Horsley Witten Group
Sustainable Environmental Solutions
90 Route 6A, Unit #1 • Sandwich, MA • 02563
Phone - 508-833-6600 • Fax - 508-833-3150 • *www.horsleywitten.com*

Assessment of Climate Change Impacts on Stormwater BMPs and Recommended BMP Design Considerations in Coastal Communities

December 2015

Prepared for:
Massachusetts Office of Coastal Zone Management
Attn: Adrienne Pappal
251 Causeway Street, Suite 800
Boston, MA

Submitted by:
Horsley Witten Group, Inc.
Teaming with:
Woods Hole Group

CZM
Massachusetts Office of Coastal Zone Management

Massachusetts Department of Environmental Protection

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1.0 Introduction

The Massachusetts Office of Coastal Zone Management (MA CZM) Coastal Pollutant Remediation Grant Program and the Massachusetts Department of Environmental Protection (MassDEP) Clean Water Act Section 319 Grant Program, as well as other state and federal agencies, municipalities and private land-owners, have funded the design and installation of a range of structural stormwater best management practices (BMPs) in coastal areas of Massachusetts. As a result of climate change, coastal areas are increasingly becoming more vulnerable to flooding and inundation, storm surge, salt water intrusion, changing precipitation patterns, rising sea levels and inland groundwater levels, and shifting vegetation hardiness. The purpose of this project is to improve the selection, siting, design, construction, and operation and maintenance of coastal BMPs to ensure their adaptability and continued performance in the face of climate change.

Climate change models predict sea level rise and increasing storm frequency and intensity, which in turn have the potential to impact stormwater BMPs as coastal areas become increasingly vulnerable to flooding, higher energy currents, and waves. Stormwater BMP design criteria may need to be refined to better account for the changing magnitude and frequency of “routine” storms, to safely convey larger, less frequent storms, and to withstand harsher conditions. Additional constraints on BMP siting and selection may need to be envisioned beyond what current conditions dictate. Flood hazard areas that are expected to become exceedingly vulnerable may no longer be appropriate locations for traditional BMP applications. Vegetation selection or soil specifications may need to be revisited to boost the effectiveness and life span of BMPs. Many of these considerations should be incorporated into BMP guidance manuals, as well as into standards for projects funded by state grant programs.

This report was developed by the Horsley Witten Group, Inc. (HW) with support from The Woods Hole Group (WHG), and was funded by MA CZM and Mass DEP. The report first presents a summary of the climate change impacts that are anticipated to affect stormwater management practices sited in the near coastal zone in Massachusetts. This analysis was coupled with the field evaluation of dozens of existing BMPs in the Massachusetts coastal area to identify potential siting and design factors subject to climate change pressures. From this evaluation, a number of design modifications are recommended to better address climate change related impacts. For a handful of specific practices, conceptual drawings of proposed design modifications were developed to provide real examples of how some of these recommendations could be implemented. These design recommendations provide a basis for future efforts to incorporate the realities of climate change impacts into the siting, design, maintenance and funding decisions for stormwater improvement projects in the future.

The remainder of this report is organized as follows:

- Section 2. Anticipated Climate Change Impacts
- Section 3. Field Assessments
- Section 4. Recommended Design Modifications and Considerations
- Section 5. Conceptual Design Examples of the Recommended Modifications

Section 6. Conclusion
Section 7. References

Appendix A presents the summary forms from the field assessments of the sites visited by the project team in the summer of 2015.

Appendix B presents the projected risk of flooding, prepared by WHG, in both a summary table and in a series of maps for all of the sites assessed for this project.

2.0 Anticipated Climate Change Impacts

The purpose of this section is to characterize the projected likely climate change impacts in coastal Massachusetts for environmental conditions that influence BMP selection, siting, design, and operation and maintenance. These environmental conditions include:

- sea level rise,
- storm intensity and frequency,
- annual precipitation,
- precipitation extremes, and
- groundwater elevation in the coastal area.

This effort drew upon the body of scientific literature and government-accepted climate change projections and understanding, including the MA Climate Change Adaptation Report (2011) and the New Hampshire Coastal Risks and Hazards Commission report, adopted in July, 2014.

Table 2.1 provides a summary of the characterization of the current environmental conditions and the projected changes on a 20-year planning horizon (approximately 2035) and a 50-year planning horizon (approximately 2065). A more detailed discussion of each of the climate change impacts is then presented in the subsequent sections.

2.1 Sea Level Rise

Sea level rise (SLR) is one of the most certain and potentially destructive impacts of climate change (Meehl et al., 2007). Rates of sea level rise along the northeastern U.S. since the late 19th century are unprecedented, at least since 100 AD (Kemp et al., 2011). Local relative sea level rise is a function of global and regional changes. As discussed in more detail below, global increases by 2100 may range from 0.2 m (0.7 ft) to 2.0 m (6.6 ft). Regional variations in sea level rise result from factors such as vertical land movement (uplift or subsidence), changing gravitational attraction in some sections of the oceans due to ice masses, and changes in regional ocean circulation (Nicholls et al., 2014).

Table 2.1 Anticipated Climate Change Impacts Potentially Affecting the Design, Function and Maintenance Needs of Stormwater Management Practices in Coastal Massachusetts

Anticipated Climate Change Impact	Current Conditions	20 Year Planning Horizon (2035)	50 Year Planning Horizon (2065)
Sea Level Rise	Rates of sea level rise along the northeastern U.S. since the late 19th century are unprecedented, at least since 100 AD (Kemp et al., 2011). The local relative sea level rise is a function of global and regional changes, and varies from location to location mainly due to subsidence levels. Boston, for example, has a mean sea level trend of 2.80 mm/yr based on monthly mean sea level data collected from 1921 to 2013.	SLR is projected to be between 5.5 cm (low-scenario based on Boston historical trend) and 37 cm (high-scenario) above 1992 global mean sea level for Massachusetts. This would result in the potential for minor additional flooding in extremely low-lying areas, particularly during spring high tides.	SLR is projected to be between 14 cm (low-scenario based on Boston historical trend) and 88 cm (high-scenario) above 1992 global mean sea level. With even the intermediate-low and intermediate-high scenarios projecting a sea level rise increase of 24 to 59 cm from 1992 levels by 2065, coastal flooding will occur even more regularly. Additionally, increased water depths will result in greater potential for wave and storm surge propagation further inland during storms.
Storm Intensity and Frequency (Bengtsson et al., 2006; Catto et al., 2011; Emanuel, 2005; NOAA, 2014)	There has already been a documented increase in tropical cyclone (hurricane) frequency and intensity in the Atlantic Ocean, which are believed to reflect increases in sea surface temperature. The frequency and intensity of extra-tropical (nor'easter) storms has not changed.	Tropical cyclone (hurricane) frequency and intensity in the Atlantic Ocean will likely continue to increase as it has done in recent decades. An increase in the intensity of these storms will affect coastal facilities by exposing them to higher winds, greater storm surges, and increased flooding. It is unlikely that climate change will lead to an increase in intensity of extra-tropical (nor'easter) storms.	As sea surface temperatures continue to warm, tropical cyclone (hurricane) frequency and intensity in the Atlantic Ocean will likely continue to rise, further increasing the potential for damage caused by high winds, wave and storm surge damage, and flooding, and potentially affecting locations further inland. It is unlikely that climate change will lead to an increase in intensity of extra-tropical (nor'easter) storms.

Anticipated Climate Change Impact	Current Conditions	20 Year Planning Horizon (2035)	50 Year Planning Horizon (2065)
Annual Precipitation (Hayhoe et al., 2006) and (MA EEA, 2011) (All estimates rounded to the nearest whole number.)	Existing conditions for the period 1961-1990: Total: 41 inches Winter: 8 inches; Summer: 11 inches	Estimated changes by 2035-2064: Total: 5-8% increase Winter: 6-16% increase ; Summer: 1-3% decrease An increase in annual precipitation is expected to occur in fall, winter and spring, with a slight decrease in rainfall volume in the summer.	Estimated changes by 2070-2099: Total: 7-14% increase Winter: 12-30% increase; Summer: 0-2% decrease An increase in annual precipitation is expected to occur in fall, winter and spring, with a slight decrease in rainfall volume in the summer.
Precipitation Extremes (Design Storm Event Precipitation Depths)	1-year, 24-hour storm: 2.71in 2-year, 24-hour storm: 3.26 in 10-year, 24-hour storm: 4.90 in 25-year, 24-hour storm: 6.19 in 50-year, 24-hour storm: 7.39 in 100-year, 24-hour storm: 8.82 in (NRCC/NRCS, 2010-2015)	1-year, 24-hour storm: NA 2-year, 24-hour storm: 3.35 in 10-year, 24-hour storm: 5.55 in 25-year, 24-hour storm: 6.90 in 50-year, 24-hour storm: 8.15 in 100-year, 24-hour storm: 9.45 in (Estimated from Figure 7-18 in CH2MHill, 2014, DRAFT)	Projection for 2060: 1-year, 24-hour storm: NA 2-year, 24-hour storm: 3.50 in 10-year, 24-hour storm: 5.75-6.00 in 25-year, 24-hour storm: 7.20-7.55 in 50-year, 24-hour storm: 8.40-8.90 in 100-year, 24-hour storm: 9.70-10.40 in (Estimated from Figure 7-18 in CH2MHill, 2014, DRAFT)
Groundwater Elevation in the Vicinity of the Coast (Horsley Witten Group, 2013; Masterson and Garabedian, 2007; Masterson et al., 2014)		As sea level rises, the elevation of groundwater in the vicinity of the coast that is directly influenced by the coastal water can be expected to rise as well, but exact changes are site specific.	As sea level rises, the elevation of groundwater in the vicinity of the coast that is directly influenced by the coastal water can be expected to rise as well, but exact changes are site specific.

A consortium of government agencies has completed a National Climate Assessment (Parris et al., 2012) that provides guidance on appropriate selection of SLR scenarios. Under this guidance, four projected rates of sea level rise (highest, intermediate-high, intermediate-low, and low) are presented. Given the range of uncertainty in future global SLR, the use of multiple scenarios encourages experts and decision makers to consider multiple future conditions and to develop multiple response options. For this reason, this report recommends using the SLR scenarios presented by Parris et al. (2012) (Figure 2.1).

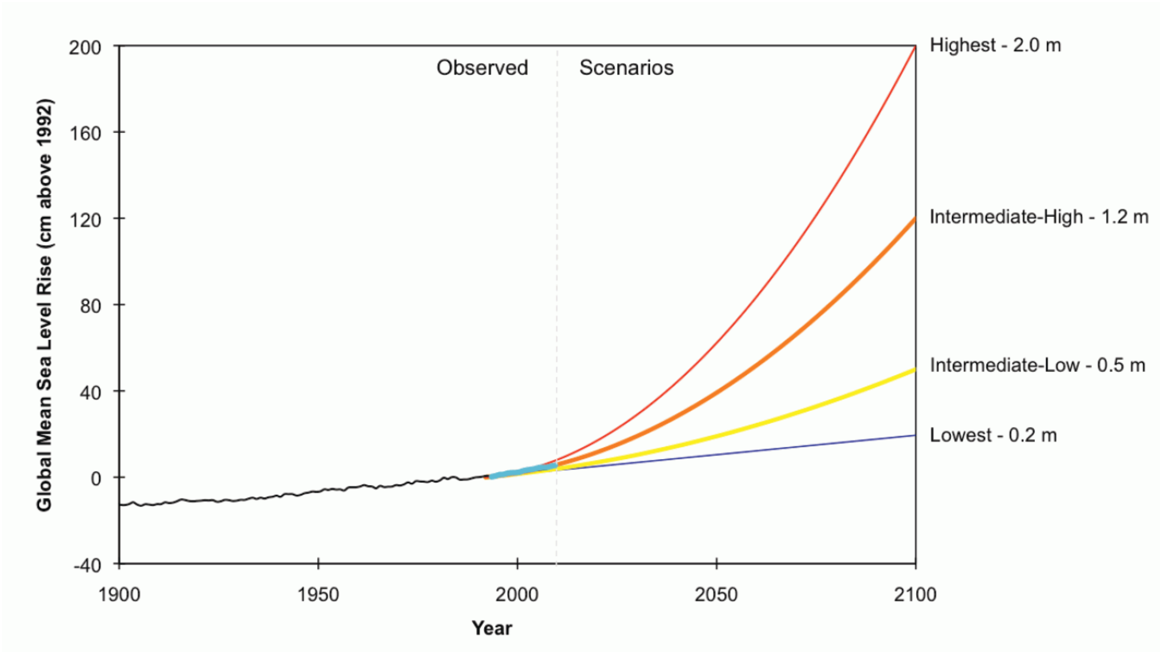


Figure 2.1. Projections of future sea level rise recommended in Parris et al. (2012)

The highest scenario in Parris et al. (2012) surpasses the maximum of 1.2 m recently presented in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) Working Group 1 (WG1) material (shown in Figure 2.2). The highest scenario from Parris et al (2012), combines thermal expansion estimates from IPCC SLR projections with the maximum possible glacier and ice sheet loss by the end of the century, and is therefore useful to consider "in situations where there is little tolerance for risk". Guidance is also provided in *Sea Level Rise: Understanding and Applying Trends and Future Scenarios for Analysis and Planning*: http://www.mass.gov/eea/docs/czm/stormsmart/slr-guidance-2013.pdf.

Additionally, there is considerable scientific support for a maximum value close to 2m (6.6 ft). The recent survey of SLR experts by Horton et al (2013) related to possible changes in SLR under a high Coupled Model Intercomparison Project, 5th Phase (CMIP5) scenario (Representative Concentration Pathway (RCP) 8.5, resulting in a temperature increase of 4.5 C above preindustrial by 2100) is shown in Figure 2.3. "Thirteen experts (out of ~ 90) estimated a 17% probability of exceeding 2m of SLR by 2100 under the upper temperature scenario" (RCP 8.5, page 5). For unmitigated emissions, half of the experts (51%) gave 1.5 m (4.9 ft) or more, and a quarter gave (27%) 2 m (6.6 ft) or more. Futhermore, the U.S. Army Corps of Engineers, in their 2011 guidance on sea-level change considerations for civil works programs, stated that 2 m (6.6 ft) is a reasonable upper bound for 21st century global mean sea level rise.

