APPENDIX A: APPLIED COASTAL RESEARCH AND ENGINEERING, INC. ANALYSIS OF SEA-LEVEL RISE AND COASTAL PROCESSES FOR THE OGUNQUIT WWTP

ADAPTATION OPTIONS TO PROTECT THE OGUNQUIT SEWAGE TREATMENT PLANT AGAINST FLOODS, STORM SURGES AND SEA LEVEL RISE: ANALYSIS OF SEA-LEVEL RISE AND COASTAL PROCESSES

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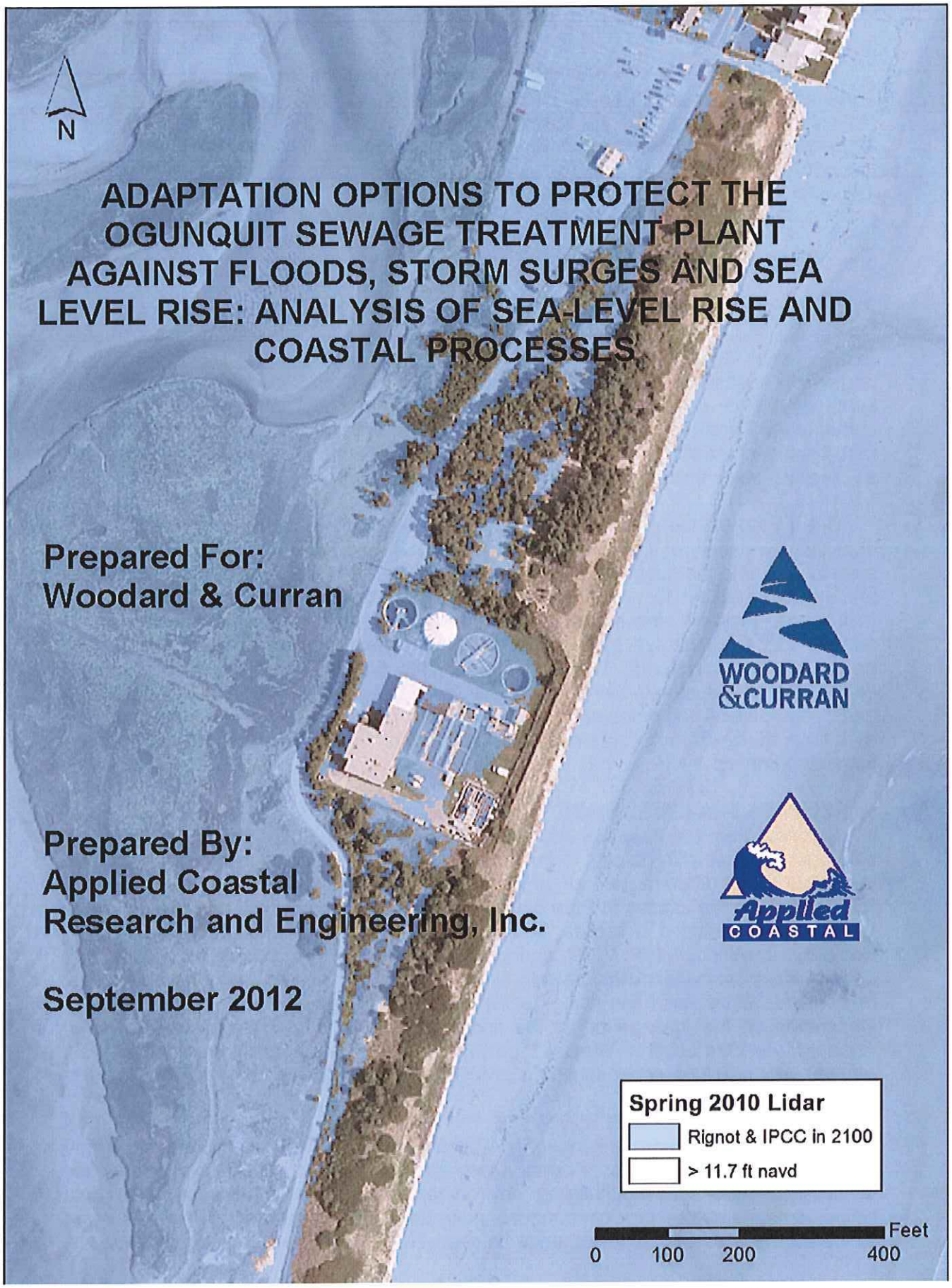

A. INTRODUCTION

The primary goal of this evaluation of adaptation options for the Ogunquit Sewage Treatment Plant is to guide future planning strategies through the identification of technical information necessary to evaluate the influence of sea-level rise on the plant and implement sound coastal hazard mitigation strategies. Development of the overall assessment of local sea-level rise and historical shoreline change, as well as the influence on future flooding and storm events, required compilation and review of existing data, creation of a range of potential sea-level rise scenarios that are specifically applicable to Ogunquit Beach, analysis of shoreline change and dune migration, and preparation of GIS data layers and maps to present the information in a usable format.

Characterization of coastal hazards is not a new concept. Recently, the U.S. Geological Survey (USGS) has developed relative coastal vulnerability assessments (e.g. Hammer-Klose *et al.*, 2004 and Thieler and Hammer-Klose, 1999). Although these large-scale assessments are useful, the unique geological and geographic setting of the southern Maine coast benefits from a more site-specific analysis. In addition, contemporary analyses techniques (e.g. GIS, rectified aerial photography, and digital topographic information) allow for more accurate delineation of coastal features, as well as other variables that help characterize local coastal hazards.

Due to the unique geologic and geographic setting, the southern Maine shoreline consists of a variety of shoreline types, ranging from bedrock outcrops to barrier beach systems. Due to the geographic orientation of the southern Maine shoreline the coast is primarily susceptible to major damage from extra-tropical storms (northeasters). As indicated in Figure 1, the Maine shoreline is characterized by glacial deposits, many forming bluffs punctuated by areas of lower-lying barrier beaches fronting estuaries and/or salt marsh systems. This stretch of the New England coast is unique, as glacial drumlin deposits dominate the regional sediment supply to beaches. Since the geologic and geographic setting of the southern Maine coast governs how the shoreline responds over time, these characteristics need careful consideration in the assessment of coastal hazards planning.

B. RELATIVE SEA-LEVEL RISE

Separate from the daily rise and fall of the tide, the average elevation of the ocean changes over time with respect to the land. This average position is called relative sea level (RSL), and different geologic and atmospheric processes contribute to changes in RSL. Some of the causes include glacial ice melt, thermal expansion of the ocean as the global temperature increases, and the rising or sinking of the earth's crust itself. While the specific causes of RSL change are the topic of much scientific and political debate, historical evidence indicates that over the past ~100 years, the relative sea-level in Portland, Maine has been rising generally in a linear fashion (see Figures 2 and 3). Depending on the time period of the analysis and/or the tidal datum selected (e.g. Annual Mean Sea Level or Annual High Water), the long-term range varies from 1.84 mm per year or 0.61 feet per century (Slovinsky, 2011) to 2.5 mm per year (0.82 feet per century).

While long-term tide records (e.g. Portland, ME) provide valuable insight into historical changes over the past century, they do not necessarily dictate future response of sea-level rise due to changing environmental conditions. In addition to data refinements, numerous predictive models have been developed over the past 15 years to predict the effects of climate change on relative sea-level rise in the coming decades.

As more data becomes available and models are refined to reflect our current state-of-knowledge, predictions should become more accurate, with a better defined range of potential sea-level rise scenarios. The Intergovernmental Panel on Climate Change (IPCC) has developed a series of sea-level rise predictions starting in 1999, and improvements in available data, analysis techniques, and modeling capabilities have further refined the range of predicted values.

