Greenwood Beach Restoration Project
Reference Beach Study

Data Collection Report

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This project received funding from 2016's Measure AA, the Clean and Healthy Bay Measure, through the San Francisco Bay Restoration Authority. The San Francisco Bay Restoration Authority is a regional agency that funds projects that restore, protect and enhance the wetlands and wildlife habitat in the San Francisco Bay and its shoreline.

SAN FRANCISCO BAY
RESTORATION AUTHORITY

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1 Introduction and Project Background

Beaches are a natural part of the living shoreline of San Francisco Bay, and support a diversity of native fish, wildlife and plants. They are found where there is a supply of coarse-grained sediments (sand, gravel, or cobble) and a wave climate competent to mobilize, transport, and deposit these sediments allowing the formation of a beach (Goals Project 2015, SFEI and SPUR 2019, SFEI and Baye 2020). Bay beaches can adjust to the local wave climate, and the permeable nature of the sediments helps to absorb the uprush of wave swash, a process that protects the upper reaches of the beach and backshore and can help manage wave erosion issues. For these reasons, there is great interest in beach restoration as a nature-based, living shoreline approach to arresting shoreline erosion and improving resilience to sea level rise, while providing enhanced habitat and public access values to the shoreline.

Historically, Central and North San Francisco Bay had many natural beaches located along its shores. They were commonly found in Marin County in various settings, ranging from flatter sandy beaches to rock beaches fronting higher energy cliff locations (SFEI and Baye 2020). As such, Marin County is an excellent location to evaluate the ability of enhanced bay beaches to inhibit shoreline erosion under a variety of conditions. Marin County is also an excellent outdoor laboratory to assess the feasibility and cost-effectiveness of constructing beaches in areas where they are not currently present or where there may be some remnant beach present that can be nourished. However, there is little information available on the basic physical attributes of existing San Francisco Bay Beaches, upon which to base the design of beach restoration projects. Bay beaches tend to have different characteristics than the much more commonly studied beaches of the outer coast that are typically discussed in the literature and taught in coastal engineering classes.

Roger Leventhal of the Marin Department of Public Works (DPW) and Peter Baye worked closely with San Francisco State University (SFSU) and the San Francisco Estuary Institute (SFEI) on two studies that included assessments of beach habitats and restoration design options at Marin County Sites (Leventhal et al. 2021, SFEI and Baye 2020). Out of these efforts, the highly eroding Greenwood and Brunini Beach site in Tiburon was selected as the best site for a demonstration project of the ability of bay beaches to inhibit wind-wave erosion of shorelines while providing habitat and public use and aesthetic values.

The Greenwood Beach Restoration Project (the project) is a nature-based beach restoration and shoreline erosion protection project proposed on approximately 1.4 acres of the Richardson Bay shoreline at Blackie's Pasture Park (the Park) in Tiburon, California (Figure 1).

The shoreline has undergone significant erosion and a loss of sand substrate, accelerating since approximately 2012, resulting in a lag-dominated shoreline with erosion of fill including asphalt entering the Bay. The proposed beach restoration approach combines beach nourishment with related wetland and terrestrial elements, including regraded shoreline scarps stabilized with native sand-trapping beach and bluff vegetation, large woody debris, and "drift-sills" (low-relief obstacles to longshore drift, projecting perpendicular to the shore) composed of cobble salt marsh, intergrading with existing salt marsh. A detailed description of the proposed project design can be found in the project Restoration Design Report (Gillenwater et al. 2025)

The Greenwood Beach Project design and regulatory compliance phases were funded by a grant from the San Francisco Bay Restoration Authority. As part of the original grant application, Marin DPW staff requested funds to conduct a data collection program at the Greenwood Beach site and several other beaches (reference sites) around northern San Francisco Bay (Figure 2) to inform the design of the Greenwood Beach project, and provide a reference dataset for the broader engineering and science community to inform the design of other beach restoration projects around the Bay. This report documents the methods and results of the reference site data collection program and provides a summary of the major findings from this study. It is assumed that users of the data collected in this effort will perform further analyses of the data, specific to their own project needs.

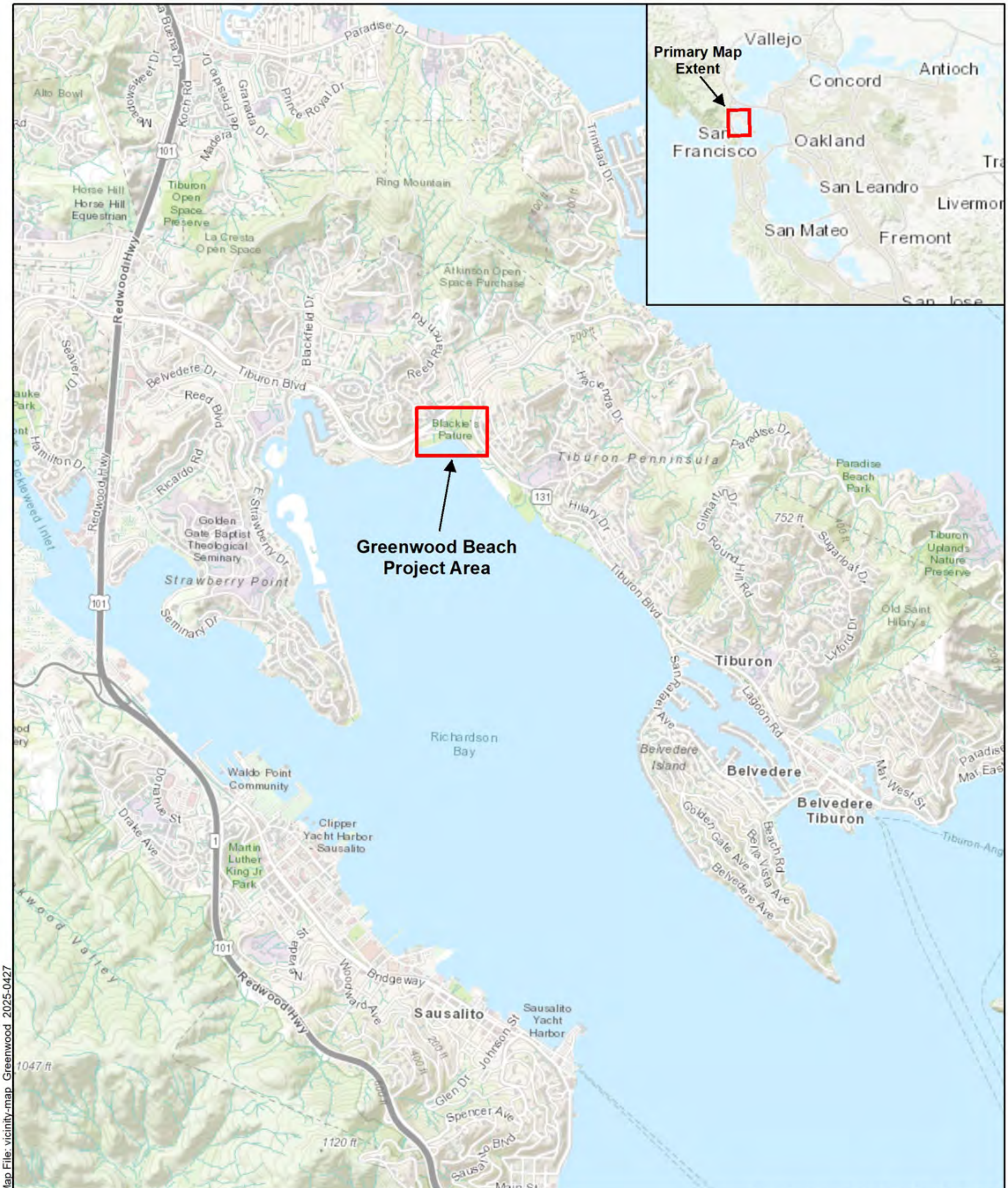
All data collected in this effort are available to the public for use and analysis. Contact Dan Gillenwater of Gillenwater Consulting (dan@gillenh2o.net) to request access to the datasets.

Note that the data are provided as-is without any warranty or guarantee as to accuracy or usefulness. Users of the data (user) are responsible and assume all liability for verification of the data and for its use in their projects. By using these data, the user agrees to hold SFBRA, Marin County DPW and the authors of this report harmless for any consequences. All interpretations presented herein are qualitative and the opinions of the authors; users are responsible for verifying these conclusions.

2 Reference Beach Monitoring Program

As mentioned above, the reference site data collection program was designed to provide data to inform the design of the Greenwood Beach project and to understand some basic geomorphic properties of selected beaches around central and northern San Francisco Bay, providing a dataset that can be used to inform the design of future beach projects. The study involved intensive data collection at Greenwood Beach, and more focused data collection at the other reference beaches. The primary questions of interest in this monitoring program are listed below. This study was exploratory, providing quantitative data on selected natural San Francisco Bay beaches that have not previously been studied. It was not designed to test any specific hypotheses, though others may attempt to use the data from this study to test hypotheses *ad-hoc*, or to inform future studies meant to test specific hypotheses.

1. What are the typical topographic profiles of at central and northern SF Bay beaches and how do those topographic profiles vary seasonally (winter storm season vs. summer calm season), and in response to individual storm events?
2. What is the range of beach material composition and grain size distribution at central and northern SF Bay beaches, and how do these vary, if at all, seasonally (winter storm season vs. summer calm season), and in response to individual storm events?
3. Specifically at Greenwood Beach:
    a. What is the magnitude and direction of beach sediment transport during storm and calm weather conditions?
    b. What is grain size distribution of the local nearshore flood control channel delta and is it a suitable source of material for local beach restoration?
    c. What is the nature and degree of bedload transport on the flood control channel delta during typical annual storm events?
    d. What is the wave climate in Richardson Bay and how does it vary seasonally?
    e. What is the nature of the infaunal community on the nearshore tidal flats?



Data sources: Air photo (ESRI basemap, 2023);

Greenwood Beach Restoration Project

1:36,000 (1" = 3,000' at letter size)

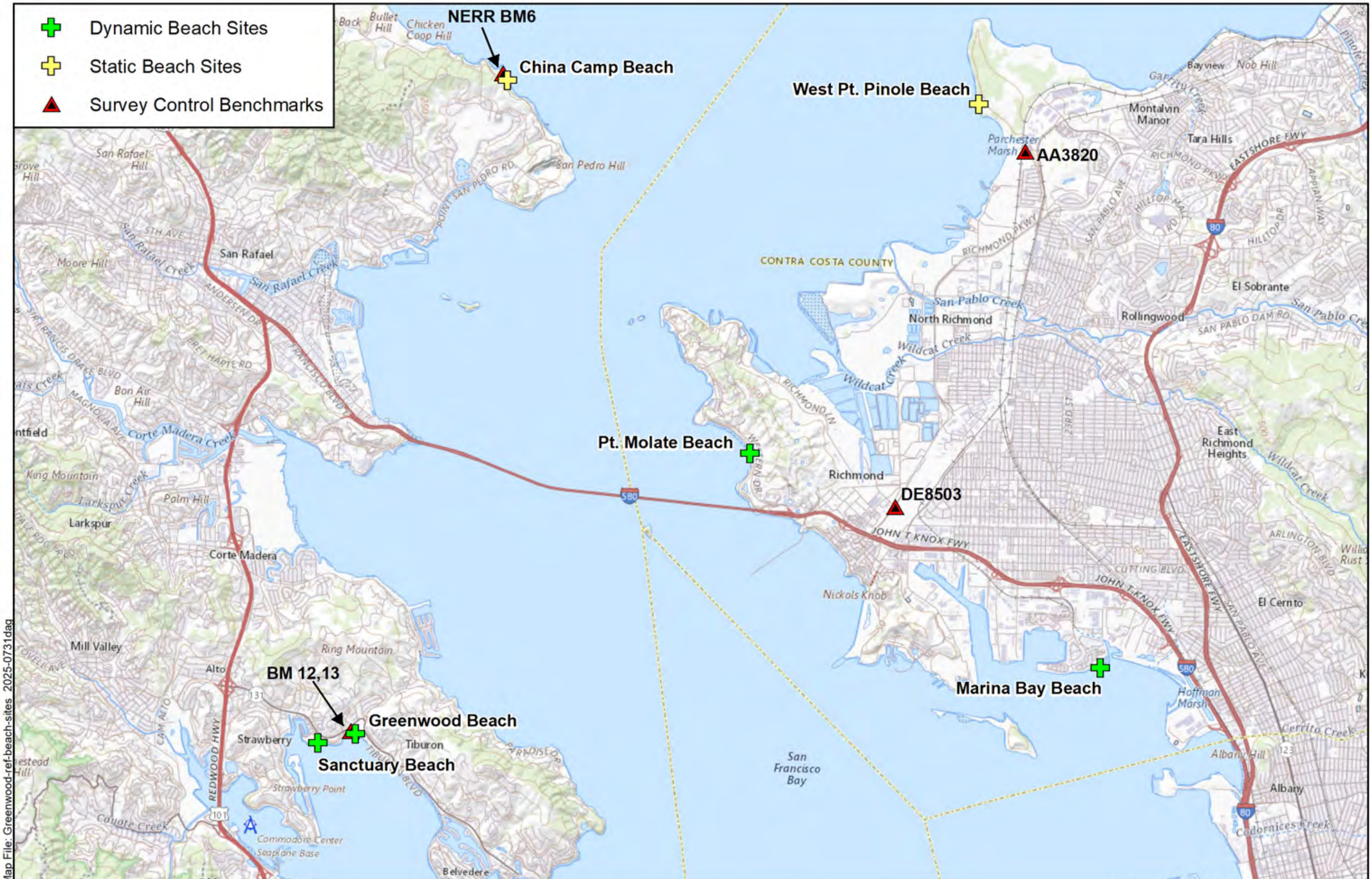
0 1,500 3,000 ft

0 500 1,000 m

Gillenwater GillenH2O Consulting

Figure 1

Project Location and Vicinity



Map File: Greenwood-ref-beach-sites 2025-0731dag

Data sources: Basemap (ESRI, 2021);
Site locations (GillenH2O, 2021); Benchmarks (NGS, 2021)

1:95,040 (1" = 1.5 mi at letter size)

0 0.75 1.5 Mi
0 1.25 2.5 Km

Greenwood Beach Restoration Project

Figure 2

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Reference Beach Study Locations

2.1 Reference Beaches

This study involved data collection at Greenwood Beach and five other reference bay beaches spread across the Marin County and Contra Costa County shorelines all within Central and Northern San Francisco Bay (Figure 2). The reference beaches consist of "Dynamic" and "Static" sites; Dynamic sites are composed primarily of mobile beach sediments (sand and fine-medium gravel) and have more dynamic morphology, whereas Static sites are composed of less mobile material (coarse gravel and cobble) and do not change much over time. Dynamic sites were monitored multiple times to understand changes and trends in morphology over time, while Static sites were monitored only once to establish baseline conditions. Basic descriptions of these beaches are provided below.

2.1.1 Marin County Beaches

Greenwood Beach (Dynamic). Greenwood Beach, the primary study site for this project, is situated on the shoreline of a reclaimed, filled historical salt marsh that was historically used as a private horse pasture, and is currently a public park (Blackies Pasture Park) (Figure 3). The site consists of two separate beach units along the Richardson Bay shoreline: Greenwood Beach, and Brunini Beach. The beaches are bordered to the south by wide Richardson Bay tidal flats. To the north of the beaches are the nearly level lowlands of Blackie's Pasture Park. A flood control channel draining a portion of the Ring Mountain watershed runs through the park and enters Richardson Bay between Greenwood and Brunini beaches, bisecting the project area and depositing an ebb tide delta of coarse sediments on the nearshore tidal flats.

Sanctuary Beach (Dynamic). Sanctuary Beach is a small south-facing pocket beach in Richardson Bay at the toe of a low vegetated bluff within a bedrock-dominated shore, located at the Richardson Bay Audubon Sanctuary in Tiburon, west of Greenwood Beach. The beach is formed within a wave-cut bench in Franciscan sandstone and shale bedrock. It is bounded by a sandstone headland at the west end, and smaller bedrock outcrops at the east end. The calm-weather beach consists of a very narrow backshore that varies temporally between seaward-sloping sand, and a gravel storm berm that sometimes persists in the calm-weather beach profile. The inner low tide terrace consists of coarse sand, variably covered with muddy sand. The outer low tide flats are mud. The beach is exposed to a long southerly wind-wave fetch over the deep water of the Central Bay and Golden Gate.

China Camp Beach (Static). China Camp Beach is a natural fringing coarse sand and fine gravel beach bounded by sandstone headlands within a shallow embayment. The beach and adjacent been only slightly altered by historic development, and it is protected within China Camp State Park. Development has been limited to alluvial flats landward of the beach, and construction of a pile-supported wooden pier. The beach consists of a relatively steep berm and beachface at the toe of low sandstone cliffs narrow valleys supporting upland oak-bay woodland. The low tide terrace below the beachface varies from rocky shore (a wave-cut bench with cobble and boulder pavement) at the south end, and sandy mud at the north end. The beach is oriented east-northeast and is exposed to wind-waves from the north, east, and south. The plan form of the beach is rectilinear and has changed little since the earliest U.S. Coast Survey T-sheets. The sources of beach sand and gravel appear to include long-term shoreline retreat, erosion of sandstone bluffs, and alluvial fan outwash from canyons and gullies within the local embayment. Beach cusps are evident at times in summer. One remnant trace of an old beach ridge with soil development is at times evident at the south end of the beach, below an alluvial fan. Little native or non-native perennial vegetation establishes on the beach; saltgrass, western ragweed, beach-bur, and Gould's wildrye are locally common in relatively stable beach sand at the bluff toe.

Map File: Greenwood-Beach-Photo 2025-0324

Data sources: Air photo (Audubon, 2022)

Greenwood Beach Restoration Project

1:1,200 (1" = 100' at letter size)

0 50 100 Feet

0 15 30 Meters

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Figure 3

Greenwood Beach Study Area

Map File: Sanctuary-Beach-Photo 2025-0324

Data sources: Air photo (Audubon, 2022)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

0 25 50 Feet

0 7.5 15 Meters

Gillenwater GillenH2O Consulting

Figure 4

Sanctuary Beach Study Area

Data sources: Basemap (ESRI, 2025)

Greenwood Beach Restoration Project

1:1,800 (1" = 150' at letter size)

0 75 150 Feet

0 25 50 Meters

Figure 6

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China Camp Beach Study Area

2.1.2 Contra Costa County Beaches

Point Molate Beach (Dynamic). Point Molate Beach is a fringing bluff-toe sand beach within a west-facing embayment between Point Molate and Castro Point in Richmond, Contra Costa County. The south end is bounded by natural low sandstone cliffs and outcrops. The north end is artificially truncated by a boulder revetment. The backshore beach is very narrow, and is composed of mostly coarse to medium sand. The beach is fully exposed to wind-waves generated from the west, northwest, and southwest. The planform of the beach is slightly arcuate, with relatively little variation in beach width alongshore. Local beach protuberances near the south end are associated with coarse gravel and sand deltas of seasonal canyon streams draining hillslopes through culverts, which discharge directly to willow thickets behind the beach. The low tide terrace consists of boulder and cobble lag armor with sand and mud, and the nearshore subtidal to lower intertidal zone supports extensive eelgrass beds. Eelgrass wrack is a common depositional feature on the beach, where it forms small swash bars on the beachface, composed of rolled eelgrass litter and sand masses. Coarse woody debris is also common on the beach. Minimal native or non-native vegetation develops in the backshore below the bluff toe. Local small patches of annual sea-rocket, Mediterranean saltwort, iceplant, and saltgrass commonly occur on the beach. Creeping wildrye extends from the riparian thickets to the beach at the south end.

Marina Bay Beach (Dynamic). Marina Bay Beach is a self-generated barrier beach on the Marina Bay shoreline of Richmond, Contra Costa County, near the mouth of Meeker Slough. It originated from wave-reworked sand deposition in artificial post-war fill and development of the Richmond Shoreline. The barrier beach links the boulder-armored bay fill lands of the Marina Bay residential development, and a shore-detached remnant artificial earthen fil island. The island adjoins a rectangular salt marsh island sheltered by an L-shaped boulder revetment. The barrier beach is rectilinear in plan form, and faces southwest to Richmond Inner Harbor, with a long fetch to the Central Bay. The barrier beach is composed of sand, shell, and gravel. The barrier is narrow, and composed of relatively uniform, coarse-grained short washover fans. The washover fans are vegetated with high salt marsh at the back, and low-relief foredunes less than half a meter in thickness. The berm is coarse-grained sand, angular shell hash, and gravel. The beachface is usually dominated by quartz-rich, well-sorted medium sand. The low tide terrace is a wide, sandy foreshore grading from rippled fine to medium sand, to muddy sand in the lower intertidal zone. The backshore vegetation is dominated by a mix of native beach-bur, gumplant, beach saltbush, saltgrass, and non-native iceplant and sea-rocket.

West Point Pinole Beach (Static). West Point Pinole Beach is a small west-facing crescent sandy pocket beach in the Point Pinole Regional Park. It occupies a gently sloping valley, nested between an ancient cobble-gravel recurved barrier beach and backbarrier salt marsh to the south, and a cobble-gravel fringing beach below the bluffs of West Point Pinole. The beach has a well-developed wide backshore and beachface, narrowing at the north and south ends. The inner low tide terrace is sandy to sandy mud, grading to muddy sand in the lower foreshore. Cobble and gravel storm berms are sometimes exposed in the backshore, particularly towards the north and south ends. The backshore vegetation is composed of a mix of non-native iceplant, perennial pepperweed, sea-rocket, Mediterranean saltwort, and annual grasses, and native saltgrass, creeping wildrye, beach-bur, and poverty-weed.

Data sources: Air Photo (Audubon, 2022); basemap (ESRI, 2025)

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1:2,400 (1" = 200' at letter size)

0 100 200 Feet

0 30 60 Meters

Figure 7

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Point Molate Beach Study Area

Data sources: Air Photo (Audubon, 2022); Basemap (ESRI, 2025)

Greenwood Beach Restoration Project

1:1,800 (1" = 150' at letter size)

0 75 150 Feet

0 25 50 Meters

Gillenwater GillenH2O Consulting

Figure 8

Marina Bay Beach Study Area

Map File: PtPinole-Beach-Photo 2025-0324

Data sources: Air Photo (Audubon, 2023)

Greenwood Beach Restoration Project

1:1,800 (1" = 150' at letter size)

0 75 150 Feet

0 25 50 Meters

Gillenwater GillenH2O Consulting

Figure 9

West Point Pinole Beach Study Area

2.2 Monitoring Elements and Schedule

This reference beach study included several distinct data collection efforts aimed at addressing the primary questions of interest. These studies are summarized below. The detailed data collection and analysis methods associated with these studies are provided in Section 3.

Static Seasonal Beach Surveys. Static seasonal beach surveys were conducted to understand seasonal (winter storm season vs. summer calm season) differences in beach morphology. These surveys were conducted twice (one winter and one summer survey) at the dynamic reference sites, and once at the China Camp and Pt. Pinole reference site. These surveys involved the following data collection activities:

1. **Shoreline topographic transect surveys**. Topographic surveys were conducted along three-four shore-normal transects extending from the backshore, along the beachface, and out onto the tidal flats to document the shoreline topography.
2. **Aerial imagery and photogrammetry surveys**. High resolution aerial imagery and photogrammetry data were collected at each beach by unmanned aerial vehicle (UAV/drone) to analyze topography and morphology. No aerial imagery was collected at China Camp beach due to the intact tree canopy at the site, which obscures approximately half of the beach area.
3. **Surface grain size sampling**. The beach surface grain size distribution across the shore-normal transects was assessed by either (1) laboratory analysis of material grab samples, or (2) by field-based line intercept sampling and analysis of material *in-situ*.
4. **Beach stratigraphy surveys**. The stratigraphy (vertical profile) of the beach was assessed at multiple locations along one beach transect to understand beach material thickness and composition changes with depth.

Storm Response Surveys. Storm response surveys were conducted at the dynamic reference sites multiple times a year following storm events with winds that were assumed adequate to produce significantly greater wave energies than found under baseline conditions, and likely to induce notable changes in beach morphology. A total of six storm events were monitored at various beaches from 2022 to 2024 (Table 1). Surveys typically occurred within 3-5 days following the storm event. These surveys involved (1) shoreline topographic transect surveys and (2) surface grain size sampling following the same approaches as the static seasonal surveys. In addition, focused investigations into the stratigraphy of the beach berm at Marina Bay Beach were conducted in the winter of 2024 following notable changes in the position and height of the berm in 2023 monitoring events. The storm events that triggered monitoring events and the dates that the reference sites were monitored are provided in Table 1.

Table 1. Storm Events Monitored at Study Beaches

Storm Date	Beach Survey Dates	Survey Locations	Storm Duration (hr)	Avg. Wind Speed (mph)	Avg. Wind Gust Speed (mph)	Max Wind Gust Speed (mph)
12/9/2022	12/13/2022-12/22/2022	Greenwood, Sanctuary, Marina Bay, Pt. Molate	23	12	15	22
1/14/2023	1/17/2023-1/18/2023	Greenwood, Sanctuary, Marina Bay, Pt. Molate	16	12.9	14.3	22
4/3/2023	4/13/2023	Pt. Molate	29	11.5	13.6	21
1/31/2024	2/1/2024	Marina Bay	24	10.25	11.8	19
2/5/2024	2/9/2024	Greenwood	22	18.6	22	27
3/1/2024	3/12/2024	Marina Bay	20	14.7	17	24

Focused Greenwood Beach Studies. Several studies were conducted at Greenwood Beach to answer specific questions related to the design of the beach restoration project, including:

1. **Beach particle transport**. Beach particle tracking studies were conducted during both storm and calm conditions to understand the magnitude and direction of beach sediment transport. The studies utilized dyed native beach material “tracers” that were sampled on a grid across the study area over multiple days.
2. **Flood control channel delta and tidal flat stratigraphy**. The stratigraphy and grain size characteristics of the delta were assessed at multiple locations to understand material suitability for use in reconstructing the beaches at the site.
3. **Delta bedload transport**. A rudimentary bedload trap study was conducted on the delta during a storm event in the winter of 2024 to understand the nature and degree of bedload transport on the flood control channel delta during typical annual storm events.
4. **Wave climate**. Wave sensors (pressure transducers and wave buoys) were deployed for a year (2023) at multiple locations to assess the annual wave climate within Richardson Bay and along the Greenwood Beach and Aramburu Island shorelines.
5. **Mudflat infauna (macroinvertebrate) community**. A survey of the benthic macroinvertebrate community in the tidal flats off Greenwood Beach was conducted to understand potential fish and bird prey availability at the site.

Table 2. Monitoring Program Schedule

	2021	2022												2023												2024											
Monitoring Activity	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Static Seasonal Surveys				■ *1*			■	■																													
Storm Response Surveys	■ *2*												■	■			■										■	■									
Greenwood-Specific Studies																																					
Particle Transport												■	■									■	■														
Delta and Tidal Flat Stratigraphy				■																																	
Delta Bedload Transport																											■										
Wave Climate												■	■	■	■	■	■	■	■	■	■	■	■	■	■	■											
Mudflat Macroinvertebrate							■																														

Notes:

1. March 2022 data collection effort was focused on obtaining data for preliminary project design and consisted of topographic and grain size sampling in addition to other data collection activities

2. December 2021 survey was a baseline (pre-storm) survey and test of data collection methods

3 Methods

This section provides an overview of the data collection and analysis methods associated with the various data collection activities. Figures showing data collection locations are provided in the Results sections.

3.1 Beach Topographic Surveys

Shoreline topographic transect surveys were performed at all reference beaches in this study. Each site contained three to six shore-normal transect running from the uplands to the nearshore tidal flats, capturing the entire extent of the study beaches. The transect alignments were established on the first survey event and the landward endpoints monumented with stakes/rebar to allow easy reoccupation and confirm the transect alignments.

Topographic surveys were performed with an *Emlid RS2* real-time kinematic (RTK) GPS rover that was set up to receive real-time position corrections from the California Real-Time Network (CRTN) base station network via cellular/Bluetooth Networked Transport of RTCM[1] via Internet Protocol (NTRIP). Survey elevation control and QA/QC was performed by checking in/out at existing local or regional benchmarks (Figure 2) at the beginning and end of each survey. Survey elevations were adjusted to match the reported elevations of the control benchmarks to remove systematic survey error. Greenwood, Sanctuary, and Aramburu Beach surveys utilized local benchmarks established at Greenwood Beach in 2023 by Cinquini & Passarino Surveying (C&P) for the Town of Tiburon, while surveys at all other sites used existing National Geodetic Survey (NGS) or National Estuarine Research Reserve (NERR) benchmarks. The control benchmarks utilized for each reference beach are listed in Table 2 below.

Table 3. Survey Control Benchmarks Utilized

Reference Beach	Control Benchmarks
Greenwood, Sanctuary	C&P BM12, BM13
China Camp	NERR BM6
Pt. Molate, Marina Bay	NGS DE8503
West Pt. Pinole	NGS AA3820

Transect alignments were reoccupied by loading the data from the first survey events into the GPS rover to allow point-to-point navigation. Survey data points were taken along the shoreline at all notable changes in topographic profile, with a maximum spacing of approximately 10 ft.

[1] Radio Technical Commission for Maritime Service

The post-processed and benchmark-corrected survey data were loaded into *ArcGIS Pro* for review. Linear referencing tools were used to locate the survey data along the established transect alignments, thus allowing accurate 2-D data plotting and comparison to previous survey events. The linear-referenced data were exported into *MS Excel* and plotted for visual analysis.

3.2 UAV Imagery and Photogrammetry

UAV imagery and photogrammetry data were collected at the reference beaches with a DJI Phantom 4 Pro drone equipped with an 1-inch, 20-megapixel camera with CMOS mechanical shutter. Flight planning was done in the *Pix4D* software suite. Flight lines were set to ensure minimum image overlap of 75% (frontlap) and 65% (sidelap) to optimize photogrammetry data quality. The imagery acquisition extent included the entire beach area, plus a suitable buffer to capture adjacent uplands and tidal flats. Imagery was collected during low tides in the late morning to early afternoon to maximize the extent of exposed (dry) shoreline visible and optimize for sun angle. Ground control for image orthorectification and photogrammetric analysis was provided by a series of ground control points (GCPs) and quality control points (QCPs) set along the uplands and tidal flats, bounding the horizontal and vertical area of interest. The upland control points consisted of 2’x2’ vinyl targets anchored to the ground with 5” common nails and washers. The tidal flat control points consisted of crosses painted directly on the mudflat with white, non-toxic chalk marking paint. The center of each control point was surveyed with an *Emlid RS2* RTK GPS unit to provide position and elevation information. Survey elevation control and QA/QC was performed by checking in/out at existing local or regional benchmarks (Figure 2) at the beginning and end of each survey. Survey elevations were adjusted match the reported elevations of the control benchmarks to remove systematic survey error. See Table 2 for the benchmarks used at each reference beach.

The drone imagery was post-processed in the *Pix4D* software suite to produce a high-resolution orthorectified mosaic, photogrammetry point cloud, and resulting digital surface model (DSM). The accuracy of the image rectification and DSM elevations were assessed in *Pix4D* by calculating the root mean squared error (RMSE) between the positions of the QCPs in the orthomosaic image and DSM, and their surveyed coordinates. The DSMs were visualized in ArcGIS Pro and used to assess changes in beach elevation and volume between surveys at each reference beach.

3.3 Surface Grain Size Sampling and Analysis

Concurrently with the shoreline topographic surveys described above, beach surface grain size sampling was conducted along the shoreline topographic transect alignments. Along each of these transects, the shoreline was divided into shore-parallel zones of relatively homogenous beach sediment type, and a representative sample was taken from the surface of each of these zones. The sampling zones fell within three distinct geomorphic positions along the shoreline: (1) beach berm/backshore, (2) beach face, and (3) tidal flat (Figure 4). Typically, three to four zones were sampled per transect. Sediment sampling and grain size analysis occurred via one of two methods based on the dominant particle size found in each zone.

1. In zones where the dominant particle size was gravel or smaller, a sediment grab-sample was collected. Approximately 500 ml of sediment (enough to half fill a 6 1/2" X 5 7/8" Zip-Lock style plastic storage bag) was collected from the top 2" of the beach surface and the samples were double bagged in gallon-size freezer bags. These samples were then sent to the UC Davis Bodega Marine Laboratory where they were analyzed for grain size distribution and median particle size (D50) following standard sieving methods modified from Bunte and Abt (2001).
2. In zones where the dominant sediment type was large gravel/cobble or greater, the grain size distribution and median particle size were determined via line-intercept method similar to that described in Bunte and Abt (2001). In each zone, a 5-m transect tape was stretched across a representative area and particles intersecting the transect tape at 10 cm intervals were collected (for a total of 50 particles per sample). Each of the 50 particles was measured using a gravelometer and the data were recorded in the appropriate size class on standardized datasheets. These data were then used to determine grain size distribution and D50.

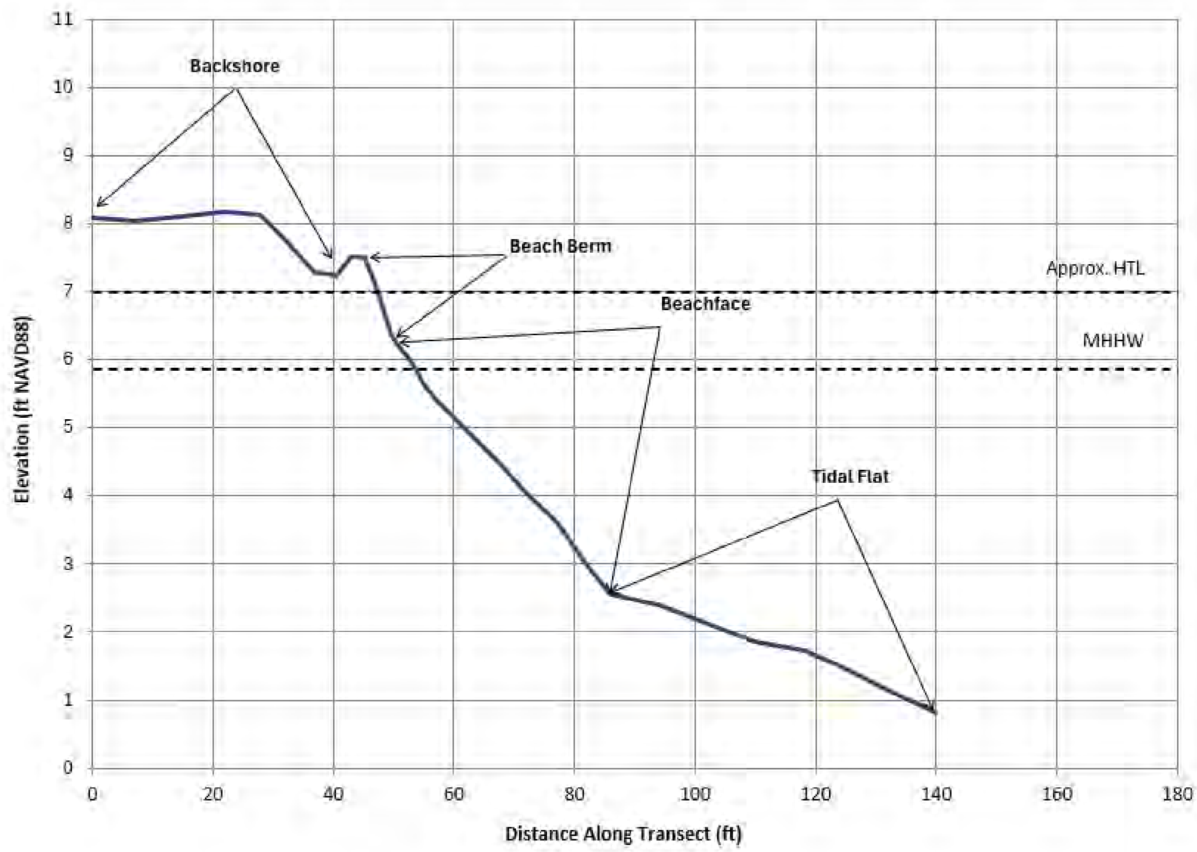


Figure 9. Typical Beach Profile Diagram

3.4 Vertical Beach and Delta Sediment Profiles

The beach vertical profile (stratigraphy) was assessed at two beach face locations along the central shoreline topographic transect at each study site. At each profile location, a pit was dug down through the profile of mobile beach sediment to the underlaying "immobile" basal surface (bay mud, cobble, bedrock, etc.). The total depth of the pit (beach thickness) was measured, and the elevations of the beach surface and basal surface were surveyed with the *Emlid RS2* RTK GPS rover (see Section 3.1 for survey methods and QA/QC). The sediment profile at each pit was described in a bore log and representative samples from distinct layers of beach sediment were collected for later grain size analysis, according to the methods described in Section 3.3.

At Greenwood Beach, the vertical profile of the nearshore tidal flats and flood control channel delta were assessed at multiple locations in March 2023 to understand the material composition and distribution. Five pits were dug along the north-south axis of the delta and three pits were dug east-west along the nearshore tidal flats off Greenwood Beach. Pit depth was between ~1.5 – 2 ft. The sediment profile at each pit was described in a bore log. Representative samples from distinct layers of sediment were collected from selected pits for later grain size analysis, according to the methods described in Section 3.3.

3.5 Particle Tracking Studies

Two separate beach particle tracking studies were conducted at Greenwood Beach to understand the nature of beach sediment transport during storm and calm conditions. The purpose of the short-term particle tracking studies was to quantify rates of sand or gravel movement alongshore in storm and calm wind-wave conditions. The methods for these two studies are described below.

3.5.1 Tracking Study No. 1 – Storm Conditions

Particle tracking study 1 was conducted following a major storm event in the winter of 2022 by Mario Accordino of UC Davis. The methods for that study are provided in Appendix F, and are summarized here. Beach sediment was collected from Greenwood Beach, Brunini Beach, the Flood Control Channel, and the Delta to create the tracer samples on December 3rd, 2021. The sediment was dyed with a fluorescent pigment according to the methods outlined by Kinsman and Xu (2012) and Ciavola and Grottoli (2017). Based on the intended sediment deployment locations, a sampling grid was established at regularly spaced intervals around each deployment point to track particle movement. Approximately 1 cubic foot of dyed sediment was placed at each deployment location on 11/30/2022 and covered with ½ to 2 inches of sediment to mimic natural beach conditions and sediment dispersion at the deployment sites. Tracer samples were deployed on Greenwood Beach, Brunini Beach, within the flood control channel, and on the flood control channel delta.

Tracer surveys were performed after dusk on 12/1/2022, 12/2/2022, 12/7/2022, 12/12/2022, and 12/27/2022. During tracer surveys, an *Emlid RS2* RTK GPS unit was used to guide researchers to the pre-established sampling grid points. At each point, a circular frame (9.75” in diameter, 0.52 sq. ft. area) was placed on the beach. A fluorescent light was used to determine the presence of dyed sediments in the framed area. Visible dyed grains were counted and recorded. Photos were taken of each grid point where fluorescent grains exceeding 0.5mm were present and the maximum grain size recorded. The data were analyzed and visualized in ArcGIS Pro to assess changes in the spatial distribution of the dyed tracer grains over time and understand shoreline sediment transport processes.

3.5.2 Tracking Study No. 2 – Calm Conditions

Particle tracking study 2 was conducted during calm weather conditions in the fall of 2024. The study methods were similar to those in the first study, but with some important modifications.

Dyed tracer samples were deployed only at Greenwood Beach in this effort to better understand longshore and cross-shore drift patterns at this beach. Two sand samples and one mixed gravel sample were deployed at the updrift end of Greenwood Beach on the surface and were not covered with native beach material. The sampling grid was also modified from the 2022 study grid to provide more extensive cover of the tidal flats and delta.

The gravel sample (green) and a single sand sample (orange) were deployed at the site on 9/17/2024. The second sand sample (blue) was deployed on 9/18/2024 after initial sampling the evening of 9/17 discovered scattered orange grains from the 2022 study that were contaminating the shoreline and potentially influencing the study results. The gravel sample was placed in a band 1ft from the local high-water line to halfway down the beach face. The orange and blue sand samples were placed in parallel bands between the toe of the slope to approximately 1ft below the local high-water line with the blue sand in a band just east of the orange. The four corners and the center of the deployed sample were surveyed with the *Emlid RS2* GPS unit.

An initial post-deployment site inspection was performed the evening of 9/17/2022 to after the first high tide inundated the samples to understand the initial distribution and transport of dyed grains. The beach was walked from west (updrift) to east (downdrift) with a blacklight to look for the presence of dyed grains, which as described qualitatively and with photographs. Using the RTK GPS for navigation, the beach area transects (A-Q) were walked to look for the presence of dyed grain transport. If luminescence was observed, the sampling frame was placed in the area of the highest particle density and a rough count was made of the number of particles.

Formal tracer surveys were performed after dusk on 9/18, 9/19, 9/23, 9/30, and 10/3/2024. The sampling methodology was similar to that used for study 1. In addition, at all survey points where luminescence was observed (and at a fixed subset of the sampling points, regardless of luminescence), a shallow pit (~4” deep, ~6” diameter) was dug in the beach with a hand trowel to look for the presence of buried dyed grains. The data were analyzed and visualized in ArcGIS Pro to assess changes in the spatial distribution of the dyed tracer grains over time and understand shoreline sediment transport processes.

3.6 Flood Control Channel Delta Bedload Transport Study

A brief bedload transport study was performed on the flood control channel delta by staff from Audubon California during a storm event in February 2024. The methods for that study are detailed in Appendix G, and are summarized here. The study occurred between 1/29/24-2/2/24 to capture conditions during a typical winter storm event (~0.5 year recurrence interval). A series of four, 3.5 gallon buckets (4.1 gallon actual max capacity) were buried on the delta, flush to the ground, to act as pit traps for mobile sediment. Two buckets were buried on the delta bar (bar pits; BP) and two were buried within the primary delta distributary channel (channel pits; CP). Buckets were buried on 1/29/24 and 1/30/24 in preparation for the storm on 1/31/24. A wooden stake was hammed into the ground 1 ft west of each bucket and the above ground length was measured. The buckets were retrieved after the storm subsided on 2/2/24. The depth (thickness) of accumulated sediment in each bucket was measured at 5 locations within the bucket- north, south, east, west, and center point- and averaged. Additionally, the height of the wooden stakes left above ground was measured to determine local delta surface erosion/accretion patterns.

After retrieval, water was slowly drained from the buckets. After partial drying, a window was cut into the side of the bucket to observe layers of accumulated material and the lithology of the deposits recorded on a bore log. Samples from distinct sediment layers identified within each bucket were collected for laboratory grain size analysis following the methods described in Section 3.3.

3.7 Local Wave Climate Study

In 2023, researchers from the UC Davis Coastal Oceanography Group conducted a year-long study of the wave climate in central Richardson Bay and at the Greenwood Beach and Aramburu Island shorelines. The methods for this study are provided in Appendix H and are summarized here. The study employed a combination of in-water *RBRsolo3* pressure sensors and a mid-bay *SOFAR* wave buoy to measure wave activity in Richardson Bay, focusing on Greenwood and Aramburu Beaches. *RBRsolo3* pressure sensors were deployed in shallow water near the beaches, as well as on a National Estuarine Research Reserve (NERR) piling in the middle of the bay, to capture wave conditions without the influence of shoreline shoals. The SOFAR buoy, deployed in March 2023, provided additional wave height, direction, and period data. These instruments recorded data at 2Hz frequency, which were then processed into hourly values for significant wave height, wave power, and water level. Wind data from a weather station in Tiburon and NOAA buoy data were also analyzed to examine correlations between wind forcing and wave generation. The collected data were corrected for atmospheric pressure fluctuations and analyzed for seasonal variations, tidal effects, and wave event identification. To account for data inconsistencies, such as sensor exposure during low tides or pressure attenuation at high tides, only reliable wave height values were included in the final analysis. Comparisons between sites allowed researchers to assess differences in wave energy dissipation from the mid-bay to the shorelines. Additionally, wave power was calculated using established equations to determine the energy delivered to the beaches.

3.8 Mudflat Infaunal Surveys

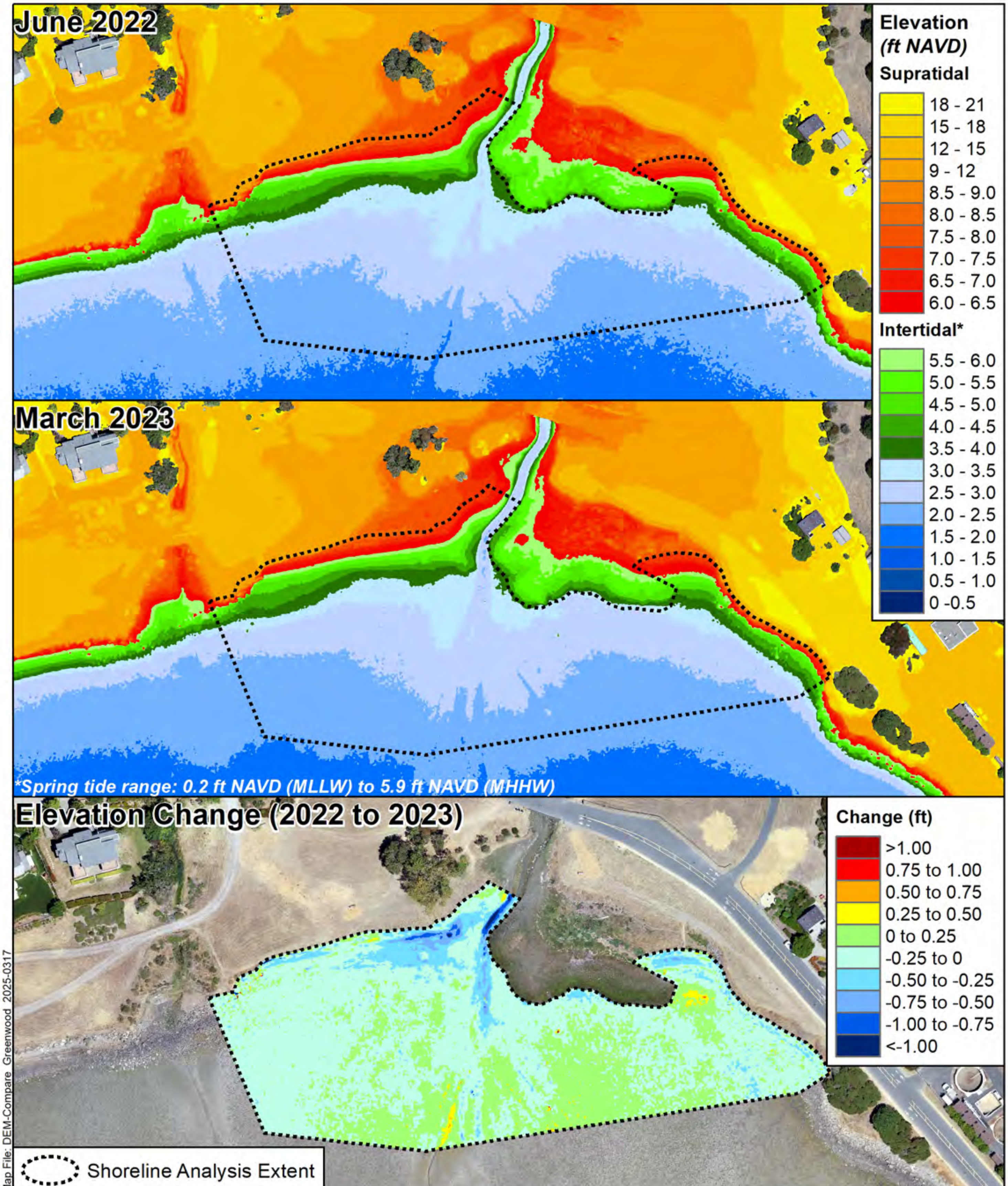
Geana Ayala, a researcher from the SF State Estuary and Ocean Science Center (EOS), conducted a survey of the benthic macroinvertebrate community along the Greenwood Beach tidal flats in June 2022. The methods for this survey are described in Appendix I and summarized here. Six sediment cores were collected parallel to the shoreline at Greenwood Beach at six pre-determined locations. Each core was collected by pushing a 5 cm diameter PVC pipe to a depth of 10 cm. A rubber stopper was placed on the top of the PVC to create a suction, and the core contents were placed into a plastic bag and stored on ice. In the lab, the cores were rinsed of all mud and debris and passed through a 1 mm sieve to collect invertebrates. Invertebrates were fixed in 70% ethanol and identified to taxonomic order. After invertebrates were counted, they were dried at 50 °C to a constant mass and weighed. When invertebrates are fixed in ethanol, it is common to us dry weights for biomass estimates.

4 Results and Discussion

This section summarizes the results and major findings of the various data collection activities. The results are organized by topic, as opposed to data collection activity, to allow a more comprehensive analysis of the findings. The beach topography and material composition data that were collected across all reference sites are presented first, followed by the Greenwood Beach specific study data. Select maps and data figures are provided in this section, while the bulk of the detailed figures are contained in appendices organized by topic and site.

4.1 Beach Topography

Beach topographic data that were analyzed in this effort include both shoreline topographic transect survey data and the UAV-based photogrammetric DSMs. The summer 2022/winter 2023 DSMs and elevation change calculations for the dynamic sites are provided in Figure 10 - Figure 14. The beach topographic survey transect locations and data plots are presented by reference site in Appendix A.



