U.S. Department
of Transportation
Federal Highway
Administration

DelDOT

Coastal Green Infrastructure to Enhance Resilience of State Route 1, Delaware

Left: State Route 1 flooding, January 24, 2017. Photo Credit: DelDOT. Right: Conceptual design of coastal green infrastructure to protect against flooding at the Read Street stormwater outfall from SR-1 in Dewey Beach, DE. Design includes constructing oyster reef, shell bags, marsh, beach, dune, flood barrier, and tide gate. Map Credit: Google Earth, Map©2018Google.

June 2018

This report documents a pilot project sponsored by the Federal Highway Administration (FHWA) and the Delaware Department of Transportation (DelDOT) to assess the potential for green infrastructure techniques to protect sections of Delaware State Route 1. It is one of five pilot projects FHWA sponsored to assess the potential for natural infrastructure to protect specific locations along coastal roads and bridges. More information can be found at: https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/green_infrastructure/index.cfm

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Executive Summary

Transportation infrastructure located in and near coastal areas may be vulnerable due to such stresses as coastal flooding, wave energy impacts, and storm surge. This vulnerability is now becoming exacerbated by sea level rise and more severe and frequent coastal storms. Additionally, coastal areas are home to a large and growing percentage of the U.S. population. Population growth further stresses these systems due to increased runoff and stormwater-driven pollution and places more properties and human capital in and near areas of acute vulnerability.

These conditions challenge state departments of transportation with providing adequate and sustainable protection for transportation assets in coastal areas. The traditional approach to protecting coastal assets is through structural “gray infrastructure” solutions, such as rock or concrete revetments and rip-rap-lined shoreline protection. These solutions are often costly, carry little or no additional benefits to the environment, and are non-dynamic in their performance in contrast to the shifting nature of climatic patterns.

A new approach to providing coastal protection is the use of green infrastructure (GI) practices (also known as green coastal infrastructure [GCI] or natural and nature-based features [NNBF]). These measures rely on naturally-occurring materials, such as oysters or coastal vegetation, that attempt to mimic ecosystem processes to the degree possible. GI practices are used in a systematic approach with other natural-based features with a goal of providing more flexible, resilient, and adaptive shoreline restoration. These systems provide enhanced environmental and ecosystem service value compared to equivalent gray infrastructure solutions. GI practices referred to as green stormwater infrastructure (GSI) also can be applied to address runoff generated in urban areas by reducing runoff volumes and by stabilizing areas that are eroding due to more frequent and severe storm events.

Summary of Problem and Context

Delaware State Route 1 (SR 1) is a significant transportation corridor that has enormous economic and social value to the State of Delaware and other regional entities. Located on a stretch of land with the Inland Bays to the west and the Atlantic Ocean to the east, this corridor is highly susceptible to flooding and erosion associated with coastal storm events. SR 1 is already being affected by sea level rise with impacts expected to grow and accelerate in the future, and throughout the corridor, growth related to urbanization is leading to an increase in urban runoff volume and pollutant loading. In short, SR 1 is experiencing stressors from a variety of sources leading to an overall condition of vulnerability in many locations. Considering the vital nature of this transportation infrastructure segment, any major threat to the system’s integrity requires robust study and action.

To address this situation, the Delaware Department of Transportation (DelDOT), along with federal, state, and local government partners as well as supporting non-governmental organizations and technical practitioners, led an investigation into methods and practices to identify areas of high vulnerability along the SR 1 corridor and to develop GCI approaches to protect this critical transportation asset. Urbanized areas in the corridor are seeking infrastructure investments that address localized flooding and runoff treatment and reduction; however, local and regional factors create challenges in siting GSI. The main goals of this effort are to identify situations where both GCI and GSI can be integrated for holistic and cost-effective solutions and to develop replicable approaches where successful integration can occur.

Methods and Adaptation Options

The DelDOT project team developed an analysis methodology to support the investigation of coastal vulnerabilities and stormwater management needs and opportunities along SR 1 between Rehoboth Beach and Fenwick Island. This 17-mile stretch of four-lane roadway and adjacent land along this corridor comprised the study area.

The methodology involved a two-phase approach. The first phase was based on a planning-level effort using GIS-based data and other desktop-focused information to gain an understanding of a macro-scale characterization of the corridor. A total of 15 locations were chosen to be included in this initial phase. The sites were all located in areas impacted by Inland Bay forces, as oceanside forces are generally addressed by a dune system running east of SR 1 throughout the length of the study area. It should be noted that a detailed analysis confirmed the assertion regarding Bay side versus oceanside dynamics. The outcome of the first phase was to identify six of the 15 sites to focus on for conceptual design development.

The second phase included a more detailed analysis that used modeling to determine coastal flooding impacts, wave energy potential, and natural buffer protection for three storm events: the 1-, 2-, and 10-percent annual chance events. A non-dimensional scoring index was used to combine the various modeling results into a single score reflecting the overall vulnerability of each site. While the initial phase reduced the number of sites of interest to six, all 15 sites from the first phase were used in the second phase analysis to ensure a comprehensive understanding of the study area. The results of the scoring identified a range of vulnerabilities for sites of interest.

An additional facet of the second assessment phase was a review of stormwater management needs and opportunities. Of the six sites of interest, two sites were found to have compelling and unique circumstances associated with stormwater management. The first site, Read Avenue, is located in the Town of Dewey Beach, which recently performed an analysis of catchments within the town to develop a plan for stormwater management investments. The Read Avenue catchment has a series of bioretention facilities and locations for permeable pavement retrofits identified in areas located at SR 1 or to the east where soil conditions are more favorable to infiltration-based practices. Additionally, the location where Read Avenue terminates at the Bay side shore is an area targeted for investment to reduce localized flooding and to stabilize an eroding shoreline. The need for this stabilization is reflected by this site receiving the highest score on the vulnerability index. It was therefore deemed to be the most vulnerable location assessed (along with one other site with the same score).

The second location identified as having strong stormwater management potential is the National Guard site located near the Bethany Beach area. This site experiences much less coastal stress, which is consistent with this site receiving the lowest vulnerability index score. However, this site includes many elements that typify stormwater management challenges and opportunities seen throughout the SR 1 corridor. For instance, the National Guard site includes median and ditch drainage. Some of this drainage is clogged and ineffective, requiring expensive dredging. The SR 1 corridor has many areas with similar tidal drainage ditches that no longer function. Additionally, areas located upstream in the catchment draining to these systems hold potential for GSI implementation, which would reduce the pollutant and volumetric loads associated with urban runoff. Lastly, this site includes a tidal marsh system, which is currently being bypassed by the ineffective constructed drainage system. This marsh system has the potential to be enhanced and provide significant ecological uplift as well as untapped water quantity and quality management.

Considering the coastal vulnerability index scores and stormwater management opportunities and challenges at the sites analyzed, the two locations chosen for conceptual design development were Read Avenue and the National Guard sites. At the Read Avenue site, a coastal stabilization and drainage improvement project was previously constructed. The installed system has eroded over time, and its drainage capacity has been greatly diminished due to sedimentation and clogging. The adaptation of Read Avenue includes raising and enhancing the existing dune system, preserving existing marsh areas and creating additional marsh areas, and installing of oyster shell bags to protect eroding shoreline. Additionally, the drainage system will be improved by constructing larger/additional culverts and a tide gate system at the outlet area with established maintenance access. Lastly, the Town of Dewey Beach has identified further drainage capacity improvements and GSI opportunities in upstream portions of the catchment draining to the coastal stabilization project areas. A plan view of existing and proposed conditions at Read Avenue are shown on the following page.

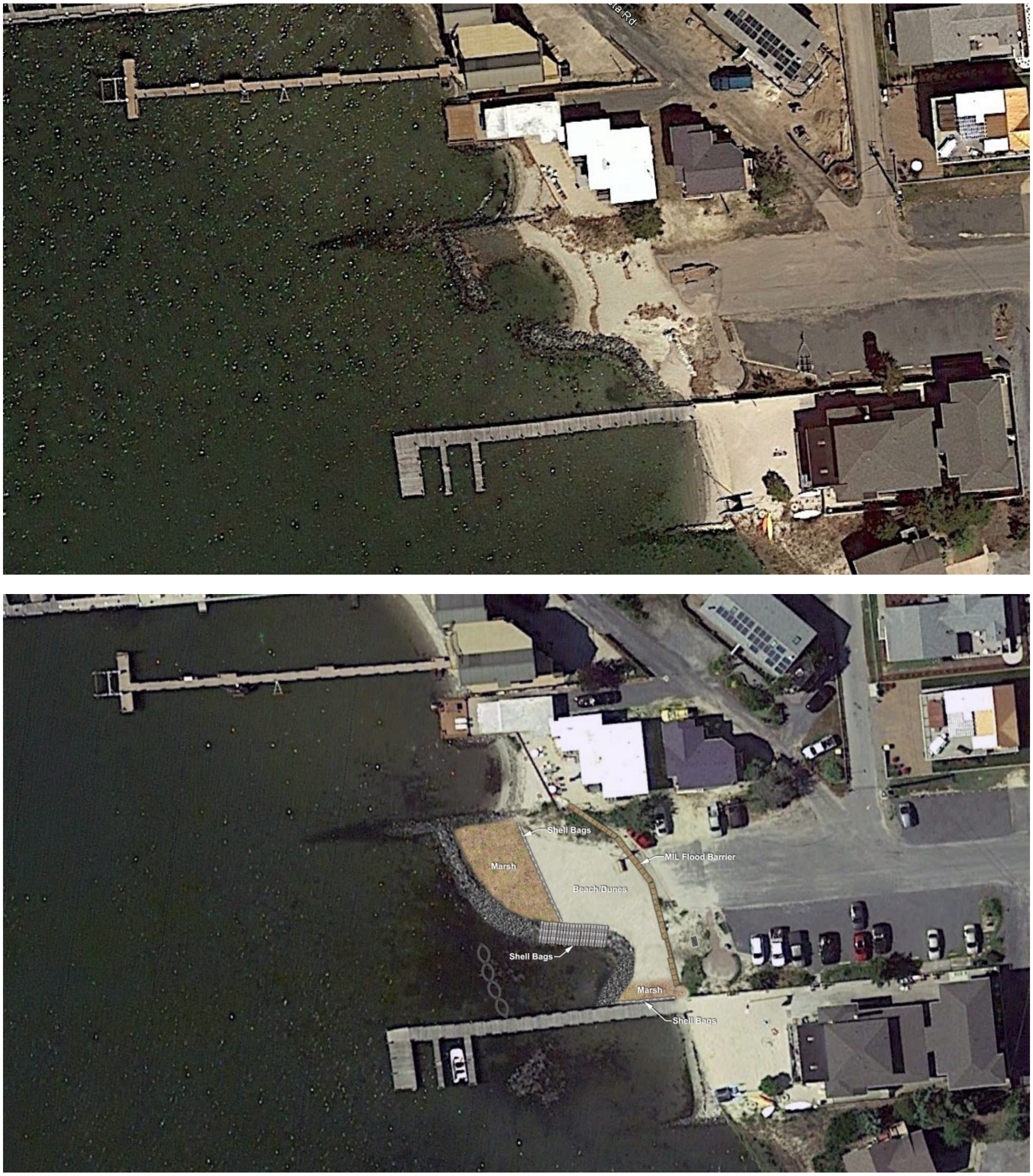
The biggest challenges at the National Guard site are associated with highway and local drainage conveyance capacity as well as sediment build up in a drainage ditch conveying most flows from the catchment. The improvements proposed for this location are not as well developed as Read Avenue. However, initial concepts provide a path forward for more detailed design development in the future. The proposed design elements include enhancing existing tidal marsh area and constructing sediment forebays and level spreaders at multiple locations coinciding with drainage conveyance delivered from the SR 1 corridor. The marsh enhancement involves removing an existing levee separating flow from the main drainage ditch through the systems and the construction of a series of runnels throughout the marsh area. While potential locations for GSI implementation exist in upstream portions of the catchment draining to the tidal marsh at this location, the specific locations and types of GSI practices have not yet been identified. A plan view of the existing marsh system with proposed changes is depicted in the figure on the following page.

Costs, Benefits, and Implementation Considerations

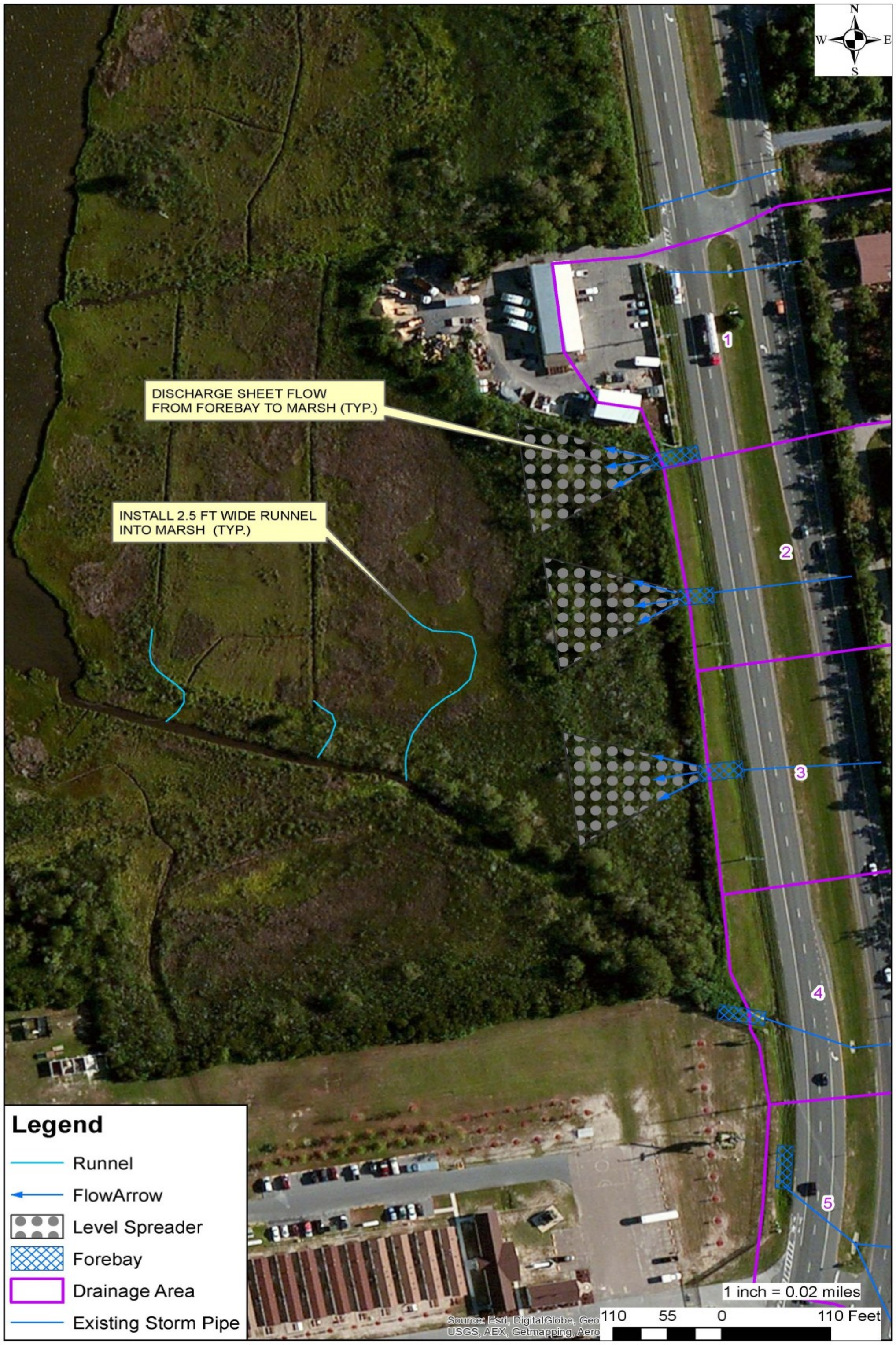
The advantage of GSI and GCI investments is that costs are often lower than traditional “gray infrastructure” projects and also have increased social, economic, and environmental/ecological value for invested areas and nearby locations. While infrastructure investments can provide benefits, there can be challenges when implementing projects.

Read Avenue Site

Two cost estimates were developed for the adaptations presented for Read Avenue. One cost estimate reflecting short-term investments (marsh protection/creation, dune enhancements, oyster rip-rap shoreline protection, drainage capacity expansion, and tide gate installation) was estimated to cost approximately $170,000. The second long-term cost estimate for this location was estimated to be nearly $600,000, which would include significant investments in expanding the drainage capacity up to the SR 1 right-of-way. These investments would enable the overall system to safely pass the 10-percent storm event. Currently, it cannot convey the even the one-year storm event. An informal cost estimate shows that a traditional approach would be between 30 percent to 100 percent higher than the proposed GI configuration.



Read Avenue Existing Conditions (above) and Conceptual Design (below) (Plan View - Not to Scale). Map Credit: Google Earth, Map©2018Google.



National Guard Site Conceptual Design (Plan View - Not to Scale). Map Credit: Google Earth, Map©2018Google.

The primary benefits of the proposed adaptations that will enhance drainage capacity at Read Avenue are stabilized shoreline areas and reduced chronic localized flooding, especially associated with backflow high-tide and wind-driven events. Benefits also include an increase in ecological value associated with enhancing and expanding the coastal marsh area and implementing the oyster bags. Additionally, established maintenance access to the tide gate area will increase the drainage system's long-term performance assurance and add recreational value associated with the protection of a stable kayak launch and improved access to birdwatching and nature photography opportunities. It should also be noted that the reduction in chronic, localized, high-frequency flooding will allow greater ease of access by emergency vehicles, which have been previously unable to access areas near the project site during storm events. These improvements will enhance the capacity, sustainability, and public safety of the coastal stabilization project area.

Private property owners will be affected by this project, and the most significant project implementation challenge at Read Avenue is ensuring that they have access, cooperate with construction activities, and engage in the permitting process as necessary. However, this is not seen as a project barrier. Regarding project permitting associated with implementation, it is unlikely that a state-level permit tailored for living shorelines can be used, which may increase the effort associated with permitting. Again, this aspect of the project is not seen as a barrier, but rather it is a consideration.

National Guard Site

The second adaptation location, the National Guard site, does not include a detailed conceptual design. Therefore, the ability to develop a cost estimate for investments is limited. However, benefits, including cost efficiency, associated with this site can be determined. For instance, it is estimated that the cost to dredge the existing drainage channel at the National Guard site may be as high as $200,000. In contrast, a configuration using sediment forebays for the drainage area associated with this location may be one to two orders of magnitude cheaper over a 20-year period. Other potential benefits exist for this location. The goal of tidal marsh enhancement will be to create cross-sectional and plan geometries to increase flow circulation throughout the marsh area. The result will be an enhanced hydraulic conveyance that will help flush sediments into and out of the marsh area in a more sustainable manner, thereby reducing maintenance needs in the long-term. Additionally, reconfiguration of flows will provide additional effluent locations for drainage from the SR 1 corridor. The marsh system's enhanced flushing capacity will increase its water quality treatment capacity as well as conditions for aquatic biota that depend on a robust and stable marsh environment for habitat and lifecycle functions.

Project implementation considerations are less well-developed for the National Guard site; however, some considerations have been determined. For instance, since the focus of the effort is to enhance a large tidal marsh area, the permitting requirements associated with this project are likely to be greater than those associated with the Read Avenue location. Additionally, performing construction activities in tidal areas has many challenges, such as the need to use lighter construction vehicles and equipment, the potential requirement to dewater and phase work throughout the project site, and minimizing habitat impacts overall. Additionally, a portion of the work is to develop a network of self-sustaining runnels throughout the tidal marsh system. However, these systems are highly complex and can be sensitive to minor changes in elevation and dynamics, so it is likely that a high level of monitoring would be needed to ensure that the system is functioning as envisioned.