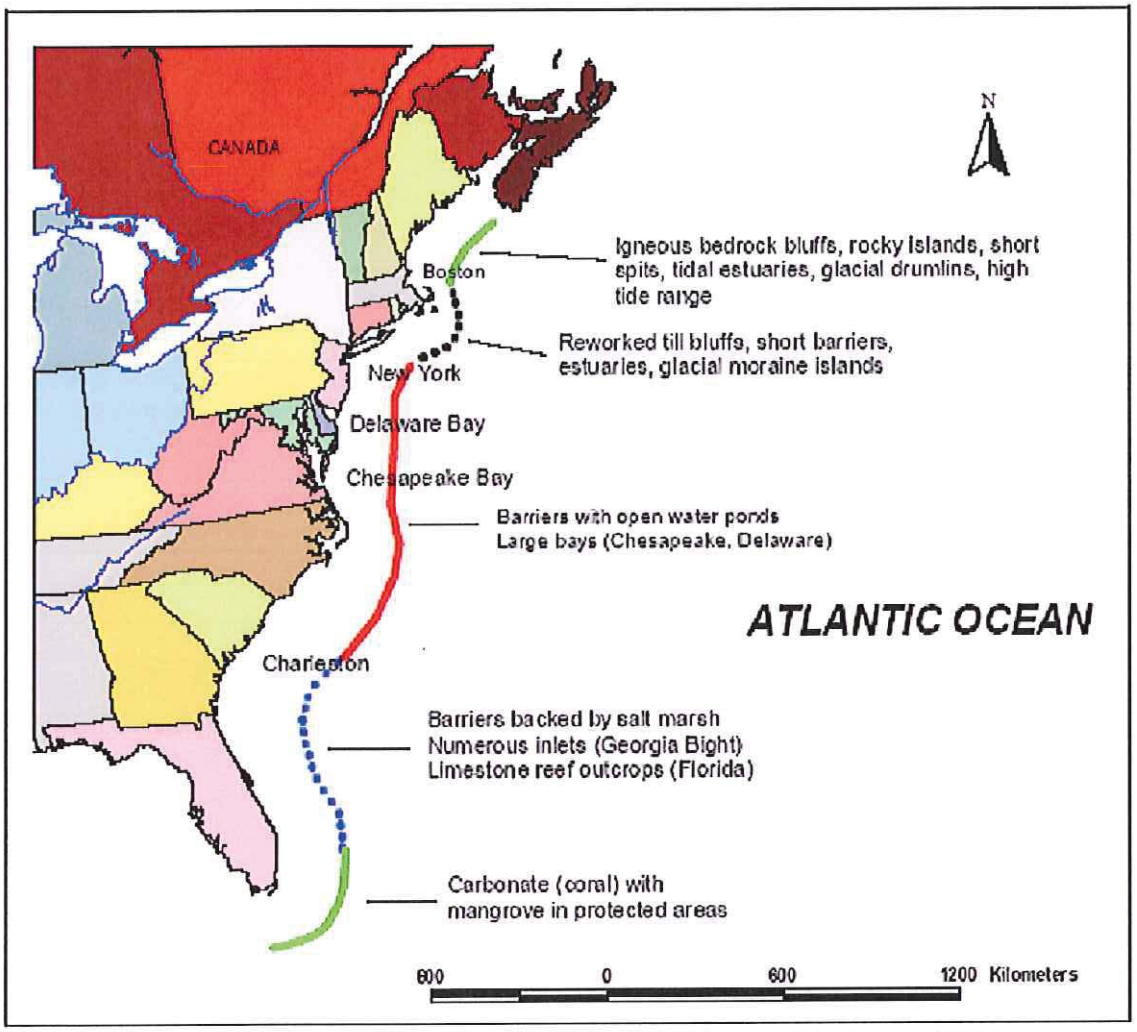

Figure 1. Atlantic coast characteristics (from the U.S. Army Corps of Engineers, 2002).

Based on the most recent available IPCC report (AR4 from 2007) regarding predictions in global sea-level rise, curves were developed for site-specific regional subsidence of the Ogunquit area (Figure 4). These curves represent the low and high best estimates of predicted relative sea-level rise for the Ogunquit area, where the subsidence rate was determined from available GPS data (Sella *et al.*, 2007). Based on the actively monitored GPS data, the subsidence rate for southern Mane was found to be 0.6 mm per year. These predictions indicate that relative sea-level rise at Ogunquit will be between 0.97 and 1.44 feet by 2100, which are both below the Chapter 355 of the state Natural Resources Protection Act that indicated 2 feet of sea-level rise by 2100 was the best estimate to utilize in support of the Coastal Sand Dune Rules.

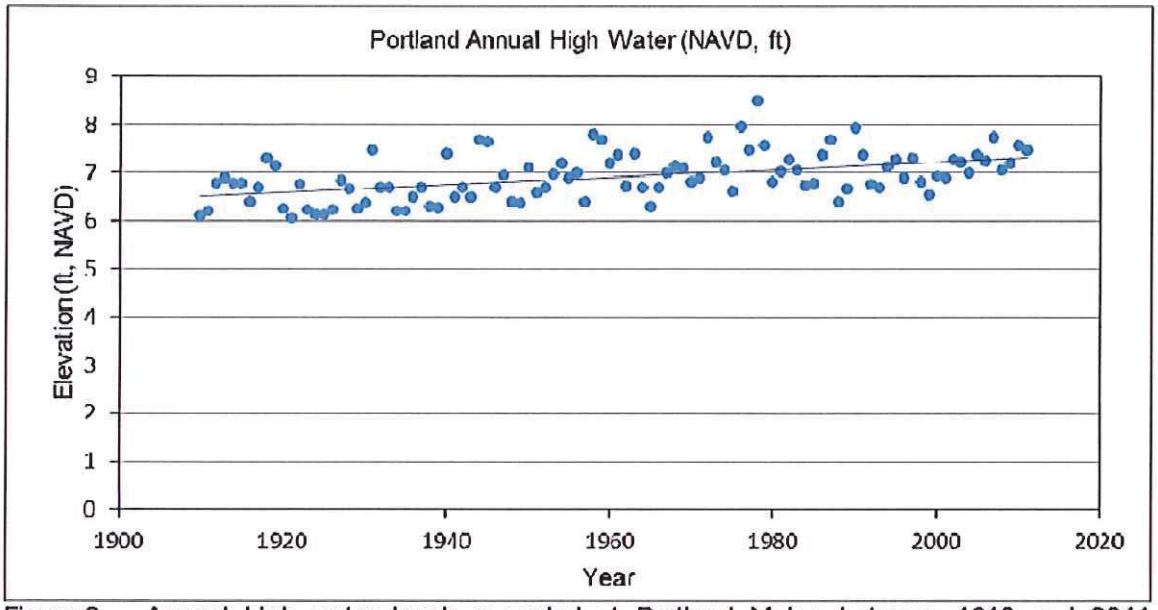

Figure 2. Annual high water levels recorded at Portland Maine between 1910 and 2011 indicate a linear trend in sea-level rise over the past century of approximately 2.5 mm per year.