The low-SLR scenarios are based on observed historical SLR trends, which can vary from region to region. For example, the mean sea level trend for Boston is 2.80 mm/yr with a 95% confidence interval of +/- 0.17 mm/yr based on monthly mean sea level data from 1921 to 2013 (Figure 2.3). By comparison, the mean sea level trend for Nantucket is 3.55 mm/yr with a 95% confidence interval of +/- 0.40 mm/yr based on monthly mean sea level data from 1965 to 2013 (Figure 2.3). Boston would therefore experience a relative SLR of 1.03 m by 2050 if current rates continued in a linear fashion (equivalent to low-SLR estimates), while Nantucket would experience 1.31 m of relative SLR in the same time period. These differences are due to local variations in subsidence (the sinking or lowering of the Earth's surface owing to subsurface movement of earth materials). L land subsidence and rising water levels combine to cause relative SLR. Subsidence can be caused by ground water withdrawals, underground mining, drainage of organic soils, and natural compaction (Galloway et al., 1999). Therefore, given the same rate of mean SLR, an area with higher subsidence will experience a higher relative sea level rise than an area with lower subsidence.

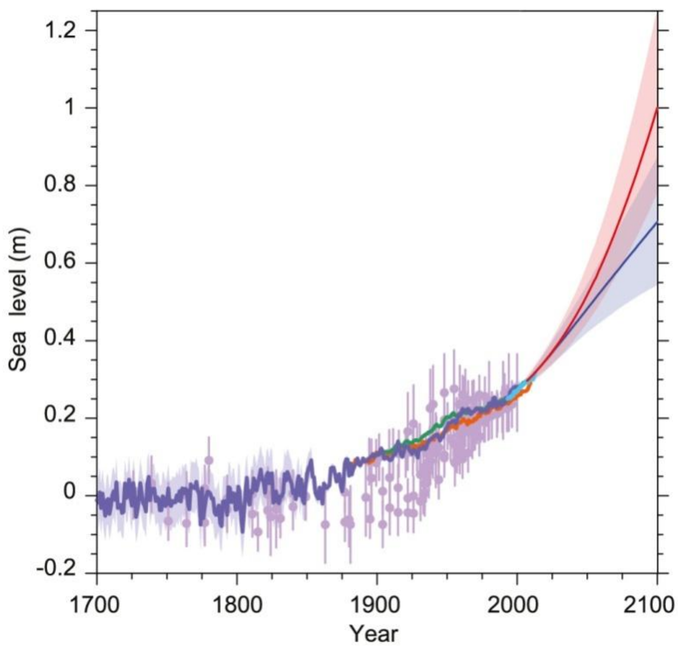
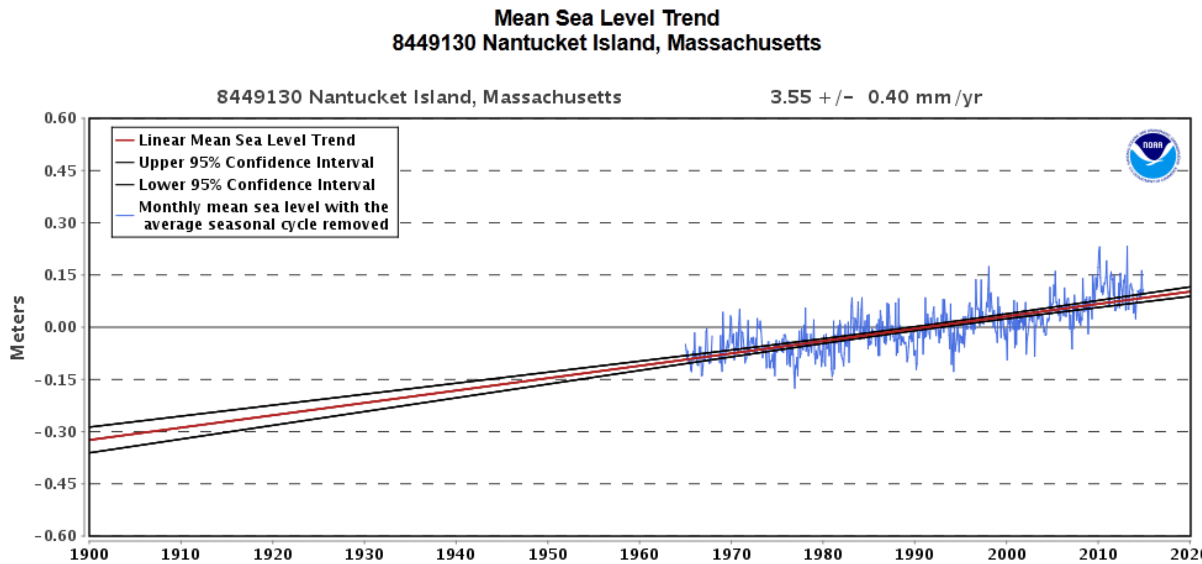


Figure 2.2. Sea level rise projections in IPCC AR5 WG1

(*From Figure 13.27: Compilation of paleo sea level data, tide gauge data, and central estimates and likely ranges for projections of global-mean sea level rise for PCP2.6 (blue) and RCP8.5 (red) scenarios, all relative to pre-industrial values*.)



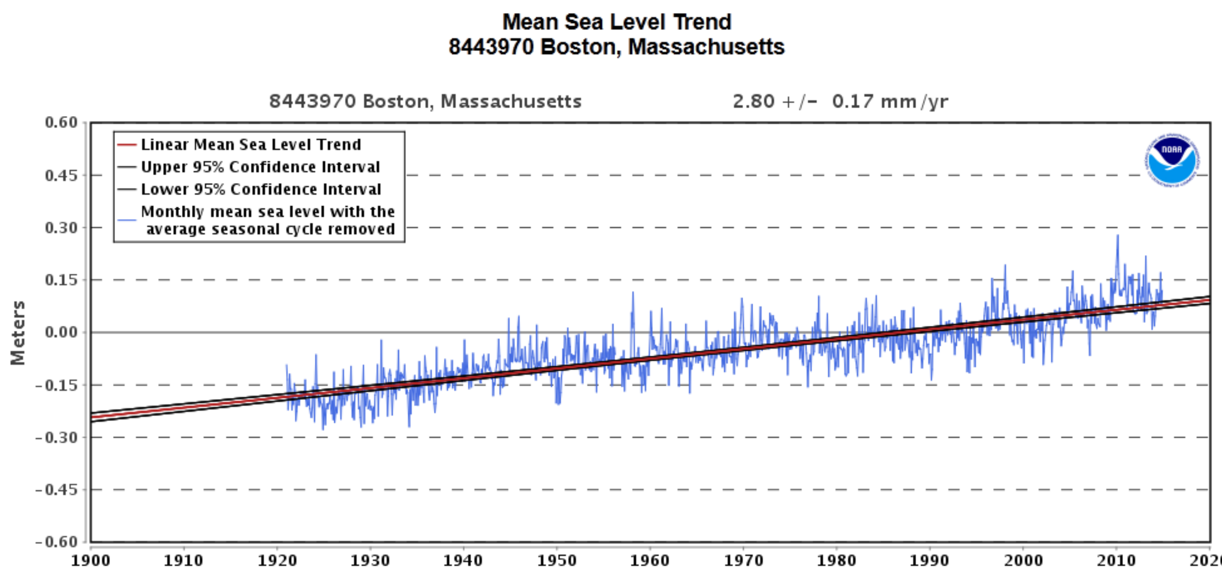


Figure 2.3. Comparison of mean sea level rise trend at different locations in Massachusetts (NOAA, 2013)

2.2 Storm Frequency and Intensity

While rising sea levels will increase water depths along the coastline, which will in turn result in the greater potential for wave and surge propagation further inland, there may also be increased intensity and frequency of large coastal storm events that are induced by the changing climate. Essentially, the heating of the ocean may also be increasing the probability and intensity of storm events.

<u>Tropical Cyclone (Hurricane) Intensity.</u>

The formation of tropical cyclones is not fully understood; however, there are typically a number of factors that are required to make tropical cyclone formation possible including:

- Water temperatures of at least 26.5°C (80°F) down to a depth of at least 50 m (150 feet).
- An atmosphere that cools fast enough with height such that it is potentially unstable to moist convection. In other words, rising water vapor from the warm ocean cools as it rises and condenses into liquid (i.e., forms clouds). This condensation also creates additional heat that continues to warms the atmosphere and air creating more wind.
- High humidity, especially in the lower-to-mid troposphere.
- Low values (less than about 37 km/hr or 23 mph) of vertical wind shear (the change in wind speed with height) between the surface and the upper troposphere. When wind shear is high, the convection in a cyclone or disturbance will be disrupted, blowing the system apart.
- Generally, a minimum distance of at least 480 km (300 mi) from the equator.
- A pre-existing system of disturbed weather.

If some or all of these factors are being modified by changes in the climate, then it is reasonable to anticipate that hurricane intensity and/or frequency will also change. Figure 2.4 shows an increased trend in the annual number of tropical cyclones in the North Atlantic, beginning in 1870. Increases in key measures of Atlantic hurricane activity over recent decades are believed to reflect, in large part, contemporaneous increases in tropical Atlantic warmth (e.g., Emanuel 2005). Figure 2.5 shows a comparison between the annual tropical storm count and average ocean surface temperature between August and October. There is a clear relationship between the increased frequency of tropical cyclones and the ocean temperature. Similarly, the intensity of tropical cyclones has also been on the rise in concert with ocean temperature. The Power Dissipation Index (PDI) is a way to calculate the intensity of a hurricane. The PDI is a measure of the total amount of wind energy produced by hurricanes over their lifetimes, and sums the cubed maximum wind velocities at each instant over the life of the storm. Figure 2.6 shows the post-1970 PDI, compared to ocean temperature in the Atlantic, and indicates that the intensities of the hurricanes in the Atlantic are also increasing.

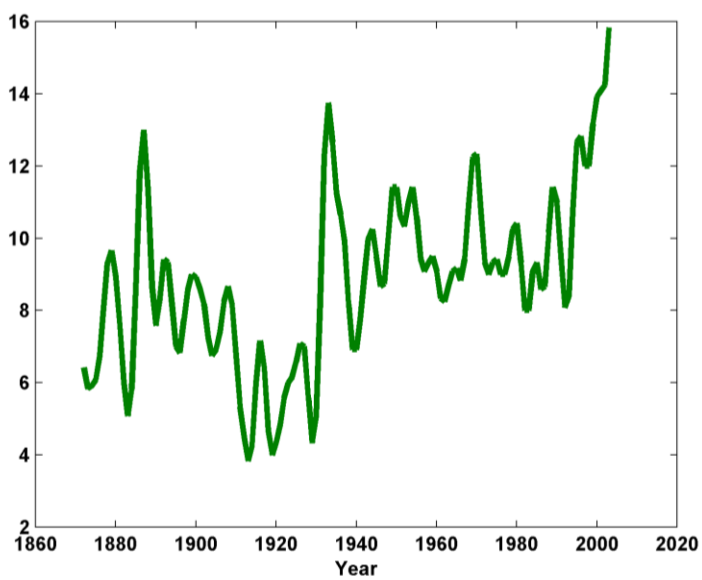


Figure 2.4. Annual number of tropical cyclones (including hurricanes and tropical storms) in the North Atlantic, beginning in 1870 (Emanuel, 2005)

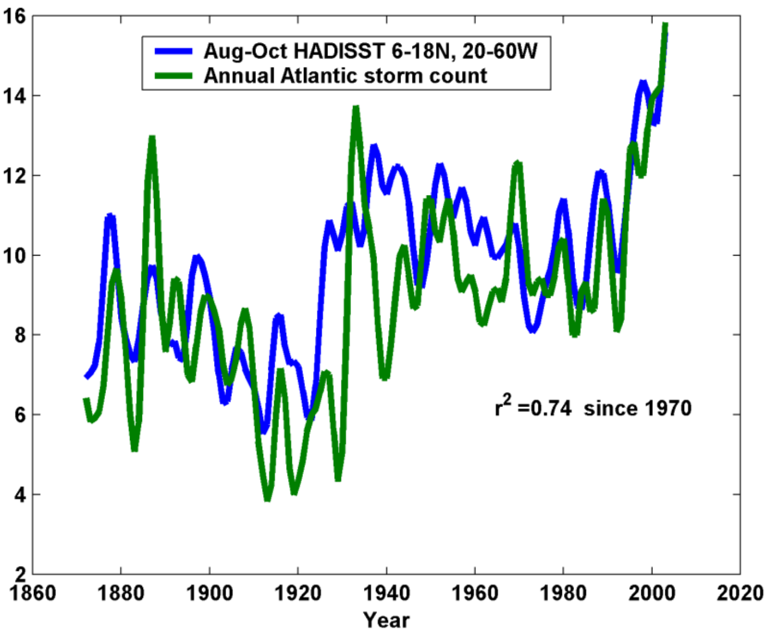


Figure 2.5. Annual number of tropical cyclones (green) compared to average ocean surface temperature (blue) during August to October (Emanuel, 2005)

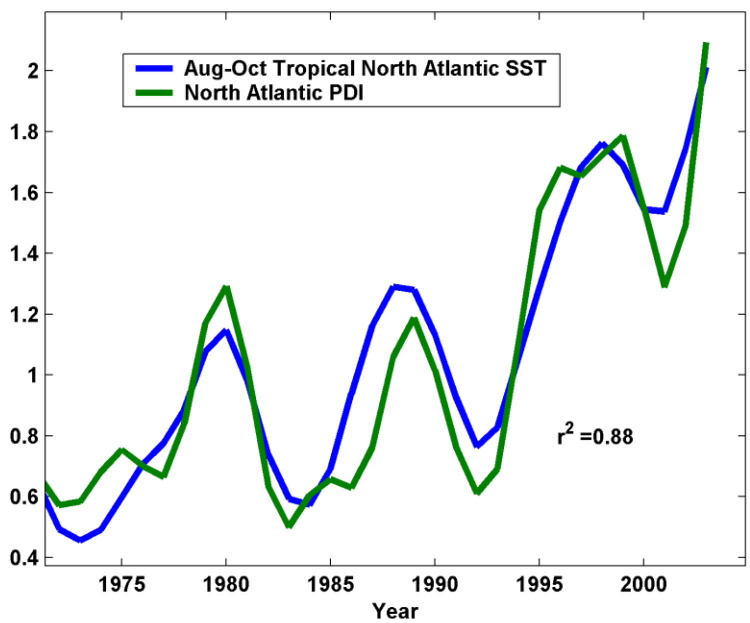


Figure 2.6. Post-1970 PDI (green), compared to ocean temperature (blue) in the Atlantic (Emanuel, 2005)

While global frequency of events has remained relatively constant, the intensity, duration, and the frequency of tropical cyclones in the Atlantic (11% of the total global hurricanes) is increasing, indicating a concurrent shift in hurricane activity with ocean temperature (Emanuel, 2005). This is also reflected in numerous Global Climate Models that are used to represent the current and projected climate (MassDOT, 2015).