Lessons Learned and Next Steps

A valuable output of this project will be the documentation of lessons learned through a set of memoranda that will summarize the critical design and policy aspects of the projects highlighted in this effort. Specifically, the information conveyed in these documents will provide technical strategies for potentially integrating CGI and GSI for more holistic and cost-effective projects. Additionally, these documents will describe the approach to identify areas where transportation infrastructure may be vulnerable to coastal and stormwater runoff impacts. By being able to target these areas, DelDOT may be able to proactively identify locations within a proposed highway improvement effort that are best suited for coastal restoration or protection investment or pair projects where dredge spoils can feed into coastal marsh areas requiring replenishment.

The purpose of these memoranda is to identify current design and policies related to GI in the context of protecting the integrity of transportation infrastructure while adapting to coastal and urban runoff stressors and shifting climatic conditions. The intent of developing these documents is to more effectively transfer the information gained in this project to other locations throughout the State of Delaware. An additional benefit is that these documents, when completed and distributed, may help other state departments of transportation with similar challenges as well.

The next steps for the projects highlighted in this report vary. The policy and design memoranda will be completed and distributed. The Read Avenue project has received grant funding needed to move forward with the short-term investments highlighted in this report as early as spring of 2018. Additional funding will be needed to develop design documents required for construction activities to begin on the longer-term investments. Permitting efforts are ongoing as well but should not pose a delay in implementing the short-term project elements. The National Guard site is not envisioned to progress without additional funding to flesh out the details of adaptations proposed for this project.

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I. Problem and Context

It is predicted that between 8 percent and 11 percent of Delaware will be underwater due to sea level rise (SLR) by the end of this century (DNREC, 2012). This should come as no surprise considering that Delaware has the lowest average land elevation of any state in the Union with one-third of its landmass covered by wetlands. The state is located between two high-value estuaries, the Chesapeake Bay and Delaware Bay, and the Atlantic Ocean. Considering these vulnerabilities, the State of Delaware has recently increased its focus on resilience in the face of changing precipitation patterns, rising sea levels, and intensity and frequency of coastal storms that drive storm surges and erosion of shoreline areas.

In this context, the Delaware Department of Transportation (DelDOT), working in partnership with the Delaware Center for the Inland Bays (CIB), the Delaware Department of Natural Resources and Environment Control (DNREC), and the U.S. Environmental Protection Agency Region III (EPA) used existing data, tools, and information to analyze the Delaware State Route 1 (SR 1) corridor between Rehoboth Beach and Fenwick Island. The goal was to identify six sites best suited for a variety of green coastal infrastructure (GCI) practices and develop conceptual designs for two selected locations that would reduce climate change impacts and maximize benefits to the local economy, public, and stakeholders, as well as the natural resources and environment within the corridor. This effort, backed by a number of supporting groups including the Delaware Water Resource Agency, the Partnership for the Delaware Estuary, and the Towns of Dewey, Fenwick Island, and South Bethany, also sought to develop a methodology for assessing sections of SR 1 that are highly vulnerable to coastal flooding and estimated wave energy impacts. Additionally, this project focused on the siting of proposed infrastructure that has the added benefit of providing stormwater management benefits.

a. Existing Adaptation Efforts and Projects

In 2012, the Delaware Sea Level Rise Advisory Committee commissioned the report, *Preparing for Tomorrow's High Tide: Sea Level Rise Vulnerability Assessment for the State of Delaware (Vulnerability Assessment)* (DNREC, 2012). This report included several recommendations regarding SLR and the state's transportation system. Recommendation 3.4 of this report, Incorporating Sea Level Rise into Delaware's Long-Range Transportation Plan, called for establishing a framework for directing investments. Recommendation 3.6 Encourage Inclusion of Sea Level Rise in Transportation Project Design focuses on updating design standards to ensure consistency with Federal Highway Administration (FHWA) updates to reflect the predicted effects of SLR. Recommendation 3.12: Designate Shoreline Zones for Adaptation Action encourages planning for and designating areas statewide where living shorelines will be encouraged in order to provide certainty for permit applicants and possibly streamlining the permitting process.

As a result of this report, an executive order, several studies, recommendations, and statewide activity approvals were completed. Executive Order 41 (EO 41) (State of Delaware, 2013), signed on September 12, 2013 by Governor Jack Markell, directed state agencies to address both the causes and consequences of climate change with adaptation and resiliency planning as one of the three categories of state action. The Cabinet Committee charged with developing recommended actions that state agencies can take to meet the goals of EO 41 for this category finalized the Climate Framework for Delaware (DNREC, 2014) on December 31, 2014. The Climate Framework, created by a multi-jurisdictional and multi-disciplinary team made up of members from each state agency, was released in December 2014. Additional areas of concern addressed in the Climate Framework include flood risks and public safety associated with coastal storms.

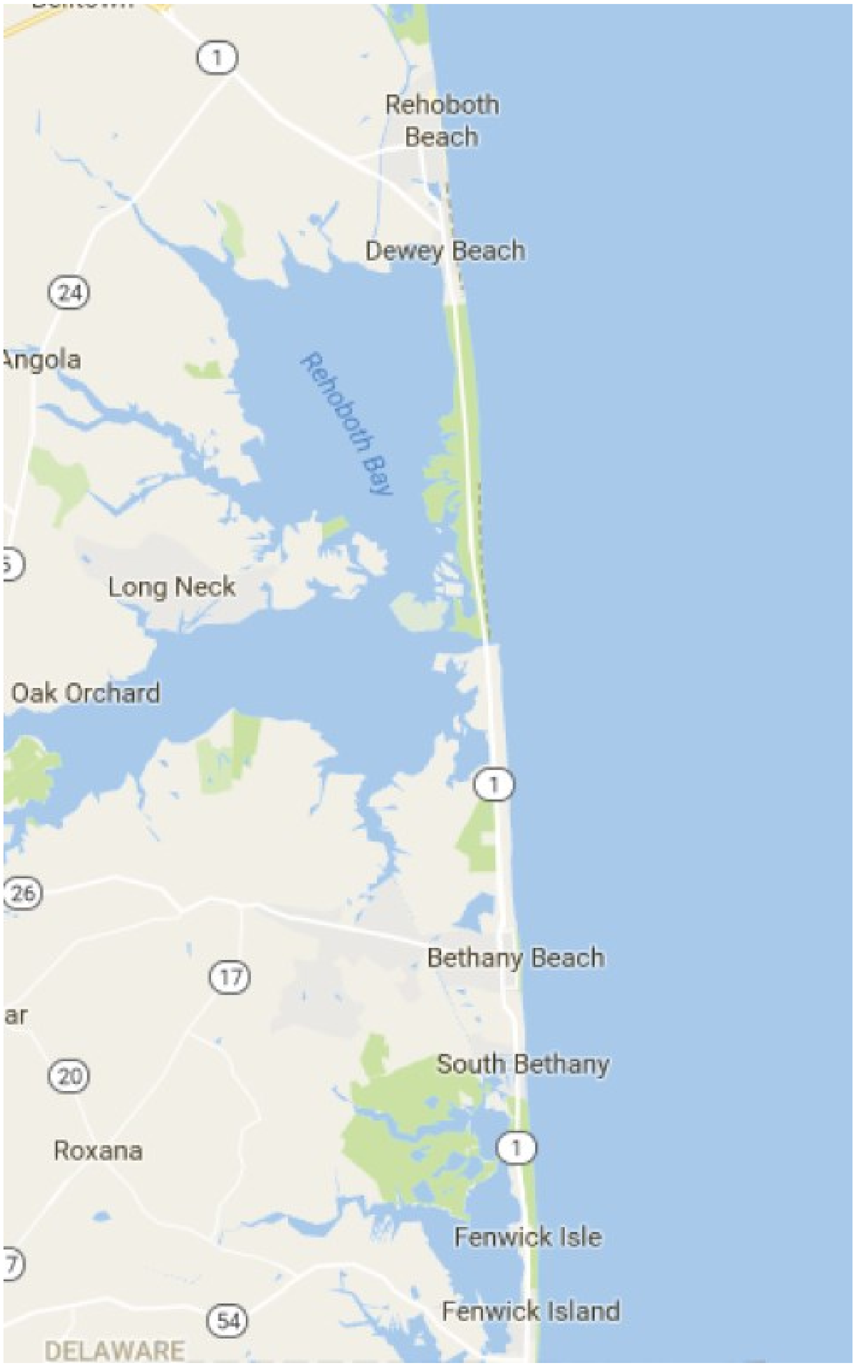

Figure 1 - Study Area Limits. Map Credit: Google Earth, Map©2018Google.

In May 2016, DNREC announced the Strategic Opportunity Fund for Adaptation (SOFA) grant program. This state program seeks to address climate adaptation by implementing solutions to protect communities and help to plan for future impacts. The SOFA program has released $1 million in grants to state agencies to facilitate the identification and construction of infrastructure projects that enhance community resilience. Grants were awarded based on the proposals' focus on implementing the Climate Framework for Delaware recommendations. DelDOT has a total of 10 recommendations to incorporate climate change into asset management.

A report titled, Creating Flood-Ready Communities: A Guide for Delaware Local Governments (Institute for Public Administration, 2016), which was sponsored and funded by DelDOT, provides information on climate adaptation ranging from incorporating planning and land use considerations to codes, ordinances, and standards associated with floodplain and drainage design and infrastructure implementation. This document notes that up to five percent of the state's total roadways could be affected with a 1.5-meter SLR. SR 1 is identified as one of three routes in Delaware that will see the most significant effects due to SLR. The report recommends using of living shorelines and GCI practices to protect coastal areas and near-shore features. To facilitate growth of living shorelines in Delaware, DNREC developed a streamlined permitting approach for small (<500 linear feet) living shoreline projects in 2012, and DNREC modified an existing grant program to match up to 50 percent, with a maximum of $5,000, for shoreline stabilization projects.

Additionally, an ongoing partnership between EPA, DNREC, DelDOT, FHWA, the United States Army Corps of Engineers (USACE), the United State Fish and Wildlife Service (USFWS), and CIB is the development of a Watershed Resources Registry (WRR). The WRR is an interactive mapping tool used to characterize and prioritize natural resource management opportunities at the watershed scale. This tool excels in identifying candidate locations for natural resource opportunities, especially in the context of comparative analyses with other locations. DelDOT was awarded a State Transportation Innovation Council (STIC) grant from FHWA in 2015 to develop the Delaware-specific version of the WRR, an effort initiated in 2016. The WRR model was not completed within the timeframe of this project, so the project team was unable to use this tool. However, some analysis methods developed in this project may be useful for informing Delaware's WRR efforts in the near future. This report includes information on how these analyses can be adapted to the WRR.

b. Project Area Description

i. General Conditions

The SR 1 corridor is vulnerable to the impacts of SLR, storm surges, and wave energy. Existing coastal landscape features, such as dunes, marsh, mudflats, beaches, and maritime forests provide protection against the impacts caused by frequent climatic events. However, some of these features exhibit stress associated with a changing climatic regime while others have failed during severe events, such as Hurricane Sandy. The transportation corridor in this region is experiencing similar impacts, which are predicted to worsen in the future. Figure 2 provides an example of the current impacts along the SR 1 corridor.

Figure 2 - Storm surge affecting the oceanside lane of Route 1 just north of Indian River Inlet Bridge. Source: capegazette.villagesoup.com (Image by: Dennis Forney)

The National Oceanic and Atmospheric Administration (NOAA) Coastal Flood Exposure Mapper (NOAA, 2017) was used to provide an initial planning-level review of potential SLR impacts on the SR 1 corridor. This online tool illustrates the scale of potential flooding (not including the effects of erosion, subsidence, or increased stormwater runoff associated with ongoing or future development. The tool uses the Mean Higher High Water (MHHW) as a reference for changes in SLR, and the elevations estimated do not include wind-driven tides. To estimate the potential effects of SLR for the year 2100, DNREC recommends three scenarios reflecting low, intermediate, and high values within the range of SLR estimates. These estimates are reflected by 0.5-, 1.0-, and 1.5-meter (1.5-, 3-, 4.5-foot) increases, respectively. A review of potential impacts using the NOAA Mapper shows that many areas within the SR 1 corridor will likely be affected using the low-end SLR increase of 0.5 meters (1.5 feet), and almost all of SR 1 within the limits of this pilot project will be inundated with a 1.5 meter (3-foot) SLR. This analysis illustrates the vulnerability of a section of transportation infrastructure that is key to the economic health and vitality of the region as well as the public safety of residents who call the Eastern Delmarva Peninsula home. Considering that this region is in the 95th percentile for populations above the age of 64, the issue of mobility is even more critical.

ii. Value of the SR 1 Corridor

Beyond public safety, SR 1 serves as an important corridor for the economic, social, and cultural health of the State of Delaware. This corridor, located between Rehoboth Beach and Fenwick Island, is comprised of approximately 17 miles of four-lane roadway. This corridor represents a major roadway network for recreation throughout the year. It has an Average Annual Daily Traffic (AADT) count of 23,755 vehicles in 2015 and is designated as a regional bicycle route. SR 1 is a key link to the infrastructure that supports and facilitates ecotourism, which has become a major source of income for the state. In 2010, the tourism industry alone contributed an estimated $2.1 billion to Delaware's gross domestic product, and this industry employs nearly 40,000 people and attracting over seven million visitors to the state annually (State of Delaware, 2012).

The Indian River Inlet Bridge, also known as the Charles W. Cullen Bridge, opened to traffic in May 2012 and it is a critical segment for SR 1 because it is part of a major evacuation route for the region. The substructure of the previous bridge was undermined by swift currents in the Indian River inlet that led to excessive erosion and scour of the channel bottom and pier supports. The new bridge was tested just months after it opened when Hurricane Sandy hit the Eastern Seaboard in October 2012. During this historic event, large sections of the SR 1 corridor including the Indian River Inlet Bridge, were closed due to high winds, flooding, and overwash deposition of sands. Enhancing the resilience of this corridor through GCI features can improve public safety and protect the economic and environmental value of the region. Figures 3 through 5 show the effects of Hurricane Sandy on SR 1 within the study corridor.

c. Targeted Challenges

SLR and stressors associated with urban stormwater runoff pose many challenges. In more urban areas, excessive precipitation runoff volumes are generated. Opportunities to reduce this runoff through green stormwater infrastructure (GSI) are limited by factors such as high groundwater tables, poorly drained soils, and existing public infrastructure. SLR and coastal storm surges create conditions where inland runoff is trapped within the corridor, increasing vulnerability. There are a number of areas where hardened or engineering solutions provide some short-term protection against coastal impacts. However, littoral dynamics and local aquatic ecology of the region are not well-served by these types of practices. For instance, the horseshoe crab's largest populations are found in this region. This crab has significant economic and ecological value; however, their habitat and ability to access coastal areas may be impeded by heavily engineered coastal infrastructure. Fortunately, this corridor has areas where coastal marshes and wetlands can enhance resilience by dampening or attenuating wave energy while providing additional co-benefits such as ecological and habitat enhancement. Based on geometry within the SR 1 corridor, other areas have the potential to provide these same ecosystem services, but local factors have limited this capacity due to drainage systems that are not appropriate for the energies and flows endemic to this area.

d. Project Overview

A focus of this project is to help characterize areas within the corridor that are vulnerable to coastal and urban runoff impacts and to develop techniques and approaches that address these current and future hazards through the use of GCI. Carefully selecting locations to apply these techniques helps facilitate GCI implementation, adding resiliency to the corridor and protecting critical transportation infrastructure and natural landscapes. The added resiliency associated with GCI provides ecosystem services to the residents that live, work, and recreate along this corridor. Additionally, protection against continued degradation of SR 1 due to climate change impacts could save the region from significant economic losses.

After reviewing and analyzing data focused on factors related to vulnerability and opportunities within the corridor, a total of six potential project sites were identified. Site visits and additional data collection and analysis identified two locations where conceptual designs were developed to inform the integration of natural infrastructure into practices throughout the corridor where possible. Lessons learned through these analyses and design efforts will be used to develop a policy and a design memorandum at a future time. DelDOT uses these memoranda as a means to explain new policies as well as provide new design and analysis methods and technical information. The intent of these memoranda is to catalyze the integration of GI into coastal and stormwater designs in the corridor, especially when targeting areas of vulnerability. The memoranda will provide critical design and analysis information in these areas as well as

Figure 3 - Route 1 closure between Dewey southbound to Bethany Beach due to flooding and storm surge impacts. Source: capegazette.villagesoup.com (Image by: Deny Howeth).

Figure 4 - Coastal Highway flooding between Dewey Beach and Indian River Inlet. Source: delawareonline.com

context and details regarding a policy of focusing on potentially vulnerable coastal areas. Ultimately, the experiences gained through this project effort will hopefully be helpful for other states with similar challenges.

Figure 5 - Erosion from Hurricane Sandy that Affected SR 1 Near the Indian River Inlet Bridge. Source: DNREC, 2012.

II. Methods

Various technical approaches were used during the project, ranging from remotely-sensed data and tools for screening project sites to site-level characteristics, such as wave energy calculations, stormwater runoff volumes, and flows generated at critical locations. Careful consideration was given to identifying appropriate techniques for the potential project locations. Specific information about the methods used in the project are listed below.

a. Methodology Overview

An analysis of the corridor was performed with information that included consideration for stormwater management opportunities, SLR and flooding impacts, and areas of coastal vulnerability. This effort was comprised of two levels of analysis — one was a planning-level initial assessment and the second a more detailed follow-on analysis that included considerations for site-level conditions.

A major factor considered in this study is coastal storm resilience. The extent to which a coastal roadway is affected by a coastal storm, or other flood event, is dependent on the structural characteristics of the road, its physical position relative to waterbodies and other land mass, the stillwater and wave elevations during the flood event, energies and vectors associated with the flood event (e.g., waves, wind, and concentrated flows), and the quality of existing buffering and other protection. For the purpose of this study, the structural characteristics and physical position of the roadway are considered constant, static conditions.

Further, the known challenges in the SR 1 corridor associated with flooding was a driver for considering both urban stormwater runoff impacts as well as coastal flooding as well as the interaction between the two flooding types. To assess resilience and vulnerabilities along a stretch of roadway, both flooding types require consideration. The level of consideration is driven by the project needs and goals. Beyond flooding and coastal vulnerabilities, a major priority was the opportunity to enhance coastal areas through GCI to improve resilience and benefit ecological value and water quality.

A goal of this study is to develop methodologies that allow for rapid, mostly desktop screening of stretches of coastal roadways and sites for the purposes of:

- Identifying vulnerability or resilience to significant or severe flooding conditions
- Prioritizing roadway stretches with the greatest vulnerability
- Integrating GCI and urban GSI practices for sites with coastal vulnerabilities as well as needs and opportunities related to stormwater management
- Providing assessment methods that can be applied to other coastal roadways.

As previously noted, the study area was analyzed at a preliminary and a detailed level. Specifically, the assessment involved three elements, as described below.

1. Initial Assessment Effort – The rapid acquisition of readily available information, much of which is accessible through the internet, followed by a screening of the information to gain a gross understanding of the regional condition relative to SLR and storm vulnerability as well as urban stormwater management challenges
2. Detailed Coastal Vulnerability Assessment – Analysis of the roadway along the SR 1 transportation corridor to identify areas of vulnerability to coastal flooding from tidal waterbodies, considering flood volumes and elevations, flood energies, wave energies and buffering potentials

3. Detailed Stormwater Management Assessment – To consider local needs related to urban stormwater runoff as well as limitations and constraints on siting of stormwater management facilities and to identify near-shore as well as upland opportunities for stormwater management investments

b. Initial Assessment Methodology

i. Initial Sea Level Rise, Flooding, and Stormwater Management Assessment Methodology

For linear projects, such as roadways, an initial assessment is often limited to information consisting of regional datasets and GIS-based information. Despite this limitation, today's regional data sources offer a great deal of information. The initial assessment focused on data collection, sorting the collected data based on relevance, and gaining a general understanding of the condition of the study area in the context of SLR, flooding, and stormwater management. The findings from this initial assessment, including policies and data, were fed into the detailed coastal vulnerability and stormwater management assessments. Basic information related to this initial assessment effort and analytical methods are listed below.