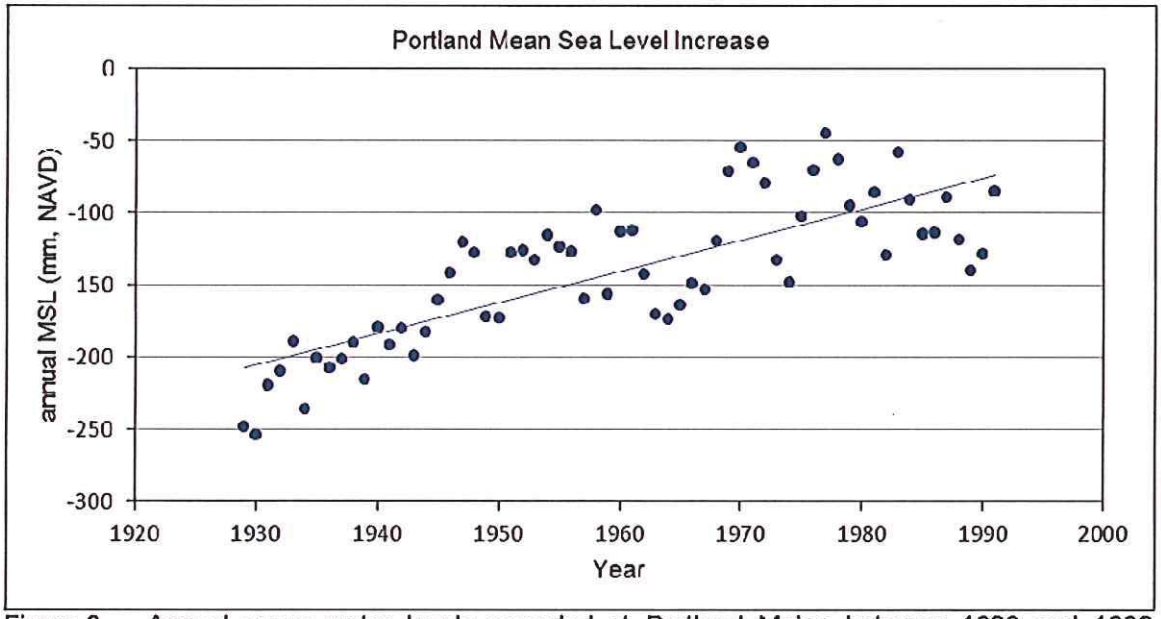

Figure 3. Annual mean water levels recorded at Portland Maine between 1929 and 1992 indicate a linear trend in sea-level rise over this time period of approximately 2.2 mm per year.

It should be noted that the IPCC (2007) report indicated that one significant area where more research was needed was the evaluation of Greenland and Antarctic ice sheets and their future contribution to sea-level rise. The range of potential contribution from these additional sources can substantially increase future sea-level rise predictions. Rignot, *et al.* (2011) developed estimates of the contributions from both Greenland and Antarctic ice sheets based upon data collected between 1992 and 2009. Over this time period, a curve fit to the ice sheet loss data indicates that ice loss is accelerating. To predict future contributions of ice sheet loss, Rignot *et al.* (2011) extrapolate this

acceleration rate into the future and provide estimates of the contribution these ice sheets will have to sea-level rise by 2050 (~15 cm) and 2100 (~56 cm) relative to 2009/2010. These future predictions are based upon the assumption that the year-to-year acceleration trend observed between 1992 and 2009 will remain constant until 2100. Regardless, this empirical approach can be utilized to provide a contemporary effective "upper bound" to sea-level rise predictions. It should be noted that the authors of this technical letter indicated that caution should be exercised when using their predictions, as the analysis is based upon a short-term data set (1992 to 2009) with relatively high inter-annual variability. The modeled predictions also require that ice cap melting continues to accelerate year-to-year through 2100 and it remains unclear whether this is possible. The predictions developed by Rignot *et al.* (2011) are shown as the upper curve in Figure 4. Overall, this figure provides a summary of applicable high and low future site-specific sea-level rise scenarios that can be incorporated into future planning efforts for both the Ogunquit and Well wastewater treatment plants.

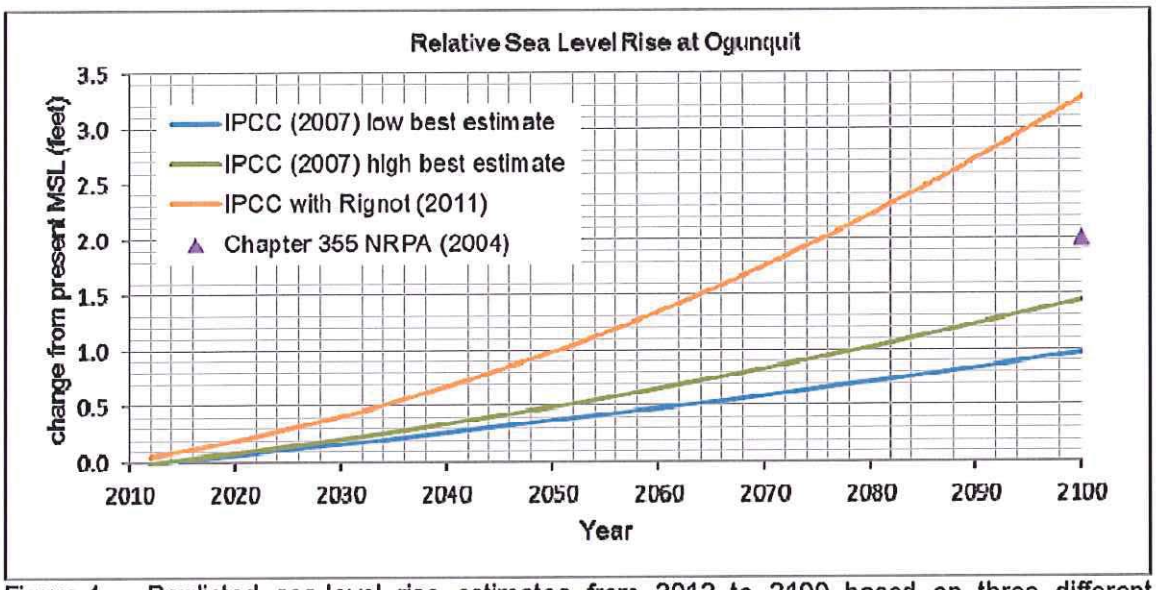

Figure 4. Predicted sea-level rise estimates from 2012 to 2100 based on three different methods: the IPCC high and low best estimates from 2007, and the IPCC high estimate with the updated contributions from ice sheets from Rignot *et al.* (2011). The anticipated rise in sea-level of 2 feet by 2100 described in Chapter 355 of NRPA also is shown.

C. INFLUENCE OF SEA-LEVEL RISE ON STORM FREQUENCY

The coast of southern Maine is primarily susceptible to the impacts of extra-tropical storms or northeasters. Typically, these storms last for several tidal cycles and can generate large long-period storm waves and relatively modest storm surge. For example, Mean Higher High Water (MHHW) is approximately 4.6 feet NAVD, where the 10-year storm surge reaches about 7.6 feet NAVD and the 100-year storm surge reaches about 8.5 feet NAVD, a storm surge of 3.0 feet and 3.9 feet above MHHW, respectively. In general, the significant storms that impact the coast of southern Maine cause relatively frequent moderate flooding, with the difference in storm surge elevations between the 1-year and 100-year return period storms only slightly greater than 2 feet. This minor difference allows nearly every significant northeaster to cause some localized flooding problems, depending on the specific tidal and wind conditions at a site. In addition, due to the low-lying areas along the landward edge of the barrier beach system

adjacent to the salt marsh, small changes can induce significant upland flooding of the roadway in the vicinity of the Ogunquit Wastewater Treatment Plant.