Extra-tropical Cyclone (nor'easter) Intensity

Extra-tropical cyclones derive their energy from unstable pressure systems in the atmosphere. These conditions arise from temperature differences between warm and cold air masses (NOAA, 2014). The most intense extra-tropical storms occur in the winter because the temperature contrast between warm and cold air masses is at its greatest in the cold months. Generally speaking, a warmer global climate would serve to reduce the temperature difference between warm and cold air masses in the winter and potentially reduce the number of extra-tropical cyclones.

Bengtsson et al. (2006) concluded that climate change will not lead to an increase in intensity of extra-tropical storms based on a comprehensive modeling study of likely future climates. They also concluded that the storm tracks of extra-tropical cyclones are likely to move pole-ward. This means that under climate change conditions, extra-tropical cyclones are more likely to form further north than they do under current conditions. The findings of Bengtsson et al. (2006) are consistent with other studies as well. For example, Catto et al. (2011) determined North Atlantic storm tracks are influenced by the slowdown of the Atlantic meridional overturning circulation (MOC), enhanced surface polar warming, and enhanced upper tropical-troposphere warming, giving a northeastward shift of the extra-tropical storm tracks, while intensities decreased.

Additionally, historical water level data were collected from the tide gauge station 8443970 in Boston, MA (NOAA, 2014). In order to evaluate the relationship between storm surge and extra-tropical cyclones for Boston, historical water level and meteorological records were compared. As a preliminary, first order analysis, the events were used to develop a cumulative distribution function (CDF) of storm surge events for Boston based on the residual water levels (excluding tides) for all total events, as well as for those events that occurred after September 1, 1957. Residual water levels refer to the component of the water level that is comprised of non-tidal processes (e.g., winds forcing, storm surge, etc.). As such, the residual water levels represent the total water surface elevation remaining after removing the deterministic tides. The two temporal time periods were evaluated to see if there was any noticeable increase in frequency (number) or intensity (surge level) of events.

Figure 2.7 presents the CDFs, with the black line representing the CDF for all storm surge events, and the orange broken line representing the CDF for storm surge events occurring after September 1, 1957. The vertical axis in Figure 2.7 presents the residual water level (in feet), while the horizontal axis presents the probability of exceedance. The probability of exceedance represents the percentage of residual water levels that exceed a given value. In other words, a 2 foot residual water level (above normal tides) occurs for less than 40% of the events. There is little variation in the storm surge residual indicating no observable difference in increased storm surge (intensity) from extra-tropical storms. If there was an increased frequency or magnitude of storm events post 1957, the orange line would show an increased probability for higher residual values. Although this represents a relatively small sample size, this provides some additional data to support the existing literature related to extra-tropical storm changes.

As such, based on both literature review and examination of the historical extra-tropical cyclones impacting Massachusetts, the extra-tropical storm intensity in the 21st century is not likely to be statistically different than storm intensity for the 20th century.

2.3 Annual Precipitation

Annual precipitation in the northeast United States, in coastal Massachusetts in particular, is expected to increase as a result of climate change. Annual precipitation in MA for the period 1961-1990 is 41 inches, with 8 inches occurring in winter and 11 inches occurring in summer (Hayhoe et al, 2006). A trend analysis of the annual average precipitation across New England suggests that annual precipitation in New England increased by about 9.5 to 10 mm/decade in the 20th century, for a total of about 4.5 inches (Huntington et al., 2009). The MA Climate Change Adaptation Report (2011) draws on projections in Hayhoe et al (2006), which show an increase in annual precipitation of 5-8% for the period 2035-2064, and 7-14% for the period 2070-2099. While the MA Climate Change Adaptation Report uses the mean dates to represent these periods, this report focuses on the earlier years in each projected time period, 2035 (20 year planning horizon) and 2070 (slightly longer than the 50 year planning horizon) in order to align with available sea level rise model results used by the project consultants. The majority of the increase in annual precipitation is projected to occur in winter (6-16% by 2035-2064 and 12-30% by 2070-2099), with a slight decrease in summer (Hayhoe et al, 2006).

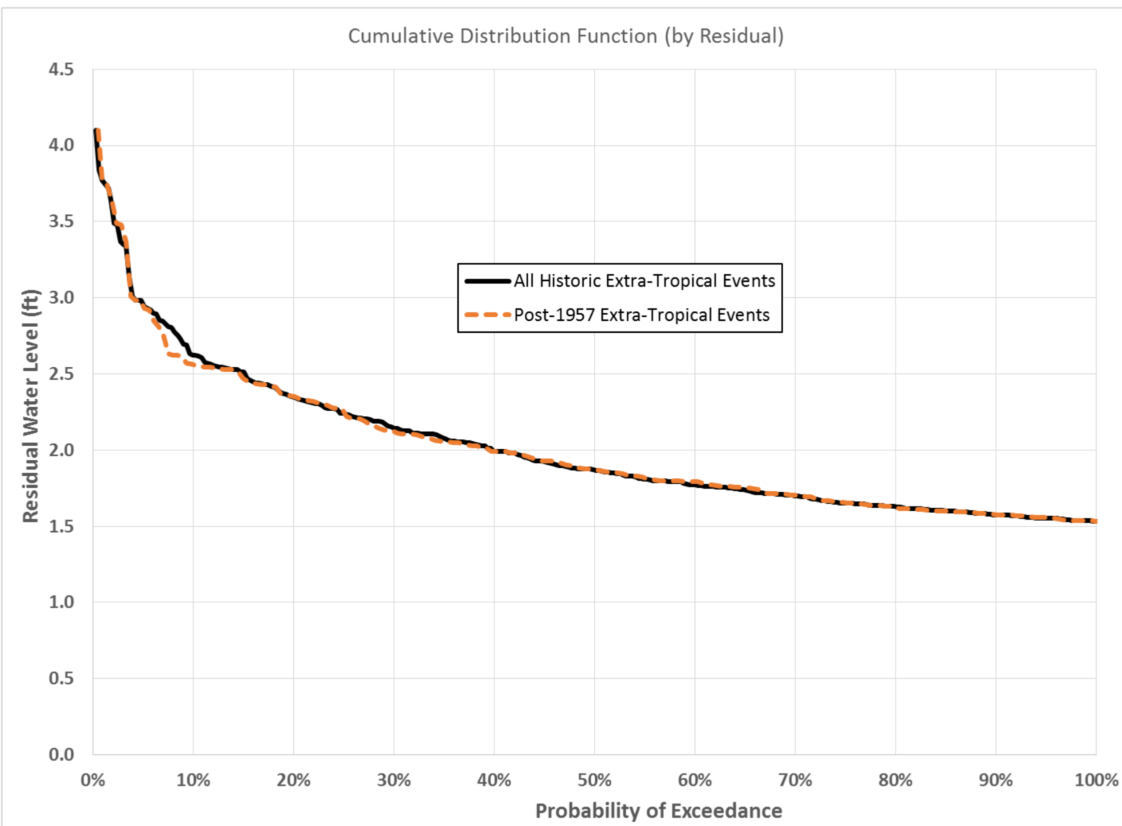


Figure 2.7. Extra-tropical storm surge CDF based on residual high water levels at Boston

2.4 Precipitation Extremes (Design Storm Event Precipitation Depths)

Until very recently, BMPs regulated by the state of Massachusetts or a local MA municipality to conform to the Massachusetts Stormwater Handbook (MassDEP, 2008) were designed using the TP-40 (Hershfield, 1961) precipitation extremes data for the 24-hour storm at different return intervals (2-year, 10-year, 100 year, etc.). These estimates are based on a small and outdated data set that extends over only an average of 40 years, with the most recent data ending in 1958. The Northeast Regional Climate Center at Cornell University maintains an online database that provides analyses of the calculated precipitation extremes for the Northeast and New York (http://precip.eas.cornell.edu/) using updated data extending through 2008 (NRCC and NRCS, 2010-2015). These data are generally accepted as the best resource for understanding precipitation extremes in Massachusetts, as reflected in the MA Stormwater Handbook and the MA Climate Change Adaptation Report. The values for Boston are presented in Table 2.1 above.

Projections of precipitation extremes as a result of climate change are not yet readily available in the published climate change literature. A recent paper assessing the latest understanding of the ability of the 26 models in the CMIP5 project (Phase 5 of the Coupled Model Intercomparison Project) of the World Climate Research Programme (Wuebbles et al., 2014) presented projections for some precipitation extremes across the United States, although not the typical 24-hour design storms used in sizing stormwater practices. However, the assessment of the CMIP5 models shows that the models still differ significantly from one another in modeling extreme precipitation events.

Consistent with this observation, The New Hampshire Coastal Risks and Hazards Commission recently (July 18, 2014) adopted the following understanding and recommendation for infrastructure design with regard to expected changes in extreme precipitation events:

> *"Extreme precipitation events are projected to increase in frequency and amount of precipitation produced; however, we are unable at present to confidently quantify exact future changes in extreme precipitation events. We do, however, recommend at a minimum that all related infrastructure be designed with storm intensities based on the current Northeast Regional Climate Center (Cornell) atlas to represent current precipitation conditions and infrastructure should be designed to manage a 15 % increase in extreme precipitation events after 2050 and that a review of these projections be continued." (Science and Technical Advisory Panel, New Hampshire Coastal Risks and Hazards Commission, August 11, 2014).*

In addition, projections of 24-hour precipitation extremes in 2035, 2060 and 2100 have recently been developed by CH2M Hill Engineers, Inc. for the Boston Water and Sewer Commission (BWSC) as part of their climate adaptation planning effort (CH2M Hill, 2014, DRAFT). The final document, *Wastewater and Storm Drainage System Facilities Plan for the Boston Water and Sewer Commission*, is expected to be completed in the summer of 2015; HW was provided with a draft of the Climate Change Section of the report by BWSC (per com. John Sullivan) for use in this project. BWSC noted that no significant changes were expected to this section in the final editing of the document. The final report should be reviewed when it becomes available from BWSC to confirm the preliminary assessment. The draft report evaluates design storm events in Boston for two emissions scenarios representing medium and high emissions at the target years of 2035, 2060 and 2100. By 2035, “rainfall depths are projected to increase by 5 to 10 percent for return periods from 2 to 100 years.” By 2060, the medium emissions scenario represents “an increase of approximately 10 to 15 percent for all return periods” and the high emissions scenario represents “an increase of 14 to 19 percent for return periods from 2 to 100 years.” These forecasted data are presented in Figure 2.8, excerpted from the BWSC draft report.

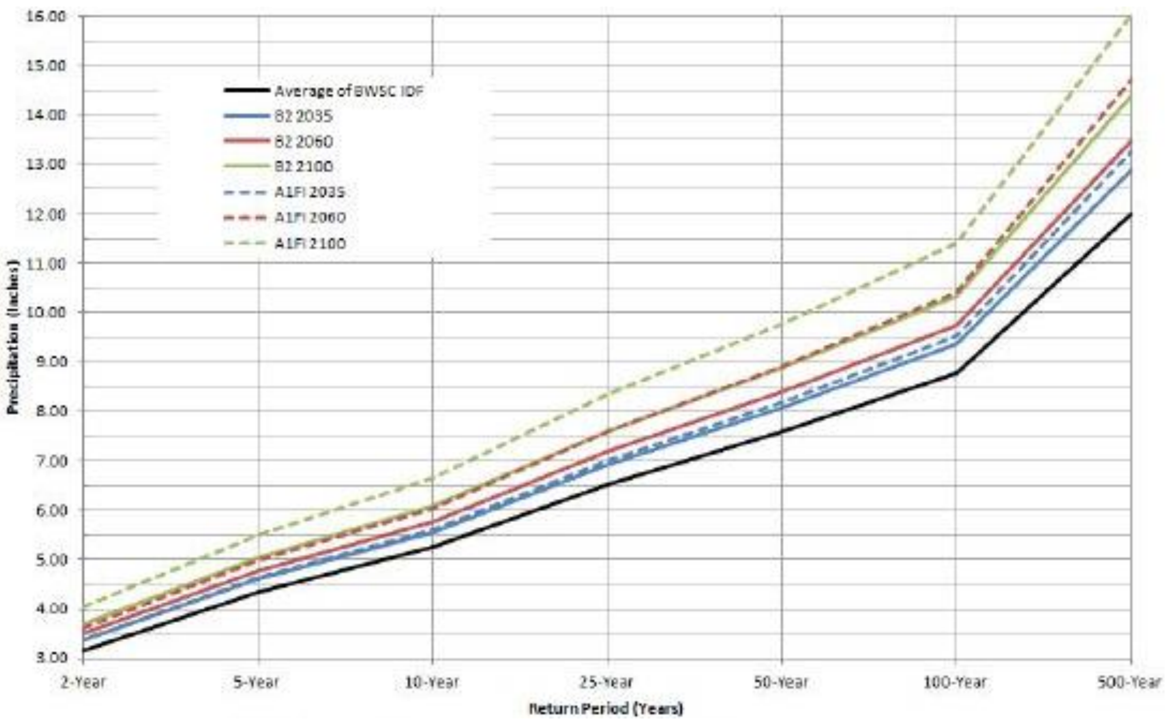


Figure 2.8. Observed and Forecasted 24-hour Rainfall for Medium (B2) and Precautionary (A1F1) Scenarios for 2035, 2060 and 2100 with Return Periods of 2 to 500 Years

2.5 Coastal-Influenced Groundwater Elevation

As sea level rises, the elevation of groundwater in the vicinity of the coast that is directly influenced by coastal water can be expected to rise as well. The timing and extent of this rise is influenced by the underlying geology and aquifer structure of the specific location. In general, groundwater will rise because the ocean represents the outlet boundary condition for all groundwater movement; and if that boundary rises, then all groundwater up-gradient must also rise (Figure 2.9). The actual rise in groundwater is site-specific, but it is expected to range from near zero to the maximum eleveation fo sea level rise at the ocean edge. Areas near hydraulically-connected streams or ponds will be less affected because the increase in groundwater rise will be offset by additional groundwater discharge into streams and more streamflow out to the ocean. Areas far from these drainage features or near the coastline will see the groundwater levels rise by the maximum SLR amount (Masterson and Garabedian, 2007; Horsley Witten Group, 2013).