Data Sources

The initial assessment included information gained on topics such as flooding vulnerabilities, energy exposures, current roadway condition, and factors affecting the siting of stormwater management facilities. Provided below is a listing of pertinent data sets reviewed for the SR 1 study:

- For General Local Information:
    - Local Historic Aerial Photography
    - LiDAR Data
    - Interviews with DelDOT, DNREC, and municipal representatives
    - As-built drawings of roadway
    - Readily available stormwater infrastructure plans
- For Sea Level Rise Information:
    - NOAA Sea Level Rise Viewer (NOAA, 2017a)
    - State of Delaware SLR Tool (State of Delaware, 2017)
- For Flooding Information:
    - Delaware Flood Risk Adaptation Map (FRAM) online mapper (1-percent-annual-chance flood event with the addition of 3 feet of SLR) (FEMA, 2013)
    - NOAA Coastal Flood Exposure Mapper (includes mapping information on a coastal flood hazard composite, shallow coastal flooding, Federal Emergency Management Agency (FEMA) flood zones, storm surge, and SLR) (NOAA, 2017b)
    - Flood Insurance Study, Sussex County, Delaware (coastal flooding information, cross-sectional data, and modeling data)
- For Stormwater Management Information:
    - Delaware DNREC's Stormwater Assessment Study GIS 2.0 (DNREC, 2017), which provides information on factors critical to siting stormwater management facilities.

Initial Stormwater Management Assessment Methods

An initial screening used DNREC's Stormwater Assessment Study GIS 2.0 while focusing on two major factors affecting stormwater management facilities, depth to water table and hydrologic soil group. Figures 6 and 7 illustrate these stormwater management factors with additional mapping provided in

Appendix A. This information is critical to understanding where stormwater management opportunities may or may not exist.

Initial Sea-Level Rise and Flooding Assessment Methods

Several tools have been developed to capture the effects of SLR as well as inland and coastal flooding. These tools provide information that feeds into other analyses, such as wave energy calculation and stormwater management design. Many of these tools, available at both the state and federal level, were used to assess areas and identify potential sites for adaption.

Sea-Level Rise Assessment

In the context of planning, SLR is a significant challenge throughout most of the study area. As previously noted, DNREC information reflecting state policy recommends that three scenarios be considered for SLR impacts based on low (0.5 meter), intermediate (1.0 meter), and high (1.5 meter) projections of SLR up to the year 2100. The intermediate value is suggested as the most appropriate for planning purposes. Considering this, the project team used the NOAA Sea Level Rise Viewer to review impacts along the corridor. Figure 8 shows areas inundated by a three-foot (0.9 meter) SLR scenario in the middle section of the study area. An online tool provided by the State of Delaware, provides very similar results to the NOAA mapping tool. The effects of a one-meter SLR rise impact SR 1 significantly throughout much of the study area. This is a consideration when attempting to provide long-term protection of critical transportation infrastructure, such as SR 1.

Flooding Assessment

In coastal areas, flooding occurs in a variety of ways. Localized inland flooding is always a significant source of flood impacts, but coastal zones also must consider storm surge and energy, SLR, and the interaction of these dynamics. One tool used during the evaluation was the Flood Risk Adaptation Map (FRAM) online mapper that illustrates areas inundated under the combined effect of the 1-percent-annual-chance flood event (similar to the 100-year storm) and a one-meter SLR rise. Figure 9 illustrates these effects, which are widespread across the entire study area. More detailed gage records and anecdotal information were used at the site-level to account for these impacts in conceptual designs. An initial vulnerability assessment for inland flooding was performed using the NOAA Coastal Flood Exposure Mapper in conjunction with anecdotal data. Specifically, the “Shallow Coastal Flooding” layer of the Coastal Flood Exposure Mapper was used to identify potential areas of poorly draining low-lying areas.

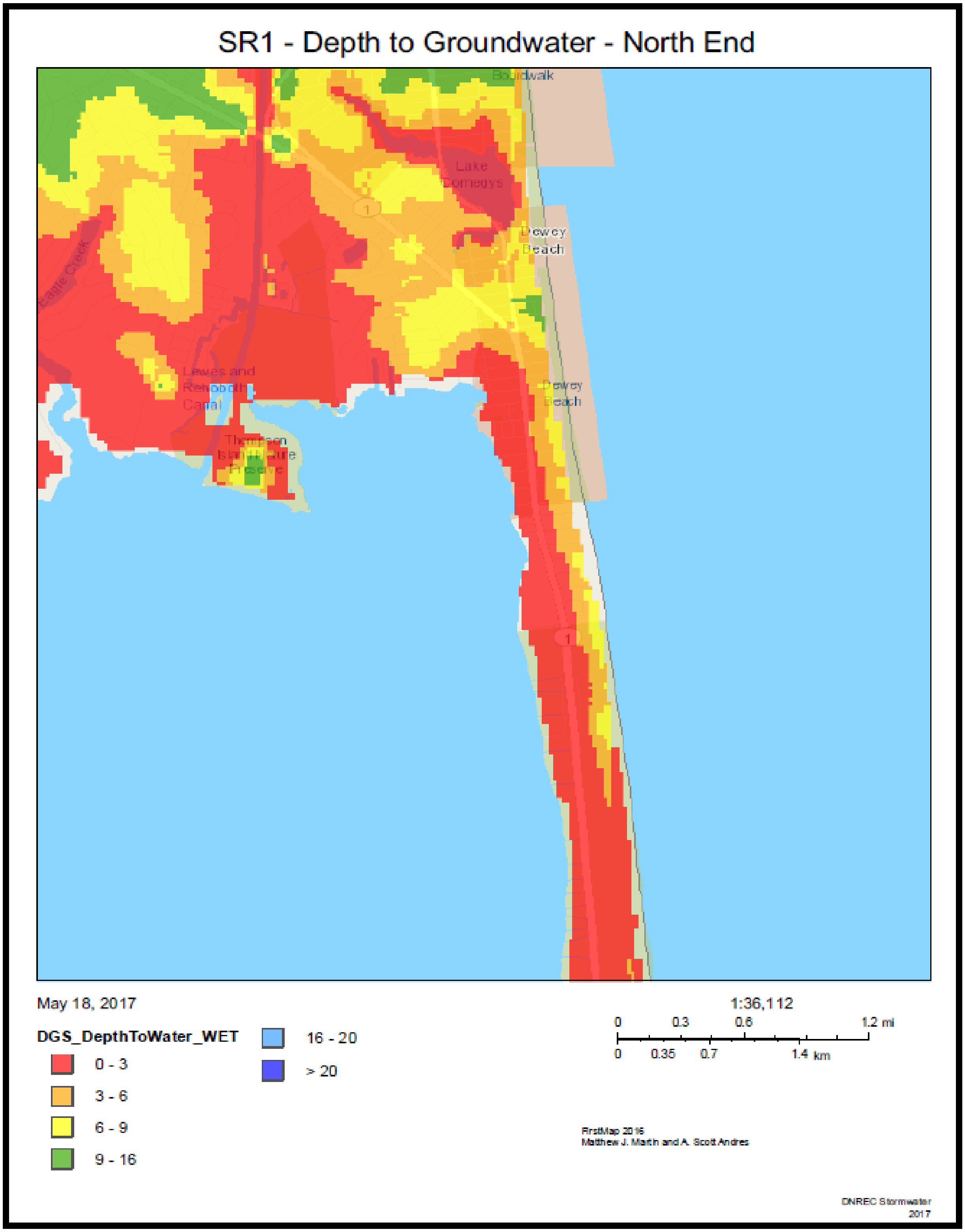

Figure 6 - Local Groundwater Table Depth in Northern Section of Study Area (DNREC, 2017) – Note that red is associated with areas where groundwater exists 0-3 feet below the surface.

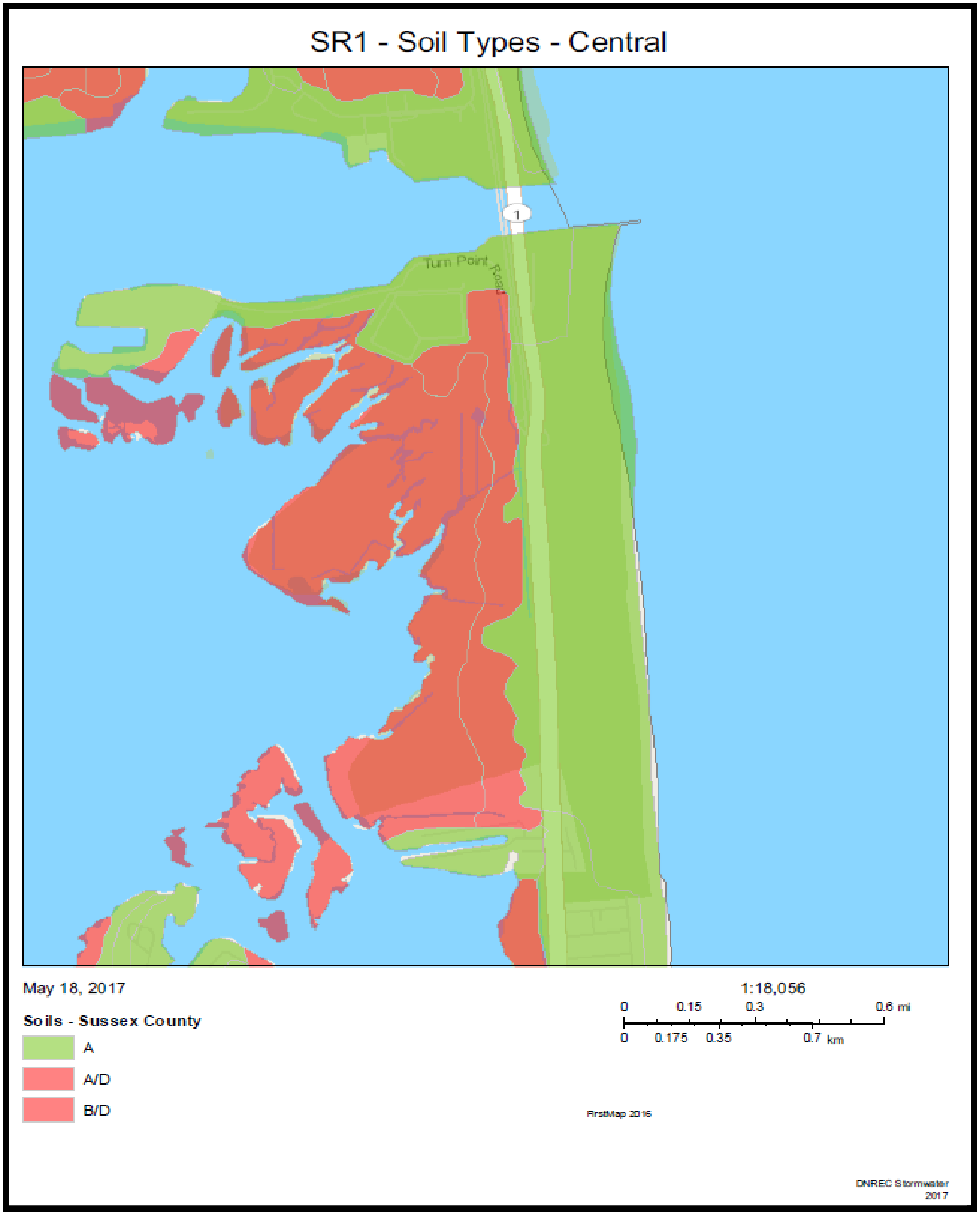

Figure 7 - Local Soil Conditions in Central Section of Study Area (DNREC, 2017) – note that red is associated with areas where the dominant soil type is "D," which is poorly-draining soils.

Figure 8 - Inundation along Middle Section of Study Area for 3 Feet (0.9 Meter) of Sea Level Rise (NOAA, 2017) – note that the area shaded light blue reflects inundated areas.

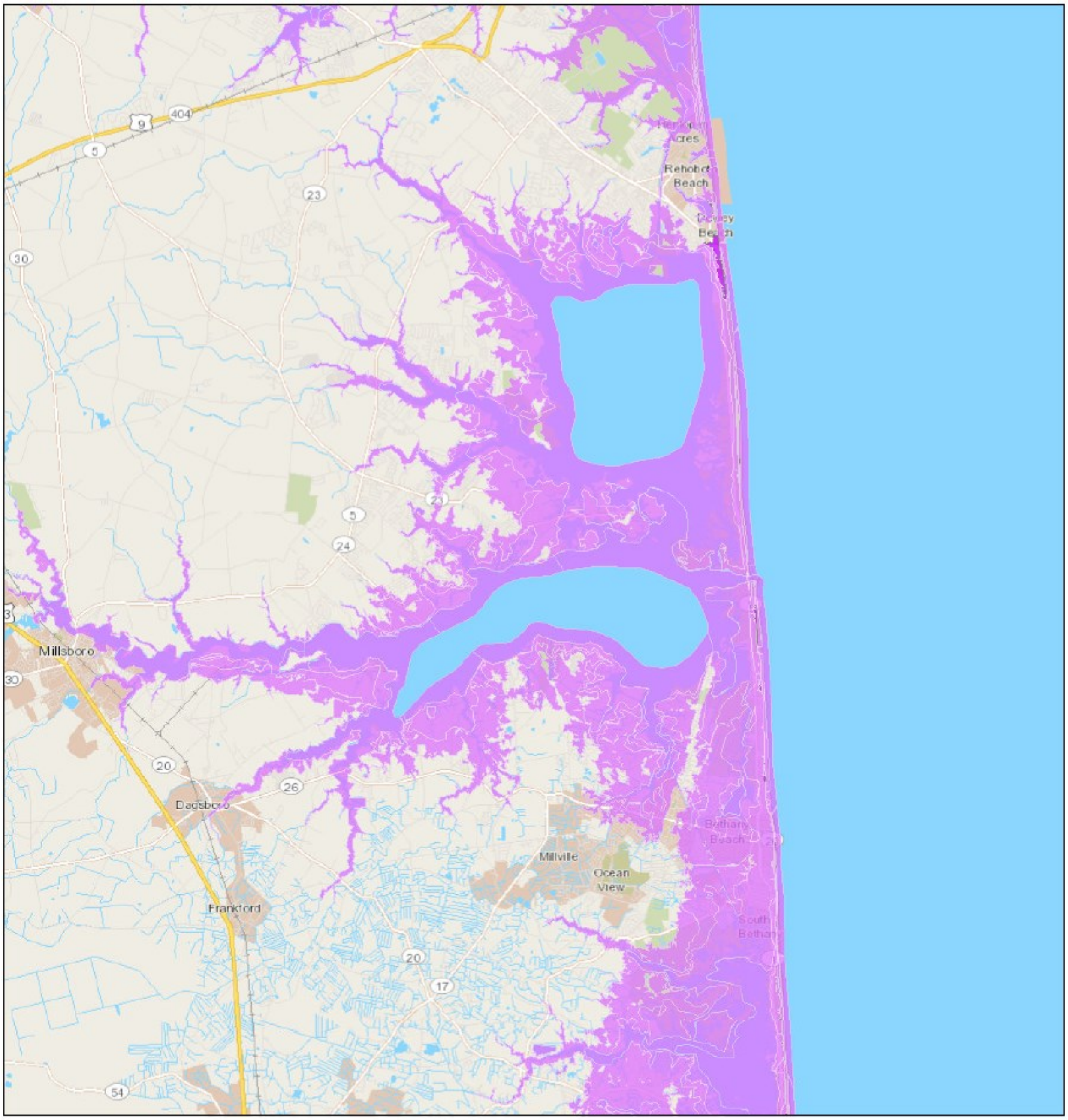

Figure 9 - Inundated Areas within the Study Area Based on the 1-Percent Storm Event and 1 Meter of Sea Level Rise (DNREC, 2017) – note that pink reflects inundated areas.

c. Detailed Assessment Methodology

i. Detailed Coastal Vulnerability Assessment Methodology

Evaluation of coastal vulnerabilities and resilience involved evaluating flood volume, wave energy contacting SR 1 during storm events, and the extent of marsh buffer. These three criteria were assessed using modeling. The model used the following information:

- FEMA Flood Insurance Study information (modeling methodologies, initial stillwater elevations for various storm frequencies, and base storm assumptions)
- The most recent LiDAR data (marsh and land elevations)
- SR 1 as-built data for the road surfaces
- Local information as available about marsh flora types, morphological characteristics, and plant spacing (in the absence of local information, the marsh wave dampening modeling methodology offers default values).

Modeling was performed over the entire 17-mile SR 1 corridor, from the Town of Dewey Beach to the Delaware-Maryland State Line.

Along the corridor, the study area was segregated into reaches established based on similarities and consistencies in physical conditions, including factors such as marsh widths and elevations, road elevations, shoreline types, and dominant land use types. Within each reach, a representative cross-section was generated representing a section perpendicular to the coastline, from the subtidal region of the adjacent waterbody to shortly beyond the upland highpoint used in the model. A total of 15 cross-sections, one for each reach, were created along the bayside (west) of the corridor and eight cross-sections were generated along the ocean side (east) of the corridor (see Figures 10 and 11).

The shoreline reaches were modeled for stillwater flooding (storm surge without energy), transmitted wave energy, and wave dampening by structural, vegetated, and elevated land features. To make the assessment more user friendly and compatible with other existing approaches, the base model is provided in the form of a spreadsheet. It uses an approach based on the FEMA Flood Insurance Study (FIS), which is based on methodologies initially presented in Methodology for Calculating Wave Action Effects Associated with Storm Surges (NAS, 1977).

Appendix B provides spreadsheets associated with the information presented in this section. The spreadsheet cells are color-coded: orange cells are data input cells; green cells are constant local default inputs; and blue cells are automatic calculation cells. As such, only the orange cells were changing variables.

Provided below are the spreadsheet inputs.

Spreadsheet Inputs: General Information – provides the basic cross-section identification and storm data

- Project Name
- Project Location/Cross Section Designation
- Start and End Coordinates of Cross Section
- N-Year Event Being Modelled
- FEMA FIS Stillwater Storm Tide/Surge Elevation (S) in feet NAVD88
- Fetch (Miles), Maximum

Spreadsheet Inputs: Initial Wave Height – using information from the General Information section, established the initial wave height (H1)

- Fetch Factor F, from the fetch factor curve provided in the spreadsheet

Spreadsheet Inputs: Breakwater Obstruction – represents the first potential obstruction, which can dampen the H1.

- The average elevation of the elongated structure (zb) in feet NAVD88 (i.e., the breakwater). This feature is not always present along the coastline.

Spreadsheet Inputs Marsh Obstruction (fringe marsh) – The first of the two marsh obstructions, the fringe marsh is a common portion of the estuary marsh occurring along the marsh edge adjacent to an open waterbody. It is typically higher in elevation than the marsh platform and consists of taller dense Spartina vegetation. Regional default values for grass height (h), marsh grass mean effective diameter (D), and marsh grass average width (b) were determined based on the Partnership for the Delaware Estuary (PDE) Mid-Atlantic Coastal Wetland Assessment (MACWA) vegetation dataset collected between 2011 and 2016 (Elsey-Quirk, 2014; Raper and Watson, 2016), which is plant data collected in the Barnegat Bay and Delaware Bay Estuary systems.

- Average Marsh Ground Elevation (zm) in feet NAVD88 (2016 LiDAR data)
- Average Marsh Width (w) in feet

Spreadsheet Inputs Marsh Obstruction (interior marsh platform) – The second of the two marsh obstructions, the platform marsh is the portion of the estuary marsh occurring on the interior platform. It represents the majority, if not all, of the marsh. It is typically lower in elevation than the fringe marsh and consists of shorter Spartina vegetation. Regional default values for grass height (h), marsh grass mean effective diameter (D), and marsh grass average width (b) were determined based on the PDE MACWA vegetation dataset collected between 2011 and 2016 (Elsey-Quirk, 2014; Raper and Watson, 2016), which is plant data collected in the Barnegat Bay and Delaware Bay Estuary systems. Some values were slightly reduced to conservatively account for portions of the marsh that may be waterlogged with lower biomass.