In addition to the concerns of general sea-level rise on making infrastructure more susceptible to the influence of storm surge, a number of climate scientists have indicated that the frequency of severe weather events will increase as the planet continues to warm. However, there does not appear to be any scientific consensus regarding an increase in storm activity in the northeastern U.S. that will potentially cause an increase in extra-tropical storm frequency. For this reason, the evaluation of sea-level rise on storm frequency described in this report only includes the influence of projected increases in sea-level on storm surges and does not address any issues related to potential increased (or decreased) future storm intensity. Based on this methodology, Figure 5 illustrates the future predicted increases in the 100-year storm conditions for the various sea-level rise scenarios described in the previous section.

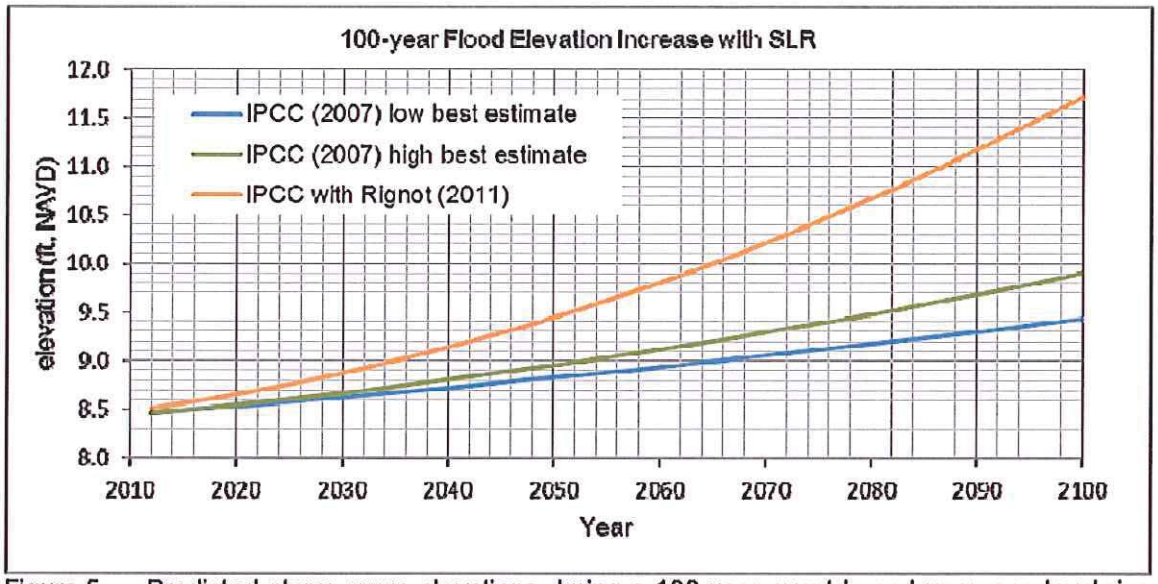

Figure 5. Predicted storm surge elevations during a 100-year event based upon sea-level rise estimates from 2012 to 2100 from three different methods: the IPCC high and low best estimates from 2007, and the IPCC high estimate with the updated contributions from ice sheets from Rignot *et al.* (2011).

The historical tide gage record in Portland, Maine extends back over 100 years to 1910, where Table 1 shows the highest water elevations observed over this time period. The two highest recorded water levels are from 1978. More recently, the April 2007 northeaster ranks as the 6th highest water level observed over the past 102 years. This long-term tide gage record was utilized to develop a return frequency curve for still water storm surge elevations (Figure 6). It is possible that river flow due to heavy rains can also locally influence the storm surge level in salt marsh systems; however, peak riverine flows typically do not coincide with the time of storm surge (major flows from rivers are often delayed by days relative to the storm surge peak), and the cross-sectional area of the flow channel through a salt marsh greatly increases as a result of storm surge, allowing better riverine flow conveyance.

Using the various storm surge scenarios from the previous section, storm return frequency curves can be generated for any range of predicted sea-level rise. In addition

to the existing conditions storm return frequency curve, Figure 6 includes storm return frequency curves for each of the predicted sea-level rise scenarios for the year 2100. As shown, the curves shown on this figure clearly illustrate the increased frequency of storm surge inundation for all future scenarios. As an example, Figure 6 shows that the flood elevation for a 100-year storm under existing conditions (8.1 feet NAVD) will be exceeded once every 10 years in 2100, even under the most conservative assumptions regarding future sea-level rise. The 8.5 feet NAVD storm surge level will be exceeded approximately once every five years under the IPCC High Best Estimate conditions expected in 2100. If the predictions presented in Rignot, *et al.* (2011) occur, ever storm in 2100 will create a storm surge that is greater than the present 100-year storm surge level.

Table 1. The highest historical water levels observed since 1910 in Portland, Maine.

Rank	Date	Elevation feet (NAVD)	Return Period (years)
1	1978 Feb 07	8.49	98.1
2	1978 Jan 09	8.37	75.5
3	1976 Mar 16	7.96	30.8
4	1990 Dec 04	7.93	28.9
5	1958 Apr 07	7.79	21.2
6	2007 Apr 16	7.74	19.1
7	1972 Feb 19	7.73	18.6
8	1944 Nov 30	7.69	17.1
9	1959 Dec 29	7.69	17.1
10	1987 Jan 02	7.68	16.7

Figures 7 through 11 illustrate the influence of flooding related to the various levels of storm surge indicated by the sea-level rise analysis. First, Figure 7 shows the storm surge for the existing conditions during a 100-year storm, where the area flooded is shown in blue. The topographic information used for the basis of this depiction is the LiDAR data from 2010. Figures 8 and 9 utilize the average of the IPCC (2007) High and Low Best Estimates for 2050 and 2100, respectively. Using this analysis technique the predicted 100-year storm surge in 2050 is 8.9 feet NAVD and in 2100 is 9.7 feet NAVD. During present conditions, LiDAR data indicates that the roadway providing access to the site experiences some flooding during the 100-year event and this condition will be exacerbated in 2050, as an additional 5 inches of surge can be anticipated according to the IPCC (2007) sea-level rise conditions.

Figures 10 and 11 utilize the High Best Estimate from the IPCC (2007) with an updated estimate of future contributions from both the Greenland and Antarctic ice sheets developed by Rignot, *et al.* (2011). High and Low Best Estimates for 2050 and 2100, respectively. Using this analysis technique the predicted 100-year storm surge in 2050 is 9.5 feet NAVD and in 2100 is 11.7 feet NAVD. Using these higher predictions of future sea-level rise indicate that the site of the Ogunquit Wastewater Treatment Plant will be inaccessible during a 100-year storm by 2050 and that most of the site will be completely inundated during a 100-year storm event in 2100. Since the storm surge elevation difference between a 10-year and 100-year storm event is only about 1 ft, a significant future increase in sea-level, as predicted by Rignot, *et al.* (2011), will cause even relatively frequent storms to flood the treatment plant site in 2100. Even with the

more conservative IPCC (2007) estimates, a storm that occurs once every 10 years will substantially flood the roadway access to the plant.