In barrier island systems with a thin vadose zone [unsaturated portion of the underlying groundwater system], "increases of as little as 20 cm in sea-level position can have substantial effects on the groundwater system and the ecosystems affected by changes in vadose zone thickness" (Masterson et al., 2014) (Figure 2.10). As presented in the schematic in Figure 2.10, the increase in sea level results in changes in both the vertical and horizontal extent of the groundwater aquifer. Sea-level rise can affect groundwater flow in barrier island aquifers by decreasing the vadose zone (shown in brown) and the freshwater lens thickness (shown in blue) as the water table rises in response to increases in sea level from current (A.) to future conditions (B.). These hydrologic responses are key determinants in the establishment, distribution and succession of vegetation assemblages and habitat suitability in barrier island systems.

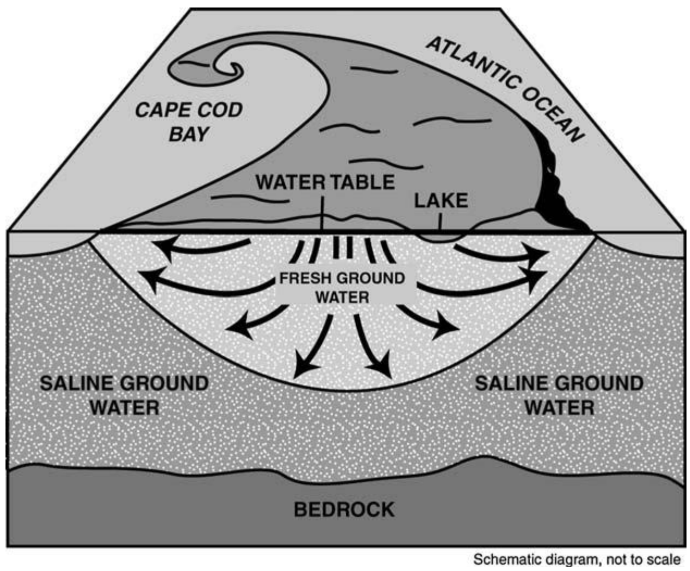


Figure 2.9. Schematic diagram of the Lower Cape Cod Aquifer system, MA (from Masterson & Garabedian, 2007)

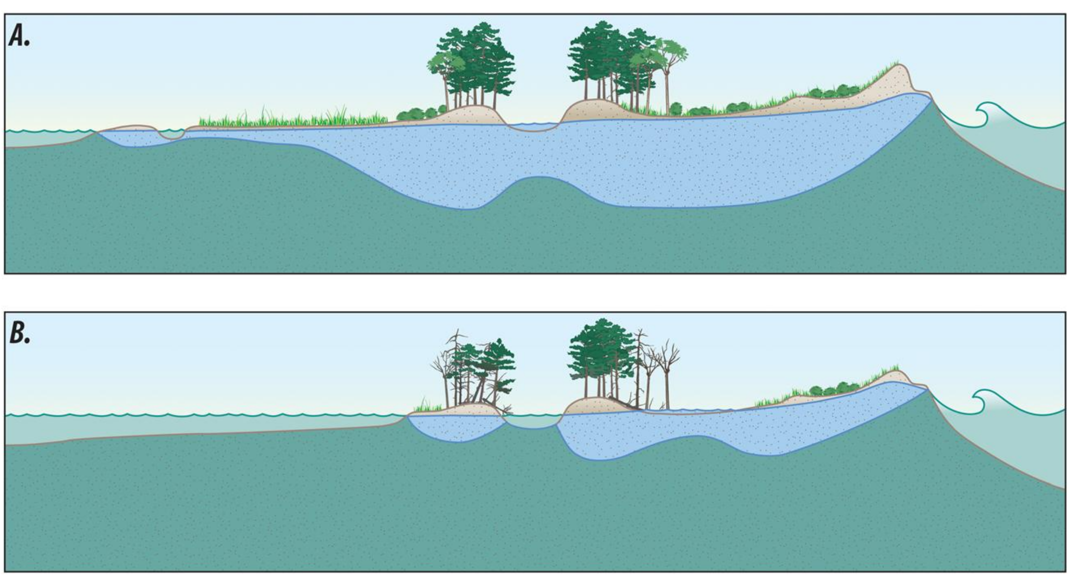


Figure 2.10. Sea-level rise affects on groundwater flow in barrier island aquifers (from Masterson et al., 2014)

3.0 Field Assessments

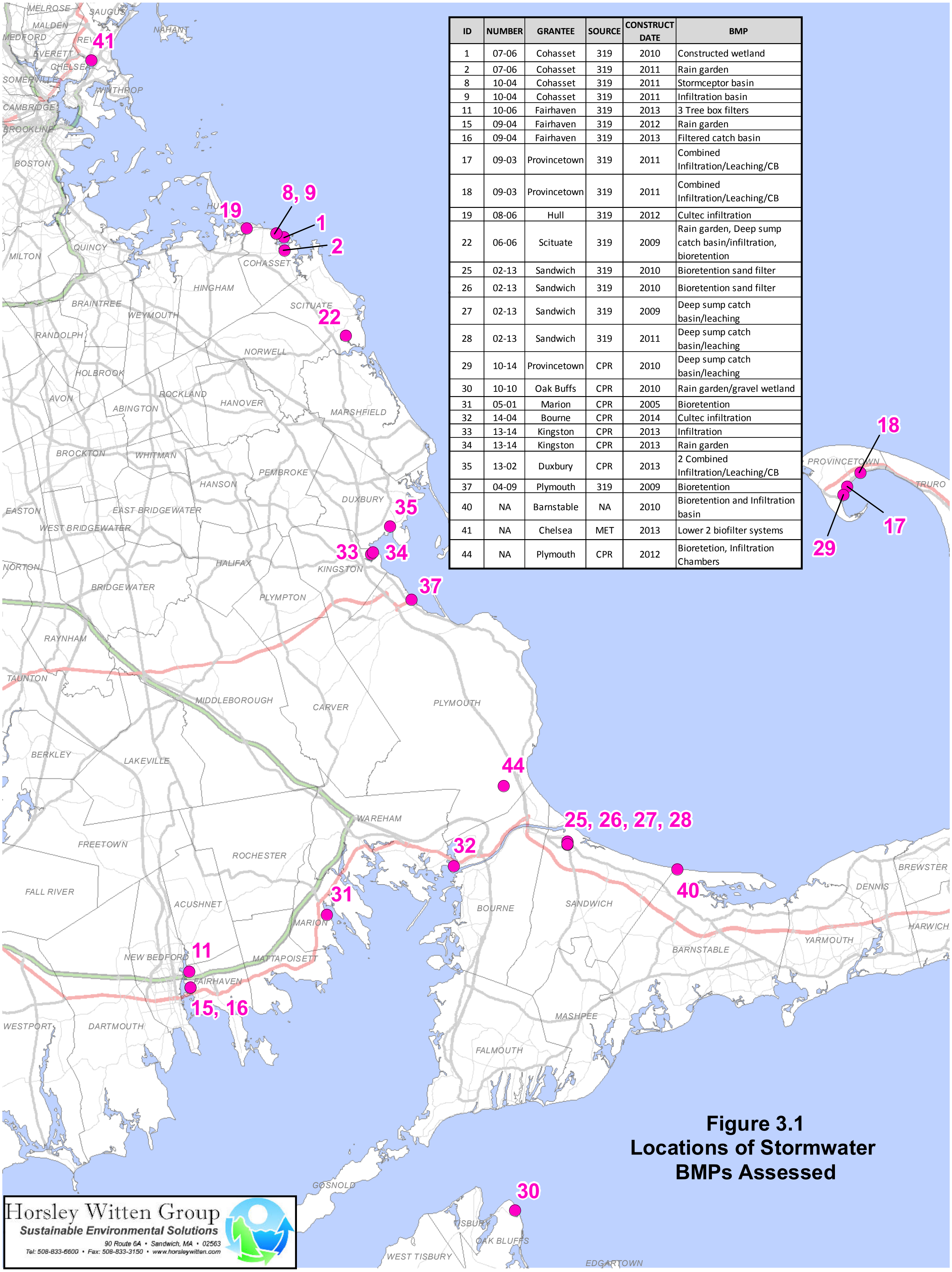
HW worked with MA CZM and MassDEP project partners to develop a list of 26 existing BMPs that would be suitable for field evaluation to assess performance and potential risk as a result of climate change. The list, shown in Figure 3.1, included BMPs that have been installed in Massachusetts coastal areas that have been funded by MA CZM's Coastal Pollutant Remediation Program and DEP's Clean Water Act Section 319 Grant Program. The sites represent a range of site and design constraints (e.g., soils, depth to groundwater, contributing area, available space, etc.) and design purposes (e.g., water quality, peak flow attenuation, infiltration).

3.1 Methods

Prior to conducting field investigations, HW reviewed available design plans, specifications, and stormwater sizing and pollutant removal calculations, where available. The data was summarized, imported into GIS, and uploaded to iPads for use in verifying design information in the field. In addition, pre-defined entry forms were developed to collect observations, measurements and photos to document the BMP condition, functionality and maintenance. HW visited the 26 sites with five sets of teams during May and June 2015. Staff from MA CZM, WHG, and Massachusetts Bays National Estuary Program joined HW to observe several sites. Data collected on the iPads were then exported to site summary forms (Appendix A).

In addition, HW reviewed the sea level rise and storm surge risk projections developed by WHG for each of the sites. The projections are presented in Appendix B in tabular and map format. WHG evaluated the flood risk at each of the sites based on the site elevation as estimated from LIDAR information available through MassGIS. The projections were based on model results WHG had developed for prior projects (Bosma et al., 2015). No new models were developed or run for this work. The models available for each location varied in resolution and these are described in Appendix Table B-1 by Class Codes and associated footnotes.

Overall, the data indicate that flooding and/or storm surge due to climate change are likely to impact a majority of the sites by 2030. The impacts vary between sites; for example, sites in Sandwich (Site IDs 25, 26, 27, and 28) are mostly dry even in 2070, whereas sites in Fairhaven (Site IDs 15 and 16) are already experiencing a 100% risk of flooding (annual storm inundation) and are projected to have a 6-inch increase in flood depth during the 1% risk of flooding (100-year flood event) in 2030. By 2070, the flood depth during a 100-year flood event is expected to increase more than 2 feet above current conditions at these Fairhaven locations.



ID	NUMBER	GRANTEE	SOURCE	CONSTRUCT DATE	BMP
1	07-06	Cohasset	319	2010	Constructed wetland
2	07-06	Cohasset	319	2011	Rain garden
8	10-04	Cohasset	319	2011	Stormceptor basin
9	10-04	Cohasset	319	2011	Infiltration basin
11	10-06	Fairhaven	319	2013	3 Tree box filters
15	09-04	Fairhaven	319	2012	Rain garden
16	09-04	Fairhaven	319	2013	Filtered catch basin
17	09-03	Provincetown	319	2011	Combined Infiltration/Leaching/CB
18	09-03	Provincetown	319	2011	Combined Infiltration/Leaching/CB
19	08-06	Hull	319	2012	Cultec infiltration
22	06-06	Scituate	319	2009	Rain garden, Deep sump catch basin/infiltration, bioretention
25	02-13	Sandwich	319	2010	Bioretention sand filter
26	02-13	Sandwich	319	2010	Bioretention sand filter
27	02-13	Sandwich	319	2009	Deep sump catch basin/leaching
28	02-13	Sandwich	319	2011	Deep sump catch basin/leaching
29	10-14	Provincetown	CPR	2010	Deep sump catch basin/leaching
30	10-10	Oak Buffs	CPR	2010	Rain garden/gravel wetland
31	05-01	Marion	CPR	2005	Bioretention
32	14-04	Bourne	CPR	2014	Cultec infiltration
33	13-14	Kingston	CPR	2013	Infiltration
34	13-14	Kingston	CPR	2013	Rain garden
35	13-02	Duxbury	CPR	2013	2 Combined Infiltration/Leaching/CB
37	04-09	Plymouth	319	2009	Bioretention
40	NA	Barnstable	NA	2010	Bioretention and Infiltration basin
41	NA	Chelsea	MET	2013	Lower 2 biofilter systems
44	NA	Plymouth	CPR	2012	Bioretetion, Infiltration Chambers

Figure 3.1
Locations of Stormwater BMPs Assessed

3.2 Observations

The following observations were made after BMP field investigations:

A. **Evaluation of climate change impacts during the design phase could help designers to understand how BMPs may perform in the long-term**. Overall, the majority of BMPs appear to be functioning and are in fair to good condition. However, there are some BMPs , such as Sites 1, 8/9, 27, 30, and 31, that appear to be impacted by coastal area influences, such as tidal cycles, coastal sands, and encroachment from invasive plants. Comparing design data to existing conditions, it seems that climate-adapted designs may be more relevant in some areas than others based on the changes already observed at those sites. Evaluations of expected site conditions and constraints over the life expectancy of a practice in conjunction with anticipated climate changes may be helpful in predicting susceptibility to coastal impacts, changes in performance, and modification requirements for design and O&M.

B. **End-of-pipe BMPs are more susceptible to coastal impacts than up-gradient BMPs.** Most BMPs were located at end-of-pipe locations, at or near the outfall of existing drainage infrastructure. These locations are the most vulnerable primarily because they sit in low spots susceptible to localized flooding; have tidally-influenced drain outlets; and are subject to tidally-influenced outlets, increased groundwater elevations, sea level rise, and storm surge. Several end-of-pipe BMPs (e.g., Sites 2, 16, and 34) exhibited signs of impact such as invasive species growth, partial submergence of the BMPs, and deterioration of infrastructure as a result of local flooding. Analysis of contributing drainage areas indicates that some BMPs possibly could have been sited in up-gradient areas, which would have lessened the impacts.

C. **BMP selection should consider the potential long-term consequences of coastal vulnerabilities, such as rising groundwater elevations and tidally-influenced backwater.** Many of the BMPs evaluated were intended as underground storage and/or infiltration practices. HW observed that groundwater levels and/or backflow may already be limiting infiltration and/or storage capacity. Constructed wetlands, wet swales or subsurface detention are examples of practices that could be more advantageous in these situations. Vegetation should be selected from species that can tolerate increasingly saline conditions.

D. **BMP sizing should be conservative to account for reduced efficiency and increased volumes over time.** As noted above, HW observed that several BMPs already may be partially or completely impacted by groundwater levels and/or backflow, or will likely be impacted in the near future. For example, observations of water elevations at the outfall and at inlet structures at Site 25 indicated that groundwater may be limiting storage capacity. It is not clear from design plans whether the BMP design accounted for groundwater impacts. For this site and others, BMP sizing should incorporate existing or potential reductions in capacity as a result of groundwater.

