Massachusetts Upper North Shore Regional Sediment Study

Prepared for:

Town of Salisbury

Town of Newbury

City of Newburyport

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1. Project Overview

1.1. Introduction

The Massachusetts communities of Newbury, Newburyport, and Salisbury, contracted Sustainable Coastal Solutions, Inc. (Coastal Solutions) to evaluate regional sediment processes and potential shore resiliency strategies for their public barrier beaches. The three communities make up the “Upper North Shore” region, bordered to the north by the Massachusetts-New Hampshire border (Figure 1.1). Each town has an eastern-facing barrier beach: Salisbury Beach (Salisbury), Reservation Terrace (inside of the jetty, Newburyport) and Plum Island Beach (Newbury/Newburyport).

Figure 1.1. The three communities represented in the Upper North Shore Regional Sediment Study: Salisbury, Newburyport, and Newbury.

While both the inlet and the beaches have relatively normally processes, similar to many others throughout the northeastern United States, the influence of the Merrimack River entrance has significant effect on the sediment migration patterns in the region. Sediment derived from the Merrimack River, updrift shorelines, and the nearshore region continue to supply sediments to the beach and dune system. The natural sediment migration patterns have been altered by the coastal structures maintaining the Merrimack River inlet. In addition, episodic storms (e.g. the “No Name Storm” in 1991 and “Winter Storm Riley” in 2018) can both deposit and remove large volumes of beach sand in a single event. Over the past several decades, shore protection efforts have primarily been emergent responses to beach erosion caused by significant nor’easters in order to protect homes along the barrier beach system. While such emergency efforts are necessary and provide temporary relief, long term planning efforts are needed to mitigate ongoing coastal erosion along the Salisbury, Newbury, and Newburyport ocean shoreline.

The Merrimack River inlet jetties and maintenance of the inlet alter the natural sediment migration patterns and sediment supply which has significant effects on the barrier beaches. Since the early 1900s, the Merrimack River entrance has been armored with jetties in a manner that alters the natural sediment transport pathways in the vicinity of the tidal inlet. Due to this influence, the bypass bar has been pushed further offshore, in many cases causing additional loss of sediment. In other cases, the position of the bar has supplied Plum Island with sediment, especially as it has attached to the shore in recent years. This is expected to fluctuate, with any holes in the bar opening up the potential for erosional hotspots as the shoreline is exposed to higher wave energy. Long-term management of the navigation channel by the U.S. Army Corps of Engineers (USACE) has led to a net loss of sediment to the nearshore littoral system, which directly impacts the stability of the regional barrier beach system. Historically, dredged sediments have been disposed offshore, with a recorded 1.3 million cubic-yard (CY) loss between 1930 to 1980. While corrective actions may be difficult to implement, the influence of removing significant volumes of sediment from the littoral system has had a profound impact along the adjacent shorelines.

The northern beach, Salisbury Beach, has had modest erosion, with the greatest issues nearest to the jetty at the south of the beach. While shoreline position has stayed relatively the same, dune heights have been decreasing, indicating some shifting sediment and loss. The low-lying dune system makes Salisbury particularly vulnerable to flood effects. Plum Island Beach has seen a period of accretion since 2014. This accretion was aided by the repair of the southern jetty in 2013, which caused a blockage on the northern end of Plum Island for local northern sediment transport is trapped up against the southside of the jetty. As a result, this has led to a lack of sediment within the inlet, causing extreme erosion along the Reservation Terrace shoreline. The lack of sediment source, combined with a gyre-like tidal movement, has led to a significant loss of sediment, threatening homes and road infrastructure.

1.2. Study Purpose and Objective

Utilizing an analysis of coastal and inlet processes occurring at the Merrimack River and surrounding barrier beaches, this study focuses on identifying collaborative efforts that could be taken by Salisbury, Newbury, and Newburyport to address present and future coastal hazards.

Both significant storm events and day-to-day processes are shown to have adverse effects on the region via erosion and flooding. Salisbury Beach has faced an increase in flood intensity in recent years, as the existing dune system continues to lower. Reservation Terrace, just inside the mouth of the inlet, has seen dramatic erosion due to a gyre formation within the inlet and a lack of sediment supply. Plum Island Beach is currently in a period of accretion, however, changes in the location of the bypass bar threaten the stability of the beach by creating erosion hotspots.

While each area has varied issues, the primary purpose of this study is to view the entire region holistically to evaluate sediment processes that transcend town boundaries. Data collection was first done to understand existing conditions and historical changes in the region. This data was used to create wave models and calibrate shoreline position for eventual sediment transport modeling. Both the data and the models were used to develop and inform the provided mitigation design scenarios. An overview of the study methodology is shown in Figure 1.2 below.

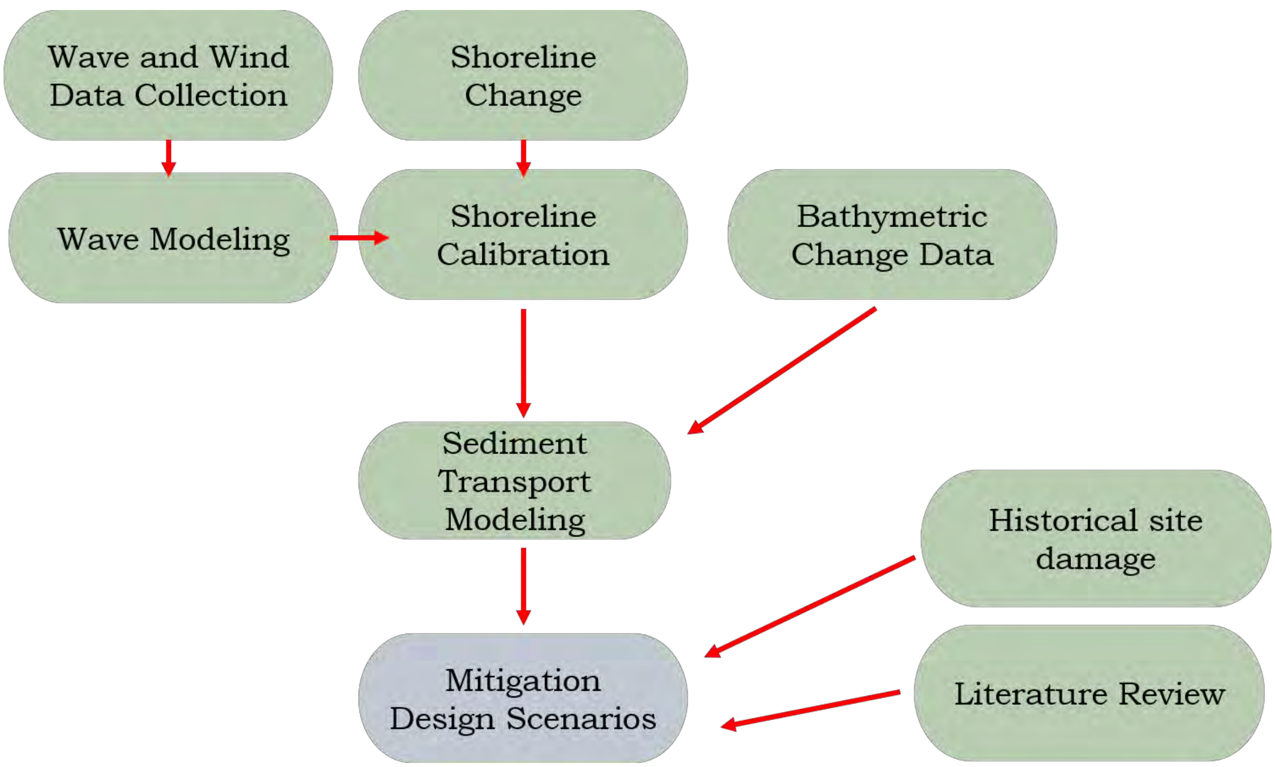

Figure 1.2. Methodology for Upper North Shore Regional Sediment Study. Data collection process followed by modeling analysis.

This effort is aimed at management goals over the next 10-to-20-year planning time horizon for the Upper North Shore Coastal Complex: sustaining the beach and dune as an attractive public resource and enhancing the dune system to provide coastal resiliency.

- *Wave and wind data collection* - A thorough review of available wave and wind data was performed. The USACE Wave Information Study (WIS) hindcast database, at station 63045, was used to generate the offshore wave conditions. The WIS has a record that spans the 44-year period from January 1980 to December 2024. The entire record was reviewed to generate mean wave conditions that result in longshore sediment transport.
- *Shoreline change data collection* - MassGIS provides shorelines measured through LIDAR. The collected shorelines for about 14 different years were collected and viewed. It was determined that the most reasonable shorelines applicable to the Upper North Shore were the 1952 and the 2005 high-water shorelines. The 1952 shoreline was used in computing a long-term shoreline change, and the 2005 shoreline was used for computing the short-term shoreline change. Both shorelines were compared against the 2026 survey collected by Coastal Solutions. Additional shorelines for 2014 and 2021 were also obtained through an analysis of LiDAR and aerial imagery for the sediment transport and shoreline change model. Grain size sampling was completed along the shoreline. Two samples were taken approximately every 2000 feet, resulting in a total of 32 samples.
- *Bathymetric change data* - Bathymetric data was obtained from NOAA Coast to inform wave modeling. Two primary sources of data were used: NOAA NCEI CUDEM, and the 2018 USACE Topobathy survey. The NOAA NCEI CUDEM informed the offshore bathymetry, while the 2018 USACE survey provided detailed nearshore topobathy and was performed after the 2018 storm season.
- *Historical site damage* - To better understand shoreline changes and jetty stabilization over time, a management history record was prepared. The jetty history, which spans 1881-2015 is well documented in both repairs and full construction updates.

Three modeling “steps” were to develop and assess performance shoreline management strategies (e.g. beach nourishment and modifications to existing coastal engineering structures) in these areas:

- *Spectral wave refraction modeling* – Spectral wave refraction modeling was used to determine how nearshore bathymetry modifies the wave climate along the open ocean beaches of Salisbury, Newburyport, and Newbury.
- *Sediment Transport and Shoreline Change* – Utilizing the spectral wave information, a shoreline change model is developed for the shorelines of Salisbury and Plum Island Beach. The 2014 shoreline is used as input in the sediment transport model, and the skill of the model is then tested by comparing the observed 2021 shoreline to the modeled 2021 shoreline.
- *Shoreline Protection Alternatives* – After calibration of the shoreline change model the modeling tools were used to evaluate several shoreline stabilization alternatives at each site.

The modeling approach described above, which incorporated different tools to assess the ocean-facing and interior Merrimack River shorelines, provided the most defensible approach for assessing shoreline stabilization methods for each of these areas. Understanding that the ‘practicability’ of an alternative (i.e. an evaluation ensuring that an alternative is available and capable of being done after taking into consideration cost, existing technology, and logistics in light of overall project purposes) is critical in ranking the viability of alternatives. For the prioritized alternatives, the report also provides identification and description of further analyses that will be needed if a decision is made to move forward with detailed design and permitting.

- *Beach nourishment* - This report provides several nourishment scenarios for each beach. Steps in the development process included existing conditions surveys performed by others; development of alternate layouts for sand placement to provide various levels of storm damage protection and volume calculations for each alternative. Sediment sourcing, is also discussed to determine how solutions could be effectively implemented.
- *Modification to jetty* - Potential modifications to the southern jetty were considered as a future method to aid in sediment movement into Reservation Terrace at the mouth of the Merrimack.

1.2.1. Previous Studies

Many previous studies have been conducted in the Merrimack River inlet area to examine regional coastal processes and sediment transport pathways. A previous sediment study, *Upper North Shore Regional Sediment Management Study*, was completed in January of 2021 for the Massachusetts Department of Conservation and Recreation (DCR) by Applied Coastal. The study aimed at understanding the variety of coastal and inlet processes that governed the Merrimack River and barrier island complex, and to recommend specific management strategies to ensure resiliency in the area. This study expands on the previous work, with updated modelling and input shoreline data. Additionally, this study seeks to capture the urgent erosion along Reservation Terrace as a result of jetty repair. This includes discussion of recent emergency nourishment projects and ground-truthing sediment budget estimates with sediment volume loss calculations.

Previous studies were consulted as a source for historical information regarding the region and works completed on both the jetties and the beaches. Particularly, the USACE reports *Merrimack Estuary and Newburyport Harbor Sediment Management Studies* and the *Newburyport Harbor and North Point, Plum Island Detailed Project Report and Environmental Assessment* provided important background on federal works, as well as previously collected hydrodynamic and sediment data.

1.3. Project Area Description

Salisbury

Salisbury is the northernmost coastal town in the Commonwealth of Massachusetts, located about 40 miles north of Boston, Massachusetts. The town is bordered to the north by the New Hampshire border, and to the south by the Merrimack River. On the western side of the town is a large swath of protected saltmarsh. The saltmarsh combined with a low elevation means that aside from coastal flooding, backside flooding is also a large issue. To the east, Salisbury has approximately five miles of barrier beach. As a result, beginning in the early nineteenth century, Salisbury has become one of the most visited vacation towns in Massachusetts.

The majority of this beach is a state-owned public recreation area, called the Salisbury Beach State Reservation (SBSR). SBSR receives over one-million visitors per year, with many staying near or on the beach and others utilizing the recreational function of the beach for swimming, fishing, sunbathing, and amusement. During the period between the 1930s-1950s, the area experienced a heyday, in which a large amount of vacation properties as well as entertainment options such as arcades, dance halls, a boardwalk, and community centers became incredibly popular. Several fires moved through the area in from the 1920s-1940s, destroying several cottages and much of the amenities. However, since Salisbury was at the height of its popularity, much was rebuilt and can still be seen today along the oceanfront (Reynolds, 2022). The Ocean Echo was built on the beach around 1900, and served as the town dance hall, and later a music venue called the Frolics in the early 1940s. Currently, this land is still being used by the Pavillion, which houses a music venue, a restaurant, and a gift shop (Figure 1.3). Disappearing from the area are remnants of town history as older commercial buildings and cottages becoming even more vulnerable to rough coastal storm damage.

Figure 1.3. The Pavillion on stilts above the beach. Salisbury, MA.

The entirety of Salisbury Beach was considered in this study, with bounds shown in Figure 1.4.

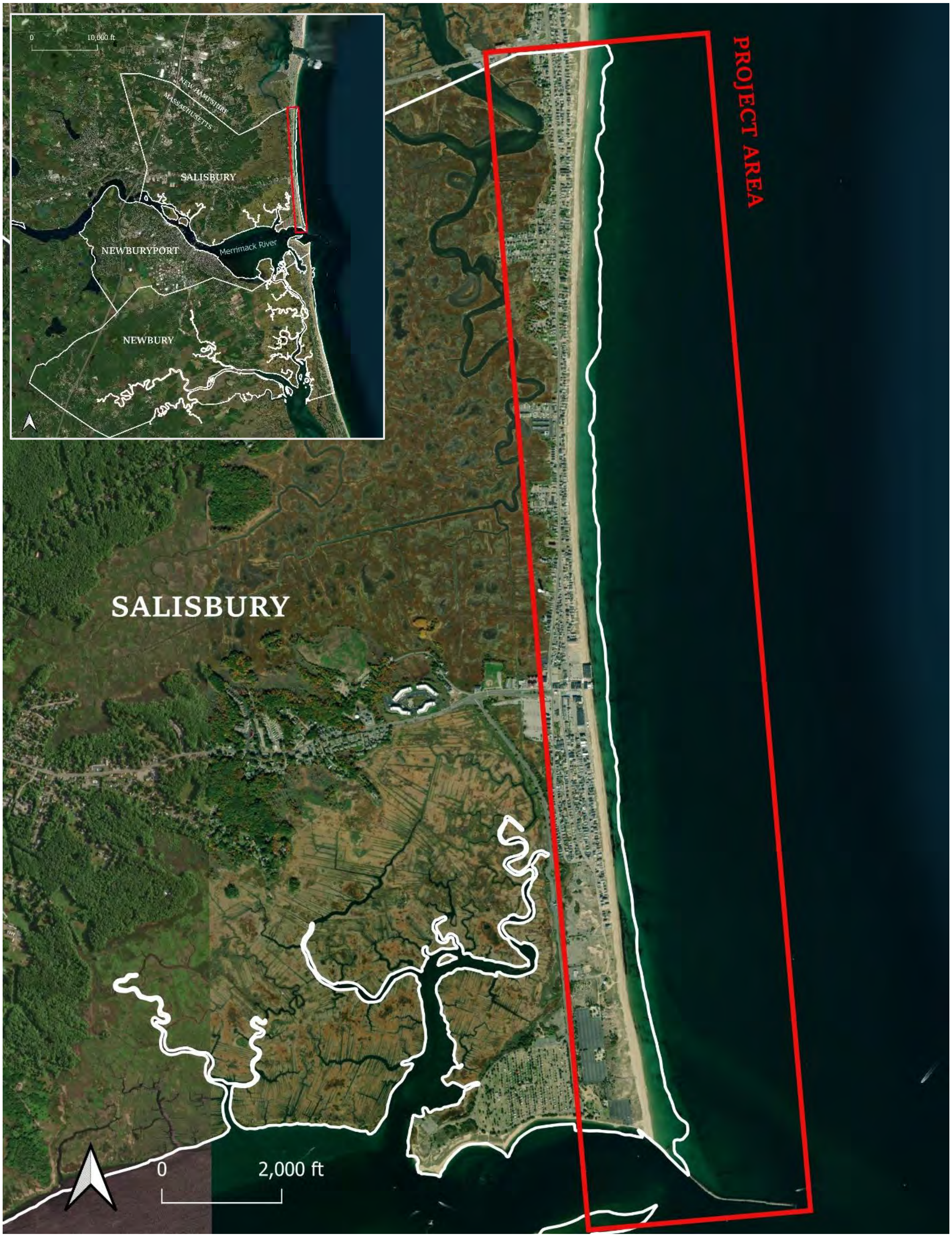

Figure 1.4. Study boundary for the Town of Salisbury, with Salisbury Beach outlined. Note that the north jetty and the inlet of the river considered in the study.

Newburyport

Newburyport is located on the southern coast of the Merrimack River, with the downtown area located approximately 3 miles inland along the river. It is bordered to the south by the town of Newbury and located about 35 miles northeast from Boston. The town has historically been bolstered by trade, fishing, and shipbuilding, all reliant on the Merrimack River as a navigation channel. There is about one mile of beach within the inlet and along the Newburyport portion of the Plum Island barrier beach. The “mainland” is connected to the island through the Plum Island Turnpike. This road serves visitors for all communities that make up Plum Island. This project focuses on both the barrier beach and the short shoreline within the inlet called Reservation Terrace (Figure 1.5).

Although the harbor has historically been the center of population and commerce, other prominent areas exist such as the eastern boundary of the town known as Joppa/Plum Island Point. Plum Island Point is a peninsula situated just at the mouth of the river, with its northern shore within the tidal inlet and its eastern shore a barrier beach. North Reservation Terrace and Reservation Terrace roads run closest to the shoreline, and thus the area along the river inlet is often referred to as Reservation Terrace. Reservation Terrace has faced several struggles throughout the years, particularly in relation to erosion caused at the inlet, which has threatened homes and the integrity of the overall beach. Erosion in the area has always been a concern, however, following a repair of the southern jetty in 2013, the issue has only grown. This has been exacerbated by both normal tides and extreme easterly storms. In 2023 the issue was so severe that over 220,000 cubic-yards (CY) of sediment was placed along Reservation Terrace as an emergency supply to buy time while more permanent solutions were designed. As Reservation Terrace has eroded, the section of beach outside of the jetty has accreted in some places at a rate of 13 feet per year (since 2015).

Newbury

The residential town of Newbury lies just south of Newburyport, and is about 32 miles from Boston, to the north. Farming, particularly of clams and of salt marsh hay also serve as an income source for some residents, however, the area is mainly residential with Plum Island village serving as the town’s oceanside community. Newbury has about 1.5 miles of Atlantic-facing shoreline in their jurisdiction (Figure 1.6). About 250 people live in this area of Newbury, with residential areas ending on the border of the Parker River National Wildlife Refuge.

Plum Island itself is split between the communities of Newbury, Newburyport, Ipswich, and Rowley. Of the four towns, Newbury and Ipswich own the largest parcels of the island. Much of the island however is managed by the federal or state level, Parker River National Wildlife Refuge and Sandy Point State Park. These areas are not considered in this study, however they both are connected to the inhabited portion of Newbury and were considered on a larger scale for wave and sediment modelling. Newbury is not alone in facing severe coastal flooding that threatens homes and infrastructure. The Plum Island Turnpike floods regularly, leaving those who live on the island stranded from the mainland. The eastern-facing Atlantic beaches mean that easterly storms are a large hazard for many homes, especially those that sit atop the dune.

Overall, this study seeks to provide a basis for resilient coastal solutions along the entire region and within each town.

Figure 1.5. Study boundary for the Town of Newburyport. Reservation Terrace sits within the inlet and the stretch below the southern jetty is considered part of Plum Island Beach.

Figure 1.6. Study boundary for the Town of Newbury. Plum Island Beach was considered to the end of the residential area and beginning of the federally owned beachfront.

1.4. Executive Summary

Sustainable Coastal Solutions, Inc. (Coastal Solutions) performed a regional sediment management analysis for the coastal communities of Newbury, Newburyport, and Salisbury. These three communities comprise the upper North Shore of Massachusetts. Central to this region is the Merrimack River, one of the largest rivers in the area, and an important federal navigation channel. Both the mouth of the river, which straddles Salisbury and Newburyport, as well as the barrier beaches in each of the three communities offer a variety of challenges and opportunities for promoting storm and erosion resiliency in the region. For over a century, the shoreline on the upper North Shore has been armored and modified, resulting in dramatic changes to the sediment system.

This study assesses the impacts of coastal processes on the barrier beach complex and provides a basis for the planning and implementation of future coastal resiliency projects. Development of erosion control strategies, sourcing compatible dredge material on public beaches, and beach management for the three communities require a comprehensive regional approach. To accomplish these goals, Coastal Solutions completed:

- An in-depth review of historical records, including but not limited to: beach management history, aerial imagery, previous local studies, and historic tide gauge data.
- Data collection of the most up-to-date shoreline, grain size, and bathymetry data.
- Coastal modeling for the eastern-facing barrier beaches.
- Assessment of beach nourishment scenarios.
- Development of additional alternatives such as alternative sediment sourcing and changes to existing coastal infrastructure.

Once naturally shifting, the position of the Merrimack River inlet was stabilized in the beginning of the 20th century. The construction of two stone jetties created an important federal navigational channel within the Merrimack River, but has also caused significant impacts to the resiliency of surrounding beaches and communities. Changes in the structural integrity of the jetties throughout the years have changed sediment dynamics and thus, the surrounding shorelines. The northern end of Plum Island, called Reservation Terrace, has the most visibly drastic changes. Slight changes in jetty structure have been shown to interrupt the movement of sediment both within the mouth of the river and on a regional scale. While the general movement of sediment is from the north to the south, wave refraction around the southern jetty causes a reversal that allows sediment to supply Reservation Terrace when the jetty is open. Without this supply, the shoreline is sediment starved, leading to accelerated erosion. Additionally, the extension of the jetty has pushed the bypass bar further offshore, creating temporary “erosion hotspots” along Plum Island when there are openings in the bar. To the north, Salisbury Beach has seen devastation from storm events, oftentimes damaging existing frontal dune systems. The proximity of infrastructure to the beach and low-lying elevation has made Salisbury particularly vulnerable to coastal flooding.

Literature review provided insight on the formation of the region via existing coastal processes and the eventual transformation as armoring and other beach management practices were implemented. Additionally, previous studies offered baselines for coastal trends occurring on the upper North Shore. Much of this literature was used to contextualize the motivations and findings of this study. Data collection was completed to provide the most updated information for modeling coastal processes, which in turn served as the basis for sediment transport modeling.

Models used in the study included:

- SWAN (Simulating Waves Nearshore): SWAN is able to simulate wave refraction and shoaling induced by changes in bathymetry and by wave interactions with currents. The model includes a wave breaking model based on water depth and wave steepness.
- One-line Shoreline Model: Shoreline evolution modeling was performed using a "one-line" longshore transport computer code. So called "one-line" models simulate the evolution of a shoreline through time, at one specific contour level, e.g. the beach berm crest or mean water level, based on the assumption that the nearshore bathymetry (to the depth of closure used to define the active extent of the beach profile) can be adequately represented.

Existing impacts from shoreline armoring is among one of the biggest concerns for sediment transport in the area. In particular, Coastal Solutions reiterates the finding that the repair of the southern Merrimack River inlet jetty has resulted in a gyre-like circulation pattern that erodes the shoreline of Reservation Terrace, resulting in significant loss of the beach nourishment placed in 2023. Additional coastal structures were not considered to be practical as a result of this study. Beach nourishment and overall changes to existing infrastructure indicate the most practicable outcomes for decreasing erosion and flooding, while maintaining the beaches.

Coastal Solutions considered alternatives for three areas: Salisbury Beach (from the MA/NH border to the northern Merrimack River inlet jetty), Plum Island (from the southern Merrimack River inlet jetty to the beginning of the Parker River National Wildlife refuge, or the ocean fronting shorelines of Newburyport and Newbury), and Reservation Terrace (the shoreline of Newburyport inside the Merrimack River inlet).

For Salisbury Beach, a large-scale nourishment project is suggested to address the net erosion of the shoreline as well as low-lying dune elevations. A large-scale nourishment project would extend both the seaward portion of the shoreline as well as increase the overall elevation of the beach, providing increased protection to adjacent coastal infrastructure. In recent years, the Plum Island shoreline has been accreting, due to both the location of the bypass bar as well as the repair of the southern Merrimack River inlet jetty, which cuts off the sediment supply to Reservation Terrace. Nourishment alternatives for Plum Island were generated in the case of a future erosion hot spot. The erosion hot spot would be identified through monitoring of the shoreline, and ideally preventative nourishment would be implemented, before significant erosion impacts adjacent coastal infrastructure. Modeled nourishment scenarios for Salisbury Beach and Plum Island are shown in Figures 1.7 and 1.8, respectively.

Figure 1.7. A close up of Scenario 4 immediately after 100-foot berm construction (dark red), as well as modeled shorelines 5 and 9 years (red and pink, respectively) after placement. The 2026 shoreline is shown (dashed black).

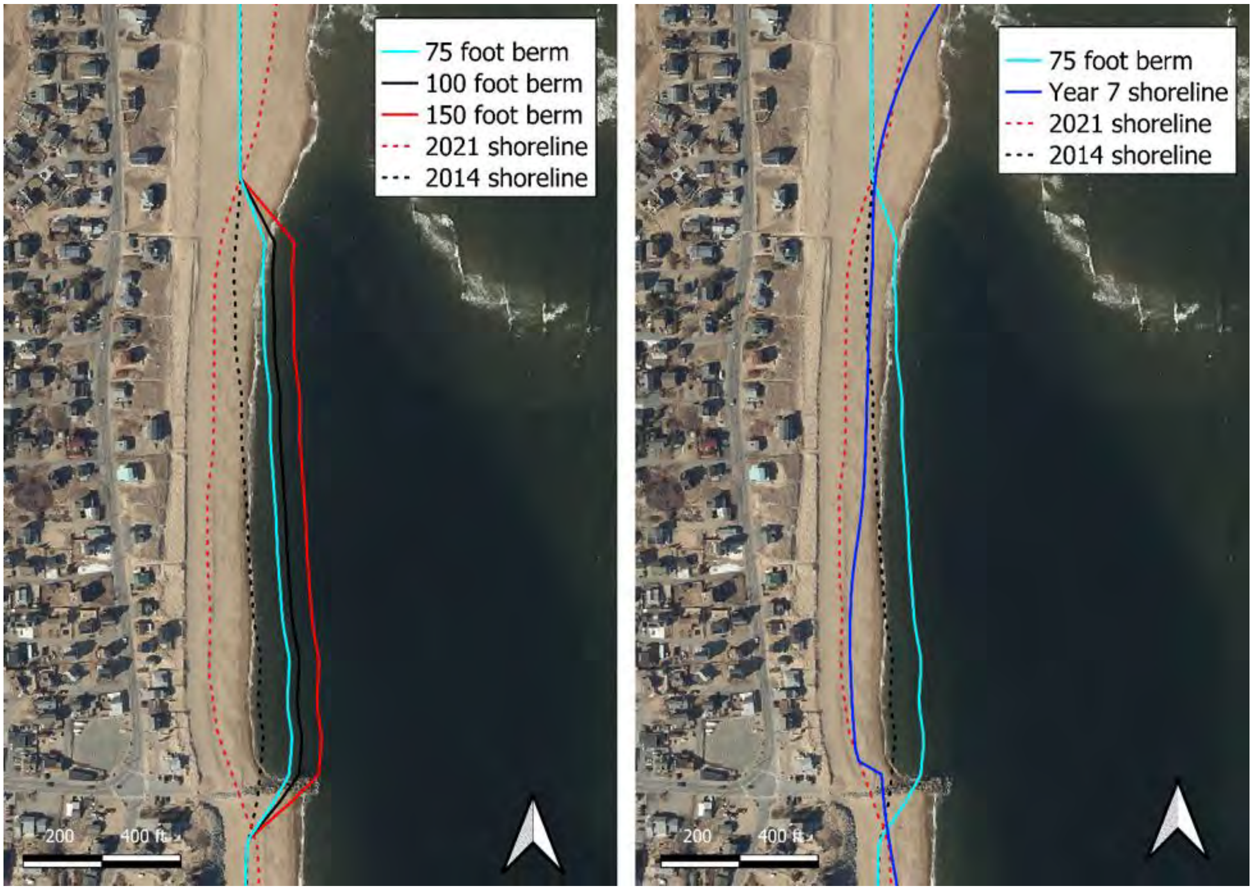

Figure 1.8. Plum Island nourishment scenarios with 75-, 100-, and 150-foot berms shown on the left panel (cyan, black, red lines respectively). The modeled shoreline seven years after original fill placement is shown (blue line) for the 75-foot berm scenario (cyan line) on the right panel. The observed shorelines for 2014 (dashed black) and 2021 (dashed black) are shown on both panels.

For Reservation Terrace, the previous sediment study recommended a weir jetty to allow sediment migration from Plum Island as well as interrupt the gyre-circulation pattern. USACE is now considering implementing a weir jetty (Applied Coastal Research and Engineering, 2021). In the meantime, Coastal Solutions explored an alternative to allow manual bypassing of the jetty through dredging a portion of the northern Plum Island shoreline to act as a sediment supply for Reservation Terrace. The shorelines of a modeled “bypass scenario” that would provide approximately 128,000 cu-yd of sediment to Reservation Terrace is shown in Figure 1.9. The model results show that the excavated shoreline recovers to the original position in 2.6 years.

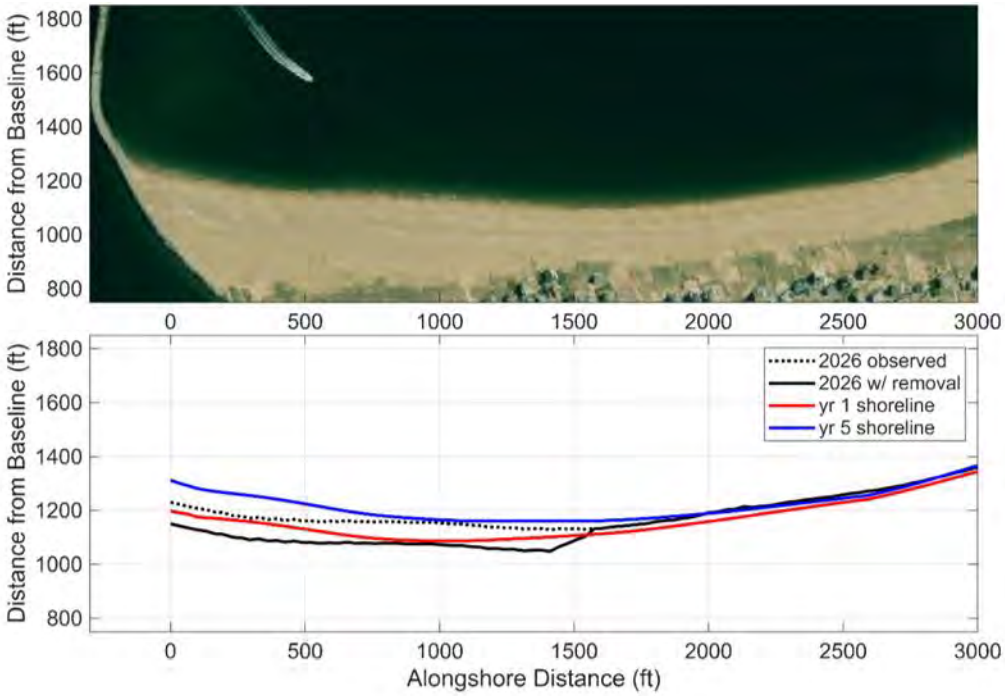

Figure 1.9. Shorelines for bypass scenario 2, where the observed 2026 shoreline and the shoreline immediately after excavation are shown (dotted black and solid black respectively). Modeled shorelines 1 year and 5 years after excavation are shown (red and blue respectively).

Currently, around 40,000 cubic-yards/year is available to be dredged from the inlet. This study finds that this amount is not large enough to satisfy the overall resiliency needs for the upper North Shore and that additional sources of sediments, offshore or upland, should be heavily considered.

2. Historical Background

What was once a naturally shifting barrier beach complex and river inlet has now seen over a century of man-made modification and armoring. While this has created an important federal navigational channel within the Merrimack River, there has also been significant impacts to the resiliency of surrounding beaches and communities. More recently, reconstruction in the jetty and management of dredged materials has negatively changed the sediment transport, morphology, and sediment budget of the area. Table 2.1 provides a brief overview of the challenges that have arisen following historical changes to the Merrimack inlet system.

Table 2.1. Impacts resulting from historical changes in the jetty	
Historical interventions	Resulting impacts
1937-2010: Routine dredging of the Merrimack inlet	Sediment cleared from navigational channel, lost or potentially lost to the system. There is ~ 1.3M cu-yd loss to system (placed offshore) and ~1.1M cu-yd loss to subject beaches (placed on bypass bar).
1968-1970: The jetties underwent the first of their two major rehabilitations. They were extended to approximately their current lengths and a rock revetment was constructed at the south jetty.	Reservation Terrace experienced similar effects observed after the 2012-2014 jetty repair, described below.
2012-2014: Both normal wear and storms damaged the jetties, creating a “leaky jetty” on the southern jetty. Phase I of an alternatives assessment of sediment management scenarios saw the height of the jetty restored by placing additional stone.	Sand that had previously supplied Reservation Terrace was now blocked, leading to large accretion at the point of Plum Island. At the same time, this blockage led to the development of a gyre within the inlet and starved Reservation Terrace of sediment.

2.1. Morphology

Plum Island has captured the focus of researchers for the last century. The island’s complex morphology, combined with wave and wind dynamics, the marsh and tidal inlet, as well as man-made stabilization of the inlet has led to dramatic shoreline changes even within the last 150-years. Plum Island was formed over the course of about 7000 years B.P. (before 1950) through a series of post-glacial sea level movement. As the land, originally packed under ice, began to thaw, it is hypothesized that the rebound in land outpaced that of the sea-level rise. This, however, was relatively short lived as the land began subside and relative sea-level quickly grew. Around the year 3000 B.P., it is predicted that Plum Island reached equilibrium with the sea-level. Further development of Plum Island was then dominated by longshore sediment transport, to which the southern portion grew (Hubbard 1975; Jones and Cameron 1976).

Differences in the northern and southern portion of the island are postulated to have diverged due to offshore bathymetry as well as storm energy. Plum Island is mostly made up of unconsolidated sands: sand, gravel, and silt. Additionally, the southern portion of the island is made up of transported glacial till in the form of drumlins. The northern end of Plum Island is generally considered to have a steeper-slope than its southern counterpart, as well as coarser sediments. The northern part of Plum Island also has higher-energy littoral zone, meaning stronger waves, currents, and sediment movement. Despite these differences, Plum Island as a whole generally behaves naturally in comparison to other similar tidal inlets (Jones and Cameron 1976). Considering that northern Plum Island is the populated residential area, the variability of this area brings many challenges.

Changes in the formation of Plum Island since them have dramatically occurred within the last 150 years, particularly at the northern tip, and what we now refer to as Reservation Terrace and the northern section of Plum Island Beach (Figure 2.1).

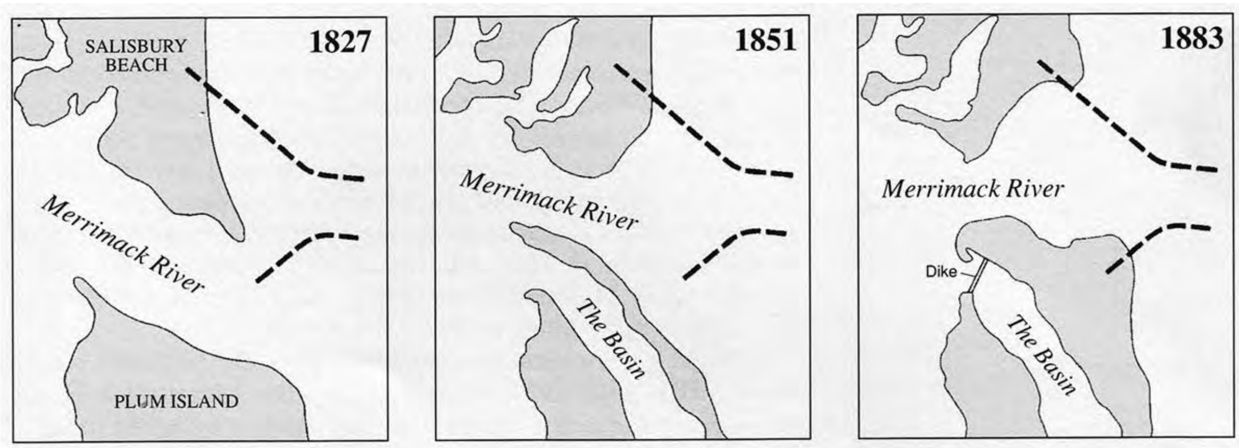

Figure 2.1. Three maps, based on surveys by USACE in 1827, 1851 and 1883, show the changing contours at the mouth of the Merrimack River in relation to the present-day jetties indicated by dotted lines. The views represent the high-water marks on both the Plum Island and the Salisbury shores (Weare, 1996).

The addition of the jetties resulted in the formation of downdrift trailing bars; these are series of bars running parallel to the downdrift shorefront of the inlet (Hubbard 1975). This is still evident in both aerial imagery and bathymetry data collected, where a bypass bar just south of the jetty and parallel to the beach is regularly forming and moving. The bypass bar has significant effect on the wave dynamics and resulting sediment transport in the area, as it serves to shelter much of Plum Island from wave energy by shoaling and refracting the waves. The regular movement of the bypass bar often results in the formation of erosion hot spots along Plum Island due to the focusing of wave energy in areas where the bypass bar has disconnected or moved offshore. Figure 2.2 demonstrates the significant movement of the bypass bar in just the span of four years. From 2014 to 2018, the region of the bypass bar highlighted in the red box has moved to the nearshore and accreted significantly (~10 feet). The bypass bar also can act as a source for the Plum Island shoreline, with sediment migrating off of the bar to the nearshore. In Figure 2.3, the movement of the bypass bar from 2014 to 2020 is shown with aerial imagery, where the outline of the bypass bar is highlighted and the migration of sediment to the Plum Island shoreline can be seen in the 2020 aerial photo, highlighted in the yellow box.

Northeasterly waves near the ebb shoal refract around the inlet mouth, creating an immediate reversal of sediment transport direction (towards the north) just south of the the inlet and north of the bypass bar attachment to the shoreline. This is later confirmed throughout this study via sediment transport modeling. Despite the direction change just below the inlet, north-to-south is still the dominant longshore sediment transport direction along both the Salisbury and Plum Island barrier beaches.

Since jetty management began in 1881, the inlet entrance has been generally stable. For the shorelines along Plum Island, significant change has occurred. While the normal patterns of wave refraction would occur without the jetties, the jetties have been found to cause increased erosion on Plum Island due to restriction of inlet drift. The changes brought about by engineering intervention have had observable effects on the Reservation Terrace area since even 1969. In February of 1969, three major storms entered the area, affecting about 18 high tides and removing over one-million cubic yards of sand, as well as up to 200 feet of property loss (Figure 2.4) (Hubbard 1975; Jones and Cameron 1976).

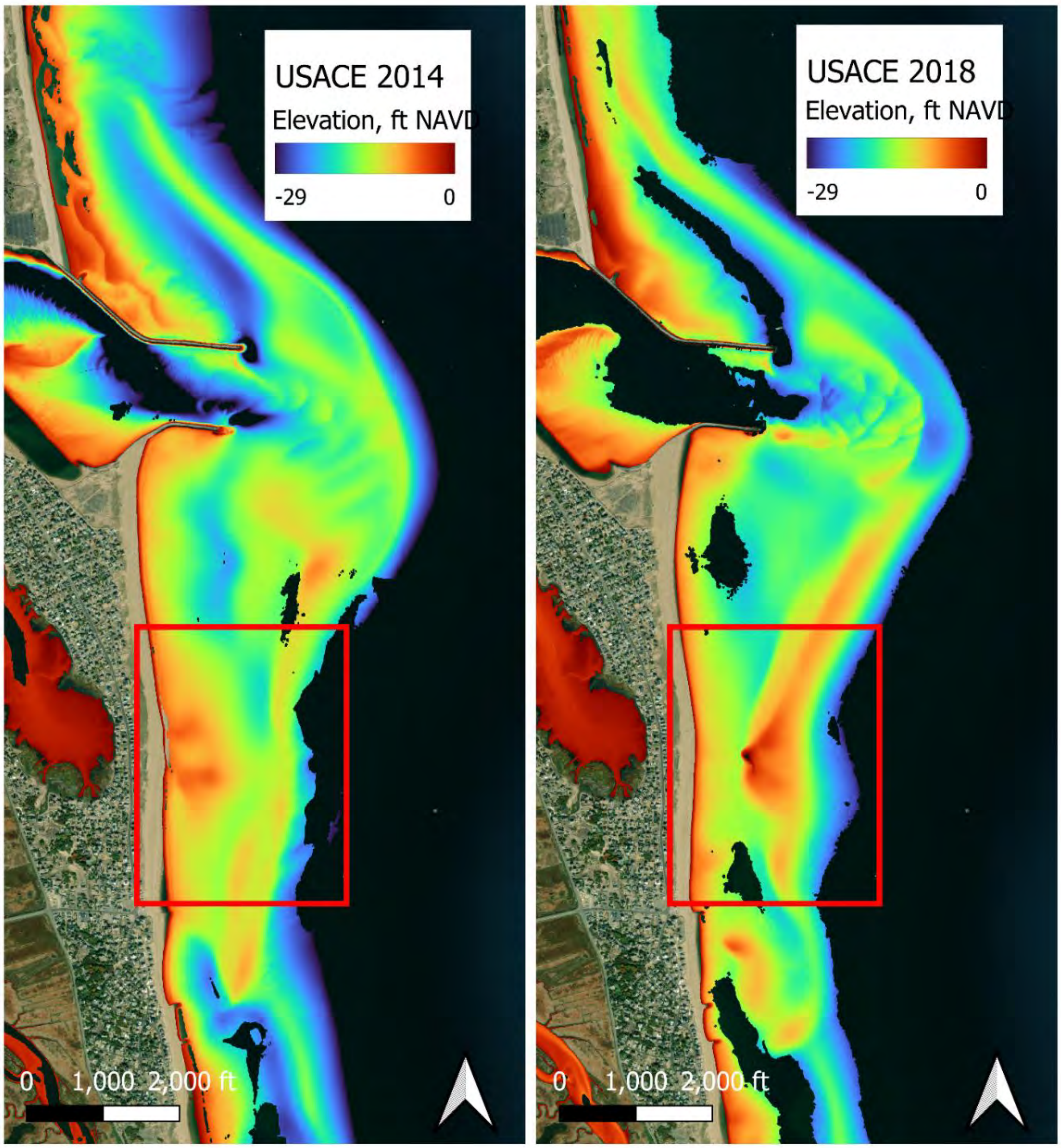

Figure 2.2. Recent changes in bathymetry demonstrating the location of the shifting bypass bar (red box) in 2014 versus 2018.