- Average Marsh Ground Elevation (zm) in feet NAVD88 (2016 LiDAR data)
- Average Marsh Width (w) in feet

Spreadsheet Inputs Dune/Sloped Obstruction – evaluating wave dampening associated with a dune or other non-armored sloped feature. The corridor has dunes along the eastern side and a significantly lower vegetated slope on the western bayside. Using the dune dampening formula for well-vegetated slopes is a conservative approach to avoid false-negative conclusions.

- Dune Top Elevation (zd) in feet NAVD88 (lowest road elevation within reach from as-built drawings)

The model was run for all 23 cross sections for three n-Event storm scenarios that included:

- 10-percent Annual Chance (~10-year event)
- 2-percent Annual Chance (~50-year event)
- 1-percent Annual Chance (~100-year event)

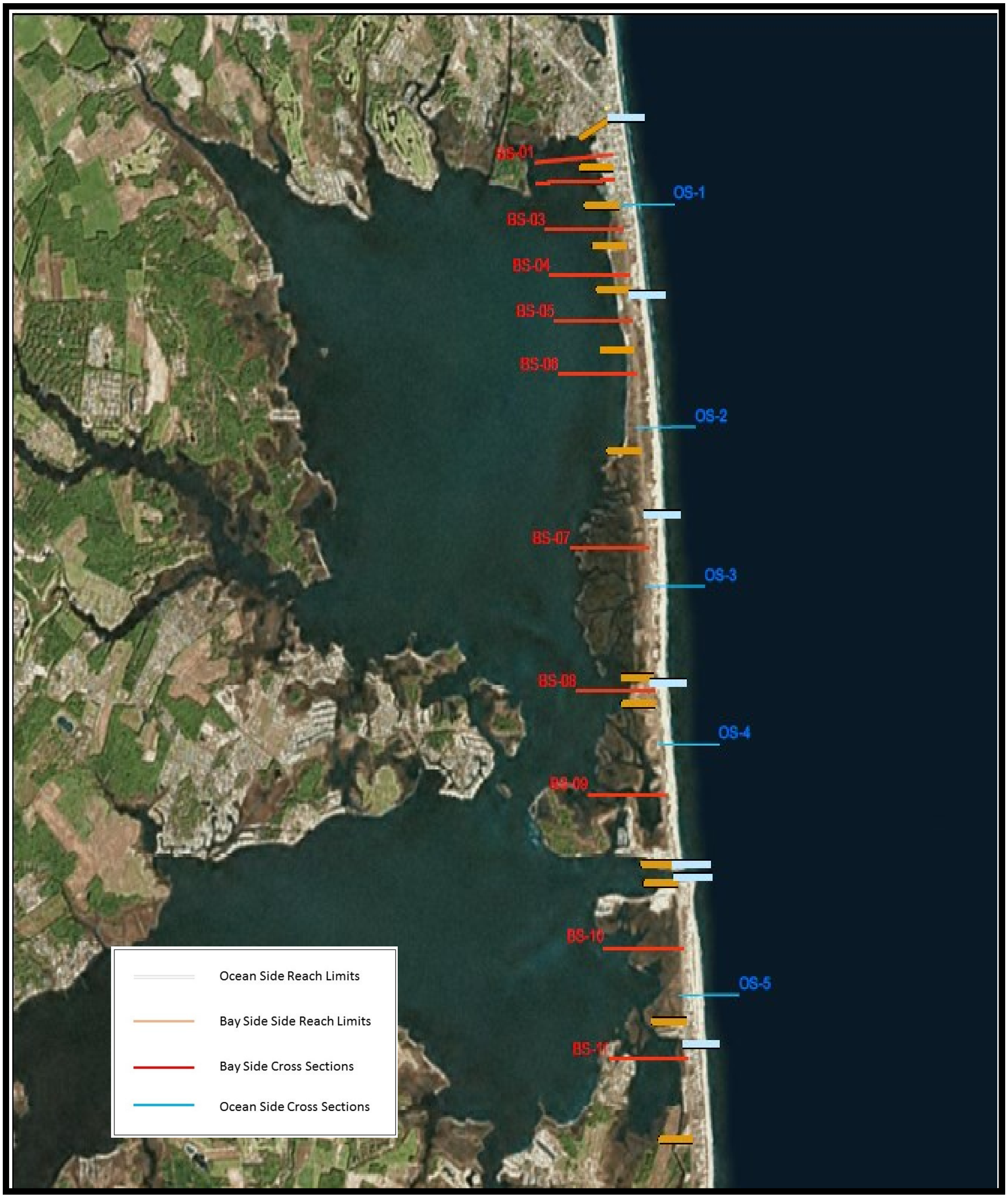

Figure 10 - Cross-Sections BS-01 through BS-11 and OS-1 through OS-5. Map Credit: Google Earth, Map©2018Google.

Figure 11 - Cross-Sections BS-12 through BS-15 and OS-6 through OS-8. Map Credit: Google Earth, Map©2018Google.

The 2-percent annual event is the chosen target because it best matches the Design Criteria Frequency for Pipe Culverts based on the functional classification of the roadway. Coastal highway is classified as a principal arterial, which requires a 50-year return period as in the DelDOT Road Design Manual. The severe nor'easter event, a relatively common event in the fall and winter, represents a unique scenario for the bayside coastline because it assumes the prevailing wind is coming out of the east, away from the coastline of concern. As such, no surge or waves are associated with the event, only a blow-in bay tide. Tables II.1 through II.3 in Appendix B are modeling summaries for each n-Event scenario.

Evaluation of Historic Marsh Gains and Losses - Using GIS techniques, the footprints of the bayside marsh adjacent to coastal highway, as existing in 1968 and 2015 aerial photography, were delineated. Care was taken to match aerial photography, to the greatest extent practical, with similar positions in the tidal cycle. The 2015 delineated marsh layer was superimposed over the delineated 1968 marsh layer. Losses and gains of marsh edge or shoreline and marsh acreage conversion to open water were plotted and calculated for each reach (Appendix B - Table II.6).

Modeling Minimum Marsh Widths for Wave Dampening – The desktop data collected and model allows for estimating the minimum required marsh width to dampen transmitted wave energy to a nondestructive size. According to the FEMA FIS, a wave height (amplitude) as low as 1.5 feet is sufficient to "cause significant damage to structures when constructed without consideration to the coastal hazards." FEMA developed guidance on mapping the landward limit of the 1.5-foot wave referred to as the Limit of Moderate Wave Action (LiMWA). This limit was developed as a communication tool to help describe elevated risk to certain coastal areas. Along a highway corridor, however, wave energy affects more than structures. It also affects roadways, sloped banks, drainage system infrastructure, and natural buffers. As such, there is an interest in eliminating as much destructive wave energy as possible prior to contacting the edge of a roadway, its toe of slope, or supporting infrastructure. There is a point where the amplitude of a wave is small enough that it no longer has enough concentrated energy to be destructive. The maximum non-destructive wave amplitude is dependent on factors such as substrate type (e.g., loam, silt, sand, gravel, stone, etc.), slope, water depth, and vegetation or other obstructions. Along the coastal corridor, a wave amplitude of 2.5 to 5.0 inches (0.2 to 0.4 foot) appears to be an acceptable range of low to non-destructive energy.

Using the model and inputs for each transect, the user can determine an estimated platform marsh width that would dampen the transmitted wave to just under 0.2 feet in height for a particular n-Event. This calculated "ideal" minimum dampening width ($Wm^{n\text{-}Event}$) was calculated for all bayside reaches for each of the three n-Event (see Appendix B -Tables II.1 through II.3). Additionally, there is a relationship between the wave crest (WC) divided by the freeboard (F):

- WC/F = wave limiting elevation relationship (ER)

Where:

- WC = Stillwater elevation (S) for the FEMAS FIS plus the wave height entering the marsh (H1) which was modelled
- F = average height of the water column over the marsh platform, calculated as WC minus the average platform marsh elevation using USGS LiDAR, last modified 2017 (h)

The wave-limiting elevation relationship for each reach in the study area was plotted against the modeled minimum dampening width. Based on the generated slope of the plotted curve, the following empirically-derived formulas were developed to estimate, for each n-Event, the minimum platform marsh width ($Wm^{n\text{-}Event}$) needed to dampen wave energy to a nondestructive size at any given reach within the study area. The high R^2 values for these relationships (as listed below) reflects the amount of explained variance in the datasets and illustrates the close relationship between the variables in the empirical relationships listed below. Graphical and tabular information on these relationships is provided in Appendix C.

- n-Event = 10-percent annual event

- $Wm^{10} = 1881 * ER^{-4.197}$, $R^2 = 0.9252$
- n-Event = 2-percent annual event
  - $Wm^{2} = 2588.9 * ER^{-3.755}$, $R^2 = 0.9428$
- n-Event = 1-percent annual event
  - $Wm^{1} = 2909.9 * ER^{-3.685}$, $R^2 = 0.9522$
- Below is an example of applying this information using a given dataset:
  - For reach BS-05
    - Given:
      - WC = 6.40 ft
      - F = 6.40 ft – 2.46 ft = 3.94 ft
    - ER = (6.40 ft /3.94 ft) = 1.62
    - Using the 10-percent annual event calculation above:
      - $Wm^{10} = 1881 * ER^{-4.197} = 1881 * (1.62)^{-4.197} = 248.34$ ft.
      - Note, if available use the modeled value for the W^{mn}-Event, otherwise use the calculations above.

Summary of Coastal Vulnerability Assessment

The results of this modeling effort enable an individual, using easily attainable desktop information (i.e., LiDAR and FEMA FIS) to evaluate the level of vulnerability or resilience along a given bayside portion of the SR 1 corridor. Specifically, the methodology laid out in this section results in outputs that can be used to develop coastal vulnerability scores, which will be detailed in a subsequent section titled, “Adaptation Options.” This coastal vulnerability scoring is based on a non-dimensional index that enables a comparative analysis between varying potential candidate restoration sites.

Ultimately, the application of the methodology outlined in this document is to reduce the vulnerability of coastal areas through actions. An example of such an action is targeting areas with insufficient buffer width. Such areas may be candidates to receive dredged spoils from nearby dredging projects. This methodology may facilitate “win-win” cost-efficient solutions. Further, understanding the natural buffering capacity along a reach of shoreline provides insights for planning resilience strategies.

ii. Detailed Stormwater Management Assessment

The analysis associated with stormwater management was based on findings from the initial assessment complemented by additional resources and information, including documents associated with stormwater management siting and planning provided by municipalities in the study area. Information revealing ongoing stormwater projects in the study area was also considered along with information gathered through field investigations made by the project team. The main factor included in this assessment is the ability to combine CGI projects with GSI elements either in near-shore or upland locations. It is ideal to identify sites this CGI and GSI practices can be integrated in a manner that reduces costs, increases ecological value, and reflects challenges and opportunities common throughout the study area.

III. Adaptation Options

Areas along the SR 1 corridor have varying characteristics, are located within unique land use and landscape contexts, and also reflect differing levels of vulnerability. Solutions for enhancing resiliency through adaptation in these different areas and situations will vary as well. The process for identifying sites for adaptation, as described in the previous chapter, included an initial analysis at the planning scale following by a more detailed analysis based on the level of coastal vulnerability as well as opportunities to address other challenges, such as urban stormwater runoff volume and quality. This section describes the results of this two-step analysis used to identify sites for conceptual adaptation design development as well as basic information about the selected adaptation locations.

a. Results of Initial Assessment

The first step in selecting potential adaptation sites was to decide on general areas of focus. As explained in the previous section, SR 1 can be affected by ocean-side dynamics and bay-side dynamics. A well-developed dune system, called the Eastern Dune System, is located east of SR 1 throughout the study area and was assumed to provide significant protection against ocean side forces. Detailed analysis was performed to confirm this assumption, as described in subsequent sections in this report.

Considering bayside reaches only, the project team wanted to identify six sites that had adaptation potential and represented common challenges in the area that could also be applicable for other entities (transportation agencies, etc.). With these two goals in mind, the project team assessed the corridor using the initial assessment described in the previous section, screening for potential sites using planning-level information. The six chosen sites were considered candidates for conceptual design, and the detailed assessment determined which two candidate sites would be selected for conceptual design.

A total of fifteen potential sites were considered in the initial assessment. These locations coincided with bayside areas where detailed analyses were also targeted. The six sites chosen were spread throughout the study area and identified as having the best potential for uplift as well as reflecting the types of challenges consistent throughout the SR 1 corridor. For instance, some areas are in or near urban settings while other locations are sited near critical features, such as bridges or other transportation infrastructure. The six selected sites are listed below and shown in Figure 12. The selected sites are circled and shown along with the 15 sites considered. Note that the sites are identified in the figure as “BS-XX,” which reflects “Bay Side” and a cross-section number, as the detailed assessment used cross-sections. The selected sites along with their identifier and a brief reasoning for site selection are listed below.

- Read Avenue (BS-01) – urban area with an ongoing coastal project identified along with identified stormwater management needs
- Indian Beach (BS-03) – near urban area and located near an area with minimal marsh buffer width
- Key Box Road Area (BS-05) – located in an area with many non-functioning tidal ditches, reflecting a consistent challenge for many other areas throughout the study reach
- Indian River Inlet Bridge Area (BS-09) – located near critical transportation infrastructure
- National Guard Area (BS-12) – located in an area with significant stormwater management opportunities and potential for marsh restoration
- South Bethany Beach (BS-13) – near urban area in southern portion of the study area

Figure 12 – All Bay-Side Reach Locations with the Six Locations Selected through Initial Screening.
Map Credit: Google Earth, Map©2018Google.

b. Results of Detailed Assessment

After working at the planning scale, the project team focused in on potential project locations and eventually chose two sites where conceptual designs and associated information were developed. These designs and other technical documentation are based on sound engineering and scientific practices. The design development methods used in this project form the basis for policy and design memoranda that will, after completion, be used to more effectively integrate GI and other natural approaches into engineered designs for coastal protection and stormwater management. A total of 15 sites were analyzed, as identified in Figure 12.

Despite the fact that the initial assessment identified six sites, all 15 sites were analyzed because they were identified for detailed analysis prior to selection in the initial assessment. Additionally, an analysis of all fifteen was performed to ensure that the six sites identified in the initial assessment reflected ideal sites for conceptual design development. The results of the coastal vulnerability and stormwater management assessments are detailed in the following sections.

i. Evaluation of Coastal Vulnerability

A synthesis of coastal vulnerability and resilience modeling data for the ocean side and bayside coastlines were performed separately for several reasons. First, except for certain minor beach access points and inlets, there is a nearly contiguous dune system along the entire ocean side of the study area, but there is no dune system along the bay side. Second, the type and extent of protection systems in place vary throughout the study area. Along the ocean side of the corridor, the highest points are atop the dunes, while the bayside high points of interest are found on the southbound lane of SR 1. Third, protection along the east side of the corridor consists of beach and dune systems, without marsh contribution, while the bayside of the corridor is predominantly marsh and a small slope leading to the SR 1 southbound lanes.

Ocean Side Access Point Vulnerability Analysis for Episodic Events

The size and height of dunes over the majority of the Eastern Dune System offers SR 1 protection from both flooding and wave energy. Modeled stillwater elevations were well below the dune height. Regarding wave energy, Sussex County, Delaware FEMA FIS indicated that the 1-percent annual event – Significant Wave Height along the ocean side of the corridor ranges between 15 and 18 feet, NAVD88. These ocean waves would be depth limited, forcing them to break well before the dunes. However, it is assumed that smaller waves (circumstance specific) could reach the primary dunes.

The weakest points of the EDS are the access points from SR 1 to the Ocean Beach, as evidenced by the small breach that occurred on September 19, 2017 due to Hurricane Jose (see Figure 13). To better understand the vulnerability of these access points in the EDS, an assessment screened 11 public access points along the SR 1 corridor. The screening involved running transects along the access routes and comparing the highest points along the routes to the n-Year Flood Event Elevations modeled during this study (transects provided in Appendix D). Elevations were obtained from existing LiDAR data collected between winter 2013 and spring 2014, last updated July 2017. Aerial imagery used in the assessment was collected April 2017. The assessment did not include the accesses immediately north and south of the Indian River Inlet. Due to the extensive construction that occurred since the collection of the base LiDAR dataset, LiDAR data for this area were assumed to be unreliable. This assessment did not evaluate residential, privately owned areas adjacent to the dunes because they were determined to be out of the scope of this study. This study recognizes that any dune creation, re-establishment, and maintenance work, as well as severe storm events occurring subsequent to the LiDAR data collection may have altered the dune elevations.

Figure 13 – Breach of Eastern Dune System at Conquest Road on September 19, 2017. Source: DelDOT

The modeled stillwater elevations were all below the maximum access route elevations. However, the model assumed the primary wave to be fully dampened by the dune. It did not take into consideration smaller waves reaching the dune. Assuming the worst case, a maximum wave crest elevation can be conservatively estimated by adding the n-Year – Flood Event Elevation to the maximum depth-limited nearshore wave height for that depth. The maximum depth limit wave height for a nearshore environment can be estimated by dividing the n-Year – Flood Event Elevation by 1.3. Using the 10 percent Flood Event Elevation presented in Table 1, the access corridors at Conquest Road and Seaside Villas may be vulnerable to flooding and breaches, which is consistent with the dynamics of the September 19 breach, as noted previously. See Figure 14 for oceanside reach locations.

Table 1 – Critical Physical and Coastal Geometries and Resulting Hydraulic Impacts at Eastern Dune Area

					n-Year Flood Event Elevation				Elevations Along Access Corridor from SR1 to Beach	
Access Description	FEMA FIS Transect	Modeled Transect	Modeled Transect Dune Height	1% Annual Event – Significant Wave Height	10% Annual	2% Annual	1% Annual	Max. Est. Wave Crest for 10% Annual Event	High Point Along Access at Main Dune	High Point Along Access Between Main Dune and SR1
Towers Road	37	**OS-1**	**14.66**	**17.04**	**5.9**	**7.3**	**7.9**	**10.4**	**15.7**	**3.93**
Keybox Road	42	**OS-2**	**27.17**	**15.17**	**6**	**7.4**	**8**	**10.6**	**17.71**	**4.26**
Conquest Road	45	**OS-3**	**22.87**	**15.88**	**6.2**	**7.5**	**8.1**	**11.0**	**10.49**	**8.8**
Unnamed Crossing	45	**OS-3**	**22.87**	**15.88**	**6.2**	**7.5**	**8.1**	**11.0**	**16.73**	**5.24**
Life Guard Museum	45	**OS-3**	**22.87**	**15.88**	**6.2**	**7.5**	**8.1**	**11.0**	**14.43**	**5.57**
Road 50D	48	**OS-4**	**12.89**	**16.39**	**6.2**	**7.5**	**8.1**	**11.0**	**12.4**	**4.6**
3Rs Road	52	**OS-5**	**15.88**	**16.91**	**6**	**7.2**	**7.8**	**10.6**	**11.8**	**7.12**
Assawoman North	66	**OS-8**	**21.62**	**17.07**	**6.3**	**7.2**	**7.7**	**11.1**	**12.13**	**7.87**
Seaside Villas Access	66	**OS-8**	**21.62**	**17.07**	**6.3**	**7.2**	**7.7**	**11.1**	**11.1**	**9.18**
Ocean Park Lane	66	**OS-8**	**21.62**	**17.07**	**6.3**	**7.2**	**7.7**	**11.1**	**13.77**	**6.56**
St. Park at Fenwick Is.	66	**OS-8**	**21.62**	**17.07**	**6.3**	**7.2**	**7.7**	**11.1**	**17.38**	**4.9**

Notes:

- All elevations are in feet, NAVD88
- Elevations were either taken from FEMA FIS, Sussex County, Delaware or from LiDAR data collected between winter 2013 and spring 2014, last modified July 2017

Evaluations of flooding, wave energy, and buffer resilience, detailed below, are focused on bayside dynamics, as the analyses performed showed that all ocean side areas are highly resilient.