E. **BMPs may benefit from redundancy in design features to address climate change impacts.** At many of the sites, the pretreatment practice appeared to be failing as a result of sediment from the drainage area and/or coastal sand sources. For example, at Site 2, the catch basin upstream of the practice and the forebay were both clogged with sediment, which appear to limit stormwater runoff from entering the gravel wetland. Similarly, the trench drain at Site 34 was mostly full of sediment, which appears to result in ponding during rain events and runoff draining to the stone apron overflow instead of entering the rain gardens. If clogging and/or ponding are perpetual problems, even with regular maintenance, redundant design features such as multiple inlets or pretreatment cells may extend the functionality and/or design life of a BMP that may otherwise fail.

F. **Long-term BMP performance may be improved by adding flexibility into the design.** As noted above, many of the sites appear to be in locations where they will likely be vulnerable to climate change. To help BMPs continue to function under these changing conditions, the BMP design should incorporate structures, plants, or materials that are adaptable. For example, at Site 1, the forebay area could be better protected from windblown sand and salt by using salt tolerant vegetation to block the forebay. This vegetation can evolve with changing conditions, by either building up a small berm or converting to other more salt and sand tolerant species over time. Similarly, sites at end-of-pipe locations, such as Site 41, may benefit from a modified outlet or tide gate to help negate groundwater or tidal influences on BMP performance.

G. **Implementation of operation and maintenance plans are essential to ensuring long-term performance.** For the BMPs that were aboveground, about half of the sites required some level of maintenance, ranging from weeding, to sediment removal, to structural repairs. For subsurface BMPs, it was not clear if maintenance needs were being met. As climate change begins to impact these BMPs, more frequent maintenance will be necessary to ensure that the BMP will perform as expected. Locations more vulnerable to coastal impacts may be better able to reduce maintenance burden by incorporating design features and developing maintenance schedules that specifically address anticipated vulnerabilities. For example, locations close to a coastal sand source may benefit from a planted buffer to protect the practice against windblown sands and to limit travel of overwashed sands.

   Municipalities can help to further reduce maintenance needs by implementing targeted non-structural practices, such as street sweeping following significant overwash events. These considerations could help to better manage the long-term operation of the practices.

4.0 Vulnerabilities and Recommended Design Modifications

4.1 BMP Vulnerabilities

Based upon the climate change impacts described in Section 2 and the site assessment observations in Section 3, four categories of vulnerability have been identified for stormwater management practices installed in the coastal zone including: submerged outfalls; reduced separation to groundwater distance; storm surge inundation; and chronic exposure to the elements. Below is a discussion of each of these vulnerabilities.

Rising sea level and submerged outfalls

As sea levels rise, the geographic area subject to tidal influence will also expand. Inland tidal encroachment can influence the function of stormwater BMPs located in or discharging to tidal waters. For example, an outfall pipe may be submerged for longer portions of the tidal cycle, thereby reducing the hydraulic head in the stormwater practice and the ability of the practice to continuously move water through the system as designed. Restrictions on discharge at submerged outlet structures can result in system backups, increased ponding frequency and duration, reduced capacity to handle new storm events, and increased potential for overtopping. This could lead to extended inundation periods for non-emergent vegetation, short-circuiting of the BMP treatment mechanisms, or potential erosion problems on embankments and spillways.

Rising groundwater and shrinking separation distances

As sea level rises, seasonal high groundwater in the Massachusetts coastal region will rise. The MA Stormwater Handbook (MassDEP, 2008) requires a two foot separation distance between the bottom of an infiltration practices and seasonal high groundwater. This separation ensures that there is adequate distance to infiltrate and to remove pollutants prior to contact with groundwater. This protection will be compromised as the separation distance decreases. In extreme cases, inundation of subsurface underdrains may cause the practice to become saturated for extended periods of time. This can cause the same hydraulic head deficiency, described in the previous section, that occurs as a result of rising sea level. The storage capacity of subsurface chambers and surface detention facilities can be reduced as groundwater intercepts these practices at higher elevations. Salt water intrusion below wet detention basins and stormwater wetlands may shift vegetative communities (e.g., fewer cattails and more brackish-loving plants).

In addition, practices located within the expanded tidal influence can experience salt water impacts to the vegetation as a result of tidal overwash as well as salt water intrusion in the groundwater. This can harm the practice by introducing salt water into a vegetated environment that may not be suited to salt water. It can also fill the practice with water, reducing the capacity of the practice to capture and detain stormwater.

Physical impact of storm surge inundation

Sea level rise and increased storm intensity will result in increased storm surge elevation, which may result in BMPs being subject to more frequent and longer duration flooding along with greater wave action. Inundation of the BMP from a surge of sea water during a storm event can cause a variety of problems, depending on the type of practice. The force of waves associated with a storm surge can cause physical damage to a coastal BMP, as well as transport suspended sediments and debris that are then deposited into the practice. These materials can lead to clogging over time or in a matter of one or two catastrophic events. In particular, pretreatment forebays or chambers can become filled and subsequently bypassed by the surging water. This requires increased attention to maintenance and repair. When the practice becomes clogged, the stormwater backs up and causes ponding and then erosion as the water tries to find an alternative outlet. Inundation by sea water can also introduce excessive salt to the BMP, which can be harmful to vegetation and may contribute to structural deterioration of concrete or metal infrastructure. BMPs subject to storm surges will require significantly more repair and maintenance than a BMP under normal conditions.

Chronic wind, sand and salt exposure

Coastal BMPs can be exposed to excessive winds, blowing sand, sand from coastal overwash, salt spray and salt water overwash even during non-storm events. Vulnerability to these elements will not likely diminish with predicted climate changes. Wind, sand and salt can all cause vegetation to die back in vegetated BMPs, causing structural clogging. Increased frequency of maintenance may be required to remove sediment regularly. Premature die off can cause an unplanned shift in the BMP plant palette towards a more tolerant set of species, which often includes invasive species. This type of shift is not necessarily harmful to the success of the practice, but may conflict with the approvals and expectations of owners, permit authorities and neighbors, who were promised a particular landscape type.

4.2 Design Recommendations

Based on these findings, a number of recommendations are provided below for planners, engineers, and funding agencies to improve the long-term effectiveness of a proposed stormwater improvement project. The recommended modifications include elements of planning, site selection, practice selection, engineering design, and ongoing operation and maintenance, all of which contribute to stormwater BMP resiliency.

A. Planning Horizon of 50 Years

Similar to non-coastal practices, coastal BMPs should be designed under the assumption that there will be a 50-year design life, which is consistent with the longevity of structural materials, such as concrete, high density polyethylene (HDPE), or steel. This planning horizon is clearly within the timeframe in which climate impacts will be observed. Designers and operators should assume that the practice will need to be well-maintained throughout the life of the practice and potentially updated/overhauled in 15-20 years to address changing conditions at the site and in the contributing areas.

B. Siting of Practices

BMPs sited closest to the shoreline are likely to be most at-risk from coastal climate change impacts. Because many of the stormwater retrofit projects funded by CZM and DEP grant programs address existing development and are limited to public lands, it is logical and perhaps more cost-effective to site a single retrofit where the most drainage area can be captured. Alternatively, two or three smaller practices combined with non-structural practices (e.g., impervious cover reduction) distributed throughout the drainage area could potentially achieve the same management objectives as a single practice, with less risk of being compromised by coastal climate change impacts. If BMPs are to be sited close to the shoreline due to other constraints, the following siting criteria should be considered:

- Look at the location of proposed practice in conjunction with flood projection maps (see Appendix B) to understand the implications of climate change within the 50-yr planning horizon and to weigh the benefit of any alternative site locations.
- Site practices away from the marsh edge, not adjacent to it, in order to avoid disturbance and limit the introduction of invasive species to the marsh.
- Try to avoid installing practices with significant storm pathway exposure and direct exposure to sand sources, if clogging is a concern.
- Avoid siting a practice near high groundwater if the practice cannot evolve to function with higher groundwater or groundwater intrusion into the system. Alternatively, if siting options are limited, select a different practice that is more suited to the evolving site conditions.

C. Selection of Practices

Select practices that are appropriate not only for existing site conditions, but also anticipated conditions within a 50-year time horizon. For example:

- Use infiltration practices in areas where infiltration is sustainable, but not in areas where depth to high groundwater will likely be compromised over time. Consider whether the required depth to groundwater can be sustained over the life of the practice, in light of expected SLR and associated groundwater rise.
- The selected practice should be able to adapt to the wetter conditions. Typically, this will drive the selection toward vegetated practices over grey infrastructure. A surface infiltration basin could convert over time to a wet basin as groundwater rises. A bioretention system can convert to a wetland over time as groundwater rises or as hydraulic head is reduced due to increased tidal influence at the outfall. However, an underground infiltration chamber may not be a good choice in this same location because it cannot convert over time, and will simply fail as groundwater rises. Likewise, a swirl separator unit designed to separate out sediments and other solids cannot readily adapt to SLR impacts. SLR can cause more frequent backups in the system, which would render the swirl separator system ineffective and unable to operate.

D. Selection of BMP Construction and Landscape Materials

The designer should select materials that are appropriate to existing and future site conditions. Choose appropriate salt-tolerant plant species. A site located within proximity to the ocean that is likely to experience chronic salt spray, increased inundation, and brackish groundwater intrusion should incorporate salt tolerant plant species in the planting design for the practice.

Choose materials that do not corrode from salt exposure. If you are designing a practice in an area that currently is (or is likely to) experience increased salt spray or salt water inundation, you should avoid using materials that corrode from salt exposure to the extent possible.

E. Redundancy in Design

The BMP design features should include an element of redundancy in treatment or storage capacity to overcome any negative impacts of climate change. As the site changes, these redundancy features will help to prolong the effective lifespan of the practice.

- *Redundancy for rising groundwater.* As groundwater rises, the infiltration capacity, for example, of a bioretention cell will decrease and the practice will likely begin to hold water for longer periods of time, essentially evolving into a wet pond or wetland system. Redundancy can be built in to such a system through oversizing and duplication. Making the initial footprint of the bioretention larger than needed under current conditions could help accommodate future scenarios without sacrificing performance. Incorporating parallel or multiple-celled BMPs, for example, could provide a backup measure to manage stormwater even if one of the cells is compromised.
- *Redundancy for increased storm surge.* In an area where increased storm surge is likely to wash larger volumes of beach sand into the contributing area to the BMP, a designer could incorporate redundancy by increasing the capacity of the sediment forebay to delay complete clogging and allow for a more manageable maintenance schedule.
- *Redundancy for increased rainfall.* This same approach may also be warranted for a BMP with an erodible contributing drainage area, where one can anticipate increased and more intense rainfall. If the contributing area is steep with highly erosive soils or is anticipated to experience significant level of development that might expose more soil, a larger sediment forebay could help reduce incidences of clogging.

F. Flexibility in Design

Stormwater management practices that are likely to experience changing conditions due to climate change should incorporate flexibility in the design to allow the practice to adapt to the new conditions. Flexibility can include the provision of extra space around the practice so that future modifications can be made to the practice, or it can be design modifications made upfront to anticipate future conditions. Examples of flexibility in design include:

- Many bioretention systems are designed with an underdrain system to help convey the infiltrated water to an outlet location. If the groundwater in that system is anticipated to increase in the 50 year lifespan of the practice due to influence from nearby coastal rising sea levels, a simple adjustment can be made to include an elbow joint in the underdrain. This can raise the effective inlet elevation above the anticipated future groundwater elevation. This provides the system the flexibility to continue functioning even with rising groundwater. Essentially, the system is designed to be flexible to function under both existing and future conditions.

- An infiltration basin installed in an area that is likely to have rising groundwater in the 30-50 year time frame can be designed to allow the practice to convert to an effective wet pond or wetland treatment system over time. This can be done by designating a reserve area adjacent to the infiltration basin that can be used to expand the surface area of the practice in the future in order to maintain the treatment capacity of the stormwater practice. It could also be done by designing the practice with a larger treatment capacity at the outset so that when some treatment volume is lost over time, the practice will continue to achieve the required performance.

G. Choosing Green over Grey

Choose green infrastructure over grey. Green infrastructure is more malleable than grey infrastructure, and by its very nature is more adaptable to changing conditions. Practices that are mostly vegetated with minimal underground structures ("green" infrastructure) are more likely to successfully adapt to future conditions than substantial, hard, underground structures ("grey" infrastructure). A large concrete structure cannot move or change its elevation to adapt to changes in environmental factors, such as rising groundwater, more frequent inundation, or a shifting shoreline. Instead it will struggle to stay in place despite possible groundwater and storm surge impacts, and has no mechanism to evolve and adapt. However, soils and vegetation are natural materials that create living treatment systems. In areas that are likely to experience increased storm surge or rising groundwater or sea level impacts, it is prudent to select vegetated practices. As site conditions change, the vegetation and soils can adapt to new conditions just as they have always done in nature. Vegetation communities will evolve to match the site conditions, converting to more wet species if conditions call for wet species, and incorporating salt tolerant species if more salt spray or salt water inundation is experienced. The ability of the vegetated green practice to evolve and provide a similar, or at least positive, level of stormwater treatment service depends on the redundancy and the flexibility in the design. Is there sufficient capacity and space for the practice to evolve? Grey infrastructure does not have this ability. In areas where site conditions such as groundwater elevation, frequency of storm surge, or sea level rise are expected to affect the practice itself within a 50 year design life, grey practices can be expected to fail sooner than green practices.

H. The Even Greater Importance of Maintenance

Maintenance for most BMPs is typically intermittent, but BMPs subject to climate change impacts can experience more frequent and severe problems and will require more attentive maintenance. Increased heavy rainfall can cause more frequent clogging of inlets, outlets and infiltration beds with debris. It can also cause more erosion in the contributing area, which creates more rapid concentration of sand and potential clogging in infiltration or other practices. As climate change impacts are experienced in the coastal zone, inspections and maintenance of stormwater practices will become more important and will require a greater financial investment than they currently warrant.

5.0 Conceptual Design Examples of the Recommended Modifications

This section provides examples of how stormwater BMPs, specifically coastal stormwater retrofit projects, can be better designed for climate change resiliency. HW worked with MA CZM to select the following to be field assessed from the existing list of BMPs:

- Site 1 (Atlantic Ave and Nichols Rd, Cohasset)
- Sites 8 & 9 (Jerusalem Rd and Atlantic Ave, Cohasset)
- Site 31 (Island Wharf Rd and Front St, Marion)
- Site 32 (Buttermilk Way, Bourne)
- Site 34 (Delano Ave and Grandview Ave, Kingston)

For each BMP, the HW team evaluated the anticipated climate change impacts that would affect function, and developed recommended design modifications to improve the ability of the BMP to adapt to potential climate vulnerabilities. The approach was to consider the initial design intent based on available information and site observations, and make recommendations regarding the site selection, practice selection, engineering design and maintenance decisions as though the project were being designed at the time it was undertaken. Engineering design information available for each of these sites varied in level of detail, supporting calculations and design narrative. Therefore, HW used best professional judgment to assess and understand the existing stormwater management design, design goals and design constraints. This may differ from the original designer's goals or understanding of the site.