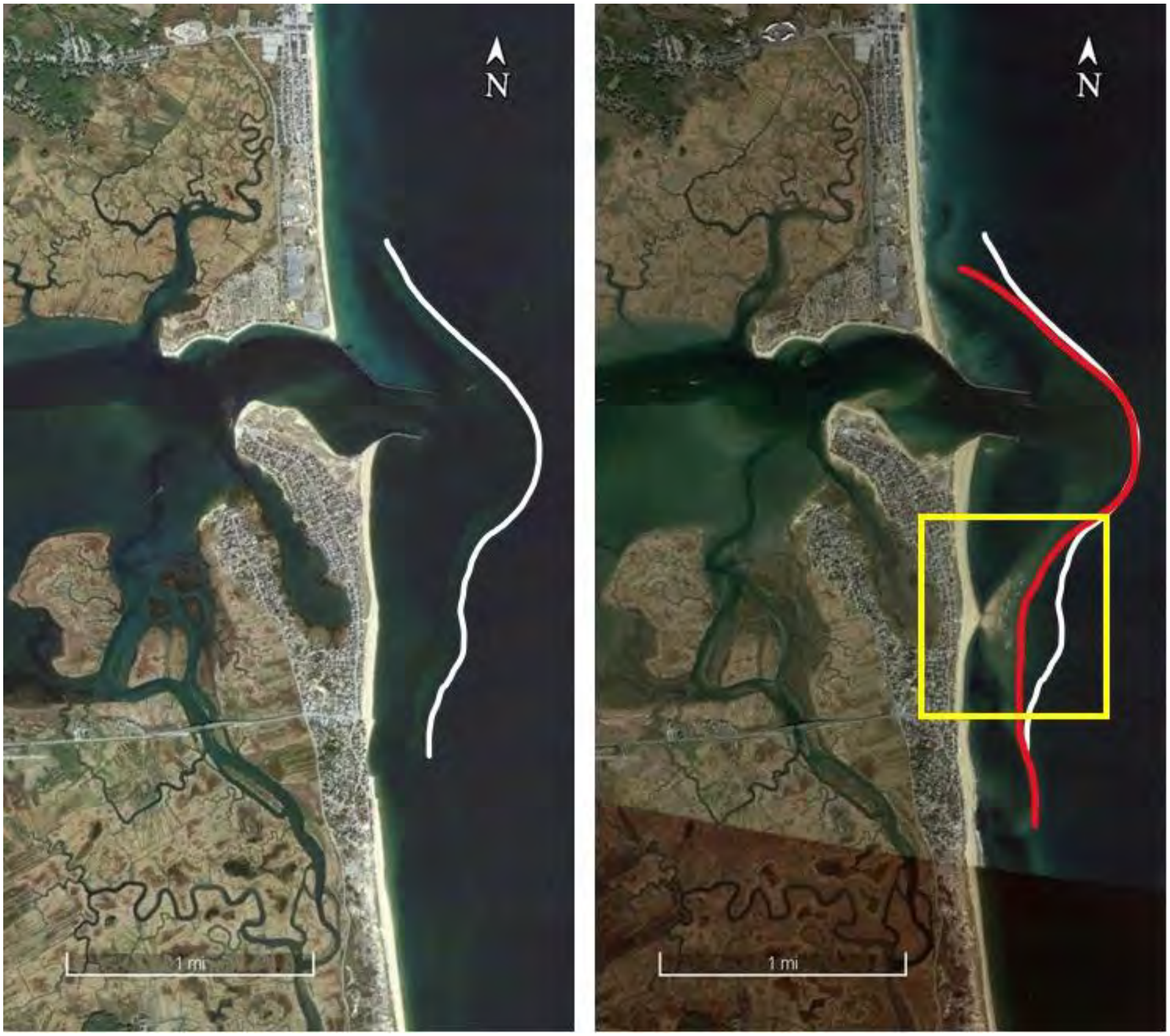

Figure 2.3. Aerial photos of the Merrimack River inlet from 2014 (left) and 2020 (right). The outlines of the bypass bar from 2014 (white) and 2020 (red) are shown. The bypass bar visibly deposits sediment in the nearshore in 2020, as shown in the yellow box (right panel).

Figure 2.4. Shear erosion from February winter storm of 1969, when the Coast Guard building still sat near the jetty. Reservation Terrace, MA (photo from Boston Globe).

2.2. Merrimack River

The Merrimack River Valley Watershed is the 4th largest in New England. Over 200 New Hampshire and Massachusetts communities are situated along the river, supplying drinking water for over 600,000 people and serving as a source of recreation, sustenance, and livelihoods for thousands of people. There are five smaller rivers draining into the Merrimack: Pemigewasset (NH), Contoocook (NH), Souhegan (NH/MA), Nashua (NH/MA), and Concord (MA) rivers. The Merrimack also has connection to the Squam Lake, Lake Winnipesaukee, and the Wachusett Reservoir (Figure 2.5).

The Merrimack River terminates between Salisbury and Newburyport, between the two constructed jetties. The river contributed greatly to the creation of the basin backing the northern end of Plum Island Point, which was later contained behind a dike to prevent river influence. Maintenance of the jetties helps to stabilize the position of the river mouth, as shown in morphological changes in the past century. The tidal portion of the river is around the final 25 miles, before emptying into the Atlantic Ocean (American Rivers, n.d.). The Merrimack Estuary as well as the inlet channel have a similar tidal range, with an amplitude of about 8.5 feet (Li et al. 2018). In turn, the Merrimack greatly impacts sediment movement within the channel and erosion along the banks. The change in tidal direction also impacts the river flow rates and how much is moved both inland and offshore.

Figure 2.5. Merrimack River watershed extent. (American Rivers, n.d.)

2.3. Management History

To better understand shoreline changes and jetty stabilization over time, a management history record was established. This record provides important background on efforts made to stabilize the region and maintain the Merrimack River navigation channel.

2.3.1. Hard engineering solutions

The central hard engineering structures are the two Merrimack River jetties. The north jetty is connected to Salisbury Beach and extends eastward approximately 4,118 feet, while the southern jetty is connected to the Plum Island Point and Reservation Terrace area and extends about 2,445 feet (Bourne Consulting Engineering, 2015). The jetties have long been maintained under the Army Corp of Engineers, who began its construction in 1881. Prior to the jetty creation, the area underwent construction of dikes and removal of several large boulder fields further down the river (Figure 2.6).

Figure 2.6. Dike crossing the “basin” inside the jetty in 1905 (Friends of Plum Island Light, n.d.).

The construction, ending in 1899, resulted in two rubble-mound jetties built up to approximately +12-feet MLW and had a top width of about 15-feet. Since then, the jetties have been in almost a constant state of repair and maintenance, with repairs occurring in: 1900, 1905, 1917, 1925, 1933, 1936, 1968, 2012, and 2013. Figure 2.7 shows the current state of the jetty.

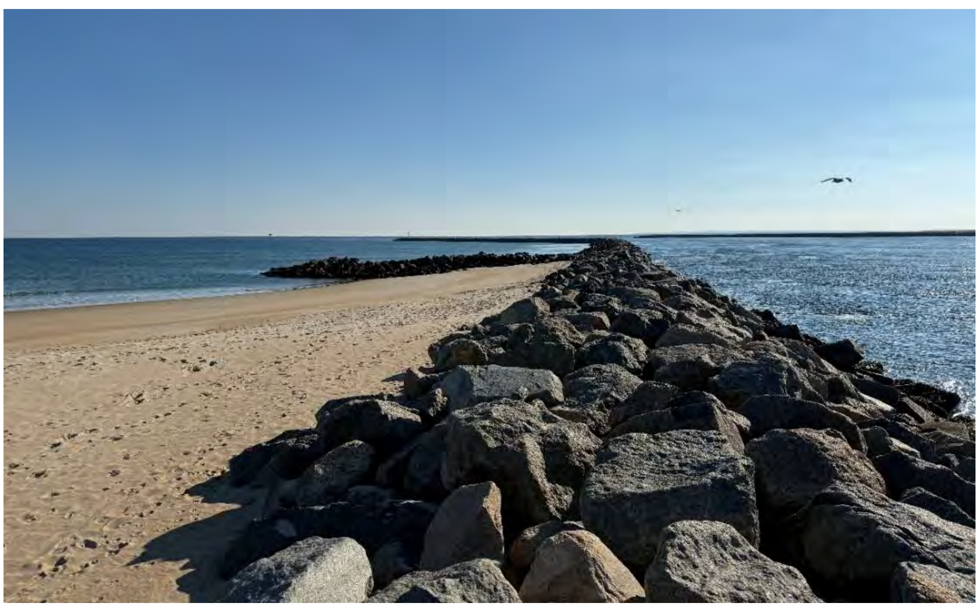

Figure 2.7. Current view of the northern jetty.

Aside from the stabilization of the location of the river mouth, the waters in this area were considered incredibly dangerous, with about 100 documented wrecks occurring in the area since the late 1800s, prompting a Coast Guard and Life-Saving Station located near the south jetty. The strong currents and rapidly shifting sediment movement made navigation in this area hazardous and were expected to be stabilized by the creation of the two jetties.

Following chronic erosion patterns, as well as Tropical Storm Irene and Hurricane Sandy, the U.S. Army Corp of Engineers secured funding in 2013 for the repair of the south jetty. The project included placement of approximately 12,000 tons of 6–12-ton armor stones meant to fill gaps in the jetty. The repairs to the jetty were estimated to aid in extreme erosion occurring in Newburyport, which affected several homes directly along the barrier beach. In the approximately 15-years since the works, severe beach erosion has continued to affect Newburyport. This problem is felt most drastically by the residents living in Reservation Terrace, where tidal currents are constantly eating away at the beach and exposing residents to high water levels and an encroaching coastline.

A full construction and maintenance history of the Merrimack River Jetties is provided in Appendix A (Newbury, MA., n.d.)

2.3.2. Dredging History

Dredging in the region began with maintenance of the jetties, and occurred to clear the navigation channel. Complete nourishment records are sparse, especially in the late 1800s to early 1900s. Coastal Solutions aggregated nourishment data from Army Corp reports, town records, and comparison with nourishment history. Dredged material has historically been placed on two nearshore bars, one in Salisbury and one off of Plum Island (Figure 2.8).

In the past two decades, increasing effort to return dredged materials to the beach have been made. This alternative allows for sediment recycling, moving the eroded sediment from the channel back onto the beach. The dredging replacement serves as a temporary solution to quick and extreme erosion. Recent projects have dredged approximately 350,000 CY for onshore beach placement. Since 1937, 3-million CY of sediment has been dredged from the Merrimack River. Table 2.2 contains a full account of inlet dredging history.

Figure 2.8. Nearshore and on-shore placement sites proposed in 2021 by the USACE (United States Army Corps of Engineers, 2021).

Table 2.2. Merrimack River Inlet Dredging History			
Date of Works	Amount (CY)	Disposal Location (when known)	Maintenance (M) or Improvement (I)
1937-1938	335,000	Offshore Placement	M
July-Aug 1940	158,092		M
September-October, 1941	141,990		M
November-December 1957	40,300	30,000 placed on Salisbury Beach	I
July-Aug 1958	35,694		I
August, 1961	250,000	Offshore Placement	M
May, 1964	131,000	Offshore Placement	M
May, 1966	50,000	Offshore Placement	M
July, 1968	86,000	Offshore Placement	M
Aug-Oct, 1970	106,190	Onshore- North End of Plum Island	M
September, 1973	93,650	Offshore Placement	M
July, 1977	54,000	Offshore Placement (Open water off Plum Island)	M
July, 1981	102,600	Bypass Bar	M
August, 1983	123,500	Bypass Bar	
September, 1983	154,000	Bypass Bar	M
September, 1987	156,265	Bypass Bar	M
July, 1990	62,460	Bypass Bar	M
September, 1991	135,290	Off Plum Island Beach	M
May, 1993	125,040	Off Plum Island Beach	M
September, 1996	125,386	Disposal off Salisbury Beach	M
August, 1999	145,017	Disposal off Plum Island Beach	M
October, 2010	165,500	Onshore - Salisbury and Plum Island	M
March, 2023	214,625	Reservation Terrace	M

2.3.3. Nourishment History

As shown in Table 2.2, most dredged material is placed offshore. In Massachusetts, onshore placement is heavily regulated, and requires that additional studies are done to determine sand compatibility for the beach. This means that a suitable source with similar grain size and level of contaminants must first be found before onshore placement can take place. Currently, offshore sites are not used for beach nourishment, meaning the sources of sand for these beaches are primarily riverine, upland sources.

In the Upper North Shore region, a majority of this dredged material has come from the Merrimack River, as shown in Table 2.3. The sediment transport system of the barrier beaches is highly connected to the river, making the sediment a reasonable match for nourishment. Where known, specific placement locations along the beach are also noted.

Since Salisbury Beach is a public beach, access points are shown in Figure 2.9. and can help provide a reference for placement locations. The placement amount ranges greatly for each beach location, making a clear pattern in historical placement relatively difficult to find.

Table 2.3. Beach nourishment record for Salisbury Beach, Reservation Terrace, and Plum Island. Specific placement location recorded if known.

Location: Salisbury Beach			
Year	Amount (CY)	Placement Location	Source
1953	100,000		
1957	30,000		Merrimack River
2007	20,000		Compatible Sand
2010	40,000	Between Murray St and Fowler Street	Merrimack River
2013	12,500		Merrimack River
2014	8,800	Beach access 6-7	
2016	9,380		
2018	4,750		
Mar-24	10,800		Upland
Dec-24	23,100	Between beach access points 5-11	Upland
Location: Reservation Terrace			
Year	Amount (CY)	Placement Location	Source
1970	106,190	"North End of Plum Island"	Merrimack River
2013	12,000	Beach west of jetty	
2018	1,000	Beach west of jetty	
2023	214,625	Beach west of jetty	Merrimack River
Location: Plum Island			
Year	Amount (CY)	Placement Location	Source
1953	56,000		
1973	43,760	800 to 900 feet of beach north of State Groin #1 (the Turnpike Groin)	Newburyport Harbor
2010	120,000	Between about 40th St and Newbury Turnpike (about 2500 ft of beach)	Merrimack River

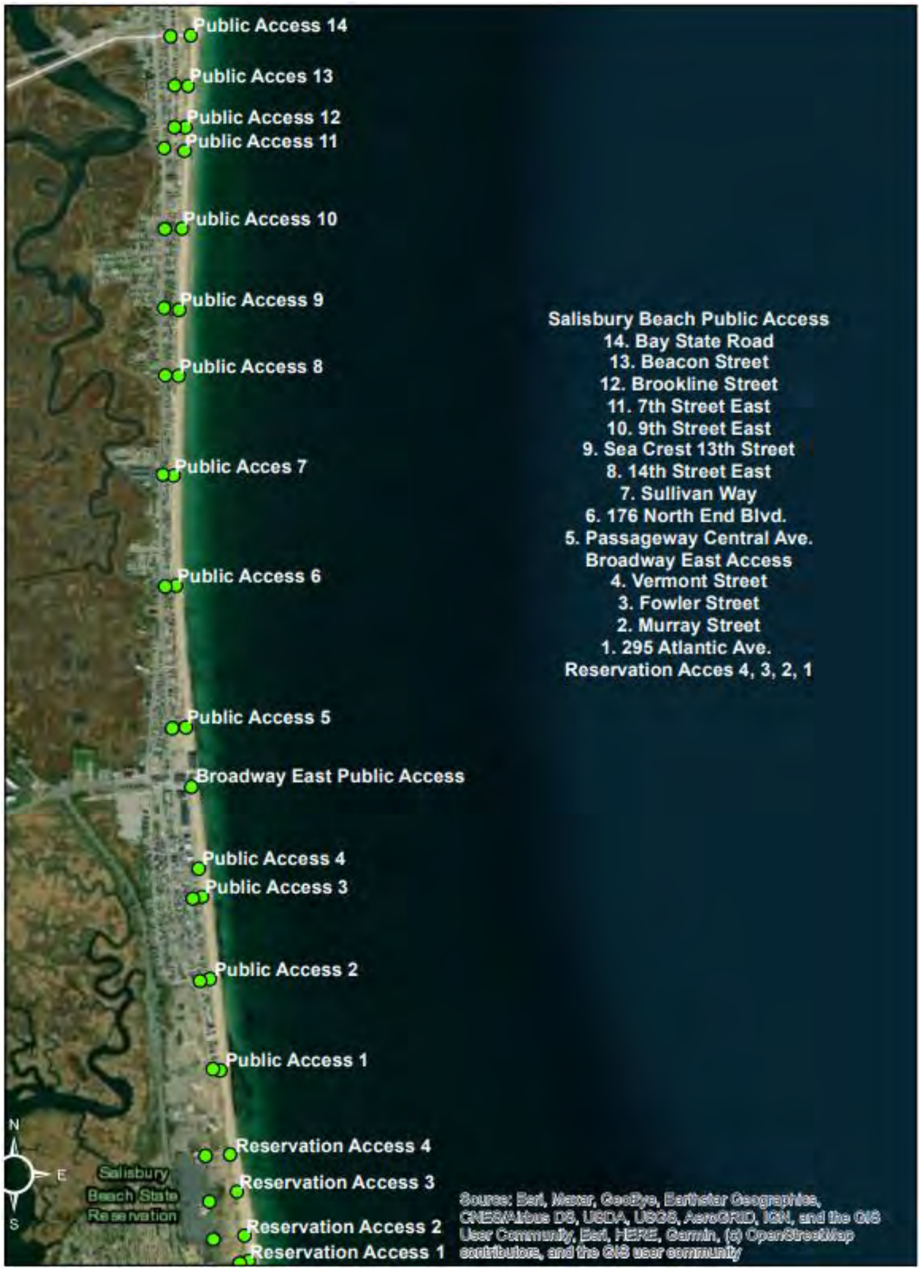

Figure 2.9. Salisbury Beach public access areas (Salisbury Parks Recreation & Youth Empowerment, n.d.).

Reservation Terrace Emergency Nourishment (2023)

As shown in Table 2.3., approximately 214,625 cubic yards (CY) of sediment was placed on the beach of Reservation Terrace following approval and funding from USACE. The project, which was set to begin during the 2021-2022 dredge season, was completed in 2023. Sediment from the 15-foot channel of the Merrimack River inlet was directly pumped onto Reservation Terrace, with a planned dredging of 220,000 CY. Any additional sediment was planned to be placed at nearby offshore placement sites.

The placement was initiated as a result of severe erosion at Reservation Terrace that required a temporary solution before long-term measures could be taken towards protecting the area from localized shoreline loss. It was estimated by the USACE that 68 oceanfront homes were at risk of damage or complete loss if action was not taken. The placement was designed to focus more on the eastern end, closest to the southern jetty, while tapering off further down to the northwestern end. The lifespan of the placement was expected to be 3-4 years from construction; however, significant redistribution and loss can be seen from aerial imagery less than a year later (from March to July).

Salisbury Citizen Nourishment Efforts (2024)

In March of 2024, led by the Salisbury Beach Citizens for Change group, approximately 10,000 CY of sand was placed across 150 properties as an emergency dune project. The project was funded by the property owners in an effort to protect their homes against the season's easternly storms. Just three days after the placement, a large nor'easter came in, bringing a tide of about 13.5 feet. While about half of the dune was washed away, the sand working as a sacrificial dune helped to protect the properties from the extreme storm surge.

Following the March, additional interest in a Salisbury Beach Sand Maintenance Project led to nourishment in December of 2024. The project was again meant to address urgent need for storm damage protection and mitigate extreme erosion of the beach and dune system at Salisbury Beach. The project brought in about 22,000 CY of sediment placed at access points 5-11 (Figure 2.9). Compared to the March nourishment, the December nourishment was intended to provide a more planned and engineered dune system to strengthen the shoreline and increase beach volume.

3. Existing Conditions

3.1. Storms

Both Salisbury and Plum Island are particularly vulnerable to extreme storms. Like other barrier beaches, these are the front line of defense against easternly storms. Episodic storms can cause significant migration of beach material, both depositing and removing large volumes of beach sand in a single event. Over the past several decades, beach erosion caused by significant nor'easters have prompted emergency shore protection efforts to protect dwellings along the barrier beach system. Overall, these efforts provide some temporary relief to affected properties; however, long-term planning efforts are needed to adapt to ongoing coastal erosion along the Salisbury, Newbury, and Newburyport ocean shoreline.

The low-lying dune system of Salisbury makes the area more prone to coastal flooding from storms and high-water levels. On the other hand, while Plum Island has more elevated dune system, the intensity of these storms tends to cause extreme erosion, exposing properties and infrastructure to damage from storm surge and winds. Recent years have brought about some high-water levels, with storms in 2018, 2022, and 2024 making records for extreme recorded water levels at above 7 feet, with the January 2024 storm bringing sea-levels of almost 8.5 feet (Table 3.1). The extreme water levels are important for informing the proposed alternatives, which will all be designed with storm resiliency as a component.

Table 3.1: Extreme recorded water levels at Seavey Island (ME) (Station: 8419870) and Boston (MA) (Station: 8443970) tide gauges.		
Location: Seavey Island, ME	Date	Height (ft. NAVD)
1	1/13/2024	8.45
2	2/7/1978	8.06
3	2/20/1972	7.71
4	12/23/2022	7.7
5	1/10/2024	7.64
6	3/10/2024	7.26
7	4/5/1973	7.23
8	1/2/1987	7.22
9	1/9/1978	7.18
10	12/29/1959	7.12
Location: Boston, MA	Date	Height (ft. NAVD)
1	1/4/2018	9.66
2	2/7/1978	9.52
3	3/2/2018	9.17
4	1/13/2024	8.9
5	1/2/1987	8.69
6	10/30/1991	8.66
7	1/10/2024	8.53
8	12/12/1992	8.49
9	12/23/2022	8.47
10	1/25/1979	8.43

3.2. Shoreline Condition

3.2.1. Shoreline Data Collection

Shoreline elevation data was completed using a Real-Time Kinematic (RTK)-GPS system to provide precise elevation and coordinate position. A high-water line/berm crest shoreline delineation survey was performed on January 13, 2026. The survey covered the entire project area. The sensor recorded continuous x, y, and z data, around 4000 points, which was then used to update the existing shoreline data for 2026.

In addition to the 2026 measured shorelines, shorelines for 2014 and 2021 were generated for Salisbury and Plum Island to inform the shoreline change discussion in the following section and shoreline change model discussed in section 4. In Salisbury and Plum Island, shorelines were derived by identifying the berm crest elevation and contour based on a November 2014 USACE Topobathy LiDAR survey and an April 2021 USGS LiDAR flight. Cross shore transects were generated to identify the mean berm crest elevation, which most similarly replicates RTK-GPS surveys of berm crest, and the derived mean berm crest elevation for 2014 and 2021 were also compared to the recent RTK-GPS survey that SCS conducted in 2026. Each shoreline was then corroborated with available aerial imagery from a similar time frame. The Salisbury shoreline is ~18,000 feet from MA/NH state line to the northern Merrimack River jetty, and the Plum Island shoreline is ~9000 feet from the southern Merrimack River jetty to a bit past the end of the populated area.

3.2.2. Shoreline Change

Prior to developing the shoreline used for calibration in the sediment transport model, a general idea of long- and short-term trends were determined for the region. MassGIS provides shorelines measured through LIDAR. The collected shorelines for about 14 different years were processed. It was determined that the most reasonable shorelines applicable to the Upper North Shore were the 1952 and the 2005 high-water shorelines. The 1952 shoreline was used in computing a long-term shoreline change, and the 2005 shoreline was used for computing the short-term shoreline change. Both shorelines were compared against the 2026 survey collected by Coastal Solutions. In the long-term, Plum Island saw a modest accretion of about 1.1 ft/year since 1952. As shown in the additional shoreline change calculations, Plum Island is in a period of accretion with an average of 7.6 ft/year since 2005. Salisbury Beach was erosional in both timespans, with only a slight erosion rate of -0.1 ft/year since 1952 and 1.1 ft/year since 2005.

After there was a grasp on general shoreline change trends, two characteristic shoreline years were used to inform model calibration. Two recent periods of shoreline change have been analyzed, 2014 to 2021 and 2021 to 2026, where the period of 2014 to 2021 was used for the calibration of the shoreline change model discussed in Section 5.

The Salisbury shoreline experienced localized spots of moderate and minor erosion, as well as minor accretion from 2014 to 2021. This was a more energetic period with a few significant storm events. Overall, the net erosion rate was -3.5 feet/year with a maximum of -14.0 feet/year near Salisbury public access point 10 (Figure 2.9). Salisbury has experienced relative stability in recent years with larger stretches of minor erosion and minor accretion, with a net erosion rate of -2.0 feet/year. Figure 3.1 shows shoreline change from 2014 to 2021 (left) and 2021 to 2026 (right).

The Plum Island shoreline has been largely accretional for the past twelve years. Since the repair of the jetty in 2014, the northern portion of Plum Island has accreted on average of 17.0 feet/year. The shoreline north of the groins erodes 10-20 feet/year between 2014 to 2021, indicating the development of an erosion hot spot. By 2026, the erosion hot spot has completely resolved and accreted around 50 feet/year in that area. Between 2021 to 2026, there is some erosion at the southern portion of the study area shoreline, but otherwise the shoreline is largely accretional.

Reservation Terrace changes are discussed using volume change methodology, as described in Section 3.3.2

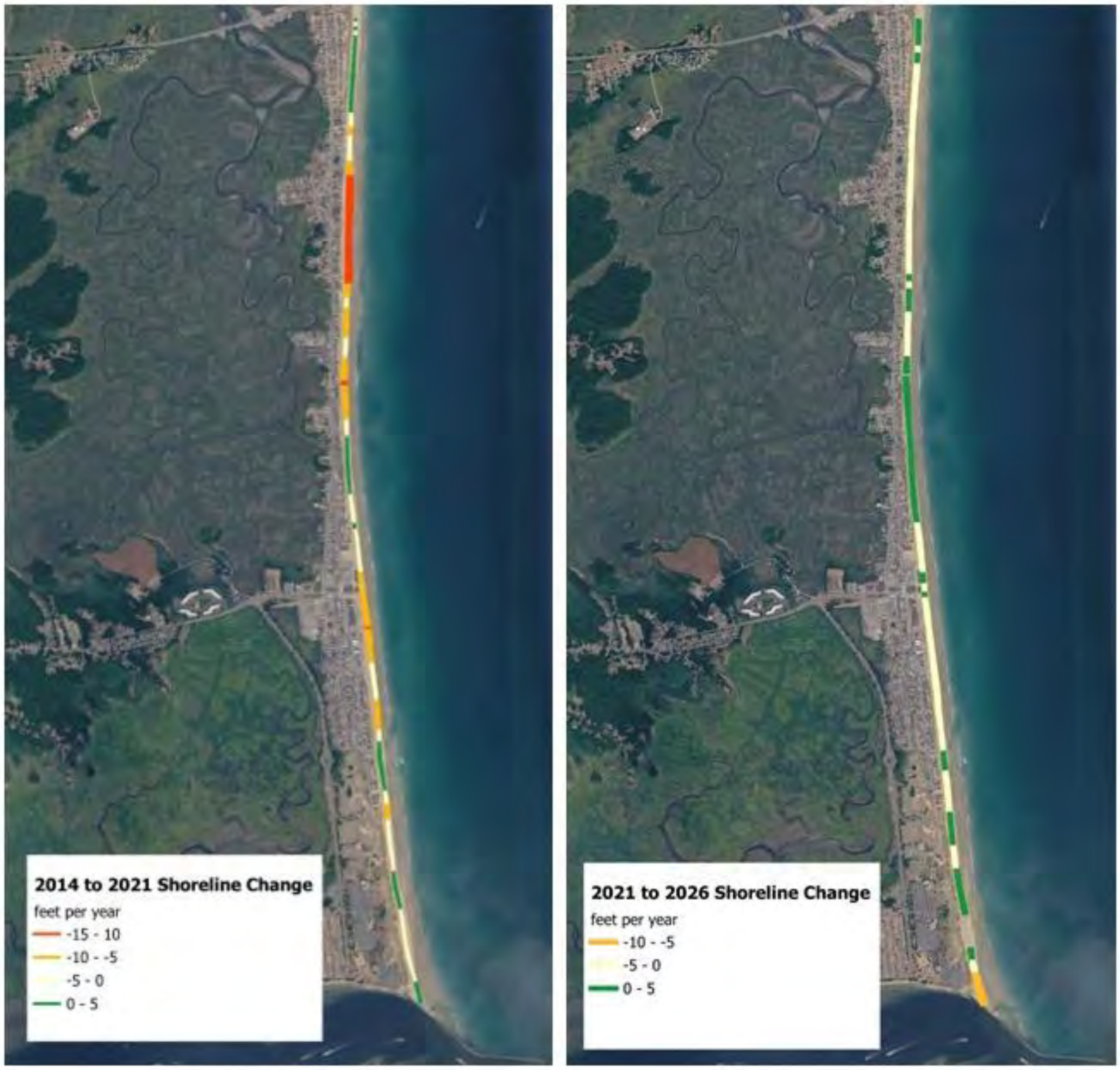

Figure 3.1. Shoreline change in feet per year for two periods (2014 to 2021, left; 2021 to 2026, right). The 2014, 2021 shorelines are derived through LiDAR and aerial imagery. The 2026 shoreline is from January, 2026 RTK-GPS survey conducted by Sustainable Coastal Solutions.

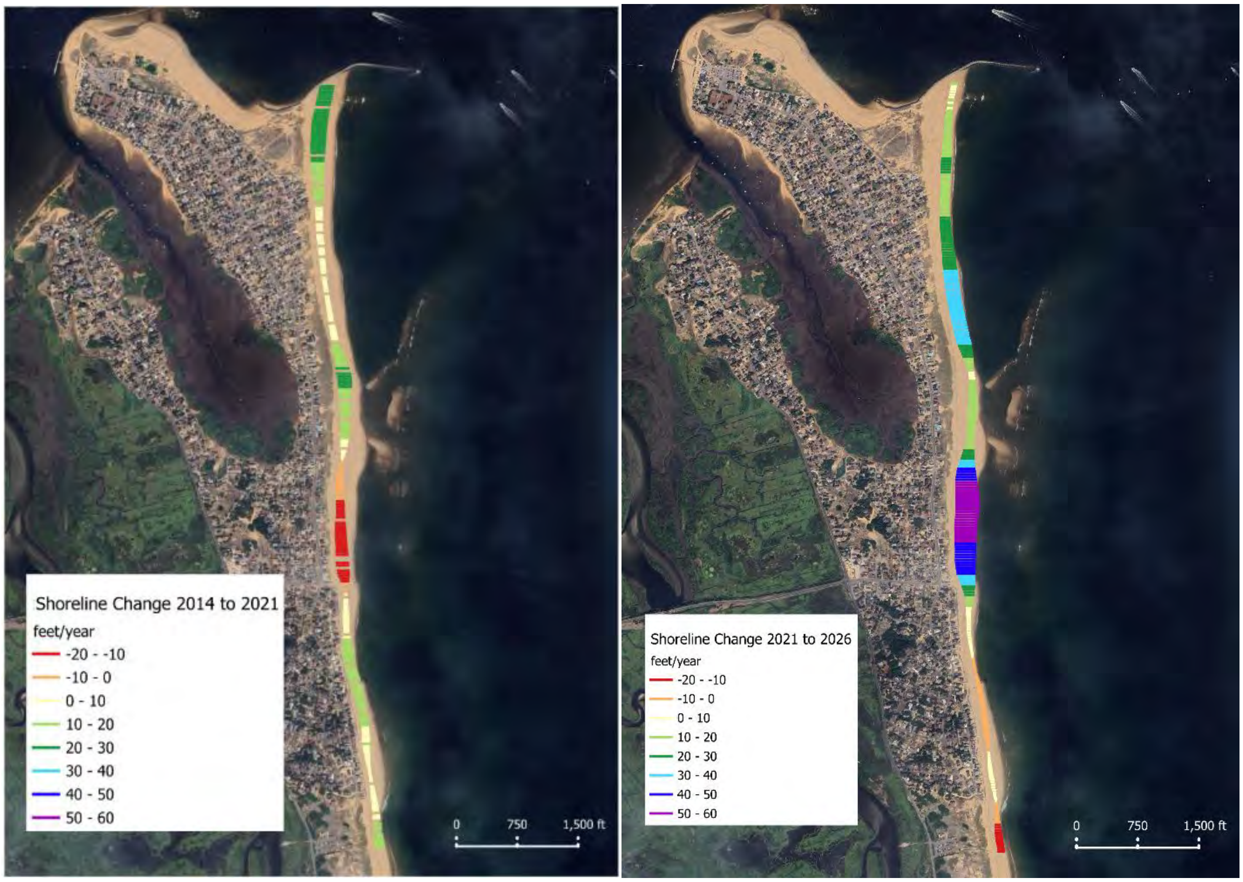

Figure 3.2. Shoreline change in feet per year for two periods (2014 to 2021, left; 2021 to 2026, right). The 2014, 2021 shorelines are derived through LiDAR and aerial imagery. The 2026 shoreline is from January, 2026 RTK-GPS survey conducted by Sustainable Coastal Solutions.

3.3. Littoral System

3.3.1. Sediment Sampling

Grain size sampling was also completed along the project shoreline. Two samples were taken approximately every 2000 feet. Sixteen sampling transects were identified, resulting in a total of 32 samples, where one sample was collected on the beach face and one sample was collected on the beach berm along each transect (Figure 3.3).

Figure 3.3. Sediment grab sample locations, both beach berm (green) and face (red), overlaid on the 2026 shoreline survey location.

20 samples were collected for Salisbury Beach (Figure 3.4), eight for Plum Island Beach (Figure 3.5), and four for Reservation Terrace (Figure 3.6). An AASHTO 11 and 27 standard sieve analysis was completed for all of the samples to determine grain size distribution. Utilizing the samples from both the lower and upper beach, the D_{50} was determined for each site. The D_{50} value is representative of the grain size, where approximately 50 percent of the samples are larger and 50 percent of samples are smaller than the specific sieve size. Reservation Terrace had the coarsest sediment, with a D_{50} of about 0.82 mm. Recent nourishment of Reservation Terrace in 2023 is likely the reason for the higher grain size. Plum Island Beach has a similar

grain size, with a D_{50} of 0.8 mm, also indicative of connection between sediments in both Reservation Terrace and on Plum Island Beach. Salisbury had the finest beach material, a D_{50} of 0.55 mm, typically indicative of “medium” sand.

The grain size distribution was used to inform a one-line longshore transport computer model, used to simulate the evolution of a shoreline at a specific contour level. This model is further discussed in Section 4. Additionally, sediment grain size is essential for determining beach nourishment sources and effectivity of nourishment activities. “Compatible” sediment is favored for nourishment projects, where equal grain size is better adept at maintaining the current beach profile, and coarser fill material may contribute to a steeper beach slope but a wider beach berm. Collecting grain size information will help inform potential future beach resiliency initiatives and projects. Appendix D provides the raw sediment grain size data for all of the samples.

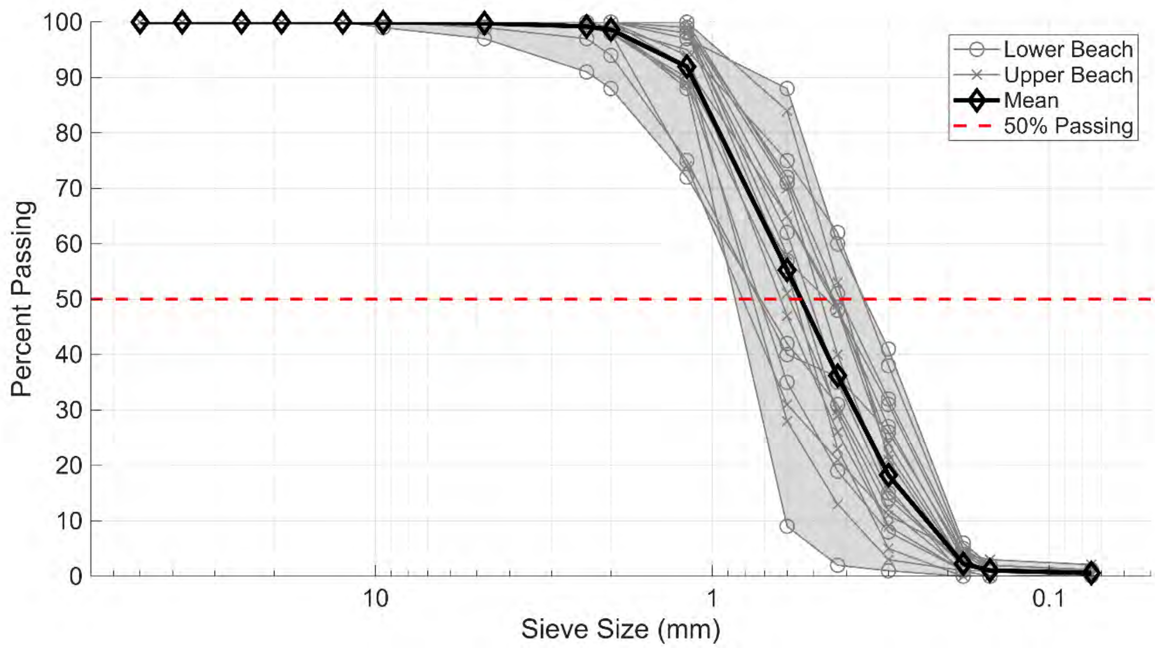

Figure 3.4. Grain size analysis of Salisbury lower (circle-marked grey lines) and upper (cross-marked grey lines) beach sediment samples. The mean of the samples (triangle-marked black line) is used to select a D_{50} value of 0.55 mm for Salisbury Beach for the one-line shoreline model described in Section 4.

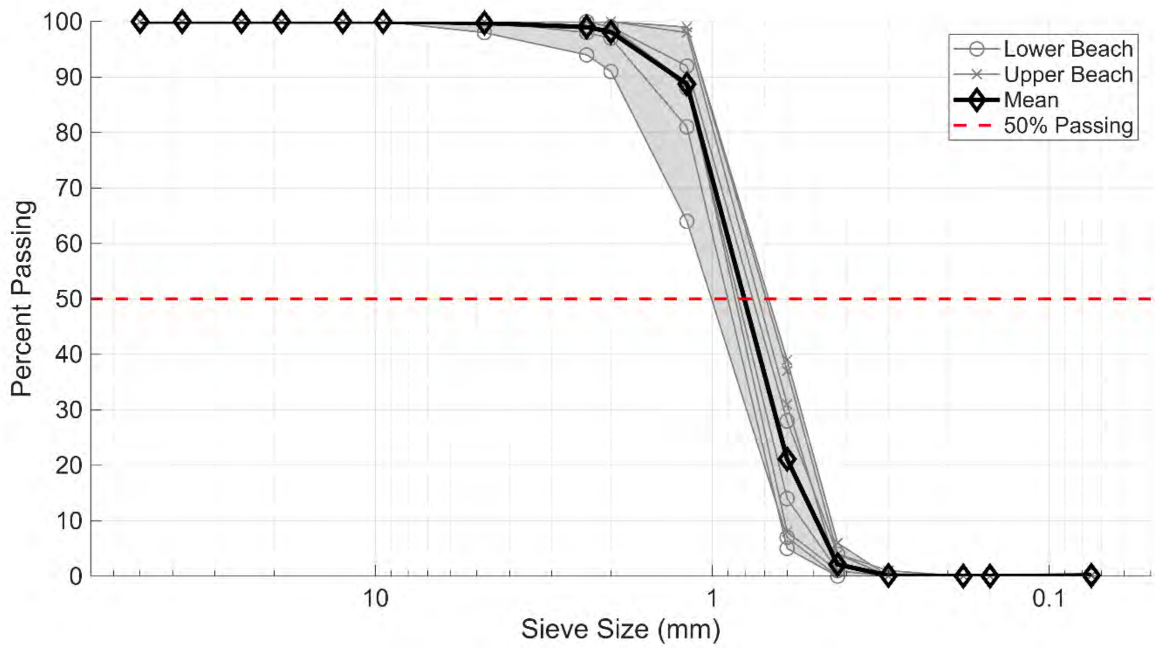

Figure 3.5. Grain size analysis of Plum Island lower (circle-marked grey lines) and upper (cross-marked grey lines) beach sediment samples. The mean of the samples (triangle-marked black line) is used to select a D_{50} value of 0.80 mm for Plum Island for the one-line shoreline model described in Section 4.

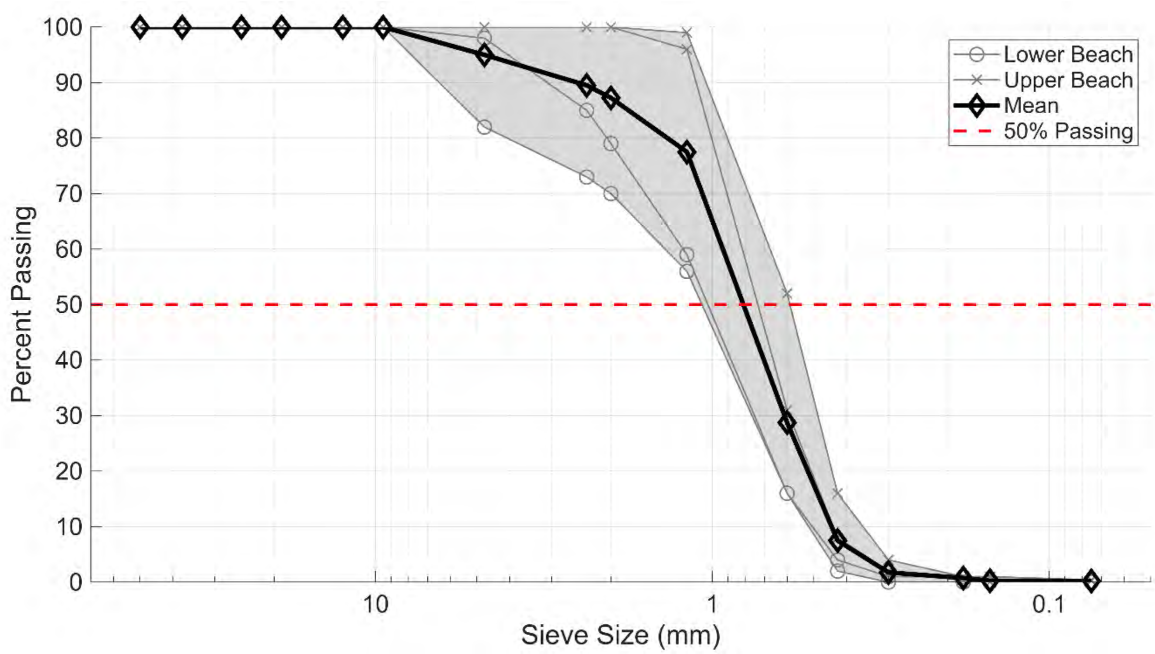

Figure 3.6. Grain size analysis of Reservation Terrace lower (circle-marked grey lines) and upper (cross-marked grey lines) beach sediment samples. The mean of the samples (triangle-marked black line) is shown with a D_{50} of 0.82 mm.

3.3.2. Volume losses (since 2023)

Volume loss/gain estimations were calculated for both Reservation Terrace and Plum Island. The loss of sediment from Reservation Terrace was hypothesized to be on the same order of accretion at the point of Plum Island. Due to available data, as well as the 2023 nourishment project that occurred at Reservation Terrace, a geometric calculation was done for the volume loss at Reservation Terrace, while for Plum Island, a characteristic shoreline shape was developed for comparison time periods.

Evident from aerial imagery (Figure 3.7), Reservation Terrace has lost a significant amount of sediment since the 2023 nourishment. To update predictions about the lifespan of beach nourishment projects in these areas, an estimate of the volume loss was conducted.

Figure 3.7. Aerial imagery of Reservation Terrace during period of relative stability (2005), following emergency nourishment project (2023), and shortly after nourishment project (2025).

A geometric method was used to approximate erosion since beach nourishment unnaturally changed the topobathy of the shoreline, meaning that the characteristic profile method was not applicable. The original USACE plans were overlaid on the site and shoreline marked. An approximate surface area of fill was used to determine an average depth of nourishment, via the use of recorded nourishment value, 220,000 CY. By moving the shoreline inward to the 2026 position, and maintaining the slopes of the placed nourishment as an assumption, it was estimated that about 86% percent or approximately 190,000 CY of the original nourishment had been lost. This estimate does not take into account the potential for sediment to equilibrate into the profile further offshore, however, due to the observed gyre effect in Reservation Terrace, it is reasonable that much of this nourishment was transported out of the inlet. Additionally, this estimate does not account of spreading along the beach, as seen by visual accumulation of sand on the western end of Reservation Terrace in Figure 3.7. Thus, it is likely that this estimate is on the high end and is more indicative of how much the sand has shifted out of its original location since the placement in 2023.

To better understand the magnitude of sediment that had accreted on Plum Island near the south jetty since the 2023 nourishment, characteristic shoreline profiles were developed. The 2018 Topobathy survey completed by USACE and shared by NOAA was utilized to understand the typical bathymetry of the shoreline in 2018 – which could then be used as a proxy to develop 2023 and current profiles based off the relative shorelines.

Bruun (1954), and later expanded upon and confirmed by Dean (1977), proposed that a characteristic equilibrium profile could be determined for a beach related to the sediment grain size and water depth. The theory made the assumption that beaches are concave up and follow a pattern of flattening slope as you move offshore, due to the transport of sediment by waves seaward. The Bruun rule states:

$$h(y) = Ay^{2/3}$$

where *h*, the water depth, is dependent on a distance *y,* from the shoreline and *A,* is known as the "profile scale parameter." The profile scale parameter can be related to the sediment grain size through a reference table, or can be determined using data from specific transects.

Five transects were taken from the northern section of Plum Island, before the bypass bar. The transects were spaced approximately 1000 feet apart. First, the elevation data was pulled from the 2018 LiDAR data, providing distance offshore and elevation. The Brunn rule shows the profile from below the High-Water Level, so this was marked. Then, using back calculation, and average A parameter was determined for each of the profiles. As expected, the A parameter was similar for each transect, around 0.43 $ft^{\frac{1}{3}}$. The Bruun rule was then used to graph a characteristic profile for each transect, which was shifted in the cross-shore position by the change in shoreline position between 2023 and 2026. The beach slope above the HWL was maintained each year, as a simplification. The resulting area between the curves was calculated and then multiplied by the associated along shore length between transects. These calculations estimated an accumulation of about 420,000 CY over the course of three years (2023-2026), about 140,000 CY/year. This value was corroborated by the Dean (2002) tool for shoreline response as a result of sediment gain or loss:

$$\Delta y_0 = \frac{V}{h_* + B}$$

The same process was done between 2014 and 2026, yielding approximately 880,000 CY (approximately 73,000 CY/year) of volumetric gain within the length of these transects.

4. Coastal Processes Assessment

4.1. Wave modeling

A long-term wave record is necessary for sediment transport calculations. Ideally, this wave record would come from an observational buoy stationed offshore of the site of interest. While there is an NDBC buoy located offshore to the north east of Cape Ann, it was deployed in 2008 and therefore does not provide a complete long-term record. Instead, a suitable alternative is the Wave Information Study (WIS) conducted by USACE which offers simulated wave records for sites along the open coast. The WIS hindcast station 63045 is chosen as it is located directly offshore of the Merrimack River inlet (Figure 4.1).

Open ocean exposed shorelines increase the potential for sediment transport and erosion, such as the shorelines north and south of the Merrimack inlet. Prominent features offshore of the shoreline include the Isle of Shoals, Hampton Shoals, and a periodic sandbar. The shoreline positioning limits much of the incident wave energy from the northerly directions, while Cape Ann shelters the study area from a portion of the incident wave energy from the south. Despite this sheltering, the study area is still along the open ocean and not fetch limited, and so the wave climate was estimated solely from the propagation of offshore waves. The contribution of locally generated wind waves was neglected due to the significant misalignment between the wind and wave directions provided in the WIS record.