Figure 13 – All Ocean-Side Reach Locations. Map Credit: Google Earth, Map©2018Google.

Flooding

The evaluation of the model results, relative to flood vulnerability, is a straight forward process. The assessment is two-fold. First, is a flooding presence-absence test for various storm event scenarios. It is recommended that these events (referred to as “n-Events” in this document) include the 1-percent, 2-percent, and 10-percent annual events (similar to a 100-, 50-, and 10-year storm event, respectively). The second test is a comparison of the calculated n-Event flood elevation to the top of dune/slope elevation in each coastal reach. For this evaluation, the southbound lane of SR 1 was the top of dune/slope elevation. A positive number greater than 1.00-foot flood event clearance indicates resilience to the applicable n-Event. A positive number between 0 and 1.00 foot or a negative flood event clearance indicates a vulnerability to the applicable n-Event. The scoring associated with the flooding analysis was assigned to the four following classes:

- Highly vulnerable to flooding - A flood event clearance of 0.00 foot or lower (Score 4)
- Vulnerable to flooding - A flood event clearance between 0.00 and 1.00 foot (Score 3)
- Resilient to flooding - A flood event clearance between 1.00 foot and 3.00 feet (Score 2)
- Highly resilient to flooding - A flood event clearance of 3.00 feet or greater (Score 1)

As previously noted, all ocean side reaches were determined to be highly resilient for all n-Events modeled. For the bayside reaches during the 10-percent annual event, modeling showed BS-12, BS-13, BS-14, BS-15 locations as resilient to flooding. Modeling showed BS-02 and BS-03 as vulnerable to flooding. The remainder of reaches were determined to be highly vulnerable to flooding. During the 2-percent annual event, modeling showed that bayside reaches BS-12, BS-13, BS-14, BS-15 were vulnerable to flooding. The remainder of reaches were determined to be highly vulnerable to flooding. For the bayside reaches during the 1-percent annual event, all reaches were determined to be highly vulnerable to flooding. Detailed modeling information for this analysis is presented in Table 2 (as well as in Appendix B - Table II.4).

It should be noted that this information reflects current climatic conditions based on historic data, which is consistent with current Flood Insurance Report information and FEMA modeling assumptions. To consider impacts associated with SLR, the FEMA stillwater projections would need to incorporate SLR rates into the storm high tide estimate and adjust the surge estimates. The adjusted stillwater elevations could be input into the model, similar to how the current stillwater elevations are input to generate a final n-Event storm elevation.

To evaluate the effects of SLR along the SR 1 corridor, preliminary modeling projected SLR out 50 years to 2067. To determine the extent of SLR, DNREC’s intermediate projection plot of 1 meter by the year 2100 was used. At the year 2067, SLR is projected to be approximately 0.54 meter (1.77 feet NAVD88). This value was applied to a current mean high water of approximately 1.19 feet NAVD88. As such, by 2067 the typical high tide will be approximately 2.95 feet NAVD88, which is higher than the SR 1 southbound lane low points at reaches SB-05, SB-06, SB-07, and SB-09. These reaches may be inundated almost daily as 2067 approaches. Preliminary modeling also was performed for the 10-percent event in 2067. In the absence of a specific SLR model identified by FEMA, and per FEMA’s recommendation (FEMA Q&A), the projected 1.77-foot SLR was added to the stillwater elevations at each transect for the 10-percent event listed in the FEMA-FIS, and the models were rerun. The model also assumed natural marsh platform elevation increases at a rate half that of the SLR rate. Preliminary modeling suggested that by 2067 the 10-percent event n-elevation will slightly exceed that of the current 1-percent event n-elevation.

Table 2 - Summary of Coastal Vulnerability Scores by Cross-Section

Reach	**n-Event = 10-Percent Annual Event**		**n-Event = 2-Percent Annual Event**		**n-Event = 1-Percent Annual Event**	
	Flood Event Clearance* (feet)	Flood Class**	Flood Event Clearance* (feet)	Flood Class**	Flood Event Clearance* (feet)	Flood Class**
BS-01	-0.73	HV	-1.81	HV	-2.27	HV
BS-02	0.55	V	-0.20	HV	-0.52	HV
BS-03	0.55	V	-0.23	HV	-0.69	HV
BS-04	-0.84	HV	-1.48	HV	-1.81	HV
BS-05	-2.28	HV	-2.95	HV	-3.29	HV
BS-06	-2.76	HV	-3.43	HV	-3.77	HV
BS-07	-2.53	HV	-3.35	HV	-3.45	HV
BS-08	-1.16	HV	-2.00	HV	-2.10	HV
BS-09	-1.71	HV	-2.62	HV	-2.74	HV
BS-10	-0.33	HV	-0.96	HV	-1.17	HV
BS-11	-0.39	HV	-1.23	HV	-1.46	HV
BS-12	1.75	R	0.25	V	-0.29	HV
BS-13	1.75	R	0.25	V	-0.36	HV
BS-14	1.63	R	0.13	V	-0.57	HV
BS-15	1.64	R	0.14	V	-0.56	HV
OS-01	8.76	HR	7.36	HR	6.76	HR
OS-02	21.17	HR	19.77	HR	19.17	HR
OS-03	16.67	HR	15.37	HR	14.77	HR
OS-04	6.69	HR	5.39	HR	4.79	HR
OS-05	9.88	HR	8.68	HR	8.08	HR
OS-06	11.38	HR	10.18	HR	9.68	HR
OS-07	10.63	HR	9.53	HR	9.03	HR
OS-08	15.32	HR	14.42	HR	13.92	HR

*Flood Event Clearance = Dune/Slope Top Elevation – n-Year Flood Event Elevation (NAVD 88).

**Flood Class: HR – Highly Flood Resilient; R-Flood Resilient; V-Flood Vulnerable; HV-Highly Flood Vulnerable

Wave Energy

Wave modeling estimates the initial wave created in open water (H1 wave) and the reduction (transmitted form) of the wave as it passes over and through obstructions (e.g., breakwaters, vegetation, and slopes/dunes), until or if it reaches the roadway or a wave-limiting feature. H_1 is the initial wave formed in the bay, and it is calculated by 0.78 multiplied by a fetch factor and the still-water storm tide elevation at the normal mean sea level shoreline. The t-wave, the dampened form of the wave once it passes over or through an obstruction, is affected by many variables, such as the obstruction type, height, width, and rigidity.

Along the SR 1, the eastern ocean side of the corridor has a high, maintained, dune system that acts as a wave-limiting feature, as previously described. None of the wave energies modeled for the different n-

Events made it past the dune system (Appendix B - Table II.5). Along the western bayside of the corridor, no continual dune systems are present. Instead, wave energy attenuation relies primarily on natural energy dampening by marshes, low slopes leading to the southbound lane, and linear structural or armored features.

Research and post-disaster damage assessments were used by FEMA to determine that a wave 1.5-feet high or greater has the potential to induce significant structural damage during a storm. FEMA identified the 1.5-foot wave to be the Limit of Moderate Wave Action (LiMWA) line (2008 FEMA Procedure Memorandum 50). The final t-wave elevation was used to set the scoring. The LiMWA or greater was adopted as a worst-case category. The following transmitted wave (t-wave) height categories were assigned the following classes:

- Significantly Destructive T-Wave Height – A t-wave height equal or greater than 1.5 feet, consistent with FEMA's LiMWA (Score 4)
- Destructive T-Wave Height – A t-wave height between 0.5 foot and 1.5 feet (Score 3)
- Minimally Destructive T-Wave Height – A t-wave height between 0.2 foot and 0.5 foot (Score 2)
- Non-Destructive T-Wave Height – A t-wave height less than 0.2 foot (Score 1)

During the 10-percent annual event, modeling showed bayside reaches BS-01 and BS-11 were exposed to minimally destructive t-wave heights. All other reaches were determined to be exposed to non-destructive t-wave heights or no t-wave at all.

During the 2-percent annual event, modeling showed bayside reaches BS-01 and BS-11 were exposed to destructive t-wave heights. Modeling showed BS-05 and BS-09 were exposed to minimally destructive t-wave heights. The remainder of reaches were determined to be exposed to non-destructive t-wave heights or no t-wave at all.

During the 1-percent annual event, modeling showed bayside reaches BS-01 and BS-11 were exposed to destructive t-wave heights. Modeling showed BS-03, BS-05, BS-06, BS-09, BS-14, and BS-15 were exposed to minimally destructive t-wave heights. All other reaches were determined to be exposed to non-destructive t-wave heights or no t-wave at all.

Buffer Resilience

Natural buffers play a crucial role in the resilience of the SR 1 corridor. Along the eastern ocean side of the corridor, the Eastern Dune System buffers the highway from all modeled n-Events, as noted in earlier sections.

Along the western bayside of the corridor, the marshes are the primary buffering mechanism, as they naturally dampen wave energy. In many coastal areas where transportation infrastructure is located, marshes are the primary buffering mechanism. The height, extent, and plant community health of the marshes dictate their buffering capacity, and in turn, the amount of resilience they add to the SR 1. To evaluate the marsh buffers for resilience, both historic marsh condition trends and the current buffering ability of the marsh were evaluated, as these play a key role in estimating buffer resilience. For each reach, the study also modeled the minimum required marsh width needed to dampen the n-Event wave down to a 0.2-foot t-wave.

Historic trends can be estimated by comparing the amount of shoreline lost and gained using aerial imagery and GIS-based information describing shoreline limits/geometry. An area with an overall trend of shoreline loss indicates a system that is losing coastal resilience over time, and it is therefore, an area that should be considered for restoration or protection efforts. It should be noted that the rate of change for shoreline loss or gain is not likely to be a linear relationship over time. However, the net change over a sufficient time period is indicative of the gross condition.

Cumulatively, it was determined that the marsh adjacent to the SR 1 within the study area lost more than 202 acres over 47 years, an average annual loss of approximately 4.3 acres. The evaluation also indicated an average shoreline loss of approximately 1.16 feet per year. The evaluation did not distinguish between causes of loss (e.g., SLR, wave energy, anthropogenic activity, etc.). Relative to the individual reaches, the marsh area rate of change ranged from 0.014 acre of gain per year to 0.778 acre of loss per year. The change in shoreline ranged from 0.415 foot of gain per year to 3.392 feet of loss per year. The overall trend is a slow loss of resilience. This evaluation described cumulative losses and gains, but it did not distinguish between acute and chronic events. However, it does include nearly one-half century of SLR. A number of SLR models project varying increases in the rate of SLR. Any increase in rate was not captured in this evaluation, but the modeling could be amended to incorporate rate changes later.

Modeling of buffer resilience for shoreline reaches within the study area was performed to determine the minimum marsh width needed to dampen the n-Event wave down to a 0.2-foot (2.4-inch) t-wave. A wave this size is typically caused by a wind less than three miles per hour, also known as light air (< 2.0 on the Beaufort wind scale). This wave size normally does not have sufficient concentrated energy to cause erosion, making it a non-destructive wave. When evaluating reaches of shoreline, reach-specific inputs (e.g., vegetation date, marsh platform elevation, marsh width, etc.) were added to the model. The model then calculated the associated estimated t-wave elevation and height. Keeping all inputs constant except for the marsh width variable, the modeler then adjusted the marsh width until it provided an estimate of the “ideal” minimum buffer, or marsh width, to dampen an n-Event t-wave to 0.2 feet in height.

To account for future conditions, the ideal minimum marsh width was then corrected to account for the measured average rate of shoreline change, and that rate was projected over the next 50 years.

Beyond horizontal coastal erosion, coastal resilience can be affected by interior marsh conversion to open water. This conversion from vegetated marsh to open water can be caused by anthropogenic disturbances (e.g., hay farming and ditching), SLR, acute events, subsidence, waterlogging, and more. Open water has a much lesser capacity to dampen wave energy than a vegetative marsh. It would be ideal to directly account for the rate of change, however, marsh degradation is highly variable and involves complex processes normally requiring significant research. To be conservative, it was assumed that 100 feet of width is added to marsh areas for every 1 acre per year rate change as determined through historical analysis. For example, a rate change of 0.5 acre per year would result in 50 feet being added to the corrected minimum width; 0.5 x 100 = 50.

To summarize, the ideal width is estimated through modeling, and the modeled width was then adjusted to account for future conditions by moving the projected shoreline location based on expected shoreline loss and marsh-to-open-water conversion. The resulting value is the corrected modeled minimum marsh width (WCM) to dampen the t-wave to 0.2 feet of height. This relationship is expressed as:

- WCM = $W_m^{\text{n-event}}$ (ft) – (Ave Net Loss of Marsh (ac/yr) * 100 ft/ac/yr) – (Average Horizontal Loss/Gain (ft/yr) * 50 yr)

Buffer resilience was evaluated for each of the 15 reaches. Buffer resilience was evaluated by calculating the percent variance between the existing marsh width and the corrected modeled marsh width:

- BR = (WE-WCM/WCM) * 100
- Where:
    - BR = Buffer Resilience (non-dimensional)
    - WE: Existing Marsh Width (feet)
    - WCM: Corrected Modeled Minimum Marsh Width to Dampen the T-Wave to 0.2 feet Height (feet)
- Example: BS-05, n-Event = 10-percent annual event, where
    - WE = 482 feet (from Table II-1);
    - Average Net Loss/Gain Per Year (acres): -0.183 (see Table II-6);
    - Average Horizontal Loss/Gain Per Year (feet): -3.373 (see Table II-6);
    - $W_{m=BS\text{-}05}^{10}$: 267 feet
        - Actual cross section-specific modeled value from Table II-1; using Wm^{10} equation above, 245.6 feet would be estimated, which is within expressed margin of error noted above;
    - WCM = 267.0 feet – (-0.183 ac/yr * 100 ft/ac/yr) – (-3.373 ft/yr * 50 yr) = 454.0 feet
    - BR = ((WE-WCM)/WCM) * 100 = ((482 ft – 454 ft) / 454 ft) * 100) = 6.17

The following buffer resilience levels were assigned the following classes:

- Highly Resilient Buffer – BR is greater than 25 (Score 1)
- Resilient Buffer – BR is between 10 and 25 (Score 2)
- Vulnerable Buffer – BR is 10 to -10 (Score 3)
- Highly Vulnerable Buffer – BR is less than -10 (Score 4)

To capture all aspects of coastal resilience, scores for flooding, wave energy, and buffer resilience were determined at all coastal reaches in the study area for the 1-percent, 2-percent, and 10-percent annual storm events. These values were then summed at each reach area. Those reach areas with the highest values should be higher priority zones for investment in reducing coastal vulnerability. Generally, if marsh widths are adequate under current conditions, measures should be taken to ensure that the health of the marsh is adequate to provide the necessary resilience over a 50-year period. If marsh widths are deemed inadequate, consider expanding the marsh width or raising the marsh elevation to provide an acceptable level of wave energy attenuation (dampening) based on the methodologies presented.

For bayside reaches during the 10-percent annual event, BS-02, BS-04, BS-06, BS-07, BS-08, BS-10, BS-12, and BS-13 were evaluated to have a highly resilient BR. BS-05 was determined to have a vulnerable BR. BS-03, BS-09, BS-11, and BS-14 were determined to have a highly vulnerable buffer. BS-01 and BS-15 have existing breakwaters with no significant marsh (Appendix B - Table II.7).

For the bayside reaches during the 2-percent annual event, BS-02, BS-04, BS-07, BS-08, BS-12, and BS-13 were evaluated to have a highly resilient BR. BS-10 was determined to be a resilient buffer. BS-03, BS-05, BS-06 BS-09, BS-11, and BS-14 were determined to have a highly vulnerable buffer. BS-01 and BS-15 have existing breakwaters with no significant marsh (Appendix B - Table II.8).

For bayside reaches during the 1-percent annual event, BS-07, BS-08, and BS-12 were evaluated to have a highly resilient BR. BS-04 and BS-10 were determined to be a resilient buffer. BS-02 and BS-13 were determined to have a vulnerable BR. BS-03, BS-05, BS-06, BS-09, BS-11, and BS-14 were determined to have a highly vulnerable buffer. BS-01 and BS-15 have existing breakwaters with no significant marsh (Appendix B - Table II.9).

ii. Stormwater Management Opportunities

A consistent pattern seen throughout the corridor is unfavorable conditions for retention-based stormwater practices immediately west of SR 1. These areas are dominated by shallow ground water depths (0-3 feet) as well as poorly draining soils (Soil Types A/D, B/D, and D). These conditions generally call for an approach that couples bay side coastal management approaches with an investigation of retention-based GI practices located upstream in the watershed (generally on the eastern side of SR 1). While site selection was not determined solely based on stormwater management potential, the potential of addressing urban runoff through the use of retention-based stormwater infrastructure within drainage catchments draining to site locations was taken into consideration.

Since all ocean side cross-sections were found to be resilient, the clear adaptation site options are on the bay side. As previously noted, the areas west of SR 1 area have generally poor conditions for stormwater management implementation. Even in those areas where well-draining soils exist, such as those near section BS-01 and BS-02, extremely high groundwater conditions are consistently present. In these areas, the ability to use the native soil's capacity to provide high infiltration rates is offset by groundwater conditions that do not allow for positive drainage.

Considering the corridor's limiting conditions for GSI implementation, the strategy for siting and designing stormwater management facilities should be multi-faceted. For instance, in locations where soils or groundwater conditions are not conducive to retention-based approaches, other practices that focus on filtration (rather than infiltration) and extended detention should be considered. Additionally, sites that have potential for retention-based stormwater management in upstream areas where soils and groundwater conditions are not limiting factors should be considered. In this context, the Read Avenue and National Guard sites held potential for stormwater management in upstream areas as well as alternative downstream treatment.

The Read Avenue site is in an area where the local near-shore configuration and wave energies allow for the use of natural features. The catchment area of the Read Avenue outfall is more than 28 acres with over 75 percent impervious cover. It represents one of the larger watersheds draining the densely urbanized areas within the Town of Dewey Beach. A reinforced concrete box culvert drains flows from this catchment into the bay at the Read Avenue site location. The current hydraulic capacity of the box culvert conveying upstream flows is extremely limited. It only has the potential to convey 33 percent of the one-year storm. However, expected upgrades to the drainage system immediately upstream of the project area will increase this capacity significantly.

A significant portion of the catchment area is located east of SR 1 where groundwater elevations and soil conditions are favorable for infiltration practices that can alleviate overwhelmed downstream drainage systems and provide groundwater recharge. An ongoing study by the Town of Dewey Beach investigating stormwater retrofit opportunities has identified the Read Avenue watershed as the highest priority area for investment due to its history of chronic localized flooding. The study suggested that shallow groundwater practices, such as permeable pavements, in upstream areas as well as bioretention facilities integrated into intersections along SR 1 hold great potential to alleviate localized flooding and increase water quality conditions. Figure 15 illustrates the relationship between soil types and infiltration-based stormwater management facility locations. The facilities in this figure (permeable pavement and bioretention) are sited in Soil Type A areas located along and to the east of SR 1.

The National Guard site has similar potential for stormwater management, although the near-shore elements differ from Read Avenue. This site features a marsh wetland located immediately west of SR 1 that is under-utilized. Like Read Avenue, runoff is collected east of SR 1, in an area with favorable conditions for retention-based practices. The runoff is conveyed to and across SR 1, where local highway runoff is collected and tied into a cross-drain that directs flow to a single ditch draining toward the bay. The marsh wetlands west of SR 1 in this area hold great potential for water quality treatment if flows are directed and conveyed appropriately within the marsh. Additionally, in this area, SR 1 is a divided highway with vegetated swales on the edge of the right-of-way on the east and west sides. A large grassed area in the median also conveys flows. These grassed areas also hold great capacity to provide enhanced water quality treatment through filtering and micro-detention practices. Lastly, like Read Avenue, the catchment area east of SR 1 is highly urbanized and has favorable conditions for infiltration-based practices, such as permeable pavement systems or shallow bioretention facilities. Less hydrologic and hydraulic information is available for this site, but a preliminary analysis shows that runoff can be conveyed and treated more efficiently and in a way that benefits upstream and downstream areas.

