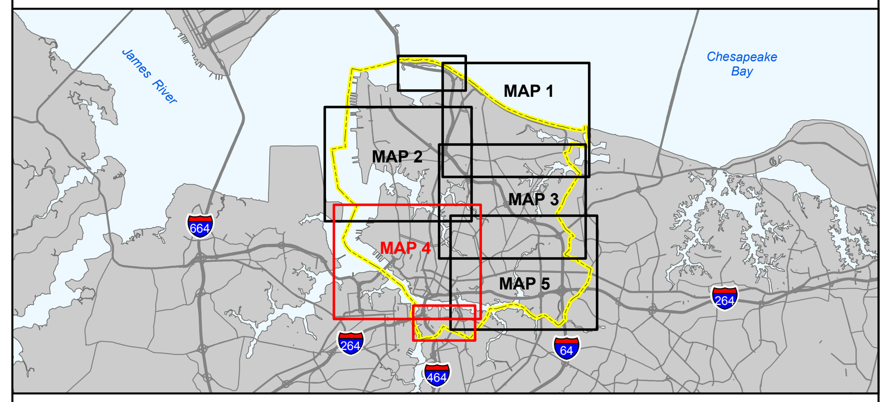
This document may only be used for the purpose for which it was commissioned and in accordance with the terms of engagement for that commission. Unauthorized use of this document in any form whatsoever is prohibited.

GEODETIC INFORMATION

SPHEROID:	GRS 1980
SEMI-MAJOR AXIS:	6,378,137.000
SEMI-MINOR AXIS:	6,356,752.314
INVERSE FLATTENING:	298.25722101
ECCENTRICITY^2:	0.006694380
PROJECTION:	LAMBERT CONFORMAL CONIC
ZONE:	VIRGINIA SOUTH
LONGITUDE OF ORIGIN:	36.3°
FALSE EASTING:	11,482,916
FALSE NORTHING:	3,280,833

N W E S

Coordinate Grid: Virginia State Plane South, NAD83, Feet



FUGRO ATLANTIC
World Trade Center, Suite 350
101 West Main Street
Norfolk, Virginia 23510
Tel: (757) 625-3350,
Fax: (757) 625-3352
www.fugroatlantic.com

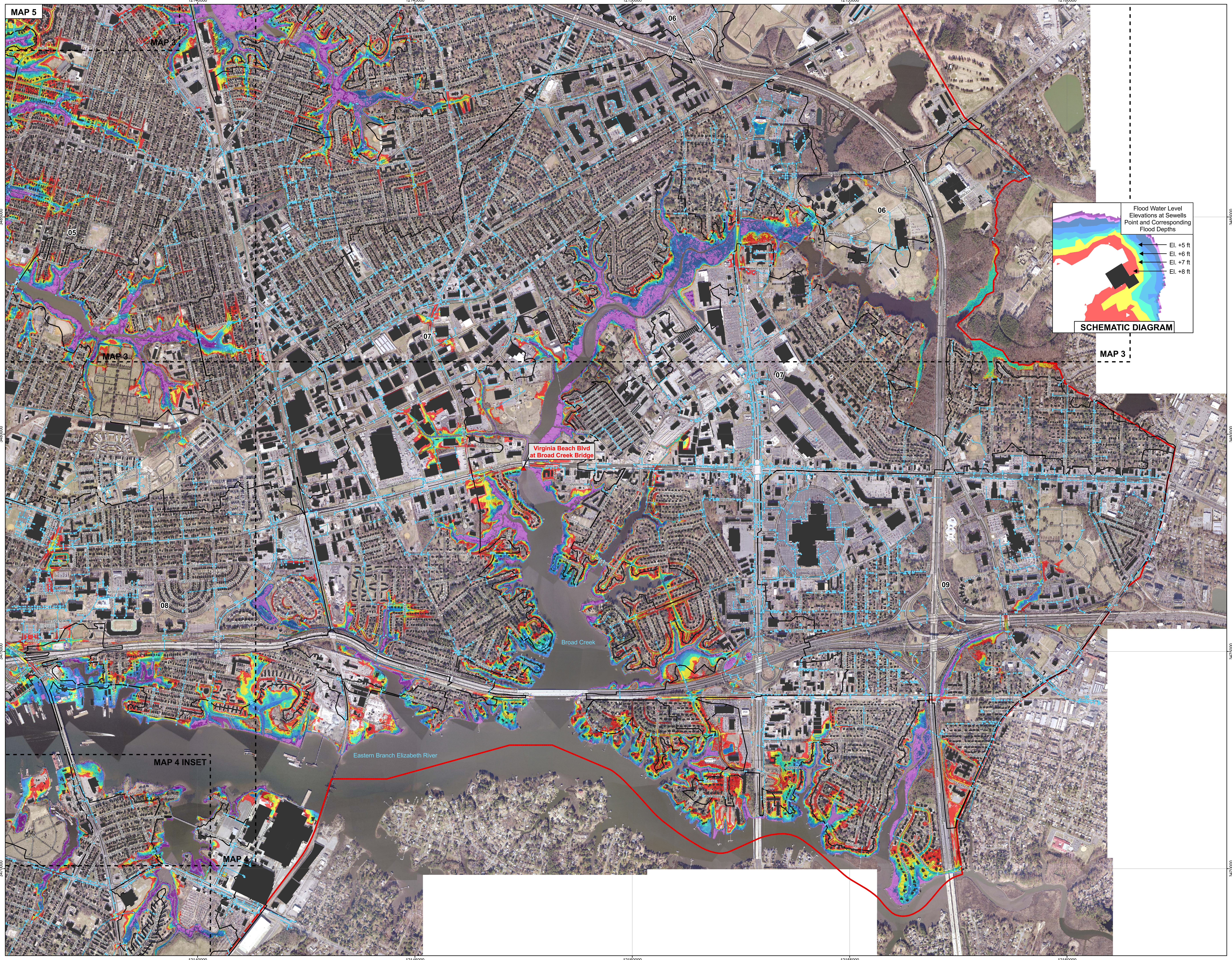
PREDICTED COASTAL FLOODING ASSOCIATED WITH VARIOUS SEWELLS POINT TIDE ELEVATIONS

Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

0 1,000 2,000 3,000 Feet

NO:	DATE:	DESCRIPTION:	DRAWN:	CHKD:	APPR:
1	June 2010	Coastal Flooding Study Draft Report	KWS	KRS	KRS
2	July 2010	Coastal Flooding Study Final Report	KWS	KRS	KRS
3					

JOB NUMBER: 3627.003 — MAP NO.: 4



LEGEND

- City of Norfolk Tide Gauge
- NOAA Tide Gauge
- Storm Water Structure
- Storm Water Pipe
- Storm Water Ditch
- Road
- Building
- 01 Major Watershed
- City of Norfolk Limits

Predicted Flood Water Depth, Feet

		+5	+6	+7	+8
	(red)	--	--	--	0.0 - 1.0
	(yellow)	--	--	0.0 - 1.0	1.1 - 2.0
	(green)	--	0.0 - 1.0	1.1 - 2.0	2.1 - 3.0
	(light blue)	0.0 - 1.0	1.1 - 2.0	2.1 - 3.0	3.1 - 4.0
	(blue)	1.1 - 2.0	2.1 - 3.0	3.1 - 4.0	4.1 - 5.0
	(dark blue)	2.1 - 3.0	3.1 - 4.0	4.1 - 5.0	5.1 - 6.0
	(light purple)	3.1 - 4.0	4.1 - 5.0	5.1 - 6.0	6.1 - 7.0
Approximate Return Period, Years	(purple)	4.1 - 5.0	5.1 - 6.0	6.1 - 7.0	7.1 - 8.0
	(dark purple)	> 5.0	> 6.0	> 7.0	> 8 .0
Based on Current Sea Level		8 yr	25 yr	80 yr	250 yr
After 0.5 ft Rise In Sea Level		5 yr	15 yr	50 yr	150 yr

← Flood Water Elevation (Feet, NAVD88) at Sewells Point

↓ Increasing Depth of Flood Water

NOTES:

1. Mapped flood depths at 1-foot increments (refer to legend) associated with an El. +6 foot tide at Sewells Point are shown by the palette of green and blue contours.
2. The yellow and orange bands show the additional areas that would be inundated by higher water levels associated with Sewells Point tides at El. +7 and +8 feet, respectively.
3. The area inundated for an El. +4 foot tide at Sewells Point can be approximated by subtracting the 1-foot contour from the mapped inundation area for an El. +5 foot water level at Sewells Point. Refer to schematic diagram in map.
4. Predicted flood depths have been determined by comparing ground surface elevations (based on the City's digital elevation model DEM) and predicted mean tide elevations within various City watersheds for various tide elevations (re: NAVD88 Datum) at Sewells Point.
5. Differences in predicted tide elevations, within City watersheds, relative to Sewells Point are based on statistical analyses of 9 months of tidal measurements from 5 City tide gauges.
6. In watersheds where tidal measurements are available, the differences between measured tides and Sewells Point are based on the tide gauge data; in watersheds where no tide gauge data are available, we have used the tide data from the nearest gauge.
7. The predicted flood depths are based on the mean of the statistical analyses of the relationship between each City gauge and Sewells Point. As discussed in the report, variability about the mean occurs due to wind, wind direction, rainfall, stormwater system discharge and other factors. A 95% confidence that includes the effects of winds and rain can be obtained by adding about 0.5 feet to the mean as shown by the predicted water depth contours.
8. The mapped water depths do not include cove effects that can occur in small narrow tributaries such as Haven Creek. Local cove effects in such tributary areas with aspect ratios similar to Haven Creek can be approximated by adding 0.5 feet to the mapped flood depths.
9. City Stormwater infrastructure are shown for pictorial purposes. The flood depth predictions do not consider efficiencies or deficiencies of the system.
10. The predicted flood levels in the downtown area ignore the presence of the Downtown Floodwall.
11. Predicted coastal flooding is not mapped in the Mason's Creek watershed, as the outlet for that watershed includes a tide gate.
12. Predicted coastal flooding is not mapped in the Lake Whitehurst watershed, as the watershed is isolated from coastal water surges.
13. Inland areas flooded by backflow through the stormwater system during coastal flooding events were screened using the rim elevation data in the City's existing stormwater data files. Verification of rim elevations was not part of the scope of this project. There is uncertainty in the accuracy of the rim elevations within the files used to develop this map. Verification of rim elevations via surveying may be required to evaluate backflow potential. Additionally, mapped flooded areas do not include the presence of engineering controls such as flap valves that may prevent backflow. Therefore this screening level effort should be considered to be preliminary.

DATA SOURCES:

1. City digital elevation model (DEM) generated from 2009 LiDAR survey conducted by Pictometry, Inc. under contract to the City of Norfolk.
2. City 2009 aerial photograph mosaic provided by the City of Norfolk GIS Department.
3. City watershed boundaries provided by the City of Norfolk GIS Deptartment.
4. City stormwater drainage system provided by the City of Norfolk GIS Deptartment.

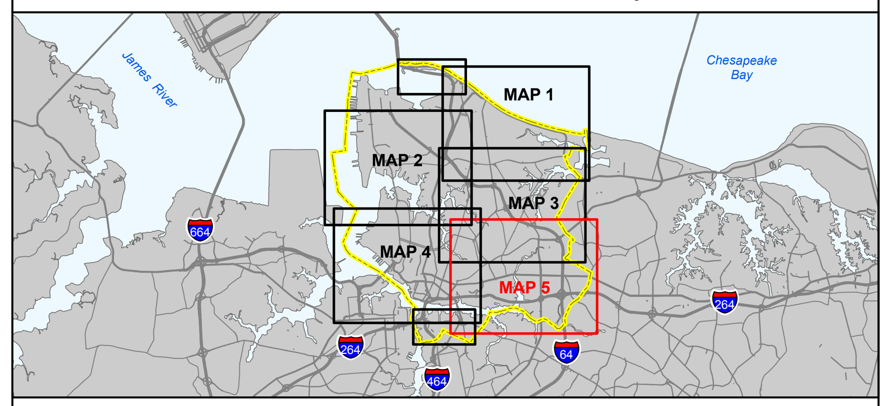
This document may only be used for the purpose for which it was commissioned and in accordance with the terms of engagement for that commission. Unauthorized use of this document in any form whatsoever is prohibited.

GEODETIC INFORMATION

SPHEROID:	GRS 1980
SEMI-MAJOR AXIS:	6,378,137.000
SEMI-MINOR AXIS:	6,356,752.314
INVERSE FLATTENING:	298.25722101
ECCENTRICITY^2:	0.006694380
PROJECTION:	LAMBERT CONFORMAL CONIC
ZONE:	VIRGINIA SOUTH
LONGITUDE OF ORIGIN:	36.3°
FALSE EASTING:	11,482,916
FALSE NORTHING:	3,280,833

N W E S

Coordinate Grid: Virginia State Plane South, NAD83, Feet



FUGRO ATLANTIC
World Trade Center, Suite 350
101 West Main Street
Norfolk, Virginia 23510
Tel: (757) 625-3350,
Fax: (757) 625-3352
www.fugroatlantic.com

PREDICTED COASTAL FLOODING ASSOCIATED WITH VARIOUS SEWELLS POINT TIDE ELEVATIONS

Norfolk City-wide Coastal Flooding Study
Norfolk, Virginia

0 — 1,000 — 2,000 — 3,000 Feet

NO:	DATE:	DESCRIPTION:	DRAWN:	CHKD:	APPR:
1	June 2010	Coastal Flooding Study Draft Report	KWS	KRS	KRS
2	July 2010	Coastal Flooding Study Final Report	KWS	KRS	KRS
3					

JOB NUMBER: 3627.003

MAP NO.: 5