The generation of wave input for the sediment transport analysis followed a three-step process. First, the long-term WIS wave hindcast data was retrieved and processed. Second, the processed wave data were used as inputs into the two-dimensional wave transformation model, Simulating Waves in the Nearshore (SWAN). Third, output from SWAN was then used to create the wave input record implemented in the sediment transport calculations.

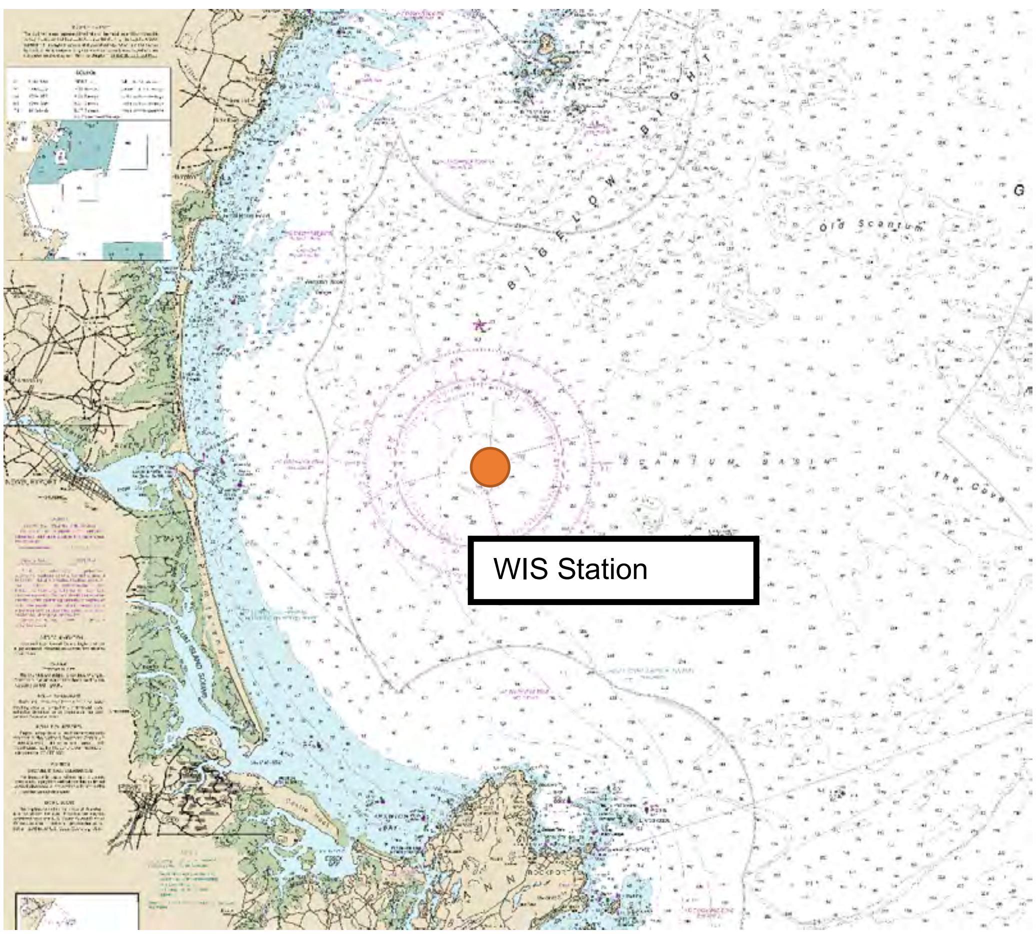

Figure 4.1. Detail of NOAA chart 13278 (Cape Ann to Portsmouth) showing the location of the WIS hindcast station (63045) relative to the study shorelines.

4.1.1. Wave and Wind Data

Wave conditions were developed using the wave data available from USACE WIS hindcast database, at Station 63045 (Figure 4.1). The WIS data were used to generate the offshore wave boundary conditions and has a record that spans the 44-year period between January 1980 to December 2024.

The entire wave and wind records from the WIS hindcast are presented in Figure 4.2 and 4.3, respectively, as compass rose plots which show magnitude and percent occurrence by compass sector. For the wave data of the WIS hindcast record, the predominant sector is from the east-southeast (ESE). Waves propagate from this direction 26.7% of the time. The second-most frequently occurring sector at this station is southeast (SE), which occurs 21.4% of the time. The majority of the waves from the SE and ESE sectors are 6.8 feet or less (32.1% of the total record).

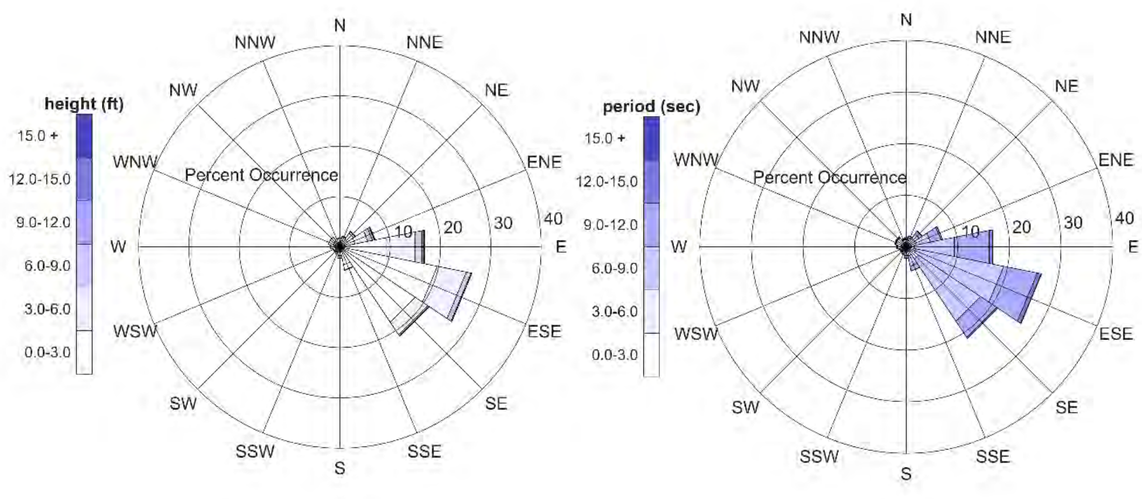

Figure 4.2. Wave height (left) and period (right) for hindcast data from WIS station 63045 for the 44-year period between January 1980 and December 2024. Direction indicates from where waves come. The color of each individual segment indicates the magnitude of the wave height and period. Radial length of the segment indicates the percent occurrence over the total duration of the record.

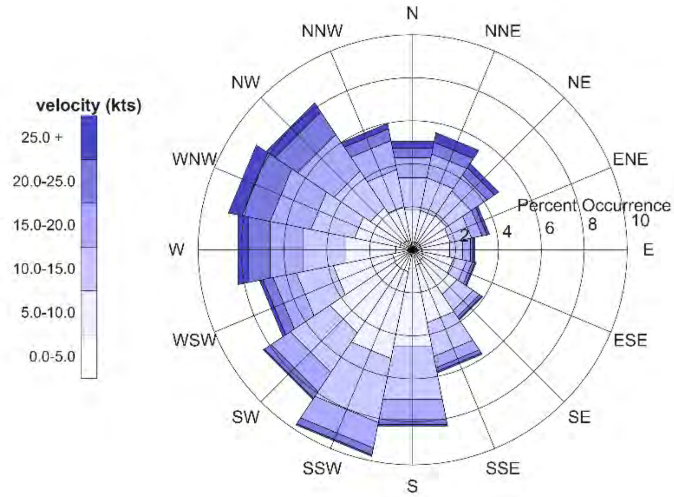

Figure 4.3. Wind compass rose for hindcast data from WIS station 63045 for the 44-year period between January 1980 and December 2024. Direction indicates from where winds blow. The color of each individual segment indicates the magnitude of the wind speed. Radial length of the segment indicates the percent occurrence over the total duration of the record.

Winds most frequently blow from the south-southwest (SSW), with a percent occurrence of 9.8%. For sectors approaching the north shore shoreline (north through south) winds blow 43.3% of the time. From all direction sectors, wind speeds are greater than 10 knots 54.4% of the record and greater than 25 knots for 3.7% of the record. While the wind data is not used for the development of the SWAN model, the compass rose is still included for reference.

To develop the input conditions for the wave model, the wave data from the WIS record were binned by 22.5-degree compass sectors and by magnitude. We are only concerned with wave directions that can drive sediment transport, so there are nine compass sectors from north (N) to south (S). In total there are twenty-seven separate model cases, with three wave cases for each compass sector; the input conditions for all model cases are presented in Table 4.1.

Each hourly WIS record includes parameters that describe the wave conditions (i.e. wave period, T_p, wave height, H_s, and direction, θ). For each separate compass sector, the hourly events from the wave record were divided into top, middle, and bottom bins by wave height, with each bin having an equal number of hourly events. The percent occurrence of each case is determined by using the number of hourly records from the WIS hindcast that falls into each bin, divided by the total number of hourly events in the record (394,476 hourly events total). Within each compass sector, the top wave case is the most impactful to sediment transport.

As previously stated, the wave model is driven solely by the propagation of offshore waves. In all cases, there is misalignment between the wave direction and wind direction, with the wind direction falling at least a compass sector away from the wave direction. Instead, the wind in the model is specified as a minor wind speed (1.94 kts) aligned with the wave direction.

4.1.2. Grid Development and Bathymetry Data

After the development of the wave boundary conditions, the extent and resolution of the computational mesh was defined. In order to capture the wave dynamics at the project sites, the SWAN model was developed with a coarser computational mesh with two nested fine-scale grids at the shorelines of interest for Salisbury and Plum Island. This allows for computational efficiency by decreasing resolution in areas outside the project sites.

The coarse grid has a 328-foot (100-meter) spacing for the region that extends into the offshore area of the Gulf of Maine (to include WIS Station 63045), including Cape Ann to the south and Isle of Shoals to the North (Figure 4.4). The two nested fine-scale grids have a 33-foot (10-meter) spacing. The upper-fine grid covers the shoreline to the north of the Merrimack River inlet and extends past the Hampton River inlet. The lower-fine grid covers the shoreline to the south of the Merrimack River inlet past the end of the populated area along the Newbury shoreline (i.e. includes the northern section of the Parker River National Wildlife Refuge).

The coarse grid was used to propagate offshore waves developed from the analysis of the WIS hindcast record for each wave case. The coarse grid outputs spatially varied wave information at points that corresponds to nodes along the open boundaries of the fine-scale grids (to be used as the boundary condition for the fine-scale grid model runs). The nested fine-scale mesh allows for highly-detailed wave information at either shoreline of interest, which is then implemented as input conditions for the respective shoreline change models.

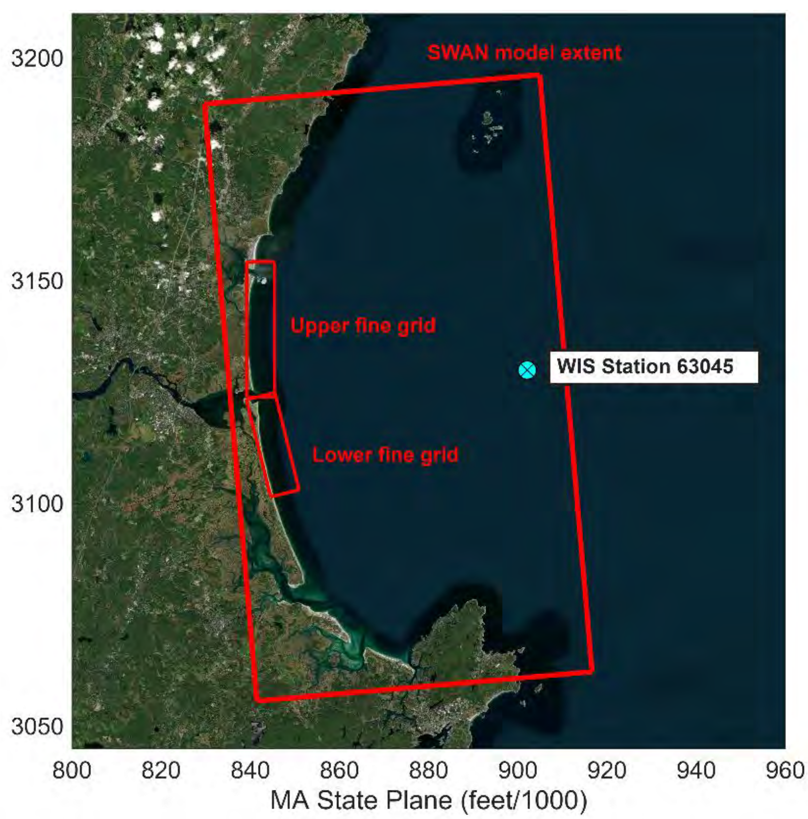

Figure 4.4. Map showing wave model grid limits of the coarse grid, and both fine-scale grids for Salisbur and Plum Island. The location of WIS Station 63045 is also shown.

All SWAN grid conventions are developed so that the x-axis points alongshore (approximately due south) and the y-axis points offshore (approximately due east) in order to be compatible with the sediment transport model. The coarse grid is made up of 94,300 computational cells with a spacing of 238 feet (100-meter). The x-axis of the grid is oriented with a compass heading of 175˚ and is 11.1 nautical miles (20.5 km) long or 410 grid cells. The y-axis of the grid is 6.2 nautical miles (11.5 km) or 230 grid cells wide. The greatest depth of the coarse grid is -370 feet NAVD (-113 meters).

The upper fine-scale grid has 176,130 computational cells with 33-foot (10-meter) spacing. The x-axis is oriented alongshore (compass heading 180˚, or due south) and is 5 nautical miles (9.3 km) long or 927 grid cells. The y-axis is 1.0 nautical mile (1.9 km) wide or 190 grid cells. The lower fine-scale grid has 137,000 computational cells with 33-foot (10-meter) spacing. The x-axis is oriented alongshore (compass heading 166˚) and is 3.7 nautical miles (6.9 km) long or 685 grid cells. The y-axis is 1.1 nautical miles (2 km) or 200 grid cells wide.

NOAA NCEI Continuously Updated Digital Elevation Model (CUDEM) was used for the offshore bathymetry. A higher resolution 2018 post-storm LiDAR survey by USACE was used for the nearshore bathymetry and topography. All elevation data were transformed to the NAVD datum. Figure 4.5 shows the coarse grid and two fine scale grids with interpolated topo-bathy survey data.

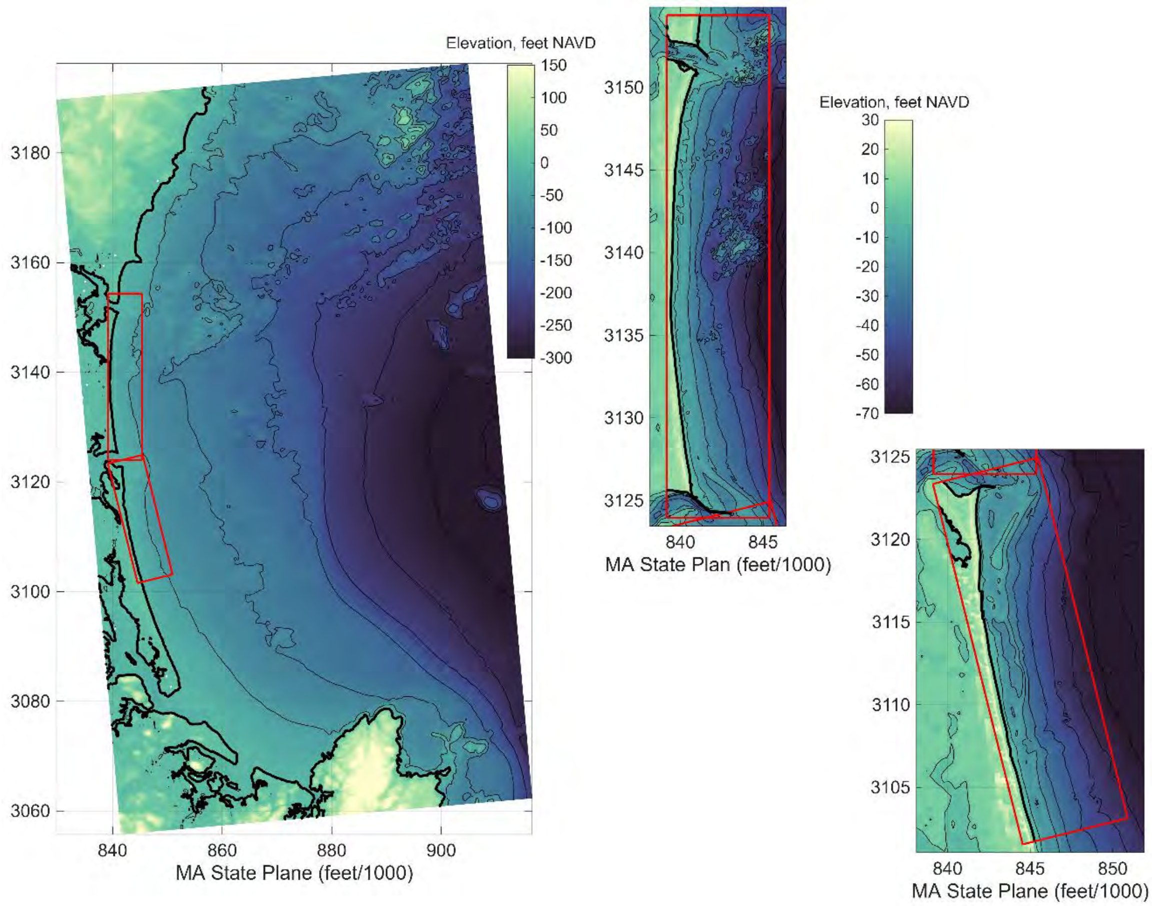

Figure 4.5. Map of SWAN model bathymetry for coarse grid (left) with upper and lower fine-scale grids outlined in red. Bathymetry derived from NCEI CUDEM and 50-foot contours are shown. Fine-scale bathymetry derived from USACE 2018 Topobathy for the nearshore and NCEI CUDEM offshore (upper fine-scale grid, middle panel; lower fine scale grid, right panel) and 10-foot contours are shown.

4.1.3. SWAN Model Development

After the specification of the wave boundary conditions, development of the computational mesh, and grid bathymetry, other model parameters must be specified. Model parameters include the wave physics, such as wave breaking and wave-wave interactions, as well as the directional and frequency resolution of the wave spectrum.

As offshore wave components propagate into shallower water, the waves will shoal (i.e. increase in wave height), and they will gradually refract due to the localized bathymetry. The SWAN model enables us to input simple wave height, period, and direction data (Table 4.1) and estimate how waves will change as they propagate across the Gulf of Maine towards the shoreline.

Developed at the Delft University of Technology of the Netherlands, SWAN Cycle III version 41.20 is a steady state, spectral wave transformation model (Booij et al., 1999). Two-dimensional (frequency and direction vs. energy) spectra are used as input to the model. SWAN is able to simulate wave refraction and shoaling induced by changes in bathymetry, and includes a wave breaking model based on water depth and wave steepness. Model output includes significant wave height Hs, peak period Tp, and wave direction θ.

Table 4.1. Wave model input parameters, listed by compass sector and wave height bin (i.e., bottom, middle, and top thirds). Listed offshore wave parameters include significant wave height ($H_{s,o}$), peak wave period (T_o), and mean wave direction θ_o. Wave directions are given in the meteorological convention (i.e., from where the wave originates with from North as 0˚).

Sector		Percent occ.	$H_{s,o}$ (feet)	T_o (seconds)	θ_o (deg)
N	bot 1/3	0.58	1.60	5.16	2.82
	mid 1/3	0.58	2.66	5.32	2.94
	top 1/3	0.58	4.41	5.78	2.5
NNE	bot 1/3	0.73	1.61	5.82	23.36
	mid 1/3	0.73	2.74	6.19	22.53
	top 1/3	0.73	5.23	6.90	23.72
NE	bot 1/3	1.26	1.64	6.22	45.46
	mid 1/3	1.26	3.18	6.34	45.79
	top 1/3	1.26	6.62	7.21	44.87
ENE	bot 1/3	2.39	1.74	7.23	68.9
	mid 1/3	2.39	3.50	7.25	68.56
	top 1/3	2.39	8.03	8.09	68.49
E	bot 1/3	5.71	1.35	8.36	91.9
	mid 1/3	5.71	2.79	8.44	91.87
	top 1/3	5.71	6.30	9.22	90.45
ESE	bot 1/3	8.91	1.05	7.86	114.64
	mid 1/3	8.91	2.02	7.87	113.59
	top 1/3	8.91	4.53	8.90	112.74
SE	bot 1/3	7.12	0.90	7.57	130.7
	mid 1/3	7.12	1.64	7.51	132.22
	top 1/3	7.12	3.68	7.88	132.68
SSE	bot 1/3	1.59	1.42	6.72	156.3
	mid 1/3	1.59	2.19	6.61	155.56
	top 1/3	1.59	3.95	6.76	155.56
S	bot 1/3	0.75	1.36	6.38	178.77
	mid 1/3	0.75	2.11	6.09	178.57
	top 1/3	0.75	3.73	6.62	179.44

SWAN is a flexible and efficient program based on the wave-action balance equation that can quickly solve wave conditions in a two-dimensional domain using the iterative Gauss-Seidel technique. For this study, the model was implemented using a steady state finite-difference scheme, on a regular Cartesian grid (grid increments in the *x* and *y* directions are equal), though other options are available (including a finite difference formulation using an unstructured mesh). An advantage of the iterative technique employed in SWAN it that it can compute spectral wave components for the full 360-degree compass circle.

The wave spectrum resolution for the model runs of both coarse and fine model grids include the full 360-degree compass circle divided into 72, five-degree segments, with 40 discrete frequencies between 0.06 and 2.00 Hz (corresponding to periods of 16.7 and 0.5 seconds). Examples of wave model output with color contours for wave heights and vectors to denote direction of wave propagation are shown for the coarse grid (Figure 4.6), and the upper (Figure 4.7) and lower (Figure 4.8) fine-scale grids.

In Figure 4.6, offshore waves with heights of 8.0 feet approach the entrance to the Gulf of Maine in the coarse grid. Waves refract due to the effect of the Isle of Shoals to the north as well as the Hampton shoals just off the Salisbury and Hampton shoreline. Shorelines that are more exposed (such as Salisbury Beach and southern Plum Island) experience wave heights that are around 6 feet. Wave heights are reduced along sheltered shorelines; the northern portion of Plum Island experiences wave heights around 4 feet due to the sheltering of the bypass bar.

Refraction effects of the Hampton inlet to the north and Merrimack inlet to the south are further demonstrated in the upper fine wave results (Figure 4.7). The refraction effect of the bypass bar and the resulting reduction in wave heights can also be clearly seen at the northern portion of Plum Island (Figure 4.8). Further reduction in wave height occurs due to breaking as the waves roll in to the surf zone at the shoreline. Wave heights at the perimeter of the bypass bar are around 7 feet, before they are refracted towards the north (or coming from a more southerly direction) and reduced to about 4 feet by the effects of the bypass bar.

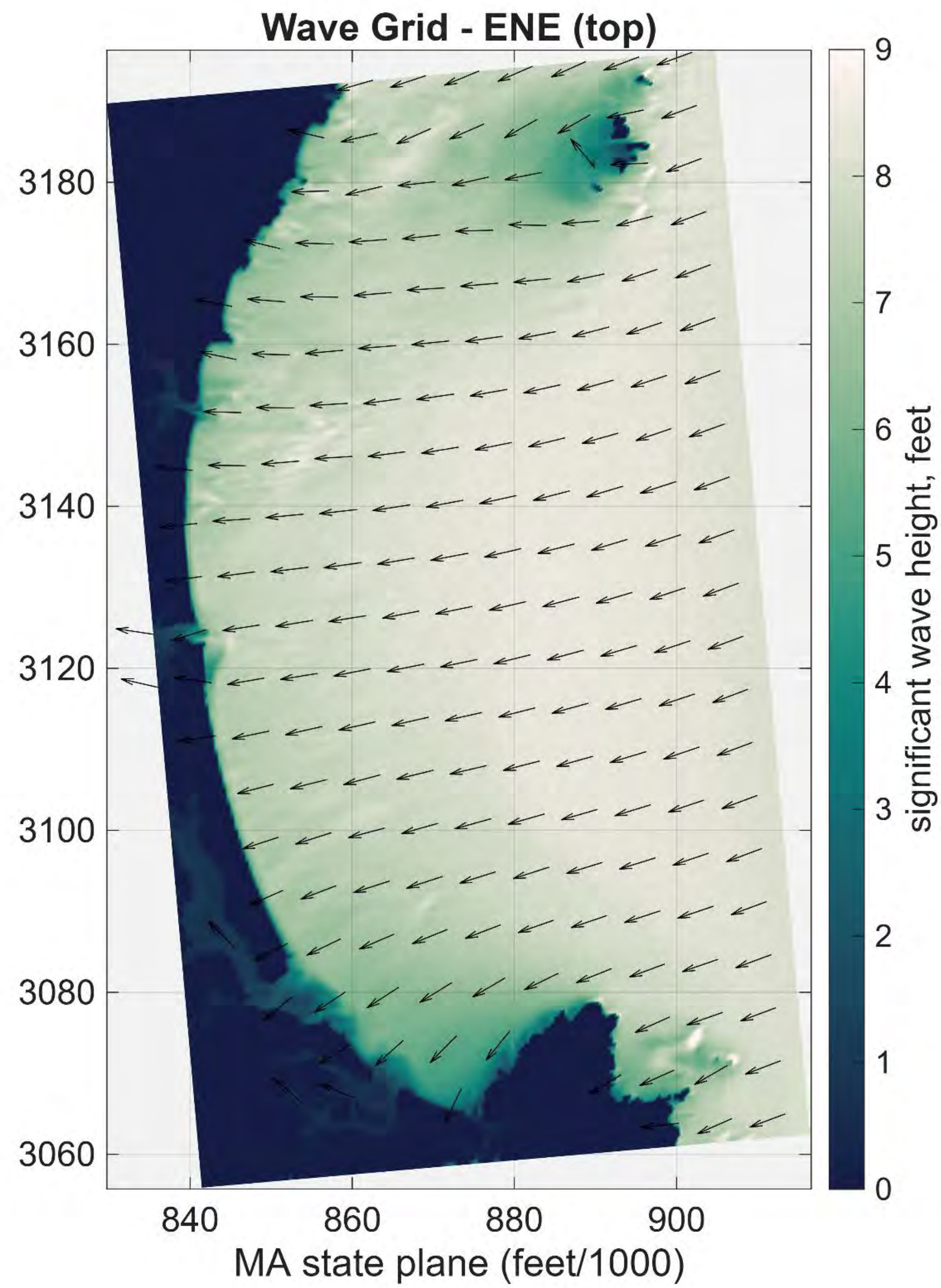

Figure 4.6. Coarse grid output for top East-North-East (ENE) case (an 8.0 foot and 8.1 second offshore wave approaching from the ENE sector, Table 4.1). Color contour indicates wave heights (feet) and vectors show peak wave direction.

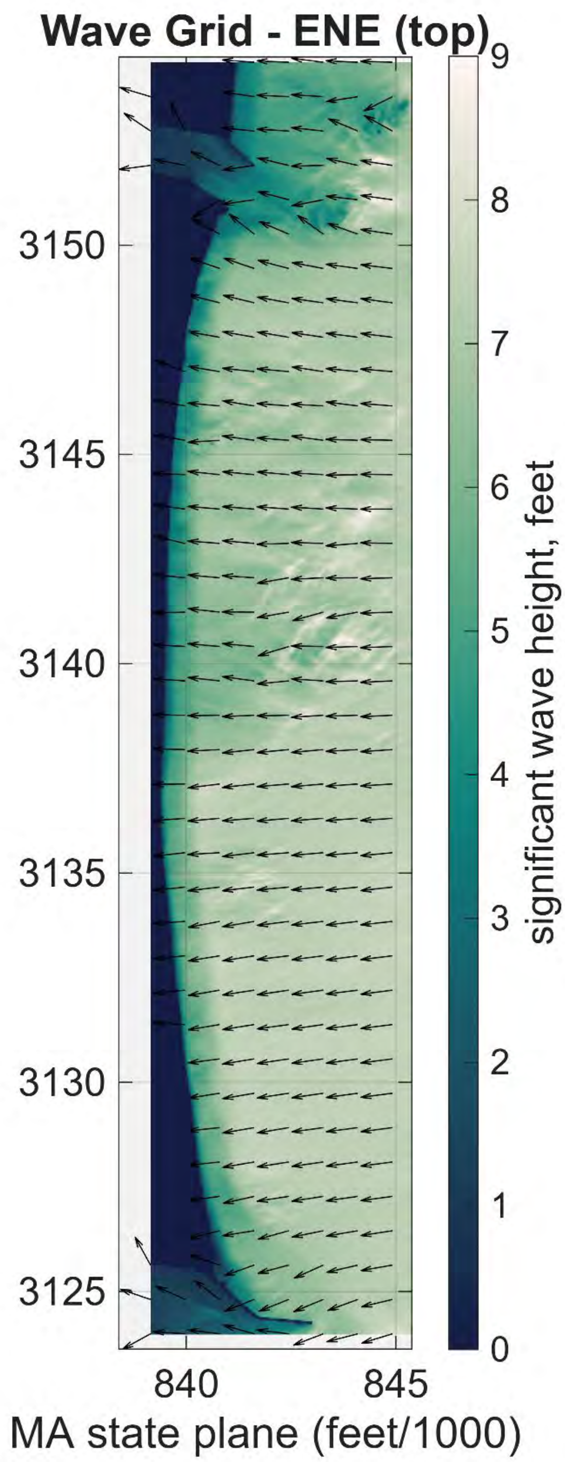

Figure 4.7. Nested upper fine-scale wave model output for the top ENE case (Table 4.1). Color contours indicate wave heights and vectors show peak wave direction.

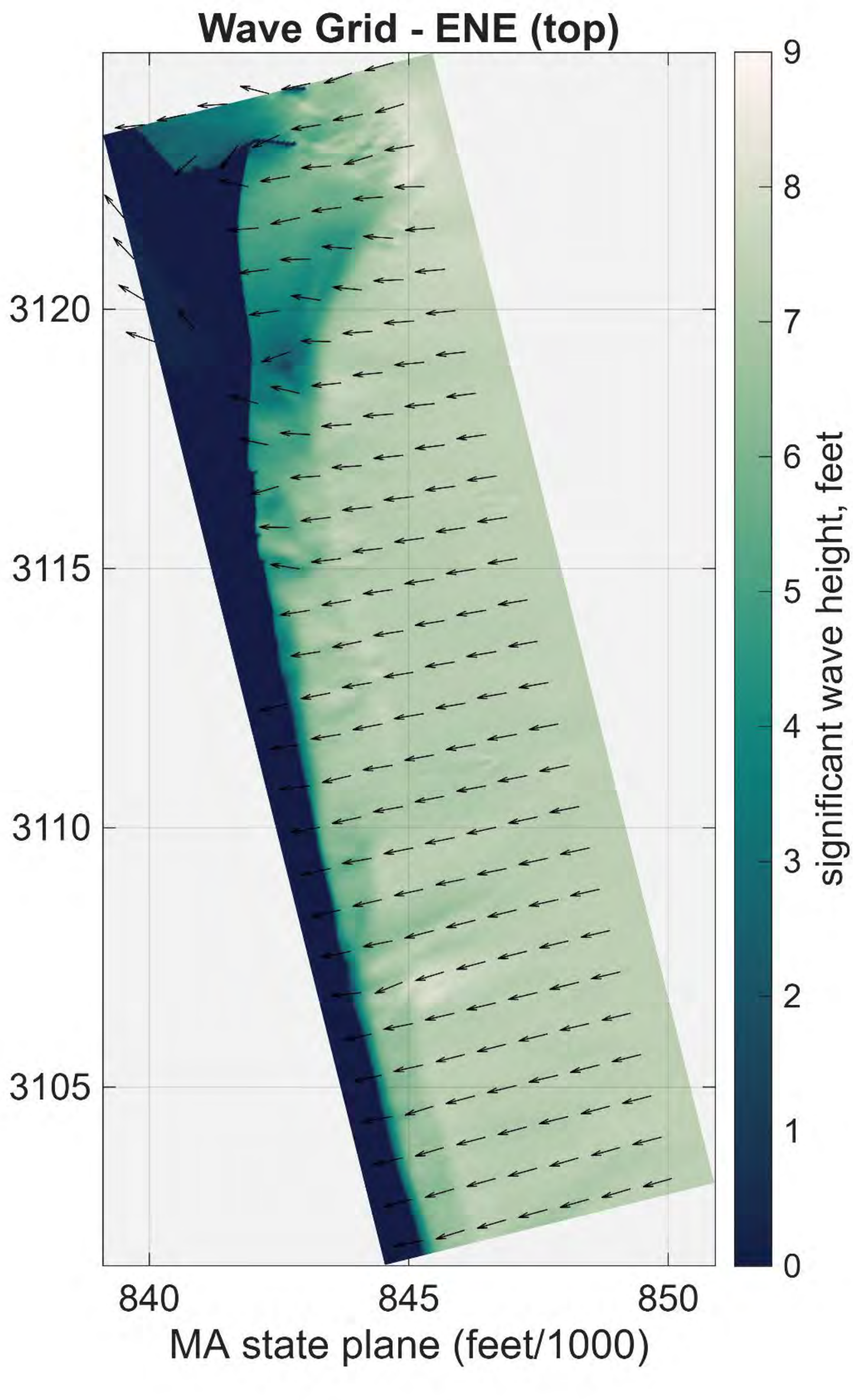

Figure 4.8. Nested lower fine-scale wave model output or the top ENE case (Table 4.1). Color contours indicate wave heights (feet) and vectors show peak wave direction.

4.2. Shoreline Evolution modeling

An evaluation of sediment transport along Salisbury Beach and Plum Island is essential to understand the coastal processes that shape the project shorelines. Wave-induced longshore sediment transport and the resulting shoreline change depends on a variety of wave parameters such as wave breaking height, wave period, and wave direction. In order to assess the coastal processes that result in shoreline change, a variety of models were implemented.

In general, there is a broad technical range of models that can assess shoreline change, from simple analytical modes to the most complex computer models that three-dimensionally simulate natural phenomena that contribute to sediment movement. Such three-dimensional models require detailed input data, are computationally expensive, and simulate the inter-relation of physical phenomena that are not fully understood by scientists and engineers. Analytical models implement simplified mathematical solutions of equations governing broad physical principles and can neglect to capture the more detailed effects of wave dynamics on a coastline.

The models best suited for studying coastal processes along the shorelines of Salisbury and Plum Island fall in the middle of this technical range. Two models were implemented for this study: an analytic model to study patterns of sediment transport and a more involved one-dimensional shoreline change model. Both models use an observed shoreline and spectral wave information from the SWAN study, and are governed by the same base equations for sediment transport. These models are a computer code developed in-house by Sustainable Coastal Solutions. The sediment transport model assesses general sediment movement patterns and maximum magnitude, i.e. the sediment transport potential, using mean wave information.

Shoreline evolution (or change) modeling was performed using a “one-line” longshore transport computer code that simulates the evolution of a shoreline through time at one specific contour level (i.e. beach berm crest or mean water level). The base assumption for the “one-line” model is that the nearshore bathymetry within the active extent of the beach profile (from the contour level chosen to the depth of closure) can be adequately represented by straight and parallel contours. Examples of formulations of this type of shoreline model are very well documented in the literature, e.g., Dean and Dalrymple (2001), Hansen and Kraus (1989).

4.2.1. Sediment Transport Modeling

To properly evaluate natural forces influencing nearshore sediment movement along the ocean-facing beaches, an analysis of coastal processes (primarily waves) governing beach sediment transport was performed. Spectral wave refraction modeling was used to determine how nearshore bathymetry modifies the wave climate along the open ocean beaches of Salisbury, Newburyport, and Newbury. The shoreline limits of the study area are shown in Figures 1.4, 1.5, and 1.6.

Typical of any modeling effort, model results can only be as good as the data used for boundary conditions and calibration. Nearshore wave climate, grain size, and historic shoreline change data are required to accurately simulate sediment transport.

Grain size for the project beaches was derived through sediment samples taken in January, 2026 (detailed in Section 3.3.1). A 0.55 mm and 0.80 mm representative grain size was determined for Salisbury and Plum Island, respectively (Figures 3.4 and 3.5). Shoreline data used to validate the model effort focused on the period from 2014 to 2021, as this is an energetic time frame that included multiple significant storms which allows for the design of conservative solutions. Shorelines for 2014 and 2021 were derived through a combination of LiDAR derived berm crest elevations and contours, corroborated with aerial imagery from a close time to the LiDAR flights. Figure 4.9 shows the shoreline change along the Salisbury and Plum Island study areas.

Results from the spectral wave modeling effort formed the basis for computed sediment transport rates along the modeled beach segment since wave-induced transport is a function of various parameters (e.g., wave breaking height, wave period, and wave direction). Longshore transport depends on long-term fluctuations in incident wave energy and the resulting longshore current; therefore, annual transport rates were calculated from the long-term average wave conditions developed and described in the previous section.

An evaluation of sediment transport potential along the shoreline allows for a deeper understanding of the coastal processes that work to shape the project beaches. The following section details the equations that form the basis of the sediment transport model (as well as the one-line shoreline change model).

Figure 4.9. Shoreline change along Salisbury Beach and Plum Island between 2014 and 2021.

4.2.2. Formulation of Sediment Transport Calculations

The overarching method for deriving sediment transport based on spectral wave information comes from deriving breaking wave parameters from offshore wave parameters, which is then related to the sediment transport rate. The sediment transport equation employed for the longshore analyses is based on the work of USACE (1984). In general, the longshore sediment transport rate is proportional to the longshore wave energy flux at the breaker line, which is dependent on wave height and direction. The transport equation was calibrated in sediment-rich environments and therefore typically over-predicts sediment transport rates. Despite the tendency for overprediction, the transport equations provide a useful basis for understanding erosion/accretion trends along the shoreline of interest. In the method detailed by USACE, the volumetric longshore transport, Q, past a point on a shoreline is computed using the relationship:

$$Q = \frac{I}{\rho g a'(s-1)}$$

where I is the immersed weight longshore sediment transport rate, ρ is the density of sea water, a' is the void ratio of the sediment, and s is the specific gravity of the sediment.

There are two methods to compute the immersed weight longshore sediment transport, I. The original, "CERC formula", defines I such that

$$I = KP_{ls}$$

where K is a dimensionless coefficient. The longshore energy flux factor, P_{ls}, is computed using the following relationship:

$$P_{ls} = \frac{\rho g^{\frac{3}{2}}}{16\sqrt{\gamma}} H_{sb}^{\frac{5}{2}} \sin(2\alpha_b)$$

where H_{sb} is the significant wave height at breaking, γ is the wave breaking index ($\gamma = \frac{H_b}{b_d}$), and α_b is the breaking wave angle. A value of $K = 0.39$ is designated for use with significant wave heights (outputted from SWAN).

For this study, the method used to compute the immersed weight longshore sediment transport is a modification to the original CERC formula and was described by Kamphuis (1990). The Kamphuis method adds a dependency on the median grain diameter of the beach sediment, as well as the surf similarity parameter, ξ_b, which is expressed as

$$\xi_b = \frac{m}{(H_b/L_o)^{1/2}}$$

where m is the bottom slope and L_o is the incident wave length. The complete expression of Kamphuis is

$$I = K^* \rho g \left(\frac{g}{2\pi}\right)^{0.75} \xi_b T^{0.5} (mD_{50})^{-0.25} H_{sb}^{2.5} \sin^{0.6}(2\alpha_b)$$

where the coefficient K^* is typically given as 0.0013 but offers flexibility as a tuning parameter for transport calculations, and all other variables are defined previously.

Again, the value of transport potential derived using this method represents the maximum possible at a particular location, given a rich sediment supply, and with no structures (i.e. seawalls and groins) to modify the movement of sediment along the shoreline.

Sustainable Coastal Solutions developed a computer code based on the governing empirical expressions to compute sediment transport potential along the Salisbury and Plum Island shorelines. Calculations of sediment transport are computed at evenly spaced grid cells (32.8 feet or 10 meter), with positions that correspond to evenly spaced wave output from the SWAN grids. The November 2014 shoreline was used as the input shoreline.

The shorelines on either side of the inlet were modeled independently of each other using wave output from their respective grids, with Figure 4.10 and 4.11 showing transport potential for Salisbury and Plum Island respectively. Sediment transport potential for Salisbury was calculated from the MA-NH border in the north to the Merrimack River inlet jetty in the south, about a 3.4-mile segment. Sediment transport potential for Plum Island was calculated from the Merrimack River inlet jetty in the north to the end of the populated region of Plum Island in the south, about a 1.8-mile segment.

Figure 4.10. Computed net annual sediment transport potential rates along the Salisbury Beach shoreline. Arrows indicate the direction of transport, while the color and size of the arrows indicate transport magnitude.

Figure 4.11. Computed net annual sediment transport potential rates along Plum Island Beach shoreline. Arrows indicate the direction of transport, while the color and size of the arrows indicate transport magnitude.

4.2.3. One-Line Shoreline modeling

Sustainable Coastal Solutions developed another computer code based on the previously stated expressions of sediment transport potential, which simulates the conditions along shorelines over time, where coastal engineering structures impact actual sediment transport rates. The goal of the shoreline change modeling is first to predict measured shoreline change and longshore sediment transport rates, and subsequently to use the model to evaluate beach management alternatives for both Salisbury and Plum Island.

The model code incorporates the ability to simulate the effects of seawalls (and coastal dikes) and groins on shoreline evolution. The model is formulated using a simple explicit upwind differencing scheme (e.g., Dean and Dalrymple, 2001), which computes change in shoreline position based on the computed gradient of sediment transport. The relationship between shoreline change and the gradient of sediment transport potential can be most simply expressed as:

$$\frac{\delta y}{\delta t} + \left(\frac{\delta Q}{\delta x} + q\right)/(D_B + D_c) \ = 0$$

where Q is sediment transport at a particular shoreline transect, x is alongshore width of a computational cell, y is the cross-shore position of the shoreline, t is time, q is a source term, D_B is the berm elevation of the beach, and D_c is the depth of closure. Values of sediment transport are computed at evenly spaced grid cells, with positions that correspond to evenly spaced offshore wave output of the wave transformation model grid.

The depth of closure and beach berm crest height are two of the required input parameters for the shoreline model, as together they define the littoral area where wave induced sediment transport is the predominant transport mechanism, also known as the active beach profile. The depth of closure is an estimation of the seaward limit of the beach profile. By definition, areas where no depth changes occur are located beyond the depth of closure. Although more extreme cases (such as storms) cause sediment movement at bottom depths that are greater than the depth of closure, the net flux of sediment is not significant enough to impact the beach profile. For this study, the depth of closure was estimated using the method of Hallermeier (Dean and Dalrymple, 2001). The depth of closure is about half the depth for incipient sediment motion (Hallermeier, 1978).

The depth of closure (D_c) can be computed using the relationship developed by Birkemeier (1985),

$$D_c = 1.75H_e - 57.9\left(\frac{H_e^2}{gT_e^2}\right)$$

where H_e and T_e are the significant wave height and period, respectively, that is expected to be exceeded only for 12 hours each year. A useful approximation is given by $D_c = 1.57H_e$, where H_e is computed as $H_e = \overline{H} + 5.6\sigma_H$, and $\overline{H}$ and σ_H are the mean wave height and standard deviation of the wave record, respectively. Using the 44-year wave hindcast from WIS station

63045, H_e is computed as 13.3 feet (4.1 meters), which results in a depth of closure 22.6 feet (6.9 meters). Therefore, the depth of incipient sand motion is about 45.3 feet (13.8 meters).

Output from the wave modeling analysis is used to drive the shoreline evolution model. Previously, the sediment transport potential calculations used the output from the wave modeling analysis based on the percent occurrence of each model case. For the shoreline evolution model, a time series of wave conditions was created using the Atlantic WIS hindcast (Station 63045), where each hour was sorted by compass sector and wave height to match it to one of the 27 wave cases representing mean annual conditions (Table 4.1). At each model time step (1 hour for Salisbury, 0.5 hour for Plum Island) during the course of the 6.4-year calibration period, SWAN wave output was selected to match the wave case in the WIS record. For hourly periods where waves were not propagating onshore from any of the nine compass sectors of Table 4.1, no waves were applied to the model shoreline for that time step.

Coastal engineering structures along the modeled shoreline segment are included in this model and act to inhibit sediment transport and prevent shoreline erosion. For Plum Island, three groins are included as well as the southern Merrimack River inlet jetty. The groins are included along the lower grid by specifying the location, length, and permeability of each. The groins act to impound sand and the permeability factor functions to reduce the transport rate across the grid cell where each groin exists. Permeability ranges between 0.0 and 1.0, where 0.0 would be a completely impermeable block to transport and 1.0 represents a structure that has no sand holding capacity (e.g., completely unraveled or filled to bypassing). For the three groins at the north end of Plum Island, the permeability factors were set to 0.15, 0.1, and 0.2 (north to south) which represents the ability of the groins to contain some sediment. The southern Merrimack River inlet jetty is also included in the model, such that the jetty is specified at the northern boundary of the lower grid. The jetty is specified the same as a groin, with a permeability of 0.0 and with a length that represents the seaward extent of the jetty.

In the upper fine grid for Salisbury, the northern Merrimack River inlet jetty is specified at the southern boundary of the grid, again with a permeability of 0.0 and with a length that represents the seaward extent of the jetty. In addition, the backside of the building found on the beach (the Pavillion) was incorporated in to the model as a sea wall, which limits the shoreward movement of the shoreline. If the shoreline at any grid cell erodes to the point where it comes in to contact with the “sea wall”, the shoreline is not allowed to move further shoreward. Unlimited accretion is allowed in front of the sea wall.

The one-dimensional model grid developed for Salisbury extends along the same 3.4-mile-long shoreline segment used for the sediment transport potential calculations, and uses the same 32.8-foot (10 meter) grid spacing. For Plum Island, the one-dimensional model grid extends along the 1.8-mile-long shoreline segment with the same 32.8 feet (10 meter) grid spacing.