Figure 14 – Read Avenue Catchment Area and Proposed Stormwater Facilities. Source: Town of Dewey Beach

iii. Site Selection

Site selection was made based on a consideration of all factors assessed – flooding, wave energy, buffer protection, and stormwater management potential — in addition to the fact that both sites faced unique but representative challenges in the SR 1 corridor that are potentially transferrable to other states and locations. The summary of coastal vulnerability scores is listed in Table 3 with the six sites identified in the initial assessment highlighted in yellow.

Table 3 - Summary of Coastal Vulnerability Scores by Cross-section

n-Event	**Reaches (BS-XX)**														
	01	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**
10-Percent Annual Event Scoring															
Flooding	4	3	3	4	4	4	4	4	4	4	4	2	2	2	2
Wave Energy	2	1	1	1	1	1	1	1	1	1	2	1	1	1	1
Buffer Resilience	4	1	4	1	3	1	1	1	4	1	4	1	1	4	4
Total	*10*	*5*	*8*	*6*	*8*	*6*	*6*	*6*	*9*	*6*	*10*	*4*	*4*	*7*	*7*
2-Percent Annual Event Scoring															
Flooding	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3
Wave Energy	3	1	2	1	2	2	1	1	2	1	3	1	1	2	2
Buffer Resilience	4	1	4	1	4	4	1	1	4	2	4	1	1	4	4
Total	*11*	*6*	*10*	*6*	*10*	*10*	*6*	*6*	*10*	*7*	*11*	*5*	*5*	*9*	*9*
1-Percent Annual Event Scoring															
Flooding	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Wave Energy	3	1	2	1	2	2	1	1	2	1	3	1	1	2	2
Buffer Resilience	4	3	4	2	4	4	1	1	4	2	4	1	3	4	4
Total	*11*	*8*	*10*	*7*	*10*	*10*	*6*	*6*	*10*	*7*	*11*	*6*	*8*	*10*	*10*
Overall Total	**32**	**19**	**28**	**19**	**28**	**26**	**18**	**18**	**29**	**20**	**32**	**15**	**17**	**26**	**26**

Among these six locations, BS-01 had the highest score (32), making it the most vulnerable location among the sites analyzed. It should be noted that only one other site in the entire set of 15 locations analyzed had a score as high as 32. This high vulnerability score, along with an identified coastal project as well as stormwater needs and opportunities made the Read Avenue location an ideal candidate for concept design development.

The Read Avenue site encompasses issues common to ultra-urban areas, where site constraints and flows are significant and buffer marsh protection opportunity is limited. This site has significant upstream opportunities, including some within the SR 1 right-of-way, to enhance resilience by adding infiltration to reduce flows. These opportunities could be coupled with hydraulic reconfiguration near the SR 1 intersection area can increase capacity and reduce localized flooding impacts in and around SR 1 area. Focusing on downstream GI shoreline protection with a unique outfall configuration provides an example for other sites in urban areas with limited space. Lastly, flooding impacts in this area are significant and could continue to impact private properties and create unsafe conditions in transportation corridors, including SR 1. Developing a solution that provides near-term and longer-term flood protection and enhanced hydraulic capacity may provide a template for similarly-challenged areas.

The location with the lowest vulnerability, BS-12 (National Guard), may not seem a strong candidate for concept design development; however, this site helps to highlight a common problem in the SR 1 corridor — the challenge of maintaining channels and flows in and adjacent to marsh areas that provide drainage.

A specific benefit for selecting this site is that a solution illustrating a properly functioning coastal wetland marsh system that is self-sustaining will provide a valuable template for action elsewhere. If this solution can include a method to address incoming sediment through low-cost maintenance activities, the template solution will provide value for the corridor. Additionally, the types of stormwater practices envisioned for the SR 1 corridor in this context differ from the Read Avenue site. This highlights additional stormwater management choices in linear infrastructure systems. Lastly, the flooding impacts in this area are severe, as they are elsewhere, so a solution that addresses flooding here can help decrease flooding vulnerabilities in other parts of the corridor.

c. Description of Sites Selected for Conceptual Design

Six potential project sites were considered during the initial assessment, of which, two sites were to be selected for development of conceptual designs. The project sites considered were identified based on their potential for coastal and inland flooding. Further examination and discussion with stakeholders regarding these sites led to the two selected project sites. Factors that contributed to their selection include community concerns and participation as well as water quality benefits. The two chosen sites are known as Read Avenue (BS-01) and National Guard (BS-12).

- **Read Avenue (BS-01)**
- Indian Beach (BS-03)
- Key Box Road Area (BS-05)
- Indian River Inlet Bridge Area (BS-09)
- **National Guard Area (BS-12)**
- South Bethany Beach (BS-13)

i. Read Avenue Site

The Read Avenue Site experiences flooding caused by a combination of storm surge and localized flooding. Therefore, the proposed design includes a combination elements that help reduce flooding and provide water quality benefits. The site is located along the shoreline of Rehoboth Bay within the Town of Dewey Beach. The westernmost limits of Read Avenue and the surrounding homes experience flooding during extreme high tide events, storm surge during severe storms, and during locally heavy rainfall.

Overview of Proposed Design Elements

The proposed Read Avenue Site design includes raising or adding a sand dune levee, creating a tidal marsh, retrofitting a rock sill, adding oyster reef and oyster bag stabilization, and replacing an existing storm drain outfall with a larger concrete box culvert and tide gate.

Overview of Natural Infrastructure Elements

Natural infrastructure elements of the project include the expansion of an existing marsh and addition of a braided reef that will help to reduce wave energy and protect the outfall area. The braided reef includes oyster castles. Oyster shell bags will be placed along the riprap sill, and they will be incorporated into the braided reef. The marsh will be planted with *Spartina alternifolia* that will help reduce wave energy and provide water quality benefits. The sand dune levee will be planted with beach grasses to help keep the sand in place.

Overview of Ongoing Maintenance

The concrete box culvert includes an access manhole to remove sand and debris and to maintain the tide gate. Regularly scheduled inspection of the box culvert and tide gate will be required to ensure that the gate is not obstructed by sand and debris as well as to ensure that the gate is in good working order. The sand dune levee will require regularly scheduled inspection as well to ensure that the proposed elevation is maintained. Inspection of the *S. alternifolia* in the marsh and beach grass on the sand dune levee will also be required to ensure adequate survival and subsequent coverage.

ii. National Guard Site

The National Guard Site experiences inland flooding in the north Bethany Beach community because the community is low-lying and the outlet channel through the marsh is blocked by sediment and debris. The site is adjacent to and north of the Delaware National Guard Training Center, Bethany Beach, and the outlet channel discharges to Salt Pond. The proposed design includes a combination of design elements to help reduce the likelihood and frequency of blockage in the outlet channel.

Overview of Proposed Design Elements

Proposed improvements include adding sediment forebays and level spreaders at each of the culvert and storm drain outfalls. Additionally, runnels will be strategically placed to breach an existing levee.

Overview of Natural Infrastructure Elements

The proposed sediment forebays and level spreaders at the outlet of each culvert and storm drain outfall will be directed into the existing marsh at various locations rather than being concentrated at one outlet channel as in current conditions. This will mimic a more natural condition where freshwater sheet flows to tidal marsh. The proposed runnels through the levee will create a better connection between the marsh and the outlet channel that will enhance marsh hydrology by allowing more frequent tidal inundation and better flushing. The sediment forebays and level spreaders will improve water quality to the bay by encouraging course sediment to settle in the forebay and by filtering smaller sediment in the level spreader.

Overview of Ongoing Maintenance

The sediment forebays will require regularly scheduled inspection and dredging. However, the sediment forebays will be located immediately adjacent to SR 1 for ease of access.

Dredging the outlet channel will be required much less frequently and possibly will not be required again in the future. Currently, access to the channel is difficult, and permitting is required for access and dredging.

IV. Detailed Description

A goal of this effort was to develop conceptual designs for two sites. This section provides details related to the two selected sites: Read Avenue and National Guard. Note that the Read Avenue site has more well-developed design information, as this project is supported by other grant funds. While the National Guard site has less well-developed design information, the details provided can help to inform other areas both within the SR 1 corridor and for other states and regions with similar challenges.

a. Read Avenue Site

Previous improvements at the Read Avenue storm drain outfall attempted to reduce shoreline erosion and to prevent backflow and subsequent surcharging of the storm drain during extreme high tides, storm surge, and wave events. Previous improvements included a pocket beach, rock sill, and sand dune. An opening was left in the rock sill to allow for kayak ingress and egress. The sand dune does not extend the full width of the street and allows high tides and storm surge to enter the street. The check valves that were installed at the ends of the dual circular concrete pipes have since been removed due to clogging with sand.

Much of the pocket beach and marsh have eroded over time as wave energy has passed through the opening in the rock sill. The ground elevation in this area is approximately two feet, and the storm drain outfall at the street's terminus conveys drainage from approximately 28 acres of area that is approximately 76% impervious. The existing storm drain system is undersized and surcharges during storm events that are less than the 1-year return interval. No stormwater management practices exist within this drainage area.

The Town of Dewey Beach has partnered with the Center for Inland Bays to develop a Phase II Stormwater Plan for the Town of Dewey Beach that includes assessment of this area. The plan promotes implementing GSI practices throughout the watershed to help reduce runoff flows to the storm drain and improve water quality in the bay. To date, the Center for Inland Bays, DelDOT, and the Town of Dewey Beach have held a number of coordination meetings to discuss proposed improvements and their potential impact on Rehoboth Bay, the town, and DelDOT roads. The proposed project has also been discussed with adjacent property owners and with the community at a Town Council Meeting. Proposed improvements that address issues not resolved by the previous system are described as follows.

i. Proposed Design Elements

This proposed project will retrofit a living shoreline and upgrade a stormwater drain and outfall, eliminating flooding during storms with a recurrence interval of less than 3.7 years. There is a 27% chance of overtopping the proposed project in any given year. The project design is shown in Figure 16.

The living shoreline will be protected by a combination of oyster shell bags and realignment of existing riprap. The existing volunteer marsh will be preserved and expanded through sand nourishment and marsh plantings. The existing dune will be enhanced and raised to an elevation of 3.5 feet by stabilizing the sand with HESCO flood barriers and planting the dune. These elements were selected based on a number of factors. For instance, the proposed project is a retrofit of a previous one, so similar elements are proposed for consistency. Oyster shell bags are being added as an inexpensive, natural system that adds habitat and encourages growth of oysters, which improve water quality through filtration. Coupled with existing riprap, the oyster bags will also provide protection against wave energies anticipated at the site. HESCO barriers were chosen to raise the dune in a width-constrained area, but a groin within the remaining portion of the dune will strengthen the dune. The barriers are filled with sand, and the top is left open. Enabling beach grass to grow on top provides a more natural form of reinforcement.

The stormwater drain and outfall will be retrofit with additional or larger culverts. A maintenance access structure will be placed on the dune's landward side, and a tide gate placed at the upstream end of the proposed culverts will enable access to the maintenance structure. The tide gate will remain closed during high tide and wind events and open during rain events. Types of tide gates under consideration include top-hinged flap gates, slide gates, and rubber inline check valves.

The project will include a footpath to encourage access to the bay at a single entrance so that the 'living' components of the project can succeed without human interference, such as trampling.

ii. Natural Infrastructure Elements

The tight geometric constraints associated with this urban site create challenges in developing nature-based solutions. However, the proposed design includes a number of nature-based conceptual design retrofits that increase the project's environmental benefit and ecosystem services.

- Raising the existing dune to elevation 3.5 feet by enhancing 0.15 acres of dune
- Preserving the existing marsh and creating new marsh for a total 0.04 acres of marsh area
- Stabilizing 160 linear feet of eroding shoreline using a combination of existing riprap and installing oyster shell bags

iii. Project Costs

Two project cost estimates have been developed for this site. A short-term cost estimate of approximately $170,000 reflects the costs associated with the design presented in this document. The long-term estimate includes the design elements presented in this report as well as an additional $425,125 for upgrading drainage infrastructure upstream of the SR 1 right-of-way that will enhance the system's overall hydraulic capacity. Long-term upgrades include replacing the existing storm drain system from the end of the Read Avenue project site up to SR 1 with a box culvert and adding inlet grates at current inlets. The new system will convey the 10-year storm according to current DelDOT design criteria. Currently, the timing of these long-term upgrades is unknown. Detailed cost estimates are available in Appendix E.

Since the focus of the project is on using green infrastructure in coastal and urban stormwater management applications as a shift from traditional approaches, it is appropriate to consider the cost implications of these varying approaches. A detailed analysis comparing traditional approaches and CGI/GSI has not be performed. However, an informal contrast can be made to illustrate the cost differential between green and standard methods for coastal protection and urban stormwater management by estimating the cost for a traditional "gray" design approach. The proposed HESCO barrier spine would be replaced with a revetment or a seawall, and the oyster reef would be replaced with a stone option. Considering these options, the traditional approach is estimated to cost at least 30% more than the proposed green infrastructure option, and the cost could be as high as two times more.

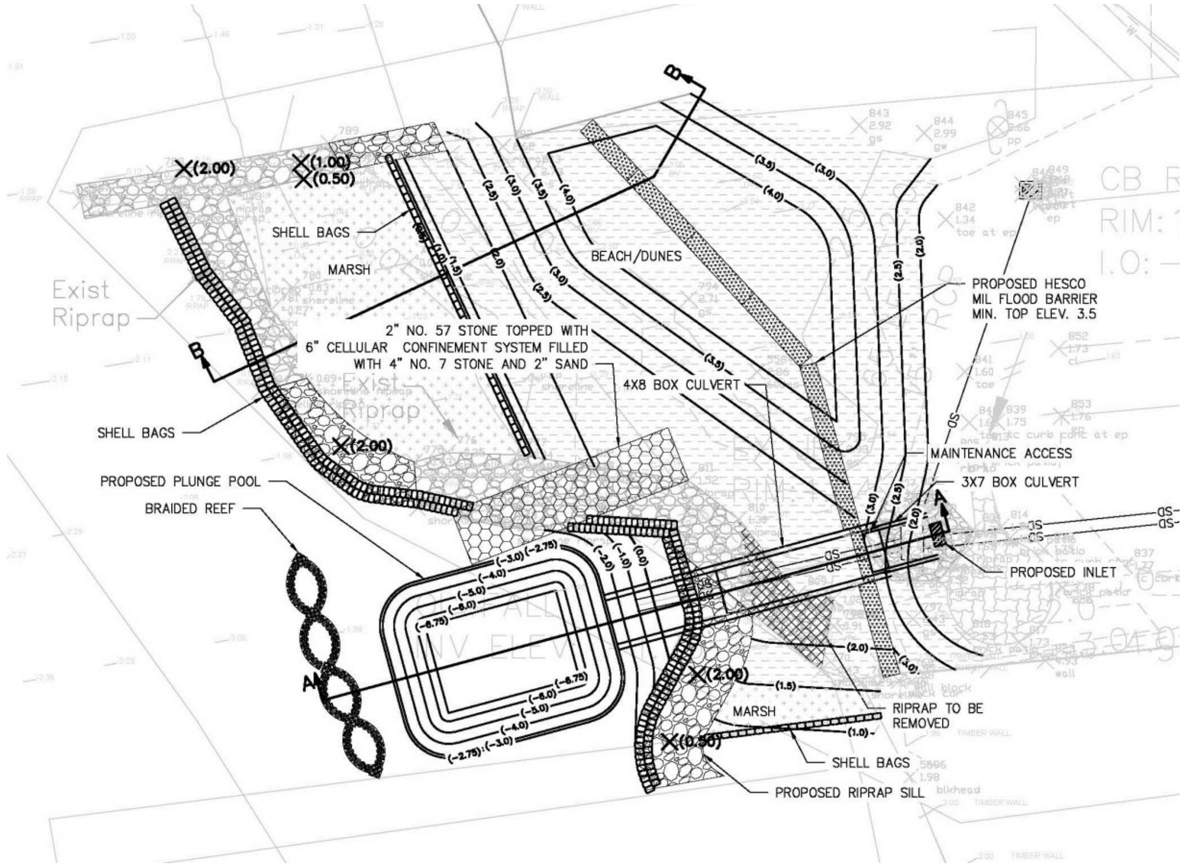

Figure 15 - Read Avenue Conceptual Design (Plan View - Not to Scale)

The braid reef was designed to reduce storm wave and wake energy and to disrupt microcurrents that could result in rapid filling of the drop pool on the landward side of the reef. The reef's height is intended to break larger waves during storm events but allow smaller waves to pass over the reef, especially during high tides. During high tide, a wave of approximately 18 inches or greater will break as it passes over the reef. During lower tide events, a wave of approximately 12 inches or greater will break as it passes over the reef. Smaller waves during both events will be damped somewhat, dependent on the water depth. If the reef was designed with greater height, it could result in significant accretion immediately landward of the reef, causing the drop pool to fill in.

Effective reefs need to have the proper three-dimensional structure to optimally disperse oxygen and nutrients over sessile organisms on the reef surfaces and to provide optimal wave orbital disruption to break-up and attenuate the wave energy. Oyster castles on either end of each oyster bag helps anchor the design. The oyster bags are placed in two levels. The lower level is continuous, and the second level consists of spaced oyster bags. The second-level oyster bags in front of the node are offset from the second-level bags at the back end of the node. In addition, there are three elevation changes as the wave passes over the node. The vertical variation and horizontal offsets create multiple energy reflections, refractions, and diffractions that work together to break down the wave orbital and place the wave energy out of phase. Figure 25 provides an example of oyster bags installed for a period of time.