Data sources: Air photos (Audubon, 2022); Elevation (Audubon and GillenH2O, 2022-2023)

Greenwood Beach Restoration Project

1:1,800 (1" = 150' at letter size)

0 75 150 ft

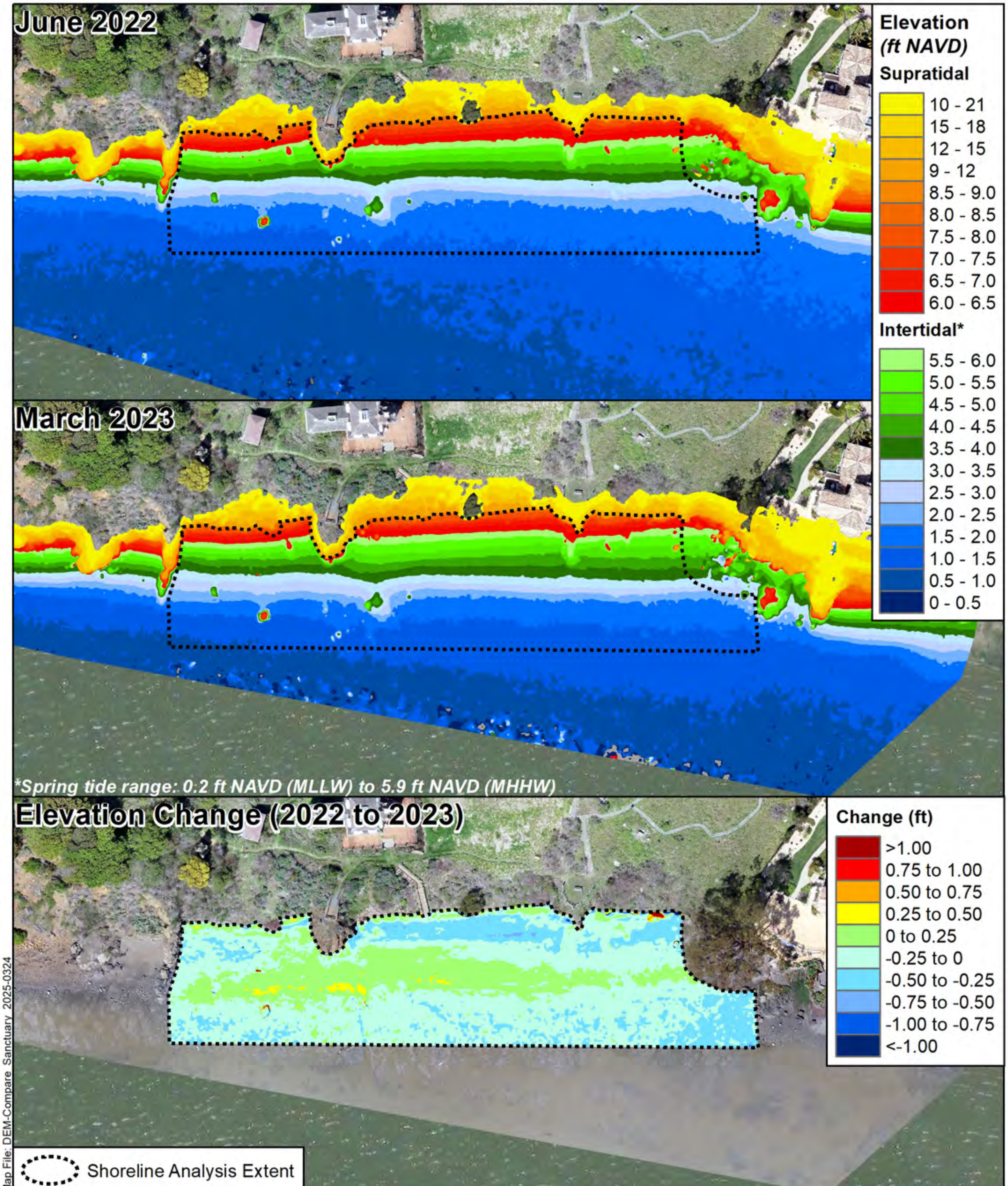
0 25 50 m

Gillenwater GillenH2O Consulting

TOWN OF TIBURON CALIFORNIA INC. 1964

Figure 3

Greenwood Beach
Topographic Change: Summer 2022 to Winter 2023



Data sources: Air photos (Audubon, 2022-2023); Elevation (Audubon and GillenH2O, 2022-2023)

1:1,200 (1" = 100' at letter size)

0 50 100 ft

0 15 30 m

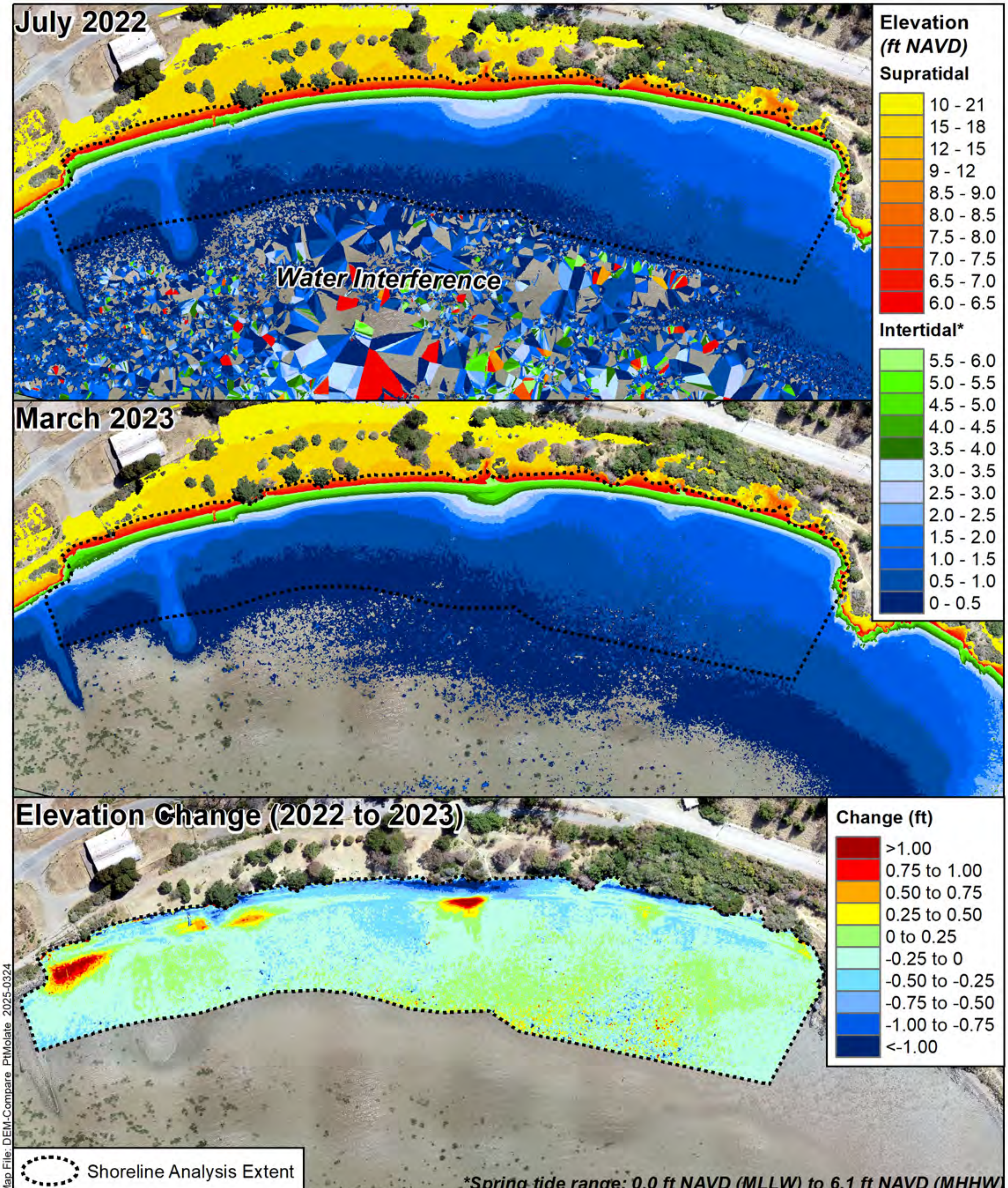
Greenwood Beach Restoration Project

Figure 3

Sanctuary Beach
Topographic Change: Summer 2022 to Winter 2023

Gillenwater GillenH2O Consulting

TOWN OF TIBURON CALIFORNIA INC. 1964



Data sources: Air photos (Audubon, 2022-2023); Elevation (Audubon and GillenH2O, 2022-2023)

Greenwood Beach Restoration Project

1:1,800 (1" = 150' at letter size)

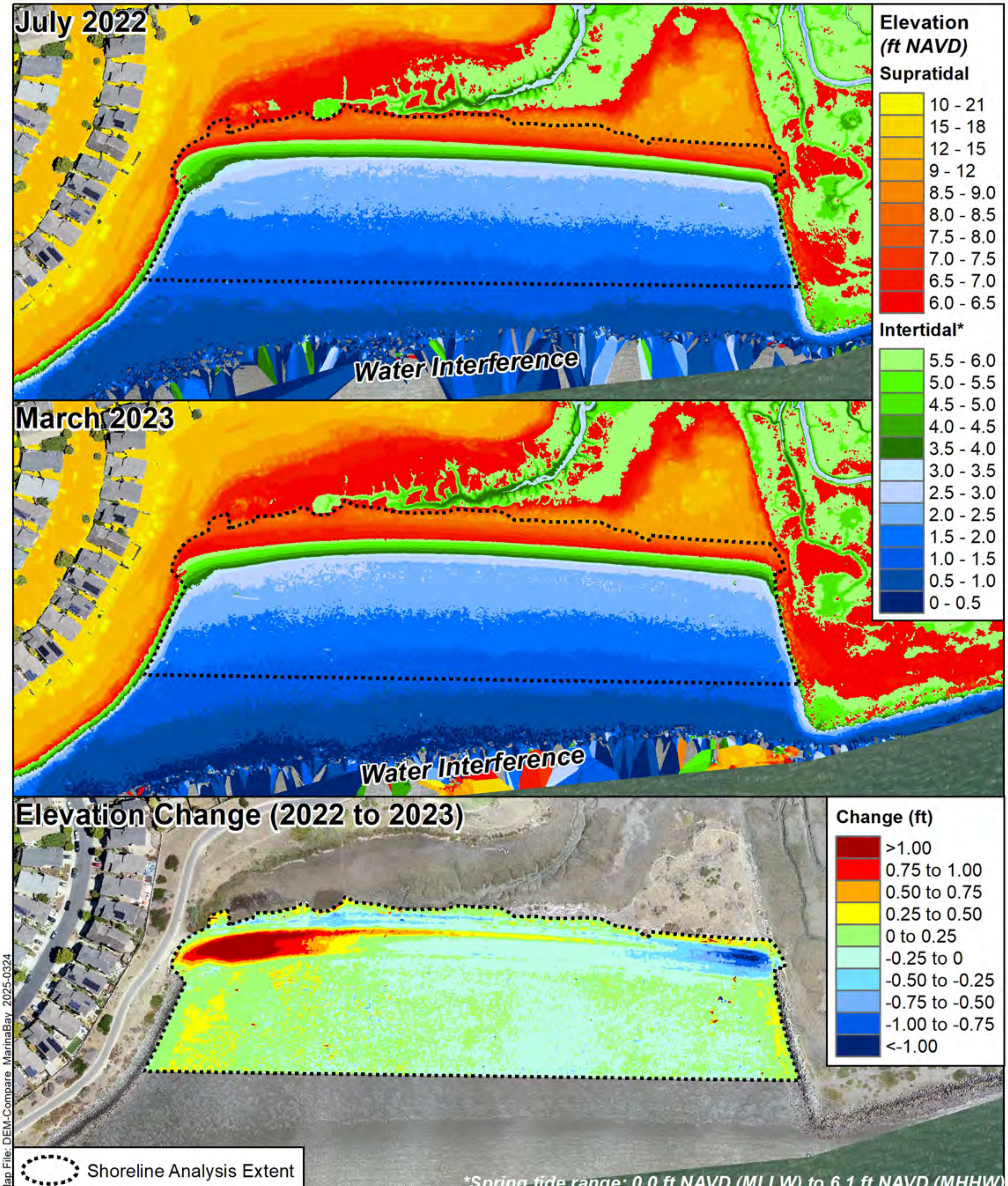
0 75 150 ft

0 25 50 m

Gillenwater GillenH2O Consulting

Figure 3

Pt. Molate Beach
Topographic Change: Summer 2022 to Winter 2023



Data sources: Air photos (Audubon, 2022-2023); Elevation (Audubon and GillenH2O, 2022-2023)

Greenwood Beach Restoration Project

1:2,400 (1" = 200' at letter size)

0 100 200 ft

0 30 60 m

Gillenwater GillenH2O Consulting

Town of Tiburon, California Inc. 1964

Figure 3

Marina Bay Beach
Topographic Change: Summer 2022 to Winter 2023

4.1.1 Results by Site

Patterns and trends observed in beach topography at the individual reference beaches are described below.

Greenwood Beach

The Greenwood site exhibited variable topographic change along the west-east (longshore) axis. The western end of the beach, dominated by gravel and cobble, remained relatively stable throughout the monitoring period. In contrast, the eastern section experienced more significant and progressive profile changes, with notable loss of material from the beachface and little evidence of recovery during summer or calm-season surveys. The most substantial beachface erosion occurred at the eastern end, where sand was stripped from the profile, exposing and eroding the underlying relict delta marsh substrates. The stripped sand was transported east where it deposited in a spit recurve at the mouth of the flood control channel. Over time, this spit also experienced erosion as the material was (presumably) transported out to the Bay during high outflow events from the channel. Brunini Beach demonstrated greater resilience, with some profile variability but evident seasonal recovery. DEM elevation change analysis from Summer 2022 to Winter 2023 revealed variable erosion along the beachface, erosion of the flood control channel, and dynamic (but minor) patterns of erosion and deposition across the channel delta, primarily associated with the migration of distributary channels. Topographic transects across the delta and DEM analysis showed very little seasonal change in delta topography outside of the distributary channels. A net sediment loss of 310 cubic yards was recorded in the shoreline analysis area between June 2022 and March 2023. Slope analysis indicated beach slopes ranging from 5.8% to 8.9% across the site, with no clear seasonal trend. Slopes were generally lowest in the middle section of the beach and steeper at both the east and west ends. Overall, average beach slope remained consistent, varying between 6.8% and 7.5% over time.

Sanctuary Beach

Compared to Greenwood, Sanctuary exhibited less longshore topographic change, with cross-shore variations being more prominent. All cross sections at the site showed erosion and profile loss during the winter season, followed by recovery by the end of the calm season. Gravel storm berms regularly formed near the base of the cliff, were reworked during storm events, and appeared to reset during calmer periods. DEM analysis between summer and winter static profiles indicated minor erosion along the beachface and corresponding deposition on the tidal flats. Overall, there was a net erosion of 165 cubic yards of sediment from the shoreline analysis area between June 2022 and March 2023. Slope analysis showed beach slopes ranging from 6.5% to 12.6%, with a general trend of decreasing slope from west to east—approximately 12% in the west to 7.5% in the east. No progressive change or distinct seasonal trend in slope was observed, and average beach slopes consistently remained between 9.1% and 9.9% over time.

Point Molate Beach

Point Molate exhibited variable patterns of profile erosion and recovery across both space and time, with clear differences observed from north to south along the site. The northern end experienced net progressive accretion, while the southern portion showed net progressive erosion over the monitoring period. The central beach area underwent phases of erosion followed by recovery. Minimal changes were observed in the location and elevation of the beach berm at transects T1 and T2, whereas upslope migration was evident at T3. DEM analysis between summer 2022 and winter 2023 showed spatially variable patterns of beach erosion and deposition, with predominant erosion along the shoreline. Small shoreline protuberances (residual gravel deltas) and large woody debris appeared to act as partial barriers to sediment transport, creating isolated pockets of deposition—most notably at the northern end of the site. Overall, there was a net erosion of 1,095 cubic yards of sediment from the shoreline analysis area between July 2022 and April 2023. Slope analysis revealed beach slopes ranging from 8% to 12.8%, with a general increase in average slope from north to south. The greatest variability was recorded at T1, where slopes ranged from 8% to 11.9%. Site-wide average beach slopes remained within a narrow range of 10.9% to 12.1%, with no clear seasonal trends identified.

Marina Bay Beach

Marina Bay exhibited the most variable topography among all monitored sites, showing dynamic patterns of profile depletion and recovery over time. Seasonal erosion and accretion patterns varied spatially across the beach: the western end experienced accretion during the winter and depletion in the summer, while the eastern end showed the opposite trend, with summer accretion and winter depletion. The central transect displayed more variable cross-shore erosion and accretion patterns that shifted seasonally. DEM analysis from summer 2022 to winter 2023 revealed distinct east-west trends, with erosion concentrated in the eastern portion of the site and deposition occurring in the west. Storm berms appeared to form seasonally, but were reworked and occasionally overwashed and flattened (i.e., no progressive landward berm migration). Variable patterns of erosion and deposition were also noted across the tidal flats. Overall, the shoreline analysis area exhibited a net accretion of 425 cubic yards of sediment between July 2022 and March 2023. Slope analysis indicated beach slopes ranging from 8.0% to 12.6%, with a slight increase in average slope from west to east. All transects exhibited similar variability in slope, and a modest seasonal trend was observed: summer (calm season) profiles were generally steeper, with an average slope of 10.9%, compared to winter (storm season) profiles, which averaged 9.3%.

China Camp Beach

China Camp is a relatively stable beach, as expected from its bay-head position and coarse sand and gravel composition it was therefore only surveyed one time to establish basic beach characteristics. This beach had the steepest profile of all reference beaches with the beachface slope ranging from 12.5% to 14.1% (average 13.1%). Transects 1 and 2, north of the pier, had very similar and almost linear slopes with little topographic variation. Transects 3 and 4, south of the pier, showed more variable topography, and captured portions of the tidal flats at the base of the beach.

West Point Pinole Beach

The West Point Pinole beach was surveyed only once to establish baseline conditions for comparison of basic beach characteristics to other sites. The West Point Pinole Beach had the most complex shoreline geomorphology of all beaches surveyed. There were three distinct beach segments captured by the surveys, each exhibiting different morphology and configuration. The distinct segments, north to south, included a fringing straight cobble-gravel beach, a crescent concave-bayward fringing sand beach, and an old convex-bayward cobble-gravel recurved spit fronting a salt marsh. The topographic transects reflect these variations in beach morphology. This site had the largest variation in beach slope across all reference sites, from 5% to 10.8%, with variations in breach profiles from rather simple to complex.

4.2 Beach Material Composition

Beach material composition data includes the surface grain size samples collected along beach topographic transects, and shallow (< 3 ft deep) vertical beach profile bore logs and grain size samples. Grain size sampling locations and data plots are provided by reference site in Appendix B. Beach profile bore logs are provided by reference site in Appendix C.

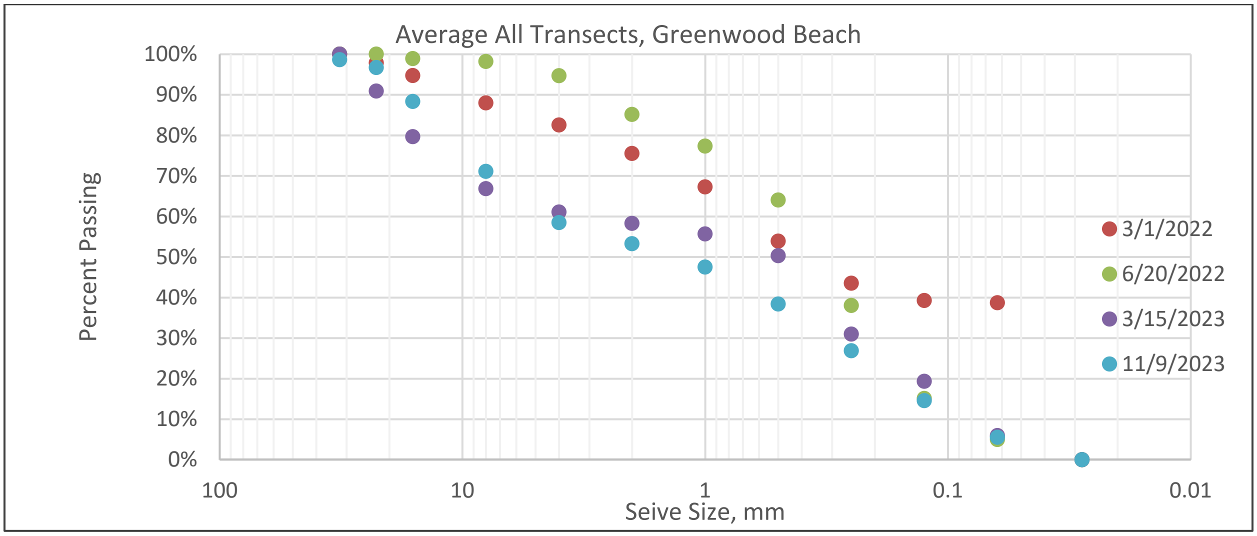
4.2.1 Results by Site

Patterns and trends observed in beach material composition at the individual reference beaches are described below.

Greenwood Beach

Averaged across dates and transects, material at Greenwood Beach was 67% sand fractions, and 33% gravel fractions. Grain size distribution of Transect 1 was skewed toward larger size classes compared to Transect 4. They were similar when comparing the average of all transects for each date (i.e., seasonal patterns were not apparent). However, compared to a baseline distribution on 6/20/22, a storm event on 1/14/23 appears to have shifted the grain size distribution towards smaller size classes by the time of the 3/15/23 survey. Variability by size class showed no discernable patterns across days and transects.

Average size of D50 across all transects and dates was 3.24 mm (range 0.11 – 13.54, SD 4.20). Time of year had no discernible effect, but at Transect 4 the storm events of 12/9/22 and 1/14/23 appear to have increased the size of D50 by 201% (from 2.34 mm on the 6/20/22 survey to 4.70 mm on the 3/15/23 survey).



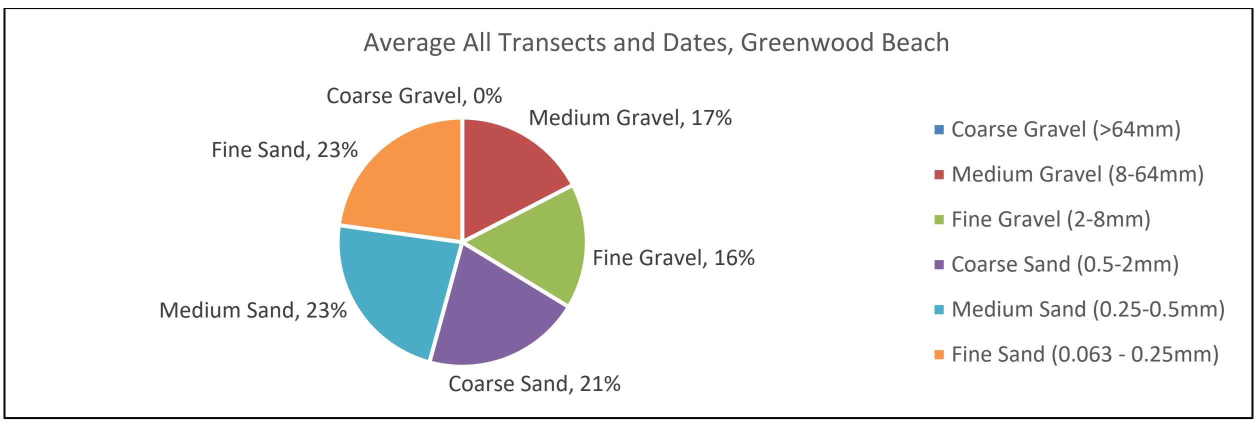
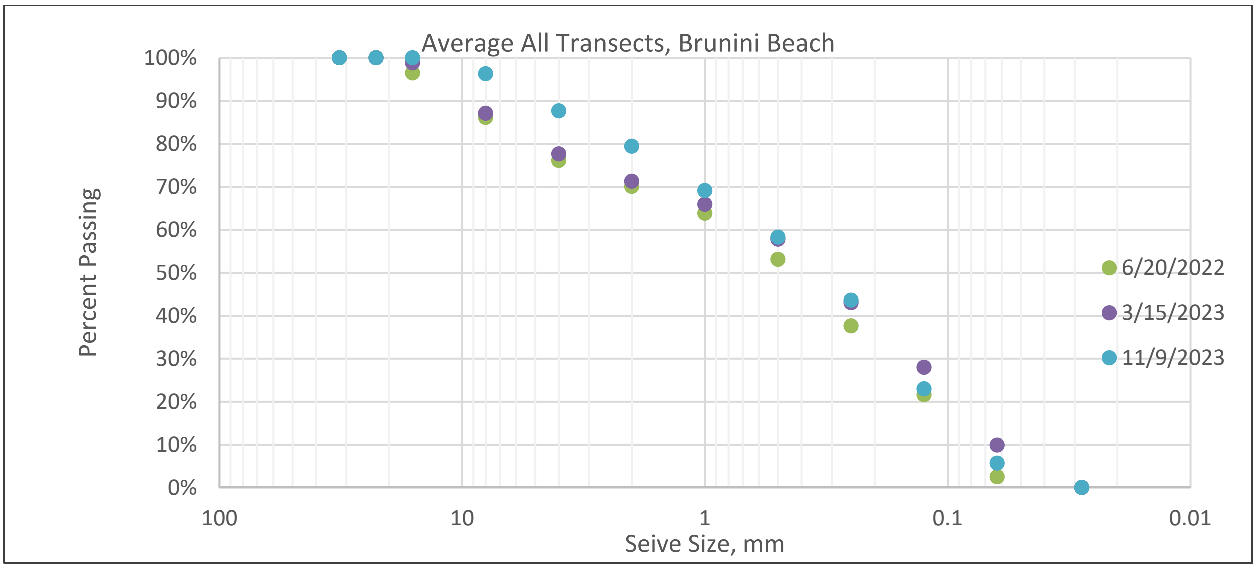


Figure 14. Overall Surface Grain Size Characteristics, Greenwood Beach

The subsurface beach profile at Greenwood Beach, along the central beach transect (T-2), was a heterogenous mixture of sand and gravel from 13" – 20" deep underlain by an immobile cobble layer , similar to the cobble armoring present at the extreme west end of the beach. Gravel size fractions made up >50% of the subsurface profile in all samples. Discrete bands of sand or gravel/cobble were present in some pits, likely representing specific depositional or erosional events. There was little change in the overall visual subsurface composition or beach thickness between the summer 2022 and winter 2023 sampling events, though the grain size data suggest a coarsening of the lower beachface profile (BP-2). This could be due to the presence of one or two larger gravel particles in the grab sample.

Averaged across dates, material at the single transect on Brunini Beach was %72 sand fractions, and 28% gravel fractions. Variability by size class showed no discernable patterns across days.

Average size of D50 across dates was 0.70 mm (range 0.11 – 2.45, SD 0.74). Time of year had no discernable effect. The storm events of 12/9/22 and 1/14/23 appear to have reduced the size of D50 by 53% (from 1.70 mm on the 3/1/22 survey to 0.80 mm on the 3/15/23 survey).



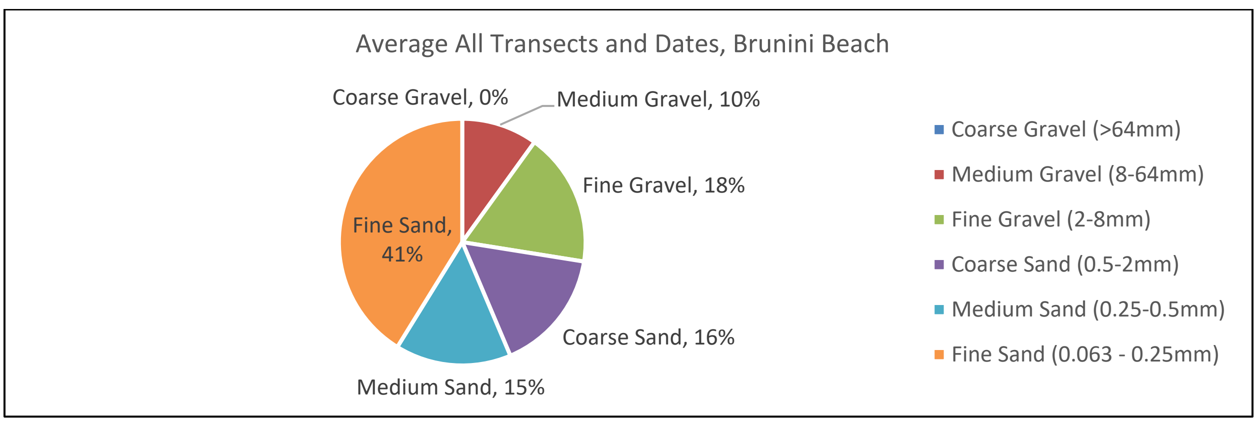


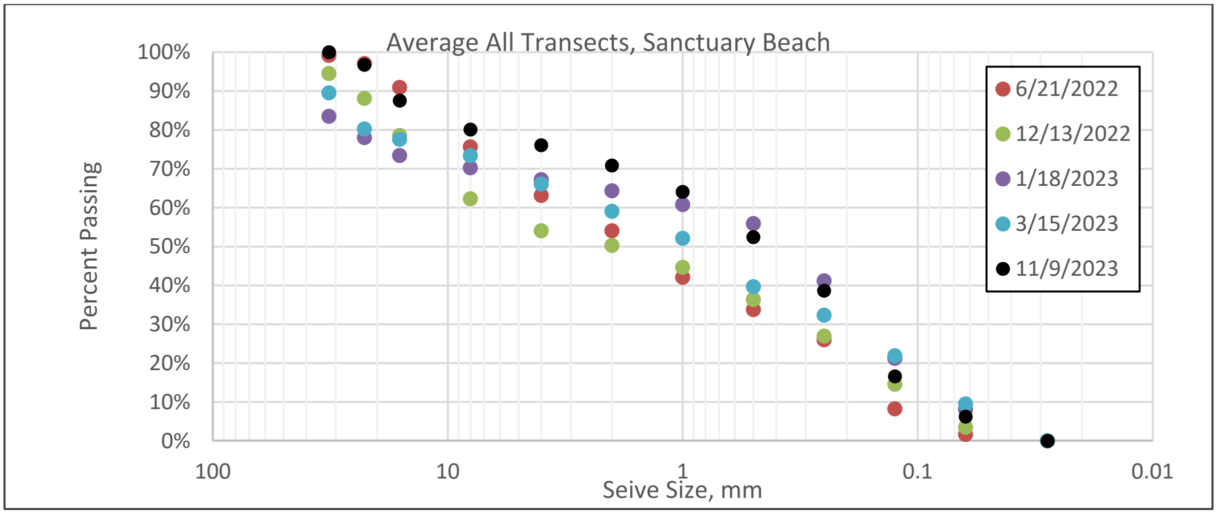
Figure 15. Overall Surface Grain Size Characteristics, Brunini Beach

Sanctuary Beach

Averaged across dates and transects, material at Sanctuary Beach was 61% fine, medium, and coarse sand, and 39% fine, medium, and coarse gravel. Grain size distributions were similar when comparing the average of all transects for each date (i.e., seasonal patterns were not apparent). Grain size distribution patterns were generally consistent across transects with the exception of Transect 3, which had a lower proportion of material in the smaller size fractions. A storm event on 1/14/23 appears to have briefly shifted GSD towards presence of mid-sized materials (i.e., removed smaller materials) by the time of the 1/18/23 survey. By the time of the 3/15/23 survey, the distribution had reverted to close to the 6/23/22 profile. Variability by size class showed no discernible patterns across days and transects.

Average size of D50 across all transects and dates was 4.49 mm (range 0.08 – 30.98, SD 7.46). Time of year had no discernible effect on size of D50, but storms had substantial apparent effects. At Transect 1 a storm event on 1/14/23 appears to have reduced D50 by 98% (from 7.75 mm to 0.16 mm) by the time of the 1/18/23 survey, with the size of D50 returning to 3.96 mm by the time of the 11/9/23 survey. At Transect 2, a storm event on 12/9/22 appears to have increased the size of D50 by 213% (from 3.1 mm to 6.61 mm) by the time of the 12/13/22 survey, and a storm event on 1/14/23 appears to have reduced the size of D50 by 92% (from 6.61 mm to 0.56 mm) by the time of the 1/18/23 survey. At Transect 3 the 12/9/22 storm event appears to have increased the size of D50 by 235% (from 2.81 mm to 6.61 mm) by the time of the 12/13/22 survey, and the 1/14/23 storm event appears to have increased it by another 18% (to 7.72 mm) by the time of the 1/18/23 survey.

The Sanctuary Beach subsurface profile was sampled along the central transect (T-2) only once in the summer of 2022. It was characterized by a mixture of sand and gravel 11” – 17” thick underlain by plastic Bay Mud. Sand size fractions made up >50% of the subsurface samples in all pits. The most bayward (lowest) beach profile (BP-3) displayed a discrete band of gravels and cobbles in the middle of the vertical profile, but was otherwise similar to the composition in the other two profiles.



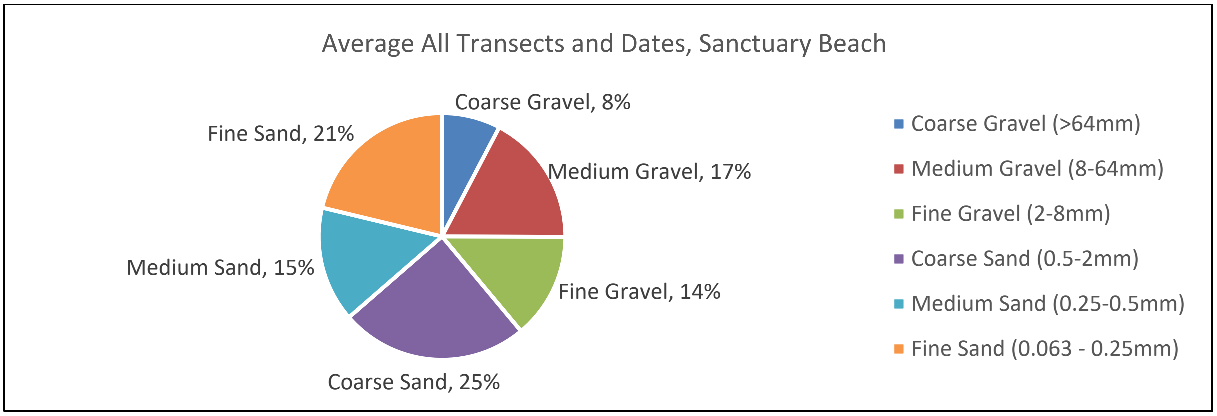
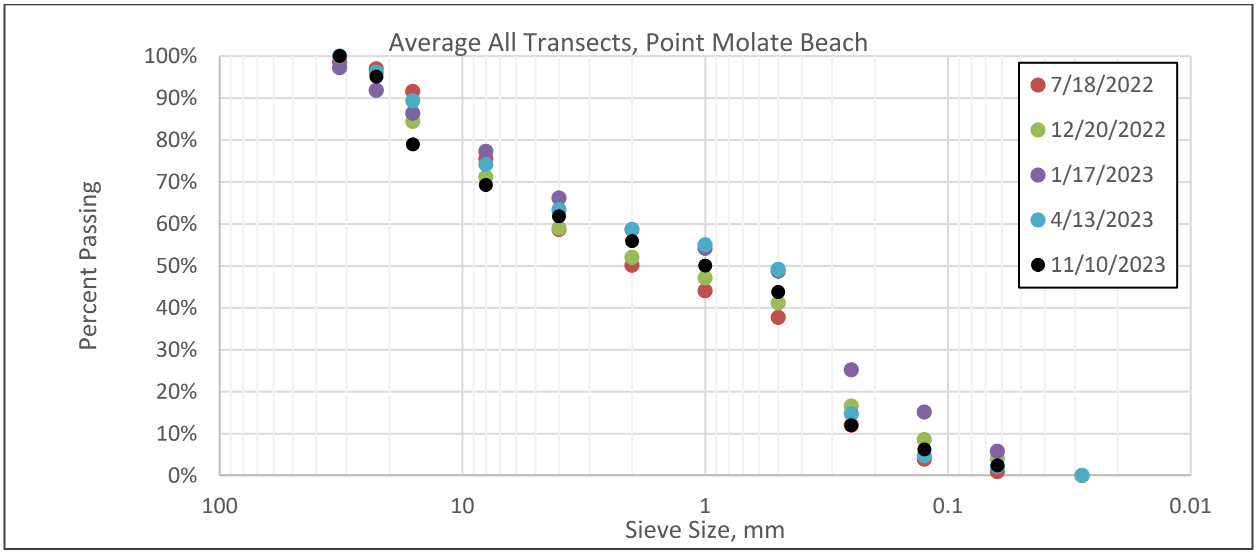


Figure 16. Overall Surface Grain Size Characteristics, Sanctuary Beach

Point Molate Beach

Averaged across dates and transects, surface material at Marina Beach was 54% fine, medium, and coarse sand, and 46% medium and fine gravel (no coarse gravel). Grain size distributions were similar between Transects 1 and 2 and slightly skewed toward smaller fractions on Transect 3. They were also similar when comparing the average of all transects for each date (i.e., seasonal patterns were not apparent). However, compared to the distribution on 12/20/22, storm events on 1/14/23 and 4/3/23 both appear to have shifted the distribution slightly towards larger size classes by the time of the survey on 4/13/23. During the following months when no further storms were recorded for Point Molate Beach, GSD then returned to close to the 12/20/22 profile by the time of the 4/13/23 survey and then closer again by the time of the 11/10/23 survey. Variability by size class showed no discernible patterns across days and transects.

Average size of D50 across all transects and dates was 3.05 mm (range 0.00 – 19.11, SD 4.64). Time of year had no discernable effect, but at Transect 1 4/3/23 appears to have increased the size of D50 by 516% (from 1.10 mm to 5.65 mm) by the time of the 4/13/23 survey, with GSD returning to 0.69 mm by the time of the 11/10/23 survey. At Transect 2 the same storm event appears to have increased the size of D50 by 273% (from 2.33 mm to 6.35 mm) by the time of the 12/20/22 survey, with the size of D50 returning to 3.51 mm by the time of the 11/17/23 survey. Also at Transect 2, an earlier storm event (12/9/22) appears to have increased the size of D50 by 272% (from 2.33 mm to 6.35 mm) by the time of the 12/20/22 survey.



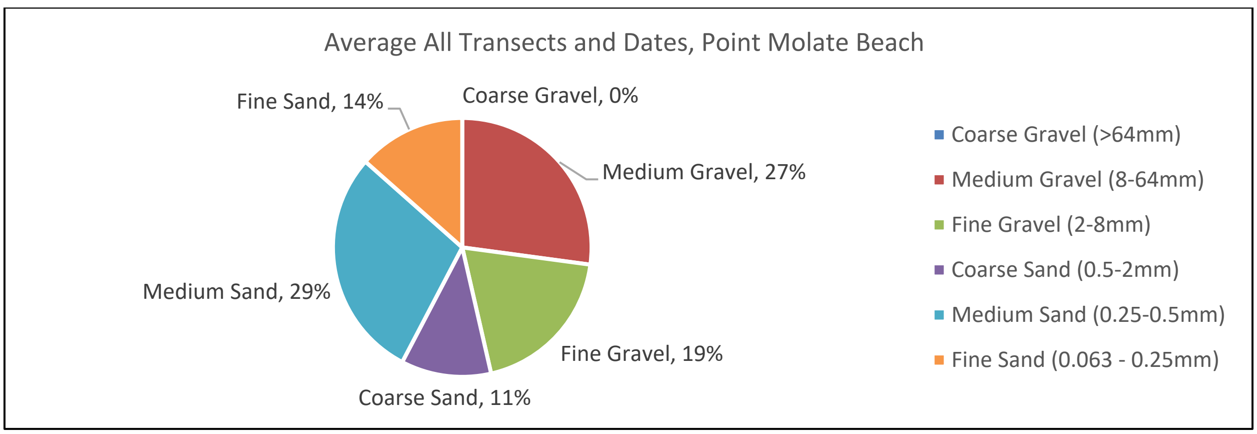


Figure 17. Overall Surface Grain Size Characteristics, Pt. Molate Beach

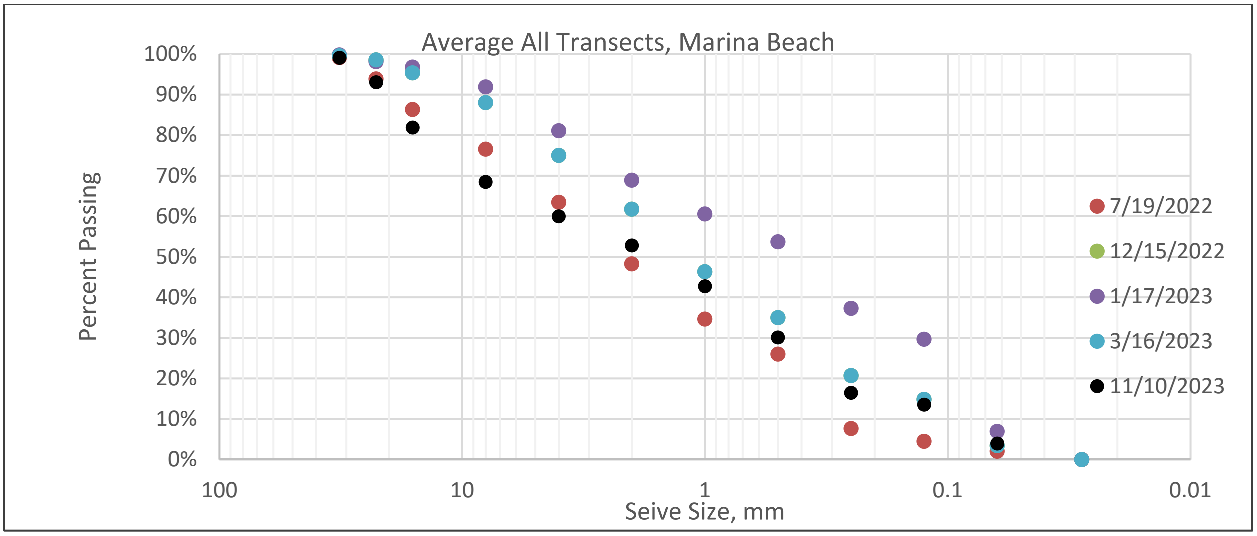
The subsurface beach profile along the central transect (T-2) at Pt. Molate Beach was characterized in summer 2022 by a layer of sand intermixed with a smaller fraction (<25%) of gravel. At the two lower beachface profiles (BP-2, BP-3), this layer was overlain by a coarser mixture of gravel and sand from 10" – 21" thick. No basal, immobile layer of bay mud, cobble, or bedrock was found in the pits, which were dug to a depth of ~3 ft below grade. The winter 2023 beach profiles indicated mixing, homogenization, and coarsening of the beach, particularly at the lower beachface profile (BP-2). At the upper profile (BP-1), and immobile layer of cobbles was encountered at 21” below grade, while bay mud was encountered at 20” below grade at the lower profile (BP-2). The sampling locations were located in an area that experienced 0.75’ – 1.0’ of erosion between the summer 2022 and winter 2023 sampling dates (see Figure 13), which could explain the reworking and thinning of the beach profile.

Marina Bay Beach

Averaged across dates and transects, material at Marina Bay Beach was 59% fine, medium, and coarse sand, and 41% medium and fine gravel (no coarse gravel). Grain size distributions were generally consistent across transects and were similar when comparing the average of all transects for each date (i.e., seasonal patterns were not apparent). However, compared to the GSD on 7/19/22, a storm events on 12/9/22 and 1/14/23 both appear to have shifted GSD towards larger size classes by the time of the surveys on 12/15/22 and 1/17/23. During the following months when no further storms were recorded for Marina Beach, GSD then returned to close to the 6/21/2022 profile by the time of the 3/16/23 survey and then closer again by the time of the 11/10/23 survey. Variability by size class showed no discernable patterns across days and transects.

Average size of D50 across all transects and dates was 2.51 mm (range 0.08 – 18.97, SD 4.05). Time of year had no discernable effect on size of D50, but at Transect 1 a storm event on 1/14/23 appears to have reduced the size of D50 by 65% (from 3.70 mm to 1.31 mm), with the size of GSD returning to 2.06 mm by the time of the 3/16/23 survey then to 3.60 mm by the time of the 11/10/23 survey. At Transect 2 the same storm event appears to have reduced the size of D50 by 80% (from 2.32 mm to 0.46 mm), with the size of D50 returning to 3.7 mm by the time of the 3/16/23 survey then to 5.22 mm by the time of the 11/10/23 survey. Similarly, on Transect 3, a storm event on 12/9/22 appears to have reduced the size of D50 by 55% (from 1.65 mm to 0.76 mm) by the time of the 12/15/22 survey, with the size of D50 returning to 2.06 mm by the time of the 1/17/23 survey.

The subsurface profile along the central beach transect (T-2) in summer 2022 was characterized by a relatively homogenous layer of mixed sand and gravel, which at the lower two profiles (T-2 and T-3) was underlain by a layer of muddy/clayey sand from 7” – 16” below grade, likely representative of the original dredged material that was deposited at this location. This basal layer was not reached at the upper beachface profile within ~3’ of the surface. In the winter of 2023, the subsurface profile was similar to summer, but the grain size distribution appeared to contain a slightly higher fraction of sand (fining), while the surface material became coarser. The basal muddy/clayey sand layer was encountered between 16” and 26” below grade.



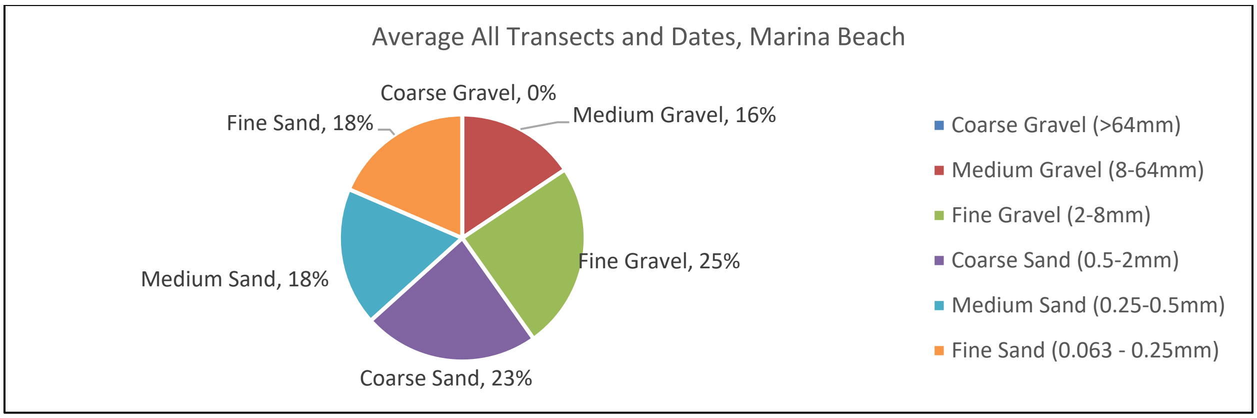


Figure 18. Overall Surface Grain Size Characteristics, Marina Bay Beach

Given significant changes observed in the elevation and position of the beach berms at Marina Bay, the subsurface profiles of the beach berm at each of the three transects were investigated during the winter-spring of 2024. At T-1, at the western end of the beach, the berm surface underwent significant coarsening over the monitoring period (from sand to gravel dominated), while the subsurface profile became finer over time (gravel to sand dominated). At T-2, in the center of the beach, the berm surface became slightly finer over time (gravel-dominated to an even mix of sand/gravel), while the subsurface remained relatively stable (predominantly sand). At T-3, at the eastern end of the beach, the berm profile remained relatively static throughout the monitoring period (~75% sand, ~25% gravel).

China Camp Beach

China Camp Beach was sampled once during the monitoring period in the winter of 2023. The beach surface composition varies, becoming progressively finer from north to south, in the shelter of the larger bedrock headland. The northern extent of the beach (north of the pier) is gravel dominated (T-1 and T-2), shifting to a mixed gravel-sand beach just south of the pier (T-3) and becoming sand-dominated at the south end (T-4). No sub-surface profiles were conducted at this beach.

West Point Pinole Beach

The West Point Pinole Beach was sampled once during the monitoring period in the summer of 2023. Similar to the beach topography, the surface sediment grain size distribution is highly variable, due to the geomorphic variability of the shoreline. The northern beach (T-1) is a mixed sand and gravel beach with gravel/cobble dominated foreshore. The central beach cove (T-2) is almost an entirely sand beach with a sand/mud foreshore. The southern beach, fronting the back-barrier tidal marsh, shifts from sand dominance at the top of the profile, and coarsens downslope to gravel dominance in the lower beachface, with a sand/mud foreshore. The vertical beach profiles were conducted along T-2, in the central beach cove. The subsurface was sand-dominated with a minor (<30%) fraction of gravel to a depth. At the upper beachface profile (BP-1), this surface layer 17" thick and underlain by a mixed sand and gravel layer to a depth of 30". At the lower beachface profile (BP-2), the mixed sand and gravel layer was 24" thick with no underlying gravel layer. The basal layer below the mobile beach sediments was peaty organic material, possibly ancient tidal marsh soil. The pit walls were unstable at this depth, and it was not possible to dig any further.

4.3 Greenwood Beach Studies

This section presents the results of Greenwood-specific studies performed to advance understanding of the system and the restoration design. Detailed results for several of the studies are presented in memoranda and reports prepared by project partners, which are provided as appendices to this document and summarized in this section.

4.3.1 Particle Tracking Studies

Tracking Study No. 1: Winter 2022

The results of particle tracking study 1 are presented in Appendix F and are summarized here. This study documented the propensity for eastward longshore transport of beach sand at Greenwood Beach. Dyed sand grains deployed on Greenwood Beach were transported eastward (downdrift) into the flood control channel, where they were then transported out onto the delta. The rate of transport in this study was difficult to determine due to the deployed sediments being buried below a surface layer of sand. The results suggest that once the sample was exposed at the surface, longshore transport to the eastern end of the beach and onto the delta occurred within days (<1 week). This finding is consistent with the hypothesis for the longshore drift mechanism of long-term beach erosion and habitat loss at this site.

The results also demonstrate cross-shore transport of beach sediments at Brunini beach, with a somewhat equal amount of east-west transport. This finding is consistent with the orientation of Brunini beach and its enclosed, bay-head position: perpendicular with the refracted dominant wave approach angle, and bracketed by marsh and rocky headlands, making it less prone to longshore drift. Interestingly, the samples placed within the flood control channel and on the delta were quickly buried by sediments and locked down, unavailable for subsequent onshore transport by waves. Very little sediment transport was documented from these samples. As mentioned above, the tracer sample deployment methods in this study involved burying the sample below a shallow layer of native sediment, which may have prevented mobilization in these locations.

Tracking Study No. 2: Fall 2024

The sampling grid for particle tracking study 2 is presented in Figure 15, while the detailed sampling result maps are provided in Appendix E. This study documented rapid longshore transport of sand under calm weather conditions, and some transport of gravel as well, but under conditions of relatively persistent sand-depleted (erosional), gravel-dominated beach states. The results of the study were complicated somewhat by the presence of dyed grains from the original transport study in 2022 (i.e., sample contamination), but were still able to confirm the sediment transport patterns observed in the original study. The presence of dyed sand grains from the 2022 study indicates retention of the original samples within the system and documents the offshore movement of sand from the beach to the delta, as well as some minor onshore movement of sand from the delta to the beach.

The distance of the sample center of mass from the original deployment location at each sampling date is presented in Table 3. The orange (sand) and green (gravel) sample results were complicated by the presence of remnant sample from study 1, almost two years later. However, the results of the blue (sand) sample corroborate the rapid sand transport to the eastern end of the beach and onto the delta within a matter of days (<1 week) that is suggested by the orange sample data. The practice of measuring the maximum particle sizes at each point where dyed grains were recovered suggests that much of the dyed green samples observed across the sampling grid were actually sand grains from the 2022 study. Therefore, gravel was likely transported more slowly than the study results suggest. These issues with sample overlap from the prior tracer study suggest the need to perform pre-deployment surveys to identify potential sources of sampling error and adjust sample colors accordingly, particularly at sites where repeat studies are proposed.

Map File: Particle-sample-point-grid_V2_Greenwood_2024-0913

Data sources: Air photo (Audubon, 2022);
Transects (GillenH2O, 2024)

1:900 (1" = 75' at letter size)

0 37.5 75 Feet

0 12 24 Meters

Greenwood Beach Restoration Project

Gillenwater GillenH2O Consulting

Figure 19

2024 Particle Transport Study Sampling Grid

Table 4. Distance from Sample Deployment Location to Surveyed Center of Mass – Study 2

Sample	Distance from Deployment Site to Sample Center of Mass (ft)				
	9/18/2024	9/19/2024	9/23/2024	9/30/2024	10/3/2024
Orange Sand	147.7	147.8	134.5	133.6	114.7
Blue Sand	0	12.9	117.5	117.5	117.4
Green Gravel	172	152.2	156.4	176.5	176.5

Measurements made of the maximum depth of dyed grains at sampling locations indicate that the majority of grains were found within 2" of the surface, suggesting primarily surface transport and very little mixing of beach material during transportation. The deepest grains were found on the delta (3-4" below the surface), which likely represent either the original buried sample from the 2022 study, or 2022 beach samples that were transported to the delta and subsequently buried.

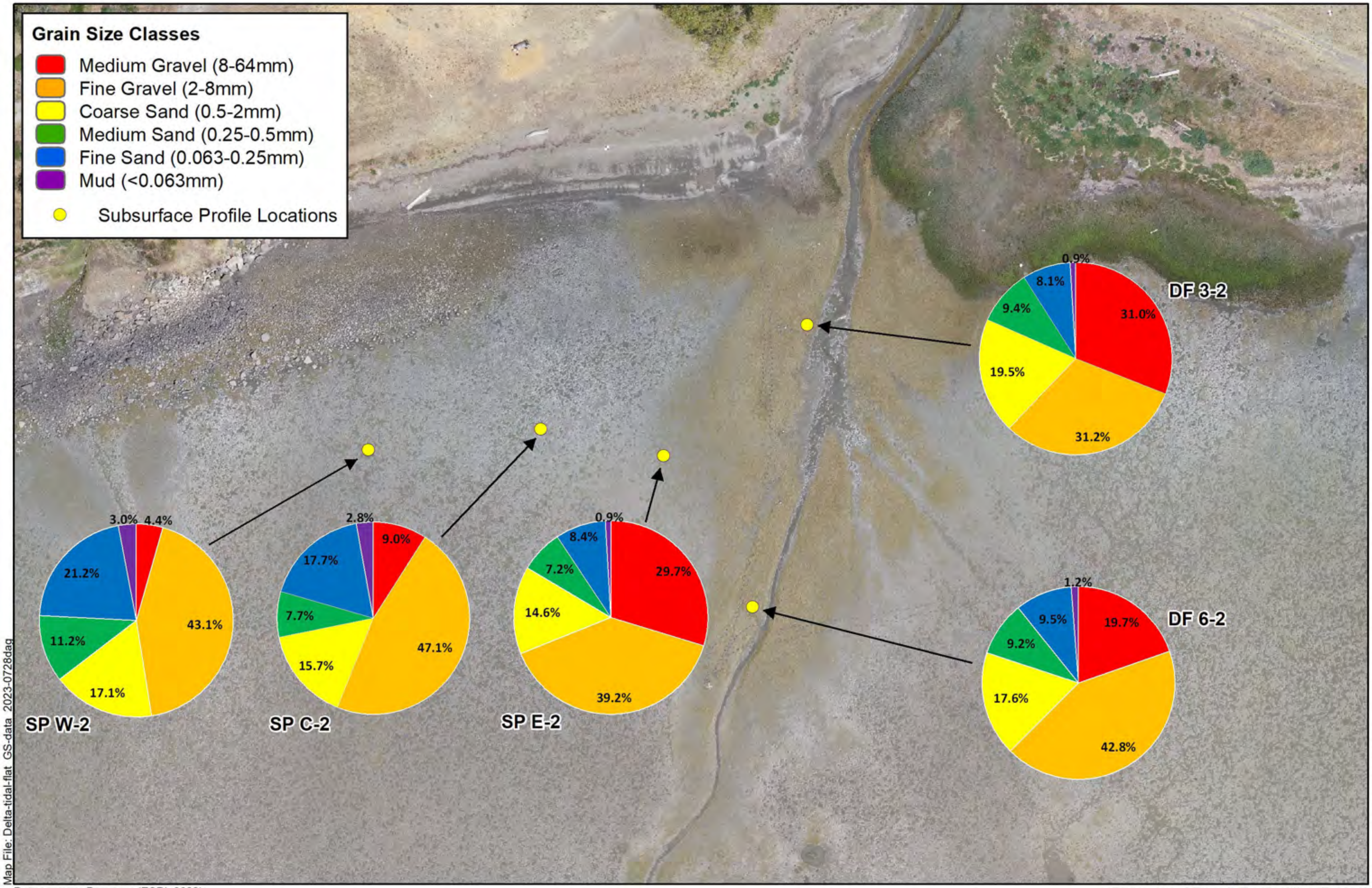
4.3.2 Delta Bedload Transport Study

The results of the delta bedload transport study are detailed in Appendix G and summarized here. By February 2, 2024 (3-4 days after pit trap deployment), all four pit traps at the delta bar and delta channel sites had nearly filled with sediment, indicating substantial material transport during the monitoring period. At the delta bar traps, BP1 reached 89% capacity with 0.79 ft of accumulated material, while BP2 reached 73% capacity with 0.65 ft. Both traps featured a homogenous mix of sediments, including gravels, sands, and a minor amount of mud, with minimal vegetation. BP1 also had a thin layer of leaf debris, and BP2 contained sparse vegetation throughout. Delta surface elevation measurements at both delta bar sites showed little to no change, with BP2 experiencing slight erosion (0.09 ft change).