Model performance was calibrated over a 6.4-year simulation between 2014 and 2021, for both the upper (Salisbury; Figure 4.12) and lower (Plum Island; Figure 4.13) grid shorelines. The WIS record had complete coverage for this 2014 to 2021 timeframe, and so time-dependent wave information was generated from the SWAN model output and WIS wave record. The model uses the 2014 shorelines as input; as described previously these shorelines were generated from a combination of LiDAR and aerial imagery analysis. The computed shoreline at the end of the 6.4-year simulation was compared to the shoreline generated for 2021.

Sediment migration offshore to onshore from the bypass bar was included in each model. For Salisbury, a sink was applied to the southern region of the grid to represent sediment migration offshore to the bypass bar. A source was then applied to the northern region of Plum Island to represent sediment migration onshore from the bypass bar. Including sediment migration relating to the bypass bar aided with shoreline calibration for both models.

Shoreline calibration was achieved with an error of 14.6 feet for Salisbury and 23.3 feet for Plum Island. The relatively higher error for Plum Island is due to an overestimation of the accretion near the area where the bypass bar connects to the Plum Island shoreline (which can be seen in aerial photographs from 2020, Figure 2.3), as well as an underestimation of accretion near the groins. The Plum Island system is complex due to the presence of the bypass bar; migration of the bypass bar shoreward or seaward alters the breaking wave direction, which then effects sediment transport patterns. The overall shoreline trend changes are very well captured for Plum Island, with a R^2 correlation coefficient of 0.99. Salisbury is also well captured with an R^2 correlation coefficient of 0.94. The calibrated one-line model was then used in Section 5 for analysis of alternatives.

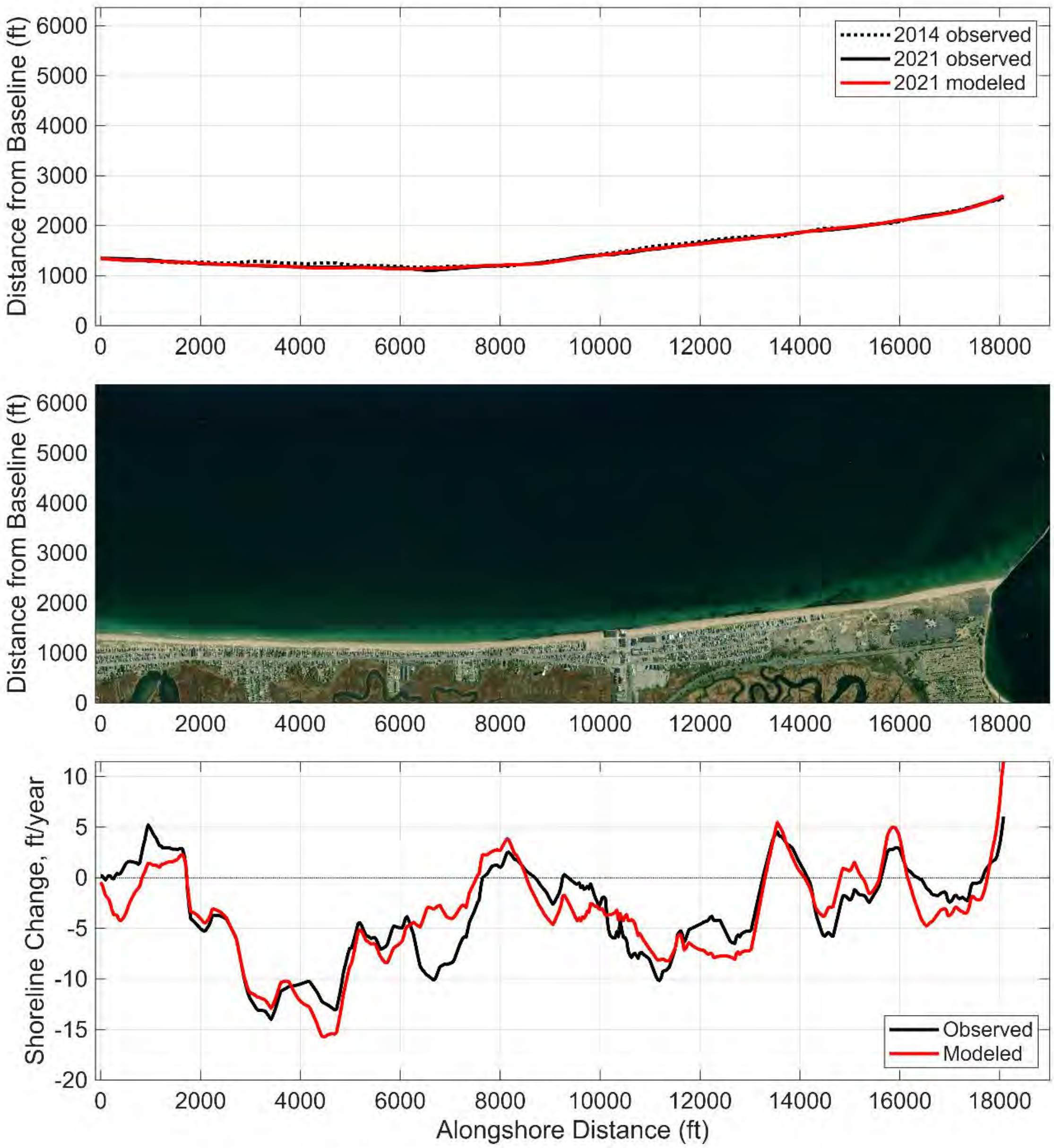

Figure 4.12. Comparison of modeled and observed shorelines for Salisbury Beach for the shoreline model calibration period between 2014 to 2021. The calculated RMS error is 14.6 feet and the R^2 correlation coefficient is 0.93.

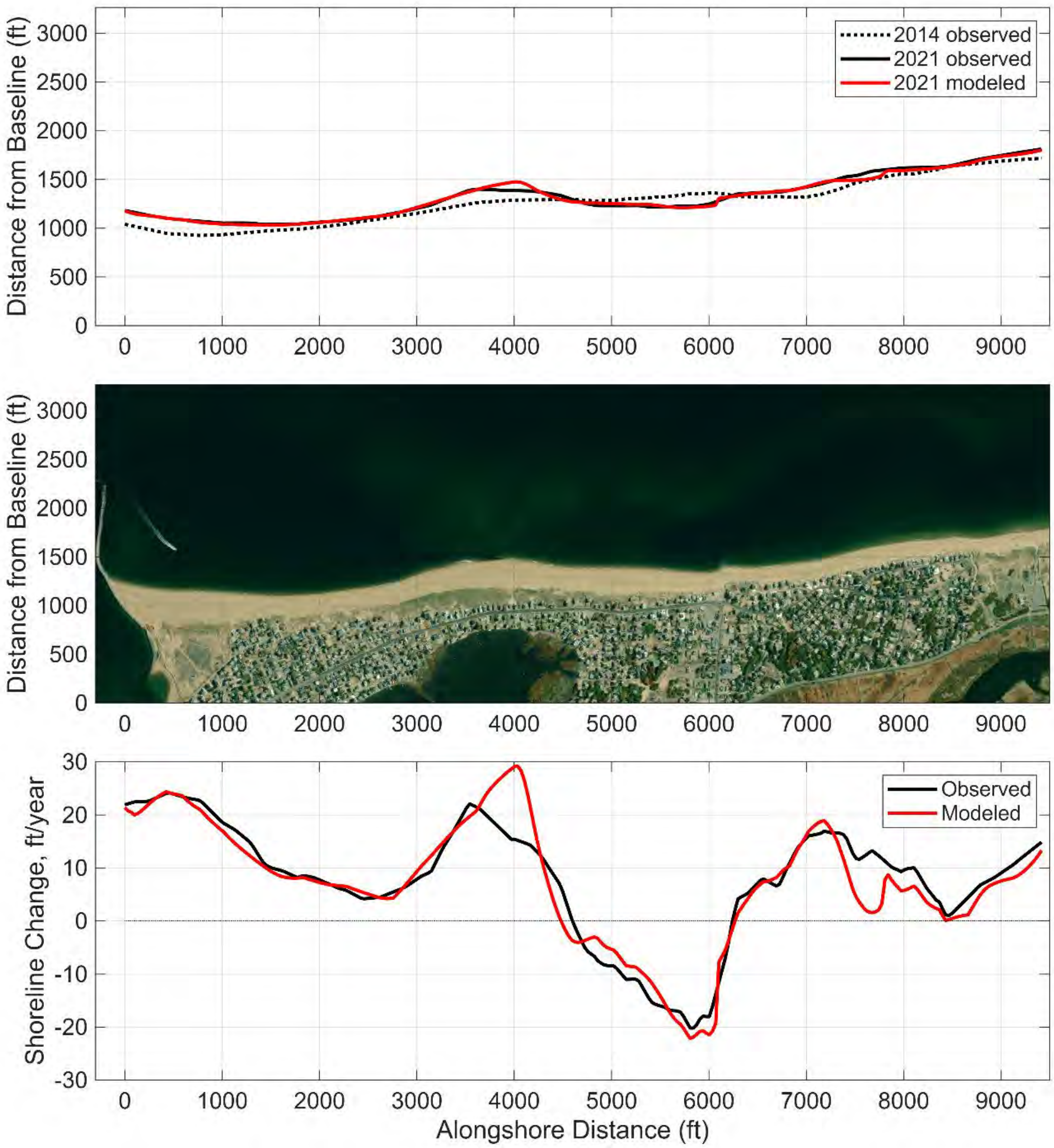

Figure 4.13. Comparison of modeled and observed shorelines for Plum Island for the shoreline model calibration period between 2014 to 2021. The calculated RMS error is 23.3 feet and the R^2 correlation coefficient is 0.99.

5. Potential Shoreline Protection Strategies

Sustainable Coastal Solutions analyzed existing conditions, historical records, and modeling studies (previous and present) to assess potential shoreline management alternatives for Salisbury, Plum Island, and Reservation Terrace shorelines (Figures 1.4, 1.5, and 1.6).

For Salisbury Beach, the two-phased wave and sediment transport/shoreline change modeling approach, provides the most comprehensive evaluation for shoreline stabilization methods. Since Plum Island has been vastly accretional in recent years, shoreline stabilization strategies were developed in the case of a future development of an erosion hot spot, using updated and previous modeling studies. Previous modeling studies were assessed to understand the impact of the jetty at Reservation Terrace and the updated modeling study was used to assess Plum Island as a source for Reservation Terrace.

The shoreline protection strategies are designed for present conditions and do not account for longer-term sea level rise scenarios. As will be discussed in the following subsections, the design life of nourishment alternatives is typically less than a decade, and therefore it is not appropriate to account for sea level rise projections beyond that. Instead, the design criteria for future nourishment projects can be adjusted to account for sea level rise. An analysis of predicted sea level rise is included in Appendix C.

5.1. Salisbury Beach and State Reservation

Located north of the Merrimack River inlet, Salisbury Beach experiences a relatively stable shoreline with a southerly littoral drift pattern typical of exposed coastlines along northern New England due to infrequent but impactful northeast storms. Despite a relatively stable shoreline, Salisbury Beach features jetties both located in the north (Hampton Harbor) and the south (Merrimack River inlet), which limit longshore sediment migration. Historical dredging of the Merrimack River inlet and subsequent offshore (or nearshore and not on beach) further contributes to the net sediment losses experiences at Salisbury Beach. The lack of consistent sediment supply and storms events have resulted in a net erosion of the shoreline. Salisbury Beach is low lying with minimal dune protection, making beachside properties and roadways vulnerable to flooding and erosion during storm events.

As detailed in Section 2.2.3, several small nourishment projects have been attempted along Salisbury Beach, either to extend the shoreline seaward or to increase the elevation of the upper beach/dunes for additional storm surge protection. These smaller nourishments have been beneficial in the short term, but are only on the order of 10,000-40,000 CY. Sustainable Coastal Solutions recommends a substantial nourishment in order to combat the long-term sediment losses and mitigate net erosion of the shoreline.

5.1.1. Salisbury Beach Nourishment

A nourishment at Salisbury Beach would increase protection to infrastructure and property currently threated by overtopping and storm damage. By adding sediment, an engineered beach typically increases the upper beach elevation and extends the seaward profile of the beach. This provides two-fold protection against storm conditions: the seaward extension of the existing beach absorbs and dissipates wave energy away from coastal infrastructure, and the increase in upper beach elevation protects against overtopping.

The design of a successful nourishment project, lasting several years, depends on multiple factors, including ensuring compatible beach sediment, as well as the berm width and fill length of the engineered beach. Success of a nourishment project is also dependent on the local sediment transport dynamics and berm overtopping potential. Once nourishment material is in place, coastal processes will rework the nourishment material to create an equilibrated beach profile. The ongoing sediment transport will migrate the material both cross-shore and alongshore, and migrated sediment remains within the system which is an additional benefit to beach nourishment as it mimics natural processes.

The sediment transport potential modeling results show that rates reach a maximum south-directed magnitude south of the Pavillion. There is some variability to the transport rates along the shoreline. Nourishment project locations are determined by stretches that have seen historical damage. Due to low-lying nature of Salisbury Beach, much of the shoreline would benefit from nourishment.

The shoreline model was used to simulate different nourishment templates to investigate how the increasing berm widths and sediment volumes would evolve with time along the project area. Each nourishment was designed to raise the berm elevation to 11.0 feet NAVD88, which is chosen based on the most extreme FEMA 100-year still water elevation (SWEL) for the region of 10.0 ft NAVD88 plus an additional 1.0 foot (Flood Insurance Study, 2025). In addition, the nourishment scenarios extend the existing shoreline seaward widths ranging from 25 to 100 feet (Figure 5.1). Dimensions of the nourishment were selected based on the likely availability of resources based on cost and typical dredging volumes. Figure 5.2 shows the approximate extent of each alternative (ranging from 5,000 to 9,000 feet).

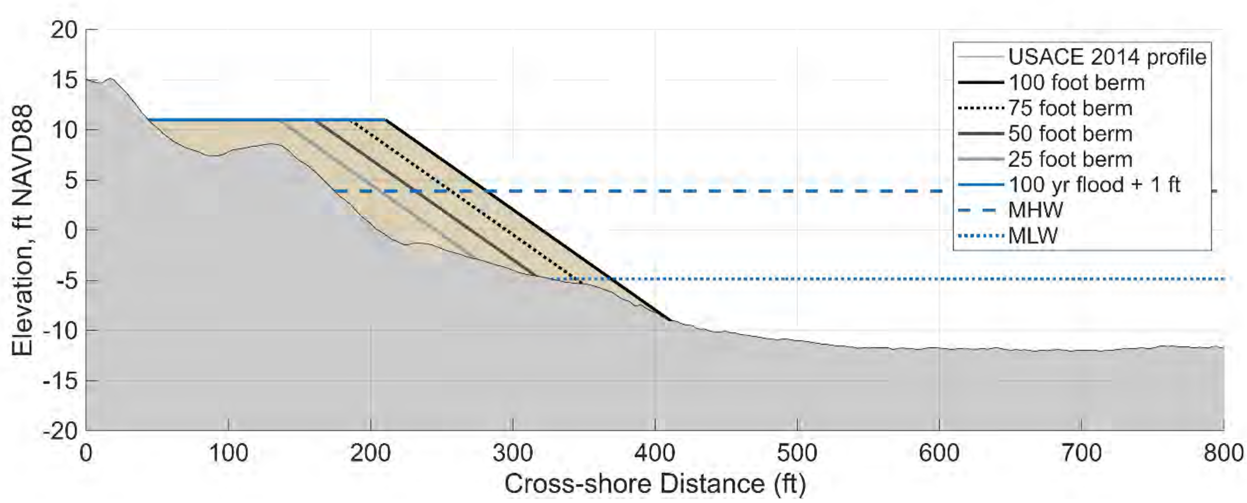

Figure 5.1. Proposed nourishment templates for Salisbury Beach.

The design life of a fill project is typically considered to be the point at which 30% of the fill remains within the original placement area. At this point, additional nourishment projects or other management decisions are suggested. Model runs for each nourishment scenario (Table 5.1) were simulated for a 15-year period to assess the design life for each scenario and analyze longshore migration of the sediment. The percent fill remaining is computed as the volume of the sand remaining (V, at a particular point in time $t = n$) within the original project limits, divided by the total volume of the nourishment at time zero:

$$\%_{remaining} = \frac{V_{t=n}}{V_{t=0}} x100$$

Sediment from the original nourishment that disperses up- and down-drift from the original nourishment template can benefit the beach outside of the original project limits. However, such sediment migration is not counted in the estimation of fill performance. Based on the results of the shoreline modeling, a nourishment with a wider berm width (Scenario 2 and 3; 50- and 75-foot berm widths) is able to maintain 30% of fill for around 10 years. A comparison of fill performance for the four scenarios is included in Figure 5.3, where it can be seen that the nourishment in Scenario 1 (25-foot berm width, 9,000-foot fill length) disperses outside of the original project area the fastest. Since wider nourishment designs have more shoreline to erode, it will logically last longer than a design with less width. The modeled position of the Scenario 4 berm immediately after placement and 5, 9 years into the future relative to the 2026 shoreline is shown in Figure 5.4.

Table 5.1 Modeled nourishment scenarios for Salisbury Beach.

Scenario	Volume (cu-yd)	Berm width (ft)	Fill length (ft)	Year of 30% remaining
1	110,000	25	9,000	4.3
2	180,000	50	7,000	6.7
3	200,000	75	5,000	7.5
4	270,000	100	5,000	9.4

Figure 5.2. Approximate extents of nourishment scenarios for Salisbury Beach detailed in Table 5.1.

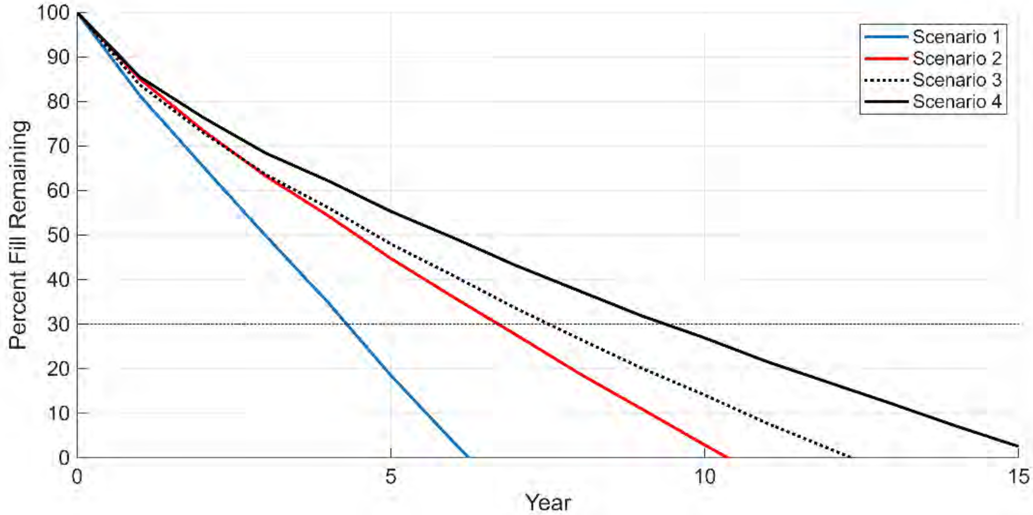

Figure 5.3. Percent fill remaining through time for Salisbury Beach nourishment Scenario 1, 2, 3, and 4 (blue, red, dashed black, and solid black).

Figure 5.4. A close up of Scenario 4 immediately after 100-foot berm construction (dark red), as well as modeled shorelines 5 and 9 years (red and pink, respectively) after placement. The 2026 shoreline is shown (dashed black).

After the nourishment is placed, the cross-shore nourishment profile will equilibrate to more closely match the beach profile before fill is constructed. Natural forces will act on the sediment to generate longshore movement. A visual of the cross-shore beach profile 1 year after construction (as well as selected later years) for each nourishment scenario is shown in Figure 5.5. The profiles represent the mean shoreline position over time, as some areas along the fill template will have eroded more or less than what is shown. Since erosion along the fill metric is not uniform, monitoring for the emergence of erosion hot spots along the fill template is necessary. Such erosion hot spots could emerge due to minor or moderate hot spots, and may necessitate a smaller scale nourishment project.

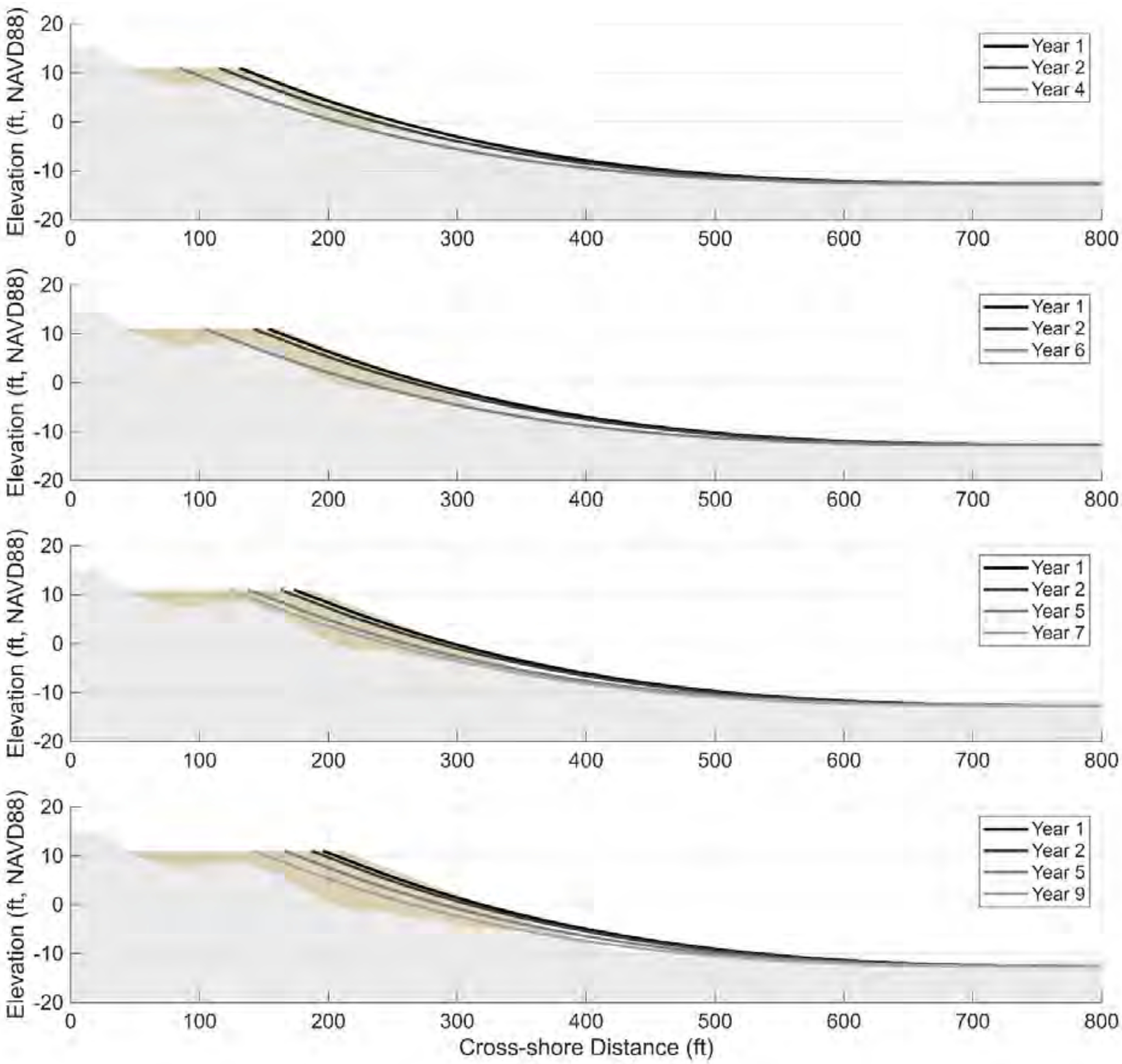

Figure 5.5. Shoreline position and cross-shore profiles for the 25- (top), 50- (middle top), 75- (middle bottom), and 100-foot (bottom) berms shown for selected years following construction based on the design life of each scenario.

5.2. Plum Island

As mentioned previously, the sediment transport patterns in Plum Island are complex due to the effects of the bypass bar. Overall, the northern portion of Plum Island has a net transport pattern to the north, which is atypical to the north shore region. Northeast storms, while infrequent, dominate the sediment transport for most of the state, resulting in a net southerly directed transport for most of the exposed Atlantic coastlines. Sediment migrates off the bypass bar to Plum Island and acts as a source, in addition the bypass bar acts to shelter the Plum Island shoreline by shoaling and refracting waves and towards the north (or coming from a more southerly direction) which drives a net northerly sediment transport with recent rates around 73,000 cubic yards per year (as calculated in Section 3.3.2).

Erosion hot spots immerge in areas where the bypass bar has shifted and causes a focusing of wave energy. As mentioned previously, there was a significant erosion hot spot in the region of the Plum Island groins in the early 2010s. From the analysis of 2014 to 2021 shoreline change, that area has accreted around 10 to 20 feet per year. Another erosion hot spot emerged farther north, although it was not detrimental to infrastructure in the area. Since 2021, the majority of the Plum Island shoreline has accreted between 10-60 feet/year and the previous erosion hot spots have been resolved.

Since the presence of an erosion hot spot along Plum Island is highly dependent on the location of the bypass bar, Sustainable Coastal Solutions suggests monitoring of the bypass bar location and shoreline to assess potential development of an erosion hot spot. Nourishment scenarios can be designed based on the emergence of the erosion hot spot and ideally implemented before it becomes detrimental to infrastructure. The previous sediment study developed three nourishment scenarios: 50-, 100-, and 150-feet berms that each span the same 2,000 feet of the erosion hot spot (Figure 5.6) (Applied Coastal Research and Engineering, 2021). The specifications and design life of each scenario is included in Table 5.2.

Table 5.2 Modeled nourishment scenarios for Plum Island from Table 5.2 in (Applied Coastal Research and Engineering, 2021).

Scenario	Volume (cu-yd)	Berm width (ft)	Fill length (ft)	Year of 30% remaining
1	70,000	50	2,000	6.1
2	95,000	100	2,000	12.4
3	120,000	150	2,000	15.8

As forementioned, the erosion hotspot from the early 2010s resolved, likely due to the shifting of the bypass bar, but had significant impact on the homes in the area. Monitoring of the bypass bar and development of hot spots would allow for proactive interventions, instead of reactive solutions after adjacent infrastructure has been impacted.

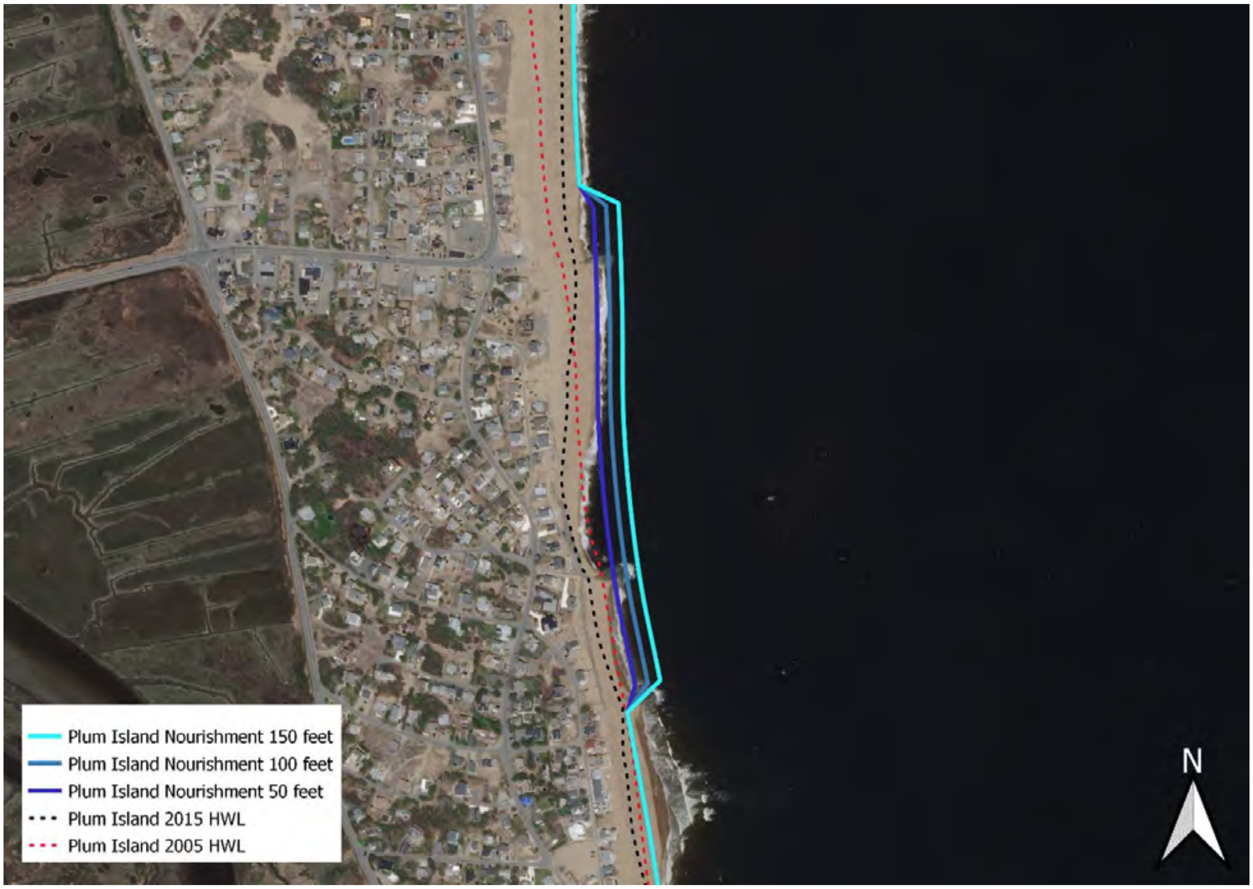

Figure 5.6. Plum Island nourishment scenarios for the early 2010s erosion hot spot from Figure 5.17 in Applied Coastal Research and Engineering, 2021.

We also developed nourishment scenarios for the 2014 to 2021 erosion hot spot to further demonstrate the efficacy of preventative strategies. Nourishment scenarios are implemented using the 2014 shoreline to mitigate the erosion that occurs by 2021 (Figure 5.7, left panel). The year of 30% fill remaining for a 75-,100-, and 150-foot berm is detailed in Table 5.3. While each of the scenarios has less than 30% of fill remaining after only a couple years, the nourishment still acts as an effective short-term preventative strategy against the effects of an erosion hot spot. For each scenario, the modeled shoreline 7 years after the original fill is still seaward of the 2021 observed shoreline (as shown in Figure 5.7, right panel for the 75-foot berm scenario).

Table 5.3 Modeled nourishment scenarios for Plum Island 2014-2021 erosion hot spot.

Scenario	Volume (cu-yd)	Berm width (ft)	Fill length (ft)	Year of 30% remaining
1	90,000	75	1,700	1.7
2	117,000	100	1,700	2.3
3	176,000	150	1,700	3.4

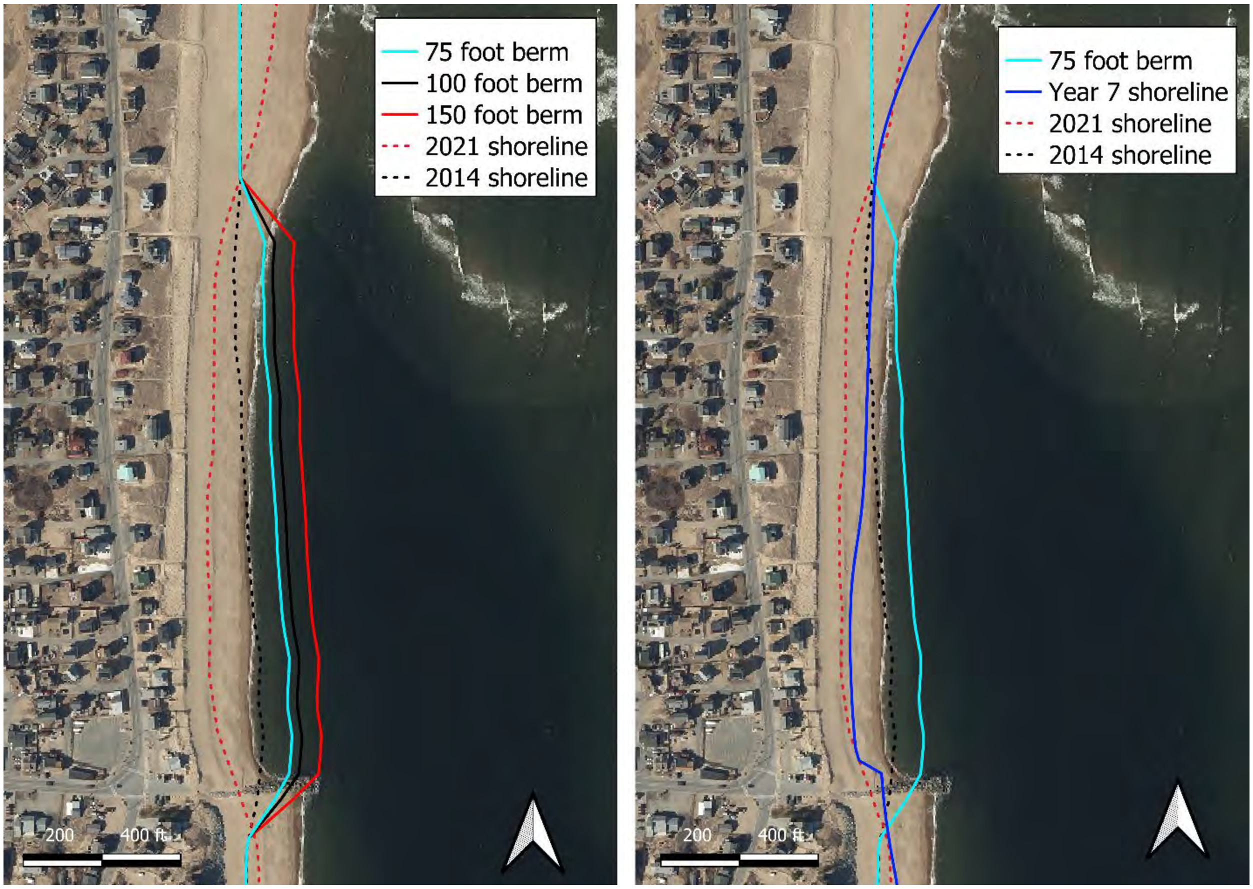

Figure 5.7. Plum Island nourishment scenarios with 75-, 100-, and 150-foot berms shown on the left panel (cyan, black, red lines respectively). The modeled shoreline seven years after original fill placement is shown (blue line) for the 75-foot berm scenario (cyan line) on the right panel. The observed shorelines for 2014 (dashed black) and 2021 (dashed black) are shown on both panels.

5.3. Reservation Terrace

The repair of the Merrimack River Inlet jetties, while in the short term has been beneficial to the seaward portion of the Plum Island shoreline, has been determinantal to Reservation Terrace. The sediment supply to Reservation Terrace has been limited (or almost cut off) due to jetty repair, resulting in significant erosion of the shoreline. In addition, the previous sediment study assessed the circulation patterns within the inlet and discovered that with the repaired jetty, a gyre circulation pattern forms with velocities that are on the order of 2.50-3.0 feet/s (Figure 5.8, top panel) (Applied Coastal Research and Engineering, 2021). The currents transport sediment away from the shoreline.

As discussed previously, almost 80% of the 2023 nourishment at Reservation Terrace washed away. The previous sediment study recommended a weir jetty which would both disrupt the gyre circulation and allow sediment from Plum Island to migrate to Reservation Terrace (Figure 5.8, bottom panel) (Applied Coastal Research and Engineering, 2021). Sustainable Coastal

Solutions also recommends this for the long-term management of Reservation Terrace, and USACE is currently exploring the implementation of a weir jetty.

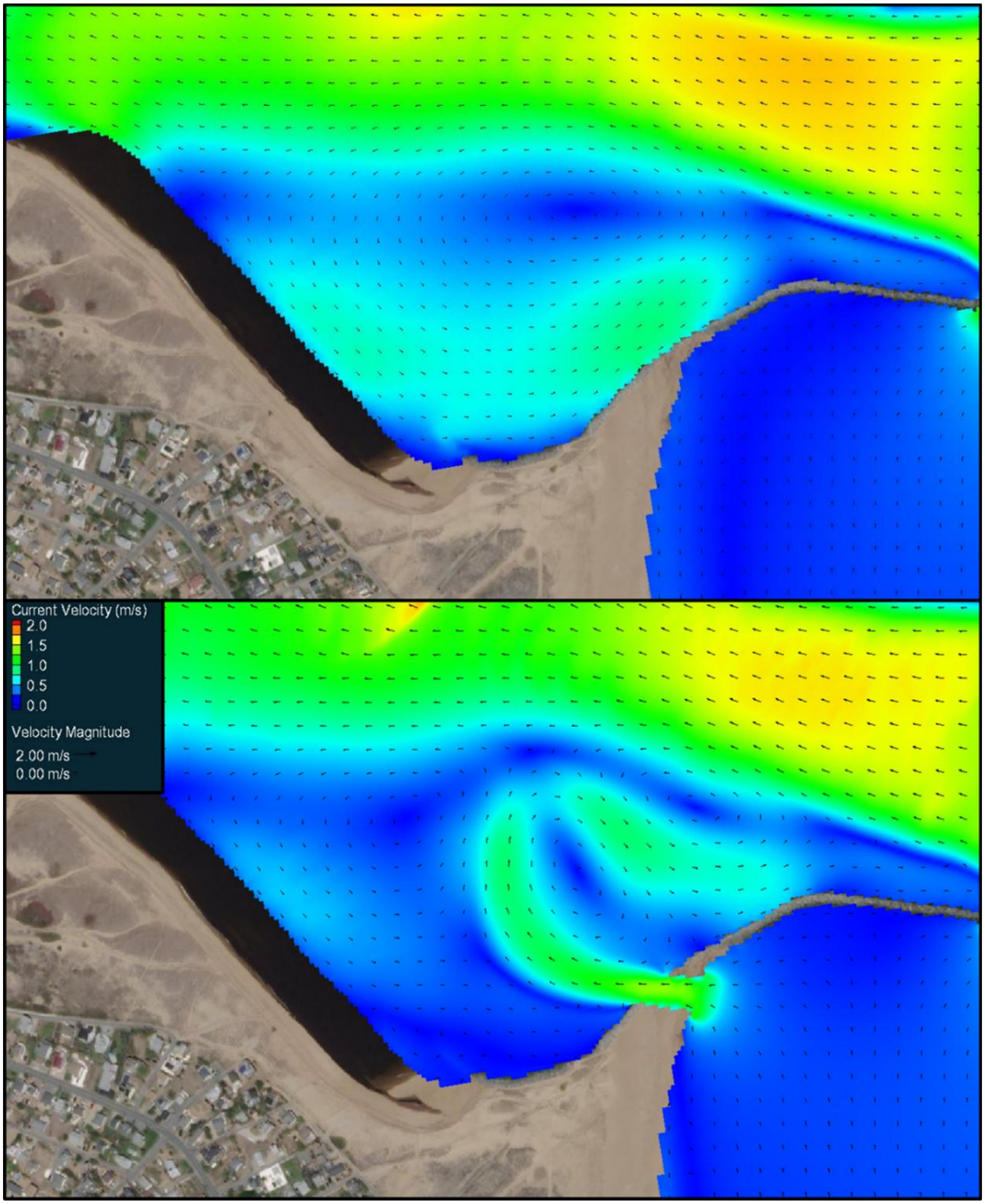

Figure 5.8. Current velocities (m/s) from CMS model results of Reservation Terrace (Figure 5.8 of Applied Coastal Research and Engineering, 2021). The top panel shows current velocities for existing conditions, and the bottom panel shows current velocities with the implementation of a 100-foot (30 meter) weir scenario. Velocities in the weir jetty scenario are reduced by half.

In the interim, an augmentation scenario for Plum Island could be implemented to provide sediment to Reservation Terrace, where the Plum Island shoreline would be excavated near the southern jetty to provide sediment to nourish Reservation Terrace. These nourishment alternatives, which allows us to manually “bypass” the jetty will be referred to as bypass scenarios, not to be confused with the bypass bar that has been discussed. We implement our shoreline change model with an altered 2026 shoreline, where the northern region of the shoreline is altered as described in Table 5.4. These three bypass scenarios could provide 91,000-166,000 cubic yards of sediment, with the Plum Island shoreline recovering to its original location in 2.2-3.7 years (Figure 5.9). By year 5, all bypass scenarios have shorelines that have accreted well past the original 2026 shoreline (bypass scenario 1, Figure 5.10; bypass scenario 2, Figure 5.11; bypass scenario 3, Figure 5.12).

Table 5.4. Bypass scenarios for Reservation Terrace. For a visual of the wedge shape of the removal width for scenario 3, see Figure 5.12.

Scenario	Volume (cu-yd)	Berm Width (ft)	Removal length (ft)	Year of 30% remaining
1	91,000	-130	700	2.2
2	128,000	-80	1400	2.6
3	166,000	Wedge: -200 to 0	1400	3.7

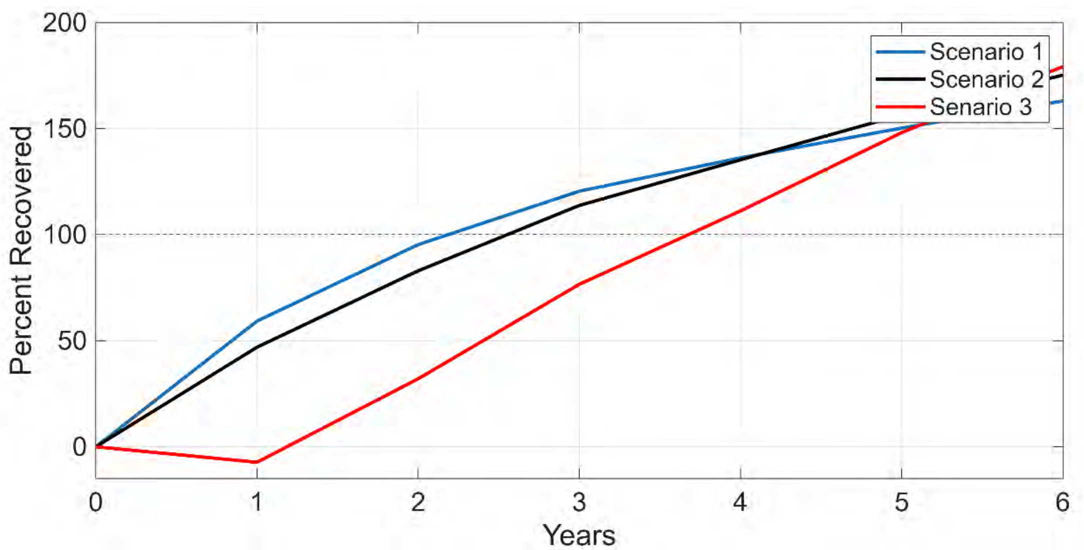

Figure 5.9. Percent recovery over time for each bypass scenario detailed in Table X, where 100% recovered indicates return to the 2026 shoreline before excavation.

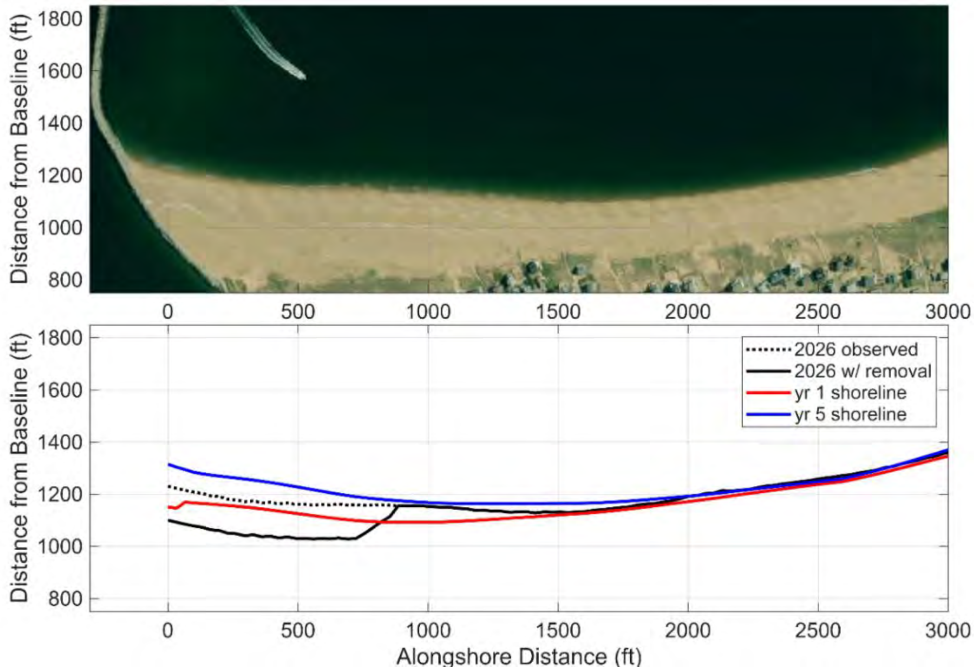

Figure 5.10. Shorelines for bypass scenario 1, where the observed 2026 shoreline and the shoreline immediately after excavation are shown (dotted black and solid black respectively). Modeled shorelines 1 year and 5 years after excavation are shown (red and blue respectively).