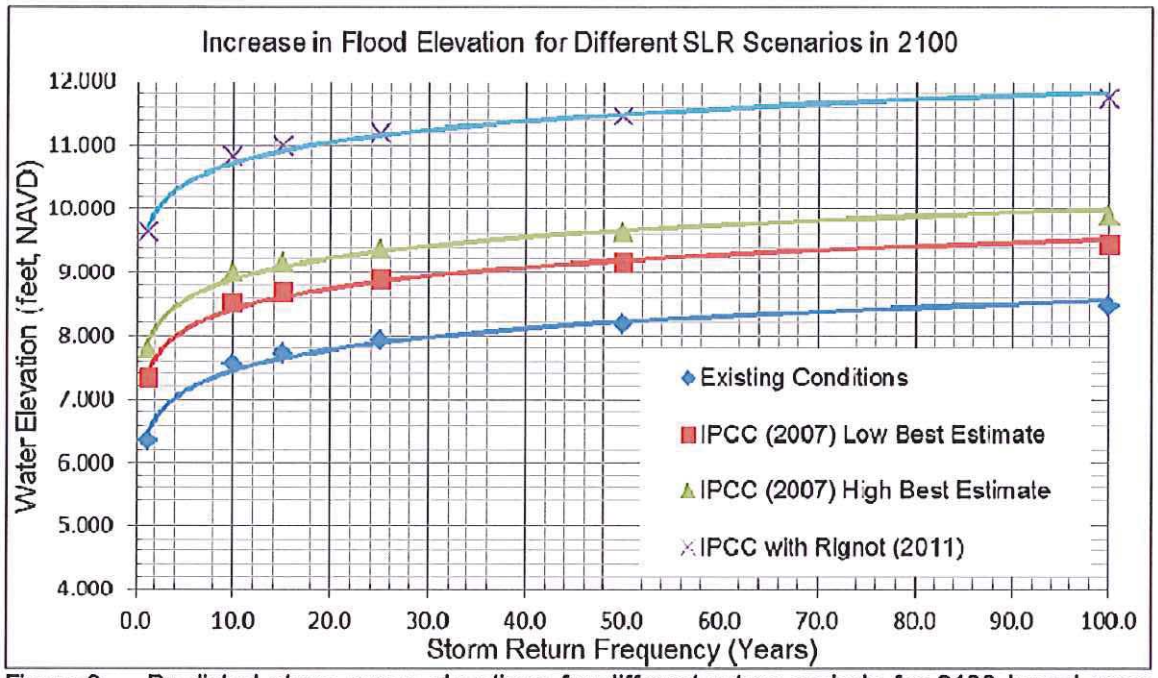

Figure 6. Predicted storm surge elevations for different return periods for 2100 based upon sea-level rise estimates from 2012 to 2100 using the three different methods: the IPCC high and low best estimates from 2007, and the IPCC high estimate with the updated contributions from ice sheets from Rignot *et al.* (2011). The existing conditions storm surge frequency curve is shown for comparison.

Figure 7. Aerial photograph from 2010 showing the areas that are inundated by flood waters for a 100-year storm event (8.5 feet NAVD) based on existing conditions. The areas shaded in blue would be under water during the storm event. Topographic and bathymetric data utilized for this representation were derived from the 2010 LIDAR survey.

Figure 8. Aerial photograph from 2010 showing the areas that are inundated by flood waters for a 100-year storm event (8.9 feet NAVD) based on IPCC predicted average sea-level rise increase in 2050. The areas shaded in blue would be under water during the storm event. Topographic and bathymetric data utilized for this representation were derived from the 2010 LiDAR survey.

Figure 9. Aerial photograph from 2010 showing the areas that are inundated by flood waters for a 100-year storm event (9.7 feet NAVD) based on IPCC predicted average sea-level rise increase in 2100. The areas shaded in blue would be under water during the storm event. Topographic and bathymetric data utilized for this representation were derived from the 2010 LIDAR survey.

Figure 10. Aerial photograph from 2010 showing the areas that are inundated by flood waters for a 100-year storm event (9.5 feet NAVD) based on IPCC predicted sea-level rise increase in 2050 including updated input for ice sheet contributions (Rignot, *et al.*, 2011). The areas shaded in blue would be under water during the storm event. Topographic and bathymetric data utilized for this representation were derived from the 2010 LIDAR survey.

Figure 11. Aerial photograph from 2010 showing the areas that are inundated by flood waters for a 100-year storm event (11.7 feet NAVD) based on IPCC predicted sea-level rise increase in 2100 including updated input for ice sheet contributions (Rignot, *et al.*, 2011). The areas shaded in blue would be under water during the storm event. Topographic and bathymetric data utilized for this representation were derived from the 2010 LIDAR survey.

D. HISTORICAL SHORELINE CHANGE

Ogunquit Beach system provides protection for the Ogunquit Waste Water Treatment Plant from the high water levels and intense wave action experienced during coastal storms. Severe erosion of the beach and dune fronting this plant could potentially result in a breach in the dune and a catastrophic failure of the plant. In order to quantify this risk, the morphological patterns of Ogunquit Beach should be evaluated relative to other coastal hazards.

The use of historical shoreline and bathymetric/topographic change information allows the quantification of coastal processes by providing a measure of nearshore accretion or erosion. For the Ogunquit Beach shoreline, high quality shoreline data sets are available dating back to 1869. This 140+ year time period provides accurate long term information about the evolution of the shoreline fronting the treatment plant. No significant natural or anthropogenic alterations to the shoreline that would result in the severe alteration of morphologic patterns of the beach have occurred over this time period. Therefore, this historical data captures current shoreline trends and may be used to estimate the future morphology of Ogunquit Beach.

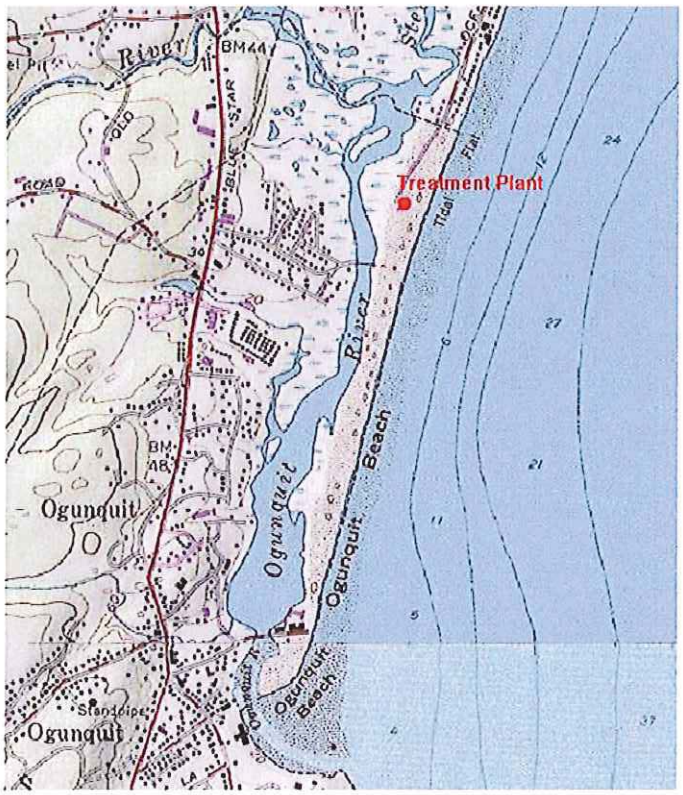

Figure 12. Topographic map showing Ogunquit Beach and the location of the Ogunquit Waste Water Treatment Plant.

Rates of change in high-water shoreline position for the two time periods 1869 to 1953 and 1953 to 2010 were evaluated along Ogunquit Beach up to 2000 ft to the north and south of the water treatment plant. The 1869 shoreline position was mapped using traditional survey procedures and complied on U.S. Coast and Geodetic Survey Topographic Sheet T-1121. The 1953 position was compiled from an aerial survey and supplemental land surveys on Topographic Sheet T-11164. Scans of the original T-

sheets were georeferenced in ArcGIS and the shorelines were extracted by on-screen digitizing using the line drawing tool. The 2010 shoreline position was visually interpreted from color orthophotographs flown at low tide and available to download from the MEGIS Data Catalog website. Elevation profiles extracted from the concurrent LiDAR dataset were also used to determine the 2010 high-water position.