At the channel traps, sediment accumulation was even higher, with CP1 and CP2 reaching 98% and 94% capacity, respectively. These traps contained more vegetation than the delta bar traps. CP1 exhibited a stratified sediment profile with denser sediments on top and organic-rich material, including mud and vegetation, at the bottom. CP2 showed a similar structure but with more pronounced vegetative content and signs of organic decay, including odor and trash. Surface elevation changes at the channel traps were negligible, suggesting limited erosion or deposition at ground level during the monitoring period. The results at both delta bar and channel sampling locations indicate a high degree of sediment mobility and (potentially) watershed resupply during storm events.

4.3.3 Delta and Tidal Flat Composition

Bore logs from the delta and mudflat subsurface investigation are provided in Appendix D. Subsurface grain size distribution at select sampling locations are presented in Figure 16. At the time of sampling in March 2022, the delta subsurface composition was characterized by a layer of fine-medium muddy sand approximately 2-6 inches thick, underlain by a poorly sorted mixture of sand and gravel. The percentage of medium-coarse gravel decreased with distance from the mouth of the flood control channel. The tidal flats to the west of the delta exhibited a similar stratigraphy to the delta, having a shallow surface layer composed of muddy sand underlain by poorly sorted sand and gravel. The subsurface material becomes finer moving west from the delta, with the sand and mud fraction becoming more dominant.



Data sources: Basemap (ESRI, 2022);
Topo data (GillenH2O, 2022); Grain size (UCD, 2022)

Gillenwater GillenH2O Consulting

1:720 (1" = 60' at letter size)

0 30 60 Feet

0 10 20 Meters

Greenwood Beach Restoration Project

Figure 20

Delta and Tidal Flat
March 2022 Subsurface Grain Size Sampling Locations and Data

4.3.4 Local Wave Climate

The results from this study are provided in Appendix H and are summarized here. The wave measurements at Greenwood Beach and in Richardson Bay showed notable differences in wave height, frequency, and energy levels. The buoy located in the middle of Richardson Bay recorded consistently higher wave heights, with a modal wave height of around 0.2 meters and maximum heights exceeding 0.5 meters. In contrast, the waves at Greenwood Beach were significantly smaller, typically below 0.1 meters, with peak wave heights only reaching around 0.2 meters during strong wind events. This discrepancy suggests substantial wave energy dissipation over shoals and shallow waters before reaching the shoreline.

Southerly wind events with sustained speed of 5 knots or more produced the most powerful wave events at Greenwood Beach. The study identified several of these winter storm events that produced wave powers on the order of 0.1 kW/m at Greenwood Beach, which are deemed to be the most important for beach material transport and morphology. As documented in the fall 2024 particle tracking study (see Section 2.5.1), even calm weather waves have adequate power to induce longshore and cross-shore transport of sand and (to a lesser extent) gravel. Therefore, the wave climate at Greenwood beach has the potential to produce high rates of longshore beach material transport, which must be considered in project design.

4.3.5 Mudflat Infaunal Survey

The results from this study are provided in Appendix I and are summarized here. Seven taxonomic groups were identified in all the cores. The most abundant invertebrate was Veneroida (Bivalvia), a clam. It was present in all cores with the highest abundance in BI-4, offshore of Brunini Beach, with 70 individuals present. BI-4 also had the highest total abundance of invertebrates. The invertebrate biomass that contributed most were also Veneroida. This makes sense as these clams have a hard shell. Species richness was similar across all cores. Simpson Diversity index measurements were more variable across all cores. Simpson Diversity index is a measure of dominance and species richness. Total abundance was also variable across the cores, with the highest total abundance in BI-4 (n = 129) and lowest total abundance in BI-2 (n=31), off the center of Greenwood Beach.

5 Discussion

In this section, we synthesize the preliminary findings from the reference beach datasets and apply them to perspectives from the limited scientific literature on bay and estuary beaches in other regions. We also provide some initial findings that can be gleaned from the limited dataset and provide recommendations for future studies in the San Francisco Estuary where beach restoration planning is evaluated.

5.1 Synthesis and Application

As previously noted, the data collection effort in this study was limited by budget and time scale. Geomorphic processes often occur over a decadal time scale punctuated by larger impact events, like major storms combined with high tides, which occur stochastically, but do a lot of work in shaping beach morphology. It is therefore difficult to draw conclusions based on a few sampling events. The following discussion represents initial impressions based on the review of the data collected in this study.

Beach slope and grain size distribution. The average beachface slopes and median grain sizes (D50) for each reference beach, across the entire monitoring period, are presented in Table 5. Average beach slopes ranged from 7.18% – 13.09% and average D50 ranged from 2.51mm – 10.39mm. It is common in coastal geomorphology to assume a linear relationship between grain size and beach slope, with coarser grained beaches exhibiting a steep beachface slope (Komar 1976, McFall 2019). At the beach-scale, across the entire monitoring period, no such relationship exists in this limited dataset (R^2 = 0.03), based on a linear regression in MS Excel. If West Point Pinole (the most geographically complex site - essentially three distinct beaches) is removed from the dataset, a weak positive correlation between grain size and beach slope exists (R^2 = 0.36). We have not yet evaluated this relationship at the level of individual transects and sampling events for this dataset. Such an evaluation is planned for future studies and may be augmented with additional sampling of beaches with variable grain size distribution in the SF Bay region.

Table 5. Average Beachface Slopes and Grain Sizes for Reference Beaches Across the Monitoring Program

Beach	Average Beachface Slope (%)	Average Grain Size (D50 - mm)
Greenwood	7.18	3.24
Sanctuary	9.56	4.49
China Camp	13.09	6.90
Point Molate	11.55	3.05
Marina Bay	9.98	2.51
West Point Pinole	7.40	10.39
Average	9.79	5.10
Min	7.18	2.51
Max	13.09	10.39

Beach morphology. All reference beaches sampled were mixed beaches, with active beachfaces composed of variable proportions of sand, gravel, shell hash, with some cobble present at several beaches. Limited development of composite beach profiles, with steeper storm gravel berms above sand beachfaces, were detected in Sanctuary and Greenwood Beach during the study period, but they were expressed as narrow, minor topographic features near the storm high tide line. Regardless of grain size, all bay beachfaces sampled exhibited a narrow range of slopes above a low tide terrace, exposed to swash only during higher tide stages, consistent with relatively reflective rather than dissipative beach profiles.

Beachface profiles were generally straight to concave, typical of microtidal sheltered beaches (Jackson et al. 2002), but the westernmost transect of Marina Bay Beach exhibited an asymmetric, mixed concave-convex profile below the beach crest during dynamic accretion phases. In contrast, concurrent stable to erosional transects of Marina Bay beach exhibited straight to concave beachfaces.

Immobile cobble and coarse gravel lag surfaces were associated with extreme updrift beach erosion and sand depletion at Greenwood Beach. Lag deposits occur on the beachface, and on the low tide terrace, which was dominated by anthropogenic rubble from erosion of historic fill. They appear to contribute to the stability of the profile at the updrift end of the beach, after maximum erosion depleted all mobile gravel and sand. Cobble and boulder low tide terrace profiles also occurred at Point Pinole and the south end of China Camp beach (outside the study transect). Coarse lag deposits within the reference beaches were not associated with vegetative colonization and conversion of beach to vegetated marsh banks, as in some bay beach systems (Freire et al. 2013), but conversion of cobble-gravel beach to cobble-gravel salt marsh occurs immediately adjacent to Greenwood Beach, outside the study boundary.

One hypothesis about mixed beach grain size and bay beach slope was suggested by preliminary review of the reference beach data. Some of the mixed sand beaches appear to have coarser-grained sediment sizes in the subsurface layer, and overall steep beachface slopes typical of gravel beaches. This raises the question of whether basal layer sediment size distribution may have relatively stronger influence on beachface slope than the upper sand strata. This relationship should be analyzed with a larger set of reference beaches with mixed sand and gravel, and well-sorted sand and gravel beaches in the region. This analysis could potentially support decisions about grain size distribution for nourished or constructed beaches that balance relatively narrow, steep, coarse beach morphology that still provide sandy beach habitat and recreational values

Seasonal beach profile recovery rates. Relatively rapid beach profile recovery, indicated by berm accretion following erosional periods, was observed at Marina Bay Transect 1 between November 2023 and May 2024, and between August 2022 and March 2023. This pattern, however, corresponded with net erosion at the opposite end of the beach, at Transect-3. Relatively small changes in beach profiles among years and seasons were detected at Point Molate and Sanctuary Beach. These profile changes are consistent with relatively confined cross-shore transport of bay beach sediments, and predominance of alongshore transport within the littoral cell (Jackson *et al.* 2002).

Beach crest elevation change. Beach crest elevations were observed to increase even in profiles that were erosional and retreating. For example, Greenwood transects T-3 and T-4 exhibited beach crest elevation gain despite net beach berm profile erosion, with mixed sand and gravel sediment. Net berm crest elevation increase was also evident over years at sand-dominated Marina Bay Beach. This is consistent with long-term monitoring of retreating of Aramburu Island beach profiles, most of which coarsened and gained elevation over a decade of shoreline retreat (Gillenwater and Baye 2022). Beach crest elevations are an expression of wave runup during either beach accretion or erosion phases. Despite significant variability in beach orientation and wave exposure, beach crest elevations occupied a relatively narrow range, mostly around 7.5 - 8.0 ft NAVD, though some probable storm deposits slightly exceed this.

Longshore drift. Longshore drift data were limited to tracer particle movement study at Greenwood Beach, where the rate of movement and distance of particle movement were large relative to the small length of the beach itself. Sand particles were transported the length of Greenwood Beach (~200 ft) and onto the nearshore delta within a matter of days (<1 week), which is significant given that the beach is located at the head of an embayment. Documentation of longshore drift rates at finer temporal scales (e.g., on the order of tidal cycles) is difficult due to complications arising from sample contamination (from previous studies) and sampling frequency. Longshore drift was relatively much greater than limited cross-shore transport, except where dispersion of sand and gravel in tidal currents of the flood control channel influenced transport to the nearshore delta. The relatively high importance of longshore transport is consistent with characterization of bay and estuarine beaches on other coasts (Jackson *et al.* 2002). Greenwood Beach data on beachface erosion were consistent with late stages of long-term net longshore drift into the sediment sink of the flood control channel mouth, unobstructed by high salt marsh vegetation that formerly provided a sill.

There was evidence of longshore drift within the 2-year study period at Point Molate and Marina Bay, where both ends of the beach were confined by artificial or natural headlands. Net short-term beach accretion was observed at the north end of Point Molate Beach, and the west end of Marina Bay Beach, corresponding with net erosion at the opposite end of the beach. At Point Molate, accretion was also noted on the updrift side of small shoreline protuberances and large pieces of stable driftwood. The long-term stability of the planform and position of these beaches, however, did not indicate long-term net accretion, erosion, or shoreline orientation change aligned with these observed drift patterns. The limited data from reference beaches, however, do indicate the potential for significant seasonal and interannual longshore drift episodes even within headland-bound, bay head beaches that appear to display no obvious long-term net drift patterns in plan form, such as differential widening or asymmetric erosion and accretion alongshore.

These findings suggest that at primarily swash-aligned beach restoration sites, it appears that nourishment with new sediments, which may have been reduced or cutoff due to development, may be sufficient to restore and maintain beach functions. Sites like Greenwood beach, which experience modest amounts of longshore drift, may require reestablishment of the “headlands” that formerly held them in place to retain placed sediments. In strongly drift aligned sites, more drastic structures may be required to retain sediments, or construction from less drift prone sediments may be necessary.

Local stream delta sediment transport. Local mouths of flood control channels or storm drains exhibit local influence on beach accretion and erosion patterns. At Point Molate, a beach protuberance with a stable position occurs at the mouth of a culverted storm drain. As mentioned above, this fan-shaped beach protuberance in the swash zone was a localized site of net beach accretion. At Greenwood Beach, short-term particle tracer data confirmed that the mouth of the flood control channel interacts with the downdrift end of the beach, where outflows are concentrated and erosional. Here, interaction with the transport reach of the flood control channel results in net erosion and loss (bayward transport) of beach material.

These contrasts in morphology of the beach in relation to stream or flood control channels or deltas may influence local erosional or depositional effects, and indicate a need for site-specific studies.

Nearshore and low tide terrace morphology and sediment. Beach profiles all lacked intertidal sand bars or sand waves, either parallel or oblique to shore. There is no evidence that intertidal sand bars play a role in beach dynamics in the reference beaches. Even Greenwood Beach, which included a large intertidal delta of fluvial sediments, had no bars on the low tide terrace. This is consistent with early general characterization of low-energy beaches (Jackson *et al.* 2002). Therefore, understanding post-storm erosion recovery processes at San Francisco Bay beaches with similar profiles would require data collection focused on redistribution of beach sediments from the inner foreshore (including sand ripple transport under wave action), backshore, and local terrestrial or fluvial sources. Few Central and North Bay beaches exhibit intertidal sand or gravel bars on tidal flats or deltas, such as the deltas at the mouths of Pinole Creek and San Lorenzo Creek. Low tide terraces at Greenwood Beach and Marina Bay included some sand on the inner low tide terrace, but mud or muddy sand generally provided a shelf that dissipates waves until higher tide stages. The mud-beach material interface can form a mixed-gained material mixture that may reduce sand mobility and shoaling as (or if) the sand gets embedded in a bay mud (usually highly organic and plastic) mixture. The relatively steep beachface toe of slope in all reference beaches generally occurs as an abrupt inflection of slope around Mean Tide Level, with a low tide terrace extending to Mean Low Water at a variable distance from the beachface.

5.2 Conclusions and Recommendations

The limited data from short-term studies of reference beaches do indicate potential for significant variation in beach form, processes, and rates of change among San Francisco Bay beaches, as well as a limited range of beach profile characteristics, such as crest elevation, beach width, and beachface slope. Substantial differences from ocean beach profiles and dynamics include confirmation of lack of intertidal or subtidal sand bars in the profile, and consequently no potential role for bar migration in beach profile recovery, or “closure depth” of beach sand transport from the fine-grained outer low tide terrace. This data report did not include beach sediment budget analysis, but identified constraints on potential local bay beach sand transport pathways, sources and sinks that should be assessed in other study sites. Generalizations from outer coast beach dynamics applied to San Francisco Bay beaches should be treated with caution, and tested with local site-specific data collected over multiple storm erosion and post-storm recovery cycles.

Recommendations for additional research to better understand the trends observed in this study include, but are not limited to, the following:

1. Longer term studies are needed to assess trends in beach conditions over many years and decades to confirm or refute some of the initial findings of this study under more relevant geomorphic time scales, and to better understand the impacts of large storm events. As funding for long-duration monitoring programs is difficult to come by, such efforts may benefit from involvement by regional programs such as the Regional Wetland Monitoring Program (WRMP) and/or existing coordinated community science programs (e.g., Beach Watch).
2. More emphasis on both the surface but also subsurface stratigraphy is needed to assess the more complex multi-layered nature of bay beaches where different sediment classes from coarse-grained gravels and cobbles exist with finer grained sandy layers and often on top of very plastic bay muds bases and the lower elevation tidal sediments of the beach profile. This more complex stratigraphic nature of Bay Beaches is poorly understood or documented and may be important to understand beach responses.
3. Development of a dataset for drift aligned beach sites that are not covered under this dataset. It is possible that the typical grain size to beach slope relationships may be more applicable for beaches of this type but this has not been shown.
4. Additional sediment transport and tracer studies at multiple sites, and with both higher initial sampling frequency (to assess transport dynamics at the tidal cycle scale) and longer total study duration, would help to better understand how sediments move in response to singular events, seasonally, and annually . There certainly exists a relationship between wave heights and energy and the movement of sediment sizes. Additional wave and sediment movement data may be helpful to quantify this relationship which, as discussed above, may be complicated in San Francisco Bay beaches with heterogenous sediment types and layering.

6 References

Bunte and Abt, 2001. Sampling Frame for Improving Pebble Count Accuracy in Coarse Gravel-Bed Streams. Journal of the American Water Resources Association, Vol. 37, p. 1001-1014.

Ciavola, P. and Grottoli, E. 2017. Tracers and Coarse Sediment. Finkl, C.W., and Makowski, C. (eds.), Enclyclopedia of Coastal Science. Springer International Publishing.

Freire, P., Ferreira, Ó., Taborda, R., Oliveira, F.S.B.F., Carrasco, A.R., Silva, A., Vargas, C., Capitão, R., Fortes, C.J., Coli, A.B. and Santos, J.A., 2009. Morphodynamics of fetch-limited beaches in contrasting environments. Journal of Coastal Research Special Issue No. 65, pp. 183-187.

Gillenwater, D. and P. Baye. 2022. Aramburu Island Shoreline Protection and Ecological Enhancement Project. Year-10 (2021) Shoreline Geomorphology Monitoring Report. Prepared for Marin County Parks.

Gillenwater, D., P. Baye, and R. Leventhal. 2025. Greenwood Beach Restoration Project, Tiburon, CA. Restoration Design Report. Prepared for Marin County Public Works and Town of Tiburon.

Jackson, N.L., Nordstrom, K.F., Eliot, I. and Masselink, G., 2002. 'Low energy' sandy beaches in marine and estuarine environments: a review. Geomorphology, 48(1-3), pp.147-162.

Kinsman, N. and Xu, J.P., 2012. Fluorescent tracer experiment on Holiday beach near Mugu Canyon, southern California: Open-File Report 2012-1131, United States Geological Survey (USGS).

Komar, P. 1976. Beach Processes and Sedimentation. Prentice-Hall.

Leventhal, et al. 2021. Constructed Bay Beaches as Soft Engineering Alternatives to Shoreline Armoring at Three Southern Marin County Demonstration Sites: Greenwood and Brunini Beaches, Tiburon; Paradise Beach, Tiburon; and Seminary Drive, Marin County. Preliminary Design Report.

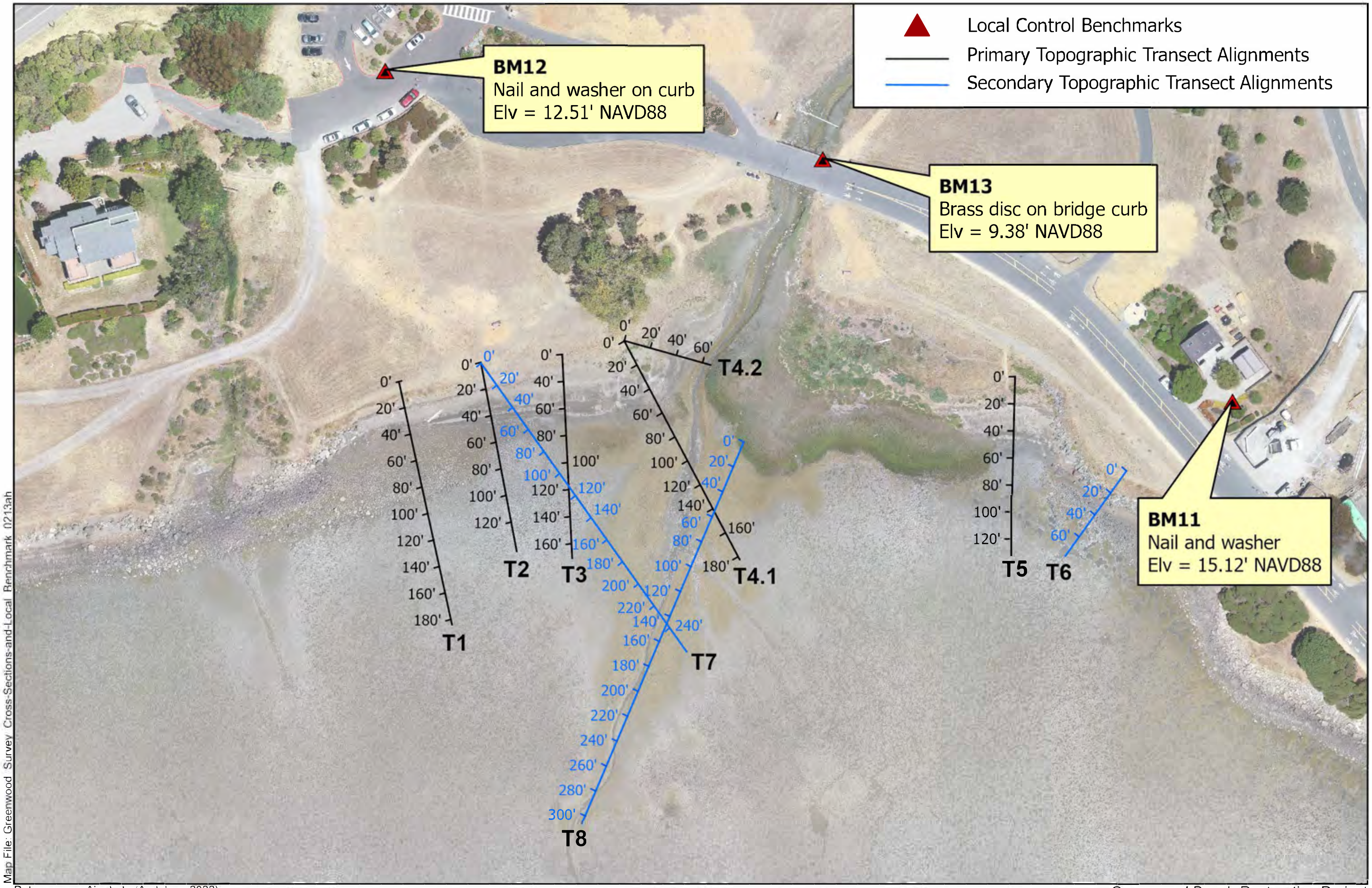
McFall, B.C., 2019. The relationship between beach grain size and intertidal beach face slope. Journal of Coastal Research, 35(5): 1080-1086.

SFEI and Peter Baye. 2020. New Life for Eroding Shorelines: Beach and Marsh Edge Change in the San Francisco Estuary. Publication #984, San Francisco Estuary Institute, Richmond, CA. Version 1.0 (April 2020)

SFEI and SPUR. 2019. San Francisco Bay Shoreline Adaptation Atlas: Working with Nature to Plan for Sea-level rise Using Operational Landscape Units. Publication 915, San Francisco Estuary Institute, Richmond, CA. Version 1.0. April 2019.

Appendix A:
Topographic Transect Data Plots

Greenwood Beach



Map File: Greenwood Survey Cross-Sections-and-Local Benchmark 0213ah

Data sources: Air photo (Audubon, 2022),
Survey Data (GillenH2O, 2023)

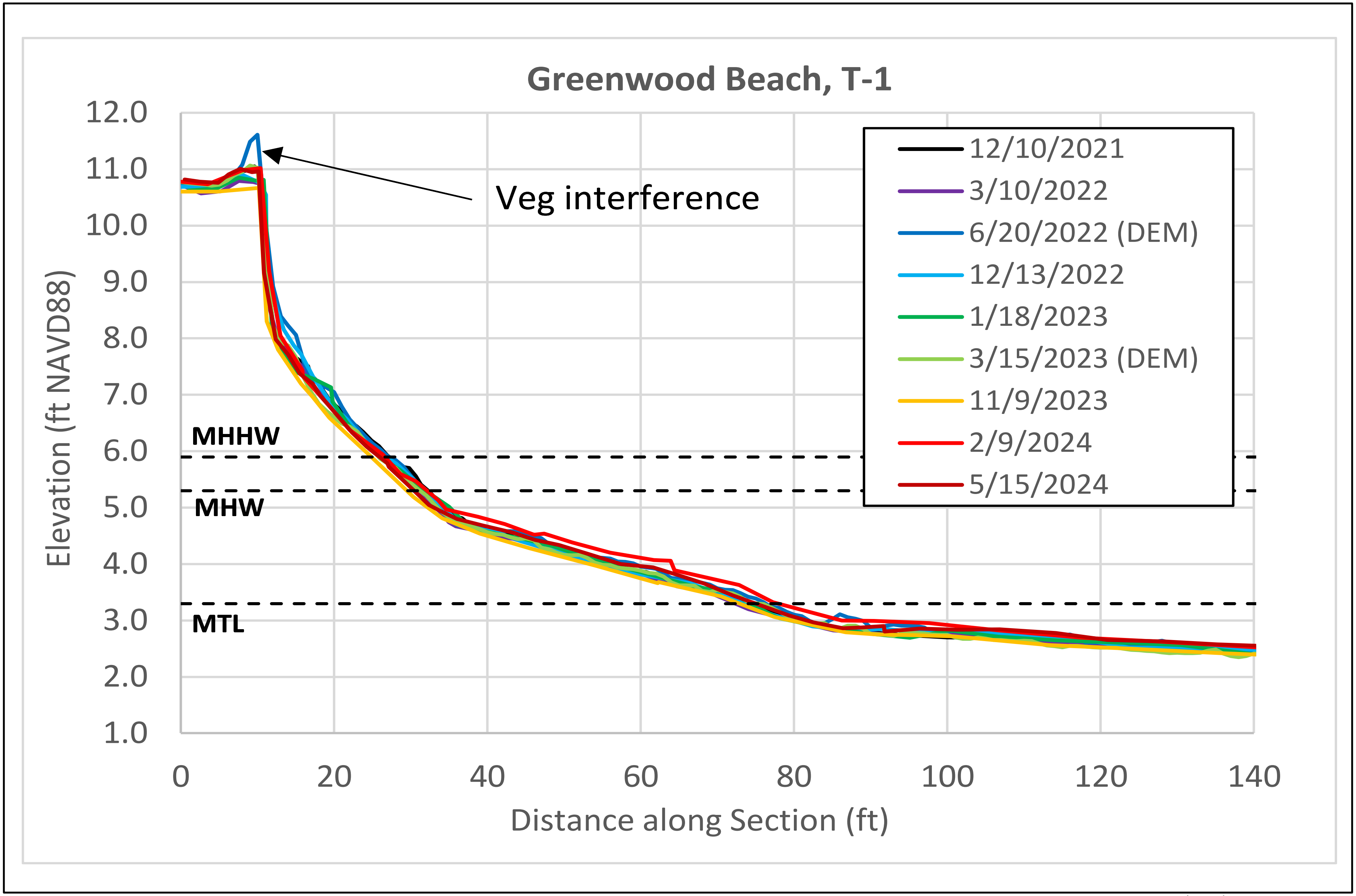
Greenwood Beach Restoration Project

1:1,200 (1" = 100' at letter size)
0 50 100 ft
0 15 30 m

Gillenwater
GillenH2O
Consulting

Figure 1

Greenwood Beach
Topographic Transect Alignments



Greenwood Beach, T-1
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
Elevation (ft NAVD88)
0
20
40
60
80
100
120
140
Distance along Section (ft)
Veg interference
MHHW
MHW
MTL
12/10/2021
3/10/2022
6/20/2022 (DEM)
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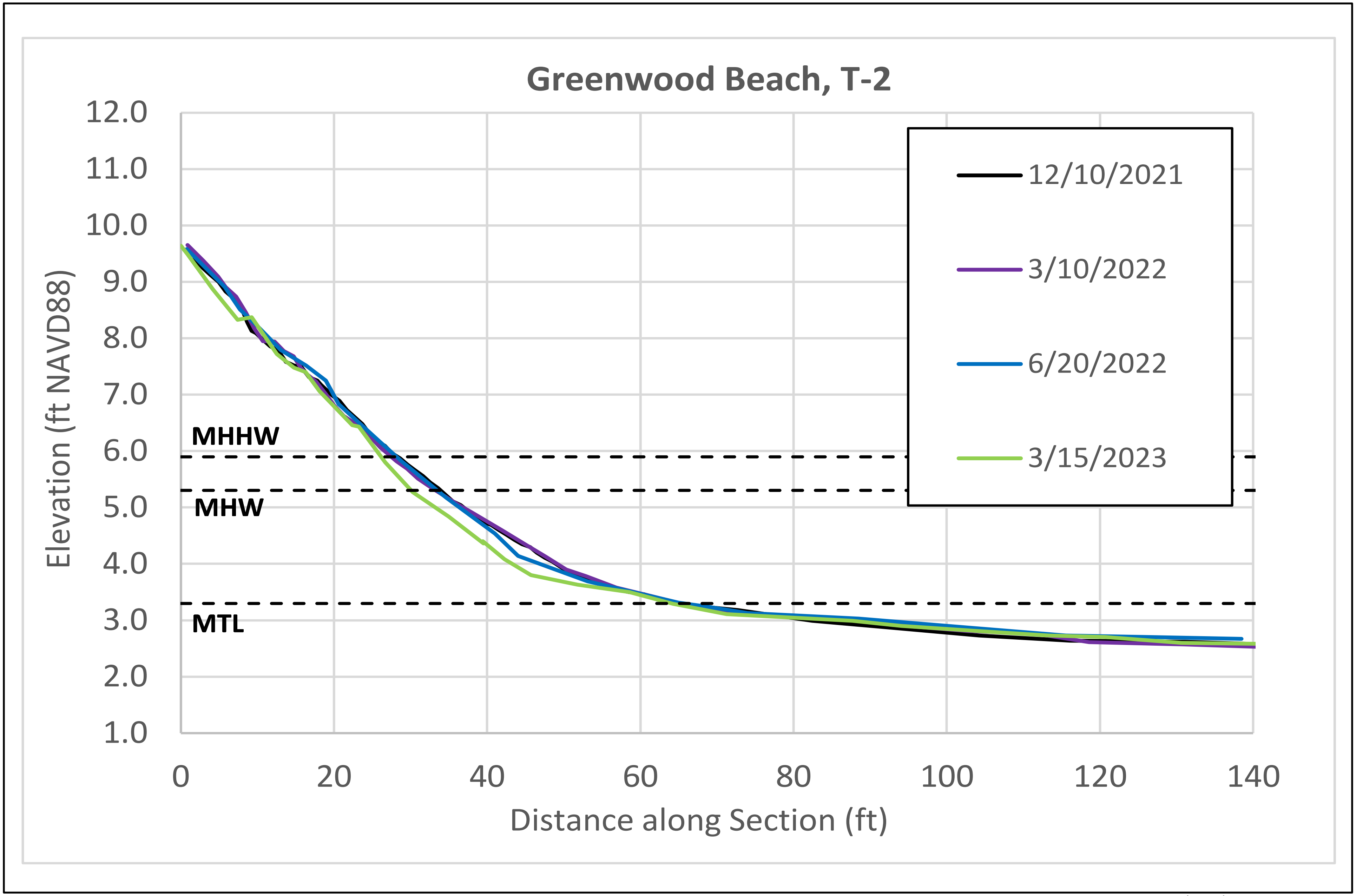
2/9/2024
5/15/2024

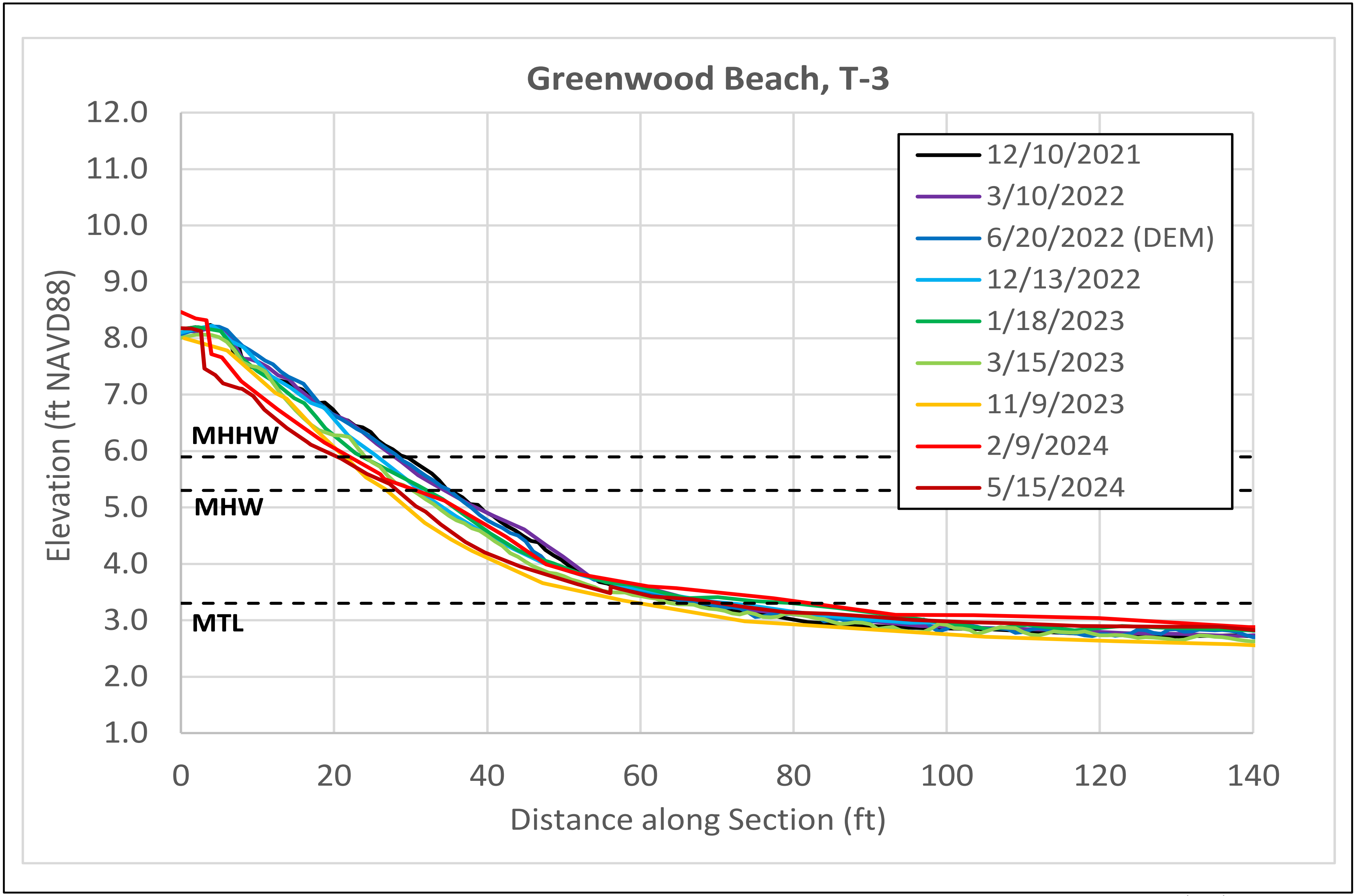


Greenwood Beach Restoration Project

Figure 3

Greenwood Beach
Transect 2 Topography

Gillenwater
GillenH2O
Consulting

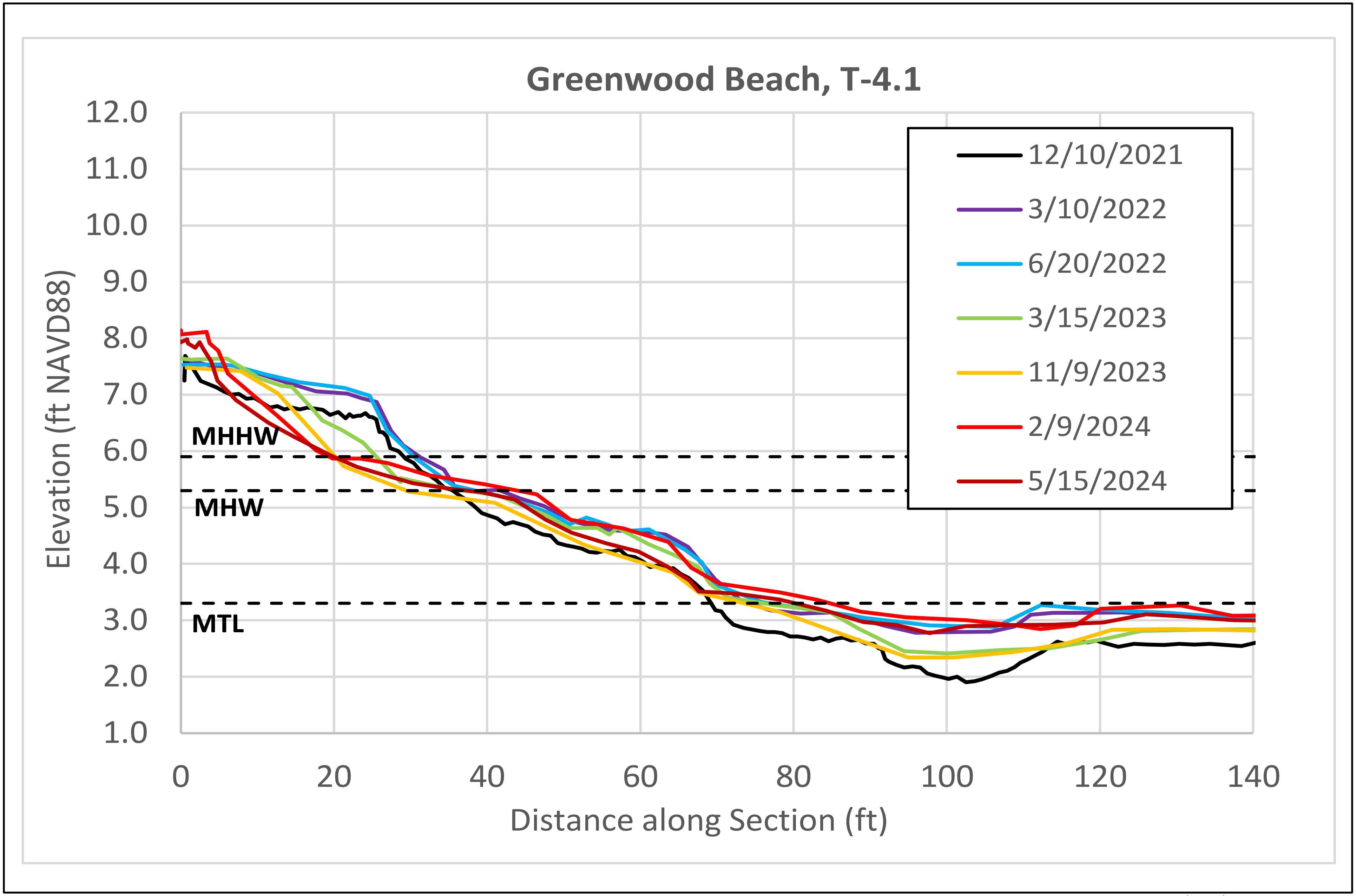


Gillenwater GillenH2O Consulting

Greenwood Beach Restoration Project

Figure 4

Greenwood Beach
Transect 3 Topography

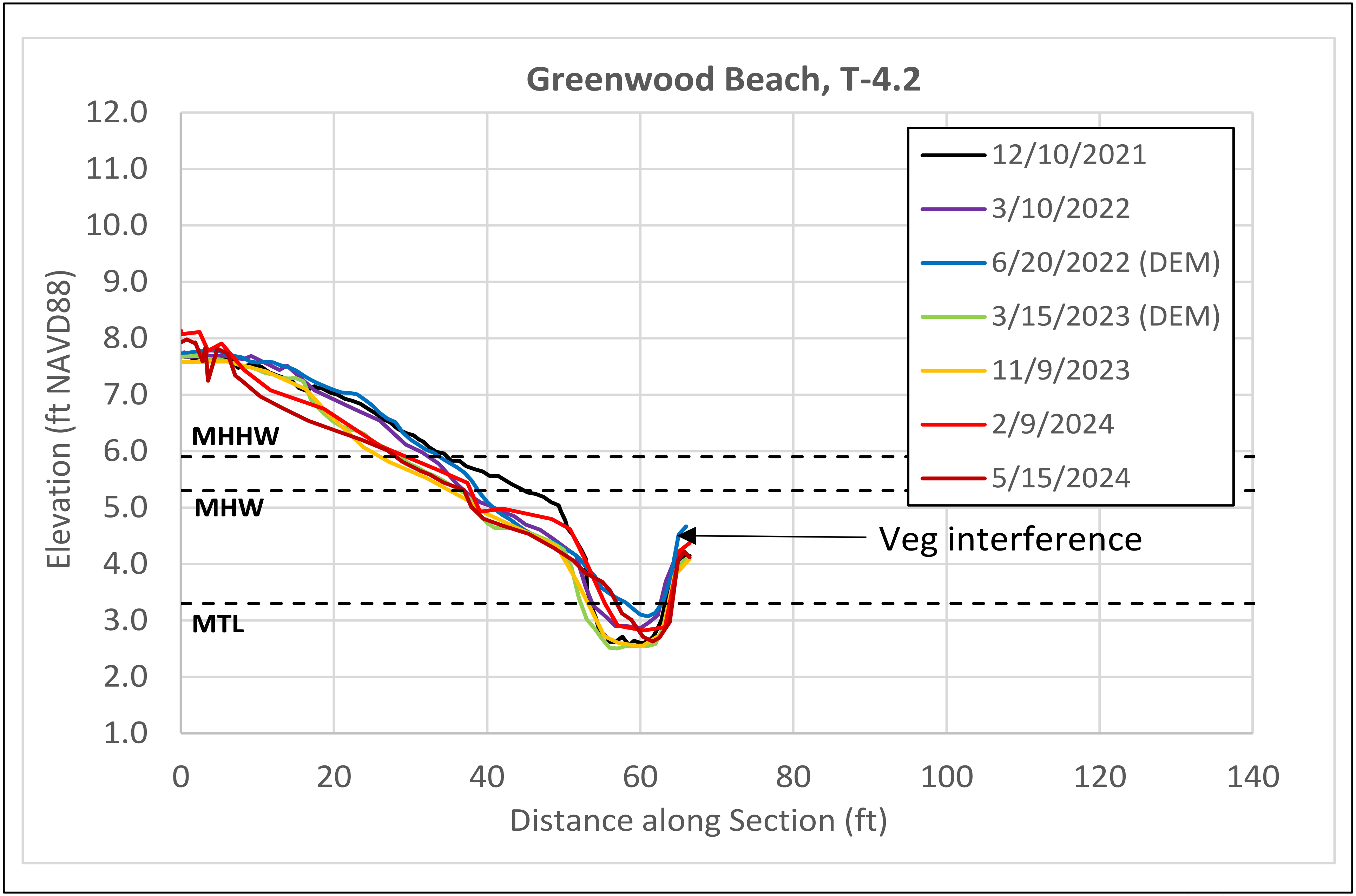


Greenwood Beach Restoration Project

Figure 5

Greenwood Beach
Transect 4.1 Topography

Gillenwater GillenH2O Consulting

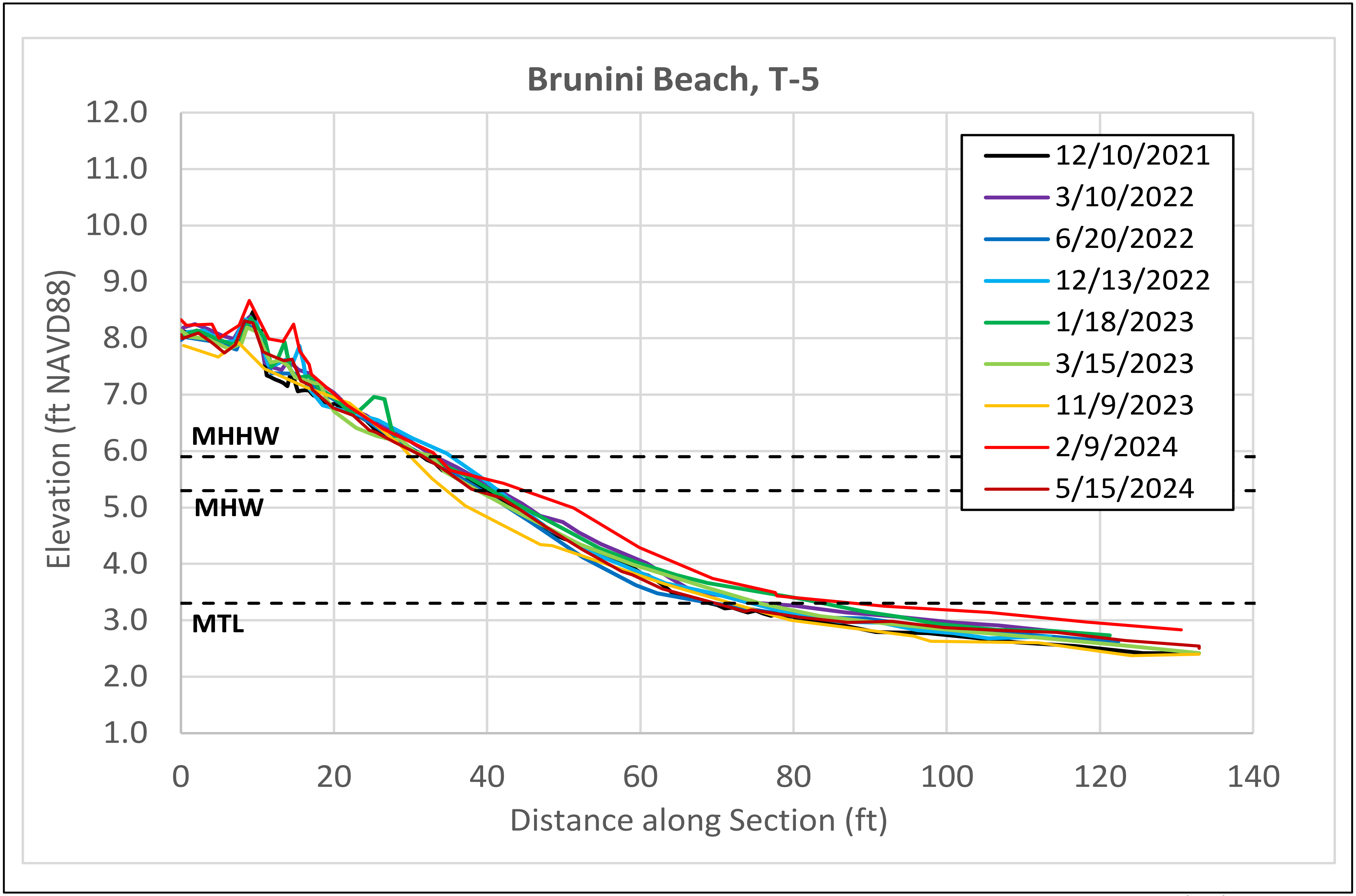


Greenwood Beach Restoration Project

Figure 6

Gillenwater GillenH2O Consulting

Greenwood Beach
Transect 4.2 Topography



Greenwood Beach Restoration Project

Figure 7

Gillenwater
GillenH2O
Consulting

Brunini Beach
Transect 5 Topography

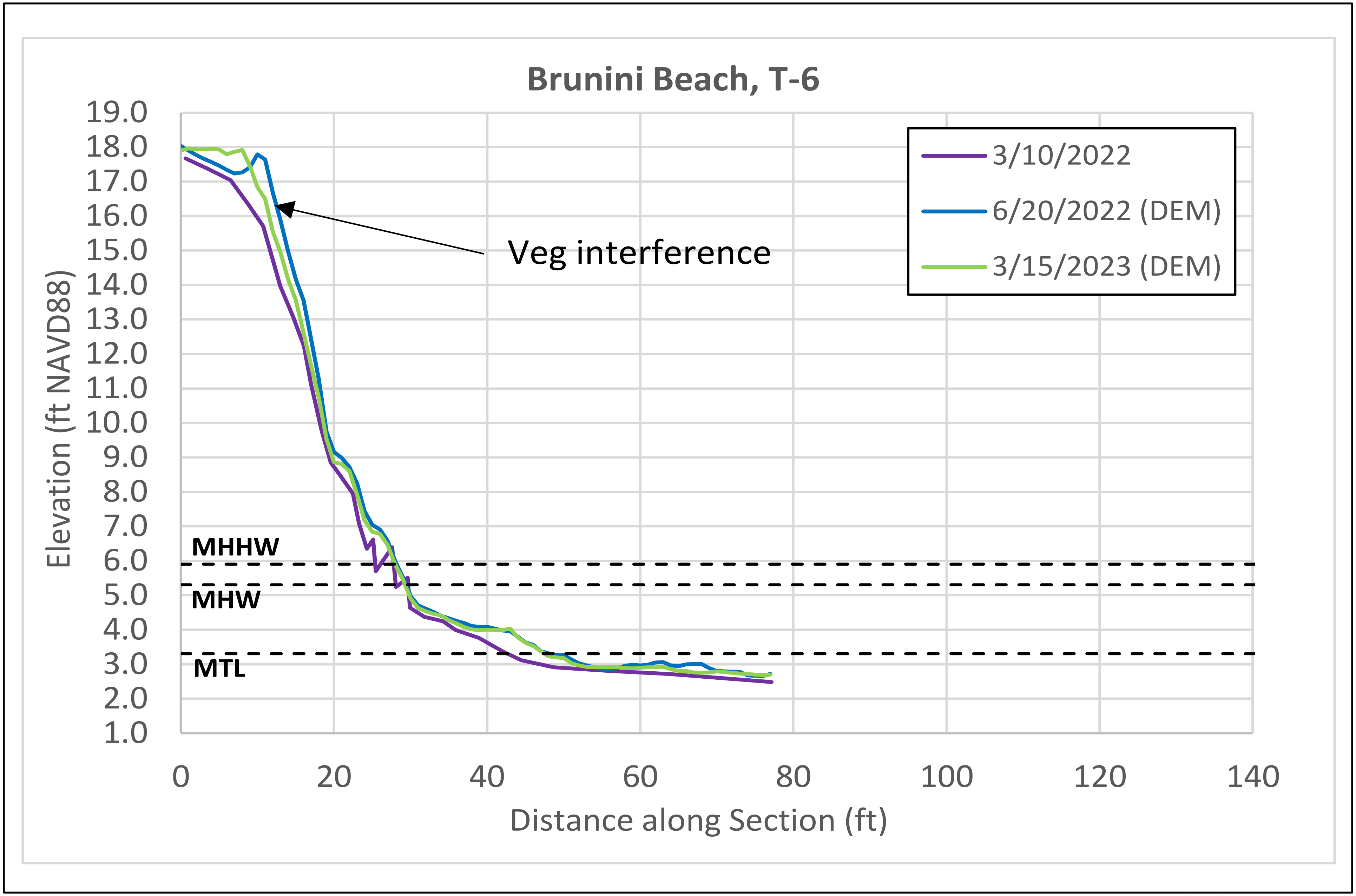
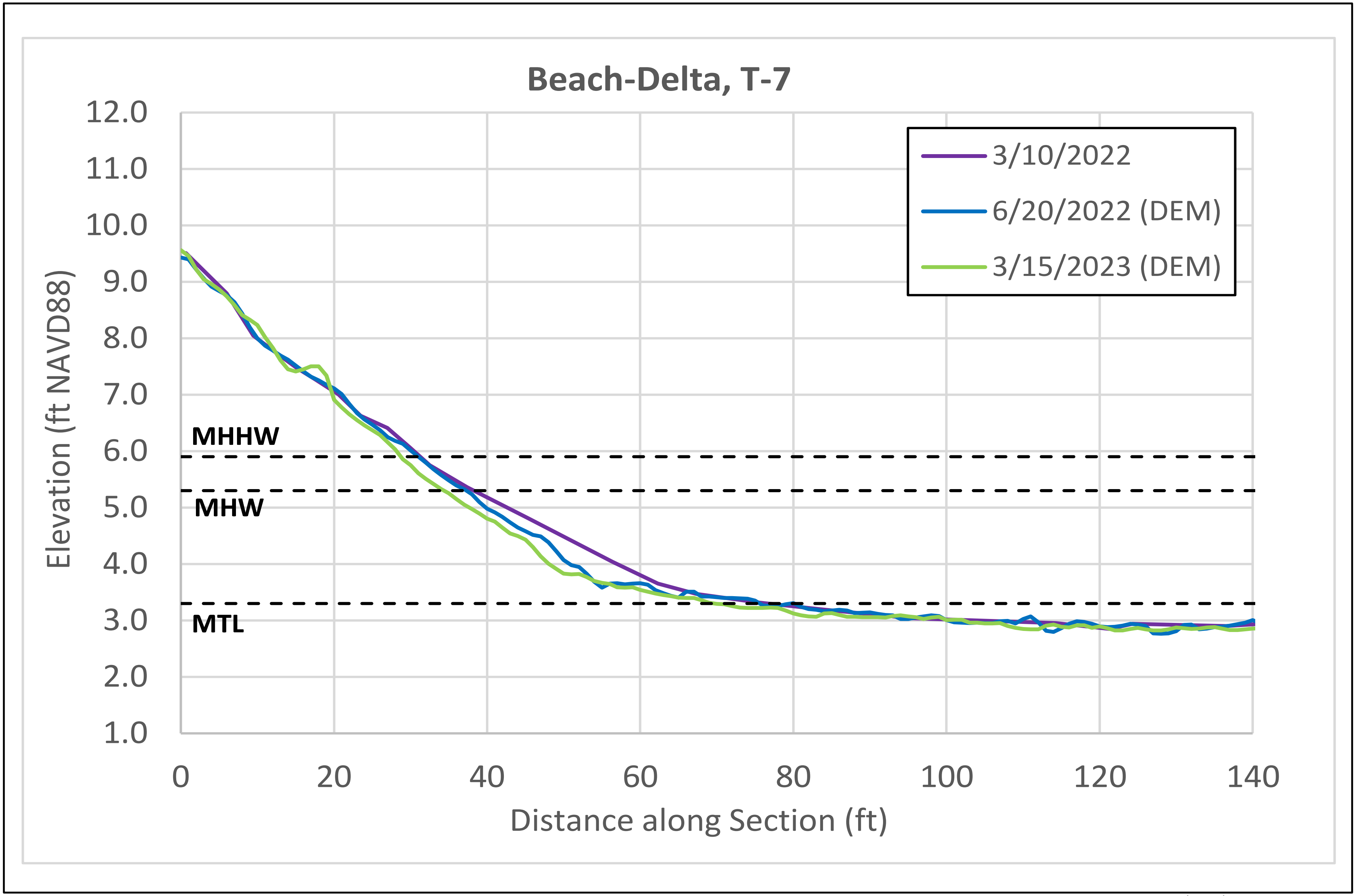