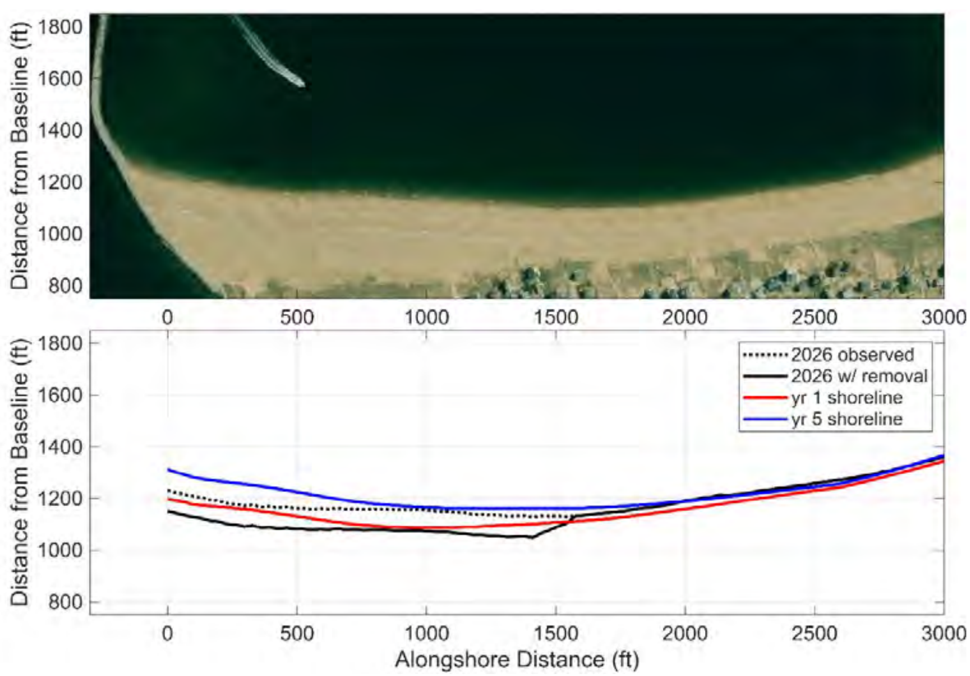

Figure 5.11. Shorelines for bypass scenario 2, where the observed 2026 shoreline and the shoreline immediately after excavation are shown (dotted black and solid black respectively). Modeled shorelines 1 year and 5 years after excavation are shown (red and blue respectively).

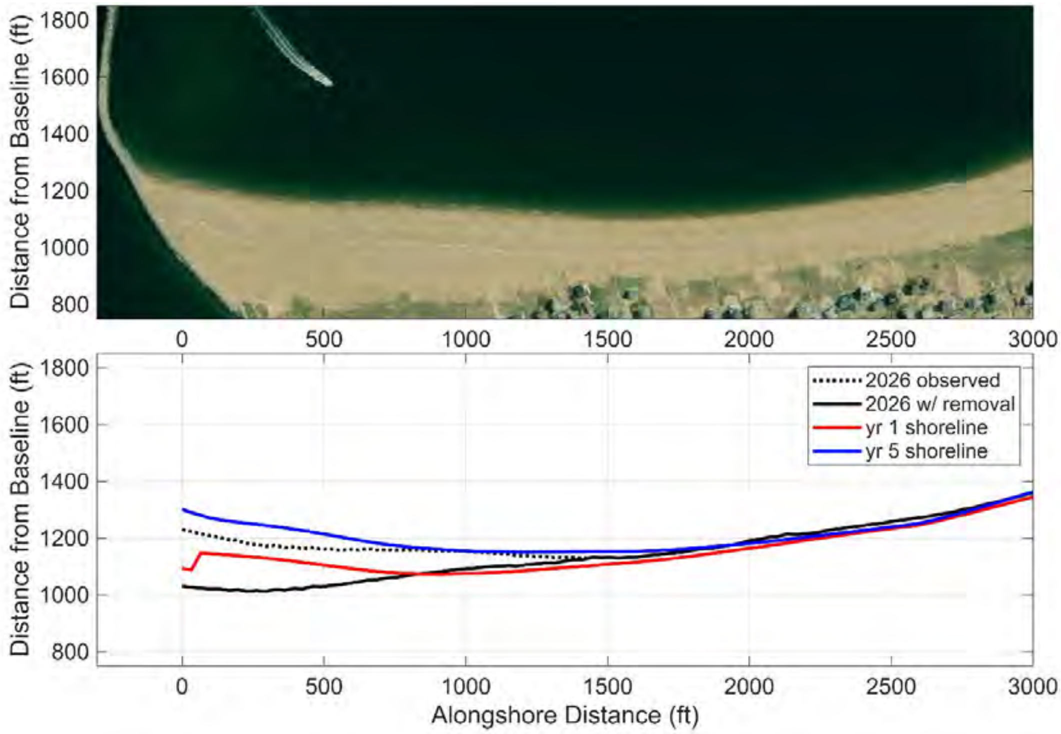

Figure 5.12. Shorelines for bypass scenario 3, where the observed 2026 shoreline and the shoreline immediately after excavation are shown (dotted black and solid black respectively). Modeled shorelines 1 year and 5 years after excavation are shown (red and blue respectively).

6. Future Implications and Recommendations

6.1. Sediment Sources and Nourishment Design

Numerous potential sources of beach compatible material are available, including upland, inlet, and offshore sources. Since the early 1900s, sediment dredged from the inlet averages about 40,000 cu-yd/yr, where dredged material placement has been primarily offshore or on the bypass bar, with limited direct placement to the beach. Future inlet maintenance dredging can and will be a sediment source to the adjacent beaches, however, upland or offshore sources will be necessary to supplement the sediment needs of each beach to augment natural sediment loss. Communities adjacent to the inlet should advocate for direct placement of all dredged material onto the beaches, as nearshore placement is not generally effective for shore protection purposes.

Upland borrows sources have been utilized to nourish Salisbury Beach. However, the beach nourishment quantities have been limited and have generally represented post-storm efforts to provide short-term protection. Previous evaluations for DCR also included potential stockpiling of upland sand at locations within the State Reservation for post-storm mitigation work. For larger-scale beach nourishment projects (i.e., project volumes in excess of 50,000 cubic yards), upland sources can become problematic due to potential impacts to traffic and roadway damage from truck traffic. Regardless, upland sediment represents a viable beach nourishment source to augment the inlet sediment supply for the beaches. Costs for upland beach nourishment material delivered and spread along the beach typically ranges from $35 to $70 per cubic yard, depending on trucking distance and local mitigation requirements.

Recent work funded by CZM has identified a potential offshore sediment source approximately 1.5 miles east of the Merrimack River entrance. Based on preliminary information, initial analyses of dredging requirements, project scale, and approximate costs have been developed (Appendix B). It should be noted that more detailed analysis of this site will be required to determine whether the material is appropriate for beach nourishment at the target beaches (i.e., is the material beach compatible) and whether dredging of the site will meet environmental regulatory standards. Due to the offshore distance and water depth of the potential borrow site, large-scale dredging equipment would be necessary to excavate to site and pump the material to shore. As mobilization costs for this type of equipment are high, only large-scale nourishment projects (over 500,000 cubic yards) would be cost-effective for the offshore borrow source. As shown in Appendix B, offshore sediment delivered and spread along the beach ranges from $39 to $58 per cubic yard.

Long-term sediment supply necessary to maintain beaches within the study area range between 60,000 and 80,000 cubic yards per year. This estimate assumes that in the short-term (i.e., the next 5 years), the USACE modifies the jetty system and/or sediment is borrowed from the south side of the jetty to maintain stability of Reservation Terrace. As discussed above, larger-scale beach nourishment projects provide more long-lasting shore protection to upland infrastructure. Example beach nourishment conceptual designs have been provided; however, more detailed work will be needed to ensure appropriate designs of nourishment projects to ensure appropriate longevity, while minimizing potential adverse environmental impacts.

If an offshore borrow site is pursued to augment the sediment supply in conjunction with beach placement of inlet dredged material, the scale of beach nourishment projects likely would have a design life that exceeds 10 years. As recommended, the design beach berm template would have an elevation of 11 feet NAVD88, which is approximately 1 foot above the 100-year flood elevation in the region. As sea levels continue to rise, the template design elevation can be designed to respond to these changes. Appendix C provides information on projected regional sea level rise over the next several decades, according to the latest scientific information available from NOAA. Based on this information, only minor changes to overall template heights associated with each renourishment cycle will be required to respond to sea level rise through 2070.

6.2. Recommended Monitoring Plan

As previously detailed, Sustainable Coastal Solutions specifically recommends monitoring of the development of erosion hot spots along Plum Island to proactively provide shore protection before adjacent coastal infrastructure becomes damaged. In general, the entire project shorelines of Salisbury Beach, Plum Island, and Reservation Terrace would benefit from long-term monitoring in order to assess future erosion mitigation strategies and/or beach nourishment needs. In addition, long-term monitoring allows for a thorough assessment of storm impacts to the beach system; ongoing monitoring and maintenance plans are critical for complying with FEMA requirements associated with potential storm-related reimbursement for episodic beach nourishment erosion. The following monitoring plans are pulled largely from the previous report (Applied Coastal Research and Engineering, 2021).

6.2.1. Existing Beach Monitoring Efforts

In the previous report, it was documented that DCR performed baseline beach surveys along Salisbury Beach and Plum Island, with shore-perpendicular transects spaced at approximate 500-ft alongshore intervals. An RTK-GPS was used to survey transects within the vicinity of the Center Groin, along the Atlantic Ocean facing coast of Salisbury Beach, and along the Reservation Terrace shoreline. Beach transects extended from the MLW elevation landward to a point approximately 600 foot above MHW, with measurements taken at every noticeable break in elevation. Elevations along each transect were reported in the NAVD88 vertical datum.

This survey protocol provides a general framework for evaluating beach erosion and accretion trends; however, site-specific monitoring protocol could provide beneficial information for the more dynamic portions of the shoreline. Therefore, the existing monitoring protocol is likely sufficient for Salisbury Beach. The two more rapidly changing areas, Plum Island in the vicinity of Center Groin and Reservation Terrace, would likely benefit from increased spatial analysis including the following:

- Rather than 500-ft alongshore spacing of transects, better spatial resolution of the Plum Island “hot spot” and the Reservation Terrace area could be achieved with alongshore transect spacing of 200 feet. This would allow more in-depth analysis of profile response to the more rapid alterations to the shoreline. This more detailed shoreline transect survey could be performed annually, preferably in the spring to represent “worst-case” beach conditions relative to the winter profile.
- The RTK-GPS survey equipment also can be utilized to trace the observed high-water shoreline based upon the observed “wrack” line at the time of the survey. To ensure this line is consistent between surveys, a comparison of the recorded elevation of the observed wrack line would need to accompany the survey results. This analysis performed on an annual basis would provide more detailed information regarding alongshore variability of shoreline shape, which is critical for assessing the impact of erosional “hot spots”. Similar to the closely spaced shore-perpendicular transect survey describe above, the high-water shoreline survey could be performed annually, preferably in the spring to represent “worst-case” beach conditions relative to the winter profile.

6.2.2. Beach Nourishment Monitoring Protocol

Again, this monitoring protocol is repurposed from the previous report as it is necessary to consider maintenance and monitoring of a potential nourishment project.

Since the purpose of the beach nourishment program is to reestablish the local sediment supply and provide storm protection for the shoreline, an evaluation of long-term nourishment needs will be required to assist the communities of Salisbury, Newburyport, and Newbury, as well as CZM, DCR, or other project proponents with future nourishment maintenance. An essential aspect to this project will be monitoring the performance of fill placed for the purpose of beach nourishment. This monitoring information will aid in determining:

- The percent fill remaining within the design template
- Accretion or erosion along adjacent beaches (either to the north or south of the project)
- The longshore variability in beach width indicative of potential "hot spot" erosion
- Future nourishment need required to maintain any nourishment for shore protection and the sediment supply

The rapid introduction of a large volume of sediment to the nearshore area would result in the material moving both alongshore and cross-shore to reach equilibrium with the waves and currents in the area. Monitoring would provide a means to measure the shoreline change and shifting of the nourishment fill. This can be determined by measuring the elevation along a series of shore perpendicular control transects (or cross-sections) along the length of the fill, as well as performing an RTK-GPS survey of the observed high-water line. For the alternative nourishment designs within this report, monitoring protocol similar to the one employed by DCR currently would be adequate. Survey transects at approximately 80 locations in Salisbury and 45 locations on Plum Island spaced 200 feet along the beach, could be employed for the monitoring effort of the nourishment alternatives described in the report. Surveys would be conducted from the landward edge of the primary dune and extend offshore. The actual distance that each transect runs offshore would need to be determined by *in situ* water depth. A pre-construction survey would be performed immediately preceding the nourishment project. In the first-year post-construction, typical regulatory requirements ask for surveys to be performed quarterly. The post-construction survey would be performed as soon as is practical after the completion of the nourishment project and would extend offshore to -15 ft NAVD88; well offshore of the proposed equilibrated nourishment toe. The remaining surveys in the first year would be wading surveys out to the -5 ft contour. The second-year post-construction would see two surveys performed: the first survey (12 months post construction) would again be to the -15 ft contour and the second survey (18 months post construction) would be a wading survey to -5 ft. Starting in the third-year post-construction, surveys would be conducted once annually out to -15 feet.

To ensure consistency between surveys, permanent benchmarks and/or markers would be installed in appropriate locations along the shoreline for the purpose of future beach measurements. The elevations along the transects would be plotted to determine changes in the fill volume. The cross-sections could also be used to determine performance of the nourishment within the original design template. In addition, RTK-GPS surveys would be performed using a backpack unit along the observed high-water line. These surveys of the high-water line would be performed immediately following construction, and would take place on the same schedule as the cross-shore transects discussed above. Shorelines plotted from this data set would help identify changes in the alongshore position of the erosion "hot spot", as well as the spreading of nourishment in the alongshore direction.

Monitoring reports would be prepared one (1), three (3), five (5), and seven (7) years after completion of the nourishment project. These reports would include a summary of all data collected, information regarding the wave climate and storm activity, volume change over time, and an evaluation of shoreline change. In this manner, the performance of the beach nourishment would be evaluated relative to environmental conditions experienced during the fill design life.

7. Conclusions

This report summarizes the completed work performed by Sustainable Coastal Solutions along the shorelines of the upper North Shore of Massachusetts for the communities of Salisbury, Newburyport, and Newbury. The study began with a review of existing literature, previous sediment studies, historical management, and available observational data, before proceeding with a coastal modeling analysis that examined the effects of waves and coastal infrastructure on longshore sediment transport along the coastlines. The coastal modeling analysis and resulting sediment transport model allowed for the development of an array of alternatives for stakeholders to consider for better management of the shoreline. The subject beaches are impacted by the presence of the Merrimack River inlet jetties and surrounding coastal processes in different ways. Salisbury suffers from net erosion of the shoreline due to the restriction of sediment migration to the north and south by jetties, as well as the southern migration of sediment to the Merrimack River inlet and bypass bar. Dredged sediment of the inlet has historically not been placed back on Salisbury Beach. A substantial nourishment project for Salisbury Beach is recommended to combat the retreating shoreline and low-lying dune elevation.

Plum Island is significantly impacted by the formation of the bypass bar, which serves to shelter much of the shoreline from incident wave energy, as well as refract waves to the north, driving northern sediment transport. Due to the supply of sediment migrating onshore from the bypass bar, and the repair of the southern Merrimack River inlet jetty, the shoreline along Plum Island has accreted significantly in recent years. Erosion hot spots develop due to the shifting of the bypass and shoreline monitoring will be necessary to implement beach nourishment to address shoreline retreat before it becomes detrimental to adjacent coastal infrastructure.

The repair of the southern Merrimack River inlet jetty significantly impacted Reservation Terrace, cutting off the sediment supply from Plum Island and causing a strong gyre-like circulation pattern to form. The majority of the sediment placed along Reservation Terrace in 2023 has washed away, likely due to this gyre-like circulation pattern. A weir jetty is recommended and being explored by USACE. In the meantime, the northern portion of Plum Island could be used a source for Reservation Terrace.

Historical placements of dredged material (primarily offshore or on the bypass bar) has denied 2.4 M cu-yd of sediment to the adjacent beaches of Salisbury, Newburyport, and Newbury since the early 1900s to 2010, or an average of about 40,000 cu-yd/yr. Since 2010, inlet maintenance dredging has been placed in the nearshore of the beaches (2010) or on the beach (2023 placement at Reservation Terrace). Future inlet maintenance dredging can and will be a sediment source to the adjacent beaches, however upland and/or offshore sources will be necessary to supplement the sediment needs of each beach.

Continued monitoring of the project site area will be necessary to inform future management plans of the beach. The broad range of public and private properties along the coastline necessitate a coordination and cooperation between federal, state, town, and private entities to implement any future design alternatives.

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Appendix A. Jetty Repair and Management History

Date of Works	Description
1828-1831	Stone-filled timber crib dike created (Between Plum Island-West, Woodbridge Island and Joppa Flats)
1834-1835	Stone pier created (Badgers Rocks to Salisbury Shore)
Sep-Oct 1870	South gangway rock removed, partial removal of north gangway rock
Sep-Oct 1880	Complete removal of north gangway rock
July 1880-Oct 1880	Removal of a Ledge between North and South Piers at Newbury Port
June-Sep 1881	Removal of South gangway rock
July 1881-Aug 1881	Removal of North Rock Spur
1881-1899	Two rubble-mound Jetties were constructed at the mouth of the Merrimack River. The north and south jetties were 4,118 and 2,445 ft long, respectively, and built up to an elevation of +12 ft MLW with a 15-ft top width.
1900-1902	Minor repairs were made on the north jetty using 640 tons of stone.
1905-1909	The south jetty was repaired in 1905 with 850 tons of stone. During 1906-09 a total of 19,800 tons of stone was used in repairing the north jetty. Repair costs during this period totaled $8,730.
1910	Drainage breach in Plum Island Basin Dike Cleared of Debris
1914	Completion of North Jetty
1917-1918	The north and south jetties were repaired with 7,140 and 1,750 tons of stone, respectively. Total costs were $18,400.
1925	The north jetty was repaired with 1,600 tons of stone at a cost of $4,600.
1933	The jetties were repaired at a cost of $5,400 for placing 1,190 tons of stone.
1936-1938	Repairs were made to the north and south jetties for a total cost of $143,700 using 29,930 and 7,810 tons of stone, respectively.
November, 1939	Removal of timber guide pilings from the Plum Island Basin as Navigation Hazards
1963	An inspection showed both jetties were in poor condition.

Date of Works	Description
1968-1970	Extensive repairs were made to 2,920- and 1,095-ft-long sections of the north and south jetties. The repaired sections would best define the existing lengths of the jetties. Also completed were 700 linear ft of revetment adjacent to, and landward of, the south jetty repairs. The north jetty repairs started from its reconstructed landward end at 1+00 and continued to the existing seaward end at 30+20. The south jetty repairs started from its reconstructed landward end at 0+00, stopped at 6+00, started again at 10+05 and continued to its reconstructed seaward end at 15+00. An undetermined length of south jetty seaward of 15+00 was not repaired. Seaward of 5+50 both Jetties were built up to +12 ft MLW with a 15-ft crown width and slopes of 1V:1H and 1V:2H on channel and sea sides, respectively. The landward sections had 1V:1.5H side slopes, a crown width of 5 ft, and maximum crown elevations of +17 and +15 ft MLW on the north and south jetties, respectively. The stone size varied from a minimum of 0.5 tons at the landward ends to a maximum of 12 tons at the seaward ends. The estimated quantity of stone was 53,600 tons which were to be placed for a total contract cost of $1,267,500. Similarly, the south jetty costs were $221,500 for placing an estimated 13,500 tons of stone and 7,000 cu yd of sand and gravel.
1974	Inspections up to this time indicate the jetties were in good condition overall. Both jetties had isolated areas of settlement, with two areas on the north jetty being severe.
1983-1987	Visual inspection of jetties indicated the jetties were in good condition.
Nov 2012 - April 2013	Repairs to Inshore 600 linear-feet of South Jetty (Phase-I). New armor stones.
2013-2015	South jetty phase 2 repair. Approximately 12,000 tons of 6- to 12-ton armor stone placed. Repairs began on the first 600 feet of the jetty during the winter of 2012-2013.

Appendix B. Potential Offshore Borrow Source – Preliminary Feasibility Study

PRELIMINARY FEASIBILITY SUMMARY

Salisbury Beach & Plum Island Regional Beach Nourishment Project

Potential Offshore Borrow Source - Study Area 1A

1.0 PURPOSE

This memorandum presents a high-level preliminary feasibility assessment of utilizing **Offshore Study Area 1A** as a potential sand source for a regional beach nourishment along Salisbury Beach and Plum Island shorelines in the communities of Salisbury, Newburyport and Newbury, Massachusetts.

The purpose of this assessment is to determine whether the borrow source appears capable of supporting long-term future nourishment and to identify potential construction approaches, rough order-of-magnitude (ROM) costs, and implementation considerations. This memorandum is intended solely for conceptual planning and screening purposes. The findings presented herein are based on available resource characterization information, generalized industry production assumptions, and recent regional beach nourishment experience.

This assessment does not constitute final engineering design, sediment compatibility analysis, contractor pricing, or permit feasibility determination. Additional field investigations, environmental studies, engineering design, and regulatory review are required prior to project implementation.

2.0 PRELIMINARY BORROW SOURCE EVALUATION

Offshore Study Area 1A (see **Figure 1**) has been identified as a potentially significant marine sand (borrow site) resource with an estimated available volume of ±47.6 million cubic yards (CY) and consisting of the following:

- Predominantly coarse, clean marine sand with a mean grain size approximately 0.66 mm and low fine-grained fraction of approximately 1.3%;
- On average, the borrow site is located ±2.5 to 3 miles from Salisbury Beach and Plum Island shorelines, respectively.
- Recoverable sand deposits occur within an average water depth of ±90 feet; and
- Typical deposit thickness varies from ±5 to 8 feet.

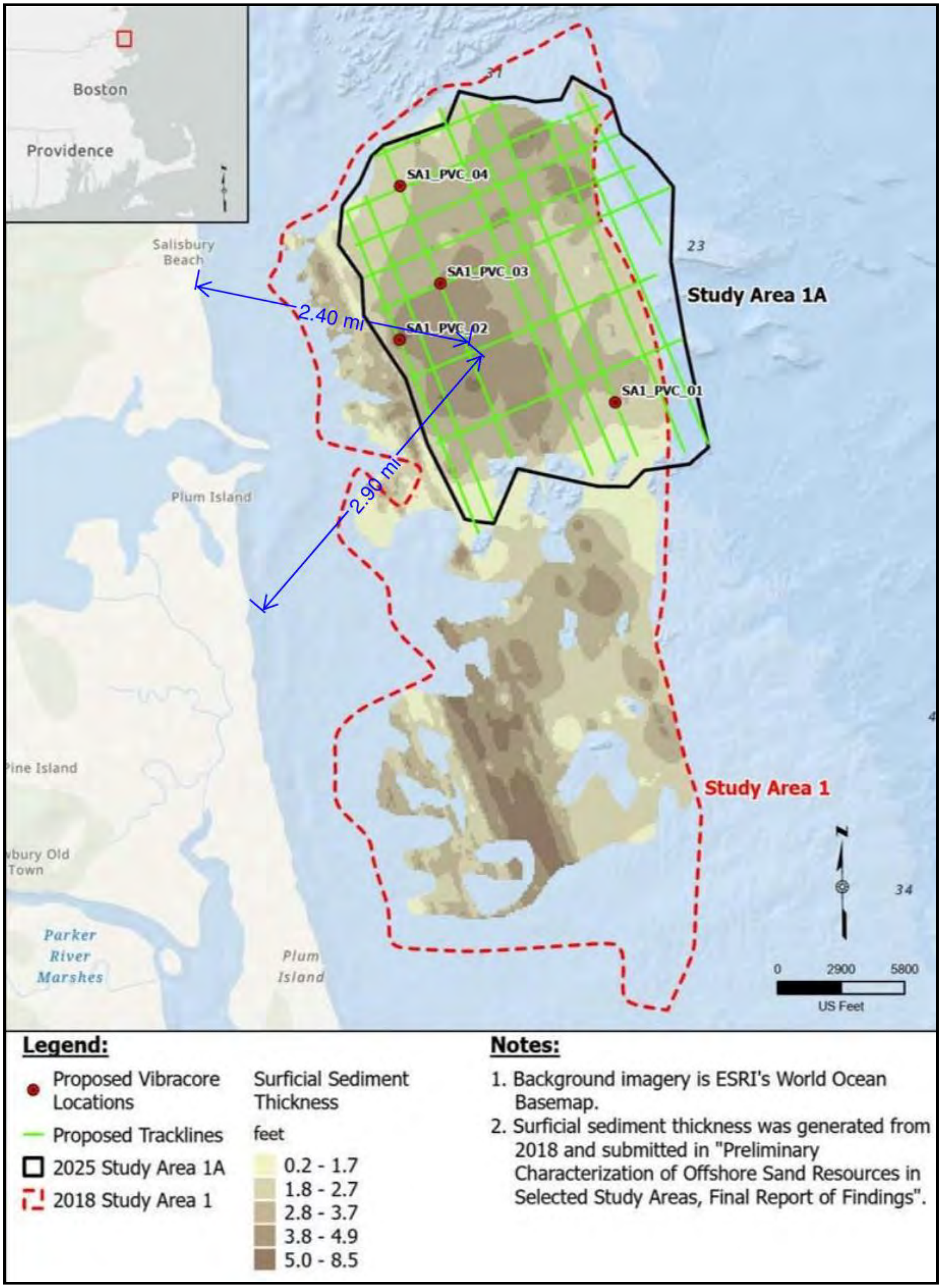

Figure 1 – Offshore borrow site (Study Area 1A) average proximity to nourishment sites located at Salisbury Beach and Plum Island.

3.0 ECONOMY OF NOURISHMENT VOLUME

While the economic break-even point varies depending on borrow site distance, dredge type, sediment characteristics, mobilization costs, and placement method, offshore borrow sources located several miles from shore generally become increasingly cost-effective for nourishment projects consisting of approximately ±400,000 CY or greater[1]. Offshore dredging projects involve substantial fixed costs that are largely independent of the volume of material placed, including dredge mobilization and demobilization, environmental compliance, hydrographic surveying, engineering support, offshore operations, temporary pipeline installation, beach discharge infrastructure, and project management. As a result, smaller nourishment projects often experience disproportionately high unit costs because these expenses are spread over a relatively limited volume of material.

Accordingly, a nourishment volume of approximately ±500,000 CY represents an appropriate minimum project scale for evaluating the feasibility of utilizing the offshore borrow source, as the larger volume allows these fixed costs to be distributed more efficiently, improving overall project economics. At this volume, the project begins to achieve meaningful economies of scale by distributing fixed project costs across a larger quantity of material. In addition, a project of this size is generally considered the practical lower limit for attracting competitive contractor interest, as smaller projects may not justify the mobilization of specialized offshore dredging equipment.

Although ±500,000 CY represents a reasonable minimum planning volume, projects in the range of ±750,000 to ±1,000,000 CY would likely provide greater economic efficiency. At these larger volumes, unit costs are typically reduced further through improved utilization of dredging equipment and more efficient distribution of fixed project costs. A project of this size could also generally be completed within an estimated ±2.5-month construction period, reducing contractor exposure to weather-related delays and operational risks associated with harsh winter conditions while still remaining within a single construction season and anticipated environmental work windows.

The lower and upper per-project nourishment volumes considered above only represent about 1% to 2% of the total ±47.6 million CY of sand estimated to be available within Study Area 1A. Accordingly, this suggests that the borrow area could serve as a long-term, sustainable sediment source capable of supporting multiple future beach nourishment projects over several decades.

From a coastal resiliency perspective, nourishment volumes ranging from ±500,000 CY up to ±1,000,000 CY are large enough to provide measurable shoreline benefits across both Salisbury Beach and Plum Island. Depending upon final design objectives, this quantity of material could support a combination of beach widening, dune enhancement, and storm damage reduction while maintaining a practical construction duration.

For these reasons, a project nourishment volume of ±500,000 CY represents a reasonable minimum planning-level threshold for evaluating utilization of the potential offshore borrow source, while noting that volumes in the range of ±750,000 to ±1,000,000 CY may offer the greatest

[1]Dean, R.G., and Houston, J.R. (2018). *Building Blocks for a Sustainable Beach Nourishment Program*, Shore & Beach, Vol. 86, No. 1. The authors note that the high mobilization costs associated with offshore dredging can make offshore borrow sources uneconomical for smaller projects and indicate that projects involving less than approximately 300,000 cubic meters (~400,000 CY) may be more cost-effectively supplied from upland sources.

balance of economic efficiency, construction feasibility, contractor interest, and resiliency benefits.

4.0 PRELIMINARY CONSTRUCTION APPROACH

Due to the offshore location of the borrow source and the average anticipated ±2.5 to 3-mile transport distance to the placement areas along Salisbury Beach and Plum Island along with the anticipated project performance required during the fall\winter season which is typically characterized by increased storm activity and more challenging sea conditions in New England, a direct hydraulic pipeline dredging operation is not envisioned to be the most practical construction method. Rather, the preferred construction methodology would require the use of a **Trailing Suction Hopper Dredge (TSHD)**. A TSHD is a self-propelled vessel commonly used for large-scale beach nourishment projects because it can efficiently dredge and transport substantial volumes of sediment from offshore borrow areas. During operation, the vessel slowly traverses the borrow area while trailing suction pipes (drag arms) equipped with dragheads are lowered to the seabed. Hydraulic suction generated by the vessel's dredge pumps entrains sediment and water through the dragheads, creating a slurry that is conveyed through the drag arms and discharged into the vessel's hopper for temporary storage and transport. As the material enters the hopper, the heavier sand settles while excess water is discharged to maximize sediment storage capacity within the vessel. Once the hopper is filled, the vessel transports the material to the nourishment site, where the sediment is then fluidized and hydraulically pumped ashore through a temporary submerged pipeline system for direct placement onto the shoreline.

The following two general TSHD dredge classes have been considered and evaluated as part of this assessment:

❖ LARGE HOPPER DREDGE

Approximate Capacity: ±4,000 to 15,000 CY

Advantages:

- ✓ Higher production rates
- ✓ Greater operational efficiency
- ✓ Better tolerance to offshore weather conditions
- ✓ Reduced overall construction duration
- ✓ Lower unit dredging costs

Disadvantages:

- ✓ Higher mobilization costs
- ✓ Potentially greater competition for vessel availability

The typical production rates of a large TSHD range from approximately ±25,000 to 35,000 CY per day depending on contractor equipment, weather conditions, pumping configuration, and sediment characteristics.

❖ SMALL TO MEDIUM HOPPER DREDGE

Approximate Capacity: ±1,500 to 4,000 CY

Advantages:

- ✓ Lower mobilization costs
- ✓ Increased flexibility for smaller projects
- ✓ Potentially improved contractor availability

Disadvantages:

- ✓ Lower production rates
- ✓ Greater weather sensitivity
- ✓ Longer construction duration
- ✓ Limited dredge depth capability
- ✓ Reduced suitability for coarse-grained sediments

The typical production rates of a small to medium TSHD range from approximately ±7,000 to 12,000 CY per day. While these vessels may be suitable for smaller nearshore nourishment projects, a hopper dredge of this size class may not possess sufficient dredging depth capability to efficiently access borrow areas at depths approaching 90 feet. In addition, the relatively coarse grain size of the identified borrow material could present operational challenges and reduce dredging efficiency. Due to their smaller size and lower seakeeping capability, weather-related downtime would also be expected to be significantly greater than for larger hopper dredges, particularly during periods of elevated offshore wave and sea conditions.

Based on the anticipated borrow area depth, transport distance, sediment characteristics, and offshore operating conditions, a large TSHD is considered the most appropriate dredge class for development of the identified offshore borrow source. Large TSHDs possess the dredging depth capability, hopper capacity, production rates, and seakeeping characteristics necessary to efficiently recover and transport the required nourishment volumes while minimizing weather-related downtime. Their higher production rates allow for a nourishment project ranging from a minimum of ±500,000 CY up to ±1,000,000 CY to be completed within a single construction season while accommodating the anticipated environmental time-of-year restrictions discussed in Section 5.0.

5.0 ENVIRONMENTAL AND PERMITTING CONSIDERATIONS

Implementation of a beach nourishment project will require compliance with numerous federal, state, and local permitting requirements. Although project-specific environmental windows will ultimately be established through permitting, coastal nourishment projects in Massachusetts are typically performed during the fall and winter months to avoid conflicts with environmental resource constraints and peak recreational use. For planning purposes and to assess the feasibility of utilizing an offsite borrow source for nourishment along Salisbury Beach and Plum Island, a construction window extending from approximately September through February has been assumed.

6.0 PRELIMINARY COST ASSESSMENT

The following costs presented in **Table 1** represent rough order-of-magnitude (ROM) planning-level estimate only and are intended solely to support preliminary feasibility evaluation based upon the dredging and placement of ±500,000 CY. Actual project costs may vary substantially depending upon final borrow area characteristics, contractor availability, market conditions, fuel prices, environmental requirements, permitting conditions, and project procurement methods.

Table 1. Preliminary Planning-Level Rough Order-of-Magnitude (ROM) Cost Estimate for Dredging ±500,000 CY from Offshore Borrow Study Area 1A & Placement of Sediment Along Salisbury Beach or Plum Island Using a Large TSHD (2026 Dollars)

Cost Item	Large TSHD (Capacity ±4,000–15,000 CY)
Mobilization & Demobilization	$5.0M – $7.0M
Offshore Dredging & Transport	$8.0M – $9.5M
Beach Placement & Pipeline Operations	$2.0M – $3.0M
Environmental Monitoring & Compliance	$0.5M – $1.5M
Engineering, Permitting & Administration	$1.0M – $3.0M
Contingency (20–30%)	$3.0M – $5.0M
Estimated Total Program Cost	**$19.5M – $29.0M**
Estimated Unit Cost	**$39 – $58/CY**

❖ While the cost estimates presented above are based on a ±500,000 CY nourishment volume, project scale is an important driver of unit cost and contractor interest. A larger project in the range of ±750,000 to ±1,000,000 CY would generally be more attractive to contractors and likely achieve improved economies of scale, potentially resulting in lower unit costs. By comparison, a ±500,000 CY project remains fully feasible and constructible; however, it would be expected to result in slightly higher per cubic yard costs due to reduced spreading of fixed mobilization and operational costs, as well as increased exposure to weather-related downtime risk during the winter operating season when offshore conditions are more variable.

7.0 POTENTIAL CONTRACTOR AVAILABILITY

Several U.S.-based dredging contractors possess equipment and experience potentially suitable for a project of this type and are listed in **Table 2**.

✓ **Table 2. List of Potential U.S.-based Contractors with Large TSHD Capabilities**

Contractor	Headquarters Address
Great Lakes Dredge & Dock Company	9811 Katy Freeway, Suite 1200 Houston, TX 77024
Weeks Marine, Inc.	4 Commerce Drive Cranford, NJ 07016
Manson Construction Company	5200 Denver Avenue South Seattle, WA 98108
The Dutra Group	2350 Kerner Boulevard, Suite 250 San Rafael, CA 94901

Final contractor participation would depend upon project timing, procurement strategy, equipment availability, and market conditions at the time of bidding.

8.0 PRELIMINARY FEASIBILITY CONCLUSIONS

Based upon this high-level screening assessment, utilization of Offshore Study Area 1A as a borrow source for nourishing Salisbury Beach and Plum Island appears technically feasible and warrants further evaluation. Using information available to date, this assessment suggests the following:

- A substantial offshore sand resource may be available for achieving long-term shoreline protection;
- Targeting a minimum nourishment volume of approximately ±500,000 CY per project appears appropriately scaled to justify offshore dredging operations while achieving economies of scale associated with marine construction. However, targeting a project volume in the range of ±750,000 to ±1,000,000 CY would likely promote a more competitive bidding environment, improve overall project economics, and provide enhanced beach fill performance and longevity;
- Based on the anticipated production rates of a large TSHD, all evaluated nourishment volumes (±500,000 to ±1,000,000 CY) are expected to be completed within a single dredging season and within typical local, state, and federal regulatory time of year work windows;
- Proposed nourishment volumes ranging from ±500,000 CY up to ±1,000,000 CY per project represent only about 1% to 2% of the estimated ±47.6 million CY of available sand within the borrow area, indicating that the site could serve as a sustainable long-term sediment source for multiple future nourishment projects; and
- Established and widely utilized dredging technologies, such as Trailing Suction Hopper Dredges (TSHDs), are readily available and capable of implementing the proposed nourishment project. Based on currently available information, a large TSHD is preliminarily considered the preferred construction alternative due to improved production efficiency, greater weather tolerance, and reduced schedule risk.

Appendix C. Sea Level Rise Analysis

The stretch of coastline along the communities of Salisbury, Newburyport, and Newbury are vulnerable from storm wave conditions associated with the open Atlantic Ocean. In addition, the low-lying nature or minimal presence of the dunes along Salisbury Beach, Reservation Terrace, and some sections of the Plum Island shoreline make these areas susceptible to coastal flooding.

Several factors including coastal urbanization, aging infrastructure, alterations to the natural environment, and sea level rise have all contributed to the increase in flood exposure and are anticipated to continue as mechanisms promoting the acceleration of future flood vulnerability (Sundermann et al., 2014). Indeed, it has been concluded that sea levels are rising; however, the pace and extent to which they may rise over the next 60 to 80 years are the topic of much scientific debate. Historical evidence indicates that over the past 100 years the relative sea level in Boston, Massachusetts has been rising generally in a linear fashion, with an average rate of approximately 0.114 inches per year or 0.95 feet per century (Figure 1). Tide data and sea level rise projections for Boston are appropriate approximations for the Upper North Shore of Massachusetts.

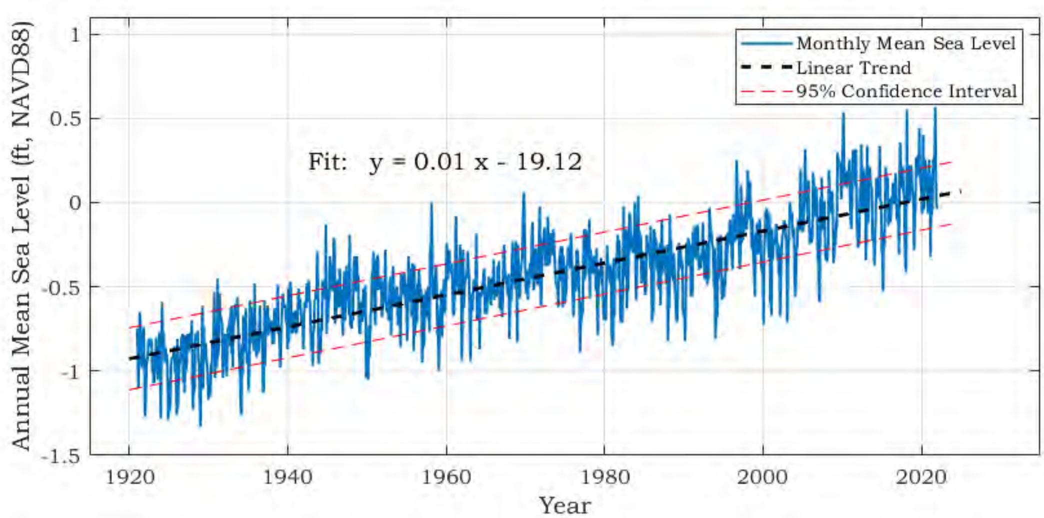

Figure 1. Monthly mean water levels recorded in Boston Harbor between 1921 and 2021 indicate a linear trend in sea level rise over the past 100 years of approximately 0.01 feet per year (*Source: NOAA*)

While long-term tide records (e.g., Boston Harbor) provide valuable insight into historical changes over the past century, they do not necessarily dictate future response of sea level rise due to changing environmental and anthropogenic conditions. Predictive models have been developed to project the effects of climate change on relative sea level rise in coming decades. New and existing models used to predict sea level rise are continually refined with augmented data sets to reduce output uncertainty; however, there still exists a large range of potential sea level rise scenarios. The recent sea level rise projections from NOAA (Sweet, et al., 2022) were determined to be the most accurate for this study.

Figure 2 provides the updated NOAA projections, where the ‘intermediate’ projection represents conditions that are about as likely as not to occur or, in other words, a 50% chance of occurrence. It should be noted that the NOAA utilization of the term ‘intermediate’ follows standard statistical terminology, where the intermediate result represents the middle curve between the two extremes (high and low) or the 50% chance of occurrence.

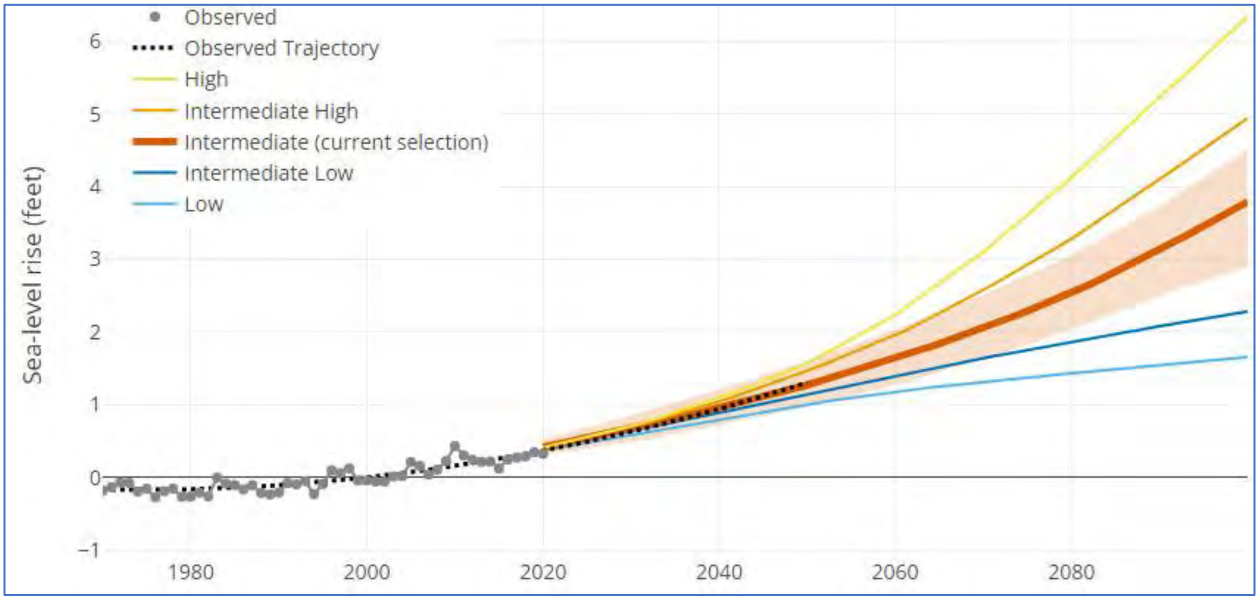

Figure 2. Projected sea level rise for Boston Harbor, Massachusetts based upon modeling analyses performed by NOAA (Sweet, et. al., 2022). Results for a full range of scenarios can be found at: https://sealevel.nasa.gov/flooding-analysis-tool/projected-flooding

As illustrated in Figure 2, the ‘intermediate’ NOAA sea level rise projection generally matches the ‘observed trajectory’ projection to 2050, which was based upon extrapolating the observed sea level rise trends between 1970 and 2020. Further, Figure 6 demonstrates the applicability of utilizing more moderate sea level rise projections, as the observed sea level rise in Boston between 2000 and 2020 (shown in gray) is below all of the projections evaluated by Sweet, et. al. (2022). Based on the NOAA tide data, the Boston sea level rose 0.33 feet between 2000 and 2020; therefore, in 2020, the mean sea level was 0.03 feet NAVD88 since the mean sea level in 2000 was -0.30 feet NAVD88.