The high-water shoreline position change rates were calculated in the Automated Shoreline Analysis Program that is run as an extension in ArcGIS (ArcASAP). This program requires a user-defined spatial interval (50 ft was used for this study) and the general shoreline orientation to determine the amount of shoreline advance or retreat for the time interval. ArcASAP performs the shoreline change calculations by casting normal transects from the earlier shoreline to the later shoreline at each analysis point specified along the input shoreline. The data output is a table of shoreline change magnitudes and rates for each transect where shoreline change denoted with a minus sign represents erosion.

All shoreline position data contain inherent errors associated with field and laboratory compilation procedures. The potential measurement and analysis uncertainty between the data sets is additive when shoreline positions are compared. Because the individual uncertainties are considered to represent standard deviations, a root-mean-square (RMS) method was used to estimate the combined potential uncertainties in the data sets. The positional uncertainty estimates for each shoreline were calculated using the information in Table 2. These calculations estimated the total RMS uncertainty to be ±41.7 ft or ±0.5 ft/year for 1869 to 1953 and ±20.0 ft or ±0.5 ft/year for 1953 to 2010.

Table 3 shows maximum, minimum, and average change rates for each of time intervals. During the 141 year time period, shoreline change rates ranged from 0.2 to -1.6 ft/year. The highest erosion rates occurred during the more recent time period, 1953 to 2010. The only rates of accretion occurred almost 2000 ft north of the water treatment plant and between 400 and 1000 ft south of the plant from 1869 to 1953. The lower average change rate, -0.4 ft/year, also occurred from 1869 to 1953. Overall, the average change rates for both time periods were negative and the erosion rates increased during the later time period.

Considering the 1869 shoreline as the "initial condition" of this study, the high water line of the section of beach that now fronts the treatment plant has moved landward (eroded) over the 141 years of data. The seasonal change in high water line was neglected for this analysis because seasonal effects on the migration of the high water line are small when compared to both the accuracy of measurement and the overall movement of the high water line throughout the analysis. Figure 13 shows the movement of the high water line from July of 1869 to April of 1953, where a section of the beach experiences landward shoreline movement of approximately one foot per year. This suggests a slightly erosional to stable beach, as much of the high water line on the beach showed little movement. From April of 1953 to August of 2010 shoreline change is more prevalent. Figure 14 shows this as most of the beach experiences over one foot of shoreline loss per year. This shoreline loss indicates general erosion of the beach. Overall, both of these analyses show a trend of landward high water line movement and the change in shoreline movement rate shown in the two figures indicates a more recent acceleration in beach erosion. Regardless, the rate of shoreline recession is relatively moderate and there is no indication that the sediment supply to the beach system has changed throughout the historical record. The long-term record

does indicate some variability in the location of the greatest erosion; however, this influence likely is in response to localized beach/dune volume, rather than an indication of a diminished sediment supply.

Based on the historical shoreline analysis, the more recent time period (1953 to 2010) indicates an increase in shoreline erosion rate. This acceleration in erosion rate also would cause a related response to dune erosion and long-term dune stability. As the shoreline retreats, the dune volume fronting the bulkhead also will decrease and this will eventually allow the dune in the vicinity of the Waste Water Treatment Plant to be susceptible to a storm-induced breach. Depending on storm severity, it is possible that the already decreased volume of the dune could allow a breach during a severe event. Regardless, continued loss of the fronting dune will make this threat rapidly increase in the next 10-20 years and this threat can be considered relatively imminent for planning purposes.

Table 2. Estimates of Potential Error Associated with Shoreline Position Surveys.	
Traditional Engineering Field Surveys (1869)	
Position of rodded points Location of plane table Interpretation of high-water shoreline position at rodded points Error due to sketching between rodded points	±3 ft ±7 to 10 ft ±10 to 13 ft up to ±16 ft
Cartographic Errors (1869, 1953)	Map Scale 1:10,000
Inaccurate location of control points on map relative to true field location Placement of shoreline on map Line width representing shoreline Digitizer error Operator error	Up to ±10 ft ±16 ft ±10 ft ±3 ft ±3 ft
Historical Aerial Surveys (1953)	Map Scale 1:10,000
Delineating high-water shoreline position	±16 ft
Orthophotography (2010)	
Delineating high-water shoreline position Position of measured points	±10 ft ±10 ft

Table 3. Shoreline Change Rates			
	Minimum ft/year	Maximum ft/year	Average ft/year
July 1869 to April 1953	-1.2	0.2	-0.4
April 1953 to August 2010	-1.6	-0.6	-1.2

Figure 13. Long-term shoreline change between 1869 and 1953 for the section of Ogunquit Beach fronting the Ogunquit Waste Water Treatment Plant. Shoreline change is color-coded, where the highest erosion rate is represented as orange and areas of minimal shoreline change are represented as grey.

Figure 14. Long-term shoreline change between 1953 and 2010 for the section of Ogunquit Beach fronting the Ogunquit Waste Water Treatment Plant. Shoreline change is color-coded, where the highest erosion rate is represented as red and areas of minimal shoreline change are represented as grey.

E. RECENT BATHYMETRIC AND TOPOGRAPHIC CHANGE

A survey of the beach and dune elevation, using LiDAR, was conducted in transects across the beach. The location of these transects may be seen in Figure 15. Surveys were conducted in September of 2000, May to July of 2004, and May of 2010. Transects B and C represent sections of the beach and dune directly seaward of the plant. Transect D is located approximately 600 feet south of the plant and Transect A is located approximately 45 feet north of the plant.

Figure 16 shows the change in beach and dune elevations at each transect. The dune immediately fronting the treatment plant may be observed between 250 and 375 feet from the start of Transects B and C. The profile of the dune at all transects remains constant during all surveys, indicating that the dune has neither eroded nor accreted over the 2000 to 2010 time period. Furthermore, there is no evidence of the dune fronting the plant is moving towards the bulkhead of the plant during this time.

A comparison of the 2004 and 2010 transects to the 2000 transects, shows that the overall beach elevation, seaward the dune, is higher at all transects during September of 2000. Furthermore the beach has a steeper slope in 2004 and 2010. Due to the timing of the surveys, this appears to be a seasonal effect, where the natural beach cycle of high wave action and erosion during the winter (which causes sand to migrate offshore), and lower wave action leading to upper beach accretion during the summer. The Ogunquit Beach profile cyclically changes in this manner, with only minor net erosion occurring on a year-to-year basis. In general, other than the seasonal variations, the beach transects show a stable beach system between 2000 and 2010.

Using the data from the 2004 and 2010 surveys, the average slope of the beach fronting the dune was calculated in the vicinity of the treatment plant for Transects A through C. As a control, the slope of the beach fronting the dune in Transect D also was calculated. The 2000 surveys were neglected from these calculations to exclude seasonality effects on the data, potentially biasing the results with a more gradual summer beach berm. Transect D shows the beach profile away from the influence of the treatment plant, while the combination of Transects A, B, and C show the beach slope immediately seaward of the plant. At Transect D, the computed slope of the beach is 1:35, while the slope of the beach seaward of the plant (Transects A through C) is approximately 1:21, where the beach slope was similar for Transects A, B, and C.

Transects B and C, located through the bulkhead fronting the waste water treatment plant, show a dune approximately 100 feet wide. In contrast, Transects A and D show the dune width of approximately 200 feet. This reduced dune width and volume illustrates an adverse effect that the plant location is having on the dune. The existence of the plant 'footprint' and the bulkhead fronting the plant prevents the dune from migrating naturally landward. This unnatural reduced dune width at Transects B and C, make this area more susceptible to a dune breach during a severe storm event. However, at least in the 10-year time period covered by the LiDAR surveys, there has been no appreciable change to the dune volume, position, or width at any of the Transect locations.