Figure 8

Gillenwater GillenH2O Consulting

Brunini Beach
Transect 6 Topography

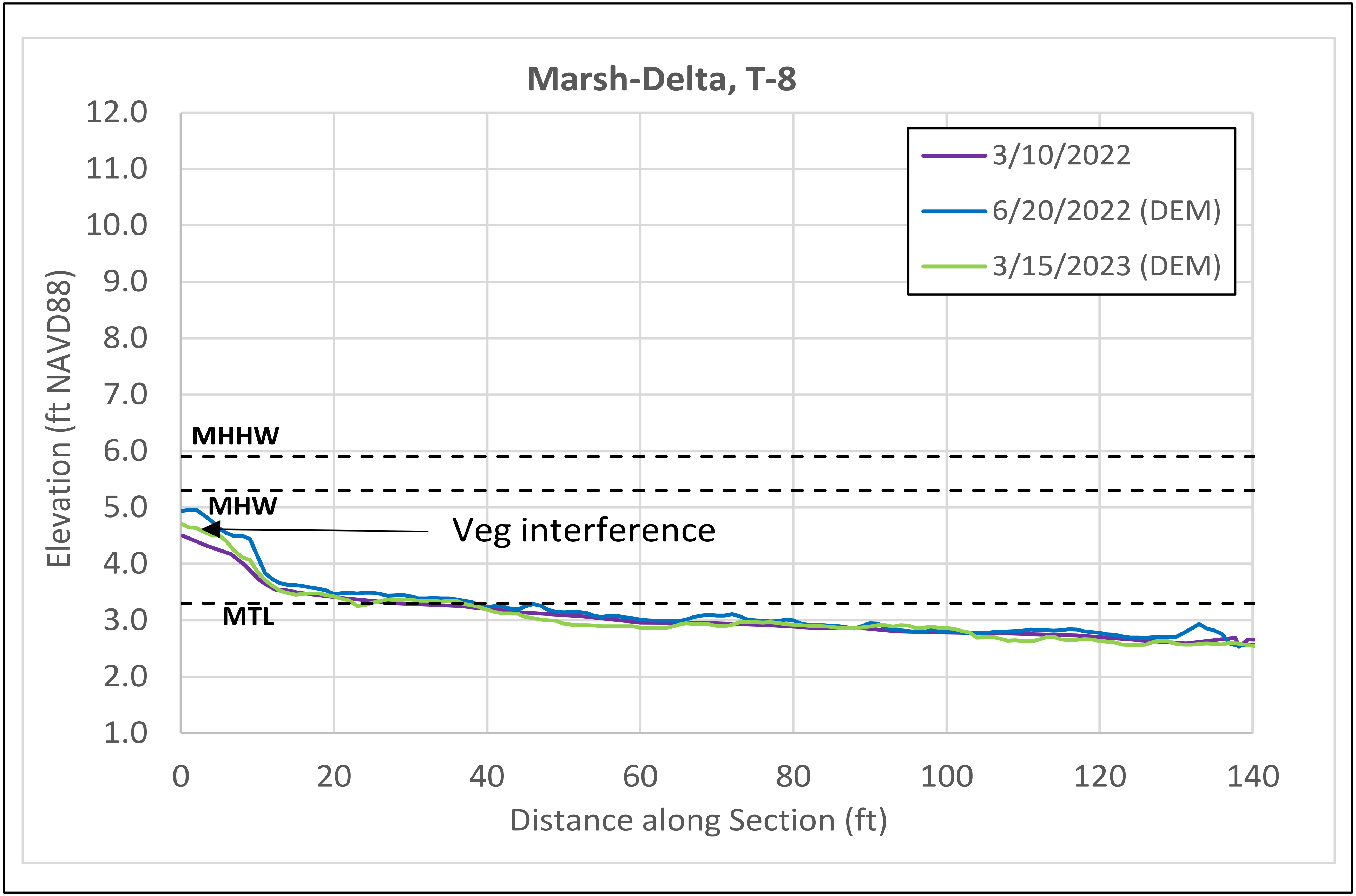


Greenwood Beach Restoration Project

Figure 9

Gillenwater GillenH2O Consulting

Beach-Delta Beach
Transect 7 Topography



Greenwood Beach Restoration Project

Figure 10

Gillenwater GillenH2O Consulting

Marsh-Delta Beach
Transect 8 Topography

Sanctuary Beach

Map File: Santuary_Survey-Cross-Section-Locations_2024_0205ah

Data sources: Air photo (Audubon, 2022); Survey Data (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

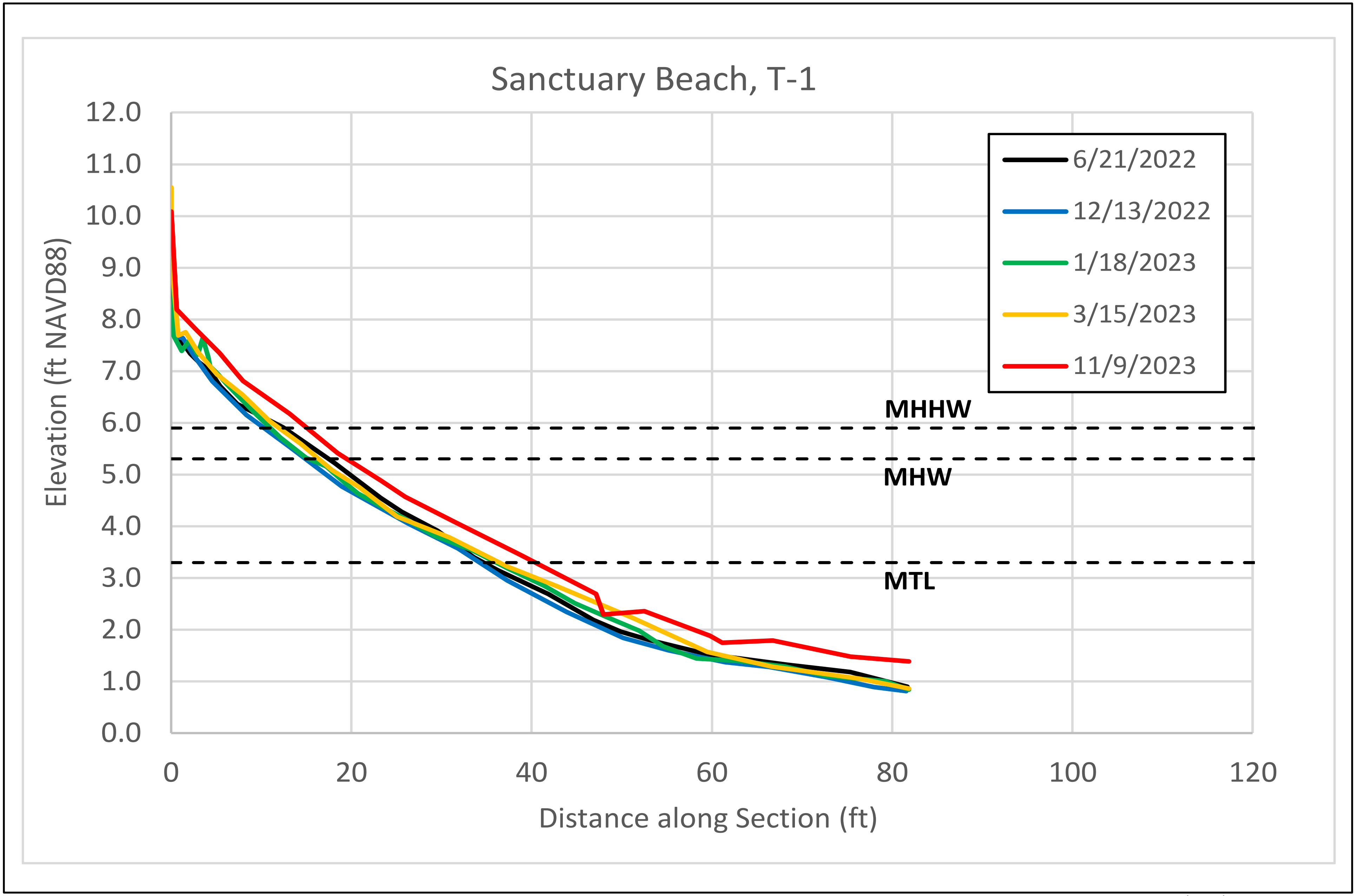
0 25 50 ft

0 7.5 15 m

Gillenwater GillenH2O Consulting

Figure 1

Sanctuary Beach Topographic Transect Alignments

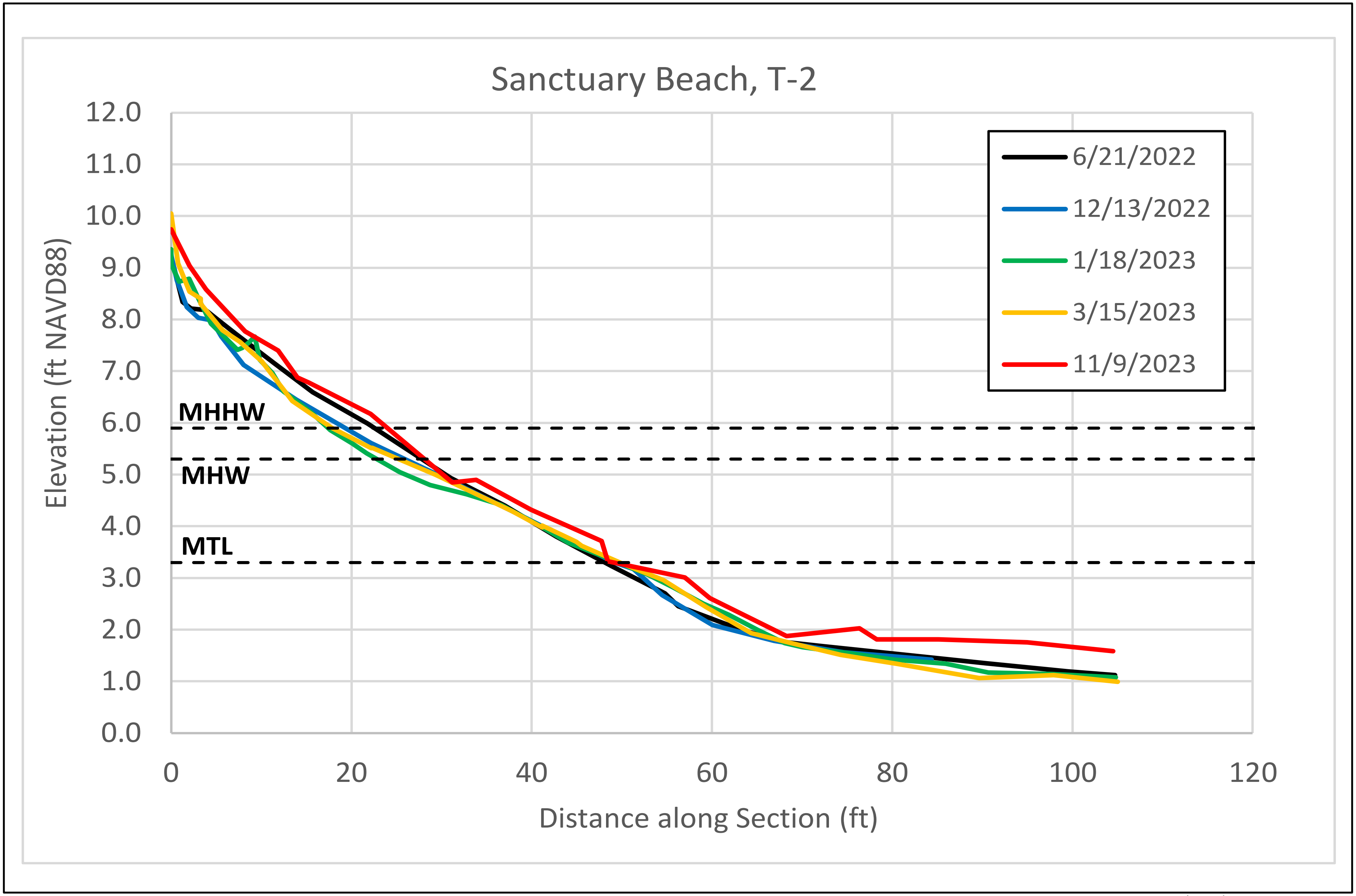


Greenwood Beach Restoration Project

Figure 2

Gillenwater GillenH2O Consulting

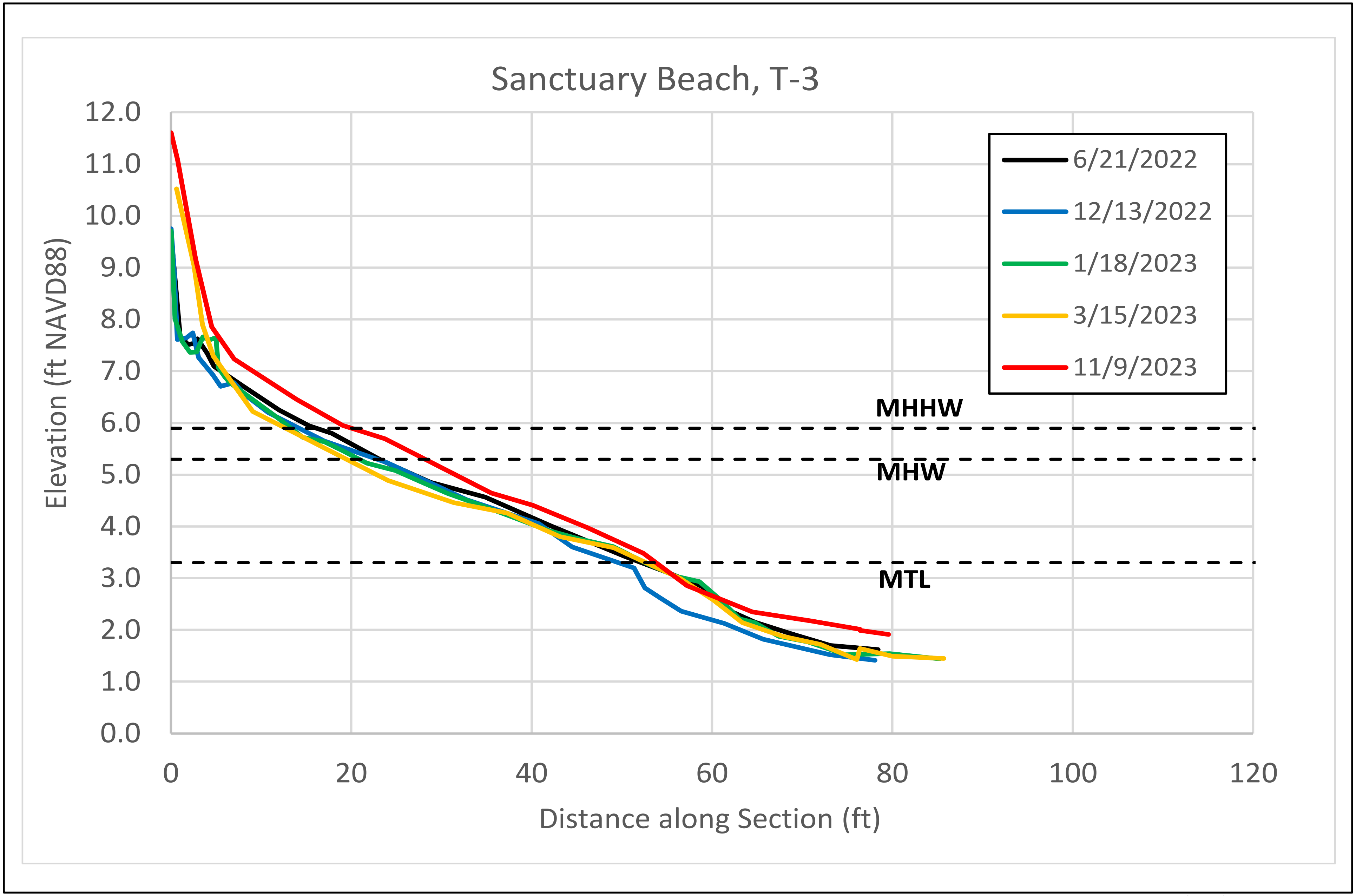
Sanctuary Beach
Transect 1 Topography



Greenwood Beach Restoration Project

Figure 3

Sanctuary Beach
Transect 2 Topography



Greenwood Beach Restoration Project

Figure 4

Gillenwater GillenH2O Consulting

Sanctuary Beach
Transect 3 Topography

Pt. Molate Beach

Map File: Pt Molate Survey-Cross-Section-Locations 2024 0205ah

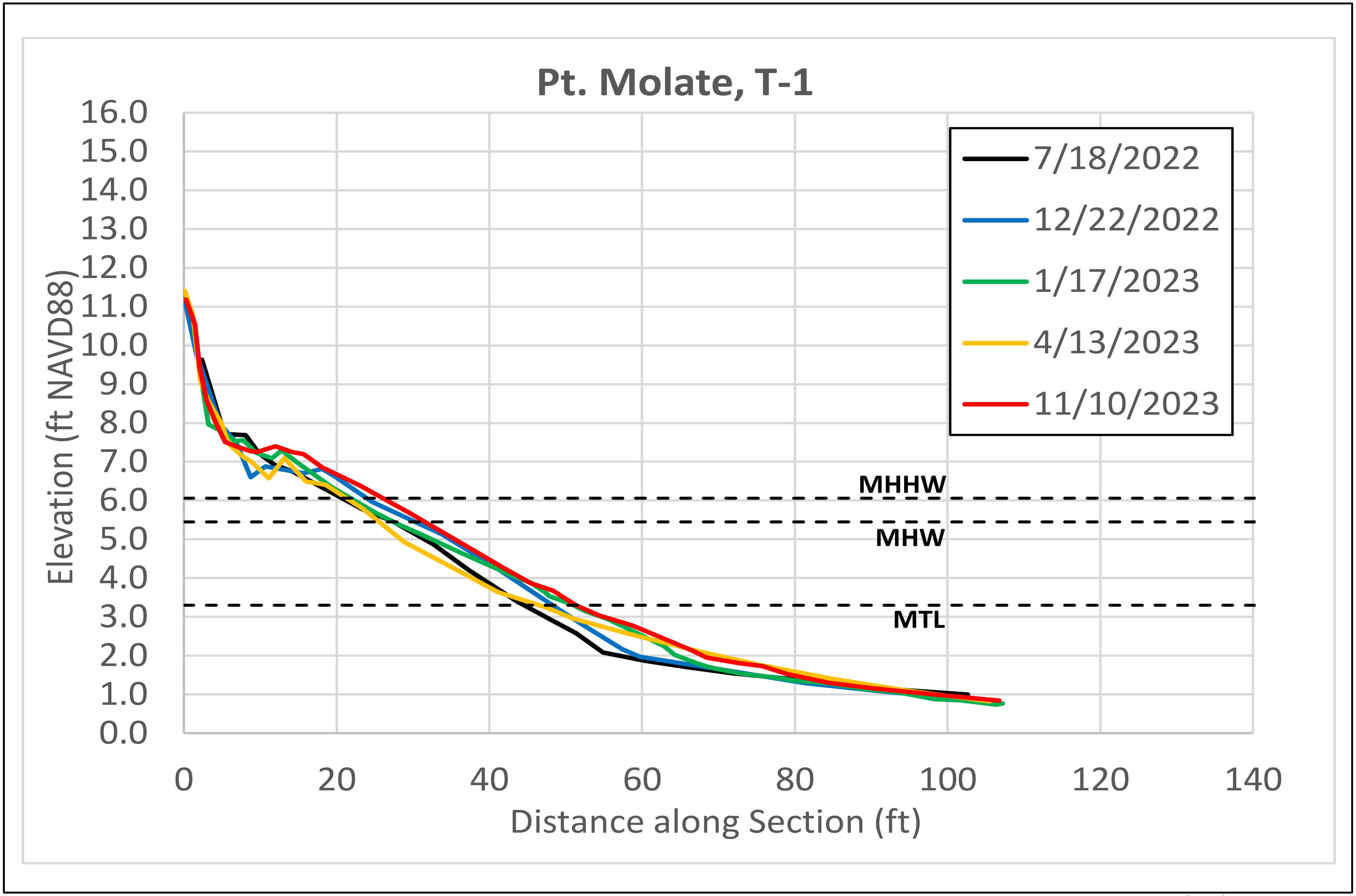
Data sources: Air photo (Audubon, 2022);
Survey Data (GillenH2O, 2023)

Greenwood Beach Restoration Project

Gillenwater GillenH2O Consulting

Figure 1

Pt. Molate Beach
Topographic Transect Alignments

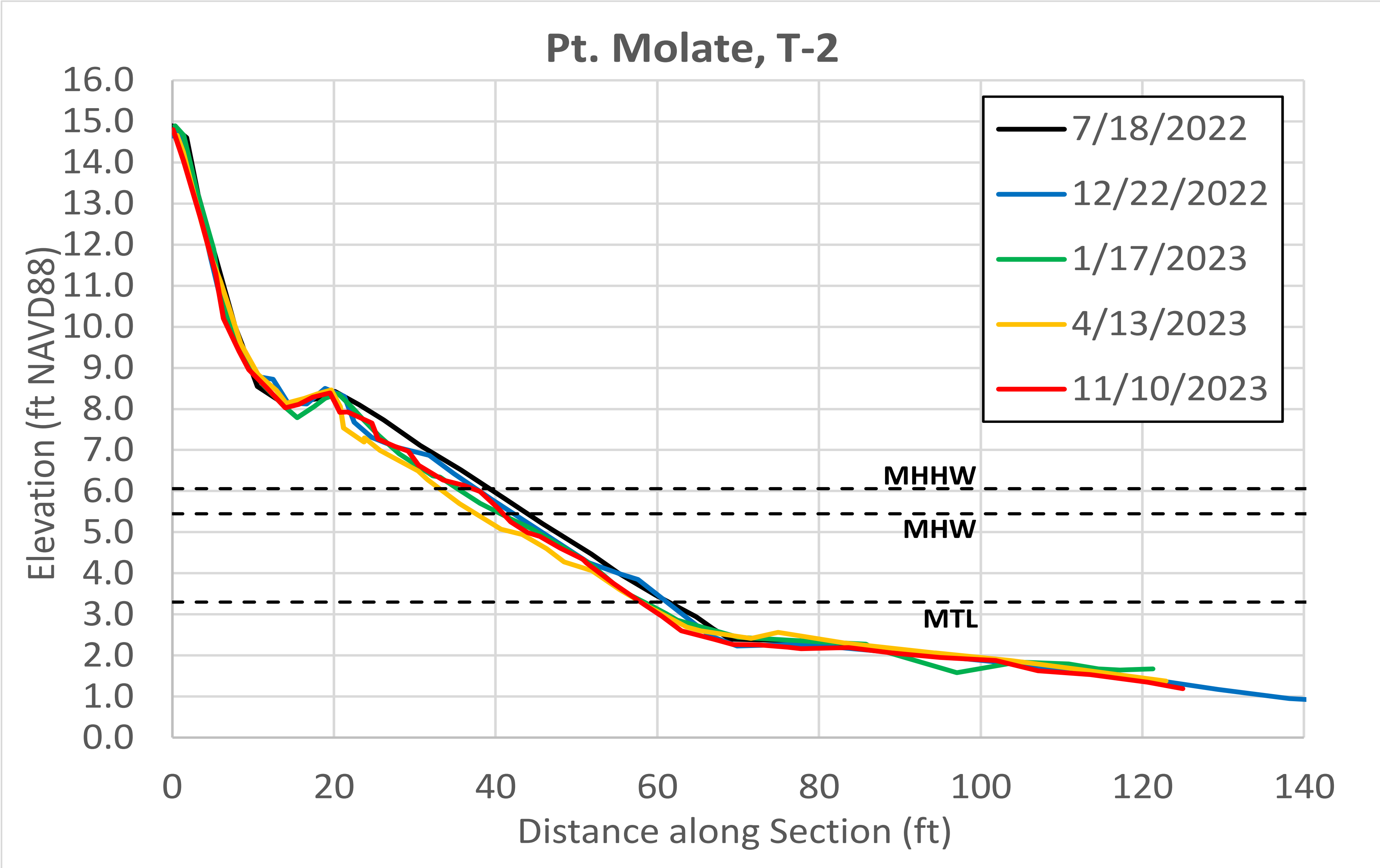


Greenwood Beach Restoration Project

Figure 2

Gillenwater GillenH2O Consulting

Pt. Molate Beach
Transect 1 Topography

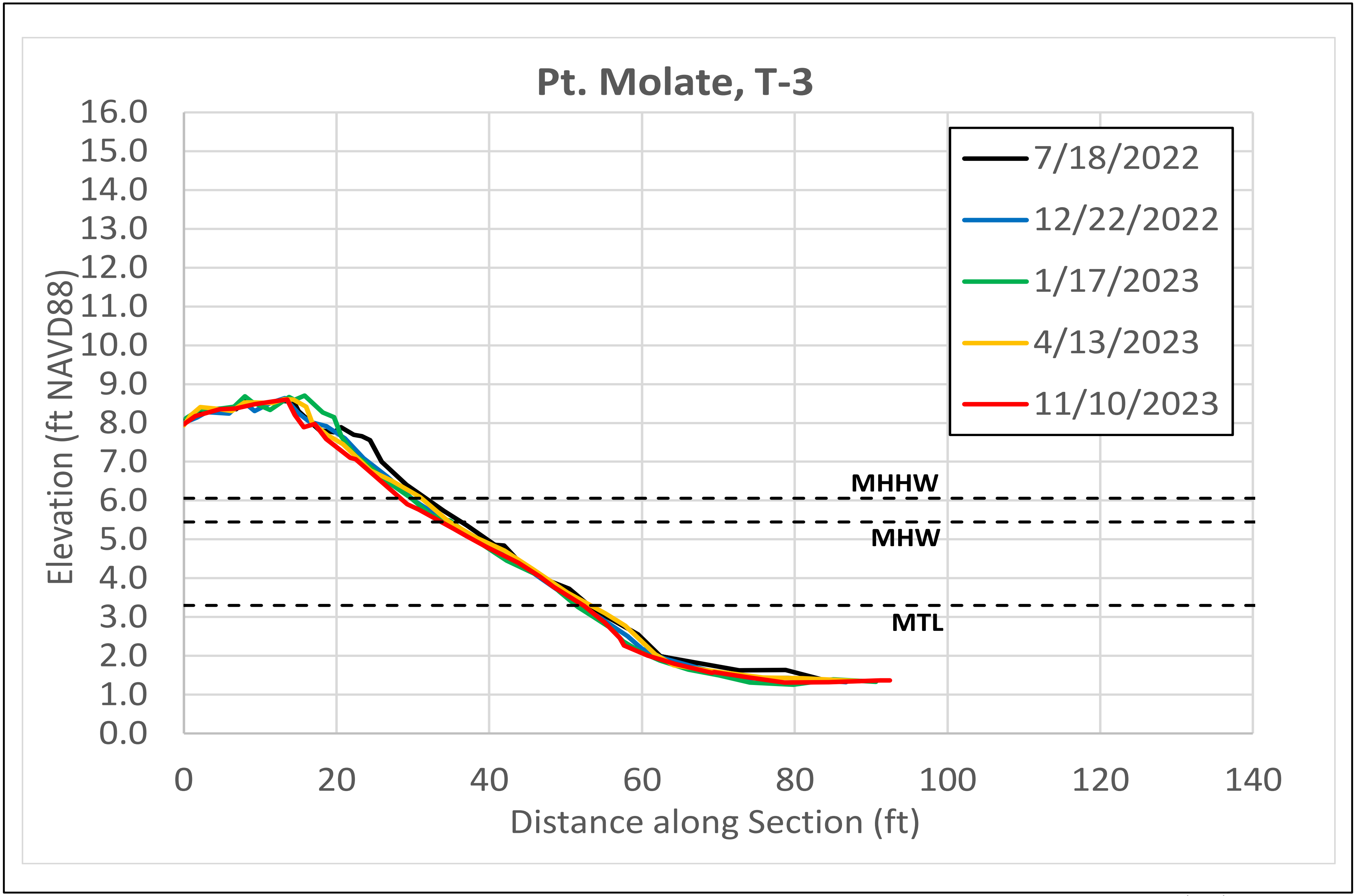


Greenwood Beach Restoration Project

Figure 3

Gillenwater GillenH2O Consulting

Pt. Molate Beach
Transect 2 Topography



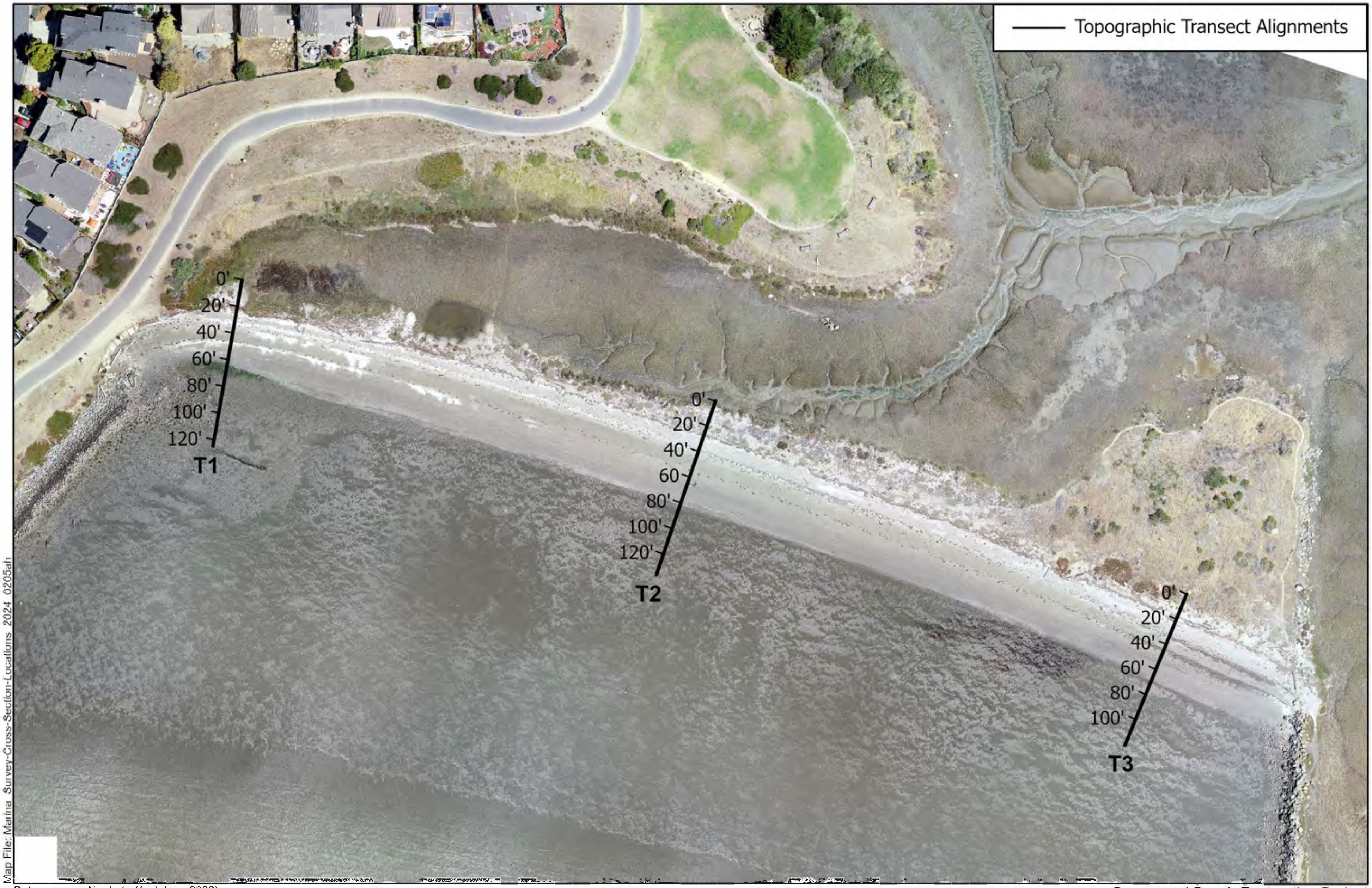
Greenwood Beach Restoration Project

Figure 4

Gillenwater GillenH2O Consulting

Pt. Molate Beach
Transect 3 Topography

Marina Bay Beach



Map File: Marina Survey-Cross-Section-Locations 2024 0205ah

Data sources: Air photo (Audubon, 2022);
Survey Data (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:1,200 (1" = 100' at letter size)

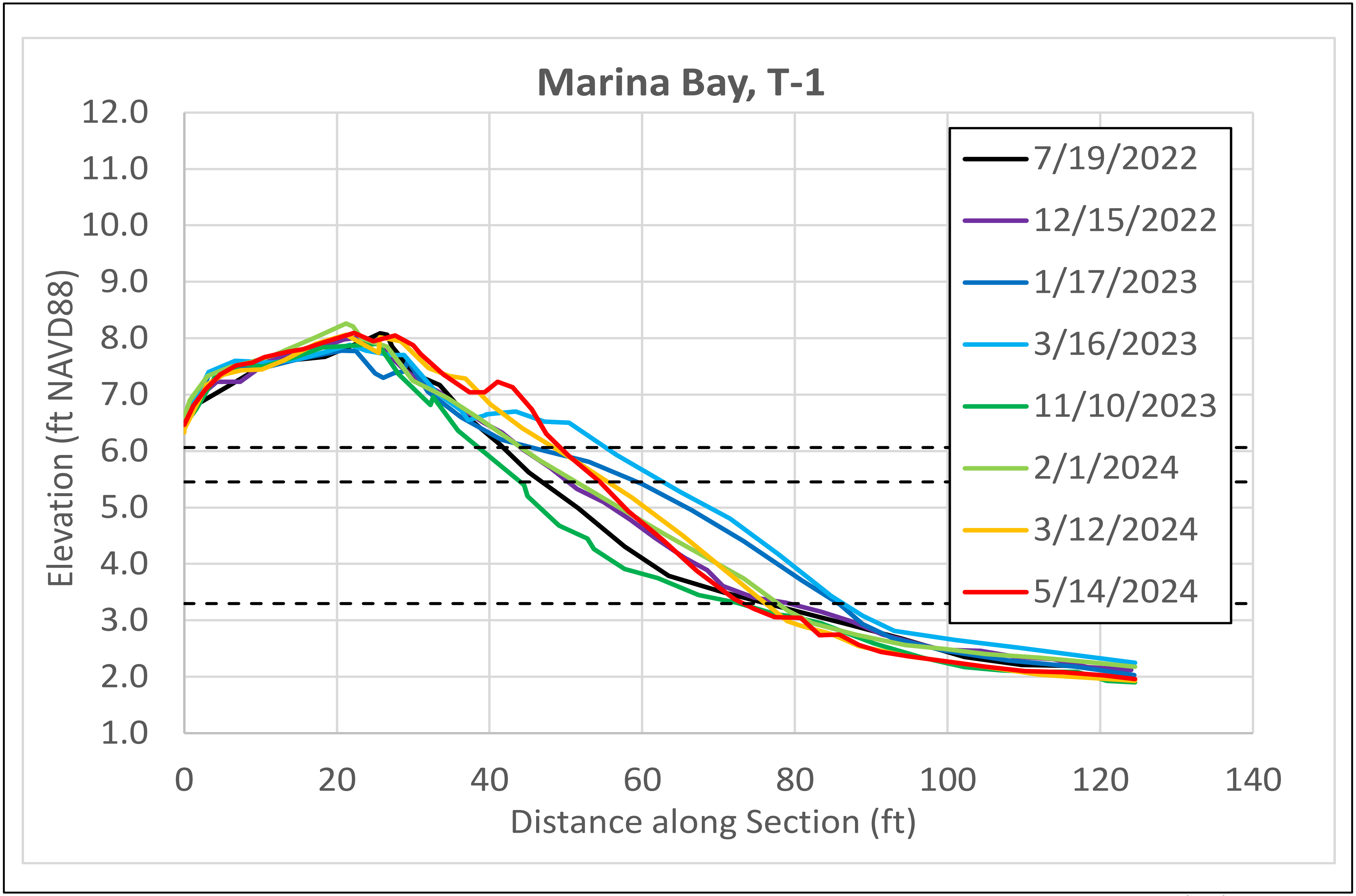
0 50 100 ft

0 15 30 m

Gillenwater GillenH2O Consulting

Figure 1

Marina Bay Beach
Topographic Transect Alignments

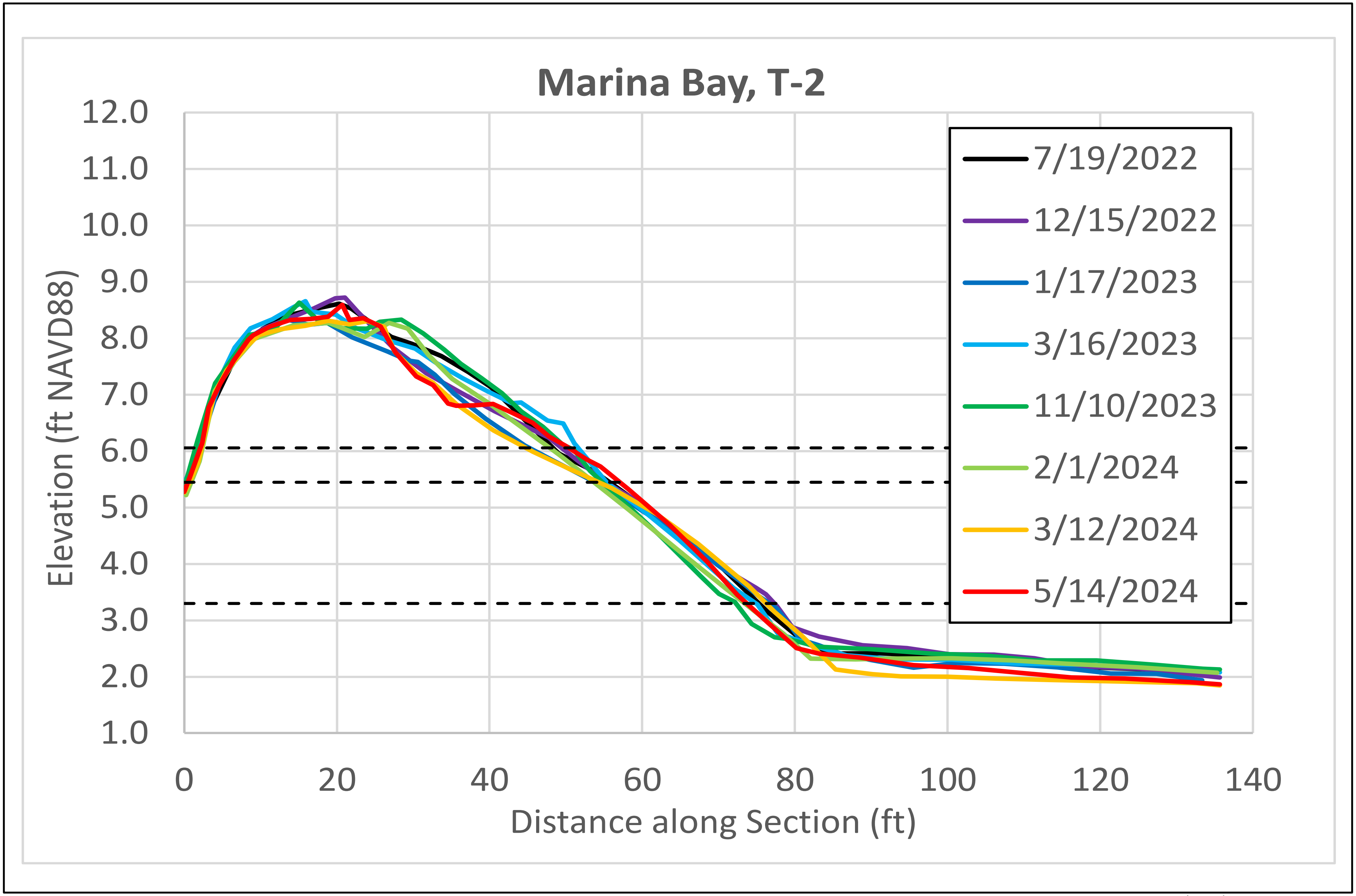


Greenwood Beach Restoration Project

Figure 2

Gillenwater GillenH2O Consulting

Marina Bay Beach
Transect 1 Topography

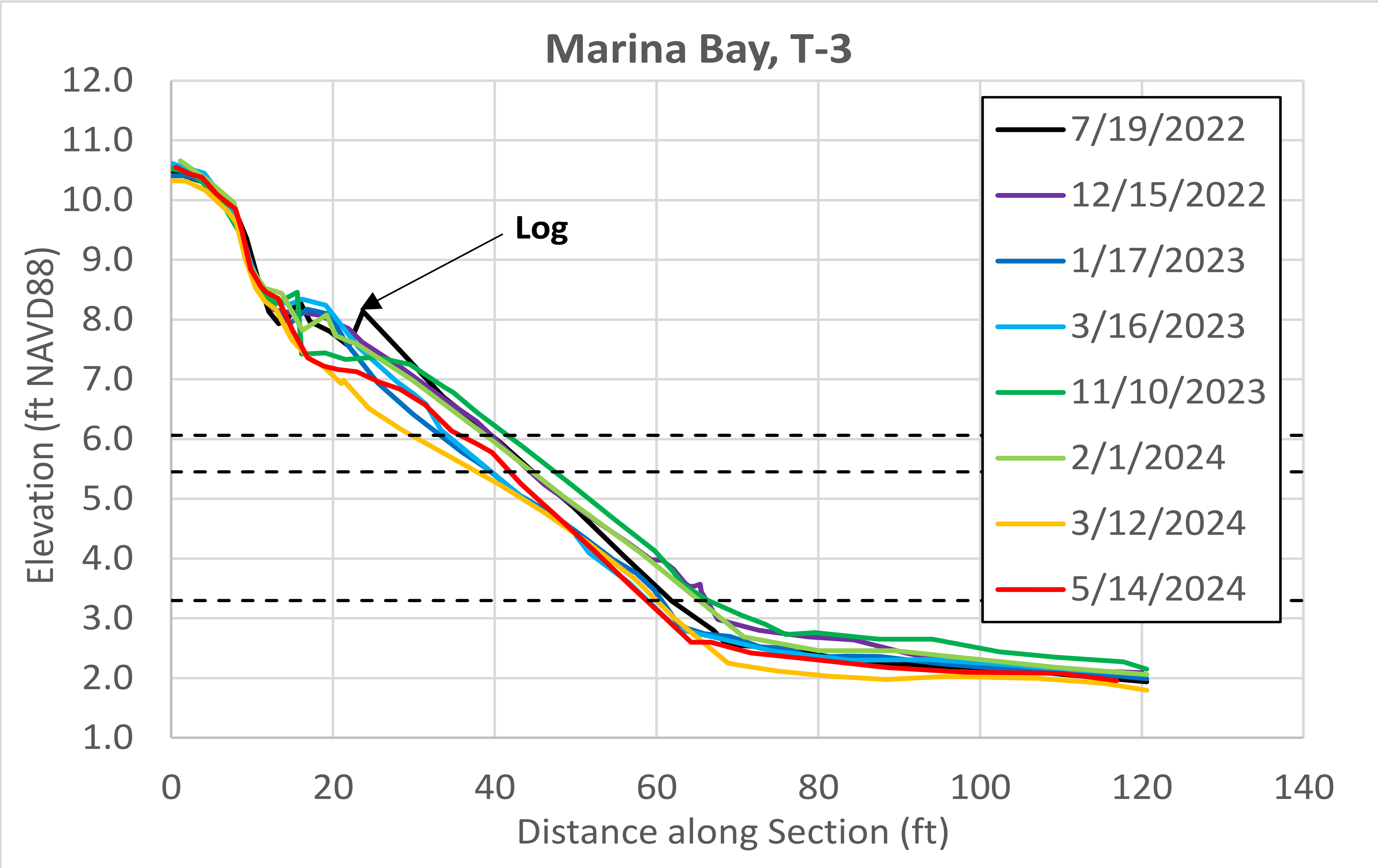


Greenwood Beach Restoration Project

Figure 3

Gillenwater GillenH2O Consulting

Marina Bay Beach
Transect 2 Topography



Greenwood Beach Restoration Project

Figure 4

Marina Bay Beach
Transect 3 Topography

China Camp Beach

Data sources: Air photo (Audubon, 2022);
Survey Data (GillenH2O, 2023)

1:1,800 (1" = 150' at letter size)

0 75 150 ft

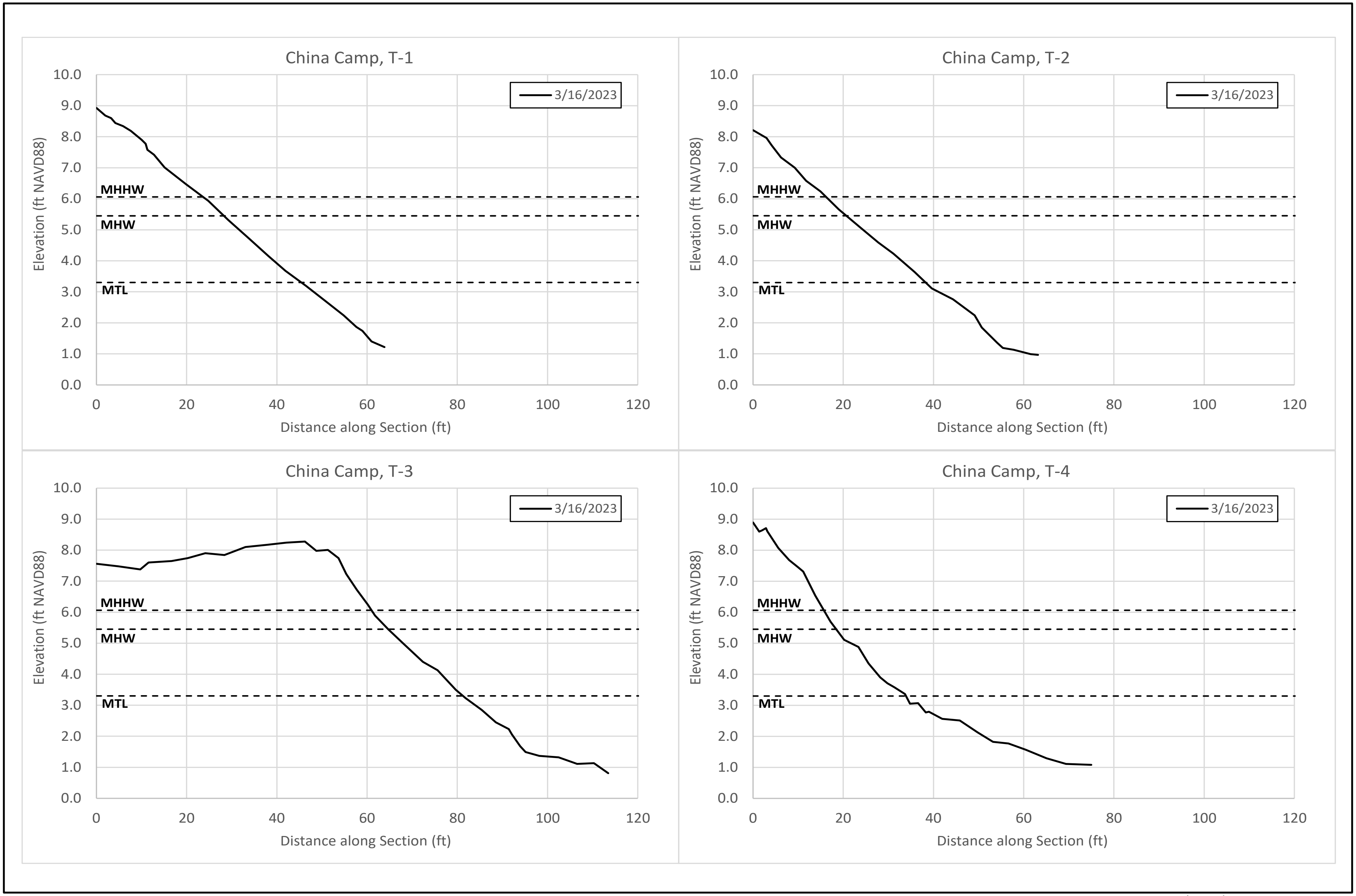
0 22.5 45 m

Greenwood Beach Restoration Project

Gillenwater GillenH2O Consulting

Figure 1

China Camp Beach Topographic Transect Alignments



Greenwood Beach Restoration Project

Figure 2

China Camp Beach
Transect Topography

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Consulting

Pt. Pinole Beach

Data sources: Air photo (Audubon, 2022);
Survey Data (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:1,800 (1" = 150' at letter size)

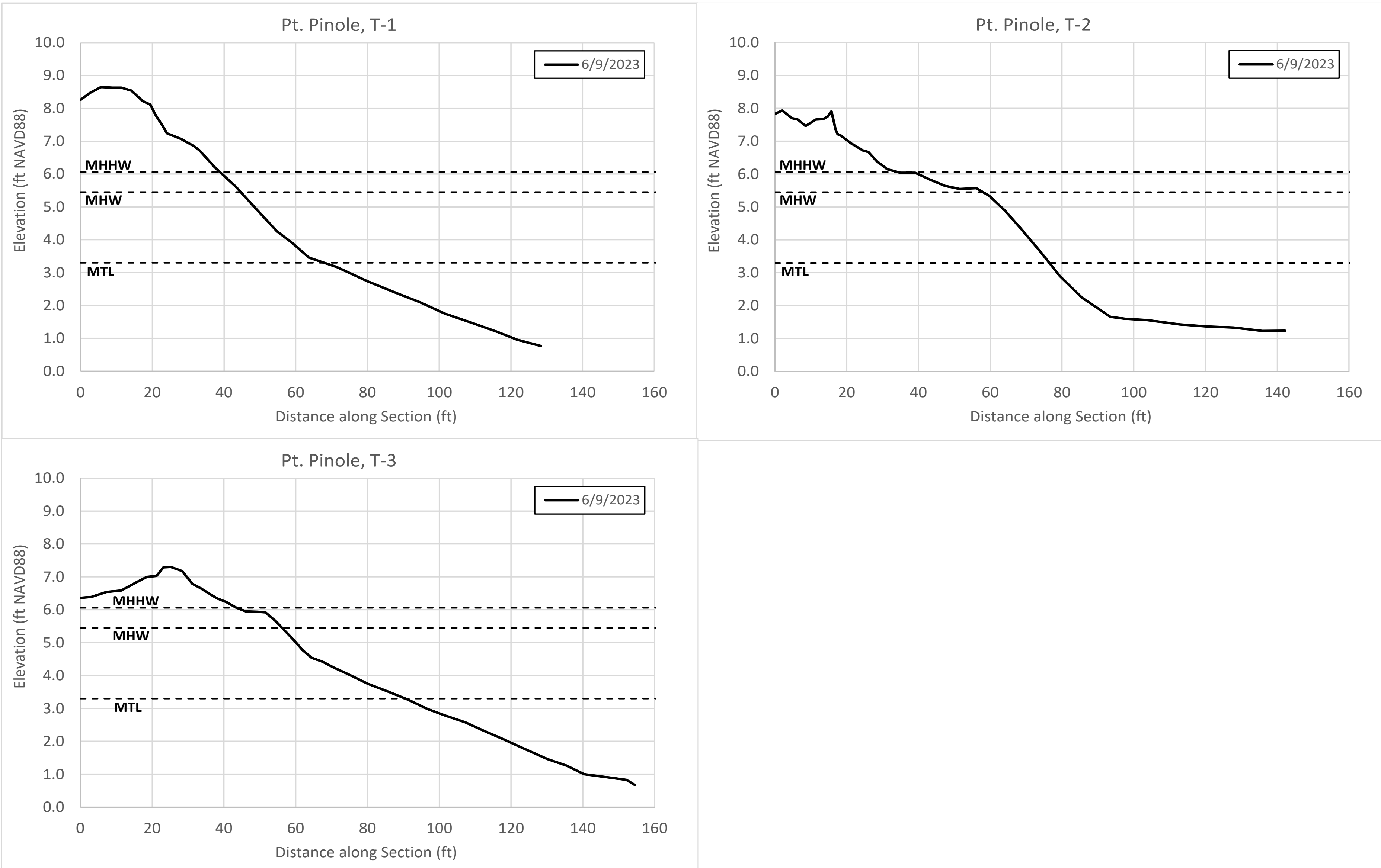
0 75 150 ft

0 22.5 45 m

Gillenwater GillenH2O Consulting

Figure 1

Pt. Pinole Beach Topographic Transect Alignments



Greenwood Beach Restoration Project

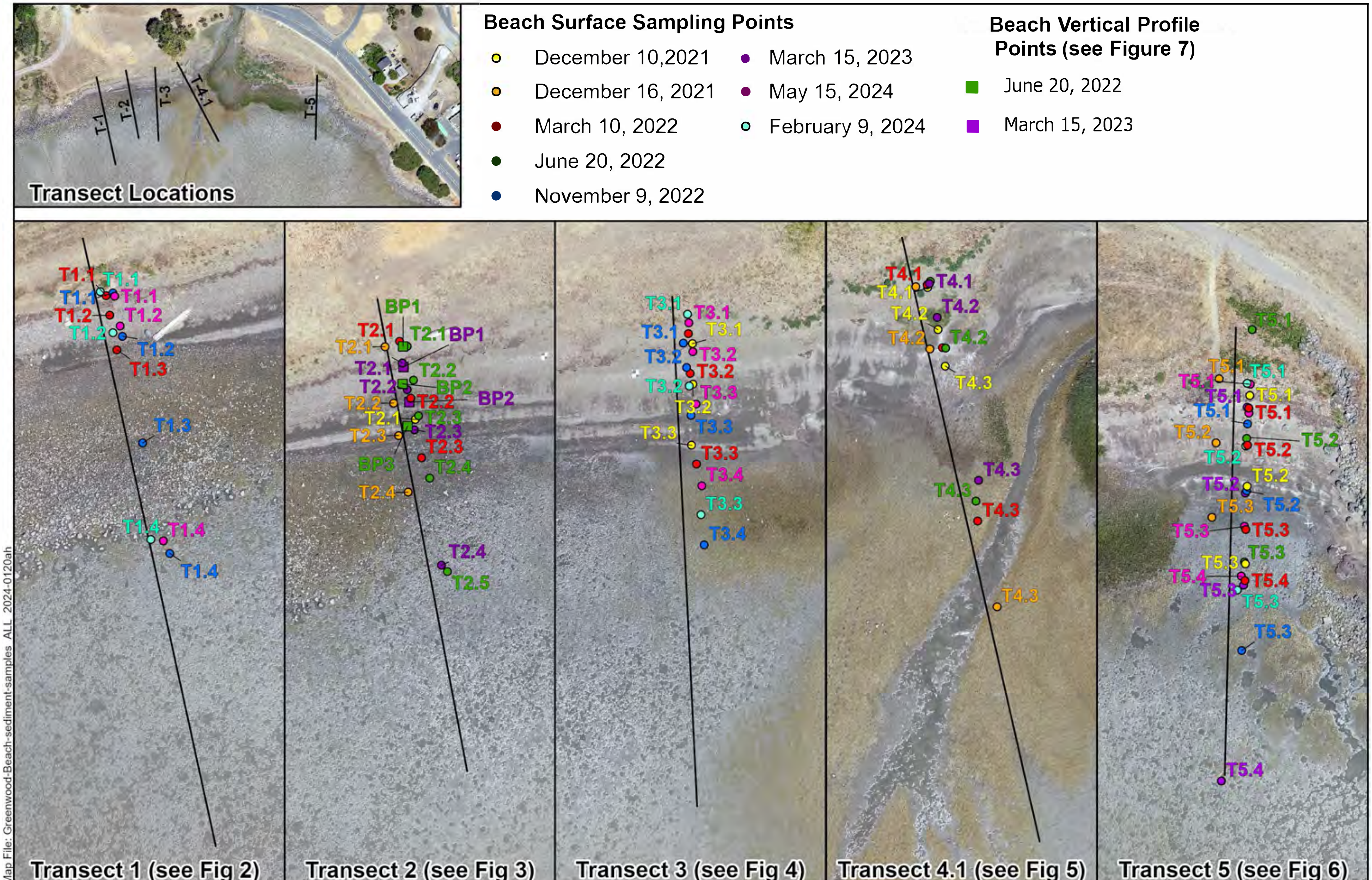
Figure 2

Pt. Pinole Beach
Transect Topography

Gillenwater GillenH2O Consulting

Appendix B:
Grain Size Data Plots

Greenwood Beach



Data sources: Air photo (Audubon, 2023);
Transects (GillenH2O, 2021)