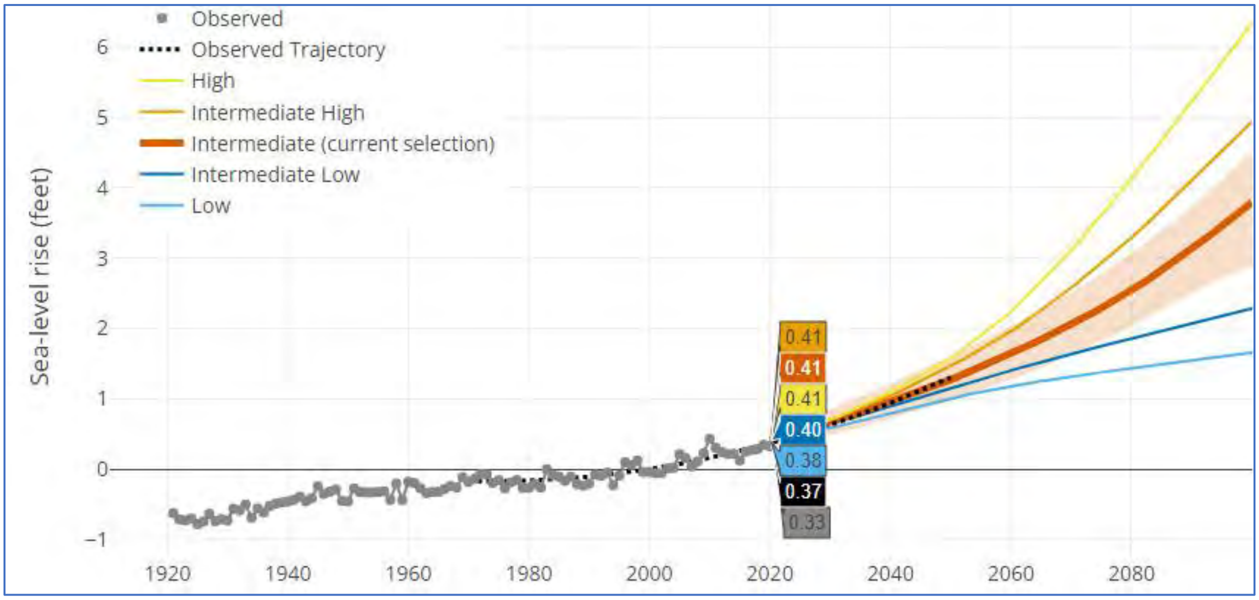

Figure 3. Projected sea level rise for Boston Harbor, Massachusetts based upon modeling analyses performed by NOAA (Sweet, et. al., 2022). The colored numbers represent the modeling results for the various scenarios for 2020, as well as the observed mean sea level. Results for a full range of scenarios can be found at: https://sealevel.nasa.gov/flooding-analysis-tool/projected-flooding

For Boston, the NOAA projections for 2050 are shown in Figure 4. According to Sweet, et al. (2022):

> *As a result of improved science and the updated framework and procedure for generating the Global Mean Sea Level (GMSL) scenarios, the time path of the scenarios - particularly the higher scenarios - is now more realistic and consistent with current process-based understanding. In this report, the range between the Low and High scenarios in 2020, 2030, 2040, and 2050 is now 0.02 m [0.07 feet], 0.06 m [0.20 feet], 0.15 m [0.49 feet], and 0.28 m [0.92 feet], respectively. In other words, there is less divergence between the GMSL scenarios in this near-term time period, which reduces uncertainty in the projected amount of GMSL rise up to the year 2050. The Low scenario remains largely the same between this report and Sweet et al. (2017); this range reduction reflects a downward shift in the higher scenarios in 2050 and times prior, as discussed above. As an example, the projected value in 2050 for the High scenario in this report (~0.4 m [1.31 feet]) is the same as that for the Intermediate-High projected value in 2050 in Sweet et al. (2017).*

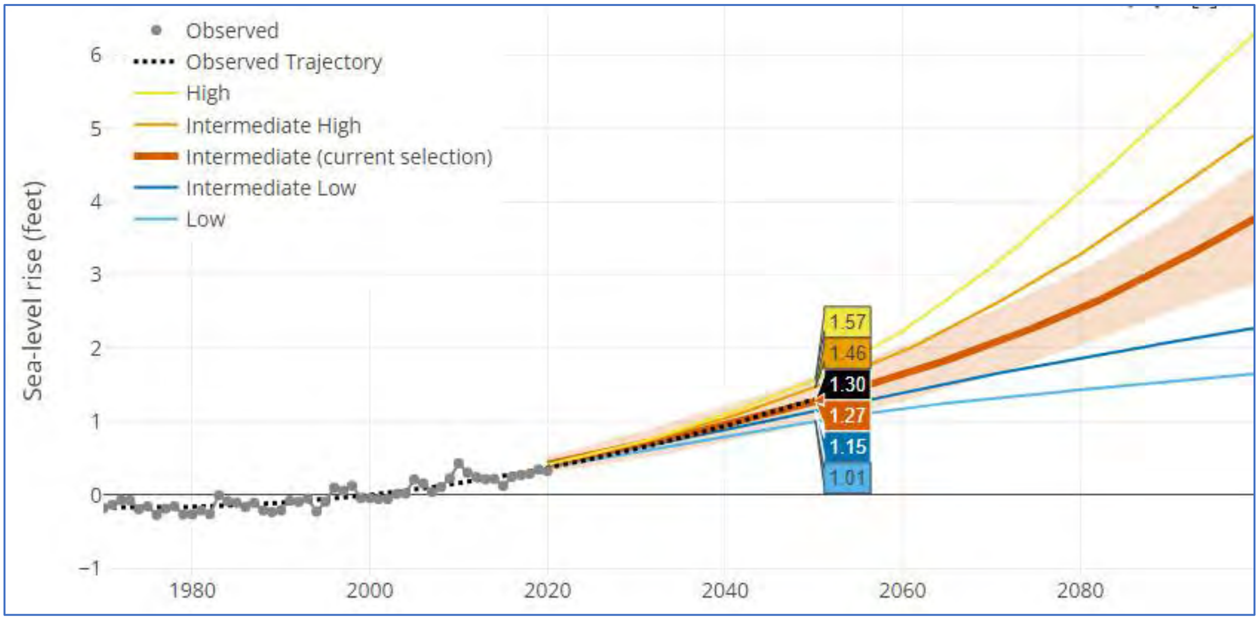

Figure 4. Projected sea level rise for Boston Harbor, Massachusetts based upon modeling analyses performed by NOAA (Sweet, et. al., 2022). The colored numbers represent the modeling results for the various scenarios for 2050. Results for a full range of scenarios can be found at: https://sealevel.nasa.gov/flooding-analysis-tool/projected-flooding?

Based on the NOAA (Sweet, et. al., 2022) predictions, a reasonable expectation for near-term (through 2050) sea level rise in the Boston region, inclusive of the project area, is within the range of sea level rise projections illustrated in Figure 4. In this case, the 2050 mean sea level can be expected to be approximately 1.3 feet above the 2000 level or approximately 1.0±0.3 feet NAVD88. In general, for the planning of existing infrastructure for future sea level conditions, the intermediate scenario is the appropriate choice as it plans for conditions that are 50% likely to occur (instead of extremely unlikely to occur, like the high trajectory indicates). Table 1 provides expected future sea level rise for 2030, 2050, and 2070, based upon NOAA estimates (Sweet, et al., 2022).

Table 1. Relative mean sea level (feet, NAVD88) projections for Boston, MA as presented in Sweet, et al., 2022

Scenario	Probabilistic projections	2030	2050	2070
NOAA - Intermediate	Conditions that are about as likely as not to occur or, in other words, a 50% chance of occurrence (RCP 8.5)	0.4	1.0	1.8

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Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf

Appendix D. Sediment Grain Size Testing Results

Briggs Engineering & Testing
A Division of PK Associates, Inc.

Sustainable Coastal Solutions, Inc
Sean Kelley
107A County Road
North Falmouth, MA 02556

Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/23/26
Received: 1/15/26

1.	Sample No.	Description	Source of Material
	M-36324	Sand	Salisbury Beach- 01

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	98	
1.190 mm	#16	90	
0.600 mm	#30	57	
0.425 mm	#40	48	
0.300 mm	#50	31	
0.180 mm	#80	4	
0.150 mm	#100	1	
0.075 mm	#200	0.9	

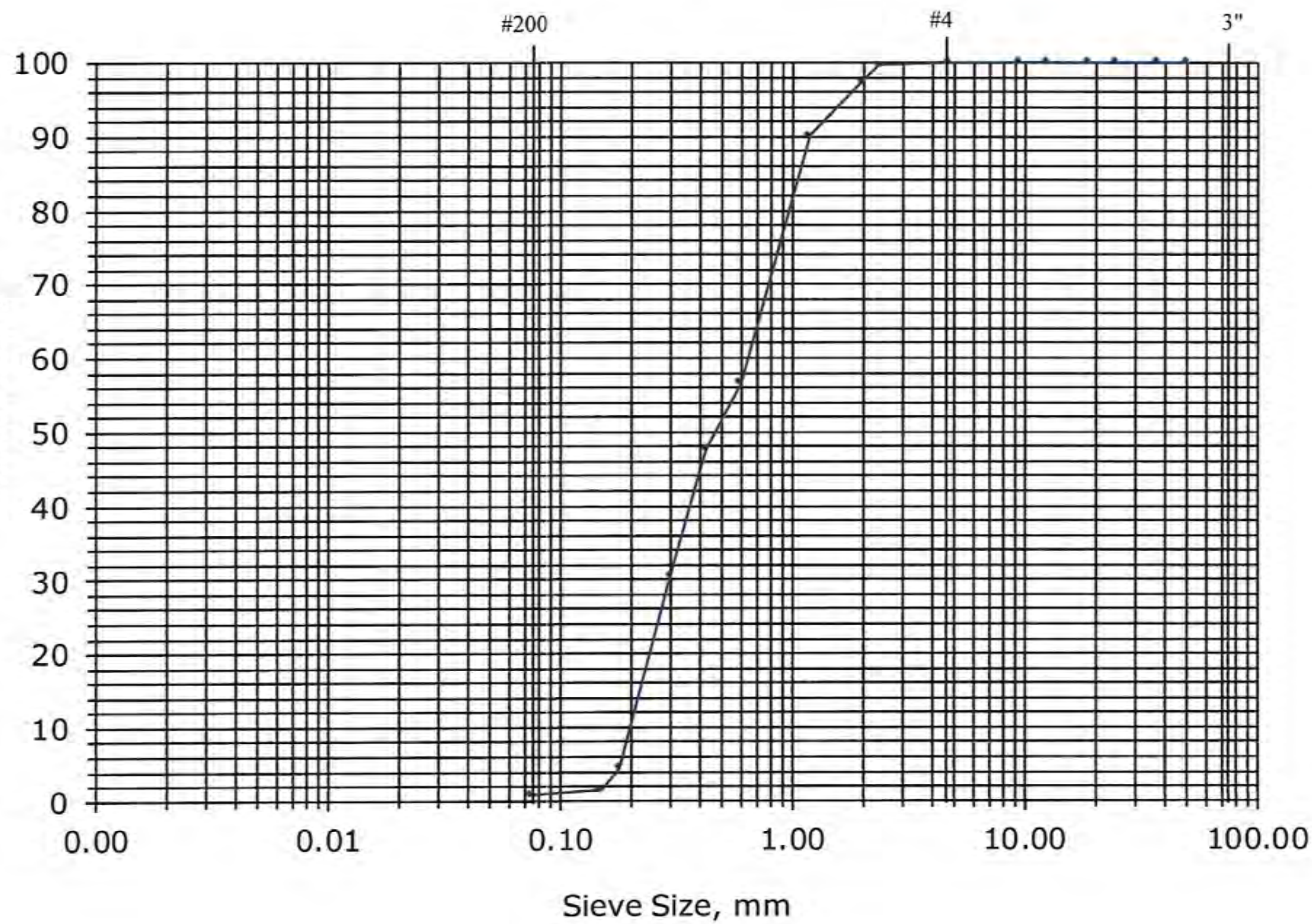
BRIGGS ENGINEERING & TESTING
A Division of PK Associates, Inc.

Sean Skorohod
Director of Testing Services
Construction Technology Division

Briggs Engineering & Testing
A Division of PK Associates, Inc.

Project:	Sustainable Coastal Solutions
Date Tested:	1/23/26
Lab Ref. No.:	M-36324

Sieve Analysis



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A Division of PK Associates, Inc.

Sustainable Coastal Solutions, Inc
Sean Kelley
107A County Road
North Falmouth, MA 02556

Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/23/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36325	Sand	Salisbury Beach- 02

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	99	
2.00 mm	#10	98	
1.190 mm	#16	89	
0.600 mm	#30	51	
0.425 mm	#40	30	
0.300 mm	#50	12	
0.180 mm	#80	1	
0.150 mm	#100	1	
0.075 mm	#200	0.4	

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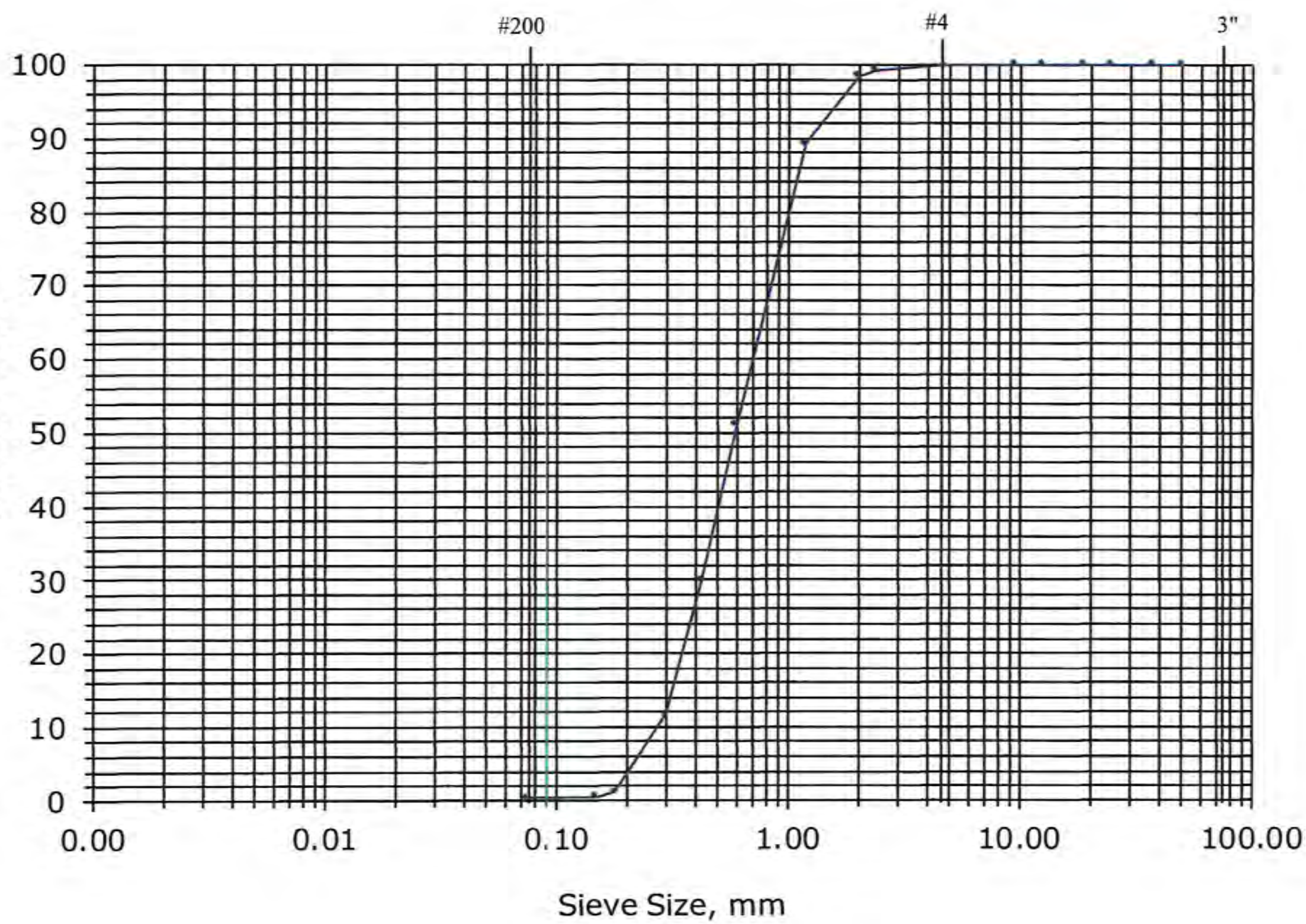
Project:	Sustainable Coastal Solutions
Date Tested:	1/23/26
Lab Ref. No.:	M-36325

Sieve Analysis



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Sustainable Coastal Solutions, Inc
Sean Kelley
107A County Road
North Falmouth, MA 02556

Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/23/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36326	Sand	Salisbury Beach- 03

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	99	
2.36 mm	#8	97	
2.00 mm	#10	94	
1.190 mm	#16	75	
0.600 mm	#30	40	
0.425 mm	#40	36	
0.300 mm	#50	26	
0.180 mm	#80	4	
0.150 mm	#100	2	
0.075 mm	#200	1.2	

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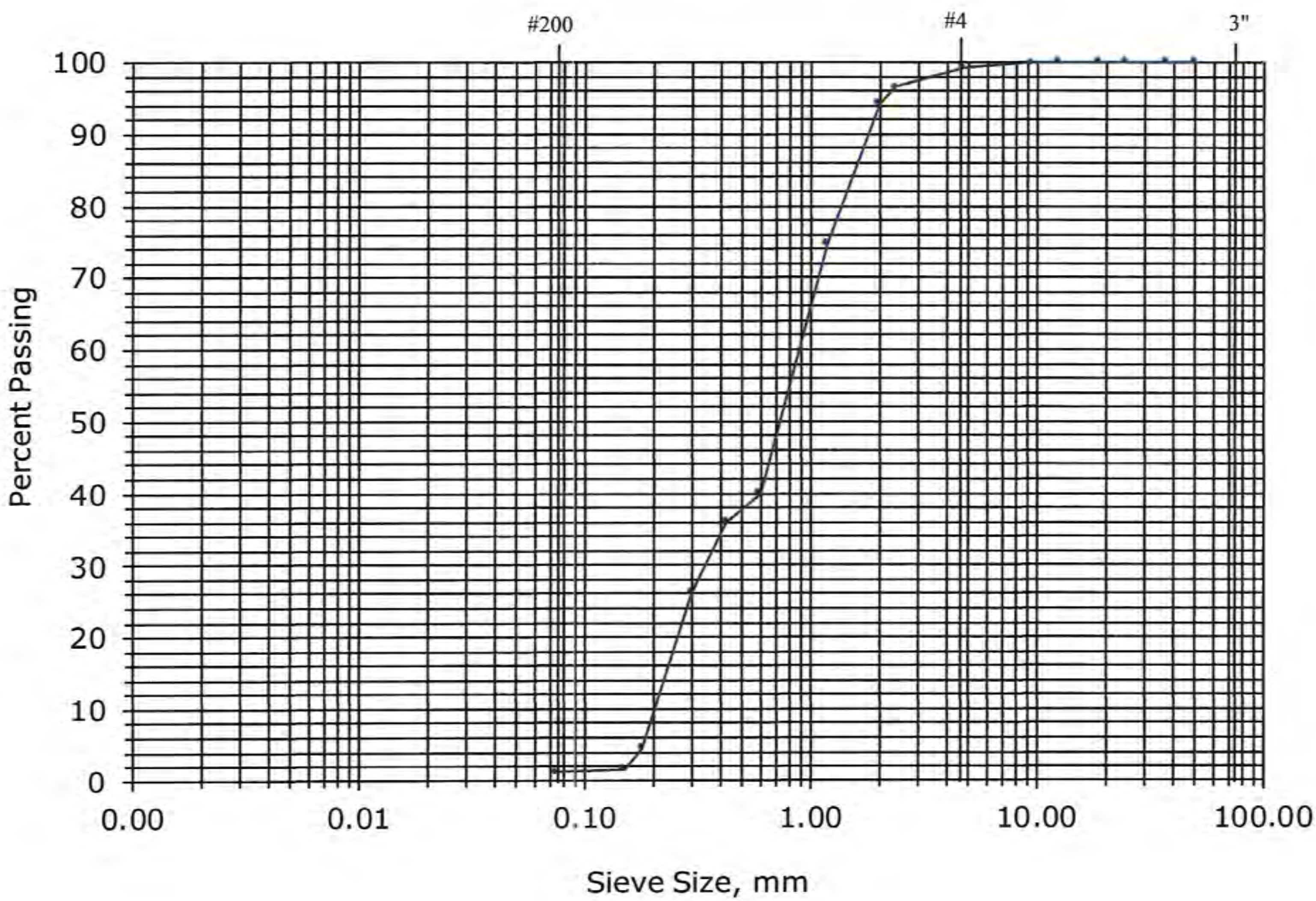
Project:	Sustainable Coastal Solutions
Date Tested:	1/23/26
Lab Ref. No.:	M-36326

Sieve Analysis



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North Falmouth, MA 02556

Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/23/26
Received: 1/15/26

1.

Sample No.	Description	Source of Material
M-36327	Sand	Salisbury Beach- 04

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	99	
0.600 mm	#30	65	
0.425 mm	#40	49	
0.300 mm	#50	24	
0.180 mm	#80	2	
0.150 mm	#100	1	
0.075 mm	#200	0.3	

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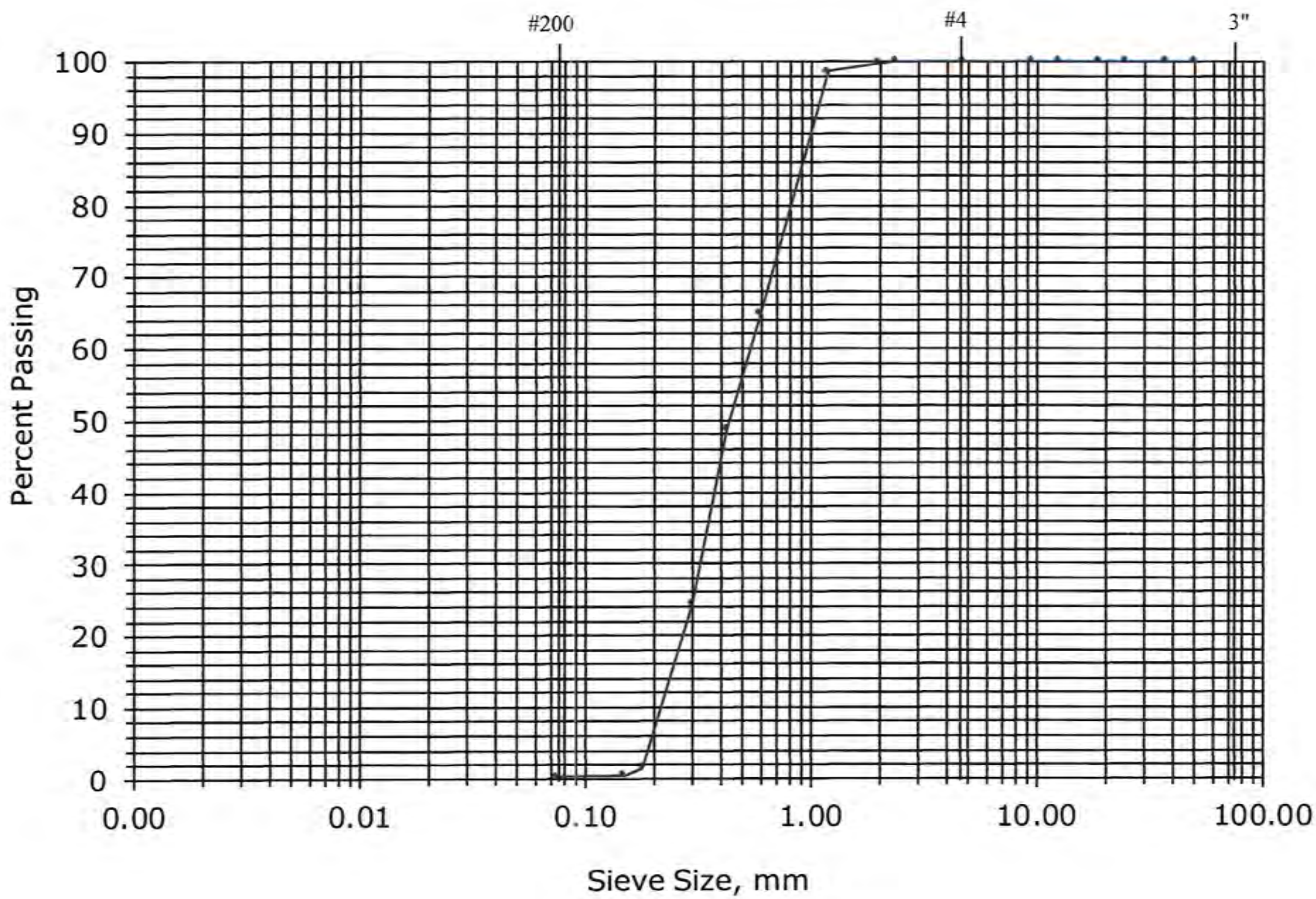
Project:	Sustainable Coastal Solutions
Date Tested:	1/23/26
Lab Ref. No.:	M-36327

Sieve Analysis



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Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/23/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36328	Sand	Salisbury Beach- 05

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	99	
4.75 mm	#4	97	
2.36 mm	#8	91	
2.00 mm	#10	88	
1.190 mm	#16	72	
0.600 mm	#30	42	
0.425 mm	#40	31	
0.300 mm	#50	14	
0.180 mm	#80	2	
0.150 mm	#100	1	
0.075 mm	#200	0.7	

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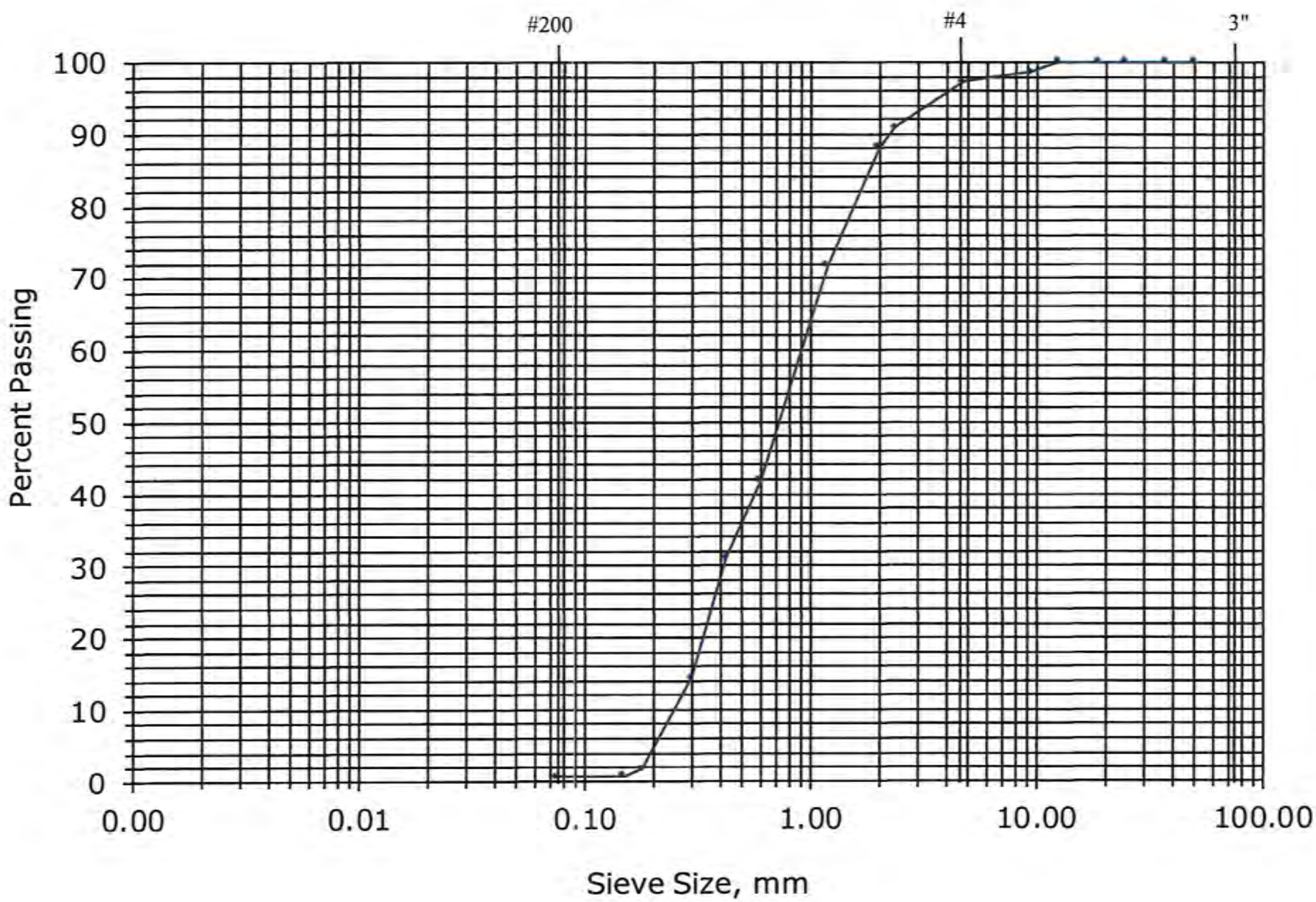
Project:	Sustainable Coastal Solutions
Date Tested:	1/23/26
Lab Ref. No.:	M-36328

Sieve Analysis



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Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/23/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36329	Sand	Salisbury Beach- 06

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	92	
0.600 mm	#30	65	
0.425 mm	#40	48	
0.300 mm	#50	22	
0.180 mm	#80	2	
0.150 mm	#100	1	
0.075 mm	#200	0.7	

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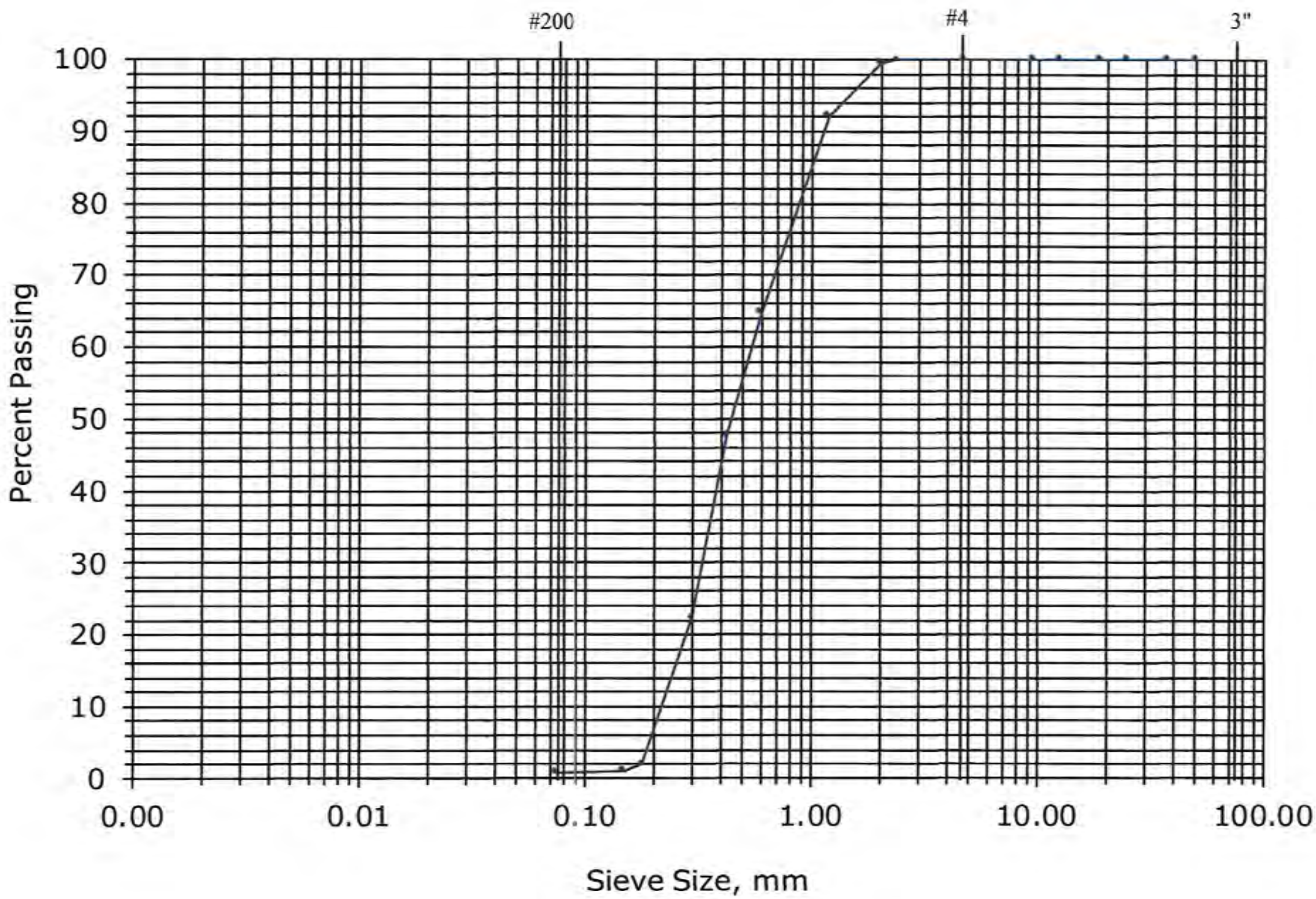
Project:	Sustainable Coastal Solutions
Date Tested:	1/23/26
Lab Ref. No.:	M-36329

Sieve Analysis



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Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/23/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36330	Sand	Salisbury Beach- 07

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	99	
1.190 mm	#16	95	
0.600 mm	#30	75	
0.425 mm	#40	62	
0.300 mm	#50	38	
0.180 mm	#80	5	
0.150 mm	#100	2	
0.075 mm	#200	1.0	

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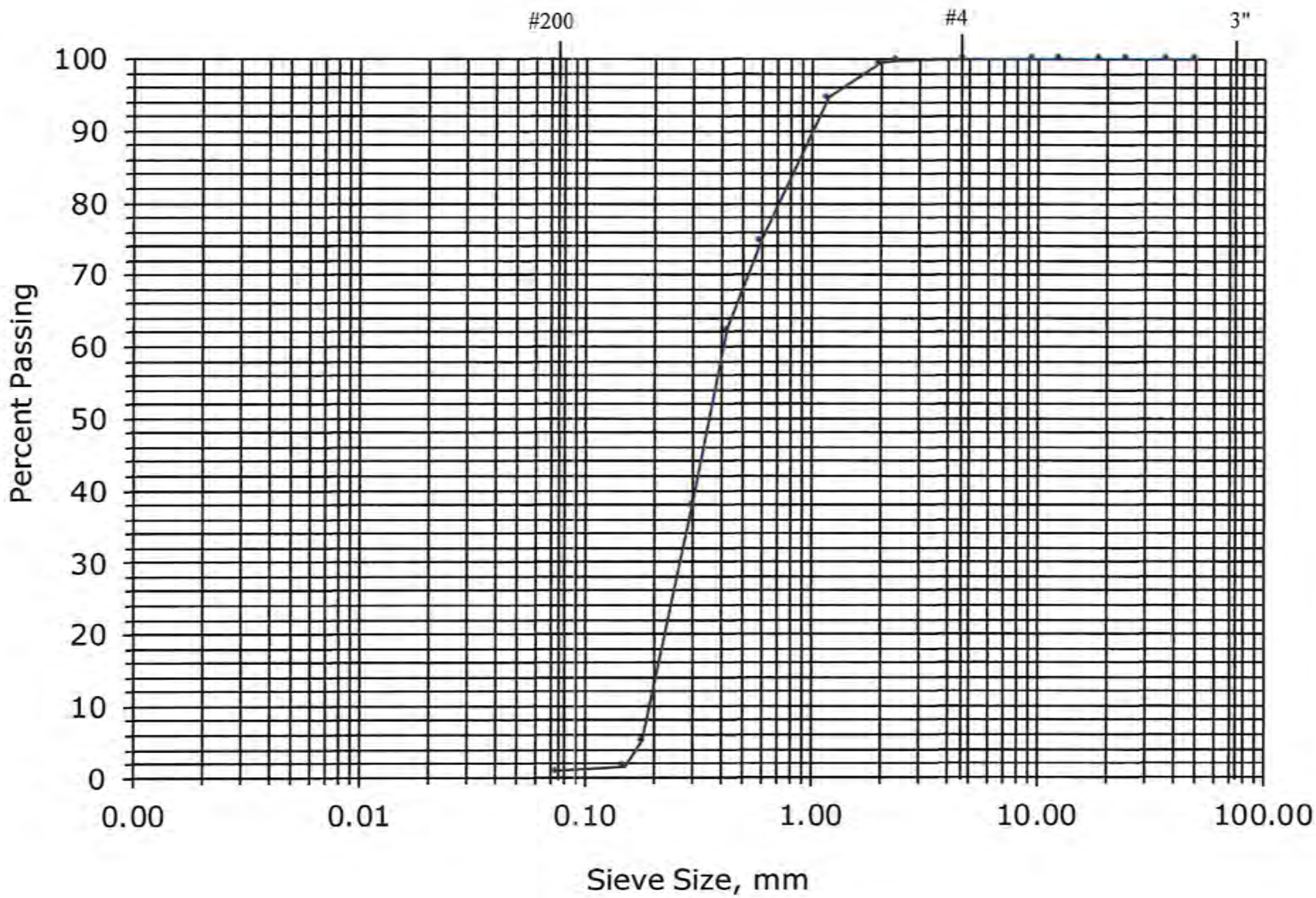
Project:	Sustainable Coastal Solutions
Date Tested:	1/23/26
Lab Ref. No.:	M-36330

Sieve Analysis



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Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/28/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36331	Sand	Salisbury Beach- 08

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	94	
0.600 mm	#30	47	
0.425 mm	#40	26	
0.300 mm	#50	9	
0.180 mm	#80	1	
0.150 mm	#100	1	
0.075 mm	#200	0.1	

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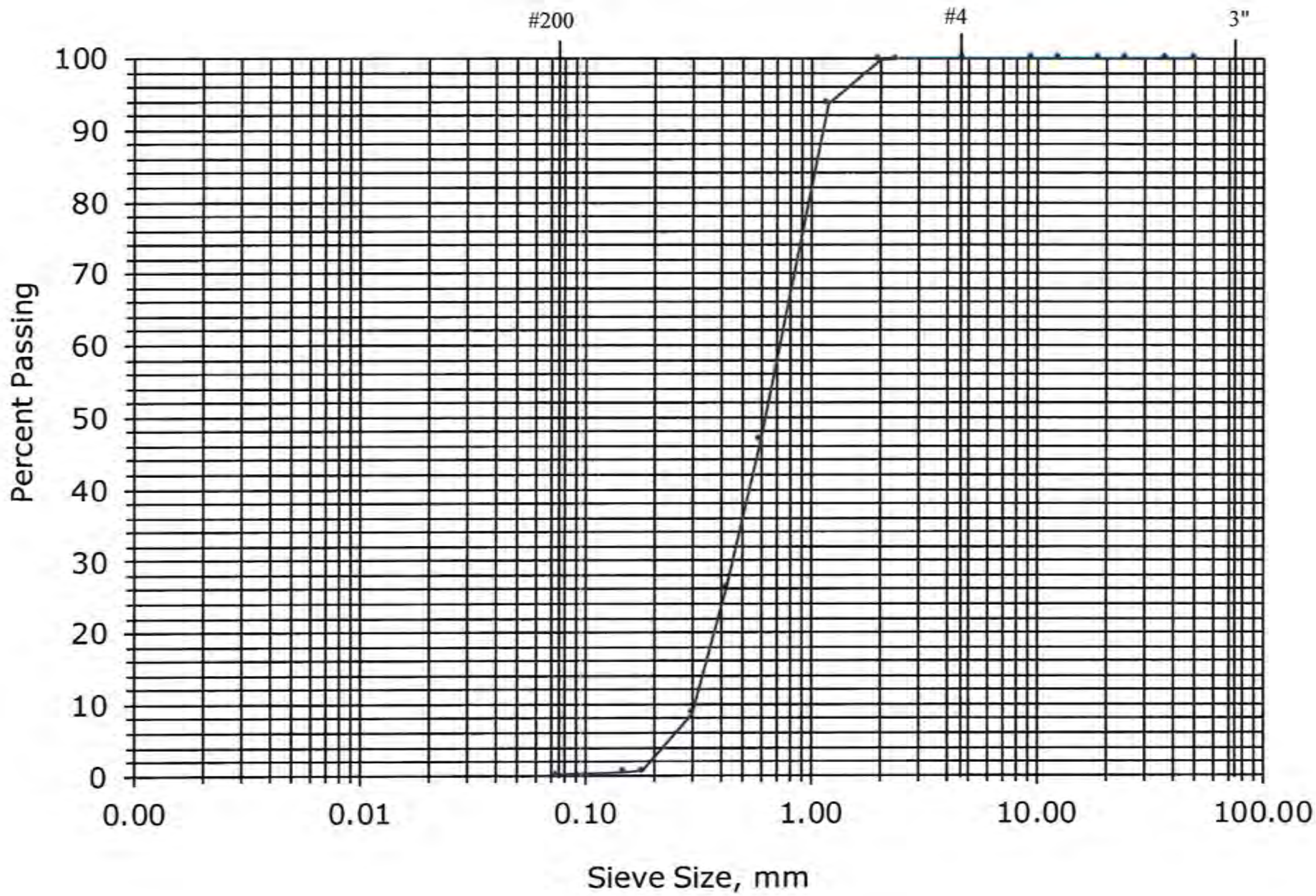
Project:	Sustainable Coastal Solutions
Date Tested:	1/28/26
Lab Ref. No.:	M-36331

Sieve Analysis



Sustainable Coastal Solutions, Inc
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North Falmouth, MA 02556

Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/28/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36332	Sand	Salisbury Beach- 09

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	97	
0.600 mm	#30	88	
0.425 mm	#40	60	
0.300 mm	#50	41	
0.180 mm	#80	6	
0.150 mm	#100	2	
0.075 mm	#200	1.0	

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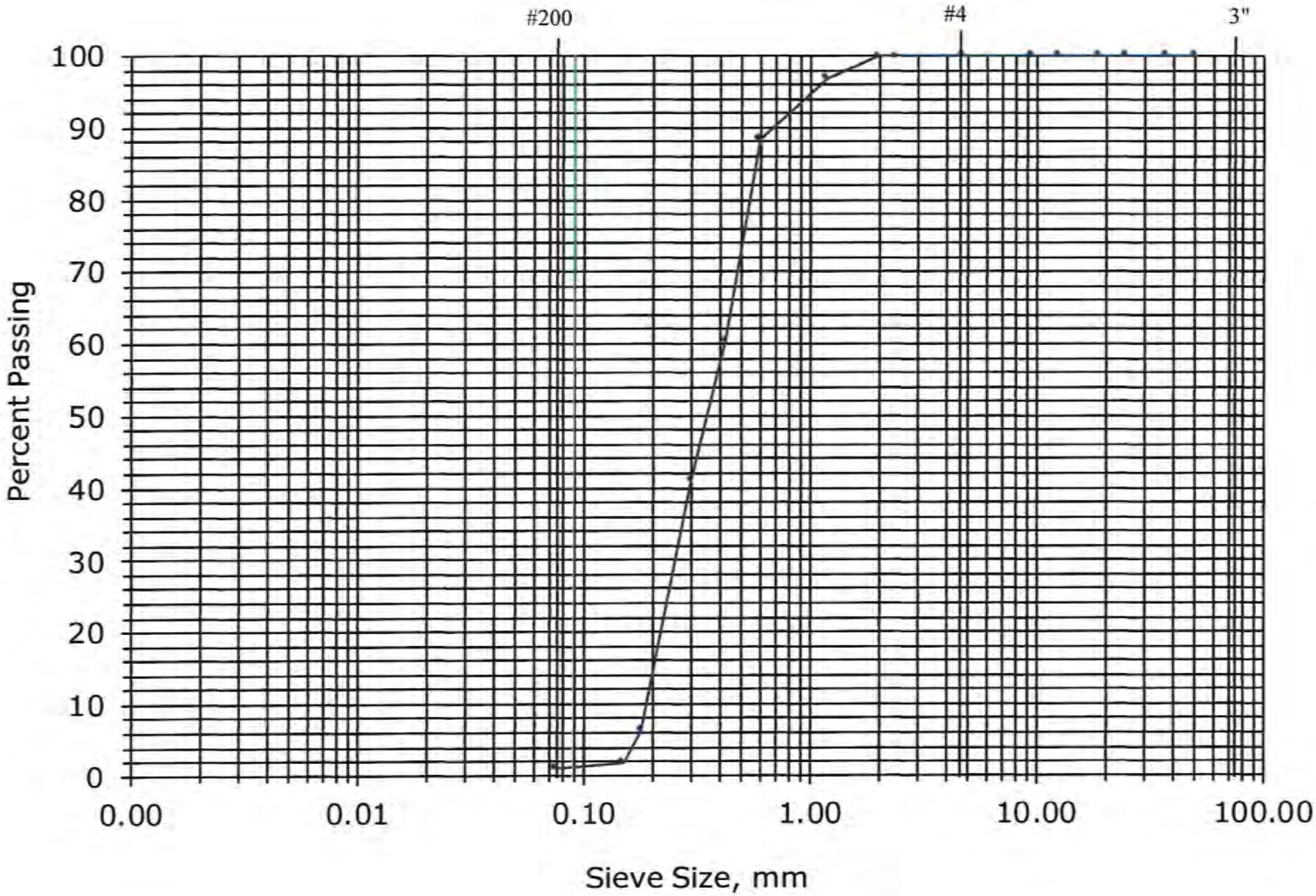
Project:	Sustainable Coastal Solutions
Date Tested:	1/28/26
Lab Ref. No.:	M-36332

Sieve Analysis



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Sean Kelley
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North Falmouth, MA 02556

Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/28/26
Received: 1/15/26

1.

Sample No.	Description	Source of Material
M-36333	Sand	Salisbury Beach- 10

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	92	
0.600 mm	#30	28	
0.425 mm	#40	13	
0.300 mm	#50	3	
0.180 mm	#80	1	
0.150 mm	#100	1	
0.075 mm	#200	0.3	

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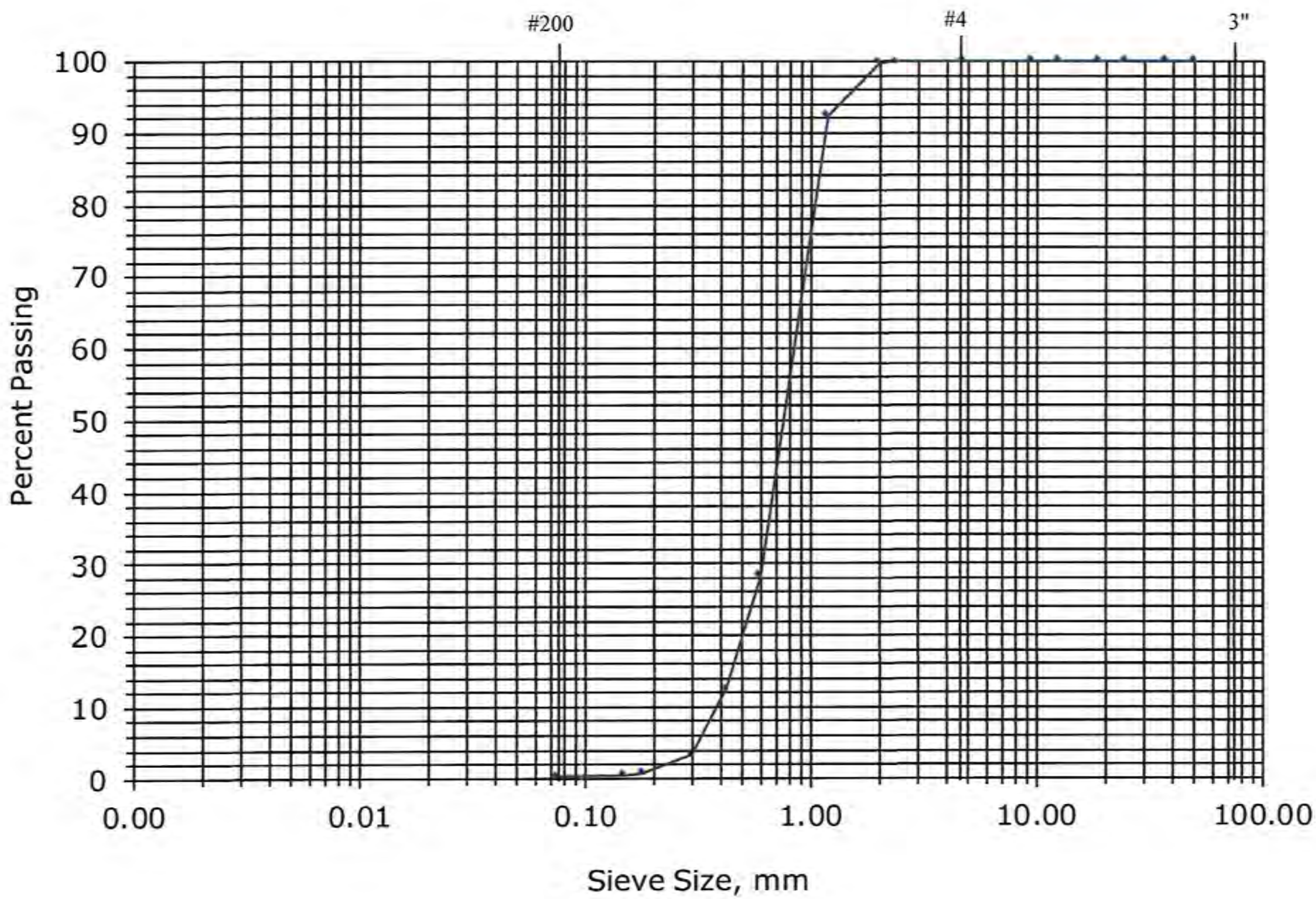
Project:	Sustainable Coastal Solutions
Date Tested:	1/28/26
Lab Ref. No.:	M-36333

Sieve Analysis



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Sustainable Coastal Solutions, Inc
Sean Kelley
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North Falmouth, MA 02556

Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/28/26
Received: 1/15/26

1.