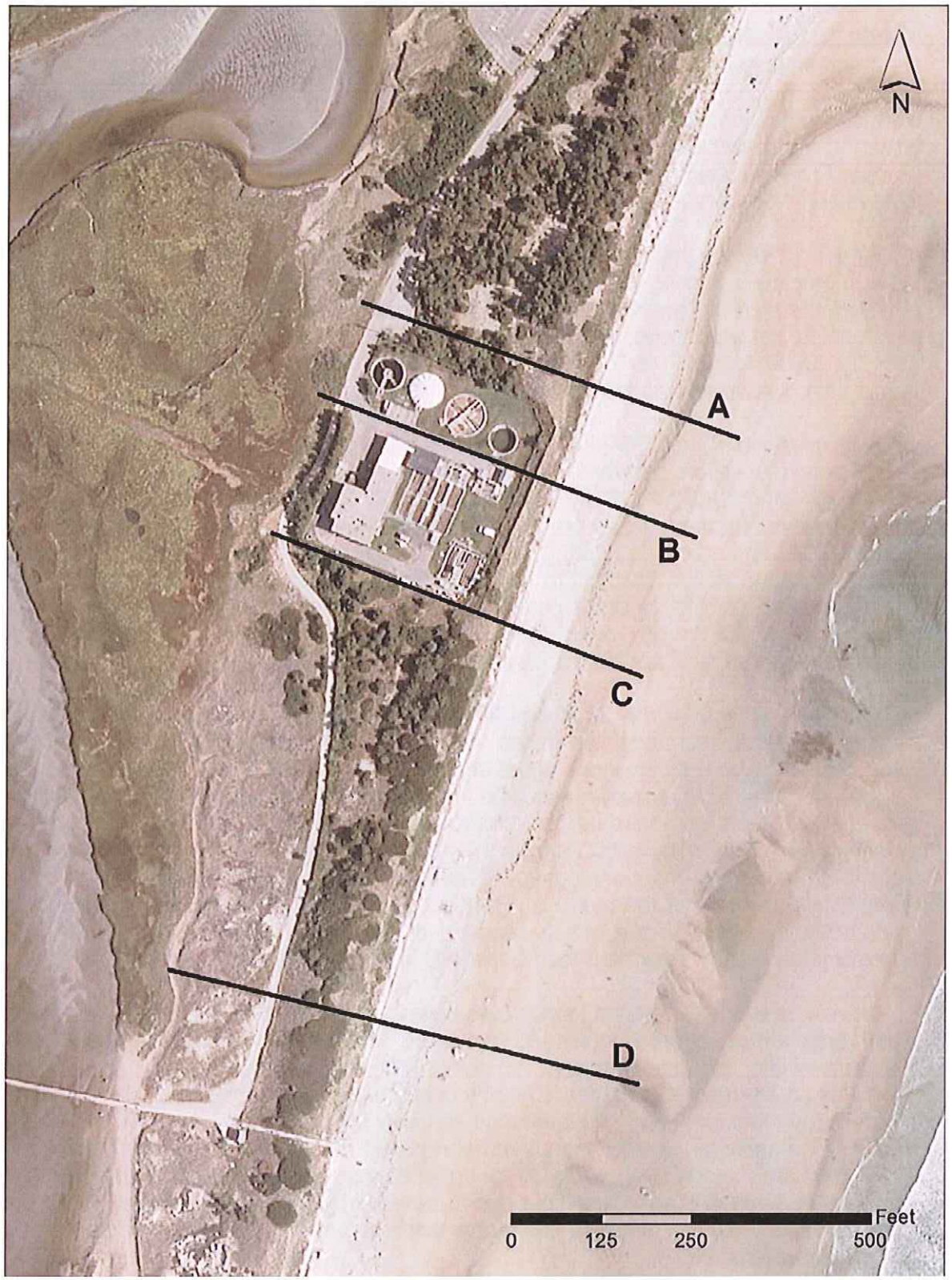

Figure 15. Aerial Photograph showing the location of each transect of Ogunquit Beach. Transect letter matches with the corresponding letter of each beach profile shown in Figure 16.

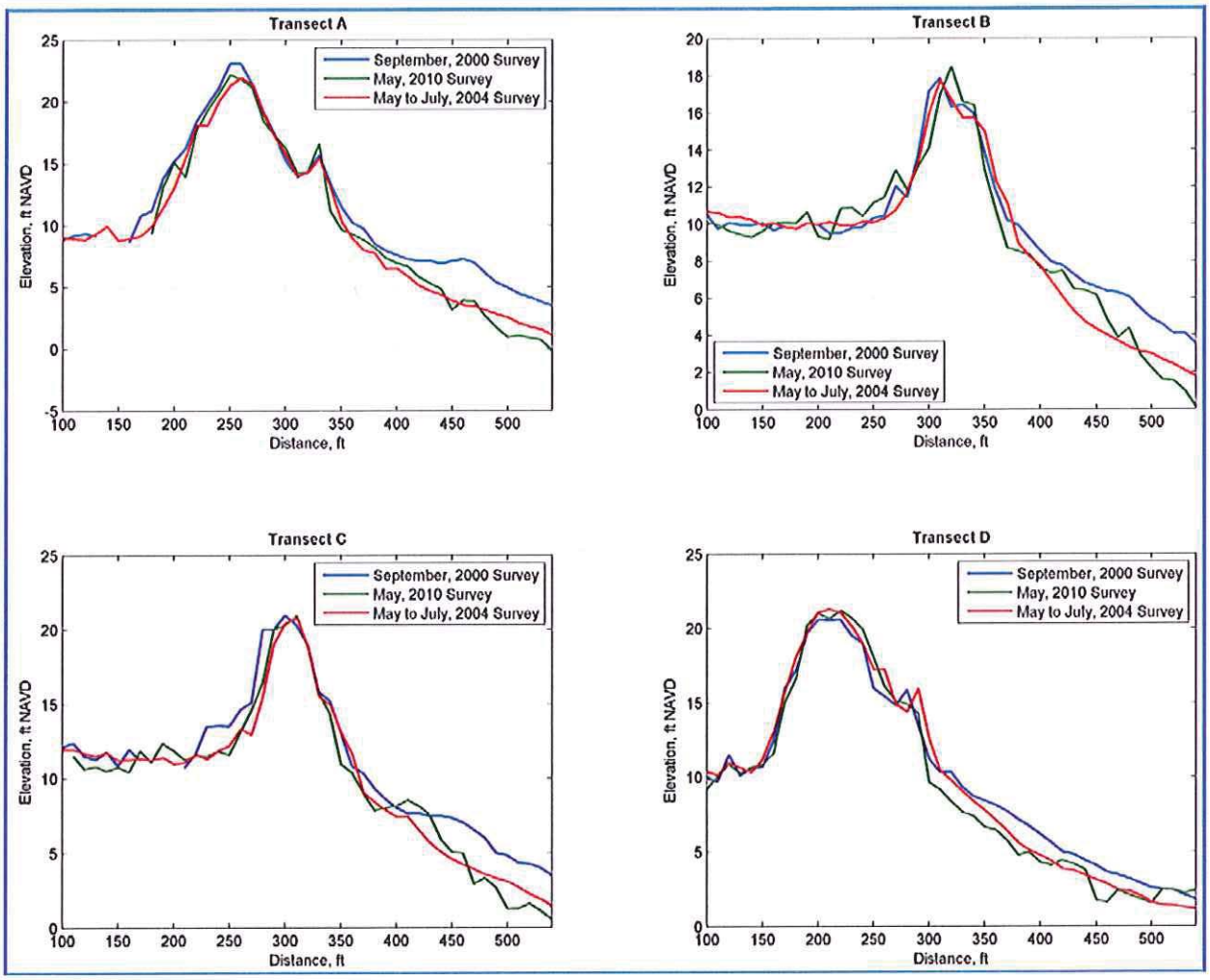

Figure 16. Ogunquit Beach Profiles from September, 2000 to May, 2010. The profiles were created using LIDAR. The location of each transect is shown in the aerial photograph seen in Figure 15.