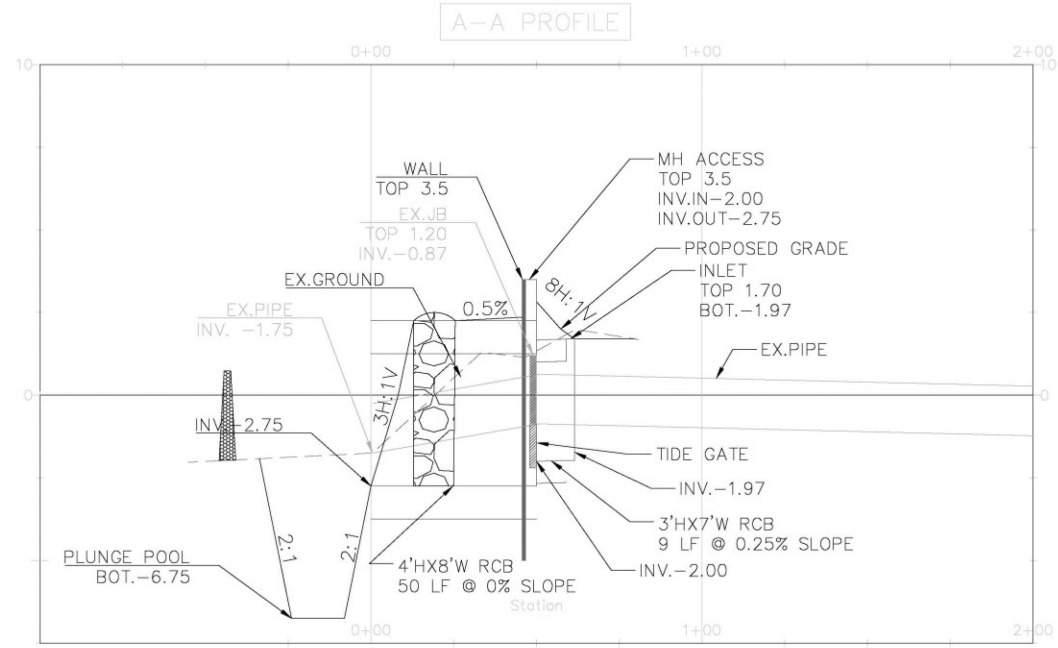

Figure 16 - Read Avenue Conceptual Design (Section A-A - Not to Scale)

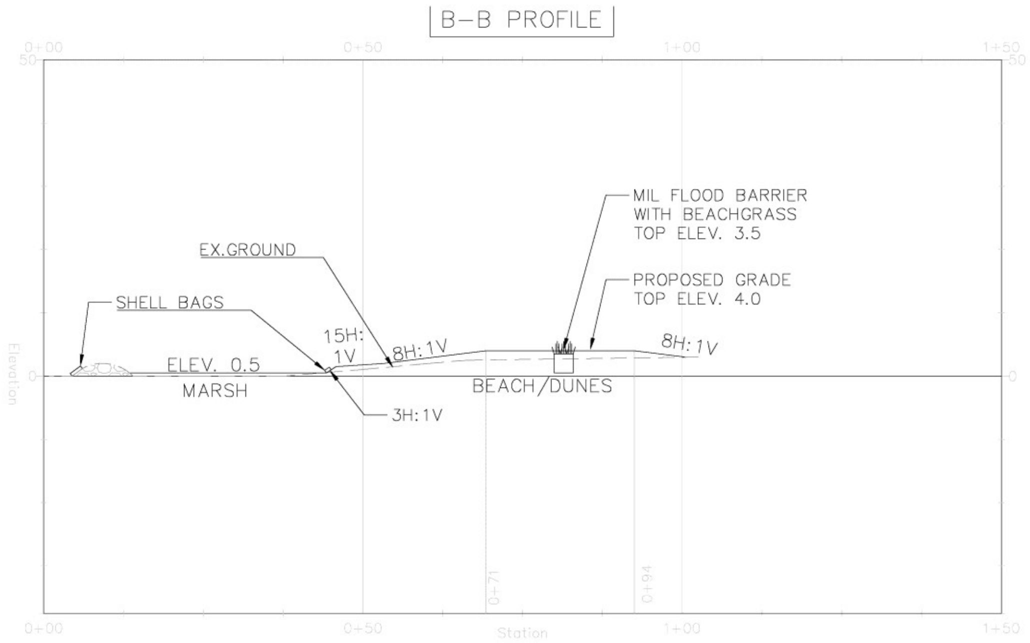

Figure 17 - Read Avenue Conceptual Design (Section B-B - Not to Scale)

Figure 189 - Read Avenue Existing Conditions (Plan View - Not to Scale).
Map Credit: Google Earth, Map©2018Google.

Figure 19 - Read Avenue Conceptual Design (Plan View - Not to Scale).
Map Credit: Google Earth, Map©2018Google.

Figure 20 - Read Avenue Conceptual Design – Existing and Proposed Conditions (Not to Scale). Photo credit: DelDOT

Figure 21 - Read Avenue Conceptual Design – Existing and Proposed Conditions (Not to Scale). Photo credit: DelDOT

Figure 22 - Read Avenue Conceptual Design – Existing and Proposed Conditions (Not to Scale). Photo credit: DelDOT

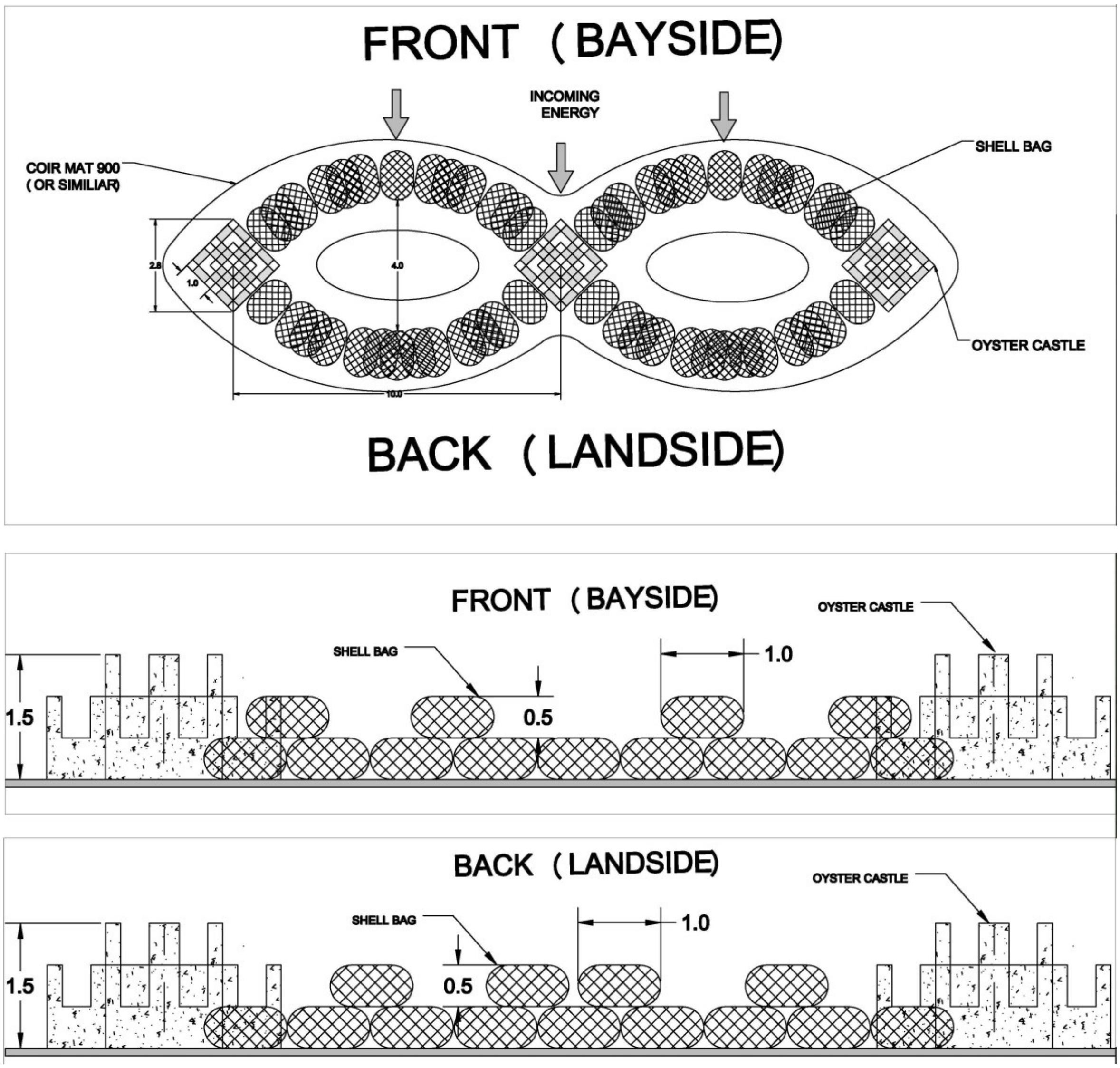

Figure 23 - Read Avenue Conceptual Design (Braided Reef Detail - Not to Scale)

Figure 24 – Oyster Bags Applied in Practice. Source: DelDOT

b. National Guard Site

A total of 26.95 acres of developed area drains to a single outlet channel that passes through a tidal marsh and discharges into Salt Pond. The outlet channel is not well connected with the adjacent tidal marsh because a levee along the channel was created by side cast material from digging and maintaining the channel. DelDOT is currently planning to dredge the existing outlet channel due to complaints by residents in the north Bethany Community. Residents complained because the storm drain system does not function properly since the outlet channel is clogged by sediment and debris. The community is located on the east side of SR 1, and the outlet channel is on the west side of SR 1. Five culverts cross under SR 1 to convey drainage from east to west, but flows from all of these culverts are combined into one ditch along SR 1 that drains to the outlet channel. Proposed improvements to this site are described in the following section. Note that designs developed for this site are highly conceptual in nature and have less detail compared to the Read Avenue site. Since the level of detail is limited, a cost estimate was not developed for this site.

i. Proposed Design Elements

The proposed project will enhance the existing tidal marsh and add sediment forebays and level spreaders to reduce the amount of sediment entering the outlet channel. This will subsequently improve conveyance in the community's storm drain system. The forebays and level spreaders will consist of an excavated pool lined with riprap. The marsh side of the pool will have a concrete or similar rigid lip so that overflows will be directed to a flat, wide, vegetated filter strip connected to the existing marsh. The tidal marsh enhancement will include three 2.5-foot wide runnels that breach the existing levee. Sediment forebays will be constructed at each of the five SR 1 culvert crossing outfalls. Each forebay will settle coarse sediment from drainage areas ranging from 4.8 acres to 7.1 acres. Rather than being directed to the outlet channel, three of the forebays will discharge to level spreaders that discharge directly to the tidal marsh.

ii. Natural Infrastructure Elements

Enhancing the existing tidal marsh by reconnecting it to the outlet channel increases tidal exchange and flushing. Sediment forebays settle coarse sediment, and level spreaders will filter water at three of the forebays to improve water quality. Via level spreaders, three forebays direct flows to approximately 15 acres of freshwater to the tidal marsh to aid in flushing.

Note that "typ" indicates "typical" in the context of Figure 26. Features noted as "typ" convey that they are typical of similar features throughout the project. For instance, using level spreaders in the project, as noted in the figure, is typical for all culverts emptying into the marsh area throughout the project site.

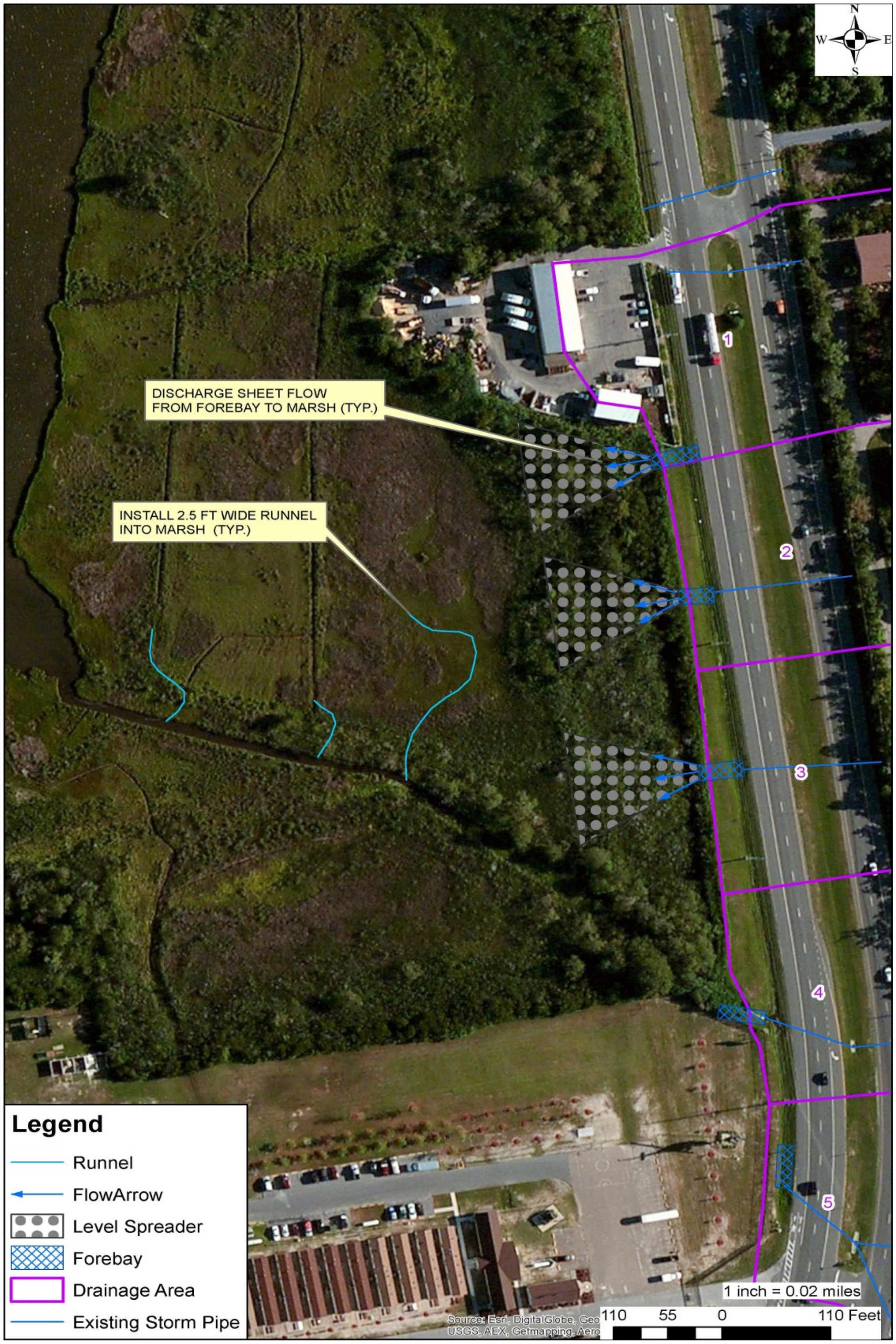

Figure 25 - National Guard Site Conceptual Design (Plan View).
Map Credit: Google Earth, Map©2018Google.

V. Benefits

The sites selected for conceptual design have the capacity to showcase multiple benefits associated with CGI and GSI implementation and maintenance investments. The most pressing benefit to focus on is the ability to provide enhanced resilience to flooding (inland and coastal), wave energy, and SLR. Reducing excessive volumes of urban runoff delivered to downstream areas will also reduce flooding issues and pollutant loading.

a. Benefits Associated with Read Avenue Site

The Read Avenue Project will provide a wide array of benefits, including those associated with coastal flood protection, nature-based elements, reduced inland flooding impacts, habitat uplifts, ecosystem service enhancements, and safety.

i. Coastal Flood Protection

Coastal Flooding was modeled for the Read Avenue site. The model evaluated the 10-percent, 2-percent, and 1-percent annual events, as well as the estimated maximum flood elevation that the design would offer full protection against. The following flood elevations were estimated:

- 10-percent annual event: 4.16 feet NAVD88;
- 2-percent annual event: 5.24 feet NAVD88;
- 1-percent annual event: 5.70 feet NAVD88; and
- Maximum Flood Elevation with Full Protection: 3.50 feet NAVD88.

The height of the design was limited by local coastal geometry. While the design provides potential protection up to 4.0 feet in height, the local geometry limits coastal protection to only 3.5 feet in elevation, which is what the design team identified as the functional height. Although the design does not prevent coastal flooding for the modeled events, it does offer protection to more than 95 percent of storm occurrences, and it will provide significant protection and flood volume reduction during severe events. When implemented, it is estimated that the design will provide protection for approximately a 3.5-year (29-percent annual) event.

While current DelDOT policies do not require consideration of future SLR impacts, doing so on this project provides an example for future projects in the study area. As noted previously, DNREC suggests one-meter of SLR for planning purposes when considering conditions for the year 2100 within the State of Delaware. Applying the one-meter SLR scenario to the current mean high-water elevation of 1.19 feet NAVD88 produces a new mean high-water elevation of 4.44 feet NAVD88. As such, the estimated normal mean high tide in 2100 would be slightly greater than the current 10-percent annual event elevation of 4.16 feet (NAVD88). It should be noted the 4.44-foot elevation does not account for higher energy conditions, such as surge or wave crest. Calculating n-percent annual storm elevations — which incorporate SLR — would involve recalculating the stillwater elevations — with projected SLR — and rerunning model. Due to topographic limitations at the Read Avenue site associated with adjacent properties, it is likely that the site will begin to experience more frequent flooding as 2100 approaches.

The local coastal geometry is the limiting factor for flood protection at the Read Avenue site, as previously noted, and this limitation will remain until the local geometry is changed. If these changes are made, the level of flood protection relative to SLR should be reevaluated.

ii. Nature-Based Elements

Past and existing coastal protection efforts were anchored by a groin and revetment with nourishment (sand backfill) that was added later. A large portion of the nourishment has since been transported from the site. Adjusting the structural component's configuration and establishing a low marsh habitat will greatly increase the shoreline's ability to dampen wave energy. The beach's reduced slope and the modified dune, with a structural spine, further dampens wave energy. Prior to wave energy contacting the beach, the created band of marsh alone reduces the transmitted wave height by approximately 20 percent to 25 percent, depending on the n-Event modeled.

iii. Reduced Inland Flooding Impacts

The design provides for a box culvert with a tidal gate. The box culvert remains open until coastal flooding reaches initial flood elevations, at which time it closes. As mentioned previously, the exact design of the tide gate has yet to be determined. Inland flood and coastal flood waters remain isolated from each other. As coastal floods recede and the gate reopens, inland floodwaters will drain more efficiently, reducing floodwater retention times.

iv. Habitat Uplift and Ecosystem Services Enhancement

The design provided for marsh creation, beach, and a vegetated dune. The design enhances the intertidal connection to uplands. The design also provides for a small subtidal shell bag reef. The reef creates attachment sites for oyster spat and structure for nekton. The new design improves aesthetics and adds opportunities for birdwatching, photography, and kayaking, all of which enhance ecosystem services.

v. Safety

Currently, the western side of Read Avenue is susceptible to severe flooding, which caused by a combination of inland and coastal flooding. The severity of the flooding is such that residential and emergency vehicles are unable to access that portion of the street. This design will significantly reduce total flood volumes, enabling street access during all but the most severe events.

b. National Guard Site

Unlike the Read Avenue Site, which is affected by both inland and coastal flooding, the National Guard site's flooding is currently driven only by inland flooding. Over time, coastal flooding may become a more significant factor due to SLR. The project at the National Guard site will provide benefits associated with reduced maintenance efforts, reduced inland flooding, enhanced stormwater treatment capacity, increased sustainability in the adjacent marsh area, enhanced ecological values, and increased resilience to future coastal changes due to SLR.

i. Reduced Maintenance Efforts

The National Guard site currently requires maintenance of storm drain lines crossing underneath SR 1, a single point outlet to the marsh, and dredging of a tidal drainage ditch — the latter being more expensive to maintain. The project will eliminate the need for tidal drainage ditch dredging and the complicated permitting associated with it. Multiple small outlets will be constructed along the marsh edge. Although these new outlets will occasionally require maintenance, the effort will occur from the land using standard mechanical excavation and limited to no permitting.

Dredging and pond maintenance costs vary wildly; however, a review of general information on costs associated with these activities reveals a significant cost differential. A New Jersey Department of

Transportation (NJDOT) study of the costs and benefits of various tidal dredging efforts provides unit costs for dredging by NJDOT ranging from $10 to $80 per cubic yard (New Jersey DOT, 2002). The estimated length, width, and depth of dredging required for the tidal ditch would be approximately 1,000 feet, 15 feet, and 3 feet, respectively, resulting in a total volume of 5,000 cubic yards. Using an average cost of $40 per cubic yard based on the NJDOT information, this would cost approximately $200,000. Considering the relatively limited size of this project, it is likely that its unit cost be higher than assumed, making the cost estimate relatively conservative.

In contrast, a DNREC report on stormwater maintenance costs highlights a New Castle, Deleware study from 2005 that estimated a cost of $1,120 to dredge material from a sediment forebay for a dry pond draining 20 acres. In the New Castle study, it is assumed that this dredging effort is needed once every 10 years (DNREC, 2005). Since National Guard project site drains approximately 27 acres, numbers from the DNREC study are assumed to be applicable to this situation.