The purpose of this exercise is solely to demonstrate how the recommendations described in Section 4 could be applied; there is no expectation that design modifications will be undertaken to retrofit the sites described here.

For each site, this report provides an overview of the stormwater practices' original design as understood from a review of available material; a functional assessment from the site visit; an assessment of the vulnerabilities of the practice in the face of climate change; and recommended design modifications to mitigate those vulnerabilities.

The reader should also refer to the completed site assessment forms in Appendix A and the flood elevation projections for each site in Appendix B.

Site 1 (Atlantic Ave and Nichols Rd, Cohasset)

Existing Condition

Site 1 is located at the intersection of Atlantic Ave. and Nichols Rd. near Sandy Beach in Cohasset, MA (See Figure 5.1). The existing stormwater management practice is a constructed wetland with subsurface infiltration chambers that is intended to treat stormwater runoff from a portion of Atlantic Ave. and Nichols Rd. that drain to a nearby catch basin. Pretreatment occurs through a small sediment forebay that receives flow through an up-gradient diversion manhole structure.

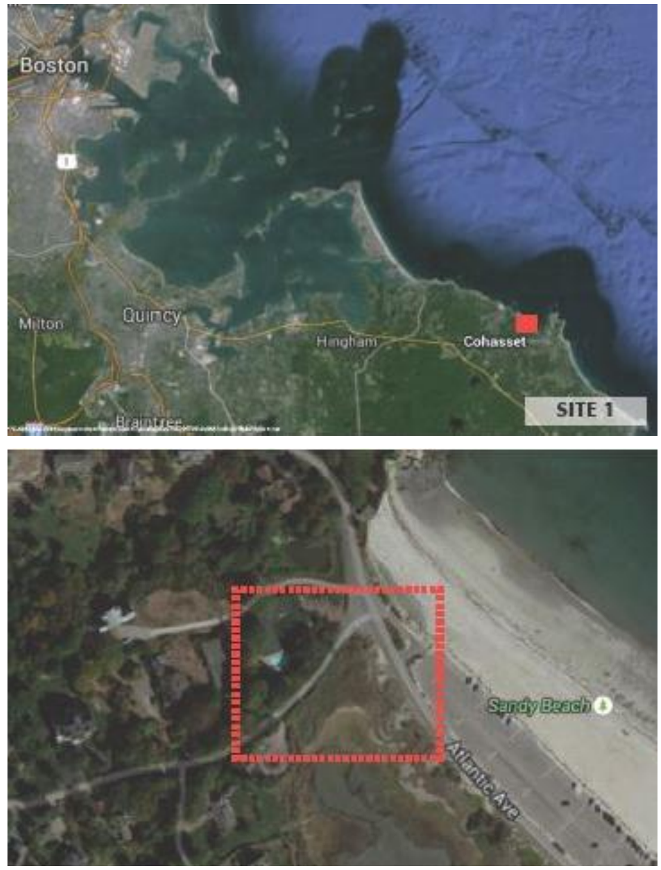


Figure 5.1. Site 1 Location Map

A review of the WHG flood elevation projections (Appendix B, Table B-1 and Figure 3.1) indicates that Site 1 already experiences a 20% risk of flooding. The flood risk is expected to rise to 50% by 2030 and 100% by 2070. This suggests that sea level rise and storm surge will have a substantial effect on the area and that groundwater can also reasonably be expected to rise at the site under the influence of sea level rise.

A site visit conducted in summer 2015 indicated that sand from Sandy Beach, as well as sediment and other debris had clogged the up-gradient catch basin and the inlet pipe to the forebay, which has led to ponding on the road. Figure 5.2 presents a photograph of the existing conditions at the site. Some damage to asphalt curbing and the adjacent retaining wall was also observed, which appears to be a result of erosive flows and ponding. In addition, P*hragmites* was observed over the extent of the constructed wetland as well as throughout the adjacent salt marsh.

Figure 5.2. Site 1 Existing Conditions Photo

Anticipated climate vulnerabilities and their potential impacts are summarized in Table 5.1.

Table 5.1. Anticipated Climate Change Vulnerabilities and Impacts at Site 1

Vulnerabilities from Climate Change	Potential Impacts
Wind, salt and sand impacts	Frequent clogging of the system and impact on vegetation species due to coastal overwash from Sandy Beach
High groundwater elevations	Increased groundwater influence due to close proximity to salt marsh and increased potential for *Phragmites* propagation
Reduced outfall capacity/treatment	Decreased capacity and treatment capability due to potential clogging from sand and debris as well as impacts from P*hragmites*

Climate-Ready Modification

Based on site observations, the recommended modifications to this site would first include addressing wind and other coastal overwash impacts by adding sand fences along Atlantic Avenue to protect the practice. To further reduce the potential clogging, an enhanced pretreatment chamber (such as a large tank or catch basin) would be added to capture greater volumes of sediment and debris, while also allowing for flows to enter the constructed wetland. This chamber would be added on the edge of Nichols Rd. Similar to the existing structure, a weir or an offset outlet would allow flows greater than the water quality volume to be discharged to the existing overflow outlet. Maintenance of both the pretreatment chamber and sediment forebay will continue to be an important factor at this site to prevent clogging of the constructed wetland and erosion of up-gradient areas.

Increased groundwater influence and the presence of *Phragmites* (and their extensive root system) will likely limit the available treatment volume in the constructed wetland. A recommended modification would be to add redundancy to the design by enlarging the wetland and designing for an oversized treatment volume. This modification would also extend the discharge pipe of the constructed wetland further into the salt marsh away from the existing *Phragmites* stand, which could potentially help reduce propagation of the *Phragmites* into the salt marsh. Lastly, the constructed wetland should be planted with species which are tolerant of the wind and salt impacts, both to ensure the success of the vegetation in the practice but to also discourage the growth of *Phragmites* in the adjacent salt marsh. Table 5.2 summarizes these recommendations. Figure 5.3 presents a conceptual plan of existing conditions, and Figure 5.4 presents a conceptual plan of the recommended design modifications.

Table 5.2. Recommended Design Modifications at Site 1

Recommended Design Modifications
Select salt tolerant and wind tolerant plant species
Enhanced size of pretreatment chamber
Enlarge the wetland area to provide treatment redundancy to mitigate loss in volume

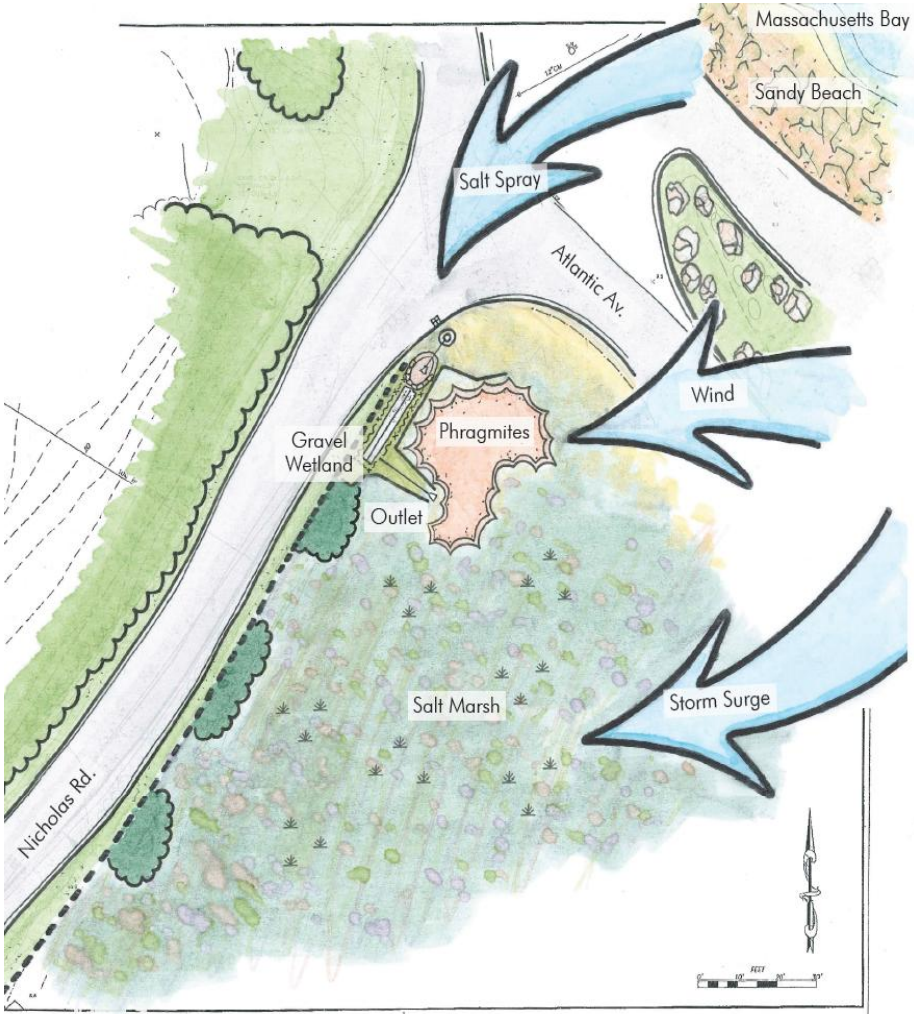


Figure 5.3. Site 1 Existing Conditions

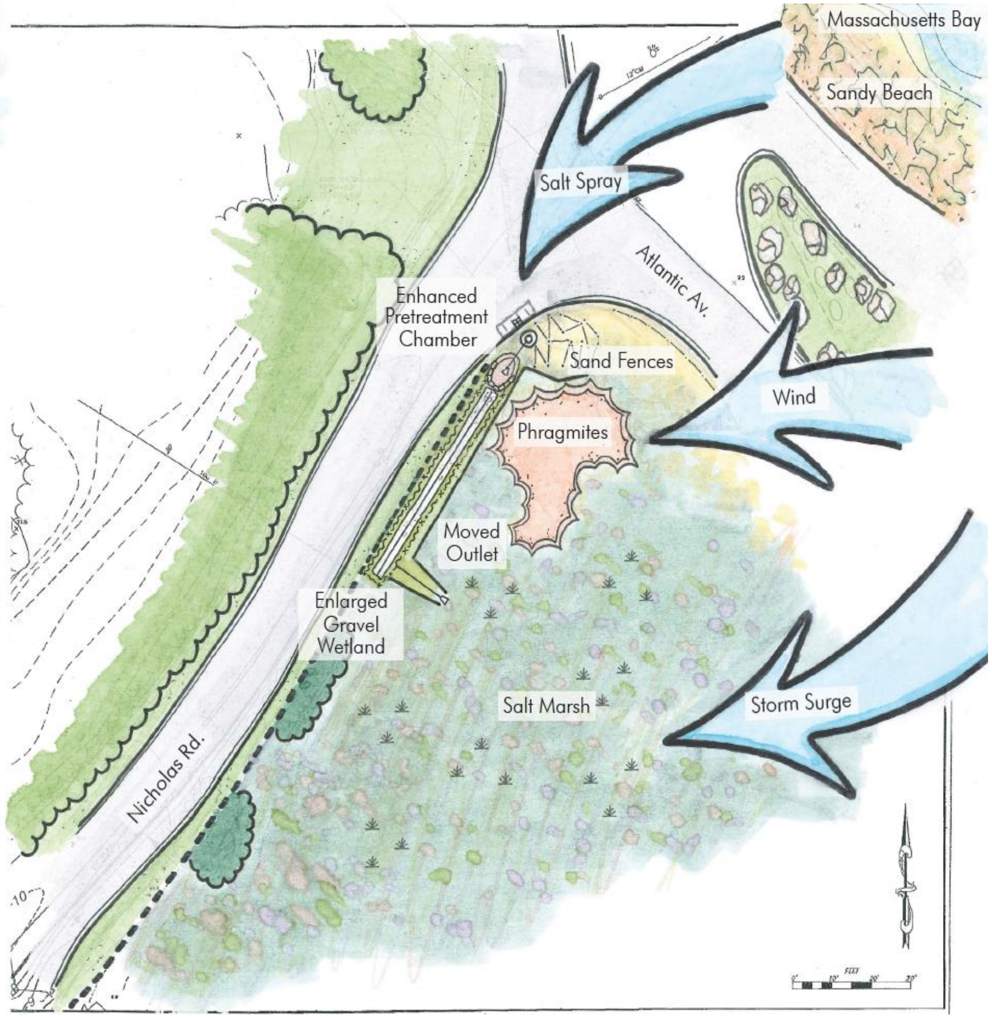


Figure 5.4. Site 1 Modified Design

Sites 8 & 9 (Jerusalem Rd. and Atlantic Ave., Cohasset)

Existing Condition

Sites 8 & 9 are located on Jerusalem Rd. near Atlantic Ave. in Cohasset, MA (See Figure 5.5). The existing stormwater management practice is a stone infiltration basin/swale that has a series of forebays and check dams prior to discharging to the adjacent marsh, either through the underdrain pipe or the level spreader overflow. The practice is intended to treat stormwater runoff from Jerusalem Rd., which drains to three existing catch basins. Pretreatment occurs through an up-gradient Stormceptor unit.

Figure 5.5. Site 8 & 9 Location Map

A review of the WHG flood elevation projections (Appendix B, Table B-1 and Figure B.1) indicates that Sites 8 and 9 already experience a 50% risk of flooding. The flood risk is expected to rise to 100% by 2030. This suggests that sea level rise and storm surge will have a substantial effect on the area and that groundwater can also reasonably be expected to rise at the site under the influence of sea level rise.

HW conducted a site visit in summer 2015 and observed that the swale was overgrown with Japanese knotweed and other vegetation. Figure 5.6 is a photograph of the site taken during the site assessment. It was not clear from the site visit if the practice was functioning as designed. A grassed area across the street, up-gradient from the existing practice, appears to be in the public right-of-way and was noted as a potential alternative location for siting a BMP.

Figure 5.6. Exiting conditions

The anticipated climate change vulnerabilities and their potential impacts are described in Table 5.3.