Greenwood Beach Restoration Project

1:480 (1" = 40' at letter size)

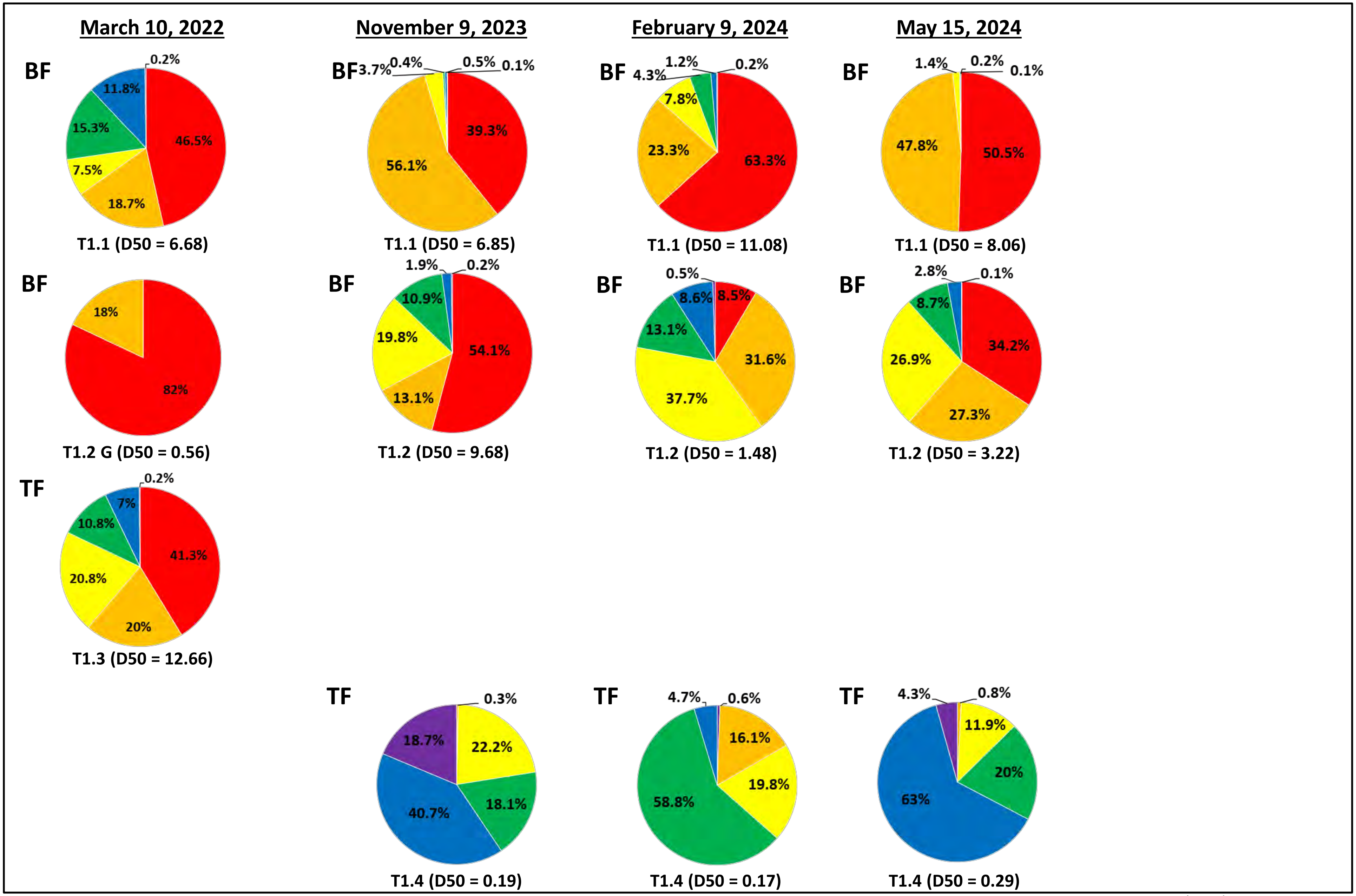
0 20 40 Feet

0 6 12 Meters

Gillenwater GillenH2O Consulting

Figure 1

Greenwood Beach
Beach Grain Size Sampling Locations



Greenwood Beach Restoration Project

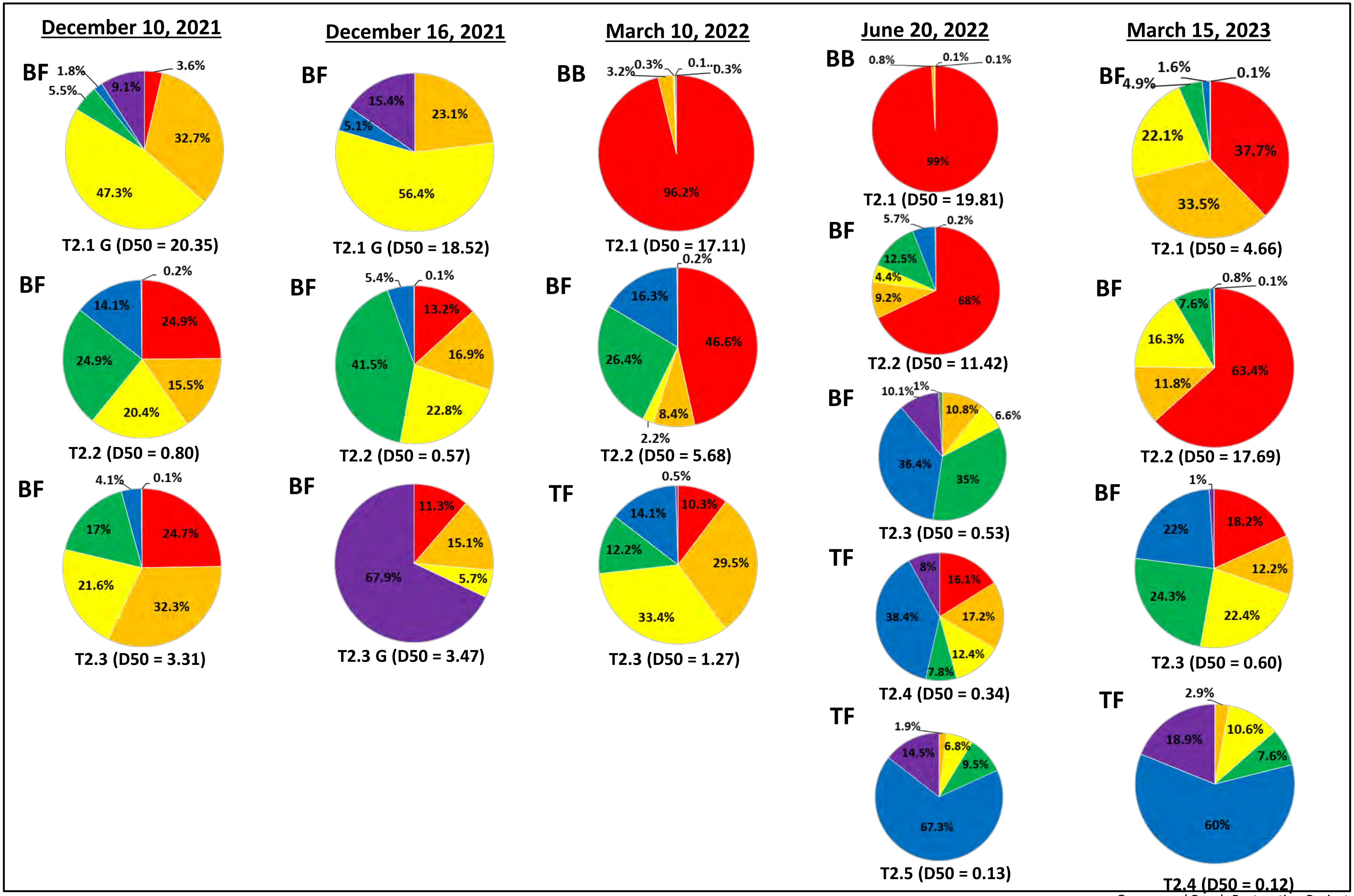
Figure 2

Gillenwater GillenH2O Consulting

Sample Position Key:
BB: Backshore/Beach Berm
BF: Beach Face
TF: Tidal Flat

Grain Size Classes:
Coarse Gravel (8-64mm)
Fine Gravel (2-8mm)
Coarse Sand (0.5-2mm)
Medium Sand (0.25-0.5mm)
Fine Sand (0.063-0.25mm)
Mud (<0.063mm)

Greenwood Beach
Transect 1 Beach Surface Grain Size Samples



Greenwood Beach Restoration Project

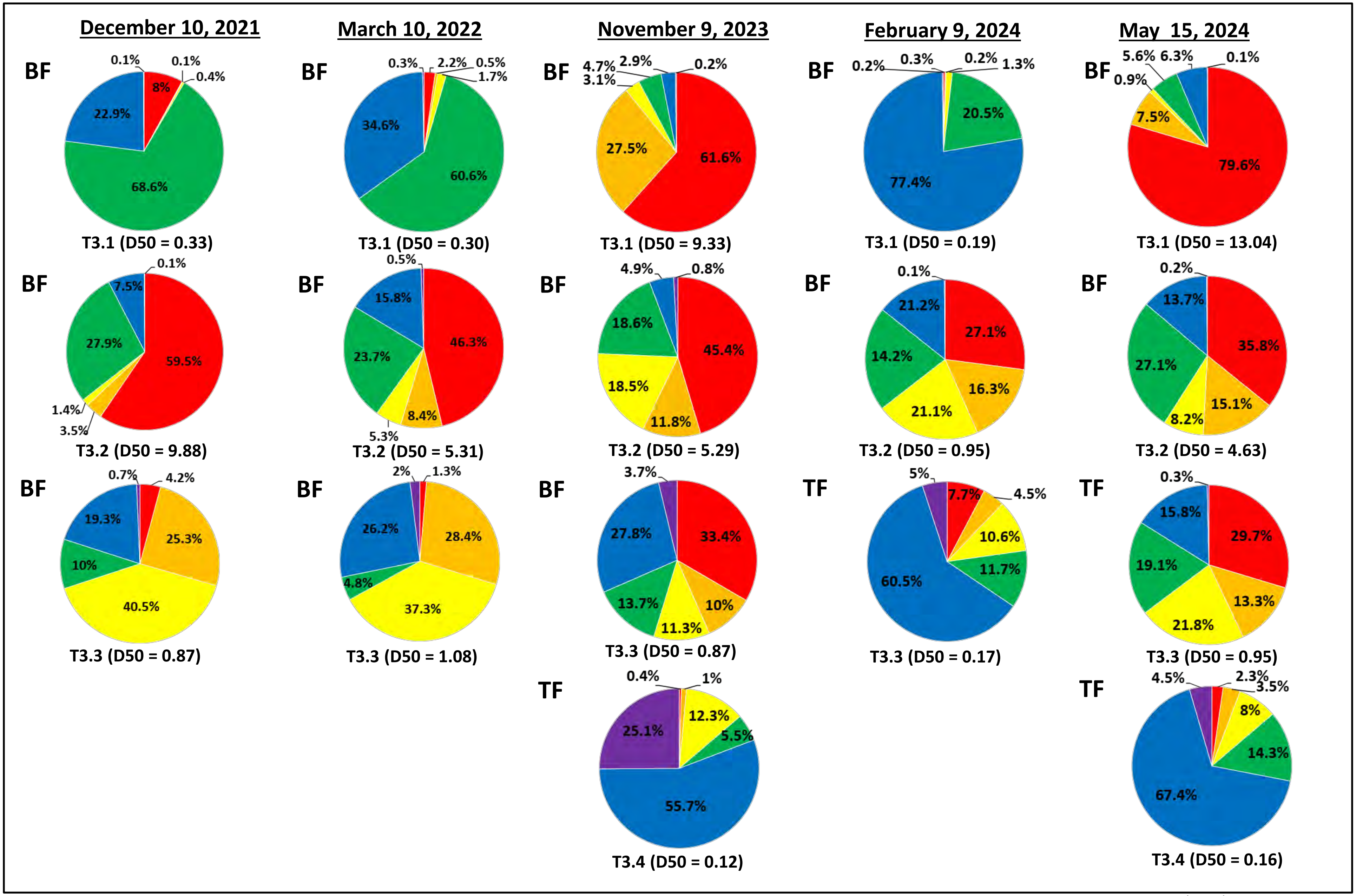
Figure 3

Sample Position Key:
BB: Backshore/Beach Berm
BF: Beach Face
TF: Tidal Flat

Grain Size Classes:
Coarse Gravel (8-64mm)
Fine Gravel (2-8mm)
Coarse Sand (0.5-2mm)
Medium Sand (0.25-0.5mm)
Fine Sand (0.063-0.25mm)
Mud (<0.063mm)

Gillenwater GillenH2O Consulting

Greenwood Beach
Transect 2 Beach Surface Grain Size Samples



Greenwood Beach Restoration Project

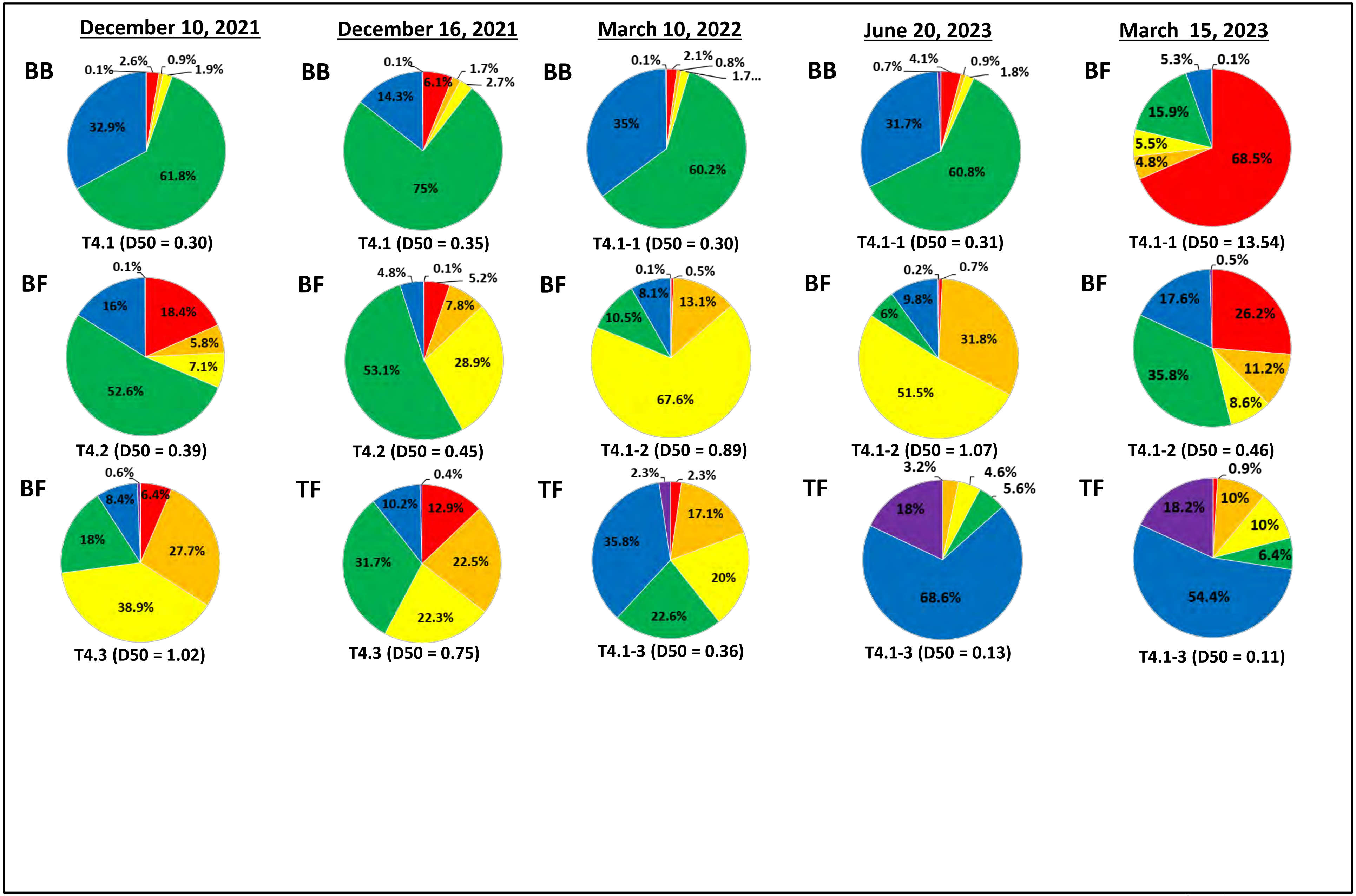
Figure 4

Sample Position Key:
BB: Backshore/Beach Berm
BF: Beach Face
TF: Tidal Flat

Grain Size Classes:
Coarse Gravel (8-64mm)
Fine Gravel (2-8mm)
Coarse Sand (0.5-2mm)
Medium Sand (0.25-0.5mm)
Fine Sand (0.063-0.25mm)
Mud (<0.063mm)

Gillenwater GillenH2O Consulting

Greenwood Beach
Transect 3 Beach Surface Grain Size Samples



Sample Position Key:
BB: Backshore/Beach Berm
BF: Beach Face
TF: Tidal Flat

Grain Size Classes:
Coarse Gravel (8-64mm)
Fine Gravel (2-8mm)
Coarse Sand (0.5-2mm)
Medium Sand (0.25-0.5mm)
Fine Sand (0.063-0.25mm)
Mud (<0.063mm)

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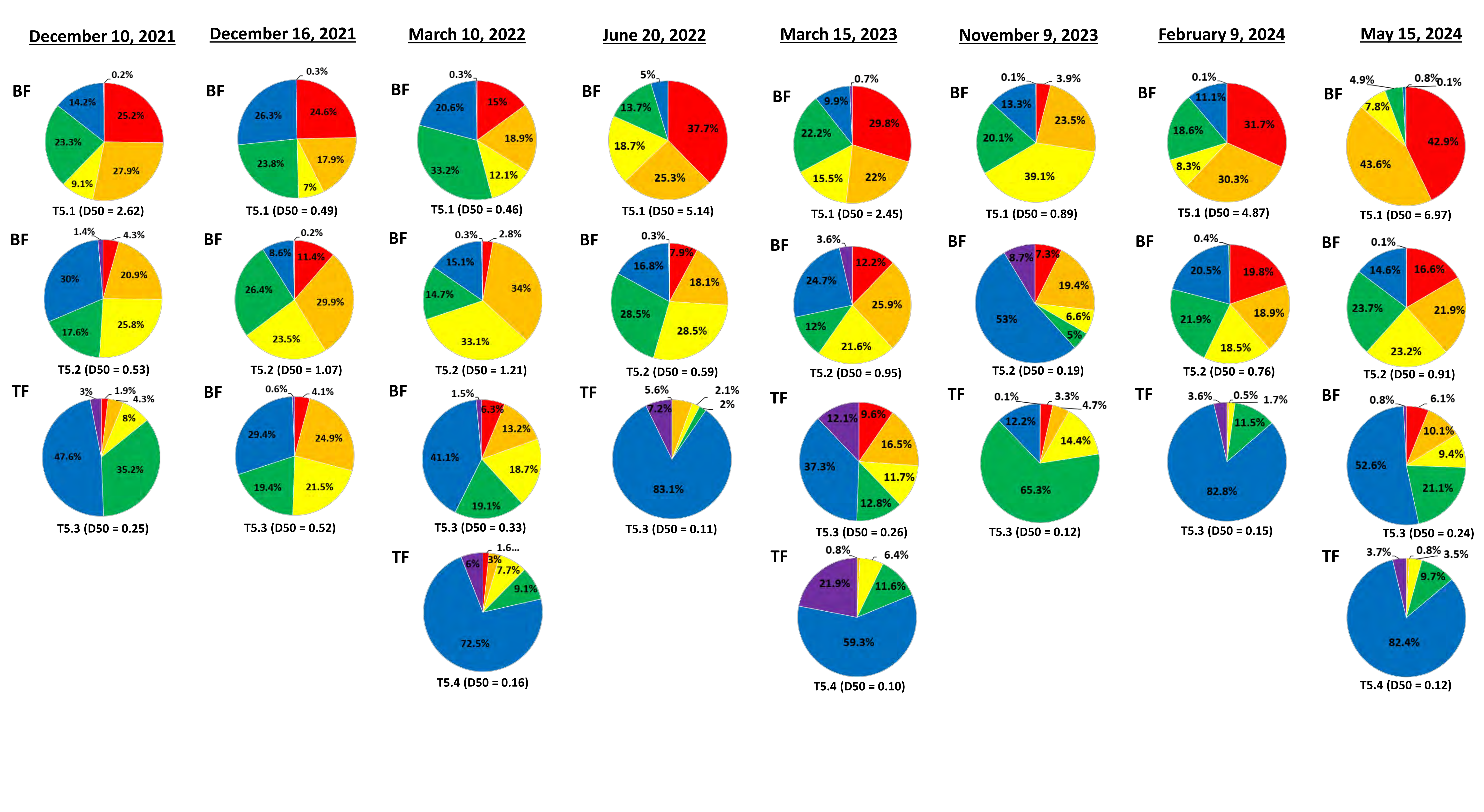
Greenwood Beach Restoration Project

Figure 5

Greenwood Beach
Transect 4.1 Beach Surface Grain Size Samples



Sample Position Key:

BB: Backshore/Beach Berm
BF: Beach Face
TF: Tidal Flat

Grain Size Classes:

- Coarse Gravel (8-64mm)
- Fine Gravel (2-8mm)
- Coarse Sand (0.5-2mm)
- Medium Sand (0.25-0.5mm)
- Fine Sand (0.063-0.25mm)
- Mud (<0.063mm)

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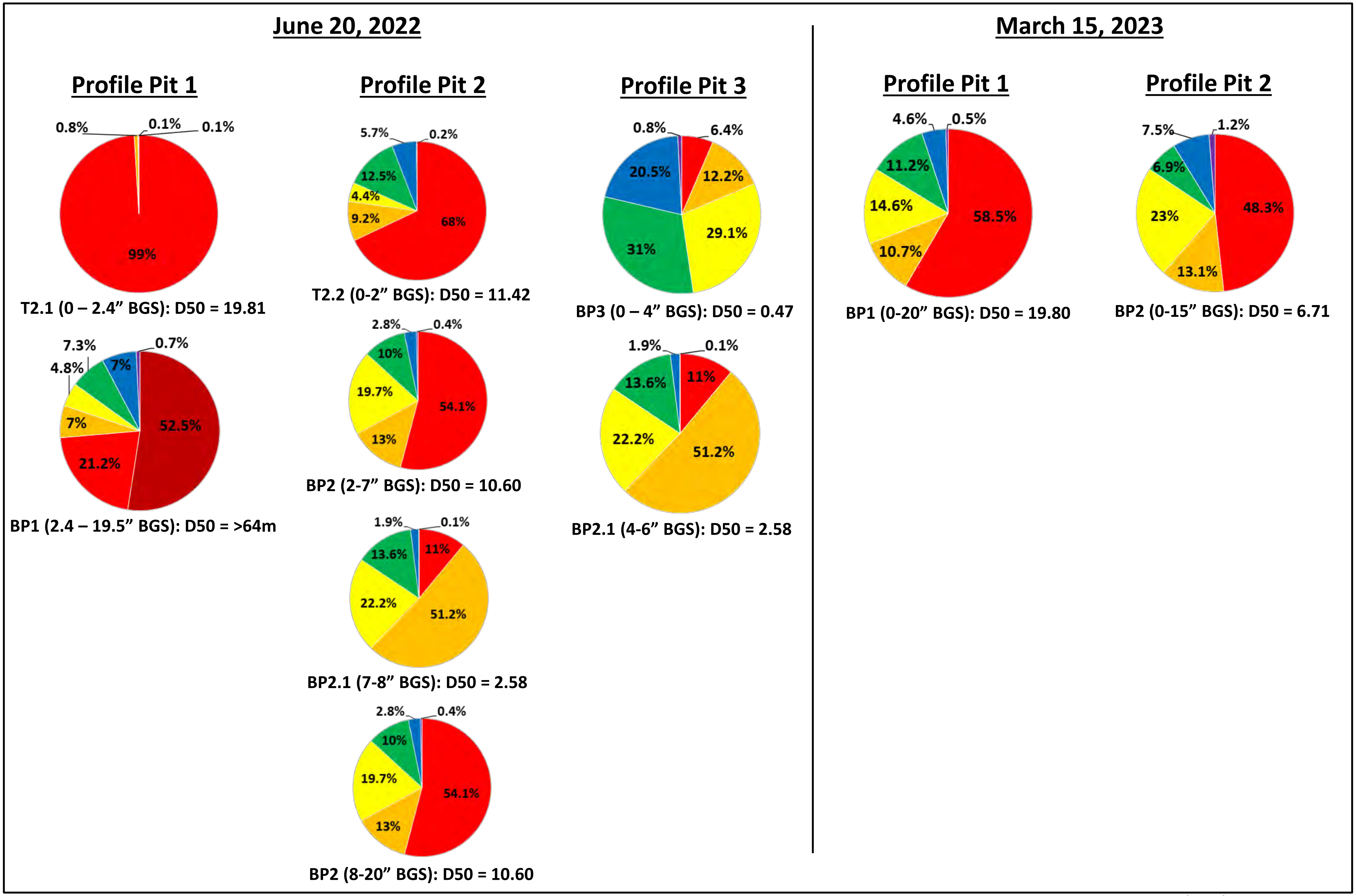
Greenwood Beach Restoration Project

Figure 6

Greenwood Beach
Transect 5 Beach Surface Grain Size Samples



Grain Size Classes:

- Cobble (64-256mm)
- Coarse Gravel (8-64mm)
- Fine Gravel (2-8mm)
- Coarse Sand (0.5-2mm)
- Medium Sand (0.25-0.5mm)
- Fine Sand (0.063-0.25mm)
- Mud (<0.063mm)

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Greenwood Beach Restoration Project

Figure 7

Greenwood Beach
Beach Vertical Profile Grain Size Samples

Sanctuary Beach

Data sources: Air photo (Audubon, 2023);
Transects (GillenH2O, 2021)

Greenwood Beach Restoration Project

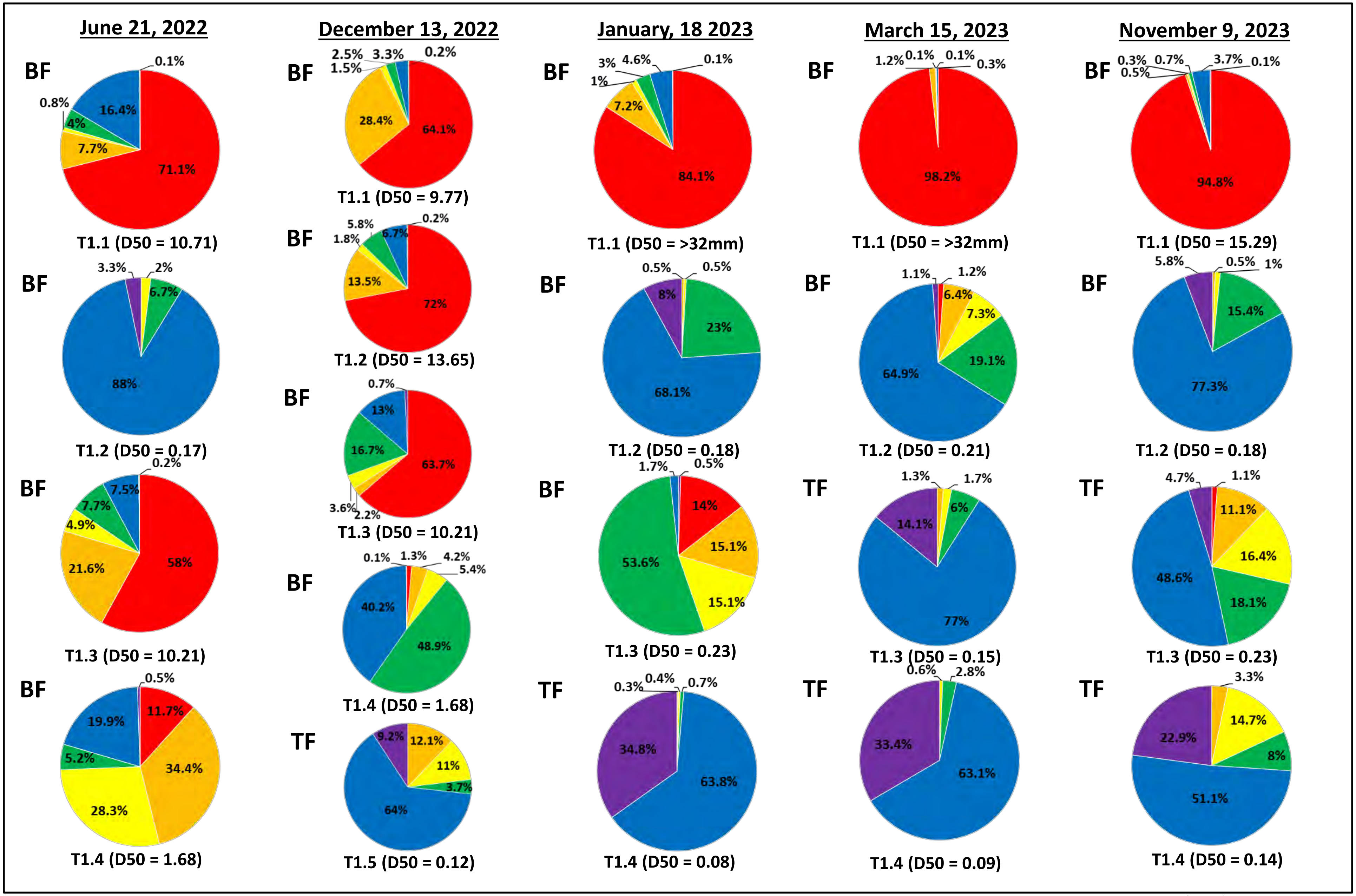
1:360 (1" = 30' at letter size)

0 15 30 Feet

0 4.5 9 Meters

Figure 1

Sanctuary Beach
Beach Grain Size Sampling Locations



Gillenwater GillenH2O Consulting

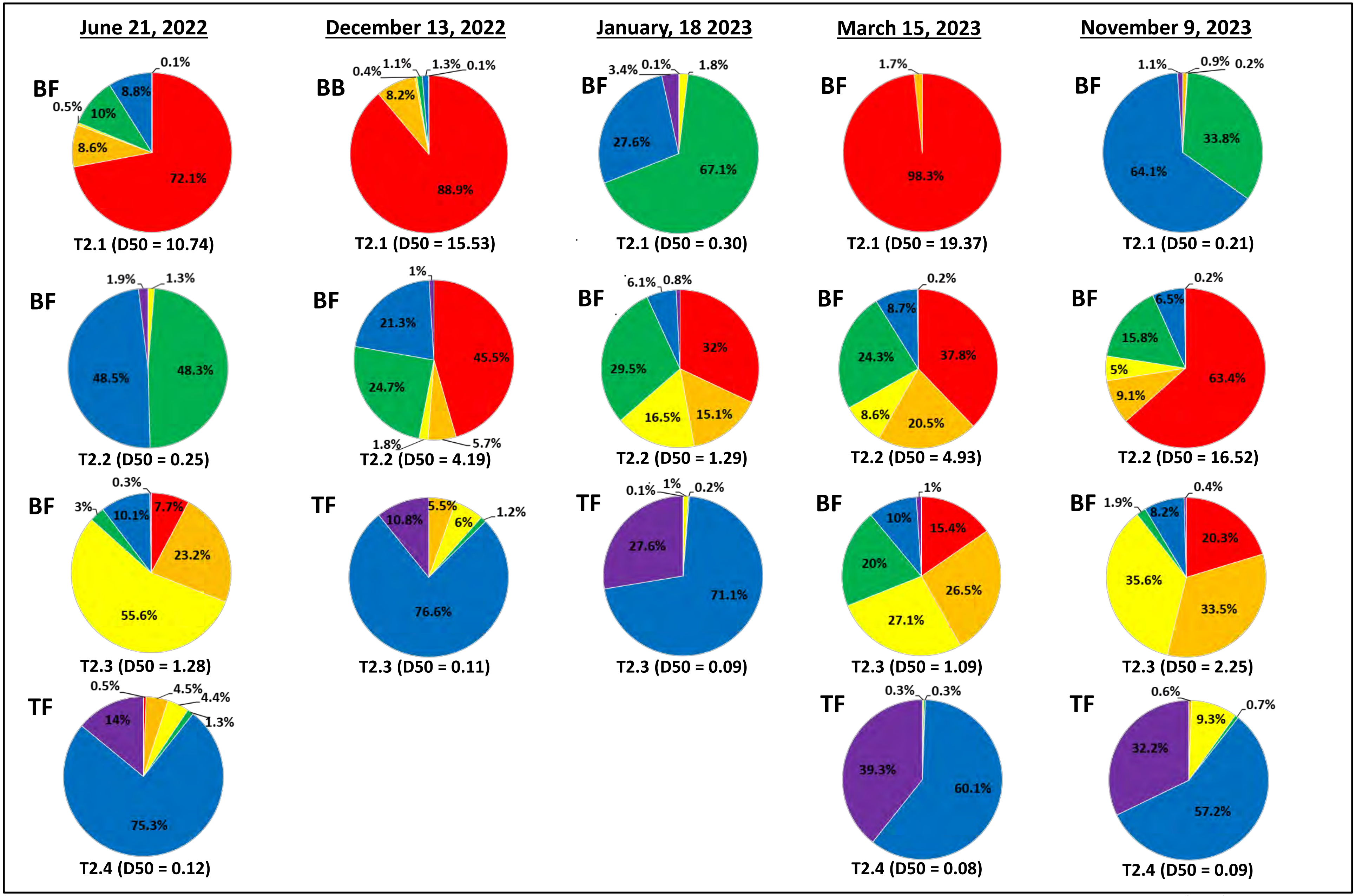
Sample Position Key:
BB: Backshore/Beach Berm
BF: Beach Face
TF: Tidal Flat

Grain Size Classes:
Coarse Gravel (8-64mm)
Fine Gravel (2-8mm)
Coarse Sand (0.5-2mm)
Medium Sand (0.25-0.5mm)
Fine Sand (0.063-0.25mm)
Mud (<0.063mm)

Greenwood Beach Restoration Project

Figure 2

Sanctuary Beach
Transect 1 Beach Surface Grain Size Samples



Sample Position Key:

BB: Backshore/Beach Berm
BF: Beach Face
TF: Tidal Flat

Grain Size Classes:

- Coarse Gravel (8-64mm)
- Fine Gravel (2-8mm)
- Coarse Sand (0.5-2mm)
- Medium Sand (0.25-0.5mm)
- Fine Sand (0.063-0.25mm)
- Mud (<0.063mm)

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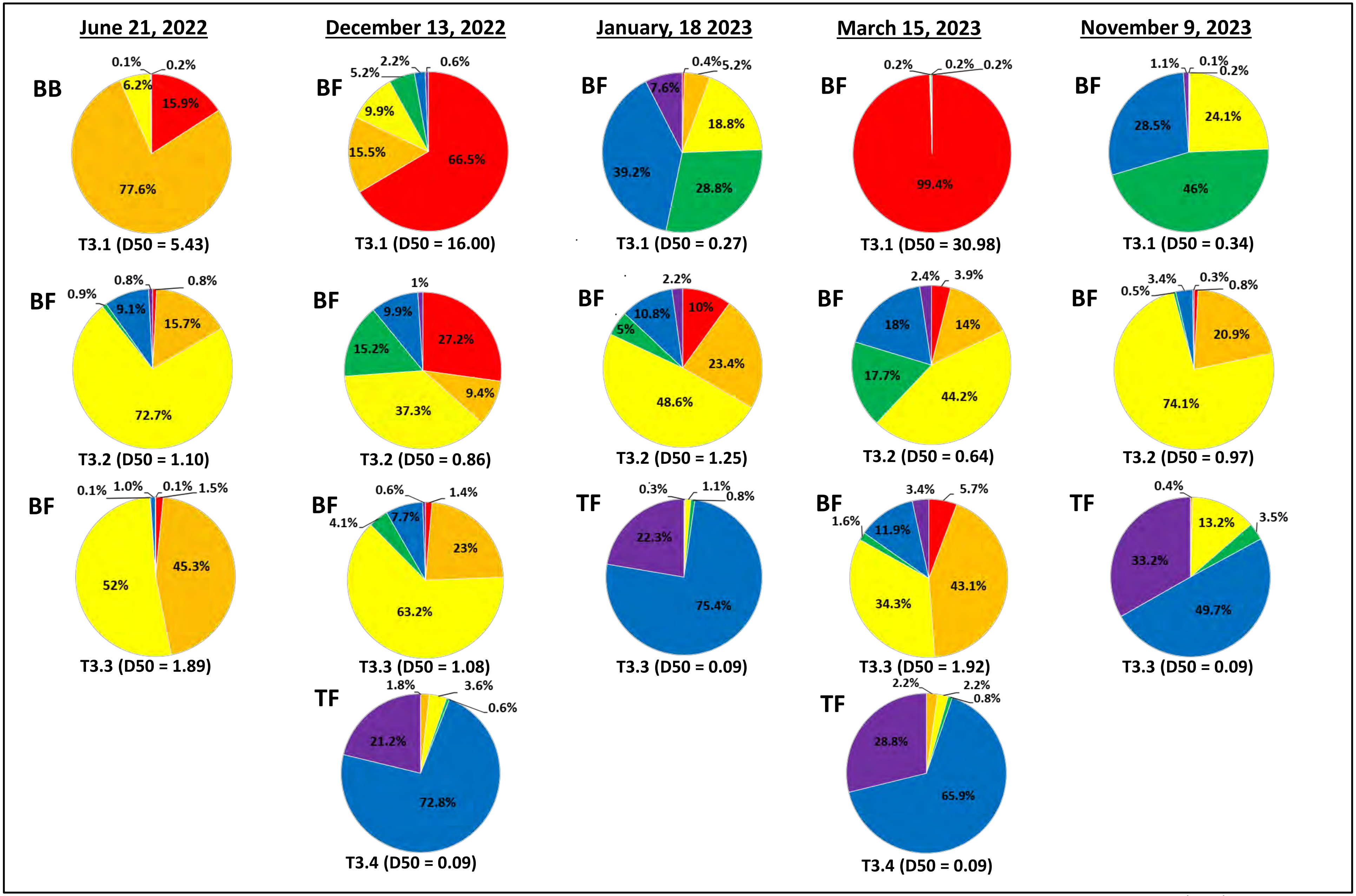
Greenwood Beach Restoration Project

Figure 3

Sanctuary Beach
Transect 2 Beach Surface Grain Size Samples



Gillenwater GillenH2O Consulting

Sample Position Key:

BB: Backshore/Beach Berm

BF: Beach Face

TF: Tidal Flat

Grain Size Classes:

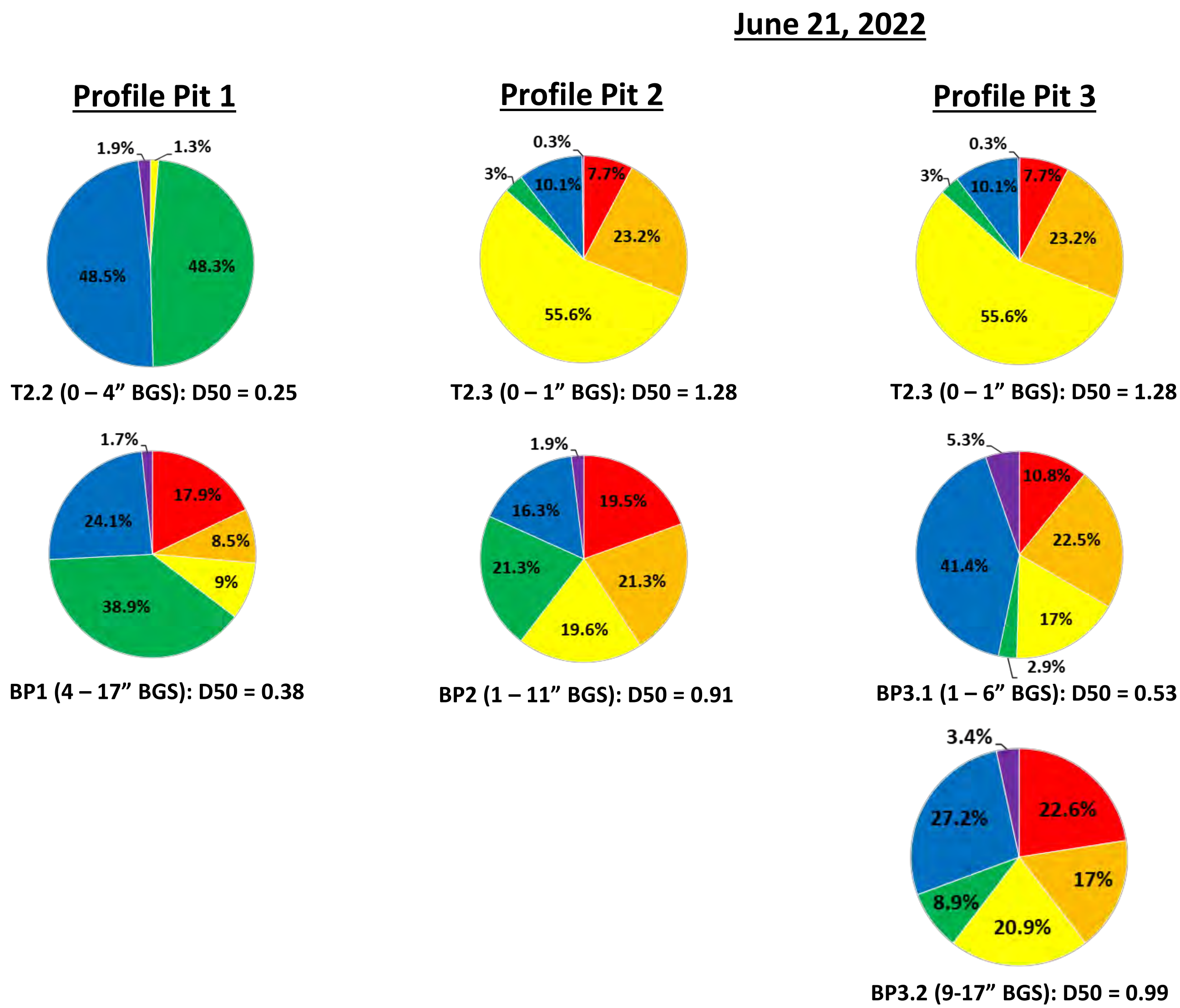
- Coarse Gravel (8-64mm)
- Fine Gravel (2-8mm)
- Coarse Sand (0.5-2mm)
- Medium Sand (0.25-0.5mm)
- Fine Sand (0.063-0.25mm)
- Mud (<0.063mm)

Greenwood Beach Restoration Project

Figure 4

Sanctuary Beach

Transect 3 Beach Surface Grain Size Samples



Gillenwater GillenH2O Consulting

Grain Size Classes:

- Coarse Gravel (8-64mm)
- Fine Gravel (2-8mm)
- Coarse Sand (0.5-2mm)
- Medium Sand (0.25-0.5mm)
- Fine Sand (0.063-0.25mm)
- Mud (<0.063mm)

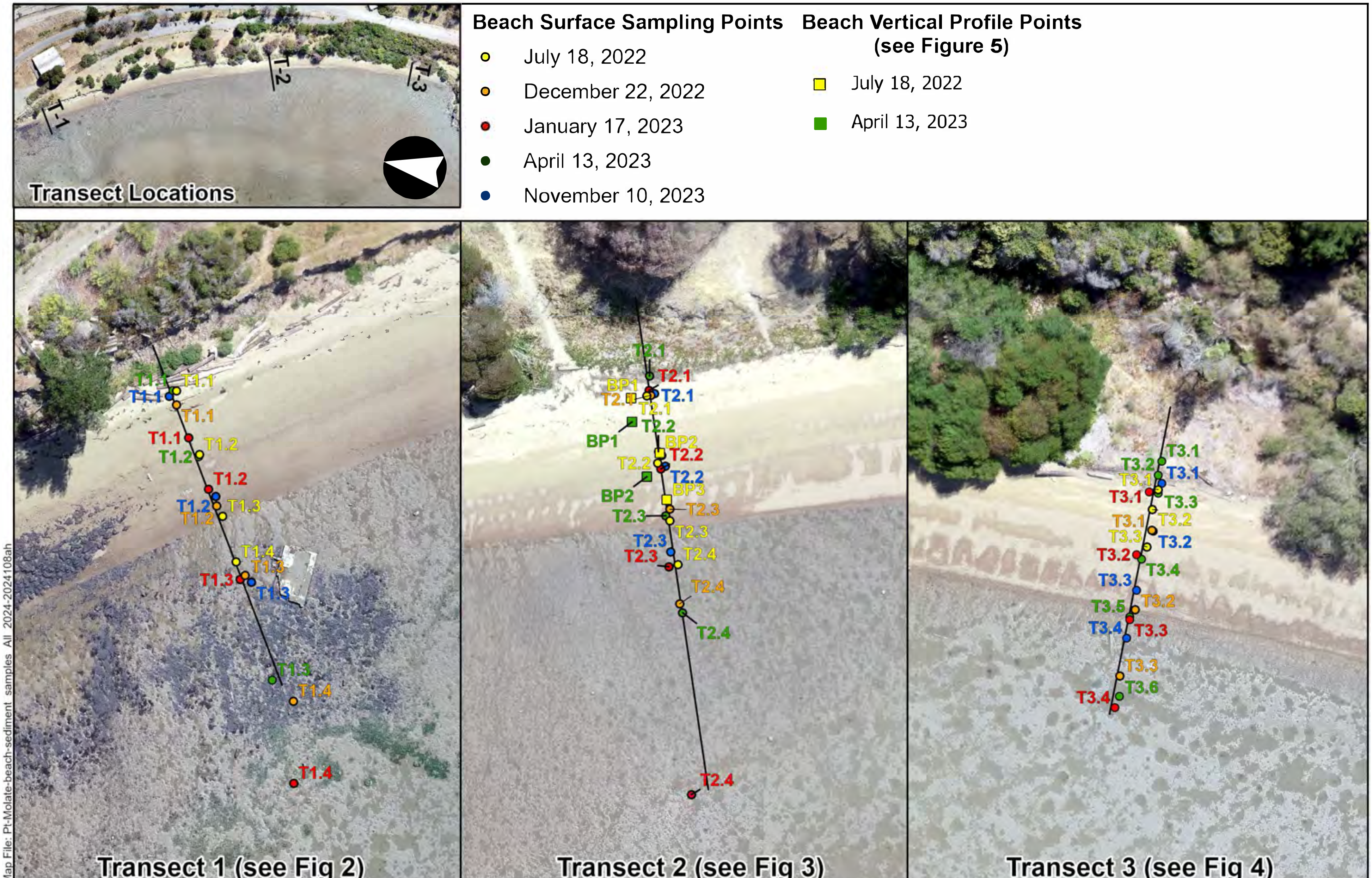
Greenwood Beach Restoration Project

Figure 5

Sanctuary Beach

Beach Vertical Profile Grain Size Samples

Pt. Molate Beach



Map File: Pt-Molate-beach-sediment_samples_All_2024-2024108ah

Data sources: Air photo (Audubon, 2023);
Transects (GillenH2O, 2021)

Greenwood Beach Restoration Project

1:480 (1" = 40' at letter size)

0 20 40 Feet

0 6 12 Meters

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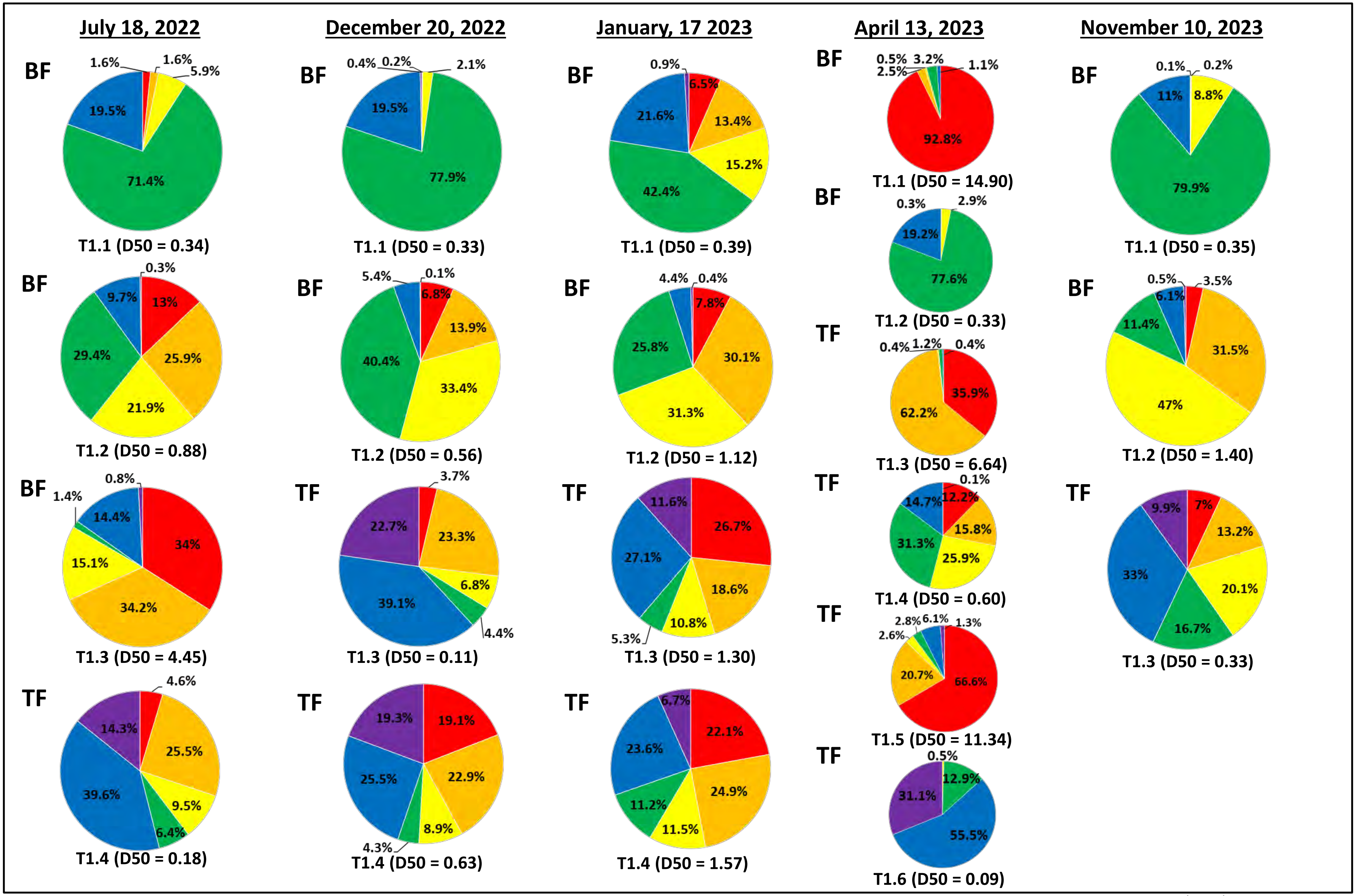
GillenH2O
Consulting