F. CONCLUSIONS

The assessment of potential sea-level rise scenarios, increased effects of sea-level rise on flood risk, a historical shoreline change, and recent topographic/bathymetric changes in the overall beach system, indicates that the Ogunquit Waste Water Treatment Plant is at risk from both sea-level rise and ongoing coastal erosion. The following general conclusions were developed from the quantitative assessment:

- The available literature and modeling analyses continue to show a relatively wide range in future predictions of sea-level rise. The Intergovernmental Panel on Climate Change (IPCC) provided high and low estimates in 2007 that were below the estimate utilized by the State of Maine for regulatory purposes (i.e. 2 feet of sea-level rise by 2100). More recent literature suggests that the contributions from the ice sheets on Greenland and Antarctica may have been underestimated by the IPCC. For this study,

estimates of sea-level rise by 2100 range from approximately 1.0 feet to 3.2 feet.

- While there is no scientific consensus regarding the increase in severe weather events created by climate change in the northeastern U.S., the continued increase in relative sea-level will cause relatively minor coastal storms to have storm surges similar to severe storms in the future. However, the severity of this impact is directly related to the future rate of sea-level rise.
- The present beach erosion rate in the vicinity of the Ogunquit Waste Water Treatment Plant is between 1.0 and 1.5 feet per year. The rate over the past ~60 years is approximately double the rate that occurred between 1869 and 1953. The rates of coastal erosion are relatively low and there is not a direct threat to the plant from long-term erosion over the next few decades.
- Because of the plant siting within a barrier beach and dune system, ongoing coastal erosion has led to a decrease in the overall dune width and associated volume fronting the treatment plant. The existence of the infrastructure prevents the dune form from naturally migrating landward. This loss in dune volume potentially makes the area fronting the plant susceptible to breaching during a storm, since the likelihood of a dune breach during a storm is directly related to the cross-sectional area of the dune. As the surrounding dune continues to migrate landward as the shoreline migrates landward, the volume of dune fronting the plant also will decrease, further exacerbating a potential storm breach of the dune at this location. At the present rate of beach erosion, the dune fronting the plant will be completely lost within the next 30-to-50 years. Depending on storm severity, it is possible that the already decreased volume of the dune could allow a breach during a severe event. Regardless, continued loss of the fronting dune will make this threat rapidly increase in the next 10-20 years and this threat can be considered relatively imminent for planning purposes. Due to the placement of the sheet pile wall along the seaward edge of the Waste Water Treatment Plant property, a future breach is most likely to occur at ether the north or south ends of the shore protection structure.
- The storm susceptibility analysis related to sea-level rise and the ongoing beach erosion indicate that the Ogunquit Wastewater Treatment Plant will be at high risk within the next 20-to-30 years. At present, a 100-year storm will not directly jeopardize the plant; however, accelerated sea-level rise and/or severe erosion of the fronting dune system during a single major storm could put the plant at significant risk well before the 20-to-30 year time period.

APPENDIX B: APPLIED COASTAL RESEARCH AND ENGINEERING, INC. MEMORANDUM ON THE INCREASE IN 100-YEAR STORM FLOODING AT THE WELLS WWTP

Applied Coastal Research and Engineering, Inc.
766 Falmouth Road
Suite A-1
Mashpee, MA 02649

MEMORANDUM

Date: **August 6, 2012**

To: **Seth Garrison, Woodard and Curran**

From: **John Ramsey**

Subject: **Increase in 100-Year Storm Flooding at the Wells Wastewater Treatment Plant**

The flooding scenarios at the Wells Wastewater Treatment Plant are identical to the scenarios developed for the Oqunquit Wastewater Treatment Plant, where Figures 1 through 5 illustrate the influence of flooding related to the various levels of storm surge indicated by the sea-level rise analysis. First, Figure 1 shows the storm surge for the existing conditions during a 100-year storm, where the area flooded is shown in blue. The topographic information used for the basis of this depiction is the LiDAR data from 2010. Figures 2 and 3 utilize the average of the IPCC (2007) High and Low Best Estimates for 2050 and 2100, respectively. Using this analysis technique the predicted 100-year storm surge in 2050 is 8.9 feet NAVD and in 2100 is 9.7 feet NAVD. During present conditions, LiDAR data indicates that the site experiences no flooding during the 100-year event and this condition is similar in 2050, as an additional 5 inches of surge can be anticipated according to the IPCC (2007) sea-level rise conditions. Figure 3 (100-year storm conditions in 2100 as predicted by the IPCC, 2007) indicates that the area to the eastern side of the wastewater treatment plant would be flooded.

Figures 4 and 5 utilize the High Best Estimate from the IPCC (2007) with an updated estimate of future contributions from both the Greenland and Antarctic ice sheets developed by Rignot, *et al.* (2011). High and Low Best Estimates for 2050 and 2100, respectively. Using this analysis technique the predicted 100-year storm surge in 2050 is 9.5 feet NAVD and in 2100 is 11.7 feet NAVD. Using these higher predictions of future sea-level rise indicate that the eastern portion of the site of the Wells Wastewater Treatment Plant will be flooded during a 100-year storm by 2050 and that this flooding will be exacrerbated during a 100-year storm event in 2100. Since the storm surge elevation difference between a 10-year and 100-year storm event is only about 1 ft, a significant future increase in sea-level, as predicted by Rignot, *et al.* (2011), will cause even relatively frequent storms to flood the treatment plant site in 2100. Unlike the Ogunquit plant, the roadway servicing the Wells Wastewater Treatment Plant will not be flooded during a 100-year storm event, even utilizing the 'worst-case' future sea-level rise scenarios.

Figure 1. Aerial photograph from 2010 showing the areas that are inundated by flood waters for a 100-year storm event (8.5 feet NAVD) based on existing conditions. The areas shaded in blue would be under water during the storm event. Topographic and bathymetric data utilized for this representation were derived from the 2010 LiDAR survey.

Figure 2. Aerial photograph from 2010 showing the areas that are inundated by flood waters for a 100-year storm event (8.9 feet NAVD) based on IPCC predicted average sea-level rise increase in 2050. The areas shaded in blue would be under water during the storm event. Topographic and bathymetric data utilized for this representation were derived from the 2010 LiDAR survey.

Figure 3. Aerial photograph from 2010 showing the areas that are inundated by flood waters for a 100-year storm event (9.7 feet NAVD) based on IPCC predicted average sea-level rise increase in 2100. The areas shaded in blue would be under water during the storm event. Topographic and bathymetric data utilized for this representation were derived from the 2010 LIDAR survey.

Figure 4. Aerial photograph from 2010 showing the areas that are inundated by flood waters for a 100-year storm event (9.5 feet NAVD) based on IPCC predicted sea-level rise increase in 2050 including updated input for ice sheet contributions (Rignot, *et al.*, 2011). The areas shaded in blue would be under water during the storm event. Topographic and bathymetric data utilized for this representation were derived from the 2010 LIDAR survey.

Figure 5. Aerial photograph from 2010 showing the areas that are inundated by flood waters for a 100-year storm event (11.7 feet NAVD) based on IPCC predicted sea-level rise increase in 2100 including updated input for ice sheet contributions (Rignot, *et al.*, 2011). The areas shaded in blue would be under water during the storm event. Topographic and bathymetric data utilized for this representation were derived from the 2010 LiDAR survey.

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