Table 5.3. Anticipated Climate Change Vulnerabilities and Impacts at Sites 8 and 9

Vulnerabilities from Climate Change	Potential Impacts
High groundwater elevations	Increased groundwater influence due to close proximity to salt marsh and increased potential for Japanese knotweed propagation
Reduced practice capacity/treatment	Decreased infiltration capacity and treatment of stormwater as groundwater rises
Sand/debris impacts	Reduced capacity of Stormceptor unit from road sand/debris

Climate Modification

Based on site observations, the recommended modifications to this site would be to first relocate the stormwater practice up-gradient of the existing salt marsh. As noted during the site visit, the open grassed area across from the existing practice may be a good option. There may be other opportunities in other portions of the drainage area to capture or reduce stormwater runoff. The recommended practice at this site would be a wet swale with a native wetland mix to provide filtering and treatment of runoff before exiting via an overflow. A wet swale is ideal in this location because of the potential presence of high groundwater and because of the shallow slope to the existing stormwater drainage system. Pretreatment for runoff getting directly to the practice would be through a sediment forebay and would enter the practice via a weir. Indirect stormwater runoff entering through nearby catch basins would be treated through a proprietary device (e.g., by relocating the existing Stormceptor if there is sufficient capacity) before entering the wet swale through a bubbler system which allows flows to "bubble up" through the existing catch basin to the forebay.

To address the Japanese knotweed, the outfall from the drainage system should be stabilized with rip rap and/or other materials to prevent clogging. Invasive species removal and management may be an option at this location if the Town and/or adjacent homeowners can provide regular maintenance.

The recommended design modifications for Sites 8 & 9 are summarized in Table 5.4. Figure 5.7 shows a schematic of the existing and proposed conditions at the site. Figure 5.8 is a conceptual rendering of the recommended design modifications.

Table 5.4. Recommended Design Modifications at Sites 8 & 9

Recommended Design Modifications
Locate BMP up-gradient and physically separate from existing salt marsh rather than directly adjacent to the salt marsh
Use a wet swale treatment practice, which is ideal in high groundwater and accommodates the shallow slope in the lower contributing drainage area
Relocate the Stormceptor to provide pretreatment for the wet swale, particularly to remove sands
Stabilize the outfall into the salt marsh with rip rap to prevent clogging by plants and erosion
Incorporate invasive species management and call on assistance of neighbors for maintenance

Figure 5.7. Schematic Design of Existing and Proposed Conditions at Site 8&9

Figure 5.8. Sites 8 & 9 Rendering of Modified Stormwater Management System (with existing site inset)

Site 31 (Island Wharf Rd. and Front St., Marion)

Existing Condition

Site 31 is located at Island Wharf, adjacent to a parking lot off of Island Wharf Rd and Front St in Marion, MA (See Figure 5.9). The site is adjacent to Sippican Harbor. The existing stormwater practices at this site include three bioretention areas north of the parking lot which flows to a 12-inch outfall pipe. Two of the bioretention systems are connected by a common underdrain system and both have overflow structures that connect into the underdrain pipe. That pipe then discharges via a single outfall at the shoreline. A 12-inch tide gate valve was installed at the access manhole downstream to mitigate tidal impacts at the outfall.

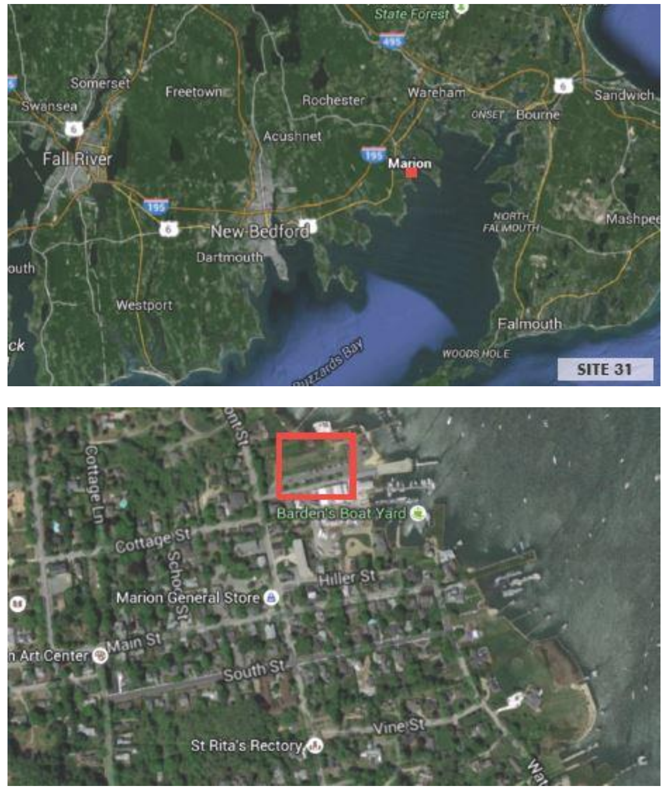


Figure 5.9. Site 31 Location Map

A review of the WHG flood elevation projections (Appendix B, Table B-1 and Figure B.8) indicates that Site 31 currently experiences only limited flooding, with only a 2-5% risk of flooding in the area of the bioretention systems (Sites 31A-C). However, the flood risk is expected to rise to 20% by 2030 and 100% by 2070. Given the topography of the site and the proximity to the shoreline, it is likely that sea level rise and storm surge will have a substantial effect on the area and that groundwater can also reasonably be expected to rise at the site under the influence of sea level rise.

A site visit conducted in summer 2015 found that the bioretention areas appeared to be working as designed and vegetation coverage was in good condition (Figure 5.10). The outfall was observed to be submerged and there was some water observed at the bottom of the outfall structures. Groundwater is likely high in this area.

Figure 5.10. Photograph of Existing Conditions at Site 31

The anticipated climate change vulnerabilities and their potential impacts are described in Table 5.5.

Table 5.5. **Anticipated Climate Change Vulnerabilities and Impacts at Site 31**

Vulnerabilities from Climate Change	Potential Impacts
Sea level rise	Increased sea levels will increase groundwater inundation time for the practice, reduce hydraulic head through the system and decrease the flow rate of water through the drainage system
High groundwater elevations	Increased groundwater influence due to close proximity to the coast
Reduced practice capacity/treatment	Decreased infiltration capacity and treatment of stormwater as groundwater rises and the outfall is submerged
Vegetation community shifts	Some existing vegetation may die back as a result of increased groundwater and may cause a shift in the species community.

Climate Modification

For demonstration purposes, HW selected the bioretention system assessed at Site 31C as the basis for recommendations at this site. The first recommended modification at this site is to reconfigure the existing bioretention to provide a permanent storage volume (i.e., anaerobic zone) at the bottom of the practice to mimic anticipated high groundwater levels under future conditions. Storage can be created by placing an upturned elbow on the existing underdrain at the existing overflow structures. This modification will provide flexibility, allowing the bioretention area to continue to function as a wet practice even with climate change influences. This can also provide additional benefits, such as additional nitrate removal through denitrification and increased plant survival by providing a buffer of saturated conditions through long dry periods (Zhang et al., 2011). Figure 5.11 provides typical profiles of bioretention areas with and without permanent storage volumes (Eadie, 2011).

Another recommended modification is to provide additional redundancy in treatment and storage capacity by enlarging the existing bioretention areas. Additional capacity can address high groundwater levels (or permanent storage volumes), impacts from sea level rise and increased rainfall. The additional bioretention area can be provided next to the existing system in the open grassed area. A final recommended modification would be to choose appropriate plant species to be able to accommodate increased inundation and wetting, either from climate change impacts (e.g., groundwater levels, sea level rise) or from creating a permanent storage volume. The recommended design modifications for Site 31 are summarized in Table 5.6 and presented in Figures 5.12.

Table 5.6. Recommended Design Modifications at Site 31

Recommended Design Modifications
Create a permanent storage volume in the anaerobic zone of the bioretention systems to mimic anticipated high groundwater levels
Provide redundancy in treatment and storage capacity by enlarging the area of the bioretention system
Choose appropriate plantings for saturated soil conditions

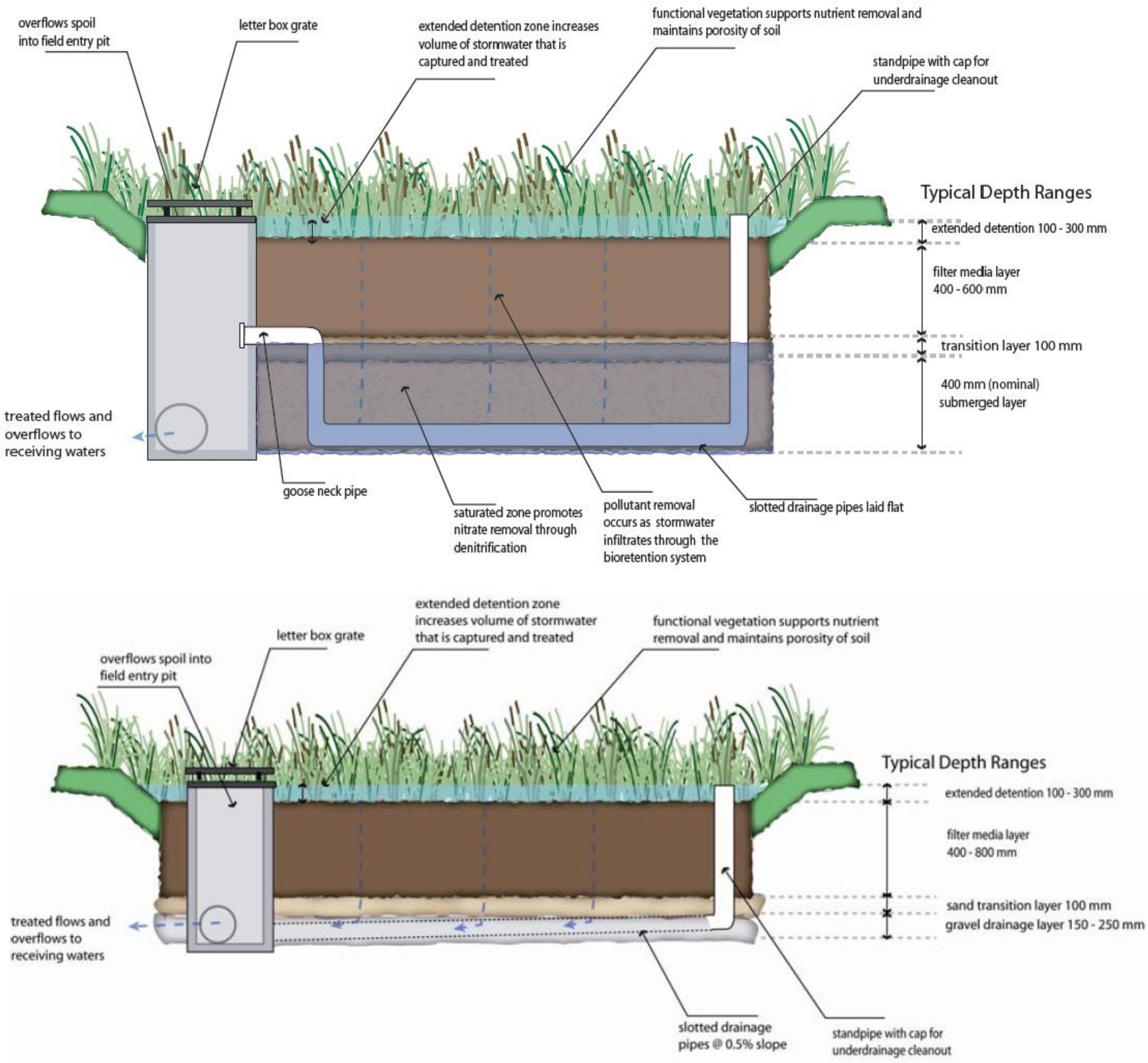


Figure 5.11. Profiles of Bioretention Areas with and without Permanent Storage Volumes (Eadie, 2011)

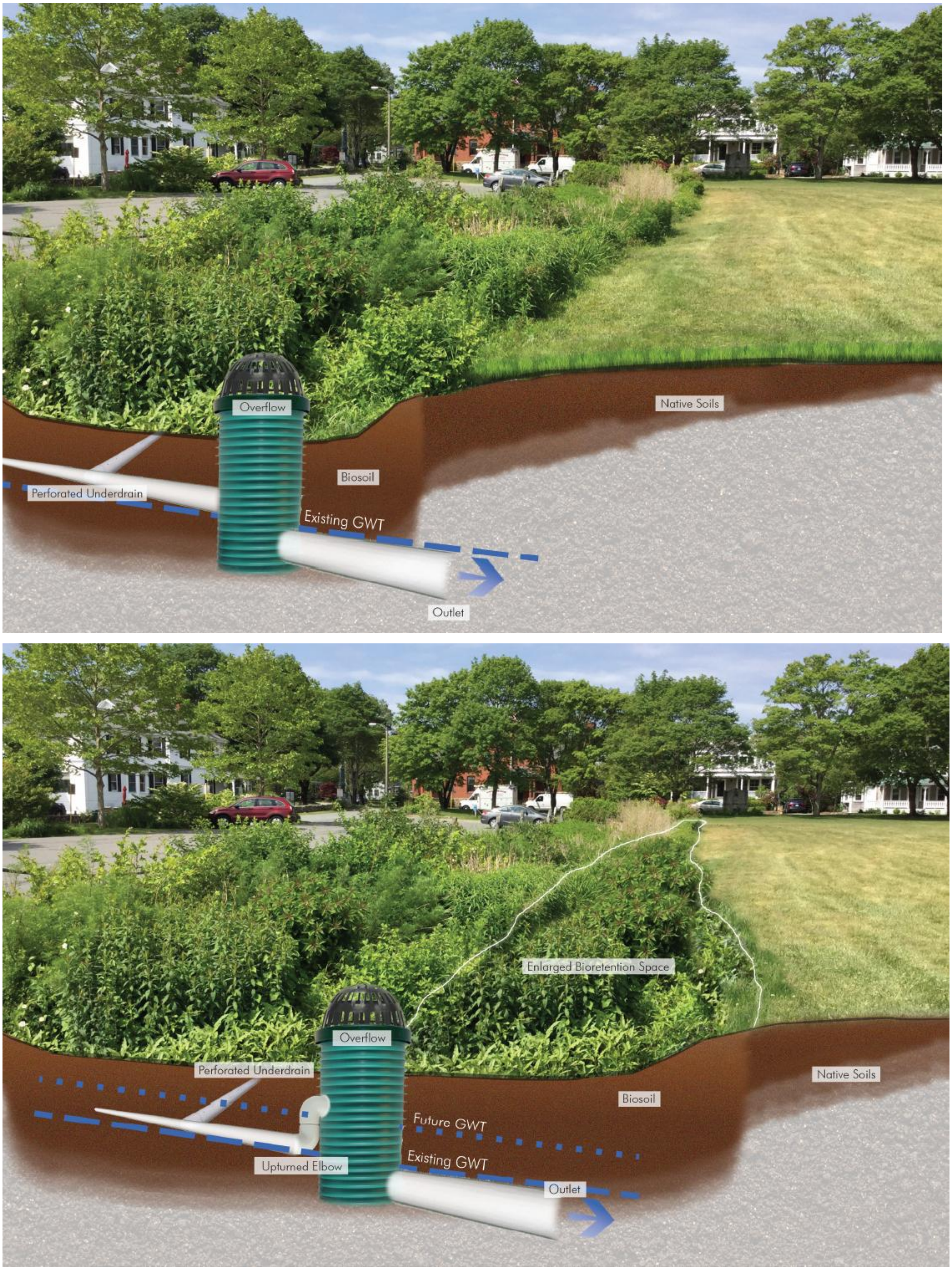


Figure 5.12. Site 31 Conceptual Design of Existing (top) and Modified (bottom) Bioretention Cell

Site 32 (Buttermilk Way, Bourne)

Existing Condition

Site 32 is located in a parking lot and nearby right of way to the beach off of Buttermilk Way near the Beachmoor Restaurant and the Massachusetts Maritime Academy in Bourne, MA (see Figure 5.13). The existing practice at this site is a set of nine subsurface infiltration chambers (Cultec units) located beneath the parking islands. Runoff from the parking lot enters the practice through a catch basin and settling tank that provides pretreatment for the subsurface infiltration chambers. System overflows are directed to the existing drainage system on Buttermilk Way. This system captures flow from area roadways and flows to additional settling chambers and a set of subsurface infiltration chambers within a right of way between number 15 and 17 Buttermilk Way, before discharging to the Bay.