Figure 1

Pt. Molate Beach
Beach Grain Size Sampling Locations



Greenwood Beach Restoration Project

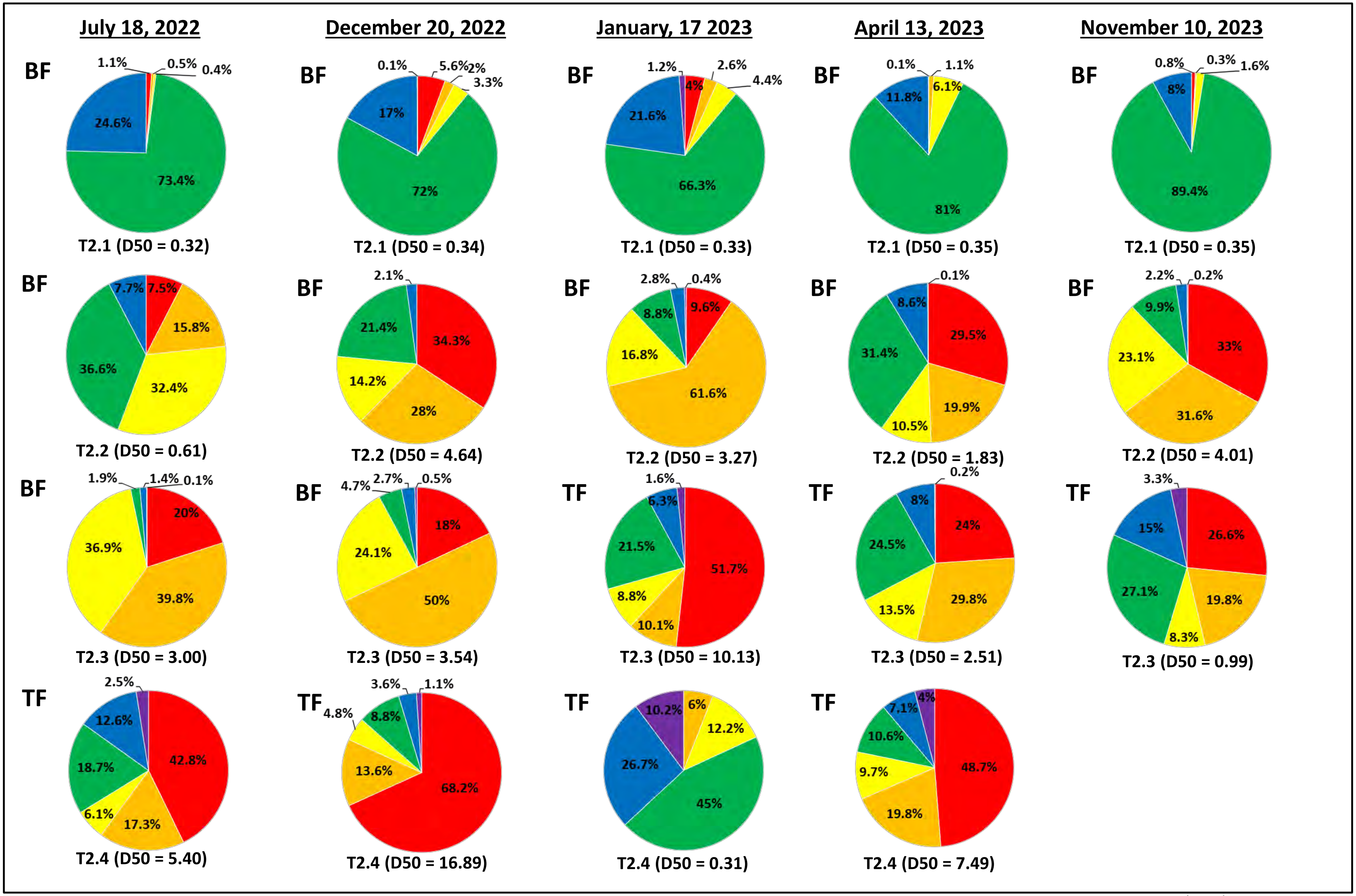
Figure 2

Sample Position Key:
BB: Backshore/Beach Berm
BF: Beach Face
TF: Tidal Flat

Grain Size Classes:
Coarse Gravel (8-64mm)
Fine Gravel (2-8mm)
Coarse Sand (0.5-2mm)
Medium Sand (0.25-0.5mm)
Fine Sand (0.063-0.25mm)
Mud (<0.063mm)

Pt. Molate Beach
Transect 1 Beach Surface Grain Size Samples

Gillenwater GillenH2O Consulting



Gillenwater GillenH2O Consulting

Sample Position Key:
BB: Backshore/Beach Berm
BF: Beach Face
TF: Tidal Flat

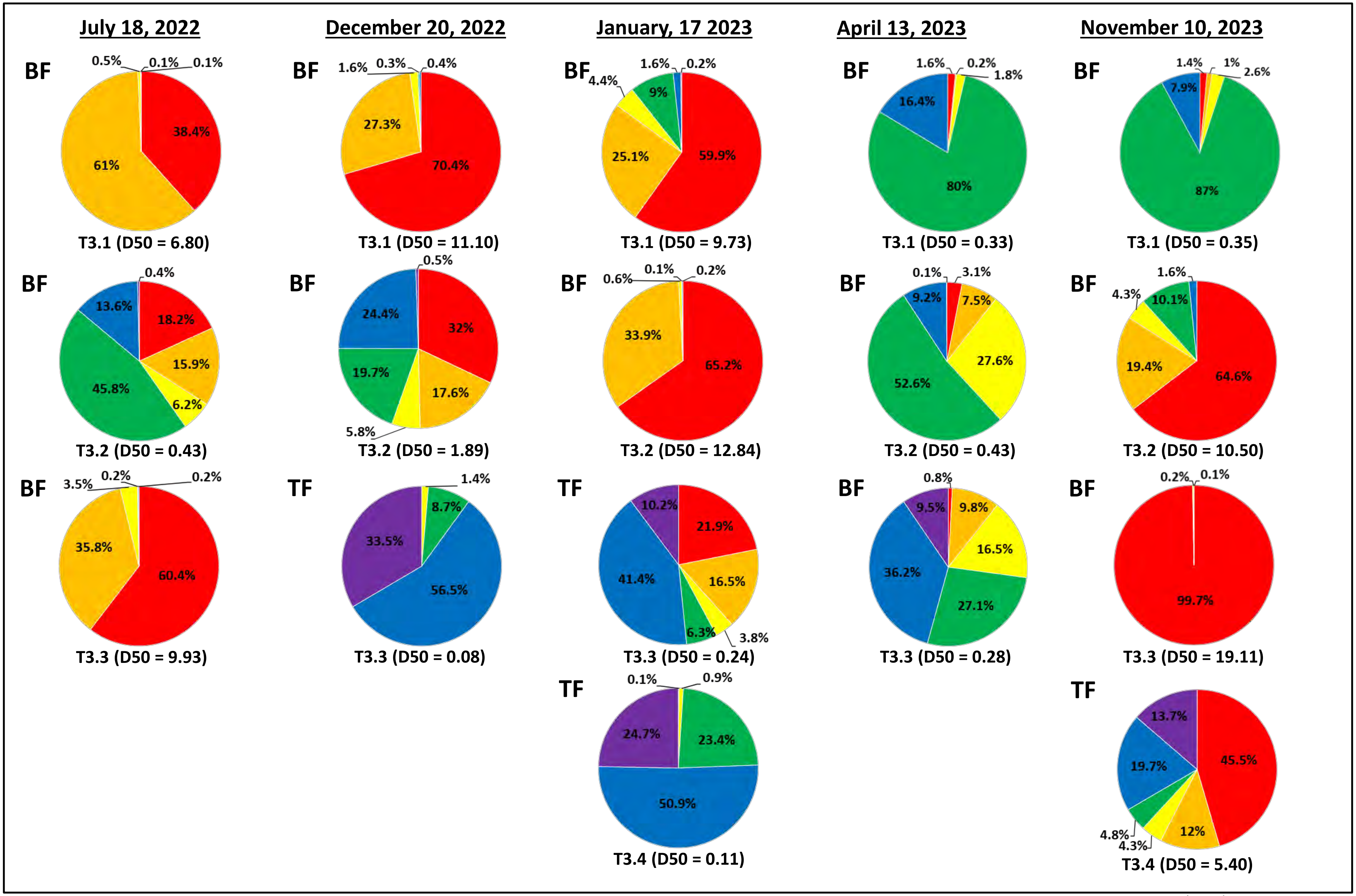
Grain Size Classes:
Coarse Gravel (8-64mm)
Fine Gravel (2-8mm)
Coarse Sand (0.5-2mm)
Medium Sand (0.25-0.5mm)
Fine Sand (0.063-0.25mm)
Mud (<0.063mm)

Greenwood Beach Restoration Project

Figure 3

Pt. Molate Beach

Transect 2 Beach Surface Grain Size Samples



Sample Position Key:
BB: Backshore/Beach Berm
BF: Beach Face
TF: Tidal Flat

Grain Size Classes:
Medium Gravel (8-64mm)
Fine Gravel (2-8mm)
Coarse Sand (0.5-2mm)
Medium Sand (0.25-0.5mm)
Fine Sand (0.063-0.25mm)
Mud (<0.063mm)

Gillenwater GillenH2O Consulting

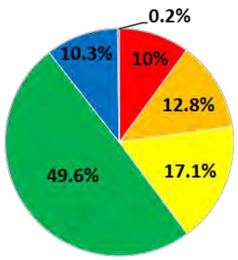
Greenwood Beach Restoration Project

Figure 4

Pt. Molate Beach
Transect 3 Beach Surface Grain Size Samples

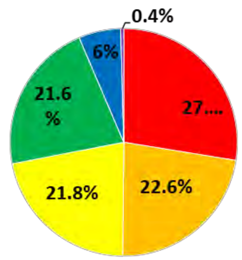
July 19, 2022

Profile Pit 1

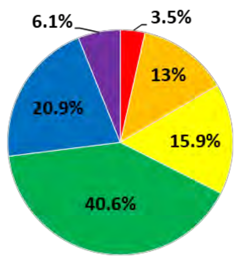


BP1.1 (0 – 32” BGS): D50 = 0.43

Profile Pit 2

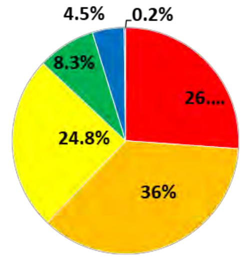


BP2.1 (0 – 21” BGS): D50 = 2.02

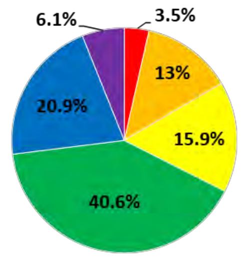


BP3.2 (4 – 10” BGS): D50 = 0.37

Profile Pit 3



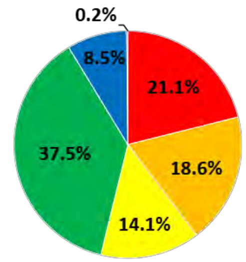
BP3.1 (0 – 4” BGS): D50 = 3.65



BP3.2 (4 – 10” BGS): D50 = 0.37

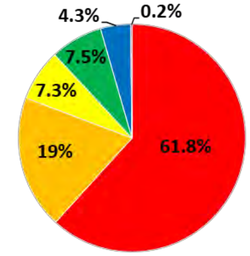
March 16, 2023

Profile Pit 1



BP1 (0 – 21” BGS): D50 = 0.67

Profile Pit 2



BP2 (0 – 20” BGS): D50 = 12.22

Grain Size Classes:

- Coarse Gravel (8-64mm)
- Fine Gravel (2-8mm)
- Coarse Sand (0.5-2mm)
- Medium Sand (0.25-0.5mm)
- Fine Sand (0.063-0.25mm)
- Mud (<0.063mm)

Gillenwater GillenH2O Consulting

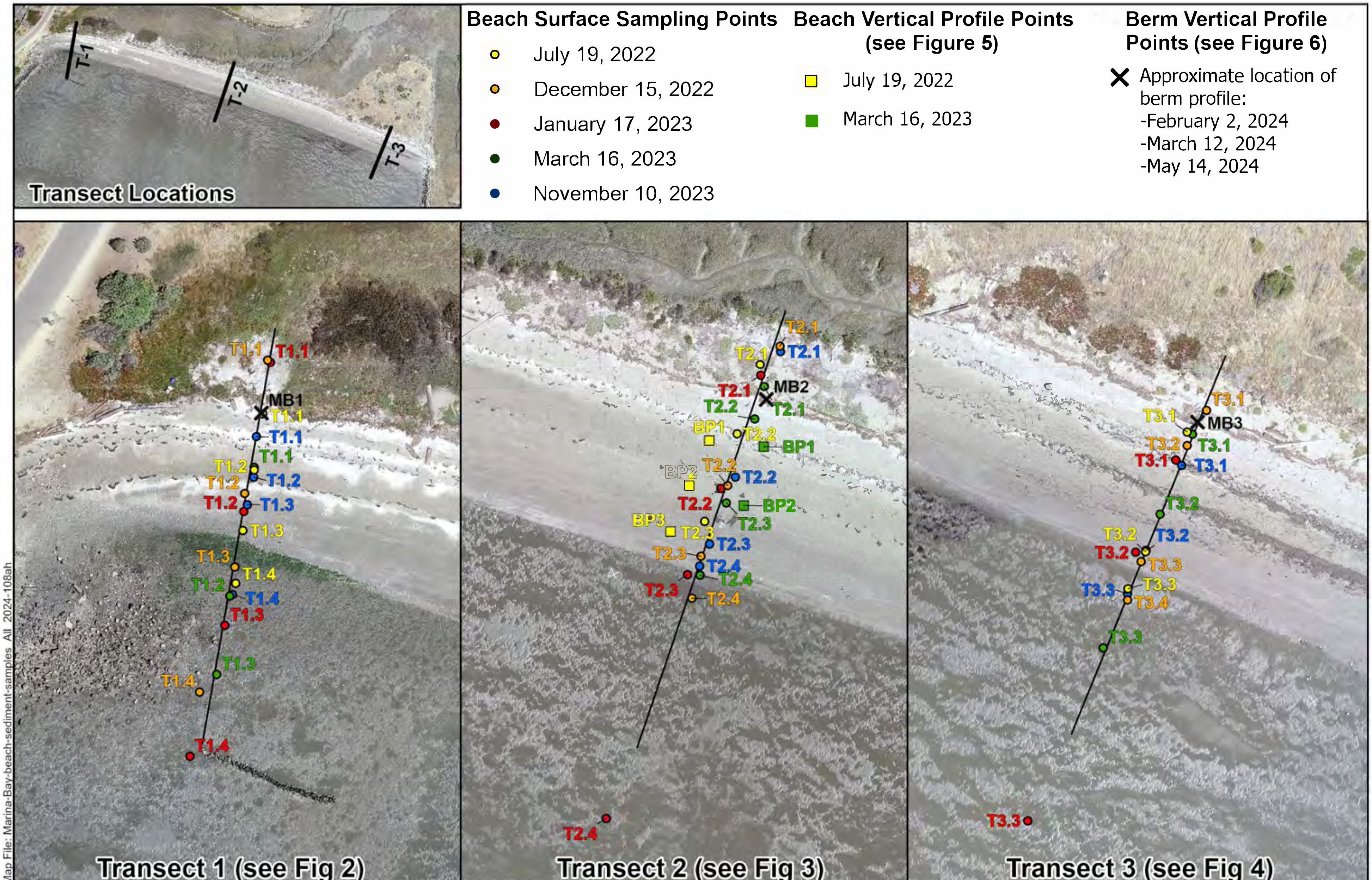
Greenwood Beach Restoration Project

Figure 5

Pt. Molate Beach

Beach Vertical Profile Grain Size Samples

Marina Bay Beach



Data sources: Air photo (Audubon, 2023);
Transects (GillenH2O, 2021)

Greenwood Beach Restoration Project

1:480 (1" = 40' at letter size)

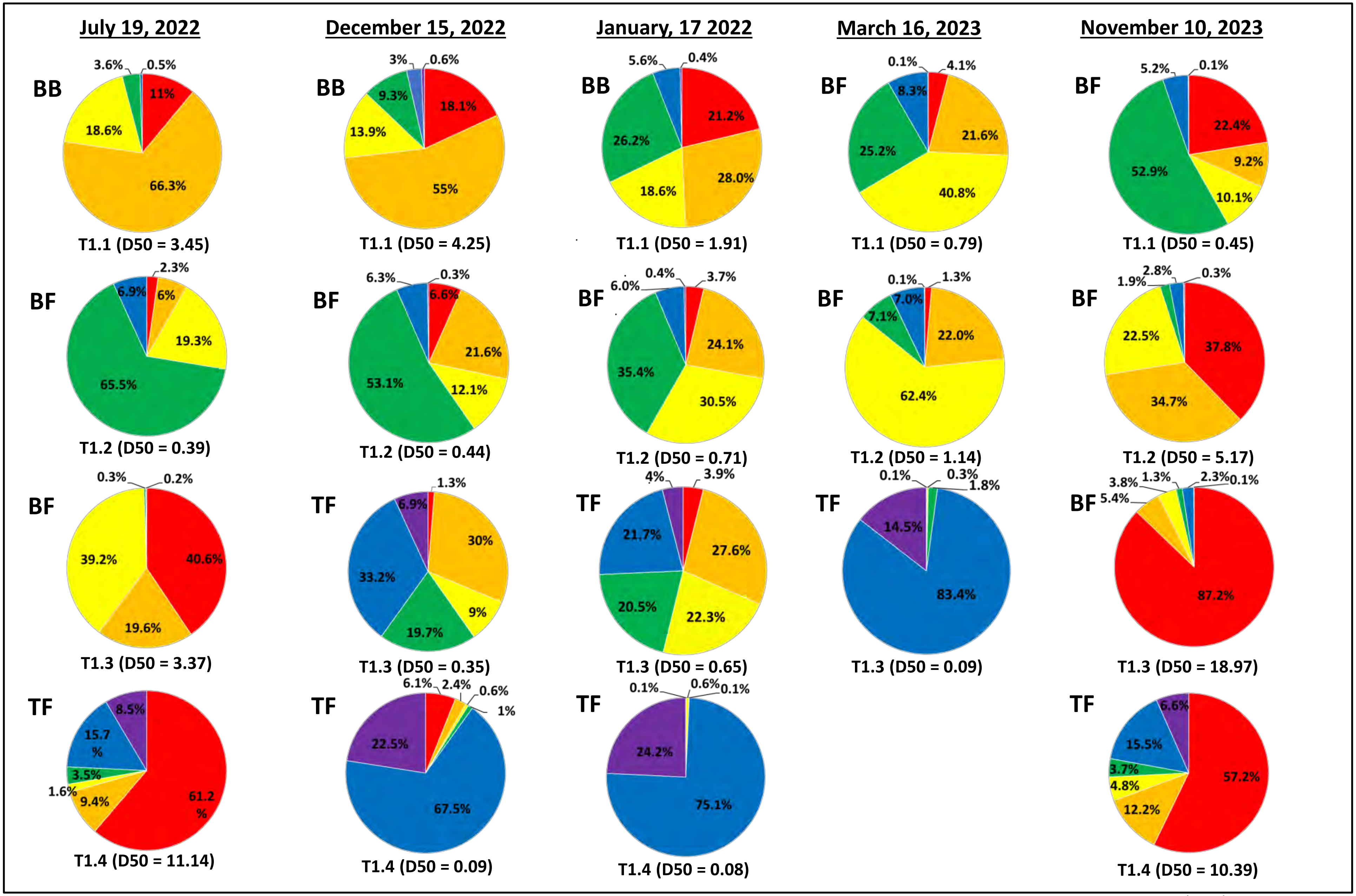
0 20 40 Feet

0 6 12 Meters

Gillenwater GillenH₂O Consulting

Figure 1

Marina Bay Beach
Beach Grain Size Sampling Locations



Sample Position Key:

BB: Backshore/Beach Berm
BF: Beach Face
TF: Tidal Flat

Grain Size Classes:

- Coarse Gravel (8-64mm)
- Fine Gravel (2-8mm)
- Coarse Sand (0.5-2mm)
- Medium Sand (0.25-0.5mm)
- Fine Sand (0.063-0.25mm)
- Mud (<0.063mm)

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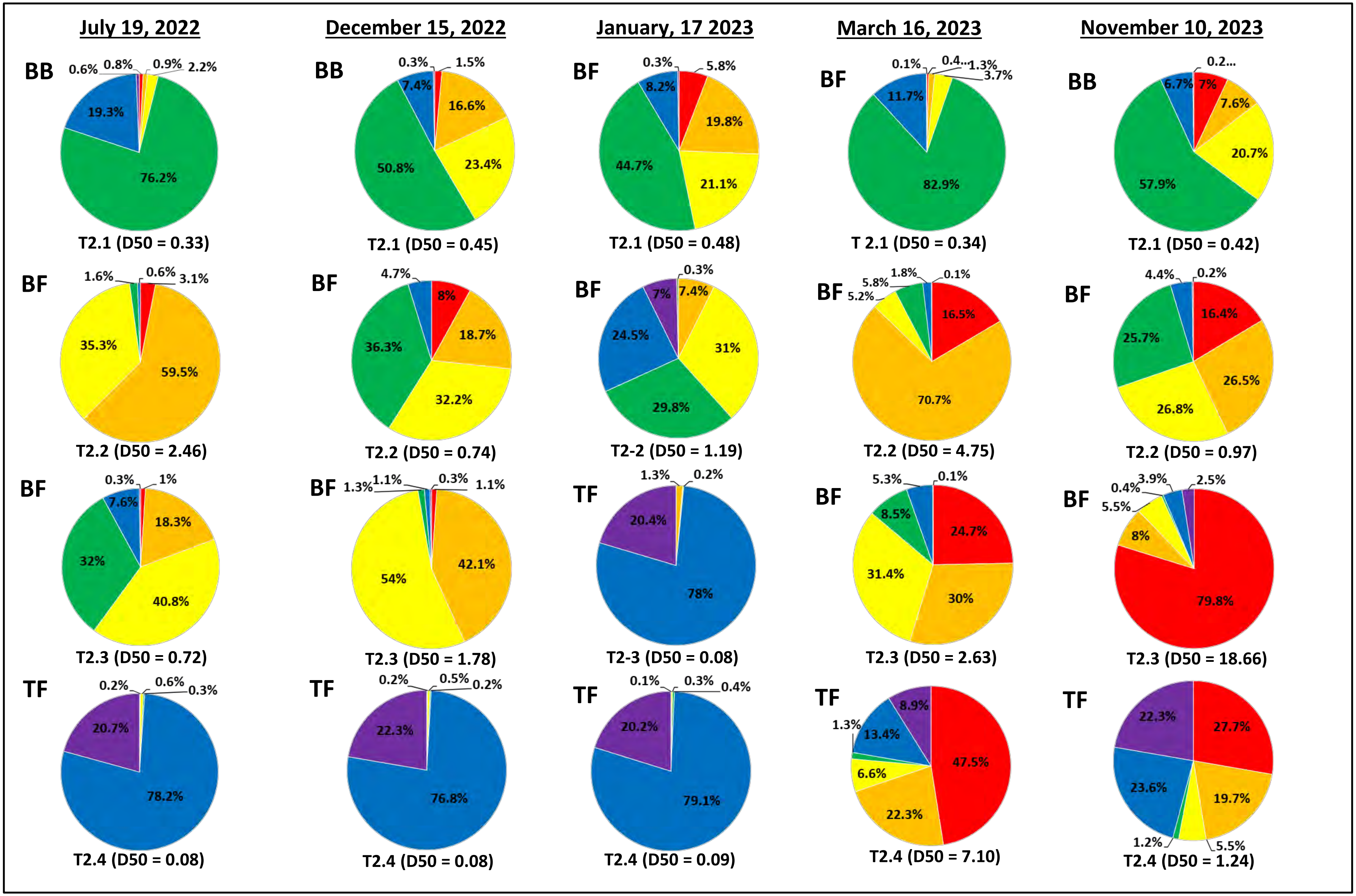
Greenwood Beach Restoration Project

Figure 2

Marina Bay Beach
Transect 1 Beach Surface Grain Size Samples



Sample Position Key:

BB: Backshore/Beach Berm
BF: Beach Face
TF: Tidal Flat

Grain Size Classes:

- Coarse Gravel (8-64mm)
- Fine Gravel (2-8mm)
- Coarse Sand (0.5-2mm)
- Medium Sand (0.25-0.5mm)
- Fine Sand (0.063-0.25mm)
- Mud (<0.063mm)

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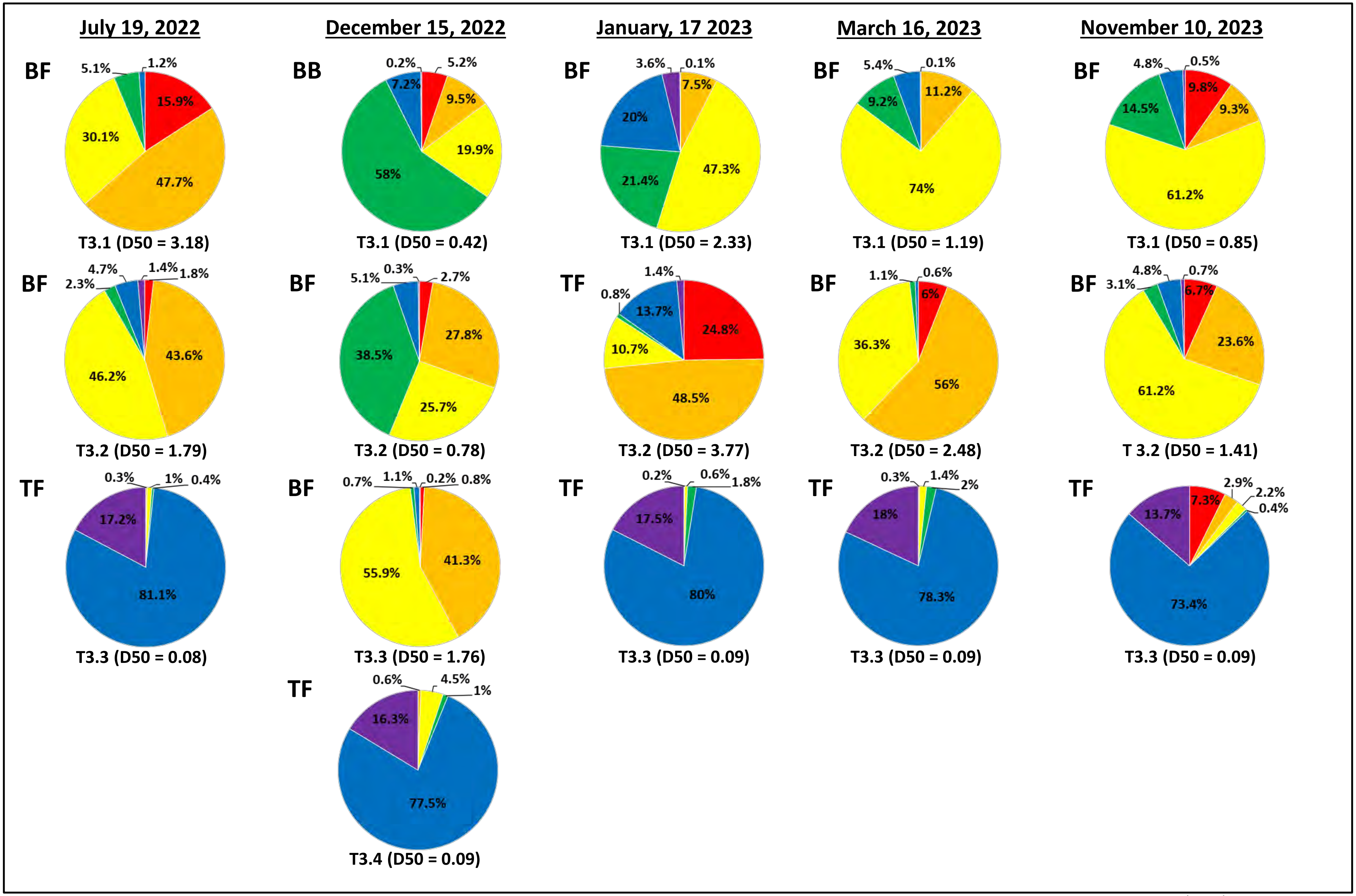
Greenwood Beach Restoration Project

Figure 3

Marina Bay Beach

Transect 2 Beach Surface Grain Size Samples



Sample Position Key:

BB: Backshore/Beach Berm

BF: Beach Face

TF: Tidal Flat

Grain Size Classes:

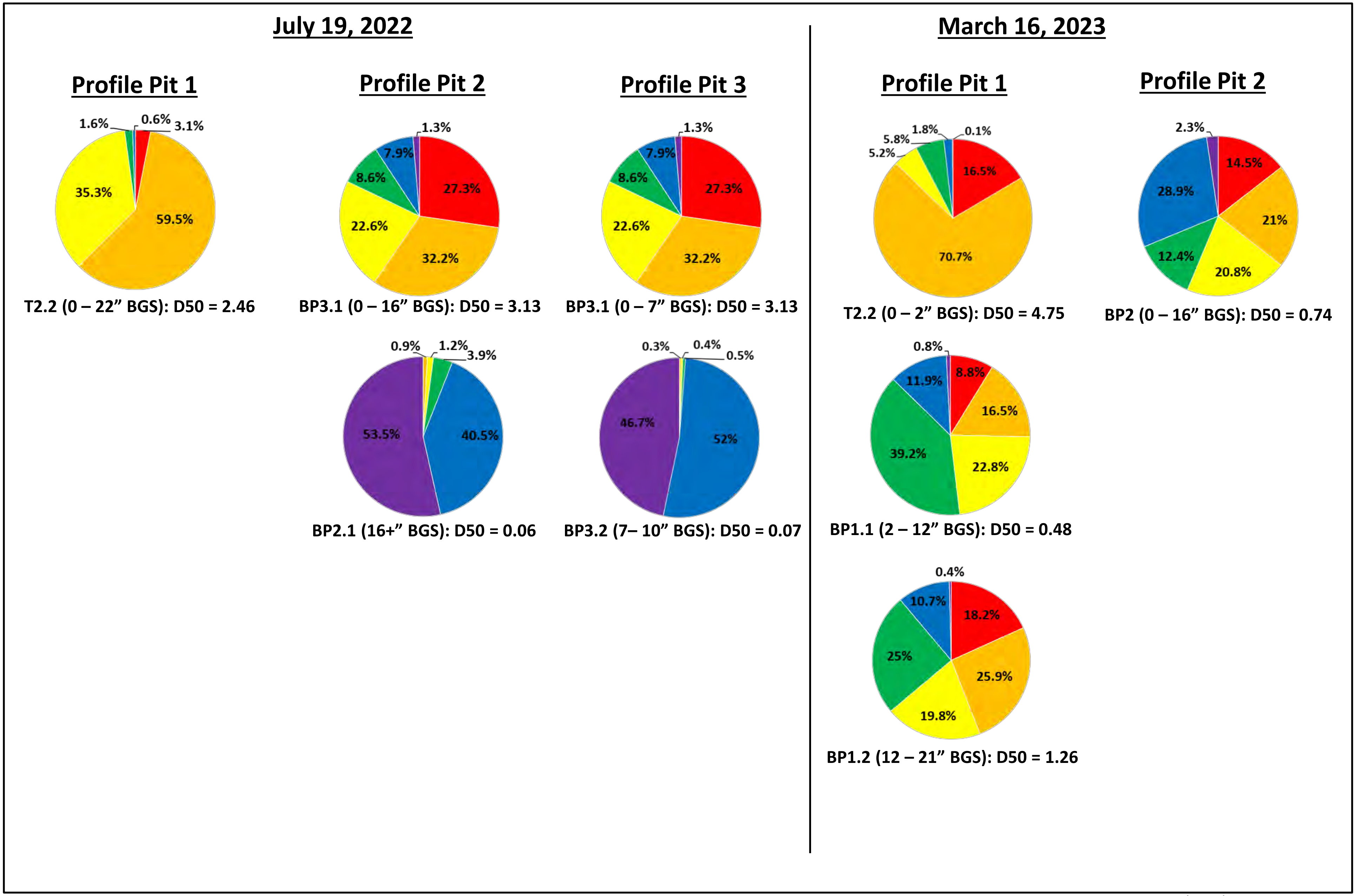
- Coarse Gravel (8-64mm)
- Fine Gravel (2-8mm)
- Coarse Sand (0.5-2mm)
- Medium Sand (0.25-0.5mm)
- Fine Sand (0.063-0.25mm)
- Mud (<0.063mm)

Greenwood Beach Restoration Project

Figure 4

Marina Bay Beach

Transect 3 Beach Surface Grain Size Samples



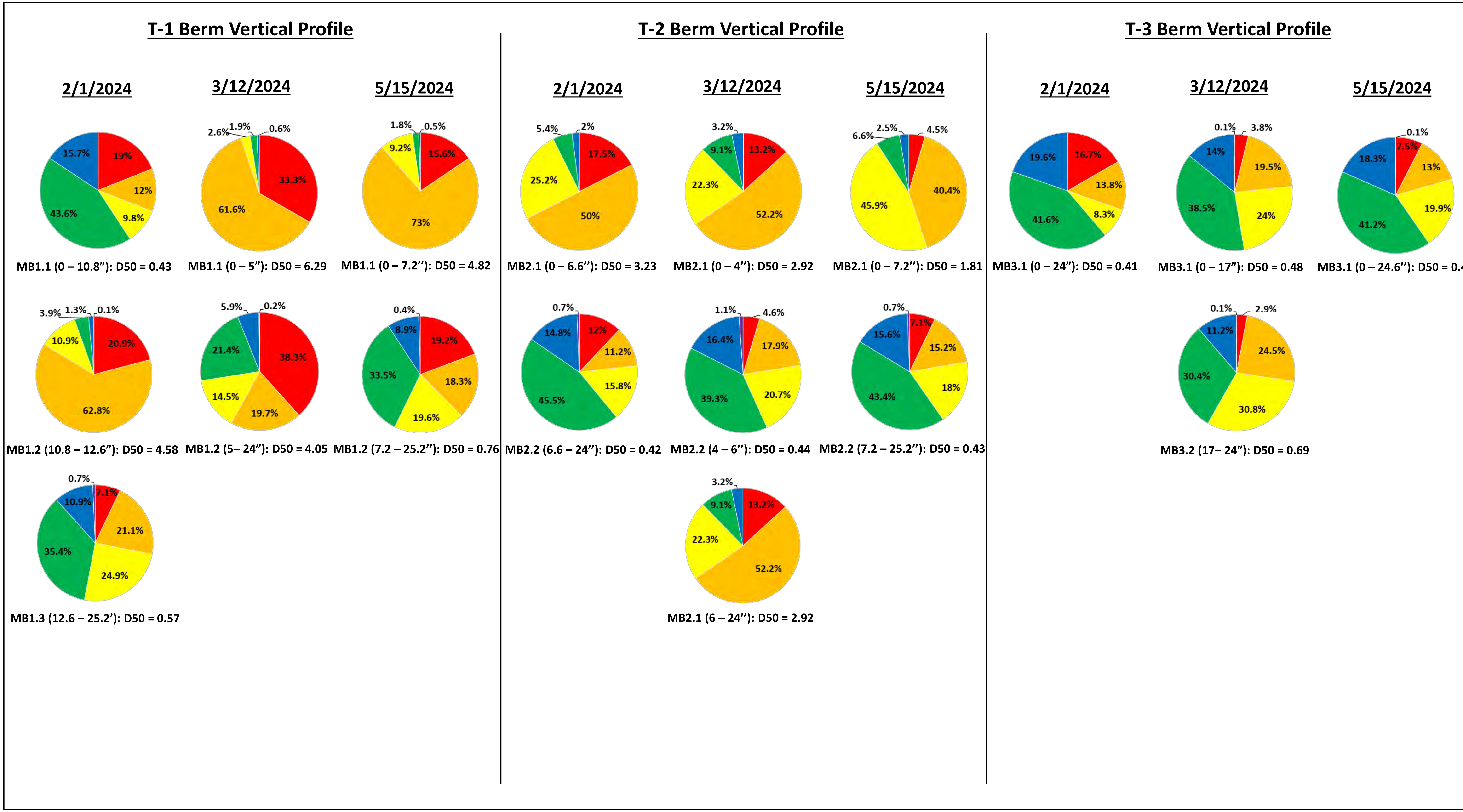
Grain Size Classes:
Coarse Gravel (8-64mm)
Fine Gravel (2-8mm)
Coarse Sand (0.5-2mm)
Medium Sand (0.25-0.5mm)
Fine Sand (0.063-0.25mm)
Mud (<0.063mm)

Gillenwater GillenH2O Consulting

Greenwood Beach Restoration Project

Figure 5

Marina Bay Beach
Beach Vertical Profile Grain Size Samples



Grain Size Classes:

- Coarse Gravel (8-64mm)
- Fine Gravel (2-8mm)
- Coarse Sand (0.5-2mm)
- Medium Sand (0.25-0.5mm)
- Fine Sand (0.063-0.25mm)
- Mud (<0.063mm)

Gillenwater GillenH2O Consulting

Greenwood Beach Restoration Project

Figure 6

Marina Bay Beach
Beach Berm Vertical Profile Grain Size Samples

China Camp Beach

Data sources: Air photo (Audubon, 2023);
Transects (GillenH2O, 2021)

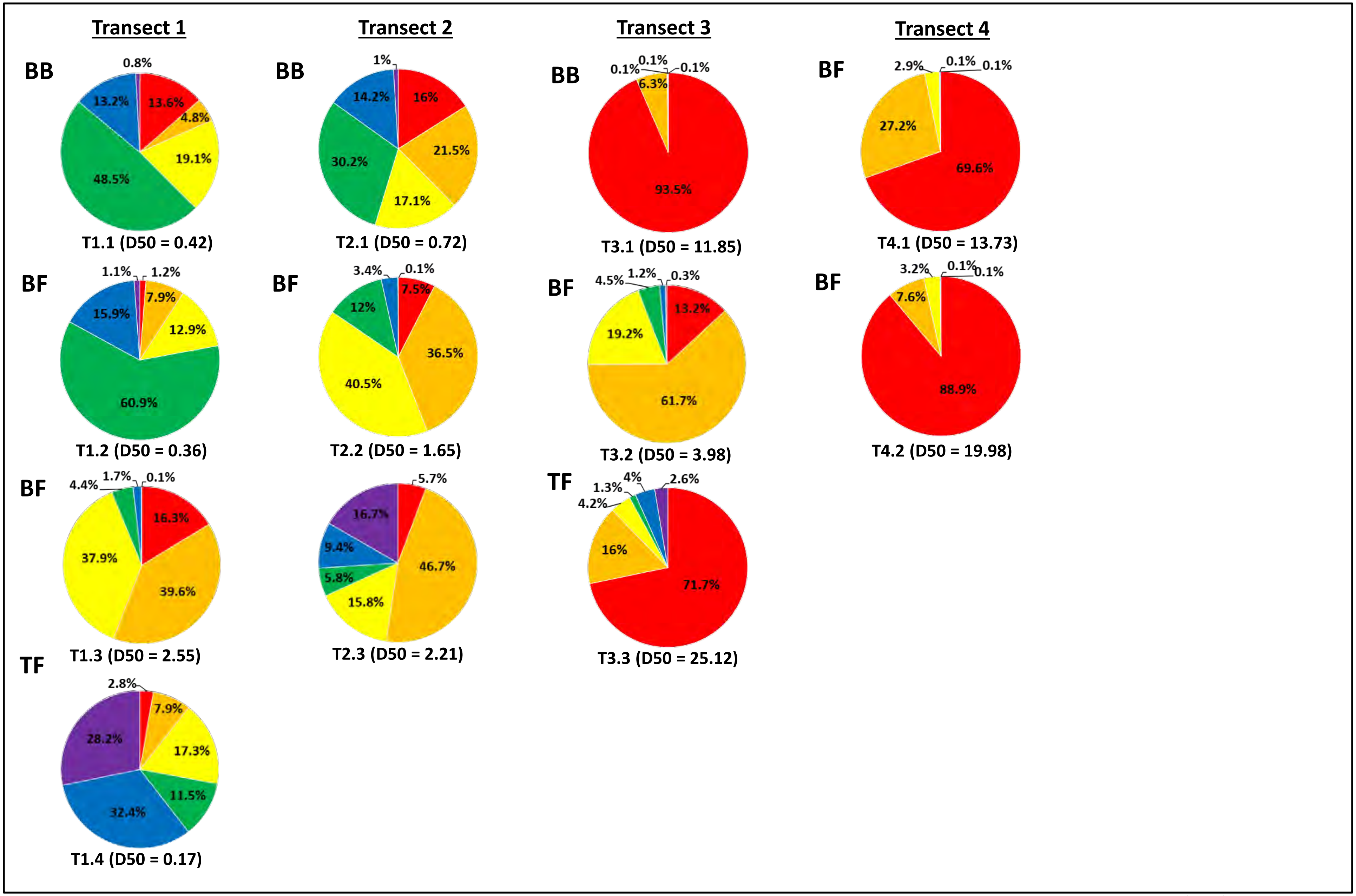
Greenwood Beach Restoration Project

1:360 (1" = 30' at letter size)
0 15 30 Feet
0 4.5 9 Meters

Gillenwater GillenH2O Consulting

Figure 1

China Camp Beach
Beach Grain Size Sampling Locations



Gillenwater
GillenH2O
Consulting

Sample Position Key:
BB: Backshore/Beach Berm
BF: Beach Face
TF: Tidal Flat

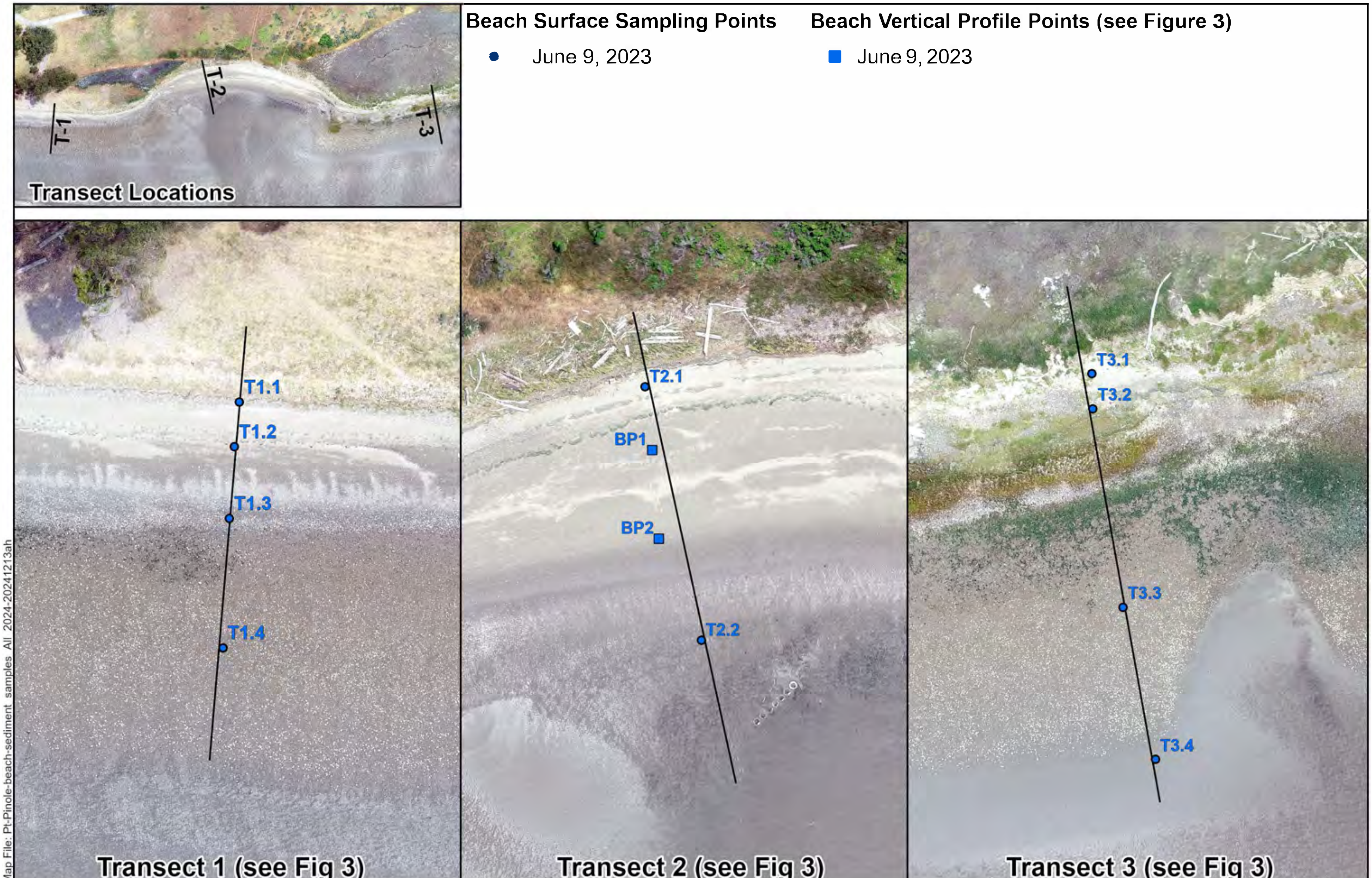
Grain Size Classes:
Coarse Gravel (8-64mm)
Fine Gravel (2-8mm)
Coarse Sand (0.5-2mm)
Medium Sand (0.25-0.5mm)
Fine Sand (0.063-0.25mm)
Mud (<0.063mm)

Greenwood Beach Restoration Project

Figure 2

China Camp Beach – March 16, 2023
Beach Surface Grain Size Samples

Pt. Pinole Beach



Map File: Pt-Pinole-beach-sediment_samples_All_2024-20241213ah

Data sources: Air photo (Audubon, 2023);
Transects (GillenH2O, 2021)

Greenwood Beach Restoration Project

1:480 (1" = 40' at letter size)

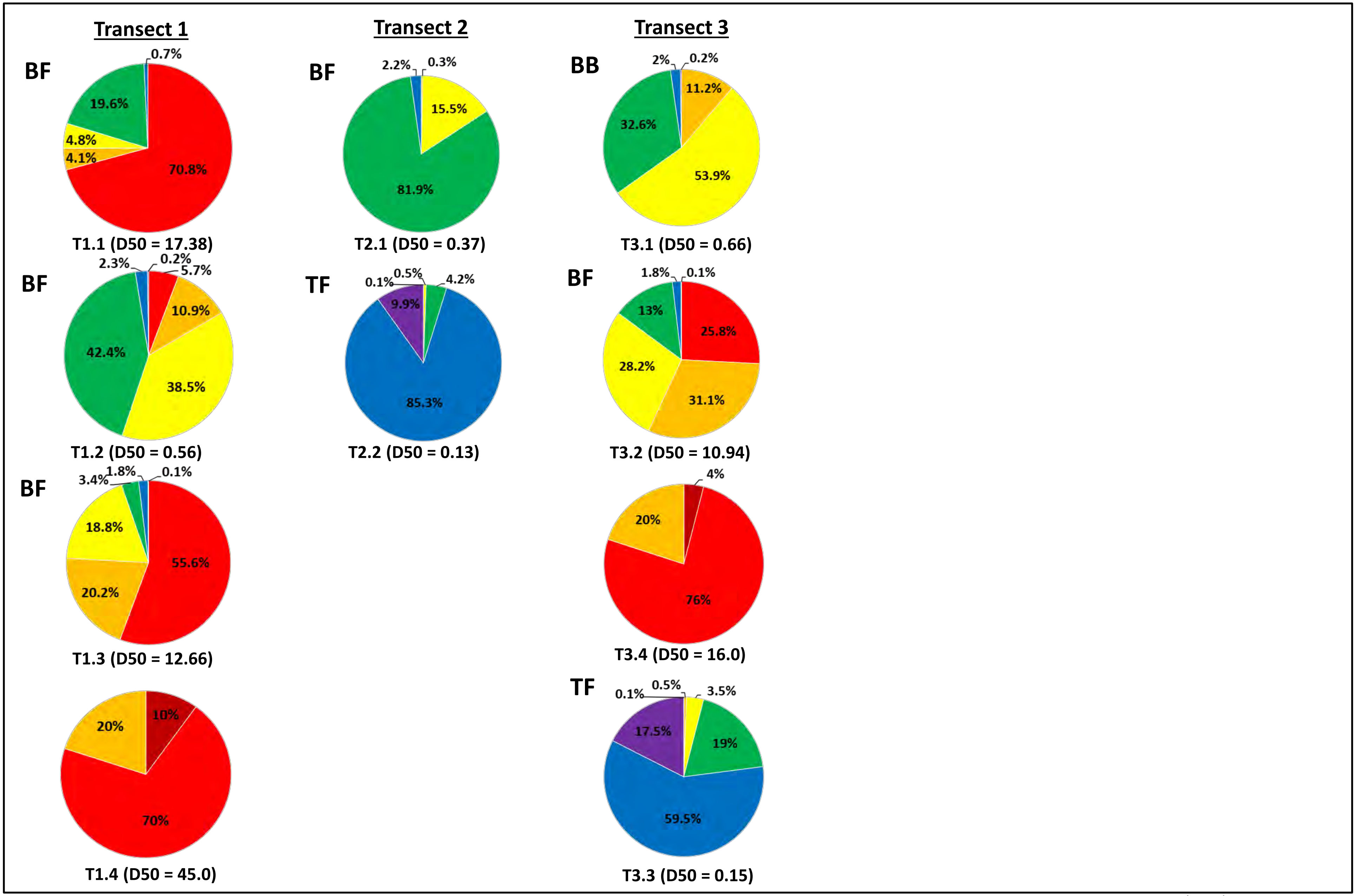
0 20 40 Feet

0 6 12 Meters

Gillenwater
GillenH2O
Consulting

Figure 1

Pt. Pinole Beach
Beach Grain Size Sampling Locations



Greenwood Beach Restoration Project

Figure 2

Gillenwater GillenH2O Consulting

Sample Position Key:

BB: Backshore/Beach Berm
BF: Beach Face
TF: Tidal Flat

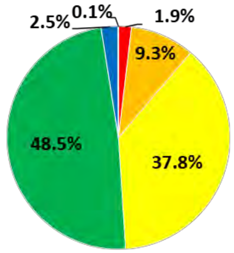
Grain Size Classes:

Coarse Gravel (8-64mm)
Fine Gravel (2-8mm)
Coarse Sand (0.5-2mm)
Medium Sand (0.25-0.5mm)
Fine Sand (0.063-0.25mm)
Mud (<0.063mm)

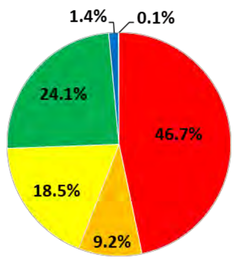
Pt. Pinole Beach – June 9, 2023
Beach Surface Grain Size Samples

June 9, 2023

Profile Pit 1

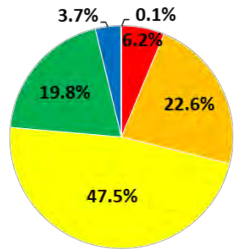


BP1.1 (0 – 17” BGS): D50 = 0.49



BP3.2 (17 – 30” BGS): D50 = 4.52

Profile Pit 2



BP2.1 (0 – 24” BGS): D50 = 0.96

Grain Size Classes:

- Coarse Gravel (8-64mm)
- Fine Gravel (2-8mm)
- Coarse Sand (0.5-2mm)
- Medium Sand (0.25-0.5mm)
- Fine Sand (0.063-0.25mm)
- Mud (<0.063mm)

Gillenwater GillenH2O Consulting

Greenwood Beach Restoration Project

Figure 3

Pt. Pinole Beach

Beach Vertical Profile Grain Size Samples

Appendix C:
Beach Profile Bore Logs

Greenwood Beach

Summer 2022 Beach Profile Bore Logs

BORE LOG

Lower Berm / Upper BF

Site: Greenwood

Location: BP-1 (beach pt)

Sample/Pit ID:
Total depth = 19.5"

Date: 6/20/2022

Driller: DG/PF

Purpose: Beach profile

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
1-2"		mixed gravel - poorly sorted	see sample 2-1	D_{50}
↓ 19.5		mixed sand and gravel w/ some small cobble. Heterogeneous no obvious lensing	BP-1	D_{50}
		layer of large cobbles - could not dig further	—	

BORE LOG

Site: Greenwood
Location: Beach Face
Sample/Pit ID: BP-2

Date: 6/20/2022
Driller: DG/PE
Purpose: Beach profile

Pit depth = 20"

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
1-2"		Poorly sorted surface gravel layer over mixed sand/gravel	—	—
2 | 7		mixed sand/ gravel	~~BP-2.1~~ BP-2	D50
7 | 8		Fine gravel and shell layer distinct band in pit	BP-2.1	D50
8 | 20		Mixed sand and gravel	BP-2 (same as above)	
↓		bare cobble layer		

BORE LOG

Site: Greenwood
Location: Beach Face - lower
Sample/Pit ID: BP-3

Date: 6/20/2022
Driller: DG/PF
Purpose: Beach Profile

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 → ~~4~~ 4		mixed sand and small gravel, most sand	BP-3	D50
4 → 6		shell and fine gravel layer - similar to pit #2	see pit #2	
6 → 9		~~large cobble~~ large gravel / cobble layer		
9 → 13		Sand + fine gravel		
13 →		large cobble / cont. ...		