Sample No.	Description	Source of Material
M-36334	Sand	Salisbury Beach- 11

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	99	
2.00 mm	#10	99	
1.190 mm	#16	89	
0.600 mm	#30	35	
0.425 mm	#40	19	
0.300 mm	#50	8	
0.180 mm	#80	1	
0.150 mm	#100	1	
0.075 mm	#200	0.4	

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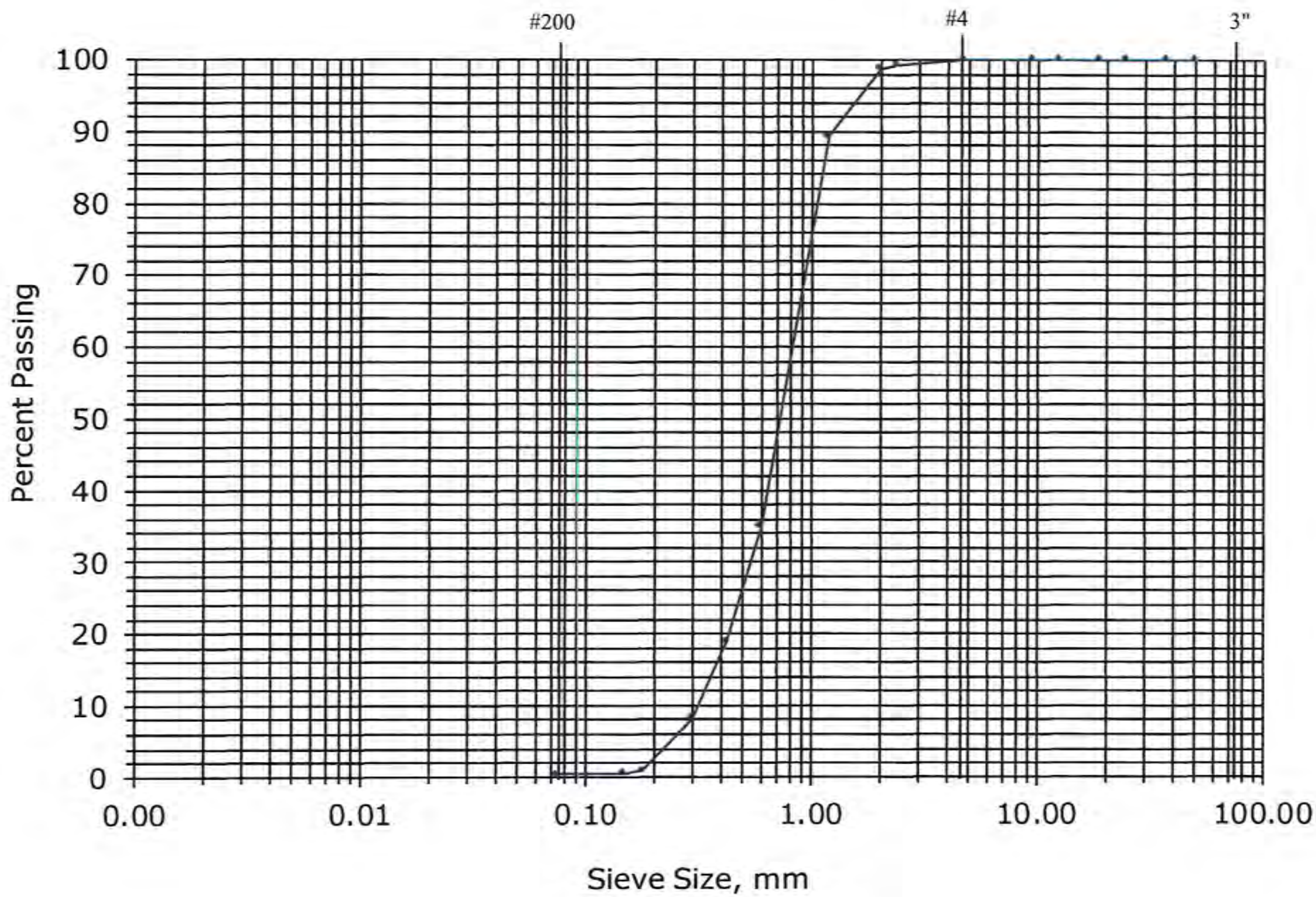
Project:	Sustainable Coastal Solutions
Date Tested:	1/28/26
Lab Ref. No.:	M-36334

Sieve Analysis



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North Falmouth, MA 02556

Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/28/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36335	Sand	Salisbury Beach- 12

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	99	
0.600 mm	#30	70	
0.425 mm	#40	40	
0.300 mm	#50	16	
0.180 mm	#80	0	
0.150 mm	#100	0	
0.075 mm	#200	0.1	

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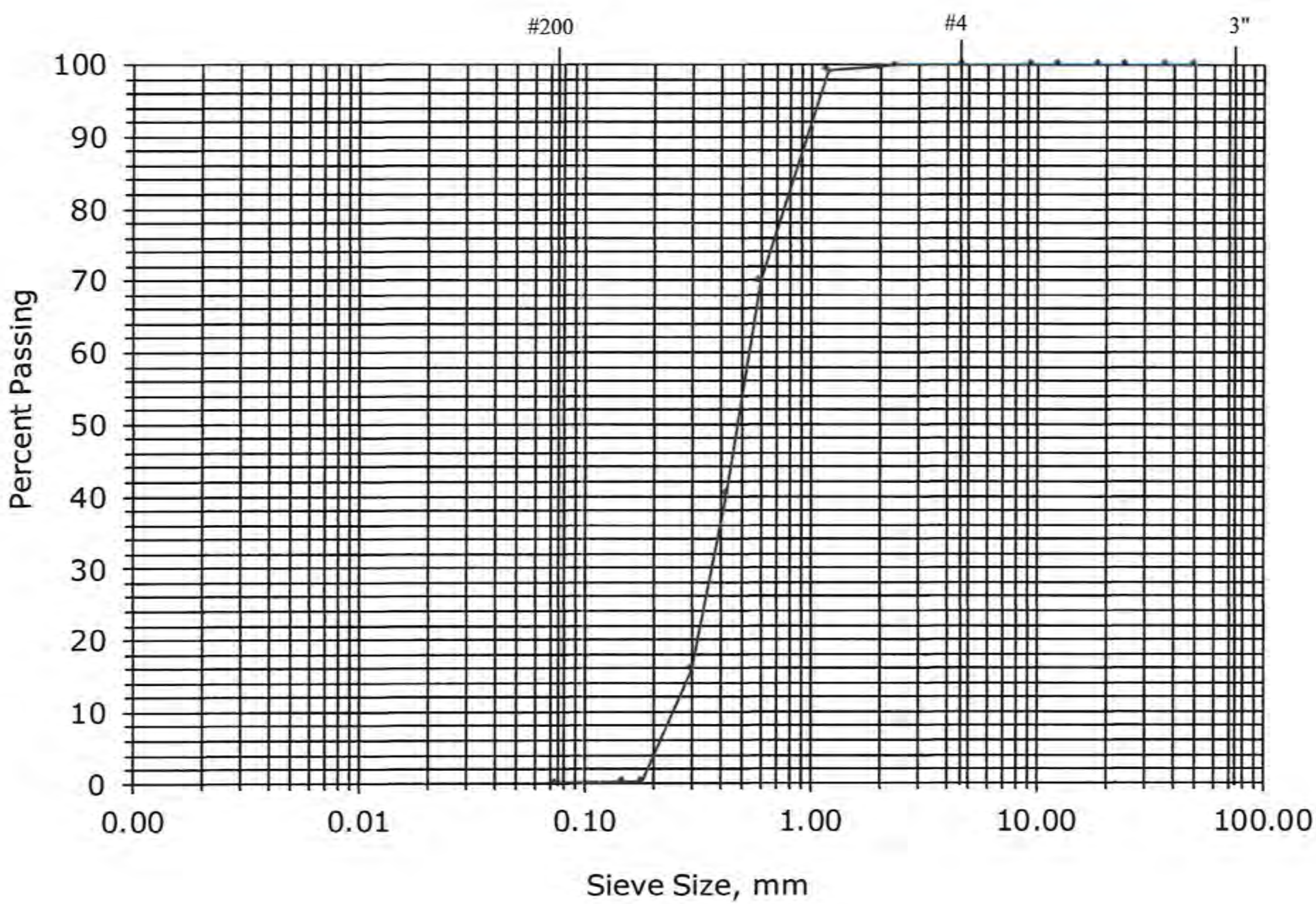
Project:	Sustainable Coastal Solutions
Date Tested:	1/28/26
Lab Ref. No.:	M-36335

Sieve Analysis



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Sean Kelley
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North Falmouth, MA 02556

Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/29/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36336	Sand	Salisbury Beach- 13

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size Standard	Sieve Size Alternate	Results {% Passing by Wt.}	Specifications
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	98	
0.600 mm	#30	62	
0.425 mm	#40	35	
0.300 mm	#50	15	
0.180 mm	#80	2	
0.150 mm	#100	1	
0.075 mm	#200	0.4	

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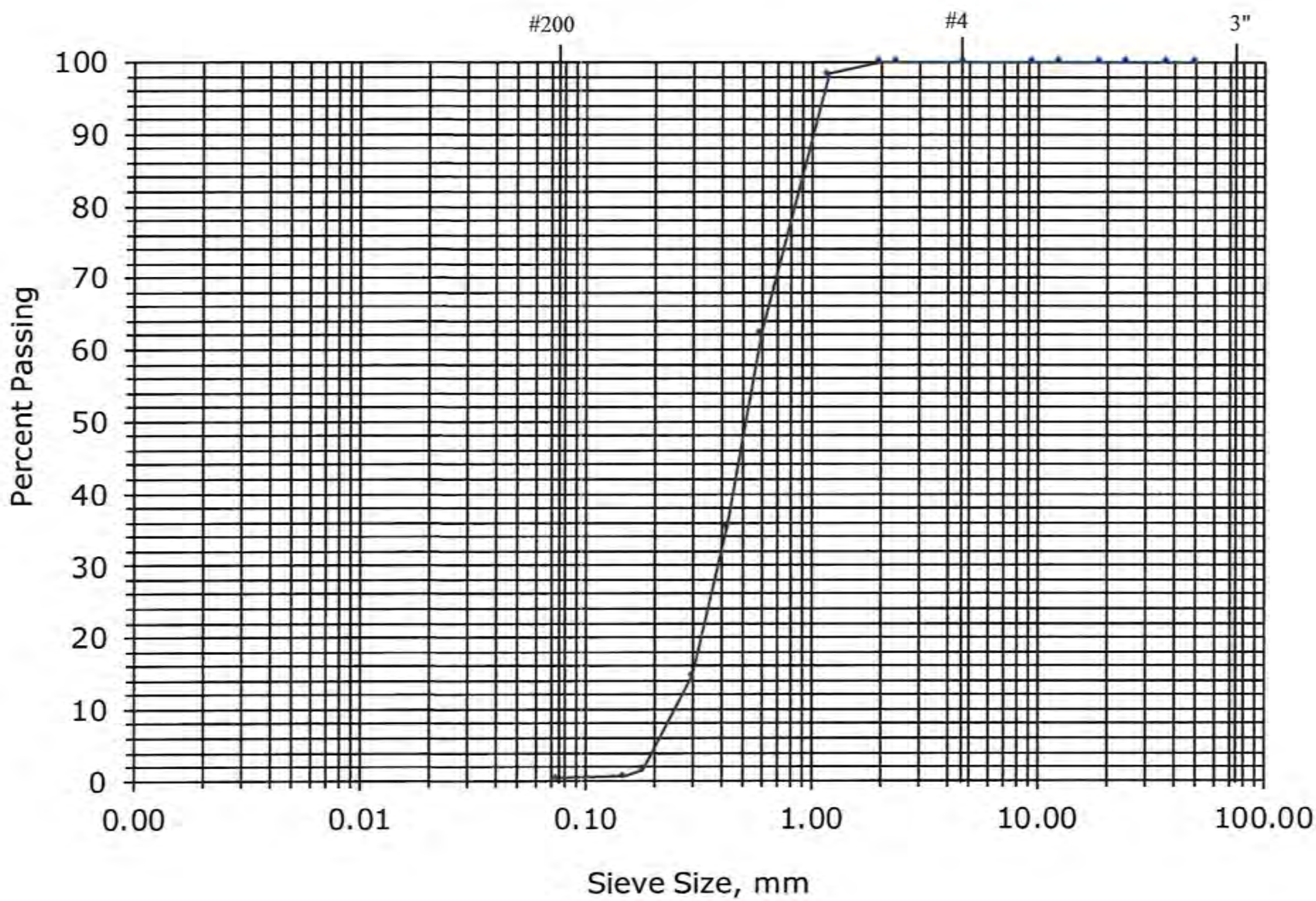
Project:	Sustainable Coastal Solutions
Date Tested:	1/29/26
Lab Ref. No.:	M-36336

Sieve Analysis



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Sean Kelley
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North Falmouth, MA 02556

Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/29/26
Received: 1/15/26

1.

Sample No.	Description	Source of Material
M-36337	Sand	Salisbury Beach- 14

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	98	
0.600 mm	#30	55	
0.425 mm	#40	23	
0.300 mm	#50	5	
0.180 mm	#80	0	
0.150 mm	#100	0	
0.075 mm	#200	0.1	

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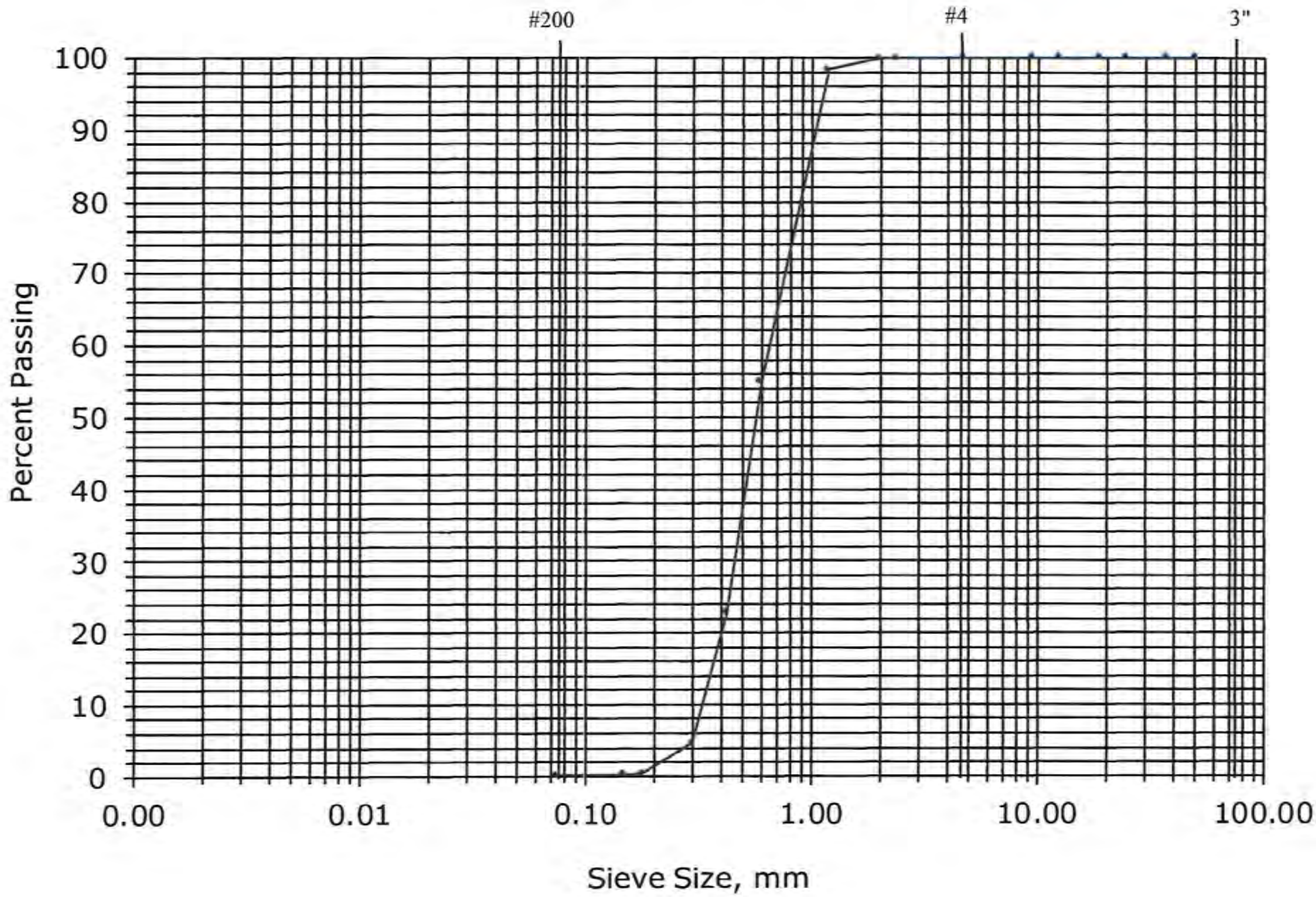
Project:	Sustainable Coastal Solutions
Date Tested:	1/29/26
Lab Ref. No.:	M-36337

Sieve Analysis



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Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/29/26
Received: 1/15/26

1.

Sample No.	Description	Source of Material
M-36338	Sand	Salisbury Beach- 15

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	99	
2.00 mm	#10	99	
1.190 mm	#16	88	
0.600 mm	#30	9	
0.425 mm	#40	2	
0.300 mm	#50	1	
0.180 mm	#80	0	
0.150 mm	#100	0	
0.075 mm	#200	0.1	

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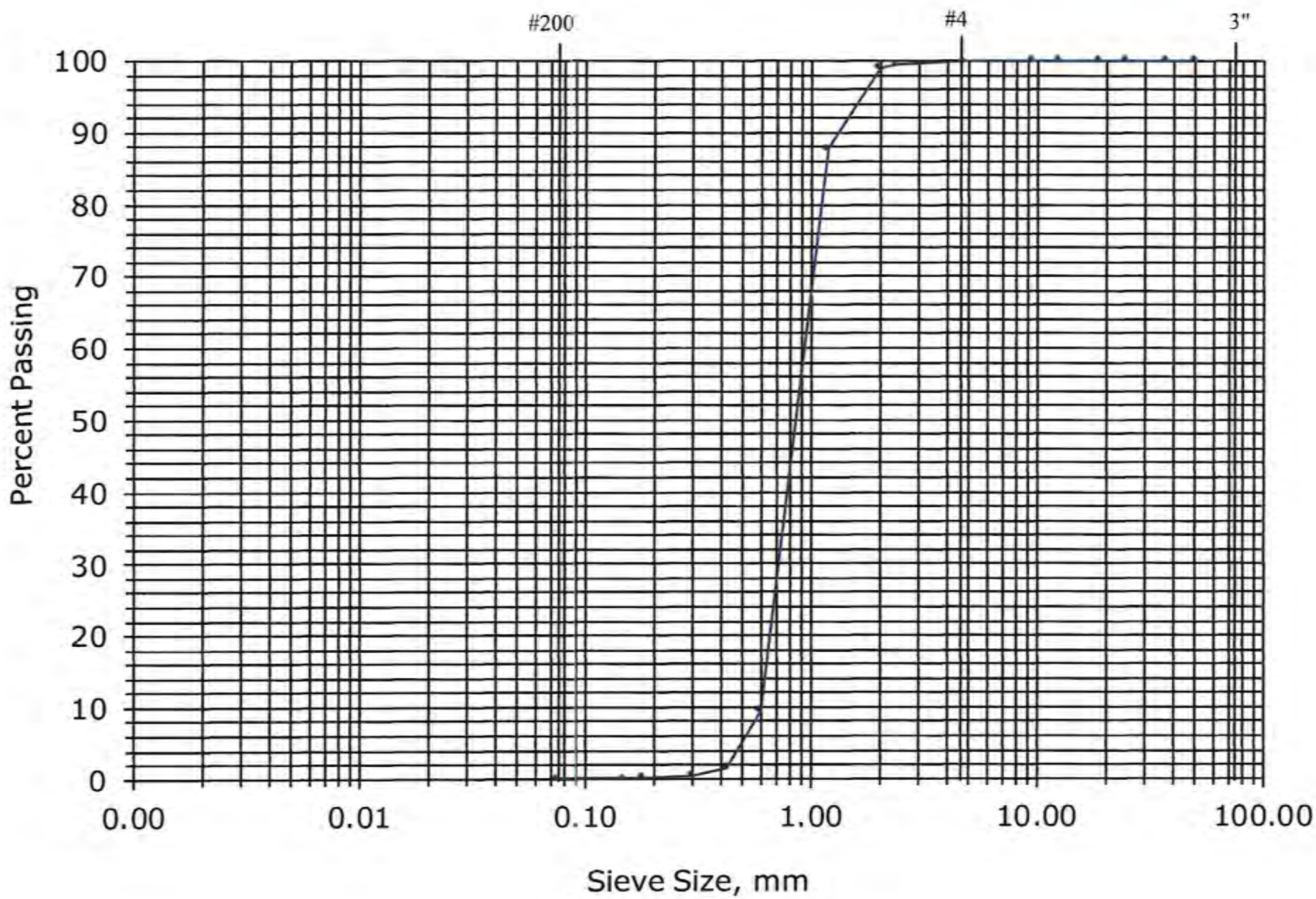
Project:	Sustainable Coastal Solutions
Date Tested:	1/29/26
Lab Ref. No.:	M-36338

Sieve Analysis



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Sustainable Coastal Solutions, Inc
Sean Kelley
107A County Road
North Falmouth, MA 02556

Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/29/26
Received: 1/15/26

1.

Sample No.	Description	Source of Material
M-36339	Sand	Salisbury Beach- 16

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	99	
0.600 mm	#30	58	
0.425 mm	#40	29	
0.300 mm	#50	9	
0.180 mm	#80	1	
0.150 mm	#100	1	
0.075 mm	#200	0.5	

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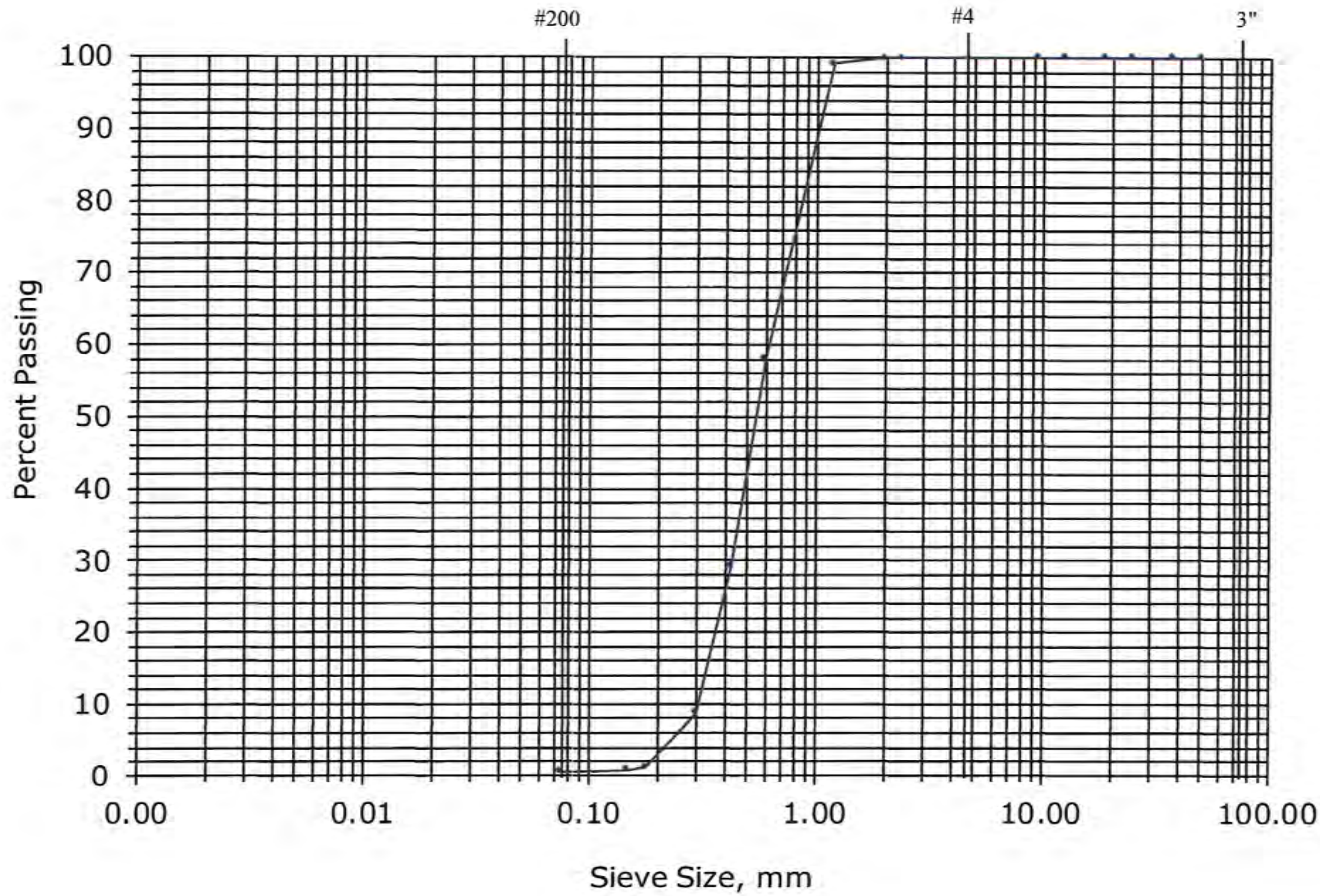
Project:	Sustainable Coastal Solutions
Date Tested:	1/29/26
Lab Ref. No.:	M-36339

Sieve Analysis



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Sustainable Coastal Solutions, Inc
Sean Kelley
107A County Road
North Falmouth, MA 02556

Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/29/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36340	Sand	Salisbury Beach- 17

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	100	
0.600 mm	#30	71	
0.425 mm	#40	48	
0.300 mm	#50	27	
0.180 mm	#80	3	
0.150 mm	#100	1	
0.075 mm	#200	0.5	

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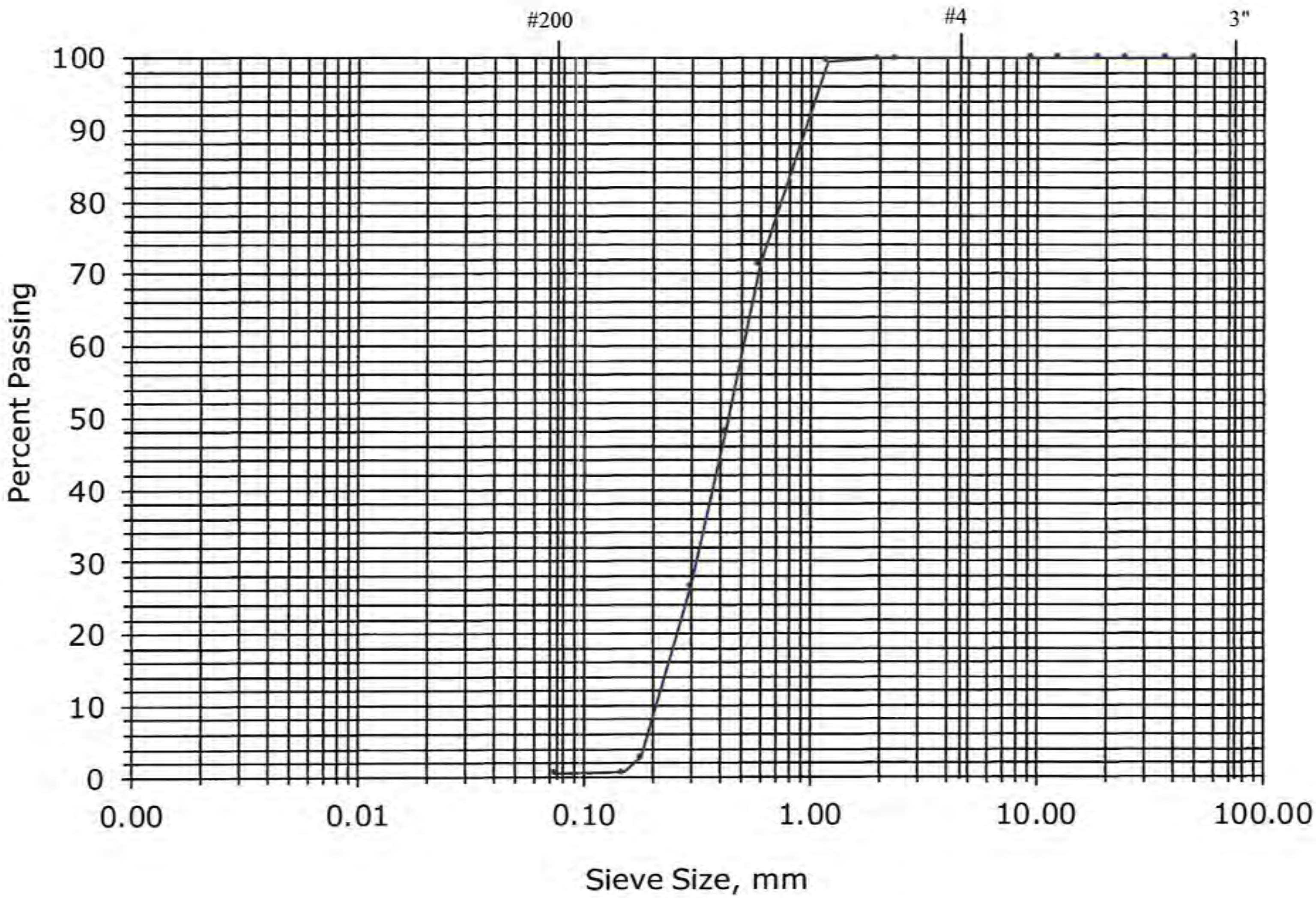
Project:	Sustainable Coastal Solutions
Date Tested:	1/29/26
Lab Ref. No.:	M-36340

Sieve Analysis



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Sean Kelley
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North Falmouth, MA 02556

Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/29/26
Received: 1/15/26

1.	Sample No.	Description	Source of Material
	M-36341	Sand	Salisbury Beach- 18

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	99	
2.00 mm	#10	98	
1.190 mm	#16	74	
0.600 mm	#30	31	
0.425 mm	#40	21	
0.300 mm	#50	11	
0.180 mm	#80	4	
0.150 mm	#100	3	
0.075 mm	#200	2.1	

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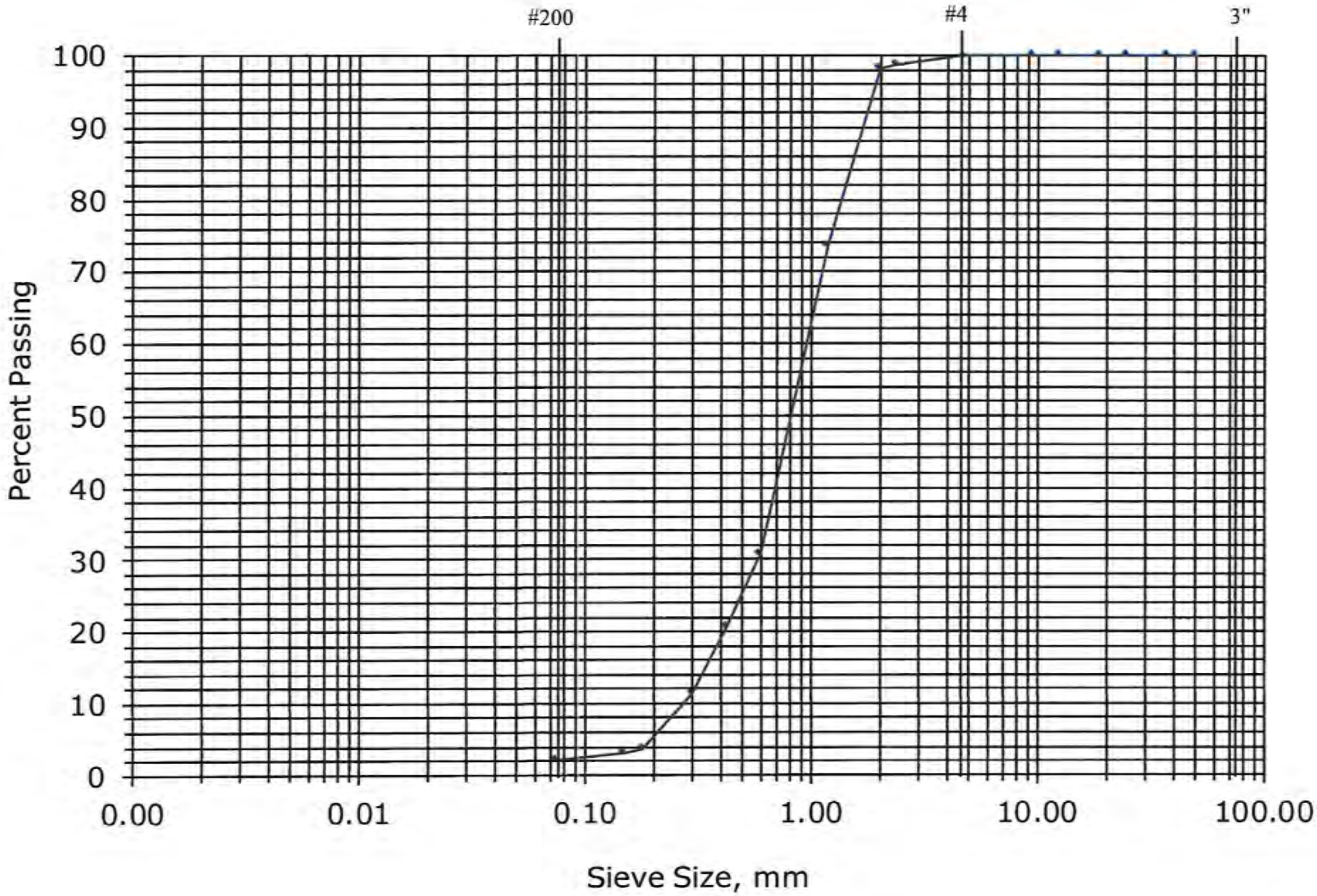
Project:	Sustainable Coastal Solutions
Date Tested:	1/29/26
Lab Ref. No.:	M-36341

Sieve Analysis



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Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/29/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36342	Sand	Salisbury Beach- 19

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	99	
0.600 mm	#30	72	
0.425 mm	#40	51	
0.300 mm	#50	32	
0.180 mm	#80	5	
0.150 mm	#100	1	
0.075 mm	#200	0.6	

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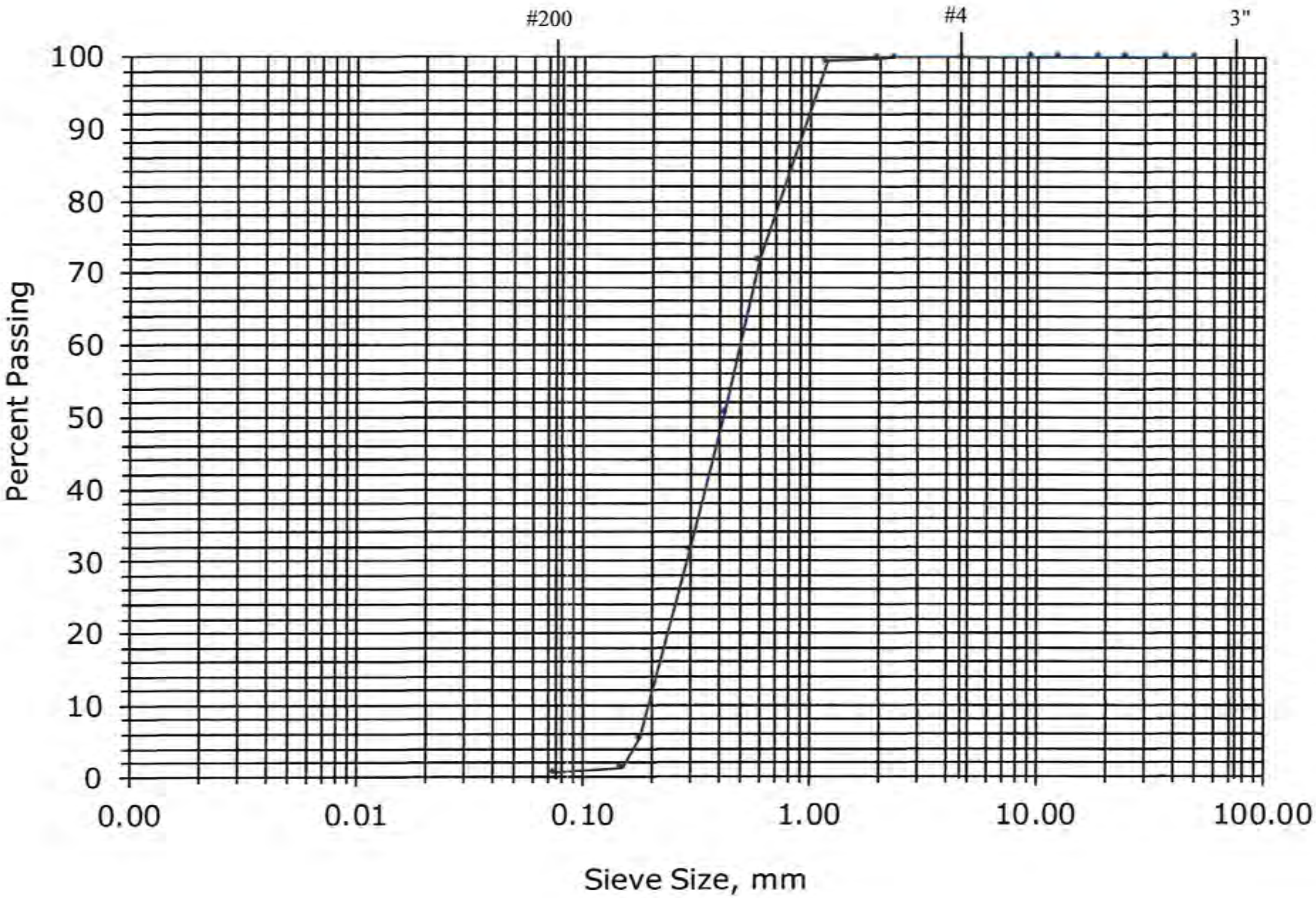
Project:	Sustainable Coastal Solutions
Date Tested:	1/29/26
Lab Ref. No.:	M-36342

Sieve Analysis



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Report Date: 1/30/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/29/26
Received: 1/15/26

1.