Figure 5.13. Site 32 Location Map

The site is estimated to have only a 5% risk of flooding currently, and is only projected to increase to 20% risk in 2030 and 50% risk in 2070 (Appendix B, Table B-1 and Figure B.9). As a result, it is likely that flooding will increase but this will not be as prominent an issue at this site as it will be in the previous sites. However, groundwater elevation will increase at the site as a result of the close proximity to the coast. For this reason, impacts on infiltration capacity and depth to groundwater are an important consideration.

HW visited the site during the summer of 2015 (Figure 5.14) and noted that there was some erosion of vegetation or settling of sediment on the surface at the north end of the parking lot system, closest to Buttermilk Way. The settling tank appeared to be functioning. However, groundwater levels are likely to be high at this site due to the proximity of the site to the shoreline and the relatively small change in elevation over that distance. HW was unable to access the subsurface chambers to assess condition or performance. Anticipated climate vulnerabilities and their potential impacts are described in Table 5.7.

Table 5.7. Anticipated Climate Change Vulnerabilities and Impacts at Site 32

Vulnerabilities from Climate Change	Potential Impacts
High groundwater elevations	Increased groundwater influence due to proximity to coast
Reduced practice capacity/treatment	Decreased infiltration/treatment as groundwater rises

Figure 5.14. Existing Conditions in Parking Lot, Site 32A (top) and Beach Access Way Site 32B (bottom)

Climate Modifications

Recommendations were developed for design modifications for the parking lot area (referenced as Site 32A in our assessment) and the right of way containing additional underground infiltration chambers between numbers 13 and 15 Buttermilk Way (referenced as Site 32B in the assessment).

The first recommended design modification at Site 32A is to select a surface practice, such as a vegetated swale or a bioretention area, rather than a subsurface practice, due to the proximity of the groundwater below the practice. A surface practice may provide greater treatment of pollutants and will provide greater flexibility to adapt to changing climate conditions, such a rising sea level and associated rising groundwater, and increased rainfall. In addition, a porous pavement (e.g., porous asphalt) could be considered in the parking spaces for the near term to both reduce stormwater runoff volumes to the stormwater treatment practices and to provide greater opportunities for infiltration into subsurface soils. Surface flows off the porous pavement can then enter the swale or bioretention through curb cuts. These modifications will also reduce potential impacts from high groundwater elevations, because the bottom surface of the system is at a higher elevation in a surface practice than a subsurface infiltration system. However, an underdrain is recommended to drain flows from larger storms. Pretreatment might occur through a pea gravel filter strip at the curb cuts. Excess flows from the swale or bioretention would discharge through an overflow structure.

Similar to Site 31, this site should be designed with a permanent storage volume through an upturned elbow to address the potential existing and future impacts of high groundwater elevations. It would also provide added nitrate reduction benefits through denitrification and increased plant survivability. Plantings in the bioretention or swale should be selected to accommodate wet conditions, due to the increased groundwater elevation of permanent storage volumes.

Within the right of way at Site 32B, the design should be modified from an underground settling tank and infiltration chambers to a dry swale. By connecting to a surface practice, the practice is elevated, thereby reducing the influence of increasing groundwater elevations. A shallow forebay could be installed using pavers along the edge of the road and curb to allow sediments to settle out before water flows into the dry swale. The location and structure of this forebay would provide for easy maintenance. High flows would be captured by a catch basin and would discharge directly out to the coast.

The recommended design modifications for Site 32 are summarized in Table 5.8 and presented in Figures 5.15 and 5.16.

Table 5.8. Recommended Design Modifications at Site 32

Recommended Design Modifications
Selection of surface practices (swale or bioretention, porous pavement) instead of subsurface practices (settling tanks and infiltration chambers)
Incorporate a permanent storage volume in the bioretention system of swale

Figure 5.15. Site 32A Modified Design Using a Bioretention System and Porous Pavement

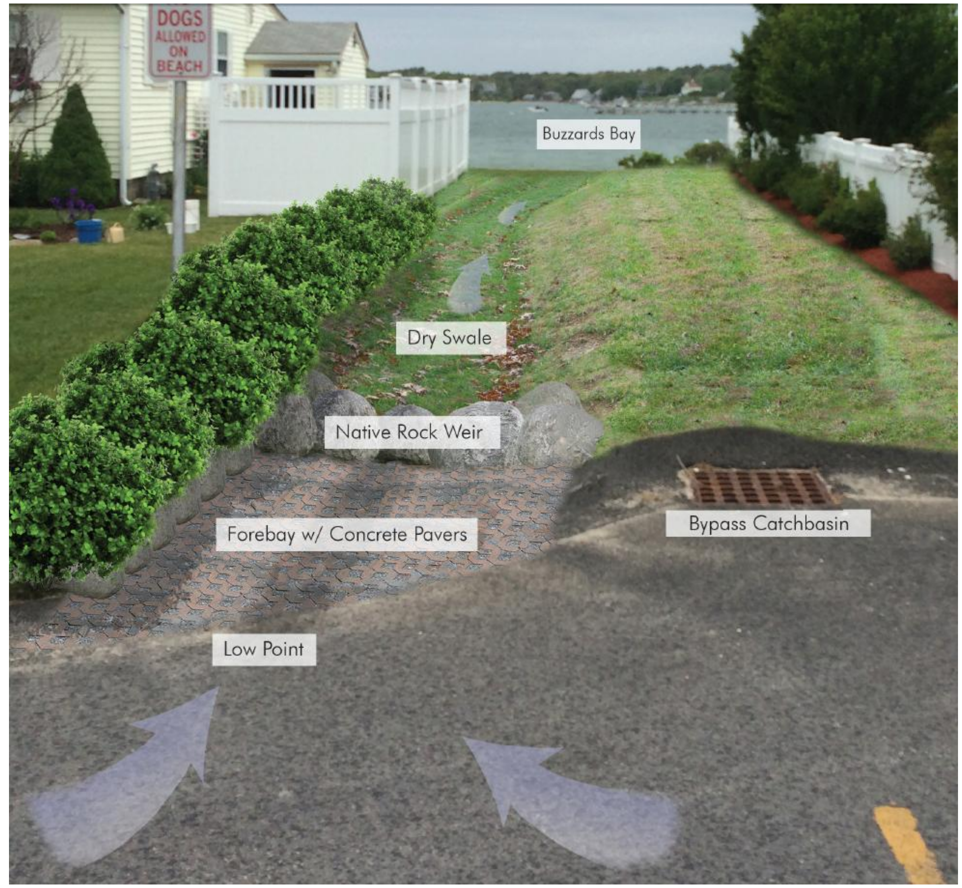


Figure 5.16. Site 32B Modified Design Using a Dry Swale

Site 34 (Delano Ave and Grandview Ave, Kingston)

Existing Condition

Site 34 is located at the end of Delano and Grandview Ave. along the Jones River (Figure 5.17). Runoff from the adjacent roadways enters through a trench drain that then flows to two parallel manholes with 4-ft sumps for pretreatment. Runoff then flows to two separate rain gardens on either side of the trench drain by "bubbling up" through a catch basin in the center of each of the rain gardens (Figure 5.18). High flows that bypass over the trench drain pass over a granite curb just down-gradient of the trench drain and flow over a stone-lined slope before discharging to the beach. This site is on a bluff is not expected to be affected by coastal flooding and storm surge, or to have an increase in flood risk through 2070.

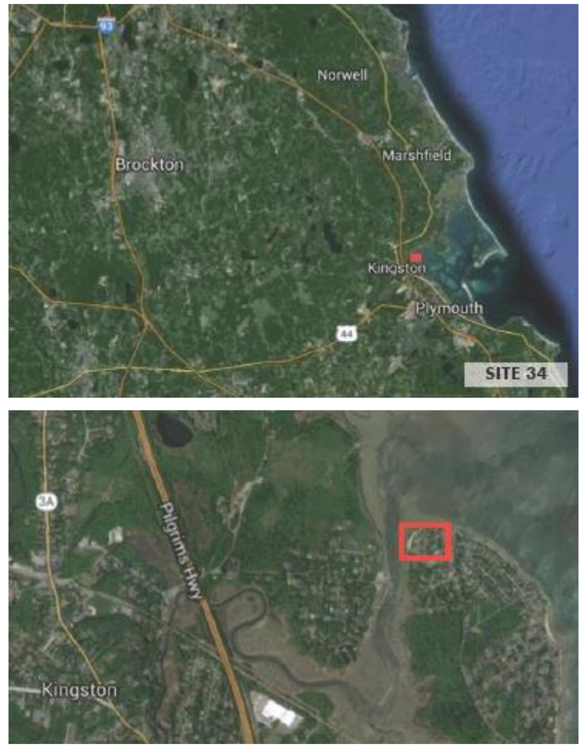


Figure 5.17. Site 34 Location Map

HW visited the site in the summer of 2015 and observed that the practice was not functioning as designed due to a completely clogged trench drain. The majority of runoff was bypassing the trench drain and rain gardens, overtopping the curb and eroding to slope down to the beach/marsh. The rain gardens and surrounding vegetation appeared to be in good condition. Minor damage to concrete curbing at the top of the rain garden was observed, which may be from snow plows. Water appeared to flow through the damaged curb directly into the rain garden, bypassing the trench drain and causing minor erosion on the rain garden slope.

Figure 5.18. Existing Conditions

The anticipated climate change vulnerabilities and their potential impacts are described in Table 5.9.

Table 5.9. Anticipated Climate Change Vulnerabilities and Impacts at Site 34

Vulnerabilities from Climate Change	Potential Impacts
Wind, salt and sand impacts	Wind may carry sand and salt into rain gardens; frequent clogging of the system from sand; and overall impact on vegetation species
Reduced outfall capacity/treatment	Decreased capacity and treatment capability due to potential clogging from sand and debris

Climate Modifications

The recommended modification to this site is to address impacts from sand, both from winter maintenance activities and the adjacent beach, by providing redundancy to the design through additional inflow points. Examples may include providing up-gradient deep sump catch basins that can be connected through pipes to the rain garden catch basins or providing a paved flume or a runnel near the trench drain that would be directed to the rain gardens for larger rainfall events and for situations when the trench drain capacity is limited due to heavy sand buildup. Another design modification would be to increase the curb height behind the trench drain to reduce the amount of overflows, which will increase the potential for stormwater runoff to enter the rain gardens and reduce the potential for erosion at the overflow.

Maintenance of both the trench drain and deep sump manholes will continue to be an important factor at this site to prevent clogging of the existing and proposed inlet points and erosion of overflow areas. In addition, occasional stabilization of the adjacent slope, including the overflow and the pea stone walk, may be necessary to ensure that the slope is not being undercut.

The recommended design modifications for Site 34 are summarized in Table 5.10. Figure 5.19 presents a conceptual rendering of the existing conditions and of the recommended design modifications.

Table 5.10. Recommended Design Modifications at Site 34

Recommended Design Modifications
Provide redundancy in design by providing multiple inflow locations to the rain gardens. In the event of sand buildup, from both windblown beach sand and winter street sanding sources, runoff will still have continued access to the rain gardens.
Increase the height of the curb/berm downgradient of the trench drain to capture and direct more runoff that bypasses the trench drain.
Perform more frequent inspections and maintenance to manage sand buildup at the site and reduce ponding.

Figure 5.19. Site 34 Conceptual Rendering of Existing Conditions (top) and Modified Design (bottom)

6.0 Conclusion

This report has presented recommendations for improving the resilience and long-term effectiveness of stormwater management practices in the coastal zone. These recommendations are based on a detailed overview of the anticipated climate change impacts to coastal Massachusetts, relevant to stormwater management design. The recommendations presented here were informed by the professional experience and expertise of project consultants who observed BMPs in the field at over two dozen locations in coastal Massachusetts. The focus of these recommendations is to guide decisions about funding, siting, selection and engineering design for stormwater improvement (retrofit) projects.

These recommendations could also begin to inform potential future revisions to the MA Stormwater Standards, which apply to new development as well as redevelopment projects above a certain scale. As more information, science and climate projections are developed for coastal Massachusetts, and as climate impacts continue to be experienced and documented, it will become more and more important to consider future site climate change impacts in stormwater management decisions.

The Coastal Pollutant Remediation Grant Program and the Clean Water Act Section 319 Grant Program, as well as municipalities and private land-owners, should make climate change impacts and the recommendations herein an important consideration in the decision-making process around the funding of stormwater management projects.

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Appendix A: Assessment Summaries for BMPs

Appendix B: Projected Risk of Flooding