Greenwood Beach

Winter 2023 Beach Profile Bore Logs

BORE LOG

Site: Greenwood Beach

Location: Greenwood Beach, Tiburon

Sample/Pit ID: BP1

Date: 3/15/23

Driller: Dan G

Purpose:

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 ↓		Sand w/ mixed gravel + cobble % Cobble increases w/ depth	GW-BP-1	
20 in		cobble restrictive layer		

BORE LOG

Site: Greenwood Beach

Location: Greenwood Beach, Tiburon

Sample/Pit ID: Beach Profile (BP2)

Date: 3/15/23

Driller: Den G

Purpose:

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 → 15 in		Sand w/ mixed gravel few scattered cobbles some shell fragments	GW-BP2	
15 in → 16 in		large cobbles + gravel cobbles too large to dig any deeper		

BORE LOG

Site: Greenwood Beach

Location: Greenwood Beach Tiburon

Sample/Pit ID: DF 3

Date: 3/15/23

Driller: Dan G

Purpose:

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 → 3in		muddy sand w/ shell fragments		
3in → 12in		mixed sand gravel layer		

BORE LOG

Site: Greenwood Beach
Location: Greenwood Beach, Tiburon
Sample/Pit ID: DF 6

Date: 3/15/23
Driller: Dan G
Purpose:

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 → 1/2 in		mud		
0 → 8 in		muddy sand		
8 in ↓		sand + fine gravel very muddy		

Sanctuary Beach

Summer 2022 Beach Profile Bore Logs

BORE LOG

Site: Sanctuary
Location: Beach Park
Sample/Pit ID: BP-1

Date: 6/22/2022
Driller: DAG/PF
Purpose: Beach Profile

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 → 4"		Sand	See surface Sample	
4 → 17"		Sand w/ intermixed med gravel. fairly homogenous	BP-1	
17 →		Bay mud. highly plastic green veins		

BORE LOG

Site: Sanctuary
Location: Beach face
Sample/Pit ID: BP-2

Date: 6/22/2022
Driller: DAG/PF
Purpose: Beach Profile

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 → 1"		Surface veneer of fine gravel w/shell and sand	NA See surface samples	
1" → 11"		Sand w/Fine gravels. Occasional large gravels intermixed	BP-2	
11" →		Bay mud - highly plastic. Dark color w/ green streaks	NA	

BORE LOG

Site: Sanctuary
Location: Beach face
Sample/Pit ID: BP-3

Date: 6/24/2022
Driller: DAG/AE
Purpose: Beach profile

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 – 1"		Fine gravel and sand veneer	See: Surface Sample	D_{50}
1 ↓ 6		Gravelly sand/mud (fine gravels mixed in)	BP3.1	D_{50}
6 ↓ 9"		large gravel and cobbles present	NA	
9 ↓ 12		Sandy gravel w/mud lots of small shells	BP3.2	
↓		Bay mud		

Marina Bay Beach

Summer 2022 Beach Profile Bore Logs

BORE LOG

Site: Marina Bay
Location: Top Beach Face
Sample/Pit ID: BP-1

Date: 7/19/22
Driller: DG/PF/PB
Purpose: Beach Profile

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 ↓ 22		mixed sand/gravel		
22 ↓		mixed sand/gravel - slightly more clay color change from brown → gleyed		
26 →		iron oxide layer - no change in material		
26 ↓ Bottom		same as		
		no clay layer present → did not reach		

BORE LOG

Site: Marina Bay

Location: mid Beach face

Sample/Pit ID: BP-2 marina

Date: 7/19/22

Driller: DG/PF/PB

Purpose: Beach profile

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 ↓ 16		Poorly sorted sand/gravel/shell		
↓ Bottom		Stiff clay - slightly sandy	BP-2.1	

BORE LOG

Site: Marina Bay
Location: Lower Beach face
Sample/Pit ID: BP-3 marina

Date: 7/19/22
Driller: DG / PF / PB
Purpose: Beach profile

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 ↓ 7		mixed sand w/ skell ~ mixed gravel	BP-3.1	
7 ↓ 10		Clay sand	BP-3.2	
10 ↓ Botom		~~[illegible]~~ clay		

Marina Bay Beach

Winter 2023 Beach Profile Bore Logs

BORE LOG

Site: Marina Bay
Location: Richmond CA
Sample/Pit ID: BP 1

Date: 3/16/23
Driller: Dan G
Purpose:

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 → 2-3 in		even mix of sand + gravel		
2-3 in → 12 in		gravely sand w/ some shell	MB-BP-1.1	
12 in → 21		more shell + gravel than above + sand	MB-BP-1.2	
21 → 26		sand		
26		basal bay mud		

BORE LOG

Site: Marina Bay
Location: Richmond, CA
Sample/Pit ID: BP2

Date: 3/16/23
Driller: Dan G
Purpose:

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 ↓		Sandy w/ mixed shell fragments + gravel. iron layer is 4-6 in from surface. ↳ reduced iron banding	MB-BP-2	
16 in		Basal bay mud		

BORE LOG

Site: Marina Bay

Location:

Sample/Pit ID: T1 -Berm

Date: 2/1/24

Driller: Paige Fernandez

Purpose: Berm crest pit

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 – 0.9		mixed sand + shell some gravel	T1-Berm-1	
0.9 – 1.05		Shell + gravel	T1-Berm-2	
1.05 – 2.1 ft		Similar to top mixed sand + shell some gravel	T1-Berm-3	

BORE LOG

Site: Marina Bay
Location:
Sample/Pit ID: T2 Berm

Date: 2/1/24
Driller: Paige Fernandez
Purpose: Berm Crest Pit

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 ↓ 0.55		shell fragments + small gravel	T2-Berm-1	
0.55 ↓ 2.0ft		Sand w/ some mixed shell	T2-Berm-2	

BORE LOG

Site: Marina Bay

Location:

Sample/Pit ID: T3 Berm

Date: 2/1/24

Driller: Paige Fernandez

Purpose: Berm Crest Pit

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 ↓ 2 ft		Sand w/ some small shell fragments + small gravel	T3-Berm-1	

BORE LOG

Site: XS1 Berm
Location: Mariner Bay
Sample/Pit ID:

Date: 3/12/24
Driller: Paige Fernandez
Purpose: Berm Pit

Depth BGS Unit: in	Symbol	Description	Sample ID	Analysis
0 ↓ 5 in		Pebbles + small gravels mixed w/ shell.	XS1-Berm1	
5 in ↓ 24 in		Sand w/ shell + gravel very homogeneous. Small band of vegetation.	XS1-Berm2	

BORE LOG

Site: XS 2 Berm
Location: Marina Bay
Sample/Pit ID:

Date: 3/12/24
Driller: Paige Fernandez
Purpose: Beach Berm Pit

Depth BGS Unit: in	Symbol	Description	Sample ID	Analysis
0 ↓ 4 in		Sand w/ some gravel + larger shell	XS2 Berm-2	
4 in ↓ 6 in		thin Band of pebbles + small shell	XS2 Berm-1	
6 in ↓ 24 in		Same as top layer.		

BORE LOG

Site: XS3 Berm
Location: Marina Bay
Sample/Pit ID:

Date: 3/12/24
Driller: Paige Fernandez
Purpose: Berm Pit

Depth BGS Unit: in	Symbol	Description	Sample ID	Analysis
0 ↓ 17 in		Sand w/ some mixed shell + pebbles.	XS3 Berm1	
17 in ↓ 24 in		higher concentration of ~~[illegible]~~ shell w/ pebbles	XS3 Berm2	

BORE LOG

Site: Marina Bay

Location:

Sample/Pit ID: XS1 Berm Pit

Date: 5/14/24

Driller: Paige Fernandez

Purpose: Berm Pit

Depth BGS Unit: survey ft	Symbol	Description	Sample ID	Analysis
0 ↓ 0.6		mixed gravel, pebbles, shell. little to no sand	MB-XS1-1	
↓ 2.1		Sand w/ mixed gravel + pebbles, shell	MB-XS1-2	

BORE LOG

Site: Marina Bay

Location:

Sample/Pit ID: XS2 Berm Pit

Date: 5/14/24

Driller: Paige Fernandez

Purpose: Berm Pit

Depth BGS Unit: feet ft	Symbol	Description	Sample ID	Analysis
0 ↓ 0.6 ft		mixed pebbles + shell in little sand	MB-XS2-1	
0.6 ft ↓ 2.1 ft		mostly sand w/ some mixed gravel + shell.	~~MBXS~~ MB-XS2-2	

BORE LOG

Site: Marina Bay
Location:
Sample/Pit ID: X53 Pit

Date: 5/14/24
Driller: Paige Fernandez
Purpose: Berm Pit

Depth BGS Unit: survey (feet)	Symbol	Description	Sample ID	Analysis
0 ↓ 2.05ft		Uniform Sand w/ some shell + mixed gravel. No Banding	MB-X53-1	

Pt. Molate Beach

Summer 2022 Beach Profile Bore Log

BORE LOG

Site: Pt Molate
Location: Beach face - top
Sample/Pit ID: BP-1

Date: 7/18/22
Driller: DG/PF
Purpose: Beach Profile

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 ↓ 32		Sand w/ mix gravel gravel concentration increases w/ depth no discrete layering no basal layer found	BP-3.1 taken from halfway down pitwall	

BORE LOG

Site: Pt Molate[r]
Location: Beach face - mid
Sample/Pit ID: BP - 2

Date: 7/18/22
Driller: DG/PF
Purpose: Beach profile

Depth BGS Unit: in	Symbol	Description	Sample ID	Analysis
0 ↓ ~~19~~ 21		mixed sand + small gravels.	BP-2.1	
21 ↓ 21+		gleyed muddy sand w/ ~~iron~~ oxidized iron + manganese Similar to sample BP-3.2		

BORE LOG

Site: Pt Molate
Location: Beach face - Lower
Sample/Pit ID: BP-3

Date: 7/18/22
Driller: DG/PF
Purpose: Beach profile

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 ↓ 4"		mixed sand and gravel	BP-3-1	D50
↓ ~10?		mixed sand and gravel w/ interspersed cobbles		
↓ ?		gleyed ~~sa~~ muddy sand. prevalent oxidized iron	BP-3-2	D50

Pt. Molate Beach

Winter 2023 Beach Profile Bore Log

BORE LOG

Site: Pt. Molate

Date: 4/13/23

Location:

Driller: Paige Fernandez

Sample/Pit ID: PM-BP-1

Purpose:

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 in ↓ 21 in		Sand + mixed gravel homogenous all the way down to rock layer	PM-BP-1	

BORE LOG

Site: Pt. Molate

Date: 4/13/23

Location:

Driller: Paige Fernandez

Sample/Pit ID: PM-BP-2

Purpose:

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 ↓ 20 in		mostly gravel + small cobbel Some sand. homogenous all the way down until reaches bay mud layer	PM-BP-2	

Pt. Pinole Beach

Summer 2023 Beach Profile Bore Logs

BORE LOG

Site: Point Pinole

Date: 6/9/23

Location:

Driller: Page F

Sample/Pit ID: ~~BA~~ PP-BP-1

Purpose: Beach profile pit

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 ↓		Sand w/ mixed small gravel + shell	PP-BP-1.1	
~~[illegible]~~ 17 in ↓		larger gravel layer	PP-BP-1.2	
30 in				
		Note: Could not dig deeper. hole kept collapsing. took photo of material at bottom of hole. seemed like old marsh material.		

5.9
3.37

BORE LOG

Site: Point Pinole

Date: 6/9/23

Location:

Driller: Paige F

Sample/Pit ID: PP-BP-2

Purpose: Beach profile pit

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 ↓ 24 in		Sand w/ mixed small gravel + shell	PP-BP-2.1	
		Note - Could not dig deeper - hole kept collapsing. took photo of material at bottom of hole. maybe old marsh material		

4.37
2.37

Appendix D:
Greenwood Delta and Tidal Flat Bore Logs

BORE LOG

Site: Greenwood
Location: Delta fan
Sample/Pit ID: 2

Date: 3/10
Driller: PB/DG
Purpose:

Depth BGS Unit: CM	Symbol	Description	Sample ID	Analysis
0 ↓ 15cm		fine - medium Gleyed sand low % mud	DF2-1	D50
15cm ↓ 35+		mixed rounded + sharp angular sand low % sand, low % mud	DF2-2	D50

BORE LOG

Site: Greenwood
Location: Delta Fan
Sample/Pit ID: 3

Date: 3/10/2022
Driller: PB/DG
Purpose:

Depth BGS Unit: cm	Symbol	Description	Sample ID	Analysis
0 → 11		Dark Gleyed fine-med sand, non plastic. High % shell fragments	3-1	D50
11 → 35+		Very poorly sorted angular coarse-med gravel. Low sand/mud. Dark gleyed.	3-2	D50

BORE LOG

photo time 11:54

Site: Greenwood
Location: Delta fan
Sample/Pit ID: 4

Date: 3/10
Driller: PB, DAG
Purpose:

Depth BGS Unit: CM	Symbol	Description	Sample ID	Analysis
0 ↓ 3		Med-fine sand. Mixed gleyed-tan. Frequent small shell. Marginally plastic.	NA	
3 ↓ 35+		Fine mostly angular gravel. Non plastic. non-cohesive. Low % sand - Gleyed - Dark grey	NA	

BORE LOG

Site: Greenwood
Location: Delta Fan
Sample/Pit ID: 5

Date: 3/10/22
Driller: PB, DAG
Purpose:

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 ↓ 2		cohesive mud veneer. poorly sorted med-fine sand. Tan-light gry		
↓ 3		poorly sorted sleyed gravel, med-small rounded		
3 ↓ 45 ft		poorly sorted sleyed coarse-small gravel. non-cohesive, trace mud, Pottery shard		

BORE LOG

Site: Greenwood
Location: Delta Fan
Sample/Pit ID: 6

Date: 3/10/22
Driller: DB, DAG
Purpose:

Depth BGS Unit: cm	Symbol	Description	Sample ID	Analysis
0 → 6		Dark gleyed fine-med sand. Dark grey-Black. Non-plastic High % fine shells (intact)	DF6-1	D50
6 → 45+		Very poorly sorted small gravel and sand. Low mud, non-plastic, high water content. Thixotropic	DF6-2	D50

BORE LOG

Site: Greenwood
Location: Sand flat - shore parallel
Sample/Pit ID: SP-W

Date: 3/10/22
Driller: PB, DG
Purpose:

Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
0 ↓ 8		Fining upward to mud. Med-fine sand. Gleyed. Marginally plastic grading to plastic @ surface. Burrowing inverts in surface layer	SP-W-1	D_{50}
8 ↓		Fine gravel in matrix of muddy sand. large shell fragments	SP-W-2	D_{50}

BORE LOG

Site: Green
Location: Shore paral
Sample/Pit ID: SP - Centr

Date: 3/10/22
Driller: PB, D
Purpose:

Depth BGS Unit: cm	Symbol	Description	Sample ID	Analysis
0 ↓ 8		weakly plastic, muddy fine-med Sand. High shell content - whole and fragments.	SP-C-1	
8 ↓ 40t		Watery medium-fine gravel (muddy). Abundant shells and shell fragments. Angular ~~gravel~~ gravels.	SP-C-2	

BORE LOG

Site: Greenwood
Location: Shore parallel mudflat
Sample/Pit ID: SP-E

Date: 3/10/2022
Driller: PB, DG
Purpose:

Depth BGS Unit: CM	Symbol	Description	Sample ID	Analysis
0 ↓ 9		med-fine Gleyed sand, w/ shell and shell fragments, fining upward ~~Gravel largest Rock~~	SPE-1	D_{50}
9 ↓ 40+		Watery fine grained sand matrix, med-coarse gravel (6cm max) Shell and shell fragments (many) Gleyed,	SP-E-2	D_{50}

Appendix E:
Particle Tracking Study No. 2 (Fall 2024) Figures

Map File: Particle Transport Study Greenwood-Beach 2024-1127ah

Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

0 25 50 ft

0 7.5 15 m

Figure 1

Gillenwater GillenH2O Consulting

Orange Sand Grain Distribution - September 18th, 2024

Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

Gillenwater GillenH2O Consulting

Figure 2

Orange Sand Grain Distribution - September 19th, 2024

Map File: Particle Transport Study Greenwood-Beach 2024-1127ah

Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

0 25 50 ft

0 7.5 15 m

Figure 3

Gillenwater GillenH2O Consulting

Orange Sand Grain Distribution - September 23rd, 2024

Map File: Particle Transport Study Greenwood-Beach 2024-1127ah

Data sources: Air photo (Audubon, 2022);
Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

0 25 50 ft

0 7.5 15 m

Figure 4

Gillenwater GillenH2O Consulting

Orange Sand Grain Distribution - September 30th, 2024

Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

Gillenwater GillenH2O Consulting

Figure 6

Orange Sand Grain Distribution - October 3rd, 2024

Map File: Particle Transport Study Greenwood-Beach 2024-1127ah

Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

0 25 50 ft

0 7.5 15 m

Gillenwater GillenH2O Consulting

Figure 7

Blue Sand Grain Distribution - September 19th, 2024

Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

0 25 50 ft

0 7.5 15 m

Figure 8

Gillenwater GillenH2O Consulting

Blue Sand Grain Distribution - September 23rd, 2024

Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

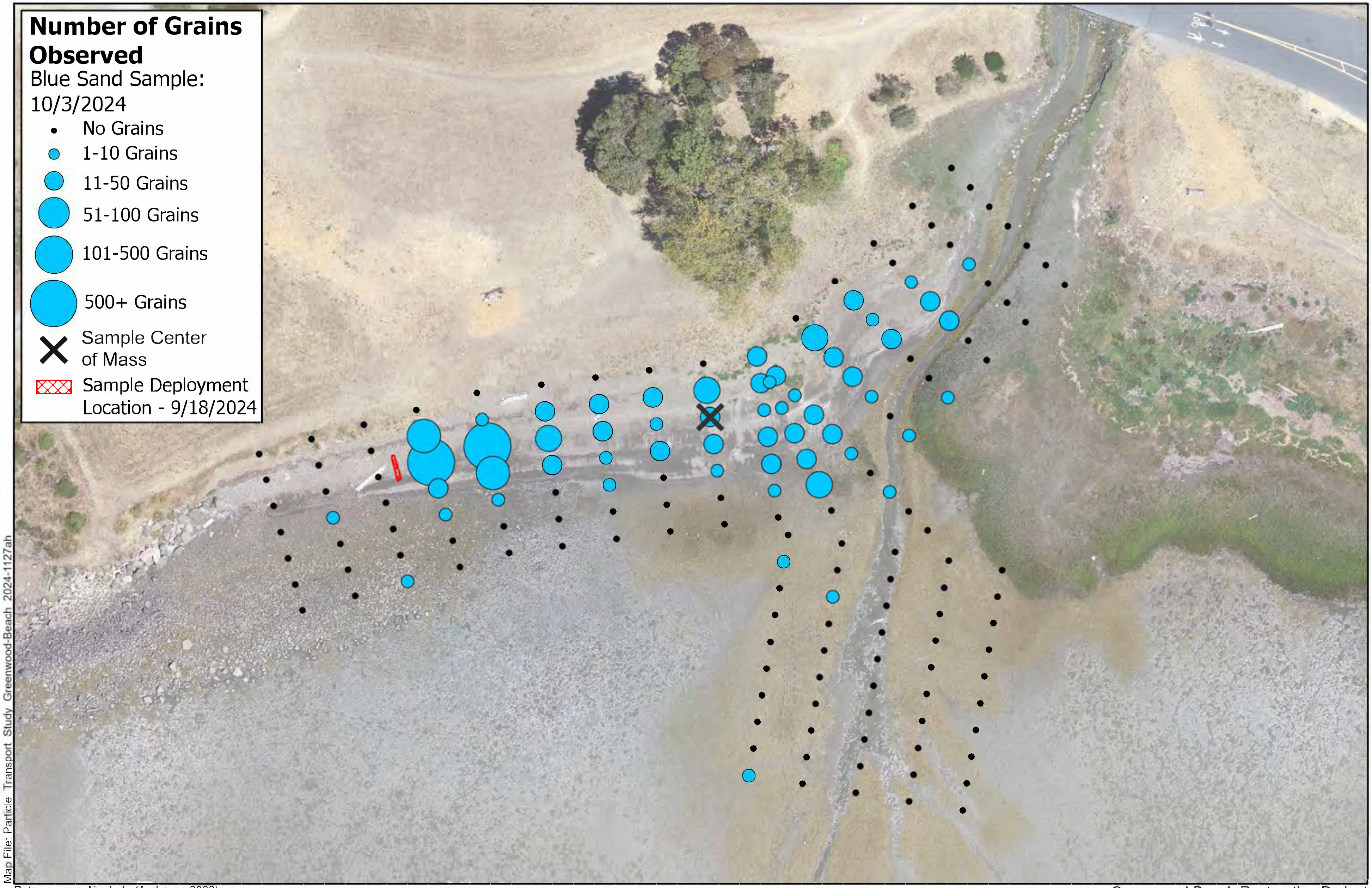
0 25 50 ft

0 7.5 15 m

Figure 9

Gillenwater GillenH2O Consulting

Blue Sand Grain Distribution - September 30th, 2024



Map File: Particle Transport Study Greenwood-Beach 2024-1127ah

Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

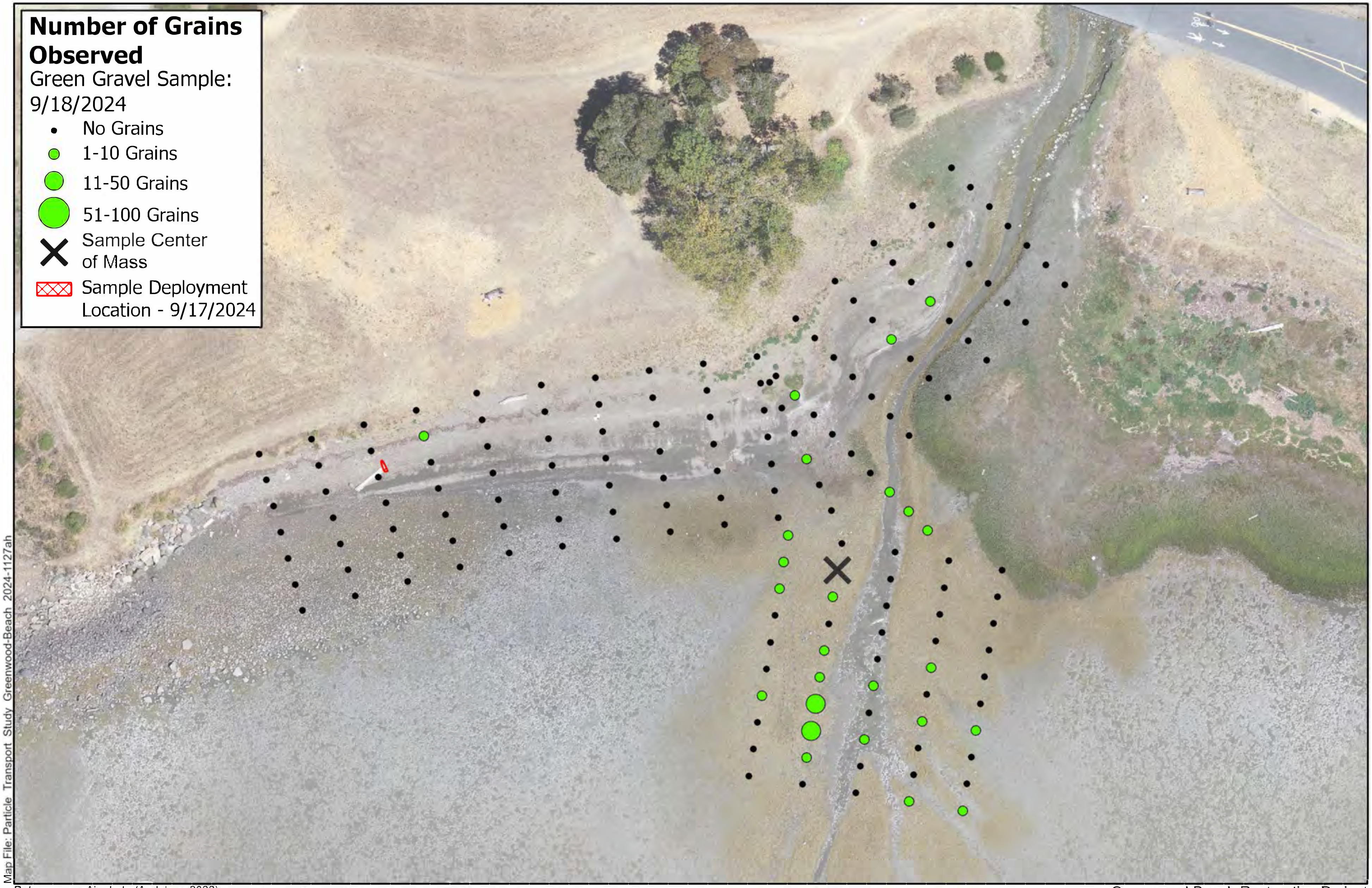
0 25 50 ft

0 7.5 15 m

Figure 10

Gillenwater GillenH2O Consulting

Blue Sand Grain Distribution - October 3rd, 2024



Map File: Particle Transport Study Greenwood-Beach 2024-1127ah

Data sources: Air photo (Audubon, 2022);
Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

0 25 50 ft

0 7.5 15 m

Figure 11

Gillenwater GillenH2O Consulting

Green Gravel Grain Distribution - September 18th, 2024

Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

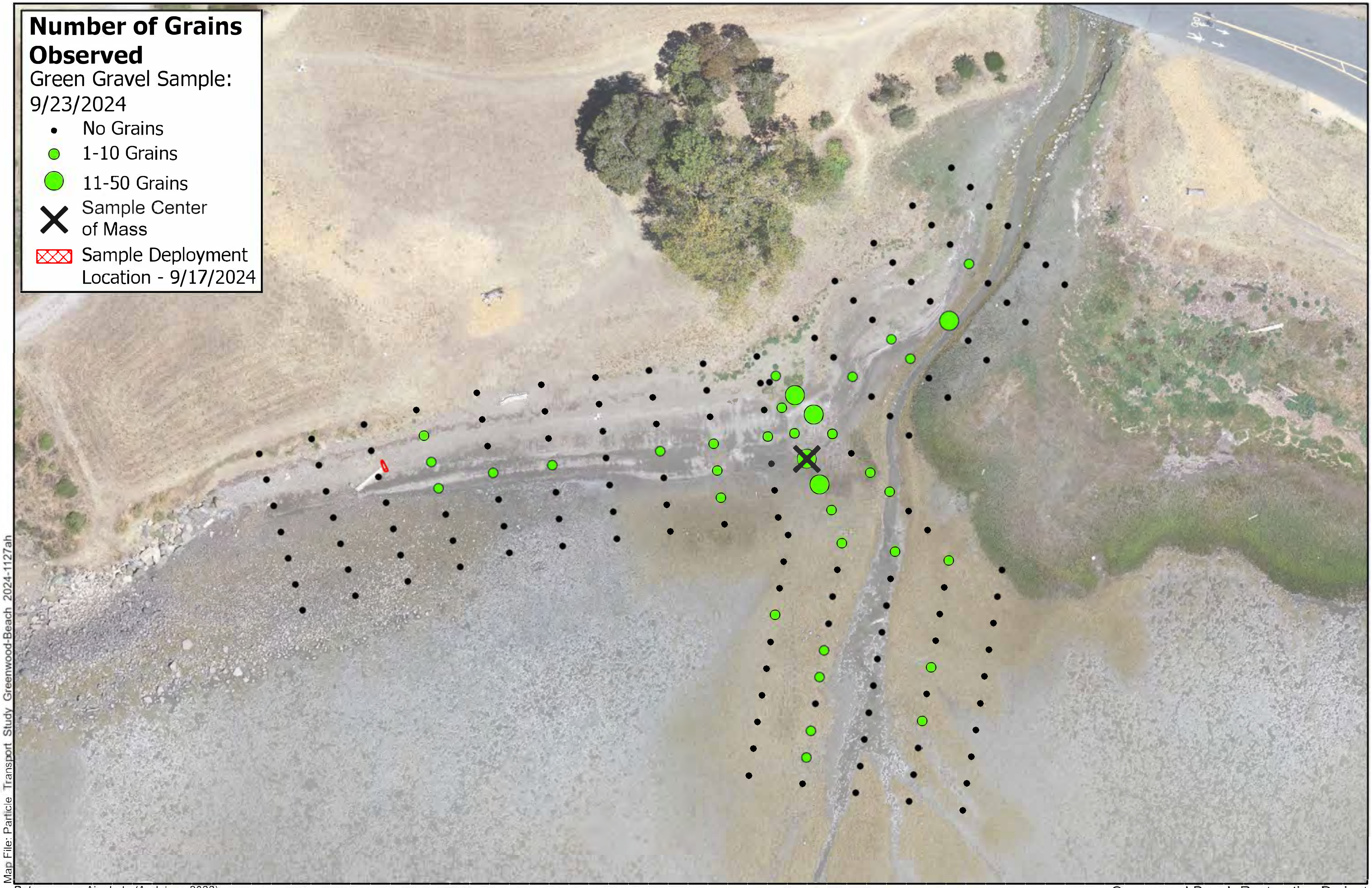
0 25 50 ft

0 7.5 15 m

Figure 12

Gillenwater GillenH2O Consulting

Green Gravel Grain Distribution - September 19th, 2024



Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

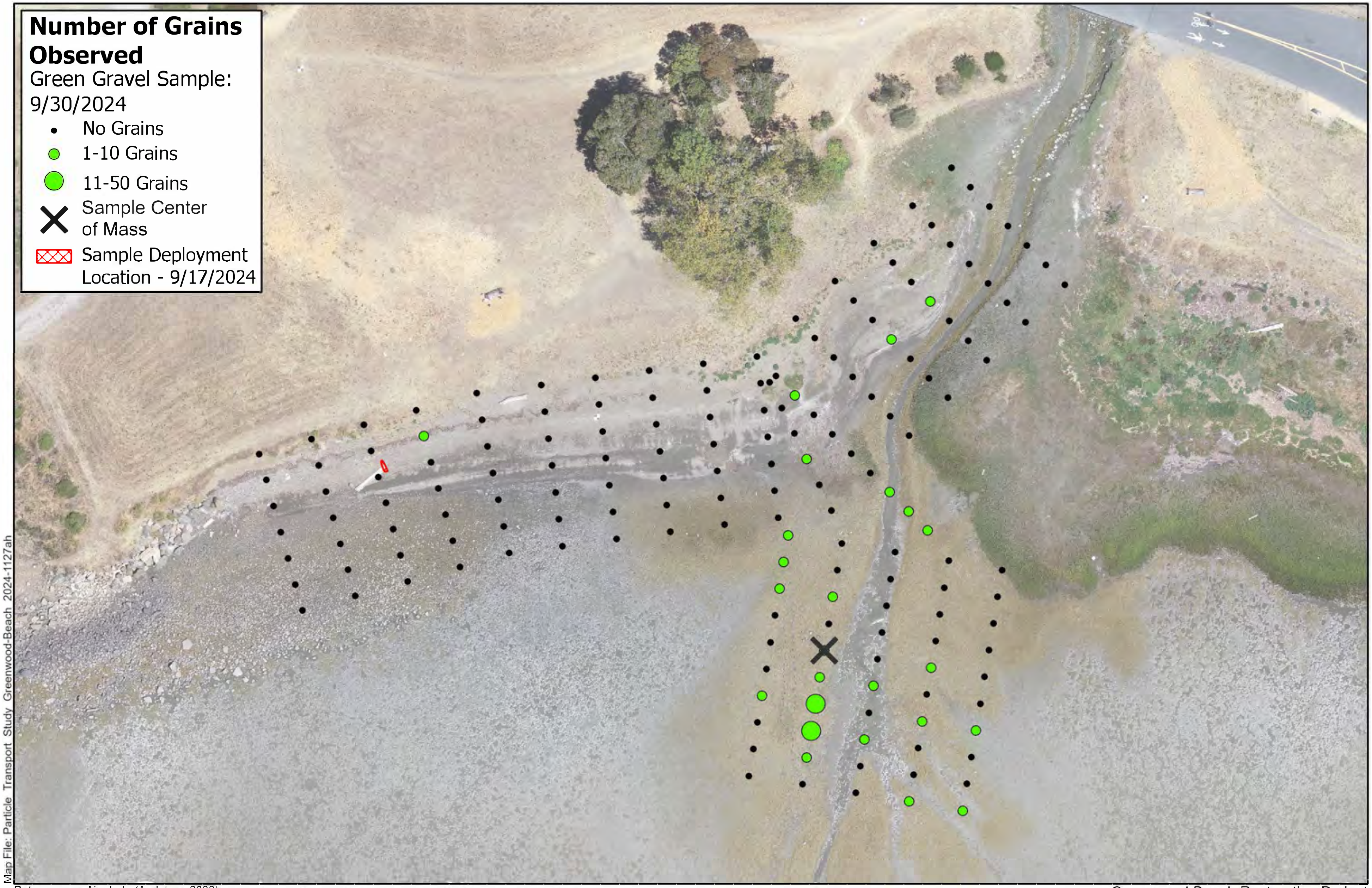
0 25 50 ft

0 7.5 15 m

Figure 13

Gillenwater GillenH2O Consulting

Green Gravel Grain Distribution - September 23rd, 2024



Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

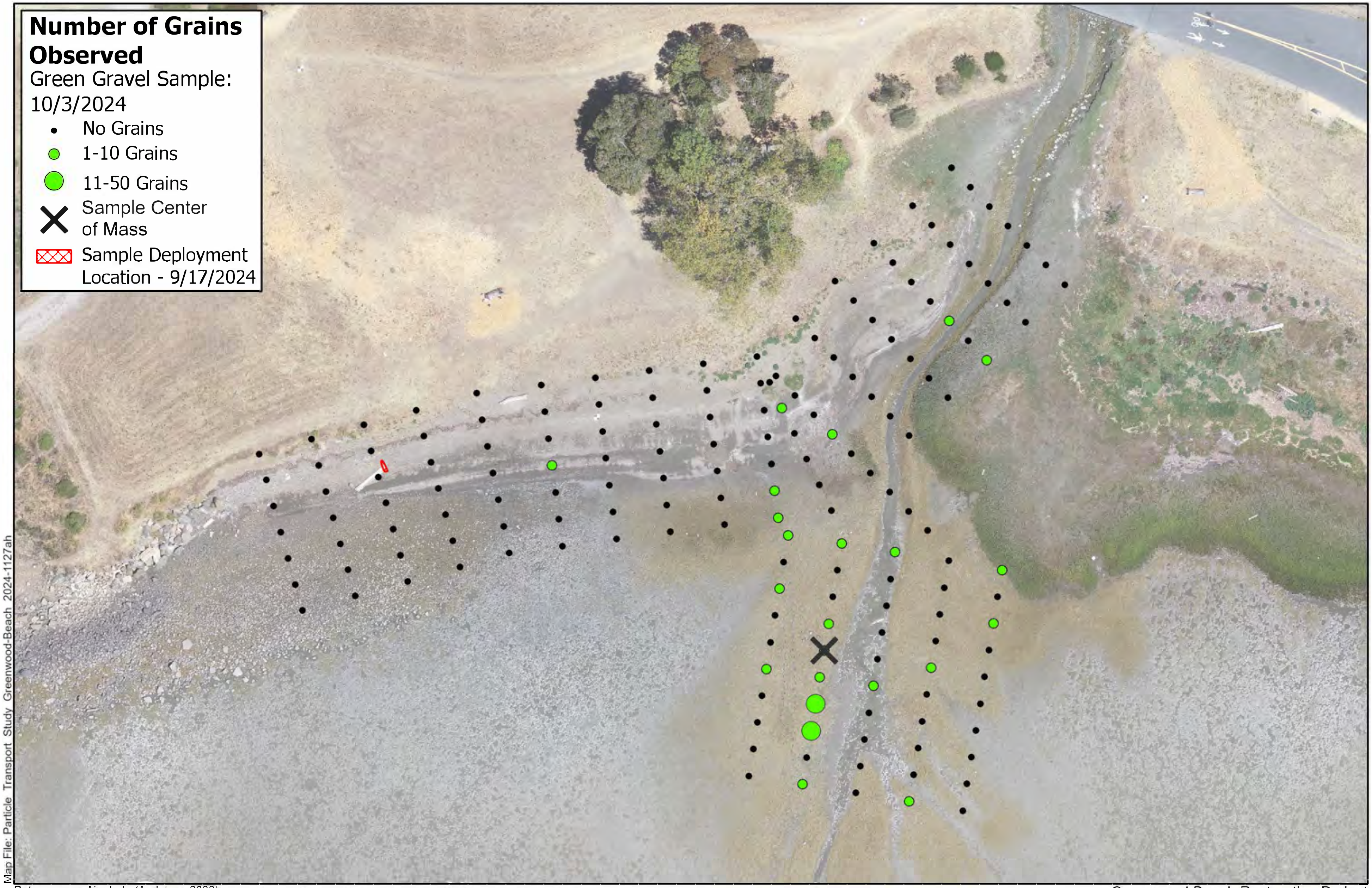
Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)
0 25 50 ft
0 7.5 15 m

Figure 14

Gillenwater GillenH2O Consulting

Green Gravel Grain Distribution - September 30th, 2024



Map File: Particle Transport Study Greenwood-Beach 2024-1127ah

Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

0 25 50 ft

0 7.5 15 m

Gillenwater GillenH2O Consulting

Figure 15

Green Gravel Grain Distribution - October 3rd, 2024

Map File: Max_Particle_Transport_Greenwood-Beach_2024-1211ah

Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

0 25 50 ft

0 7.5 15 m

Figure 16

Gillenwater GillenH2O Consulting

Max Dyed Grain Depth Distribution - September 18th, 2024

Map File: Max_Particle_Transport_Greenwood-Beach_2024-1211ah

Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

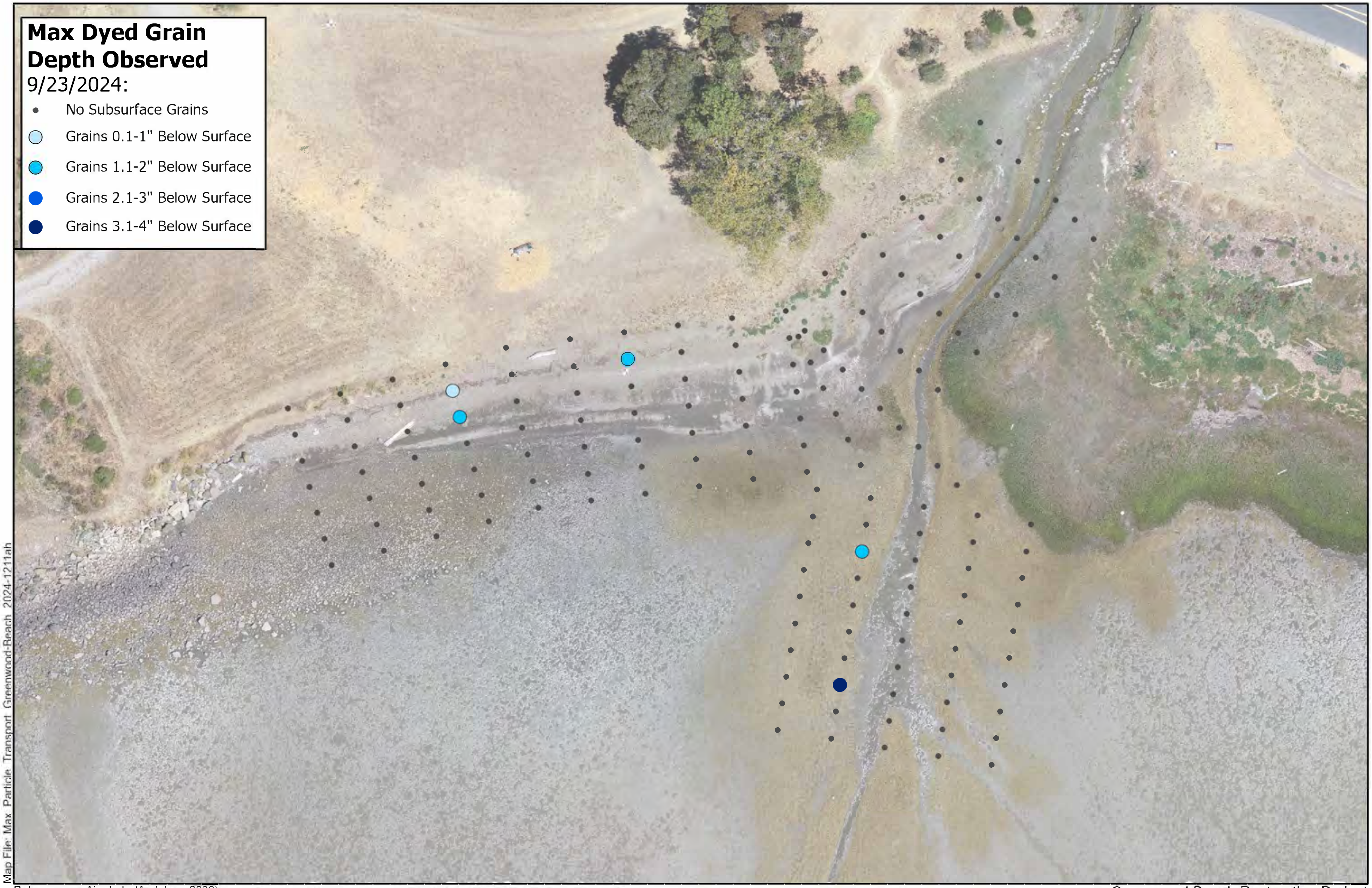
0 25 50 ft

0 7.5 15 m

Figure 17

Gillenwater GillenH2O Consulting

Max Dyed Grain Depth Distribution - September 19th, 2024



Data sources: Air photo (Audubon, 2022);
Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

0 25 50 ft

0 7.5 15 m

Figure 18

Gillenwater GillenH2O Consulting

Max Dyed Grain Depth Distribution - September 23rd, 2024

Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)

0 25 50 ft

0 7.5 15 m

Figure 19

Gillenwater GillenH2O Consulting

Max Dyed Grain Depth Distribution - September 30th, 2024

Map File: Max_Particle_Transport_Greenwood-Beach_2024-1211ah

Data sources: Air photo (Audubon, 2022);
Design (GillenH2O, 2023)

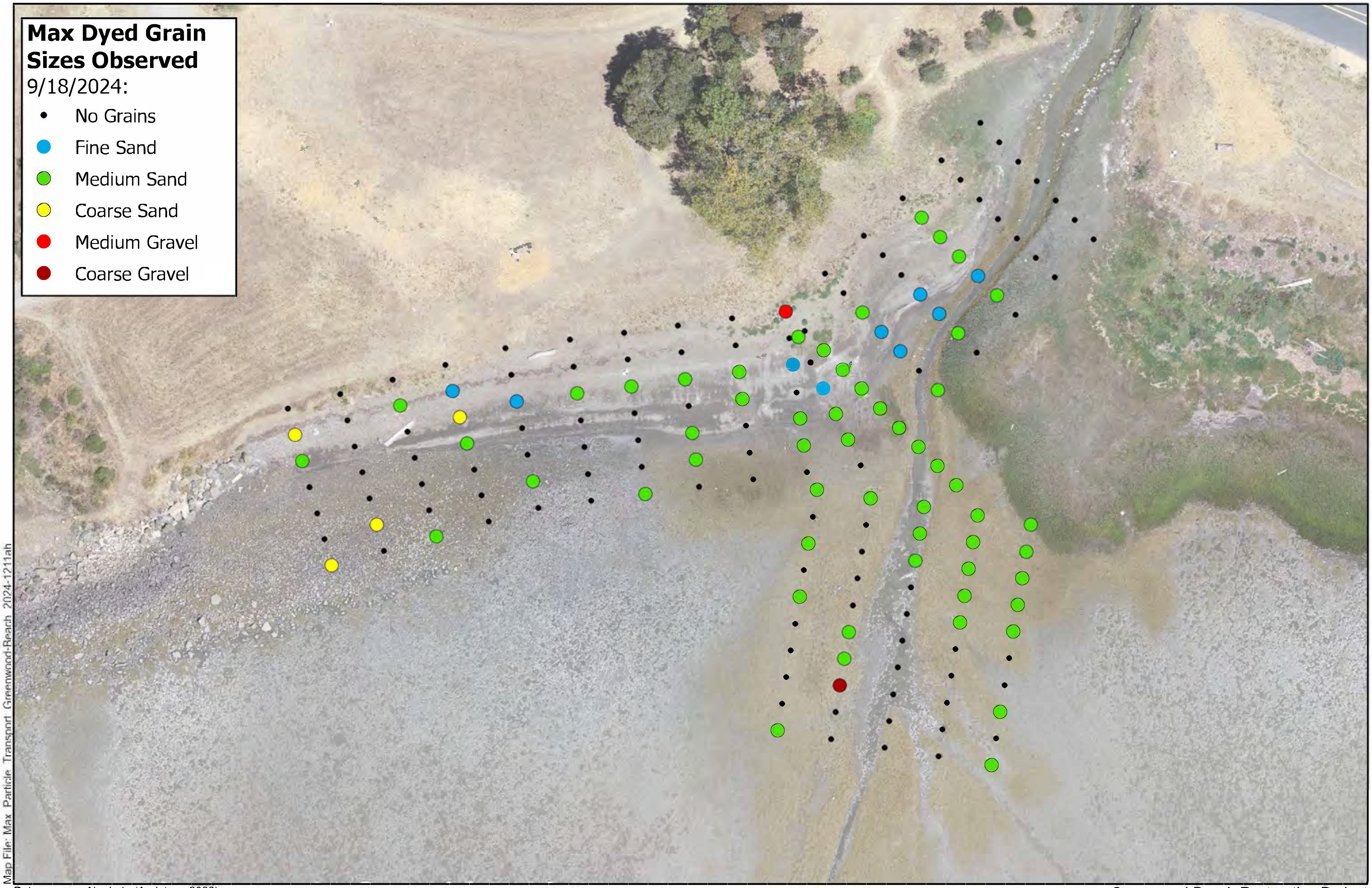
Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)
0 25 50 ft
0 7.5 15 m

Figure 20

Gillenwater GillenH2O Consulting

Max Dyed Grain Depth Distribution - October 3rd, 2024



Data sources: Air photo (Audubon, 2022);
Design (GillenH2O, 2023)

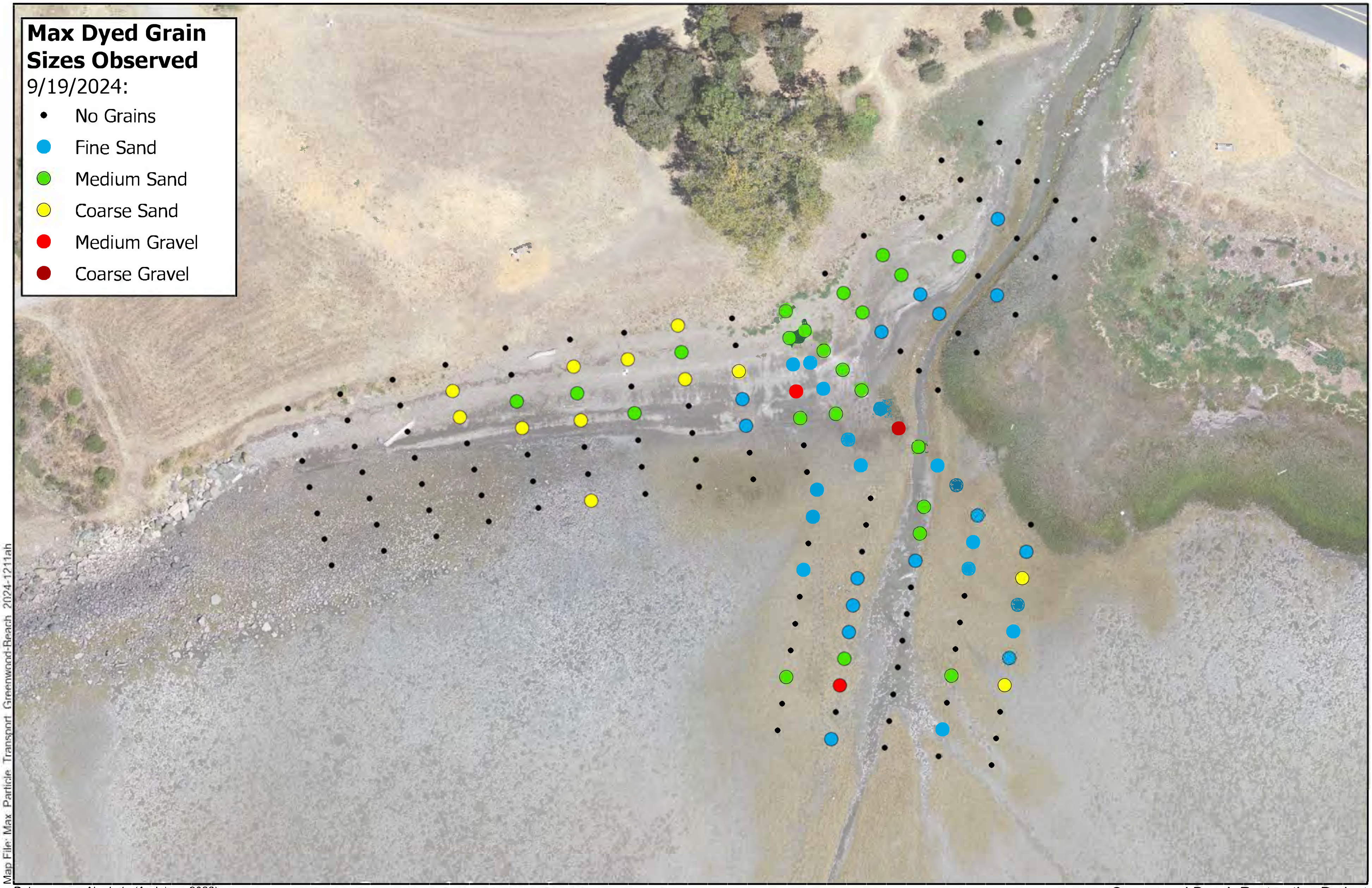
Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)
0 25 50 ft
0 7.5 15 m

Gillenwater GillenH2O Consulting

Figure 21

Max Dyed Grain Size Distribution - September 18th, 2024



Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

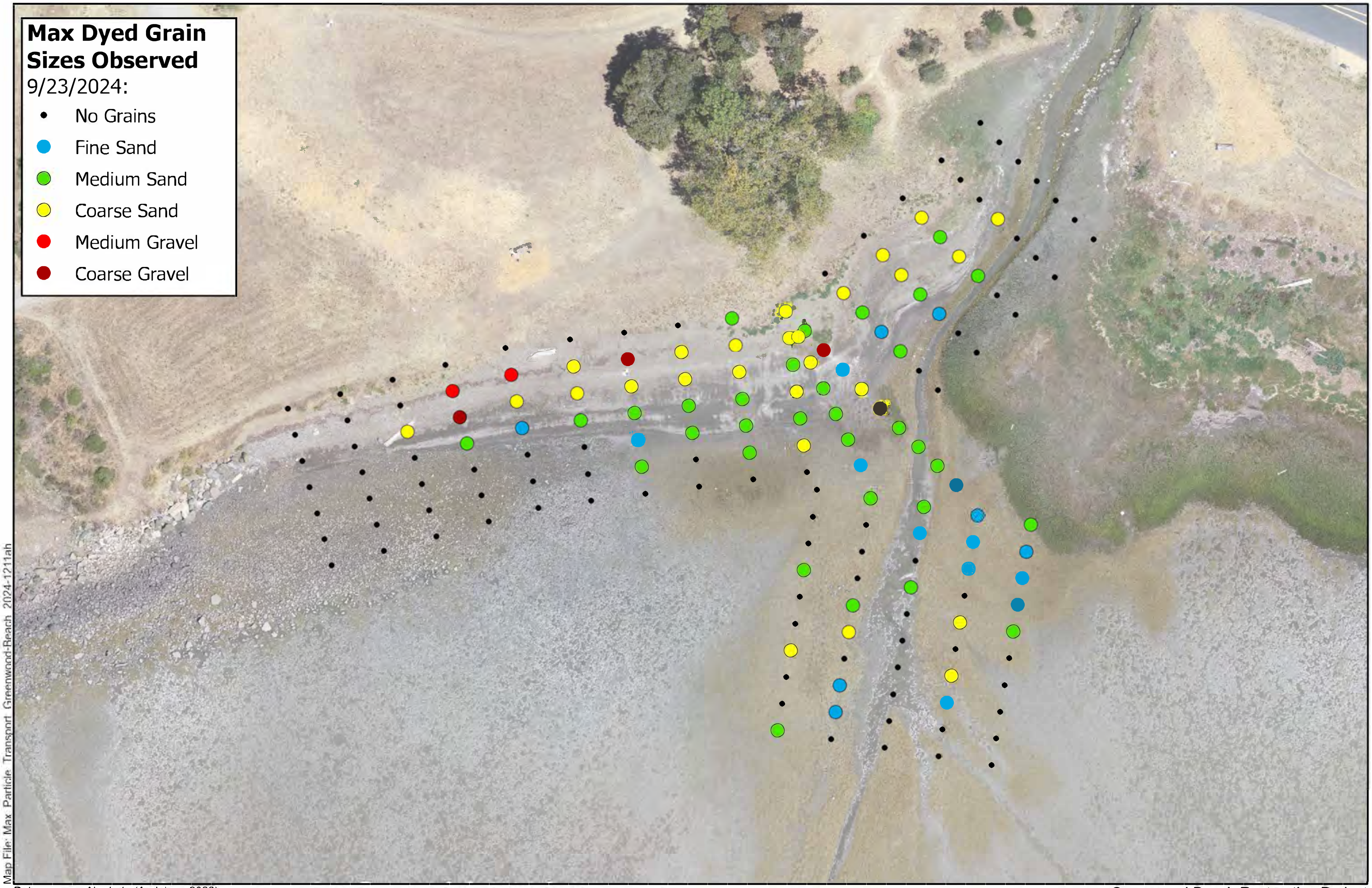
Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)
0 25 50 ft
0 7.5 15 m