While the specific costs of the two alternatives (tidal ditch dredging versus pond forebay maintenance) are very rough estimates, the relative difference illustrates the cost effectiveness of using ponds with sediment forebays to reduce sediment delivery to downstream waters.

ii. *Reduced Inland Flooding*

The proposed project will create multiple discharge points for stormwater rather than one centralized discharge point, which can bottleneck storm drainage. A number of the new discharge points will be at slightly higher elevations, adding more resilience to the drainage system. At this point, only a conceptual design has been prepared, so the degree of flood reduction has yet to be determined.

iii. *Enhanced Stormwater Treatment Capacity*

The project will enable water quality treatment in open space between the northbound and southbound lanes prior to discharging stormwater to the bay. Small water quality basins or sediment traps located at each discharge will also add stormwater treatment. Further, discharged stormwater will sheet flow across the marsh prior to entering the bay, allowing for additional natural filtering of previously treated stormwater, which is not currently provided.

iv. *Increased Sustainability in Marsh Area*

Creation of the tidal drainage ditch, and associated side-casting, has isolated a portion of the marsh from natural drainage. Reconfiguring the tidal ditch and enhancing the connection between tidal channels and the marsh platform will improve the natural tidal flush, which will keep channels open (reduce silting in of channels), and reduce marsh waterlogging. Increased plant biomass would be an indirect benefit to the effort, adding great marsh buffering capacity.

v. *Enhanced Ecological Value*

As previously noted, spreading stormwater discharge, reconfiguring the tidal ditch, and adding runnels, will improve tidal flush. The improved flush will enable natural increases in marsh biomass and natural wave energy attenuation. Improved marsh habitat benefits wading birds, nekton, and overall habitat function. The scale of impacts has not been determined or estimated, as the design is limited to a conceptual level at this point.

vi. *Increased Resilience to Future Coastal Changes Due to Sea Level Rise*

The project is expected to enhance marsh function over time. The resulting healthier marsh is better able to keep pace with SLR by trapping suspended particulates more efficiently and adding greater amounts of biomass to the system, both of which are responsible for vertical marsh growth. Additionally, discharging stormwater at slightly higher invert elevations adds resilience and function to the stormwater infrastructure.

VI. Implementation Considerations

Implementing coastal projects requires consideration of requisite permitting as well as site constraints and characteristics. Both Federal and Delaware permit programs regulate activities in tidal waters and wetlands. Delaware regulates activities through the Subaqueous Lands and Wetlands permitting program. For living shoreline projects, Delaware has developed a Statewide Area Activities (SAA) permit. Federal agencies regulate these activities through the Clean Water Act Section 404 and Section 10 of the Rivers and Harbors Act of 1899. The Section 404 program includes Nationwide Permits (NWP) specifically crafted for living shorelines (NWP 54), bank stabilization (NWP 13), and ecological restoration (NWP 27) all of which could be applicable for these activities. Depending on project location and design, the nationwide permits may require Pre-Construction Notifications. If special protected species or their habitat are affected by the activity, additional federal programs may apply.

Site characteristics that could affect the implementation of a coastal project include local soil conditions, adjacent land use types and property owners, existing infrastructure on or near the construction areas, critical habitat and water resources nearby, littoral dynamics and vegetative profile. For projects focusing on drainage and urban runoff, it is important to understand tailwater and headwater controls, critical elevations and nature of culverts in drainage systems inside and outside the project area, design storms, and pollutant loadings and expected reductions.

a. Read Avenue Implementation Considerations

i. Implementation Challenges Associated with Read Avenue Site

The biggest challenge at the Read Avenue site is elevation of the existing developed area. The western limits of Read Avenue are at an approximate elevation of 2.0 ft. Adjacent properties have created walls or raised their building structures using blocks or other means. For one property in particular, the wall elevation is only 3.5 ft. This limits how high the sand dune/levee can be raised before it forces storm surges or waves into the adjacent properties. Another consideration was providing access for kayakers. The existing conditions provide easy access for those who wish to use the pocket beach for kayak ingress and egress. However, the design calls for the pocket beach to be closed and backfilled, effectively eliminating this access. The compromise developed in the design is to provide limited – but adequate – access by adding cellular confinement systems (backfilled with stone and sand) into the design. While access is reduced, the ability to use the area for recreation is retained.

ii. Permitting Challenges Associated with Read Avenue Site

Due to the nature of the stabilization improvements at this site, the Delaware SAA for living shorelines does not apply. The project is not eligible as a SAA because it proposes fill be installed channel-ward of the Mean Low Water Line. Therefore, a Delaware Subaqueous Lands Permit will be required. Depending on the final design, USACE Nationwide Permits 54, 13, or 27 would be available for this activity. Final design will dictate whether Pre-Construction Notifications, required in most situations, and related support data will be needed or whether the project can proceed directly as per Nationwide Permit conditions. Land ownership must receive special consideration. Privately-owned lands receive a permit from the state; while publicly owned lands receive a lease from the state and require lease fees. The project affects primarily publicly-owned land, with a small amount of privately-held properties included as well. Engagement with these landowners is ongoing to gain permission to work on privately-held land affected by the project. There are no special aquatic sites or other unique resources affected for this activity, so permit processing is not expected to generate any unique challenges.

iii. Maintenance Considerations Associated with Read Avenue Site

The proposed tide gate and box culverts must be inspected and maintained to prevent sand and debris from inhibiting operation of the tide gate. The sand dune will also require inspection and occasional repair to ensure that the top elevation of the sand is maintained following high tide events.

iv. Vulnerabilities Associated with Read Avenue Site

The conceptual design reduces the Read Avenue site's vulnerability to shore degradation by protecting the near shore. However, this site faces significant flood vulnerability. The tide gate and berm protection system increases the resilience of this area to flooding. However, inland and upstream flooding still pose challenges. A robust investment in retention-based practices upstream would provide relief to downstream areas, such as Read Avenue. Future investments should be made to further enhance the resilience of this area through these upstream investments, as noted in Figure 15.

b. National Guard Implementation Challenges

i. Implementation Challenges Associated with National Guard Site

Since the National Guard site has a less well-developed conceptual design, the construction details have not been fully realized; however, some issues can be anticipated. For instance, working within wetlands has particular challenges, such as the need to use lighter equipment with rubber tracking to minimize impacts. Additionally, many areas may require dewatering and complex phasing to minimize habitat impacts and maximize the ability to "work in the dry," a construction technique where standing water is pumped out of a specified area to enable construction under "dry" conditions.

ii. Permitting Challenges Associated with National Guard Site

Due to the nature of the stabilization improvements at this site, the project does not meet all of the Delaware SAA criteria for living shorelines. Therefore, a Standard Delaware Subaqueous Lands/Wetlands (Standard) Permit will be required. A Standard Permit application submittal package includes essentially the same information required by the applicable SAA. However, the Standard Permit process requires a public notice and a slightly more rigorous review processes, adding about two extra months to the permitting process. Depending on final design, USACE Nationwide Permit 27 may be available for this activity. Final design will dictate whether Pre-Construction Notifications and related support data are needed or whether the project can proceed per the Nationwide Permit conditions.

There are special aquatic sites, tidal wetlands, that will be affected at the National Guard site. The project includes excavation of tidal wetlands and the potential conversion of existing ditches back to tidal wetlands and more naturally functioning open water bodies. A challenge this project could present is whether activities require compensatory mitigation for the activity if it is not considered "self-mitigating" by the agencies. The project may be considered "self-mitigating" because it proposes enhancing existing tidal wetlands, improving their hydrology through more frequent inundation, diverting pretreated stormwater flows into the wetlands, and enhancing flushing by tidal flows due to better connection to the channel.

iii. Maintenance Considerations Associated with National Guard Site

A primary advantage of the National Guard site design is its focus on capturing sediment in multiple locations prior to discharging water to the marsh areas. Capturing the sediment load in these locations is much more efficient than removing the same sediment load from the marsh area. Relying on sediment forebays, however, requires consistent and diligent maintenance. If the forebays are not monitored and maintained in a robust manner, the marsh may become overwhelmed by sediment, and the newly-constructed runnels may no longer be able to provide adequate flushing capacity. This could cause a change in form and function of the marsh system as well as a shift in vegetative patterns and habitat conditions.

iv. Vulnerabilities Associated with National Guard Site

Both the National Guard and Read Avenue sites were found to be highly vulnerable. However, the National Guard site is particularly vulnerable to wave action and degradation of marsh area coverage, as this site has no breakwaters or other near-shore stabilization infrastructure. In contrast, Read Avenue has near-shore infrastructure integrated into its design. Considering the vulnerability of this site, special care should be taken to closely monitor the marsh area's stability. The geometry of runnels as well as the marsh area must be maintained and protected from the forces of degradation that have negatively impacted other marshes in the corridor. Protecting the marsh preserves and enhances its buffering value for decades to come, leading to a more resilient transportation corridor.

VII. Next Steps

The information presented in this report represents a snapshot in time, as several project elements discussed in this document will be moving forward in the near future. Details on these ongoing activities are listed below.

a. Implementation Status of Read Avenue Site

The 2017 Delaware Water Infrastructure Advisory Council Community Water Quality Improvement Grant program is providing project funding. With funding secure and a conceptual design, cost estimate, and design specifications in development, it is anticipated that construction will start between fall or early winter of 2017 and early spring 2018. Additionally, it is anticipated that this project will be delivered through a design-build vehicle. The Town of Dewey Beach will be a strong partner with other stakeholders during this construction phase.

b. Implementation Status of National Guard Site

Unlike the Read Avenue site, the National Guard site does not have adequate funds identified to construct the features identified in the conceptual design. Further, there is a need to flesh out more design details, including cost estimates, cut and fill volumes, and runnel geometry (plan, cross-section, and profile). One critical piece of information needed is an example of a self-maintaining/flushing coastal marsh system in the region that can be used as a template for identifying the optimal geometry for a stable runnel system.

c. Role of Policies Developed in this Effort for Future Projects

To capture lessons learned from this effort and document specific design and implementation techniques, the project team has envisioned the development two memos, one policy-focused and the other design-focused. The goal of these documents is to better facilitate information dissemination to other DelDOT regions and headquarters. The memos can also serve organizations with an interest in nature-based solutions that address vulnerable transportation assets in coastal areas that may be affected now, or in the future, by climate change and coastal stressors, such as SLR, wave energy, and flooding. The purpose of these memoranda is to clarify policy positions and views on specific areas of interest to DelDOT and to provide basic guidance to designers and others in an effort to overcome the challenge of using non-traditional approaches.

Specifically, it is anticipated that the policy memo will suggest specific changes to the section of the DelDOT Bridge Manual that focuses on SLR impacts. One example could be to propose wording that expands the context of consideration for climate change impacts beyond SLR to include wave energy and coastal vulnerability analysis. Another example could be to proposed policy changes that speak to the need for DelDOT staff to consider opportunities to integrate GSI into GCI projects to drive more holistic efforts to manage urban runoff and improve coastal resilience. Policy and technical information can be presented as justification for any suggested changes outlined in the memo.

For the proposed design guidance memo, it is envisioned that technical information for three scenarios will be developed and presented where green infrastructure (both GSI and CGI) can be used to address challenges associated with potentially vulnerable transportation infrastructure in coastal areas. Three possible examples are listed below with a summary provided for each example.

- Addressing coastal ditches, marshes, and evacuation travel in coastal highway corridors

    - This example is based on lessons learned from the National Guard site. Information can be provided on using sediment forebays near or along the transportation right-of-way to reduce sedimentation of downstream waters and provide a more cost-effective option for sediment capture. Additionally, technical guidance can be presented on ways to use coastal marsh areas for water quality treatment and wave energy dissipation. Lastly, the example of using local roadway drainage geometry, such as ditches, can show how emergency transportation routes can be enhanced in coastal areas.

- Using coastal marshes for wave energy dissipation along a coastal highway corridor
    - The second example can provide detailed information on analyzing existing coastal marshes to estimate the relative vulnerability of these areas in the face of flooding and wave energy. An analysis can be presented that provides a scoring system to estimate the ability of coastal marshes to provide protection against internal and external erosive and degradation forces.

- Integrating downstream CGI in an urban setting with upstream stormwater management for a holistic approach to addressing coastal flooding and water quality treatment
    - The last example can provide information on specific GSI and GCI practices that should be considered for projects that are addressing coastal vulnerability. This example suggests that these practices be integrated in a holistic fashion, where possible, to enhance overall resilience and water quality treatment potential. Information presented in this example can reflect lessons learned from the Read Avenue project.

d. Water Resources Registry Enhancement

As previously noted, the Watershed Resources Registry (WRR) is a tool developed by EPA Region III. The State of Delaware is adopting this tool and currently adapting it with state data, conditions, and interests. The purpose of the WRR is to map natural resource areas that are a priority for preservation and restoration. Areas identified in the WRR through analysis include upland, wetland, and riparian areas of preservation and restoration as well as opportunities to preserve or restore areas for enhanced stormwater management. EPA is currently working with several Mid-Atlantic states to develop state-specific WRR tools that include models supporting the priorities and interests of each state engaged in WRR development. As previously noted, a WRR platform is currently being developed for the State of Delaware. The vulnerability analysis developed in this effort, as detailed in this report, should be included in the Delaware WRR to accommodate the ability for transportation planners and engineers to identify areas of high vulnerability in coastal areas. Identifying these areas will help facilitate high-priority investments in protecting transportation infrastructure that may be affected by coastal forces. Additionally, including stormwater management opportunities and GIS coverages in this tool will help users more readily identify opportunities for multi-benefit investments.

VIII. Useful Information for Other Transportation Agencies

A goal for this project is to develop solutions that are not only applicable for DelDOT but for other transportation departments across the country that face similar challenges associated with coastal and inland flooding, SLR, and wave energy impacts in a shifting climatic regime. In this context, the solutions to address impacts, or potential impacts, on transportation infrastructure can be addressed through traditional, grey infrastructure solutions. Traditional infrastructure includes detention-based stormwater management and hard coastal practices, such as a large stone or rip-rap to protect shoreline assets. In contrast, retention-based GSI practices can be used in conjunction with nature-based CGI solutions to stabilize and enhance coastal areas. These solutions must not only protect coastal areas, but deliver projects that reduce the effects of SLR and storm surge.

a. Coastal Elements for Transferability

The solutions proposed in this effort are focused primarily on protecting transportation in coastal areas. The first transferable project element to highlight is the vulnerability analysis proposed in this report. The vulnerability analysis is a methodology that captures factors common to areas with coastal vulnerability and boils those factors down into one, actionable metric for decision-makers to use. This methodology can be tailored to accommodate other local challenges, and weightings could also be used to reflect a transportation department's varying priorities.

A second transferable project element is creating CGI where no natural features existed before to provide wave dampening capacity that protects the coast and near-shore assets. Such CGI features highlighted in this document include oyster shell reefs, small marsh creation, and beach or dune reconfiguration. In this scenario, coastal flood protection is provided by either a dynamic-flow structure (tide gate) or such upland structures as existing local infrastructure assets or constructed barriers (HESCO boxes). In scenarios with existing wetlands, marshes, or other coastal assets, this project provides a methodology to assess these asset's capacity to address vulnerability. The project also provides examples of how an under-utilized costal asset can be enhanced to provide an uplift in water quality treatment, habitat and ecosystem value, and coastal resilience. Specifically, the proposal to transform a marsh area that receives flow at a single location to a system that receives flow from multiple sources creates a more hydraulically functional system. Further, the conceptual design of a flow-exchange pattern that establishes the ability for this asset to provide the flushing flows needed to maintain channel geometries and overall marsh topography provides an example of a more adaptive and resilient system.

b. Stormwater Elements for Transferability

Many challenges exist for stormwater management to be addressed in coastal areas that are vulnerable in the face of flooding, SLR, and wave-generated impacts. This project provides examples based on stormwater management potential in near-shore areas as well as in upstream areas. As in other coastal areas, retention-based practices in the SR 1 corridor are limited by physical constraints, such as soil type and groundwater table. In these instances, the ability to be opportunistic in identifying the potential for retention-based practices is key to providing holistic stormwater management. In the case of Read Avenue, there are limited opportunities in near-shore areas to provide either retention- or detention-based practices. However, areas upstream have more favorable conditions for GSI, such as permeable pavement or bioretention facilities, that will enhance the hydrologic integrity of the watershed, reduce runoff volumes and flows to downstream areas, and provide local water quality treatment. At Read Avenue, the ability to provide upstream investments in retention-based practices will help the Town of

Dewey Beach reduce the effects of local flooding and solve water quality challenges. DelDOT will also benefit from these investments as many of the proposed green infrastructure practices will be targeted for the SR 1 right-of-way. Additionally, when used in conjunction with other drainage system upgrades, these green infrastructure features will help reduce hydraulic capacity challenges in the SR 1 right-of-way, greatly enhancing conveyance capacity.

At the National Guard site, there are stormwater management asset opportunities both upstream and downstream of the catchment area. The upstream area, much like the Town of Dewey Beach, is highly favorable to retention-based practices. Retrofit opportunities may be limited, however, since much of the area is residential. To date, an analysis has not been completed on the potential for green infrastructure integrated into the existing landscape. The SR 1 right-of-way in this area holds even greater potential for retention-based practices than the Town of Dewey Beach. In this section of divided highway, a wide grass median and grass ditches on both sides of the road could easily be retrofitted with bioswales or bioretention facilities. Even an enhanced filter strip could be used at this location. A filter strip is a new approach designed to improve water treatment and retention capacity of a standard filter strip by amending local soils with biochar. Biochar is a carbon-rich solid similar to charcoal that is produced as an upcycled byproduct from the pyrolysis of waste biomass. Research led by the University of Delaware has shown this practice has great potential (University of Delaware, 2015).

Regarding downstream areas, the current configuration of the drainage system west of SR 1 is consistent with many other coastal areas. Current drainage systems often bypass potential water quality treatment offered by filtration as well as chemical and biological processes in coastal wetlands and marshes. The proposed reconfiguration of flows along with the use of pretreatment cells to reduce maintenance costs and more effectively reduce sediment loads can be replicated throughout the SR 1 corridor and in other coastal areas with similar configurations. By introducing multiple flow paths into the marsh and reorienting runnels within the marsh, this natural system will be more effective at reducing pollutants, providing quality habitat, reinforcing and protecting coastal transportation infrastructure assets, and being easily maintained. Lastly, the consistent geometry where southbound SR 1 lanes are lower than northbound lands provides an opportunity to safely convey transportation during flooding events. In this section of SR 1, the potential exists to “sacrifice” southbound lanes for flood storage by reinforcing the left shoulder of the northbound lanes with HESCO barriers (or similar products) to convey north and south-bound traffic in a strategically planned manner.

c. Partnering and Outreach Opportunities for Transferability

The research pilot project required coordination with several stakeholders that live, work, and vacation in the coastal communities along the SR 1 corridor. Early on in this project, a kickoff meeting with DelDOT Directors of the Bridge Design, Road Design, Maintenance and Operations and Planning Divisions was held to discuss the goals and objectives of the pilot project. At this meeting, the Planning Division invited a team from the National Institute of Standards and Technology (NIST) to discuss their Community Resilience Planning Guide. This guide provides a six-step framework for identifying stakeholders, infrastructure dependencies, resilience goals and objectives (recovery time), hazards, resilience plan development, plan review and approval and implementation.

For communities living along the SR 1 corridor, transportation infrastructure and associated utilities in the right-of-way play a major role in the recovery timeframes of the communities. The roadway will need to be operable to remove debris and bring in materials after a disaster. Designing and planning to make the SR 1 corridor more resilient to storm surge and climate change should be included in community comprehensive plans.

To get the community engaged, DelDOT reached out to a local non-profit agency, the Center for the Inland Bays (CIB). The CIB has worked with the community on several CGI projects focused on dampening wave energies. They have partnered with homeowners and the state environmental protection agency and secured grants for the design and construction of oyster shell reefs, log vane breakwaters, and tidal marsh restoration. CIB contacted mayors and town managers of local communities, and DelDOT invited NIST to facilitate the workshop. The goal of the workshop was to start a conversation with the communities on how they design resilience, determine where they believed they were vulnerable to storm surge and climate change impacts, and discover opportunities for partnering with these important stakeholders.

State transportation departments with limited budgets and staff can be very effective at developing policies and design standards for addressing storm surge and climate change by engaging the local communities that are most impacted. By partnering with towns and non-profit agencies, additional grant opportunities were available to DelDOT. These grants will make it possible to construct one of the projects identified during this research pilot and partnering will make it possible to share the long-term maintenance responsibility.

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