Sample No.	Description	Source of Material
M-36343	Sand	Salisbury Beach- 20

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	100	
0.600 mm	#30	84	
0.425 mm	#40	53	
0.300 mm	#50	21	
0.180 mm	#80	1	
0.150 mm	#100	0	
0.075 mm	#200	0.3	

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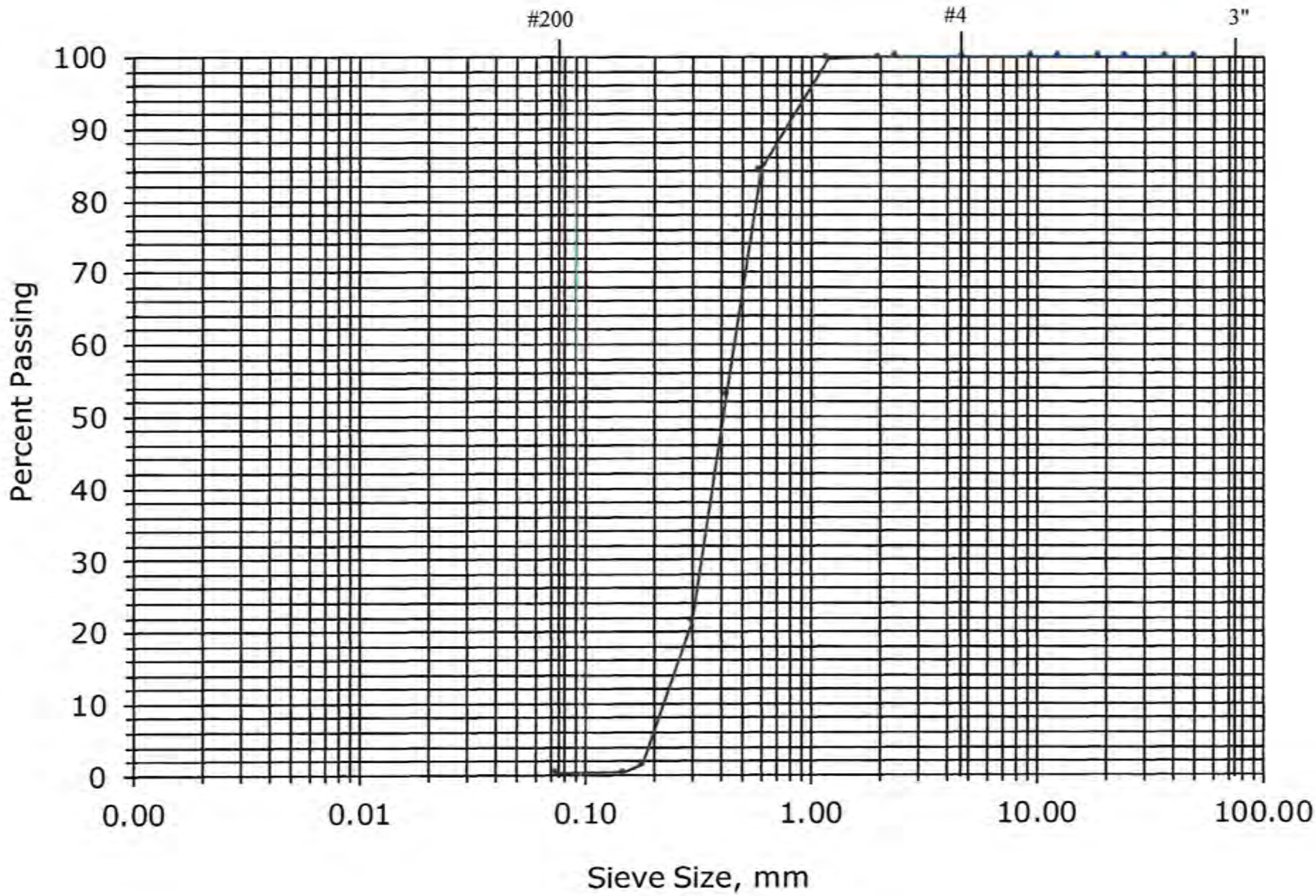
Project:	Sustainable Coastal Solutions
Date Tested:	1/29/26
Lab Ref. No.:	M-36343

Sieve Analysis



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Report Date: 2/2/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/30/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36344	Sand	Plum Island Beach- 21

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	82	
2.36 mm	#8	73	
2.00 mm	#10	70	
1.190 mm	#16	56	
0.600 mm	#30	16	
0.425 mm	#40	2	
0.300 mm	#50	0	
0.180 mm	#80	0	
0.150 mm	#100	0	
0.075 mm	#200	0.0	

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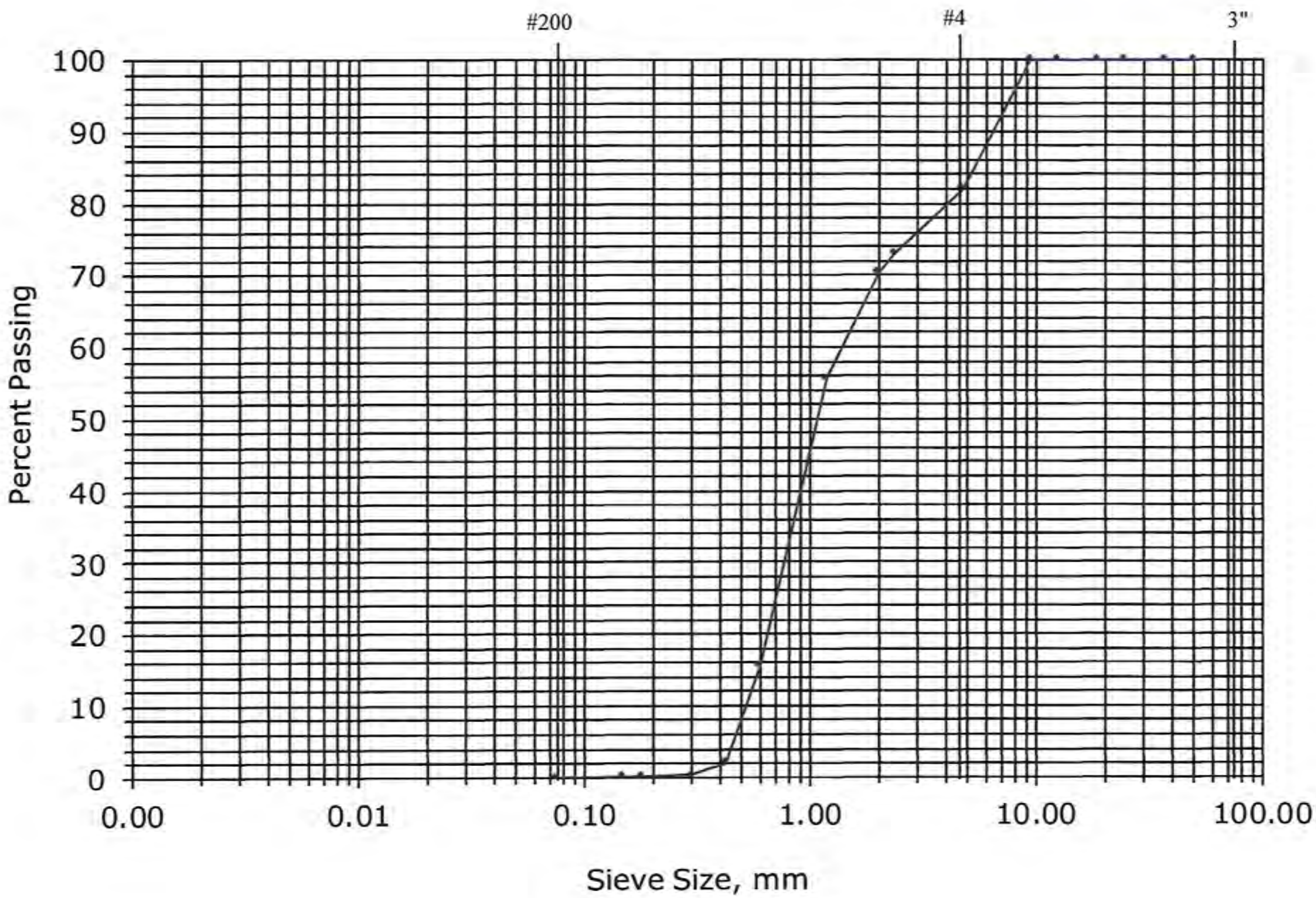
Project:	Sustainable Coastal Solutions
Date Tested:	1/30/26
Lab Ref. No.:	M-36344

Sieve Analysis



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North Falmouth, MA 02556

Report Date: 2/2/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/30/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36345	Sand	Plum Island Beach- 22

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	99	
0.600 mm	#30	52	
0.425 mm	#40	16	
0.300 mm	#50	4	
0.180 mm	#80	1	
0.150 mm	#100	0	
0.075 mm	#200	0.3	

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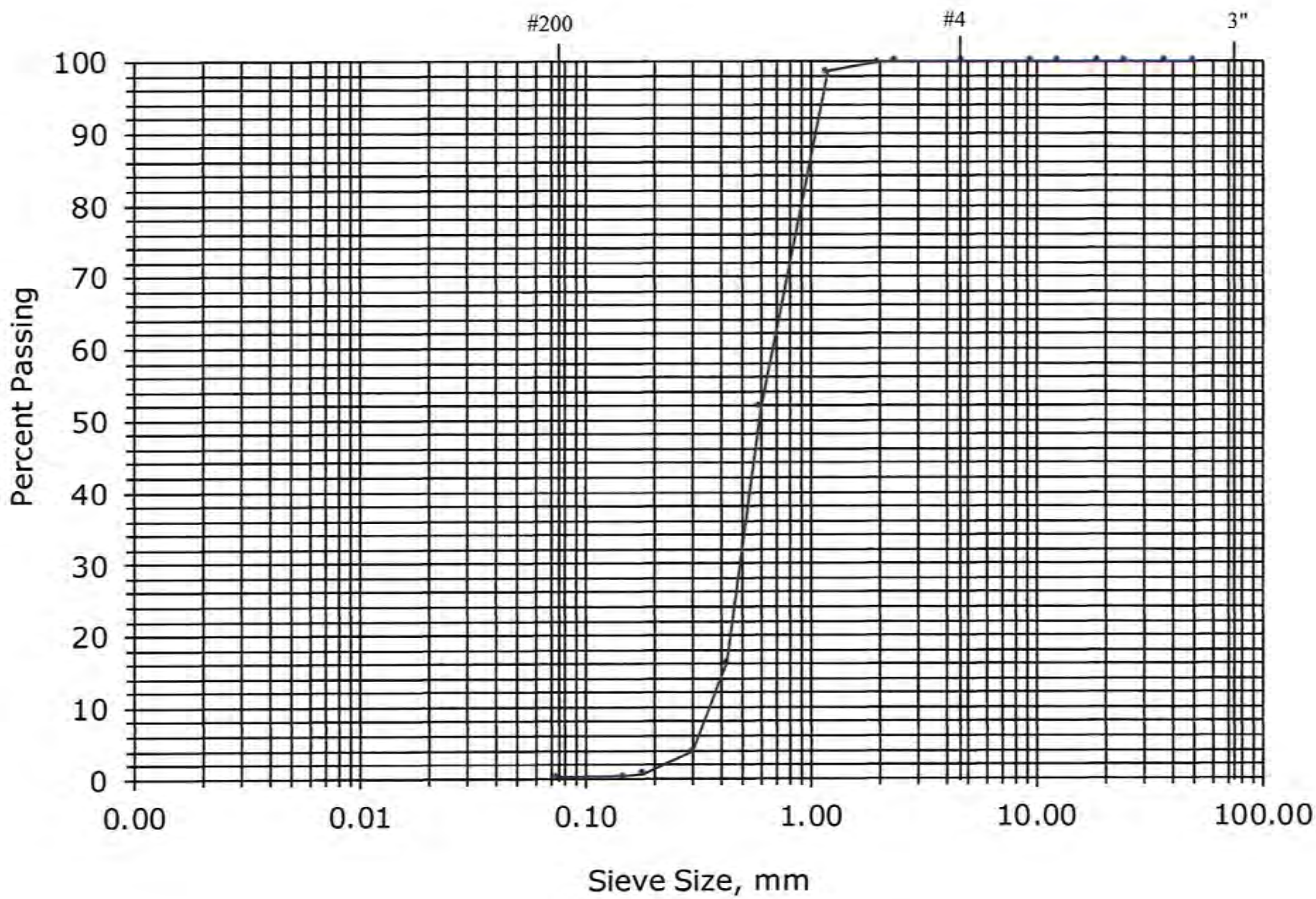
Project:	Sustainable Coastal Solutions
Date Tested:	1/30/26
Lab Ref. No.:	M-36345

Sieve Analysis



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Report Date: 2/2/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/30/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36346	Sand	Plum Island Beach- 23

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	98	
2.36 mm	#8	85	
2.00 mm	#10	79	
1.190 mm	#16	59	
0.600 mm	#30	16	
0.425 mm	#40	4	
0.300 mm	#50	1	
0.180 mm	#80	1	
0.150 mm	#100	0	
0.075 mm	#200	0.2	

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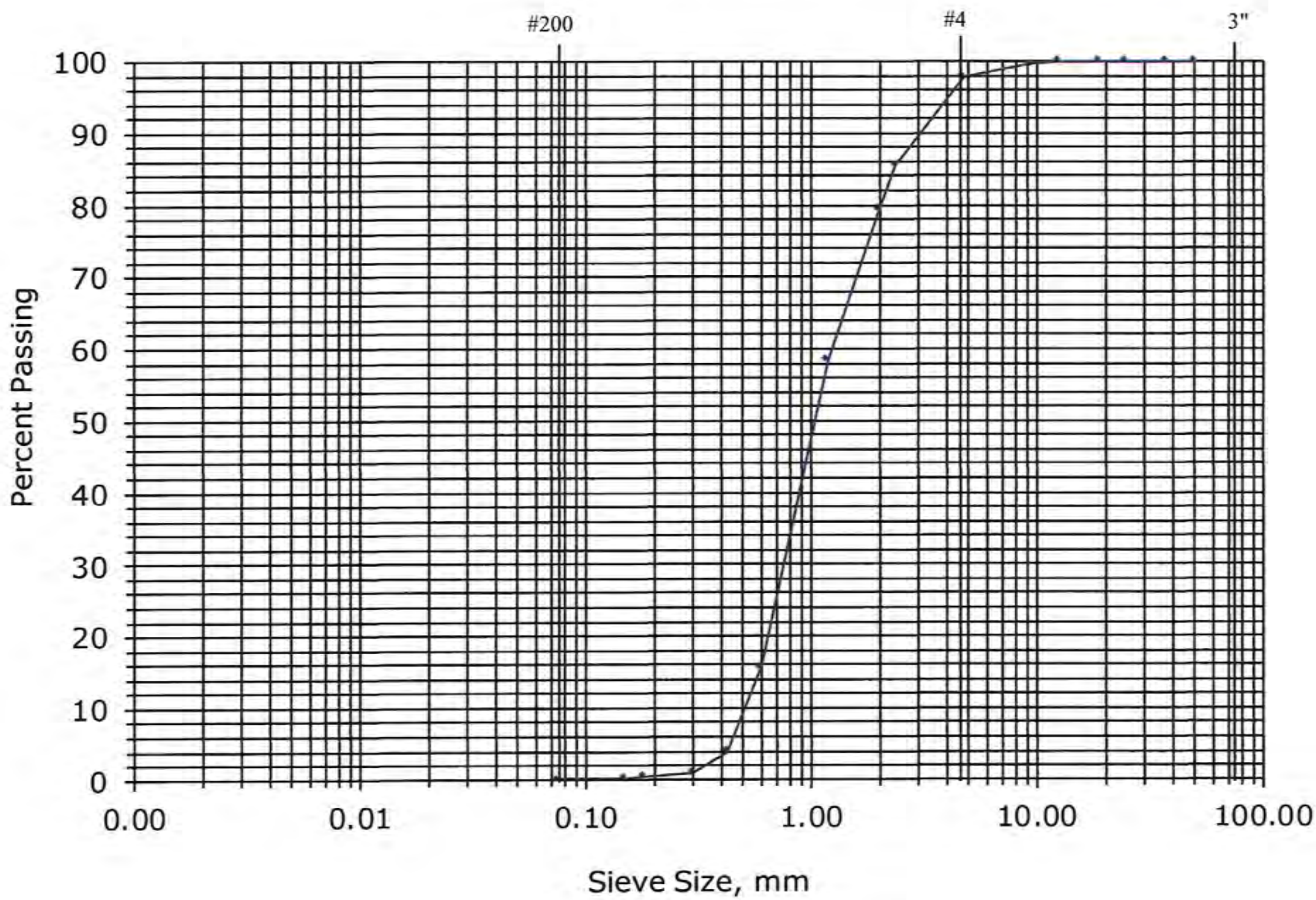
Project:	Sustainable Coastal Solutions
Date Tested:	1/30/26
Lab Ref. No.:	M-36346

Sieve Analysis



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North Falmouth, MA 02556

Report Date: 2/2/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/30/26
Received: 1/15/26

1.

Sample No.	Description	Source of Material
M-36347	Sand	Plum Island Beach- 24

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	96	
0.600 mm	#30	31	
0.425 mm	#40	8	
0.300 mm	#50	2	
0.180 mm	#80	1	
0.150 mm	#100	1	
0.075 mm	#200	0.4	

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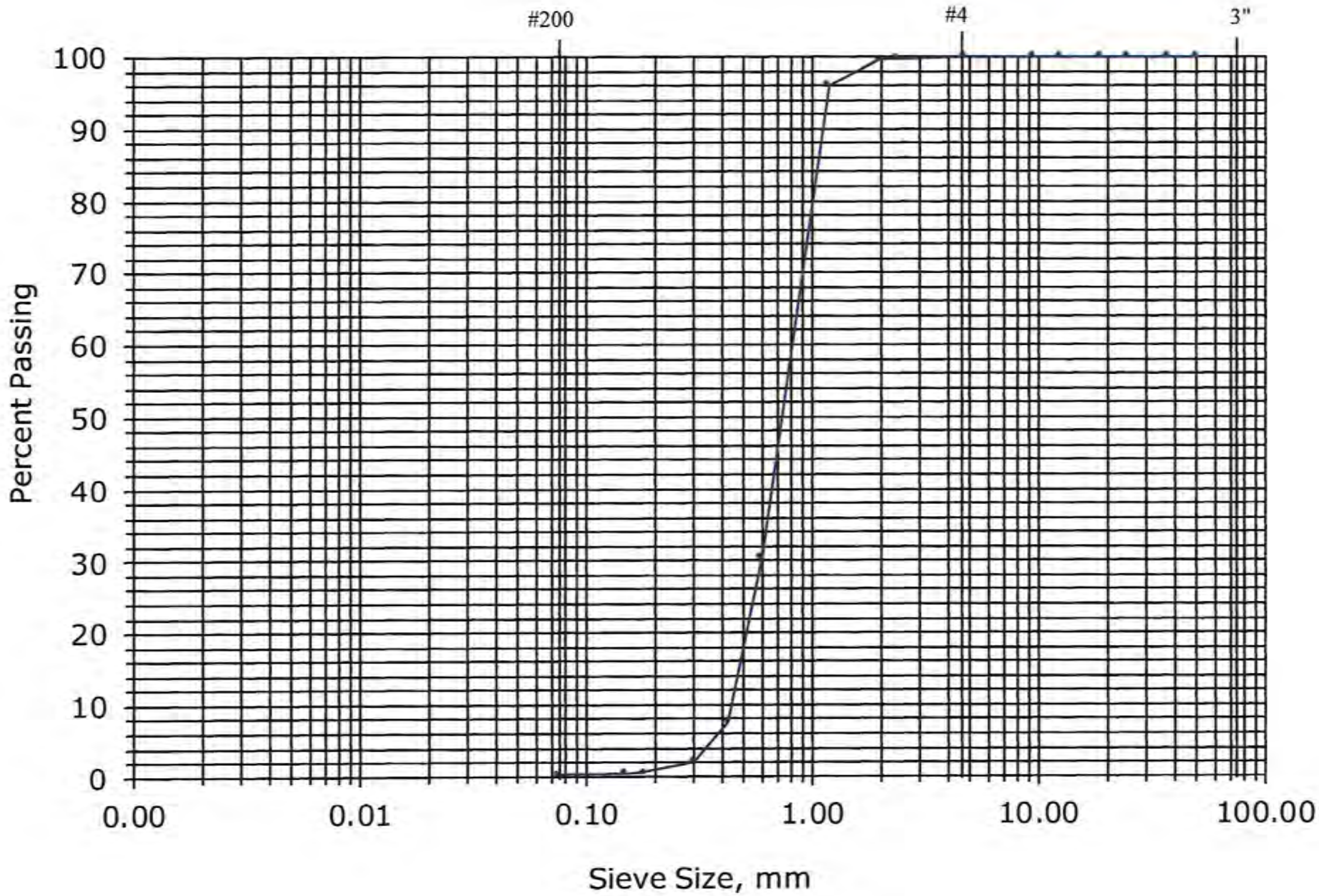
Project:	Sustainable Coastal Solutions
Date Tested:	1/30/26
Lab Ref. No.:	M-36347

Sieve Analysis



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North Falmouth, MA 02556

Report Date: 2/2/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/30/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36348	Sand	Plum Island Beach- 25

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	98	
2.00 mm	#10	97	
1.190 mm	#16	81	
0.600 mm	#30	5	
0.425 mm	#40	0	
0.300 mm	#50	0	
0.180 mm	#80	0	
0.150 mm	#100	0	
0.075 mm	#200	0.0	

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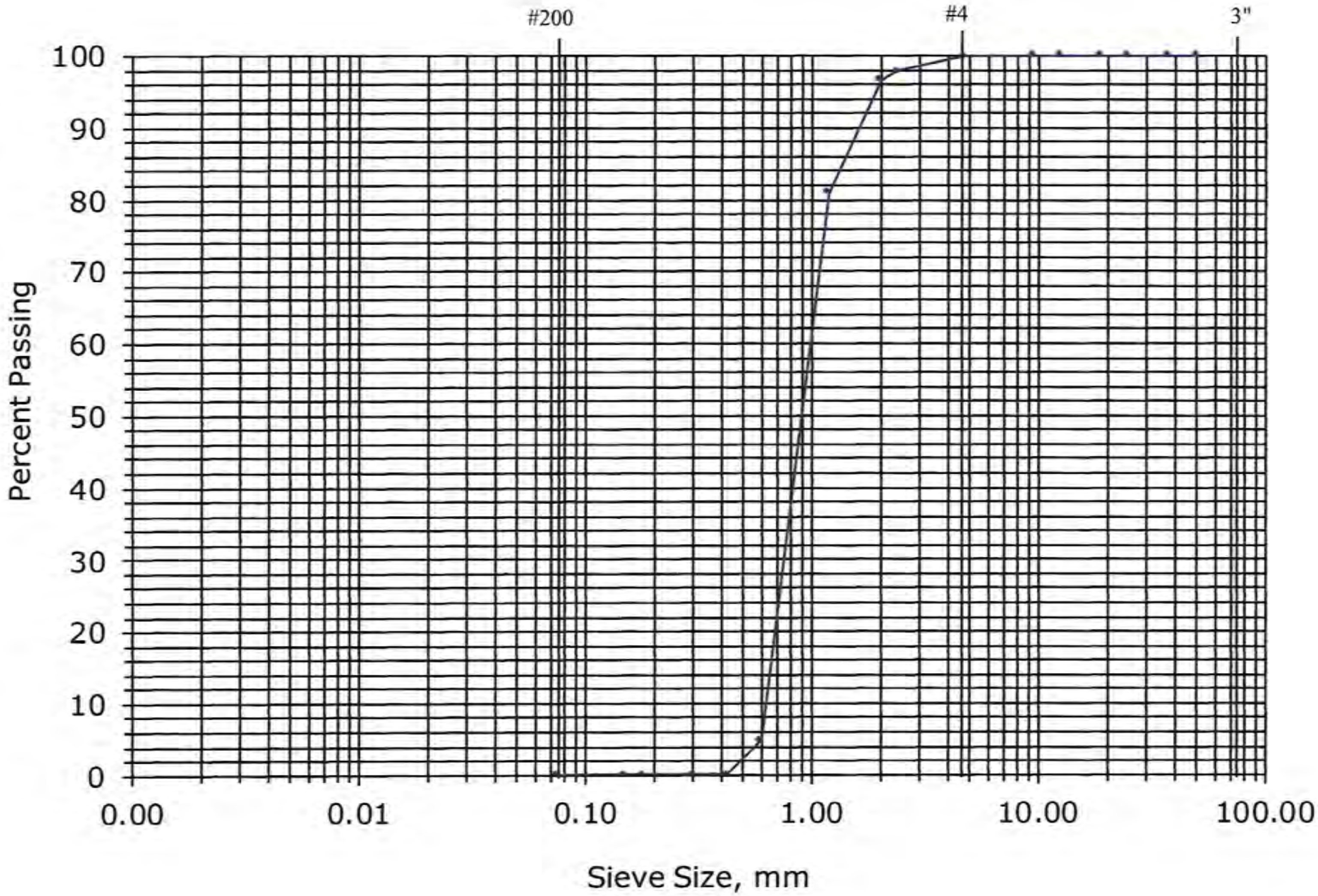
Date Tested:	1/30/26
Lab Ref. No.:	M-36348

Sieve Analysis



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Report Date: 2/2/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/30/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36349	Sand	Plum Island Beach- 26

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	99	
1.190 mm	#16	89	
0.600 mm	#30	8	
0.425 mm	#40	1	
0.300 mm	#50	0	
0.180 mm	#80	0	
0.150 mm	#100	0	
0.075 mm	#200	0.2	

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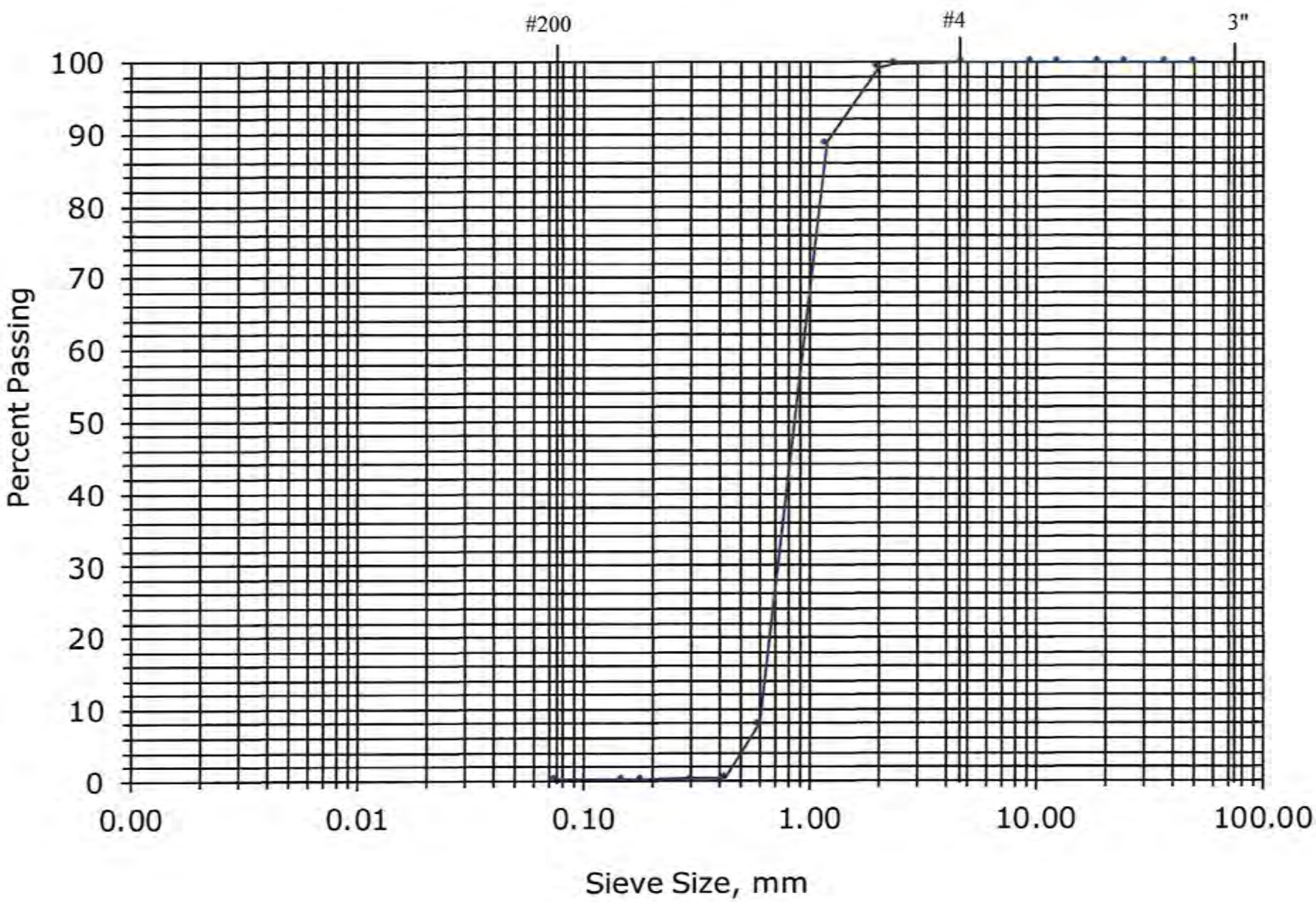
Project:	Sustainable Coastal Solutions
Date Tested:	1/30/26
Lab Ref. No.:	M-36349

Sieve Analysis



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Report Date: 2/2/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/30/26
Received: 1/15/26

1.

Sample No.	Description	Source of Material
M-36350	Sand	Newbury Beach- 27

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	99	
1.190 mm	#16	88	
0.600 mm	#30	14	
0.425 mm	#40	1	
0.300 mm	#50	0	
0.180 mm	#80	0	
0.150 mm	#100	0	
0.075 mm	#200	0.2	

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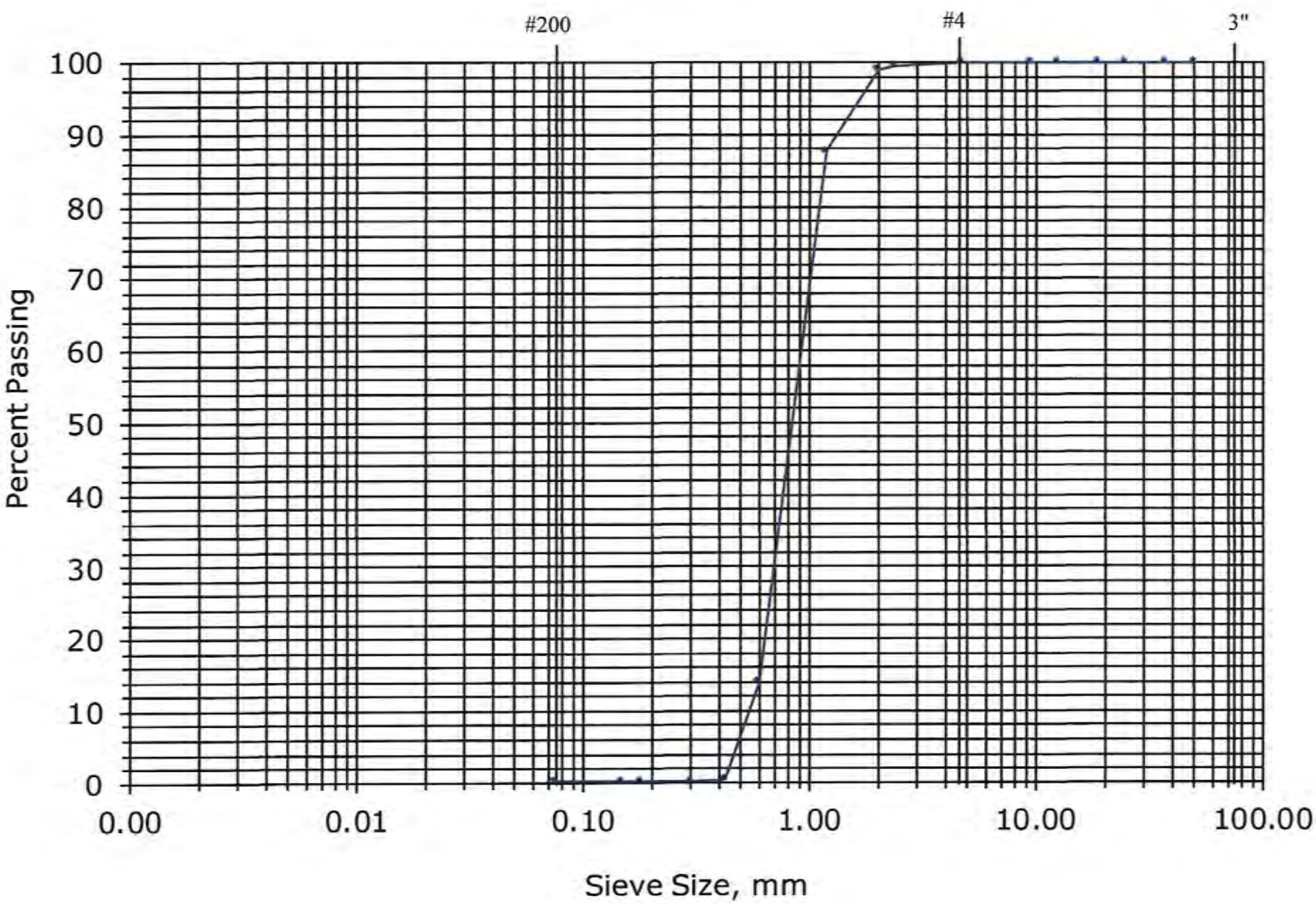
Project:	Sustainable Coastal Solutions
Date Tested:	1/30/26
Lab Ref. No.:	M-36350

Sieve Analysis



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Report Date: 2/2/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/30/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36351	Sand	Newbury Beach- 28

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	98	
0.600 mm	#30	31	
0.425 mm	#40	1	
0.300 mm	#50	0	
0.180 mm	#80	0	
0.150 mm	#100	0	
0.075 mm	#200	0.1	

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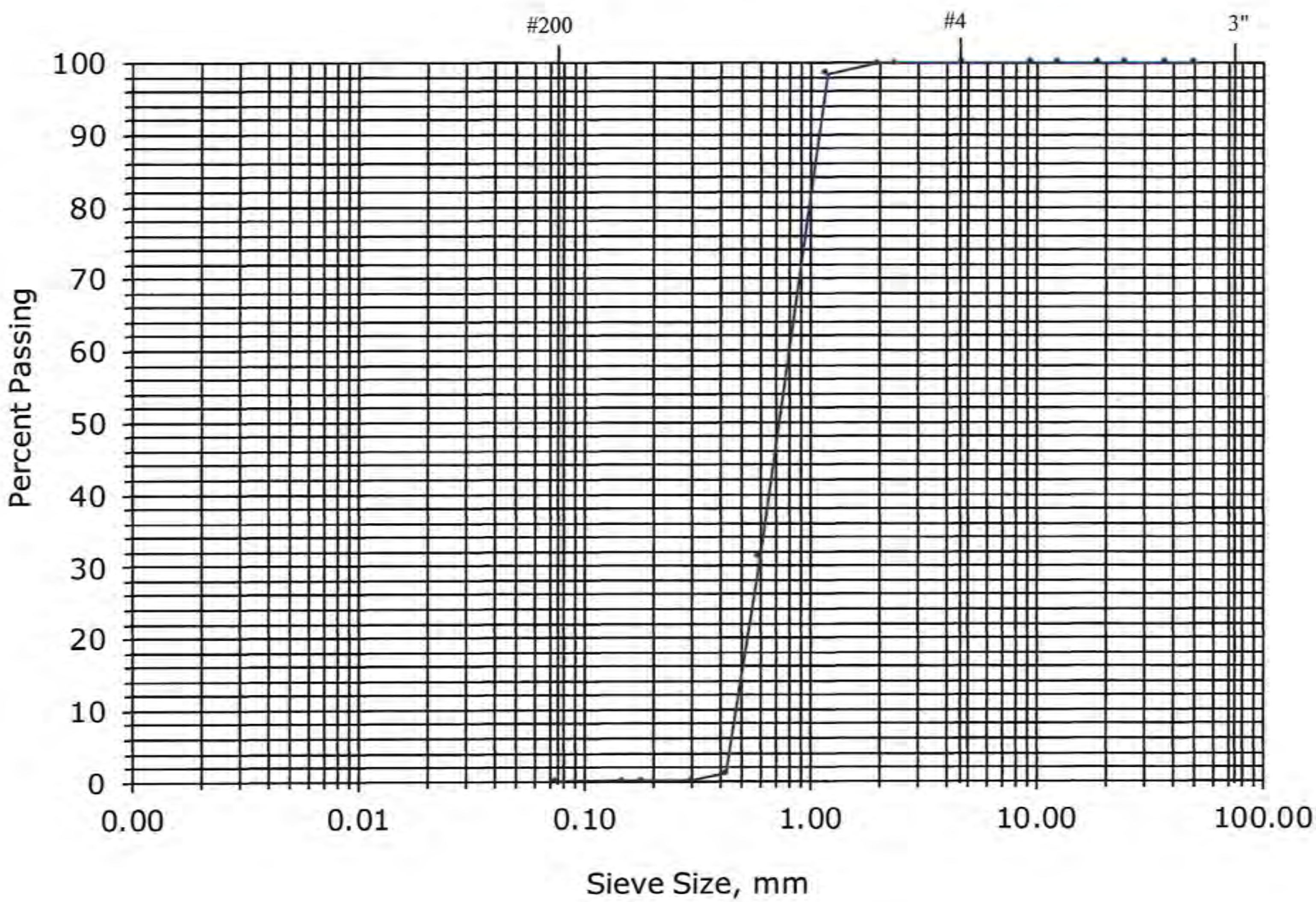
A Division of PK Associates, Inc.
A PRESSA GROUP COMPANY

Project:	Sustainable Coastal Solutions
Date Tested:	1/30/26
Lab Ref. No.:	M-36351

Sieve Analysis



Sustainable Coastal Solutions, Inc
Sean Kelley
107A County Road
North Falmouth, MA 02556

Report Date: 2/2/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/30/26
Received: 1/15/26

1.

Sample No.	Description	Source of Material
M-36352	Sand	Newbury Beach- 29

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	98	
2.36 mm	#8	94	
2.00 mm	#10	91	
1.190 mm	#16	64	
0.600 mm	#30	7	
0.425 mm	#40	0	
0.300 mm	#50	0	
0.180 mm	#80	0	
0.150 mm	#100	0	
0.075 mm	#200	0.0	

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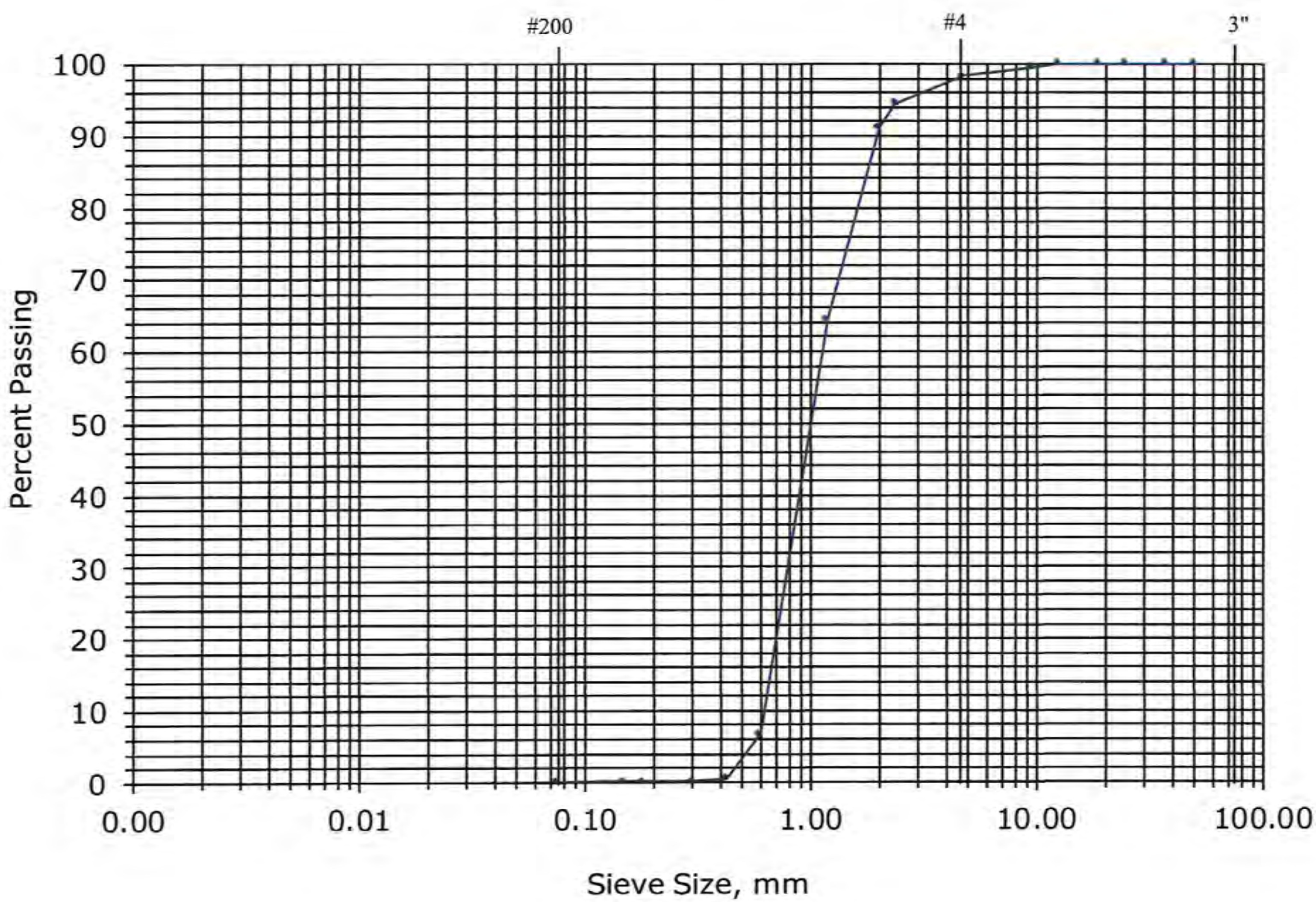
Sean Skorohod
Director of Testing Services
Construction Technology Division

Briggs Engineering & Testing

A Division of PK Associates, Inc.

Project:	Sustainable Coastal Solutions
Date Tested:	1/30/26
Lab Ref. No.:	M-36352

Sieve Analysis



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Sustainable Coastal Solutions, Inc
Sean Kelley
107A County Road
North Falmouth, MA 02556

Report Date: 2/2/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/30/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36353	Sand	Newbury Beach- 30

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	99	
0.600 mm	#30	37	
0.425 mm	#40	4	
0.300 mm	#50	1	
0.180 mm	#80	0	
0.150 mm	#100	0	
0.075 mm	#200	0.2	

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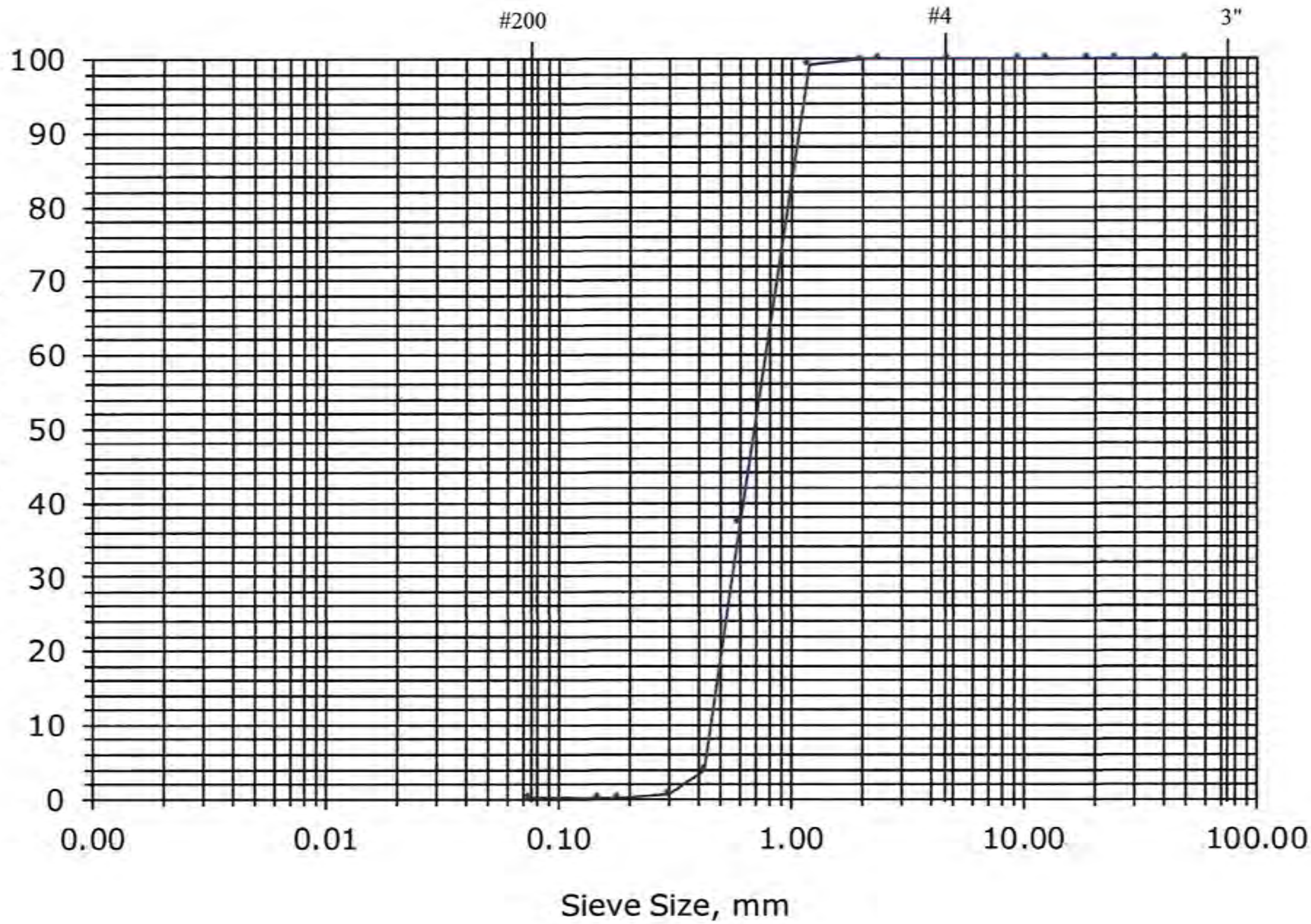
Briggs Engineering & Testing
A Division of PK Associates, Inc.

Project:	Sustainable Coastal Solutions
Date Tested:	1/30/26
Lab Ref. No.:	M-36353

Sieve Analysis



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Sustainable Coastal Solutions, Inc
Sean Kelley
107A County Road
North Falmouth, MA 02556

Report Date: 2/2/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/30/26
Received: 1/15/26

1.	Sample No.	Description	Source of Material
	M-36354	Sand	Newbury Beach- 31

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size		Results	Specifications
Standard	Alternate	{% Passing by Wt.}	
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	99	
1.190 mm	#16	92	
0.600 mm	#30	28	
0.425 mm	#40	4	
0.300 mm	#50	0	
0.180 mm	#80	0	
0.150 mm	#100	0	
0.075 mm	#200	0.3	

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Construction Technology Division

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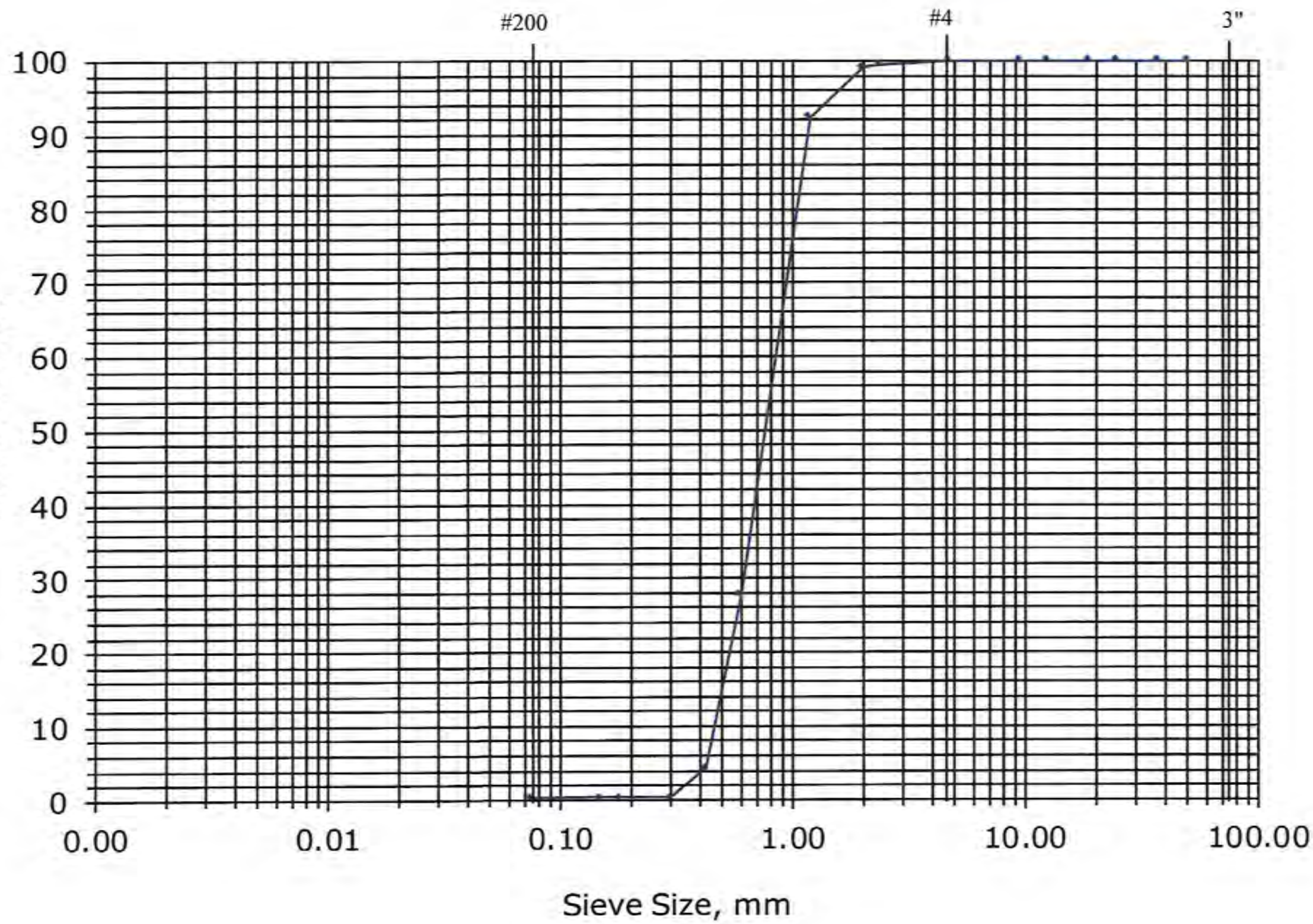
Project:	Sustainable Coastal Solutions
Date Tested:	1/30/26
Lab Ref. No.:	M-36354

Sieve Analysis



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Sustainable Coastal Solutions, Inc
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North Falmouth, MA 02556

Report Date: 2/2/26

Project: **Sustainable Coastal Solutions**
Briggs #: **31916**

Test Completed: 1/30/26
Received: 1/15/26

1. Sample No.	Description	Source of Material
M-36355	Sand	Newbury Beach- 32

2. Sieve Analysis { AASHTO T11 and T27 }

Sieve Size Standard	Sieve Size Alternate	Results {% Passing by Wt.}	Specifications
50 mm	2"	100	
37.5 mm	1-1/2"	100	
25 mm	1	100	
19 mm	3/4"	100	
12.5 mm	1/2"	100	
9.5 mm	3/8"	100	
4.75 mm	#4	100	
2.36 mm	#8	100	
2.00 mm	#10	100	
1.190 mm	#16	99	
0.600 mm	#30	39	
0.425 mm	#40	6	
0.300 mm	#50	0	
0.180 mm	#80	0	
0.150 mm	#100	0	
0.075 mm	#200	0.2	

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Briggs Engineering & Testing

Project:	Sustainable Coastal Solutions
Date Tested:	1/30/26
Lab Ref. No.:	M-36355

Sieve Analysis