Figure 22

Gillenwater GillenH2O Consulting

Max Dyed Grain Size Distribution - September 19th, 2024



Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

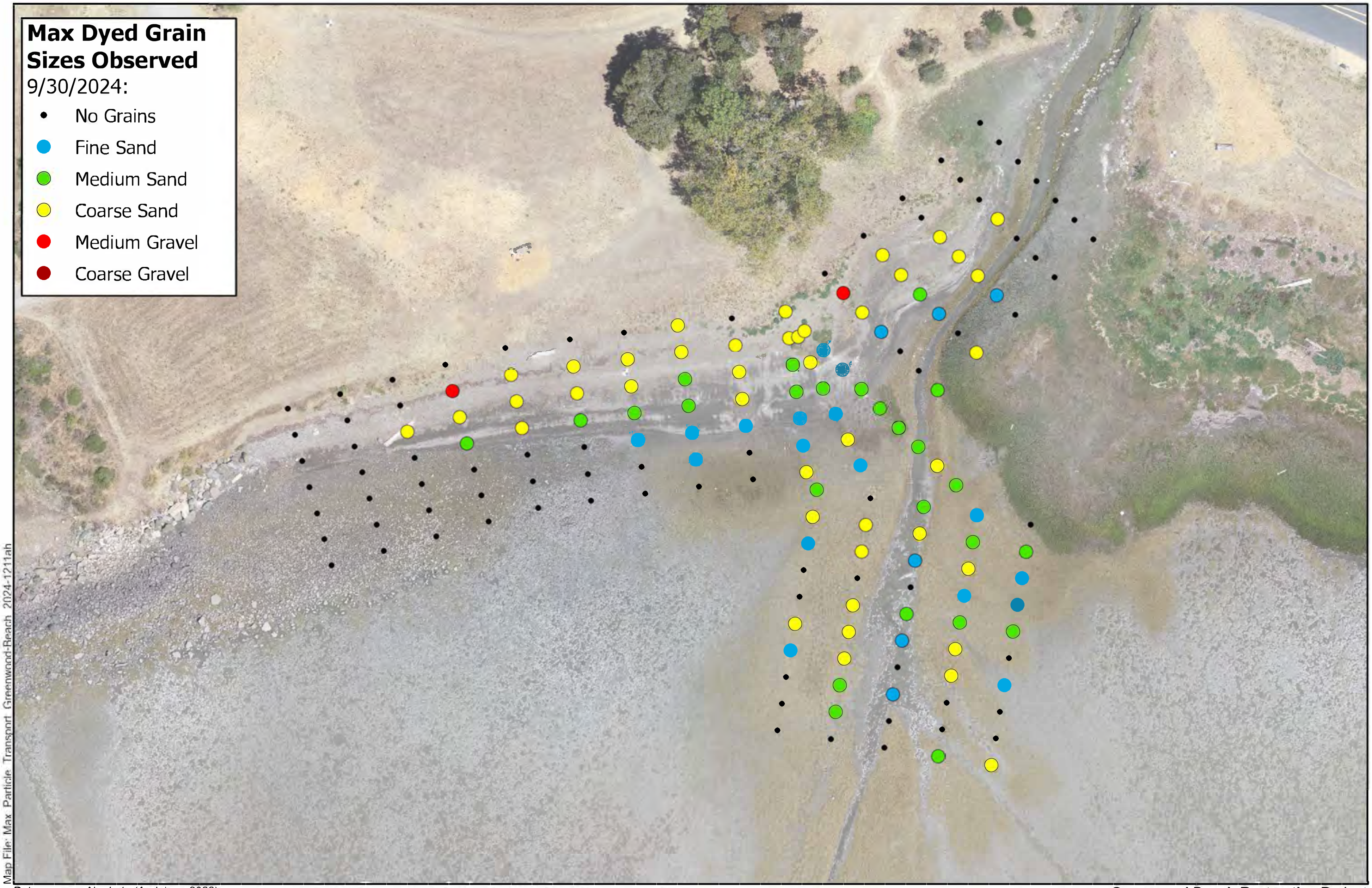
Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)
0 25 50 ft
0 7.5 15 m

Gillenwater GillenH2O Consulting

Figure 23

Max Dyed Grain Size Distribution - September 23rd, 2024



Map File: Max_Particle_Transport_Greenwood-Beach_2024-1211ah

Data sources: Air photo (Audubon, 2022); Design (GillenH2O, 2023)

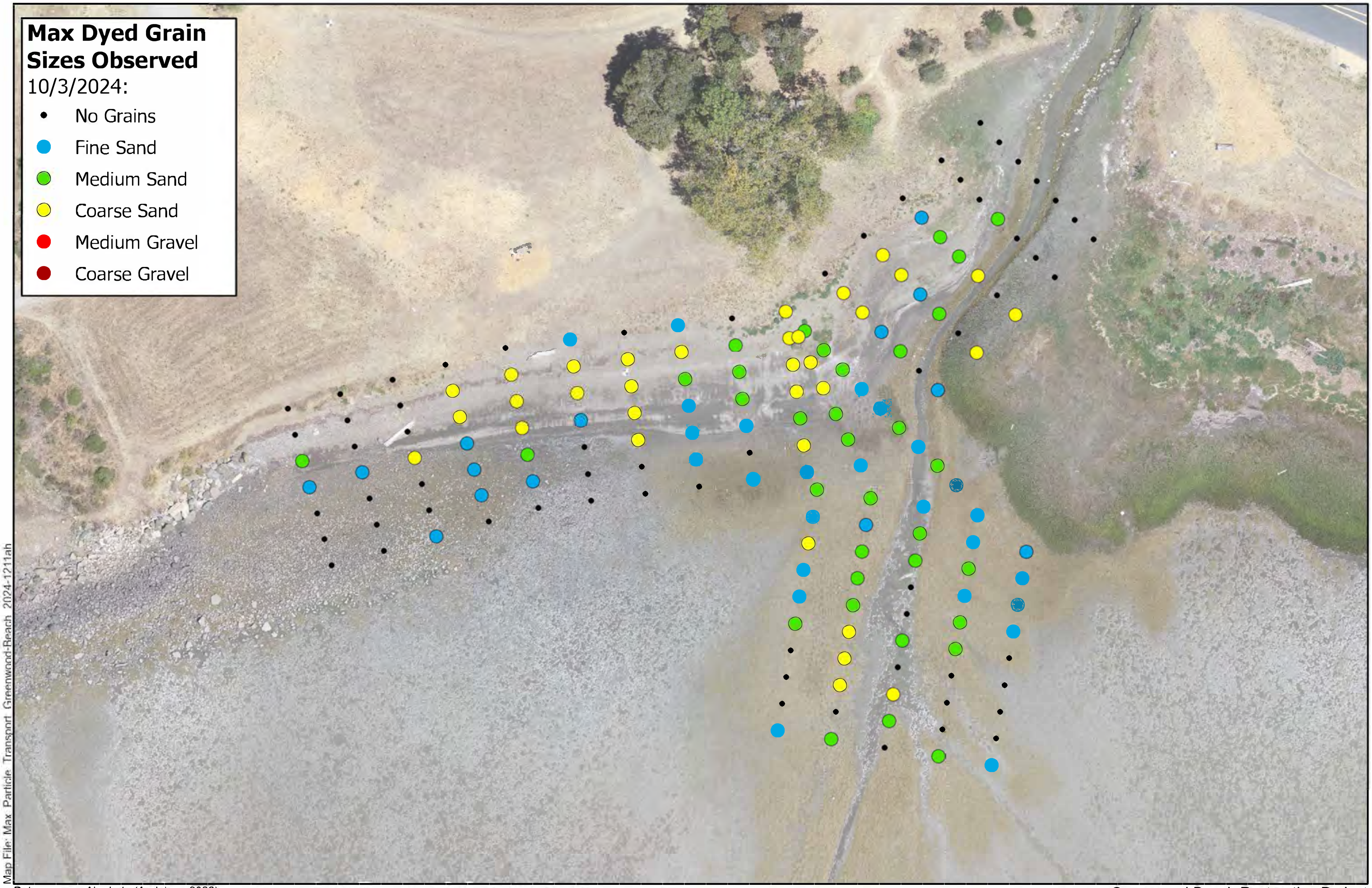
Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)
0 25 50 ft
0 7.5 15 m

Figure 24

Gillenwater GillenH2O Consulting

Max Dyed Grain Size Distribution - September 30th, 2024



Data sources: Air photo (Audubon, 2022);
Design (GillenH2O, 2023)

Greenwood Beach Restoration Project

1:600 (1" = 50' at letter size)
0 25 50 ft
0 7.5 15 m

Figure 25

Gillenwater GillenH2O Consulting

Max Dyed Grain Size Distribution - October 3rd, 2024

Greenwood Beach Restoration Project
Reference Beach Study

Data Collection Report Appendices – Technical Study Memoranda

<u>Prepared For</u>:
Marin County Department of Public Works
3501 Civic Center Dr.
San Rafael, Ca 94903

and
Town of Tiburon
505 Tiburon Boulevard
Tiburon, CA 94920

<u>Prepared By</u>:
Dan Gillenwater, PWS; Gillenwater Consulting, LLC
Peter Baye, PhD; Coastal Ecologist, Botanist
Roger Leventhal, PE; Marin County Public Works
Paige Fernandez; Audubon California

July 2025

This project received funding from 2016's Measure AA, the Clean and Healthy Bay Measure, through the San Francisco Bay Restoration Authority. The San Francisco Bay Restoration Authority is a regional agency that funds projects that restore, protect and enhance the wetlands and wildlife habitat in the San Francisco Bay and its shoreline.

SAN FRANCISCO BAY

RESTORATION AUTHORITY

Table of Contents

Appendix F. Particle Tracking Study No. 1 (Winter 2022) Memorandum

GREENWOOD BEACH PARTICLE TRACKING STUDY I

Date: January 11, 2023

From: Mario Accordino

To: Roger Leventhal, Marin County Flood Control District
Peter R. Baye,Ph.D.
Dan Gillenwater, GillenH20

This report includes the methodology ("Tracer Preparation" and "Tracer Survey") and results from the first particle tracking study conducted at Greenwood Beach. Guided by input from the project team (Roger Leventhal, Peter Baye, Dan Gillenwater and Paige Fernandez), this work was conducted by Mario Accordino as an independent contractor.

TRACER PREPARATION:

Sediment was collected from the project site on 12/03/2021 at four locations at which future tracer deployment was planned: Greenwood Beach, Brunini Beach, the Flood Control Channel, and the Delta. Approximate locations of sediment collection are shown in Figure 2.

Sediment was dyed according to the general procedures outlined in Kinsman and Xu (2012) and Ciavola and Grottoli (2017), wherein fluorescent pigment is mixed with a thinning solution and binder before coating dried sediment particles. Dyed sediment was washed and dried to ensure negligible leakage of tracer pigment once deployed at the project site.

D50 grain size comparison between native and dyed sediment is shown in Table 1. Full grain size analysis tables are found on the project's OneDrive folder under "…Data – Greenwood – particle tracking – Particle Tracking Study I – Sediment."

Table 1. D50 Comparison of Native and Dyed Sediment

Location	Native Sediment	Dyed Sediment
Greenwood Beach	0.52 mm	0.48 mm
Brunini Beach	1.09 mm	1.17 mm
Delta	0.30 mm	0.34 mm
Flood Control Channel	0.29 mm	0.31 mm

The D50 of all dyed samples is within 0.1 mm of their corresponding native sediment sample. Most dyed sub-samples display a coarser D50 than the pre-dyed condition, likely due to some clumping of finer grains. The orange Greenwood Beach sample is one exception to this trend, primarily due to the presence of a coarse gravel fraction that was not present in the dyed sub-sample.

Based on intended sediment deployment locations (see Figure 2), a grid was established at regularly spaced intervals around each deployment point and labeled individually. A map of these labeled points is shown in Figure 1.

Figure 1. Grid of Survey Points

TRACER SURVEY:

Deployment:

Dyed sediment was deployed on 11/30/21 at approximately 16:00, at locations indicated in Figure 2. Approximately 1 cubic foot of dyed sediment was used at each location.

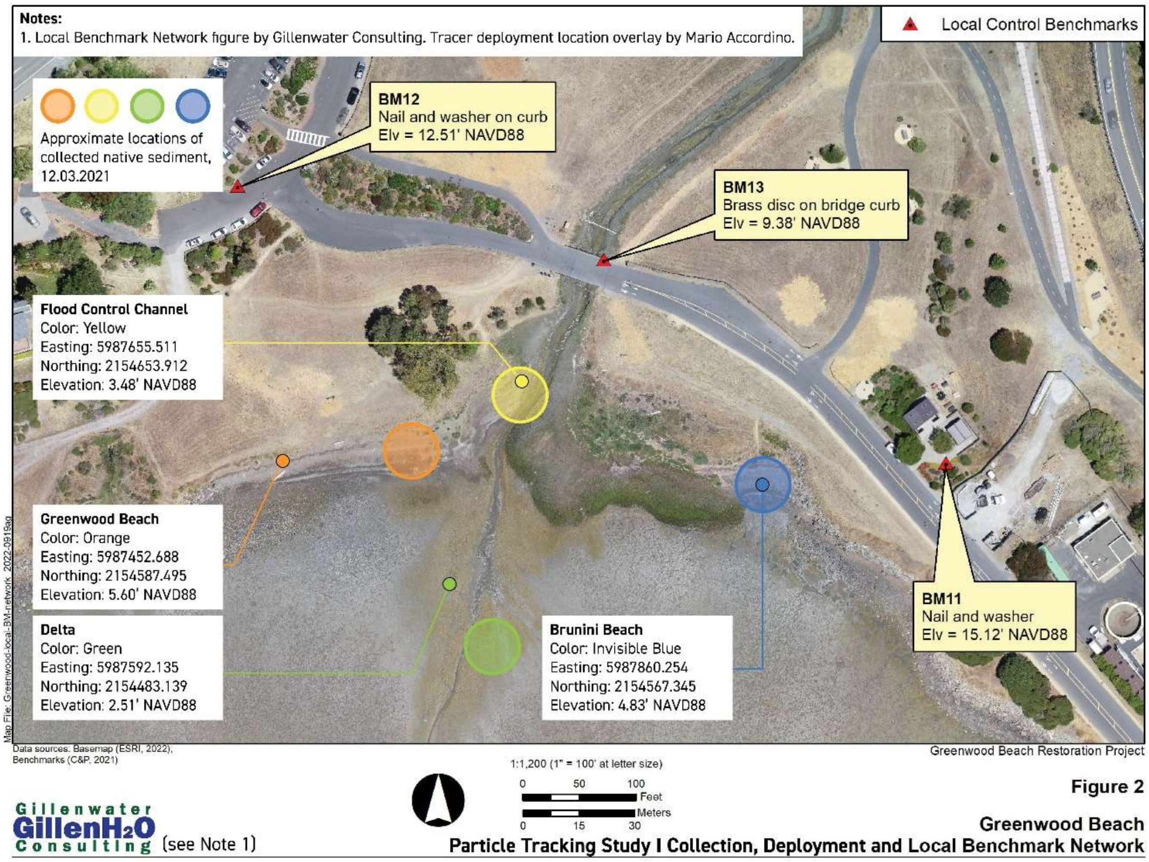


Figure 2. Native Sediment Collection and Dyed Sediment Deployment Locations

Sediment was covered with a thin (approx. 1/2 - 2”) layer of surrounding sediment. An example of tracer deployment prior to cover at Greenwood Beach is seen in Figure 3.

Figure 3. Example Tracer Deployment at Greenwood Beach, 11/30/22.

<u>Surface Observations:</u>

An RTK GPS unit guided me to each pre-established grid point. A circular black frame with a diameter of 9.75” (0.52 sq. ft. area) was placed at each grid point and a UV flashlight illuminated the ground within the frame. Fluorescent grains that were visible within the frame were counted by manual observation. Photos were taken when grain sizes exceeded 0.5 mm and the maximum grain size was recorded (photos of fluorescent grains finer than approximately 0.5mm did not register as visible when photographed). An example photo of this surface measurement is shown in Figure 4.

Figure 4. Example Surface Observation, Grid Point GB5 on 12/01/22.

Cores

With a couple exceptions when conditions were too wet, or the dyed sediment was buried too deep, shallow cores were taken at each deployment site during each survey event. Depth between top of sediment to the top of the dyed sediment was recorded, and density of dyed sediment was qualitatively evaluated. An example of this coring is shown in Figure 5.

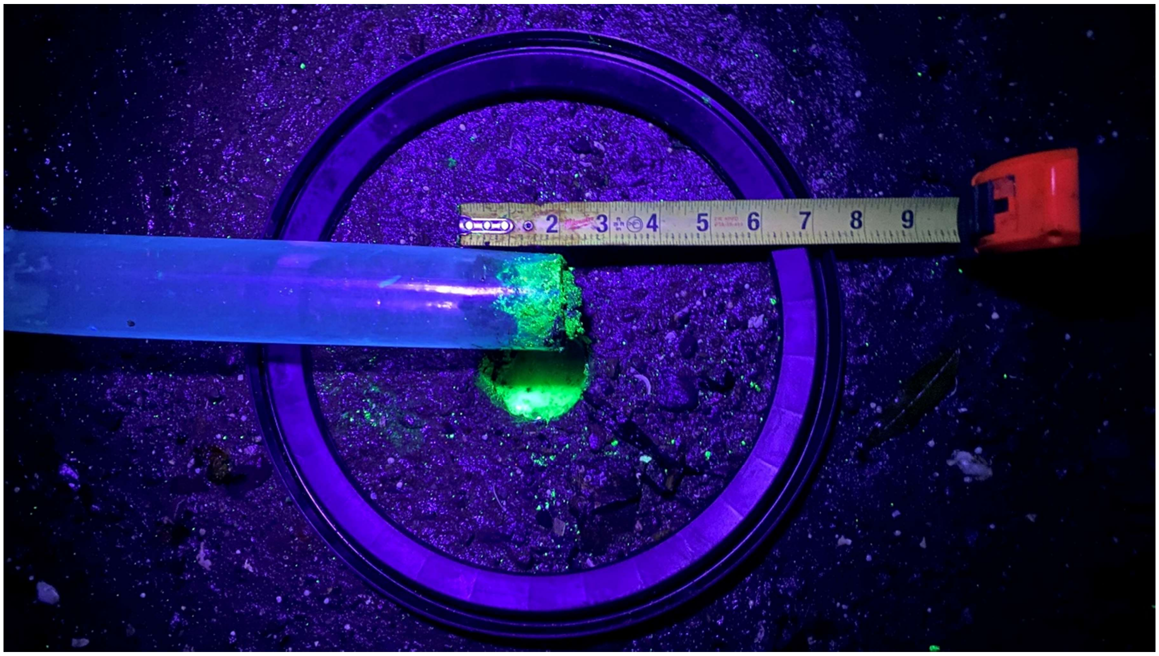


Figure 5. Example Sediment Core at Delta, on 12/12/22.

The complete set of site photographs, including all deployment, surface observation and core photos can be found in the project's OneDrive account under the folder "…Data – Greenwood – particle tracking – Particle Tracking Study I – Photos."

RESULTS:

Maps of surface grains observed at each grid point, with symbols sized to reflect the quantity of grains observed, are shown in Figures 7a-f.

Figure 6a. Surface Grains Observed, 11/30/22.

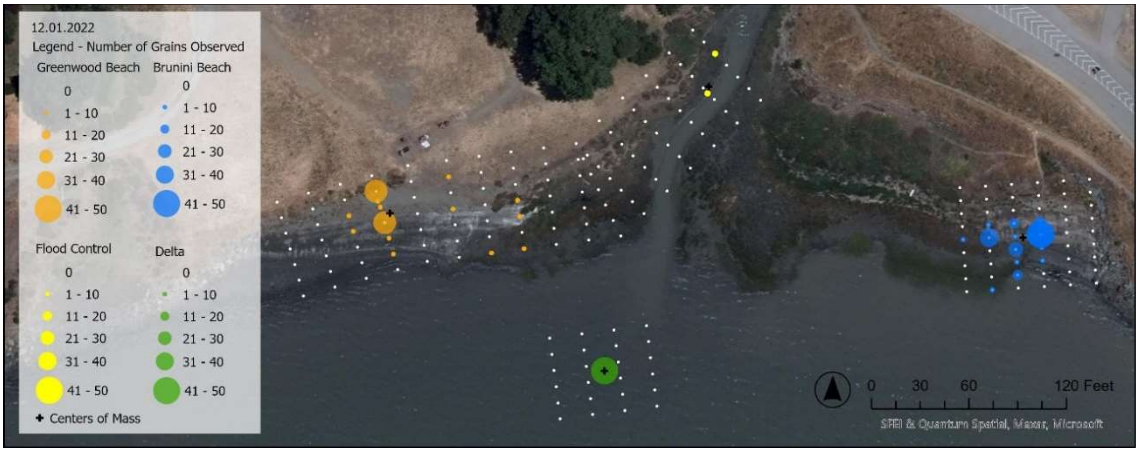


Figure 6b. Surface Grains Observed, 12/01/22.

Figure 6c. Surface Grains Observed, 12/02/22.

Figure 6d. Surface Grains Observed, 12/07/22.

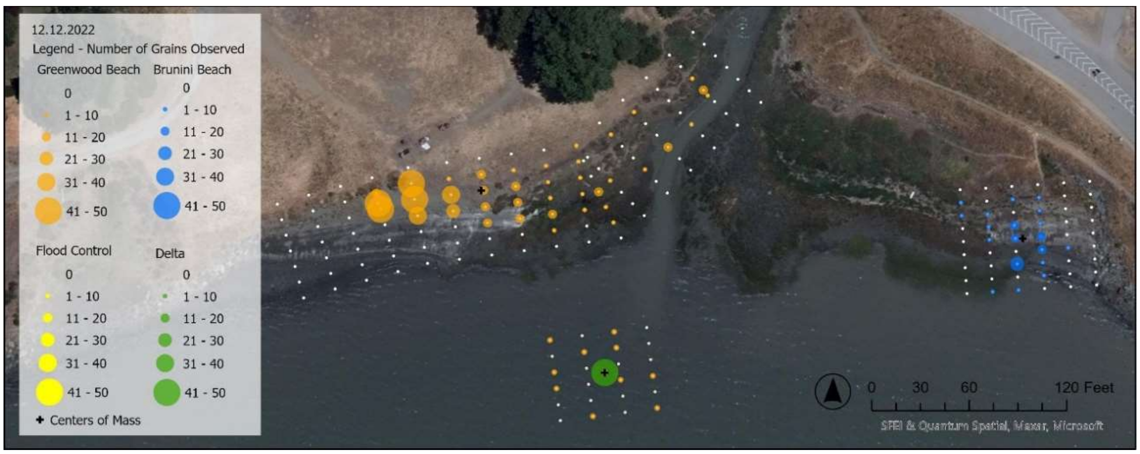


Figure 6e. Surface Grains Observed, 12/12/22.

Figure 6f. Surface Grains Observed, 12/27/22.

The number of dyed surface grains observed throughout of the site varied between observations, as shown in Table 2. Values of ~50+ signify locations where a high concentration of fine grains were detected within a grid point, typically at the deployment sites of the Delta and Flood Control Channel.

Table 2. Total Number of Dyed Surface Grains Observed at Observation Points

	11/30/22	**12/01/22**	**12/02/22**	**12/07/22**	**12/12/22**	**12/27/22**
Orange (Greenwood Beach)	63	116	59	63	570	361
Blue (Brunini Beach)	135	222	320	366	129	60
Green (Delta)	~50+	~50+	~50+	~50+	~50+	1
Yellow (Flood Control)	~50+	6	24	15	0	0

Overall, orange and blue grains were observed most often. While green and yellow grains were intermittently visible at high concentrations at their deployment locations, they were mostly not present beyond those spots.

Centers of mass, calculated using a weighted average of surface grain counts at each grid point, is also shown in Figures 7a-f as a black cross. If a cross is not shown on the map, no surface grains of that color were observed at grid points during that survey event. The distance between each of these points and the deployment origin for that color is shown in Table 3.

Table 3. Distance from Deployment Site to Centers of Mass, Weighted by Number of Grains Observed

	11/30/22	**12/01/22**	**12/02/22**	**12/07/22**	**12/12/22**	**12/27/22**
Orange (Greenwood Beach)	0.6 ft	10.4 ft	4.4 ft	7.3 ft	64.0 ft	54.6 ft
Blue (Brunini Beach)	0.9 ft	10.8 ft	13.7 ft	13.0 ft	10.9 ft	11.4 ft
Green (Delta)	0 ft	0 ft	0 ft	0 ft	0 ft	0 ft
Yellow (Flood Control)	3.1 ft	4.2 ft	0.5 ft	0 ft	N/A	N/A

Shallow cores showed mixed dyed and native sediment at Brunini Beach, but otherwise cores at Greenwood Beach, the Delta and Flood Control Channel revealed dyed sediment that was uniform and highly concentrated at a certain depth. These depths are shown in Table 4.

Table 4. Top Depth of Dyed Sediment from Shallow Cores

	11/30 Deployment	**11/30**	**12/01**	**12/02**	**12/07**	**12/12**	**12/27**
Orange (Greenwood Beach)	0.5 - 2 in	1 in	1 in	1 in	1 in	0.5 in	0.5 in
Blue (Brunini Beach)	0.5 - 1 in	0 in	0 in	0 in	0 in	0 in	0 in
Green (Delta)	1 in	1 in	0.5 in	0.5 in	1.5 in	1 in	N/A
Yellow (Flood Control)	1 in	0 in	1.5 in	1.5 in	1.75 in	4 in	N/A

Depth of dyed sediment increased at the flood control channel, significantly so between 12/07 and 12/12 following a storm event on 12/10. Meanwhile, the depth of concentrated orange tracer decreased between these dates at Greenwood Beach.

Plots of maximum grain sizes 0.5 mm or larger at each grid point were produced similar to the grain count maps. The complete set of these figures can be found at "…Data – Greenwood – particle tracking – Tracer Study I – Figures." Most of these figures do not contain many points since the majority of grains observed were medium sand or finer. However, the plot from 12/27/22 shown in Figure 7 illustrates how coarser grains within the Greenwood Beach sample were found both in the mudflat bayward of the deployment site and in the beachface upslope and slightly downdrift of the deployment site.

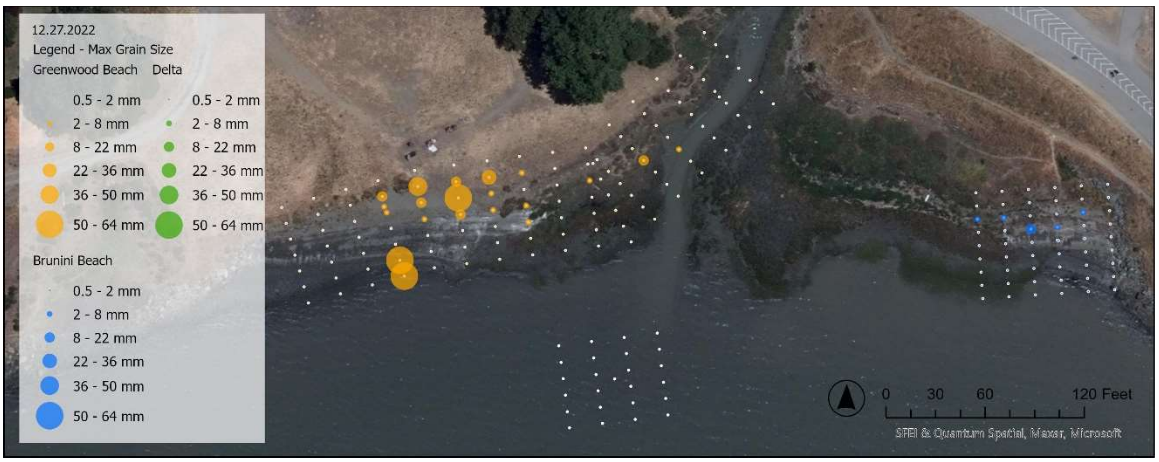


Figure 7. Maximum Grain Size Observed, 12/27/22.

<u>Greenwood Beach</u>

As discussed with the project team (pers. comm., 2022), movement of the dyed sediment at Greenwood Beach was undoubtedly deterred by the coarser lag layer of gravel covering the deployed sediment. Only between 12/07/22 and 12/12/22 did the orange sediment begin to display significant movement eastward. Even after this eastward movement was observed, the majority of dyed sediment remained below the cover layer at the deployment location. Coarser gravels were scattered both above and below the deployment site, and finer grains traveled further east towards the Flood Control Channel and south to the Delta.

<u>Brunini Beach</u>

Tracer movement at Brunini Beach was primarily west and north, with the greatest distance traveled observed soon after deployment on 12/01/22. Where an existing marsh scarp was present, further westward movement was deterred, and few blue grains were seen in the mudflat beyond the toe of the beach.

<u>Flood Control Channel and Delta</u>

Unlike Greenwood and Brunini Beach, tracer at the Flood Control Channel and Delta were nearly entirely stationary, remaining almost completely locked below their initial cover layer. In the case of the Flood Control Channel, sand deposition during the study period buried the tracer further below the ground surface.

NEXT STEPS:

Although wind and wave analyses are not included in this document, it is recommended to view such data in conjunction with these results. Particularly, elevated wind speeds and water levels on 12/01/22, 12/10/22 and 12/27/22 could have implications for the extent of tracer movement.

While the four current batches of dyed sediment will remain deployed on site, future survey events documenting this tracer's position will be limited, and it remains to be seen how long the fluorescent dye is visible. Fading of blue grains at Brunini Beach was noticeable during the survey days of 12/12/22 and 12/27/22.

As discussed during a meeting with Roger Leventhal, Peter Baye and Dan Gillenwater on 12/16/22, results and lessons learned from this particle tracking study will be used to inform a future one. The next particle tracking study will use three separate dyed samples. Two samples will consist of sandy sediment sourced from Shollenberger Park, of the same grain size distribution, that would conceivably be used for nourishment at Greenwood Beach. As shown in Figure 8, one of these samples will be placed at approximately the same location as this study's orange Greenwood Beach deployment location, updrift and within the swash zone at the mid-beachface. Another sandy sample will be placed downdrift on the beach berm top. The third sample, composed of gravel sourced from the project site's delta, will be placed at the beach toe between the two sandy samples. The three samples will be dyed with separate fluorescent pigments and will be deployed without a cover layer of native sediment to allow for unimpeded movement.

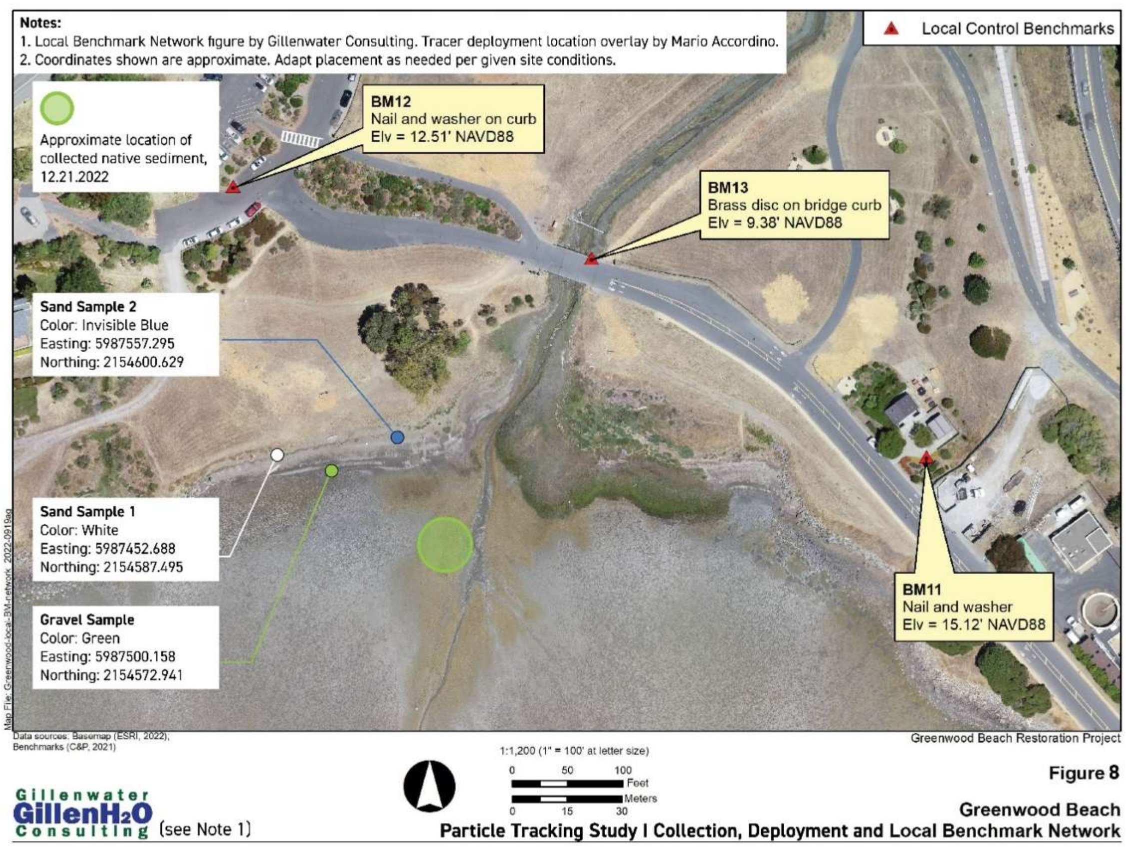


Figure 8. Planned Tracer Study II Deployment Locations

REFERENCES:

Ciavola, P. and Grottoli, E. 2017. Tracers and Coarse Sediment. Finkl, C.W., and Makowski, C. (eds.), Enclyclopedia of Coastal Science. Springer International Publishing.

Kinsman, N. and Xu, J.P., 2012. Fluorescent tracer experiment on Holiday beach near Mugu Canyon, southern California: Open-File Report 2012-1131, United States Geological Survey (USGS).

Leventhal, R., Baye, P., and Gillenwater, D. 2022. Personal communication.

Appendix G. Delta Bedload Transport Memorandum

FEBRUARY 2025

Greenwood Beach Delta Bedload Transport Study

Data Collection Memorandum - February 2025

Greenwood Beach
Photo: Paige Fernandez/Audubon California

Contents

Prepared by:

Paige Fernandez, San Francisco Bay Program Manager
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Audubon California
1901 Harrison Street, Suite 1450
Oakland, CA 94612

Greenwood Beach Delta Bedload Transport Study

The purpose of this memo is to summarize the methods and results of a brief bedload transport study performed on the Greenwood Beach flood control channel delta (delta) during a storm event in February 2024. The purpose of this study was to understand the general patterns of sediment movement on the delta during storm events to inform potential recovery of a material borrow area that is proposed as part of the Greenwood Beach Restoration Project (project). Further analysis and interpretation of the data provided herein will be done by the project design team.

Introduction

The project site is situated along the northeastern corner of Richardson Bay and located within the town of Tiburon, California (Figure 1). This location is popular with local community members who visit the area to walk, bike, bird watch, dog walk, swim, and recreate in nearby Blackie's Pasture and along the public trail. The west beach, Greenwood Beach, and the eastern pocket beach, Brunini Beach, are well-used for recreation, but the rocky concrete and asphalt shoreline around it is largely avoided by the public. The remainder of the shoreline is armored with rubble and riprap resulting in low public use (Figure 2).

The shoreline includes broad intertidal mudflats, a flood control channel delta, a small saltmarsh patch, and two small pocket beaches, surrounded by old bay fill and armored shoreline. Similar to many other locations around San Francisco Bay, the shoreline along the Greenwood Beach project site is highly eroded. The proposed project would restore and expand beach habitat at Greenwood and Brunini beaches to improve habitat and public access values while combating shoreline erosion using a "living shoreline" approach. The project proposes to excavate (borrow) sand and gravel from an area of the delta to use in rebuilding the beaches.

There is interest in understanding coarse sediment (sand and gravel) transport dynamics on the delta to estimate how quickly the proposed delta borrow pit may return to typical existing topography and composition after project construction. To that end, a rudimentary bedload transport study was implemented in the winter of 2024 to assess mobility of coarse sediment on the delta during a typical annual storm event, from a combination of local delta material redistribution and fluvial inputs from the flood control channel.

Study Methodology

This study occurred between 1/29/24-2/2/24 to capture conditions during a typical winter storm event (~0.5 year recurrence interval). This 18 hour winter storm event produced 2.13 inches of rain, average windspeed of 3 mph with a maximum of 7mph, and an average wind gust speed of 10 mph with a maximum of 19 mph.

To study bedload sediment on the delta, a total of four, 3.5 gallon buckets (4.1 gallon actual max capacity) were buried, flush to the ground, to act as pit traps for mobile sediment (Figure 3). Two buckets were buried on the delta bar (bar pits; BP) and two were buried within the primary delta distributary channel (channel pits; CP). Buckets were buried on 1/29/24 and 1/30/24 in preparation for the storm on 1/31/24. A wooden stake was hammed into the ground 1 ft west of each bucket and the above ground length was measured.

The buckets were retrieved after the storm subsided on 2/2/24. The depth (thickness) of accumulated sediment in each bucket was measured at 5 locations within the bucket- north, south, east, west, and center point- and averaged. Additionally, the height of the wooden stakes left above ground was measured.

At the office, water was slowly drained off from the buckets. After partial drying, a window was cut into the side of the bucket to observe layers of accumulated material and the lithology of the deposits recorded on a bore log. Samples from distinct sediment layers identified within each bucket were collected for laboratory grain size analysis.

Paige Fernandez, Audubon California's San Francisco Bay Program Manager based out of the Richardson Bay Audubon Center & Sanctuary, performed all surveys with the assistance of Lily Melendez, Richardson Bay Audubon Center & Sanctuary's 2023-2024 Community Conservation Fellow.

Results

DELTA BAR PIT TRAPS

Both pit traps from the delta bar had filled almost completely with sediment by 2/2/24. BP1 (Appendix 1,2) accumulated 0.79 ft of material within the bucket (89% full) and BP2 (Appendix 3,4) accumulated 0.65 ft of material within the bucket (73% full). Both delta bar pit traps contained a generally homogenous mixture of small shells, medium gravel, fine gravel, coarse sand, medium sand, fine sand, and a small amount of mud (Figure 4). BP1 contained a 0.01 ft layer of leaf debris in the middle of the bucket where BP2 contained a very small amount of vegetation throughout the entire bucket.

The wooden stake at BP1 had an above ground measurement of 0.90 ft before the storm and 0.91 ft post storm (essentially no change in surface elevation). The stake at BP2 had an above ground measurement of 0.94 ft before the storm and 1.03 ft post storm (minor delta erosion).

CHANNEL PIT TRAPS

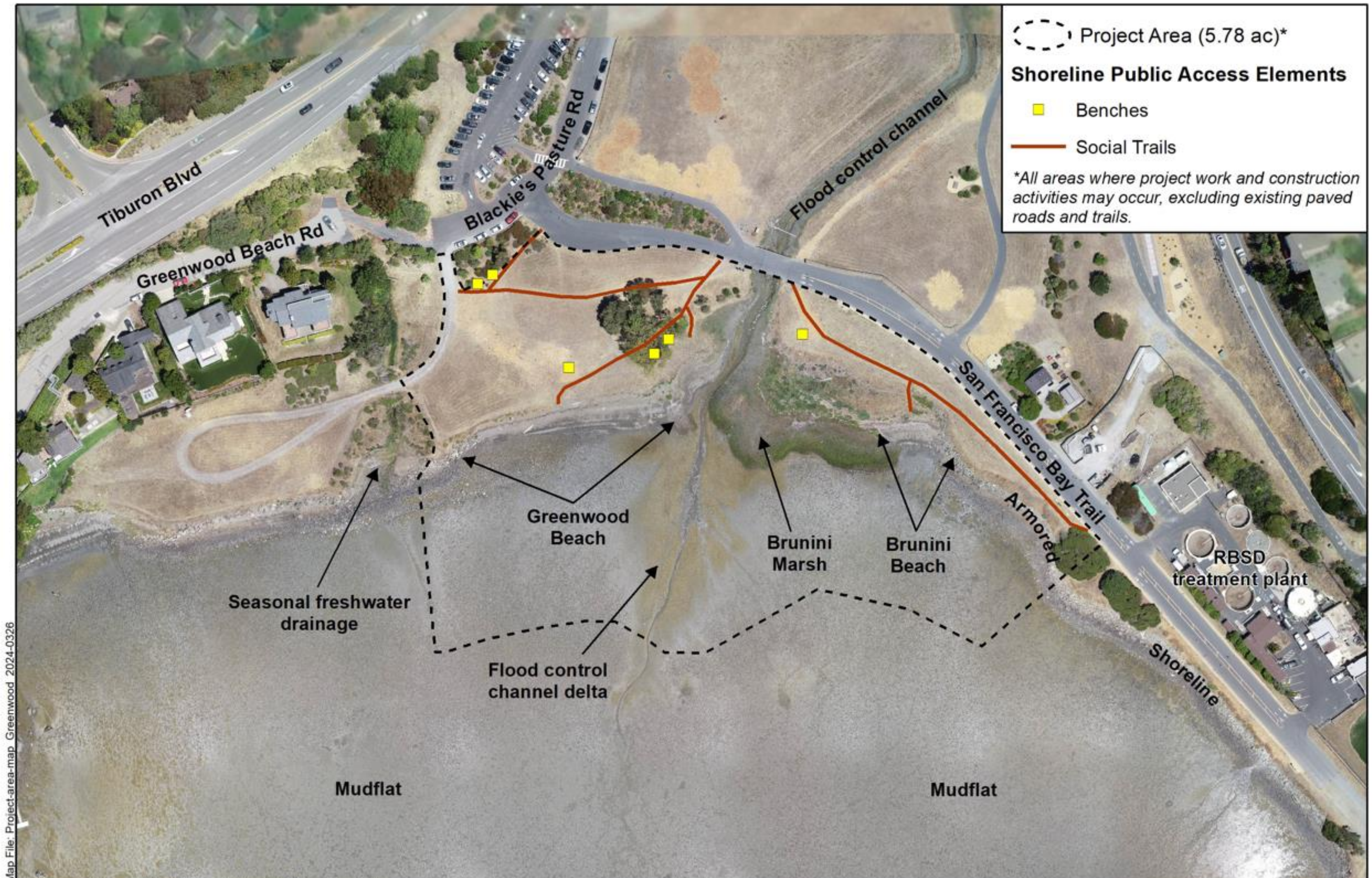
Both pit traps from the delta channel had filled with sediment by 2/2/24. CP1 accumulated 0.87 ft of material within the bucket (98% full) and CP2 accumulated 0.84 ft of material within the bucket (94% full). Both channel pit traps contained significantly more vegetation compared to the delta bar pit traps.

For CP1, the top half of the bucket was a generally homogenous mixture of small shell, medium gravel, coarse sand, medium sand, fine sand, and a very small amount of mud (Figure 5, Appendix 5,6). Some larger gravel pieces were deposited on the surface of the bucket. The bottom half contained a significant amount of vegetation debris, and mud. Few gravels were present within the vegetation layer.

For CP2, the top 0.1ft of the bucket cross section contained small shells, medium gravel, coarse sand, medium sand, fine sand, and a very small amount of mud (Figure 6a). The majority of the bucket contents (0.45ft of the cross section) contained vegetation and mud with a noticeable vegetative rot odor as well as two pieces of trash. The bottom 0.15ft of the cross section contained a thick muddy sand layer with a small amount of vegetation (Figure 6b, Appendix 7,8).

The wooden stake at CP1 had an above ground measurement of 0.93 ft before the storm and 0.91 ft post storm, while the stake at CP2 had an above ground measurement of 0.91 ft before the storm and 0.90 ft post storm, indicating no discernible change in surface elevation.

Maps, Tables, and Figures



Data sources: Basemap (ESRI, 2023); Aerial Image (Audubon CA, 2022); Public Access (GillenH2O, 2022)

1:1,800 (1" = 150' at letter size)

0 75 150 ft

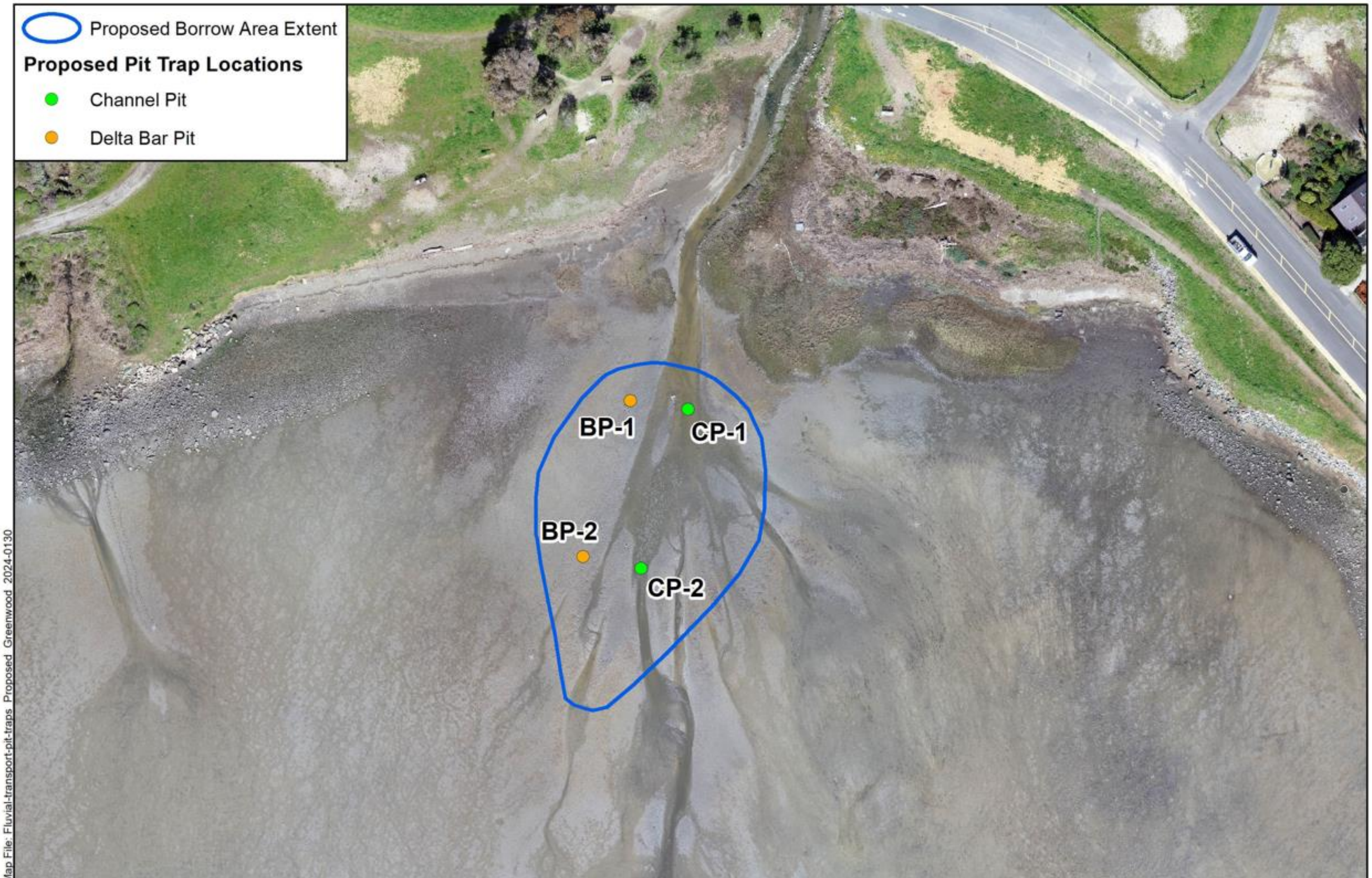
0 25 50 m

Gillenwater GillenH2O Consulting

Greenwood Beach Restoration Project

Figure 2

Project Area and Existing Features



Map File: Fluvial-transport-pit-traps Proposed Greenwood 2024-0130

Data sources: Air photo (Audubon, 2023);
Data (GillenH2O, 2024)

Greenwood Beach Restoration Project

1:1,800 (1" = 150' at letter size)

0 37.5 75 Feet

0 12.5 25 Meters

Gillenwater GillenH2O Consulting

Figure 3

Porposed Sediment Pit Trap Locations - Greenwood Beach

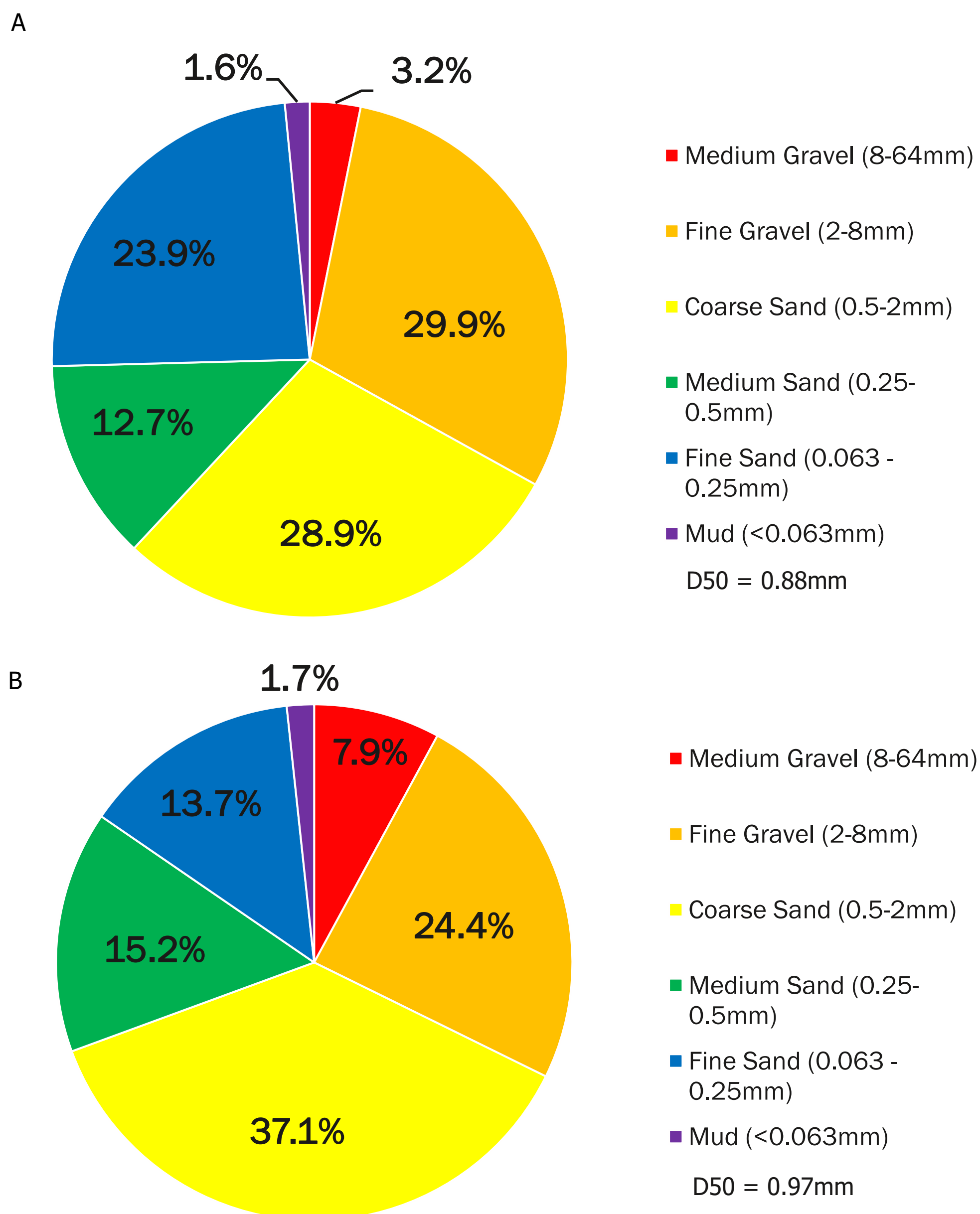


Figure 4. Grain size composition of representative samples from Bar Pits BP1 (A) and BP2 (B).

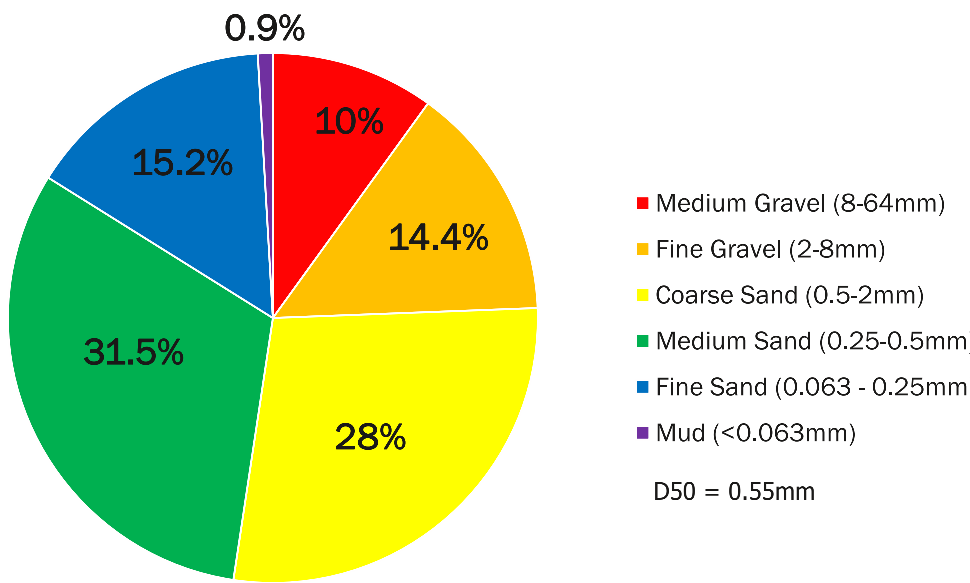
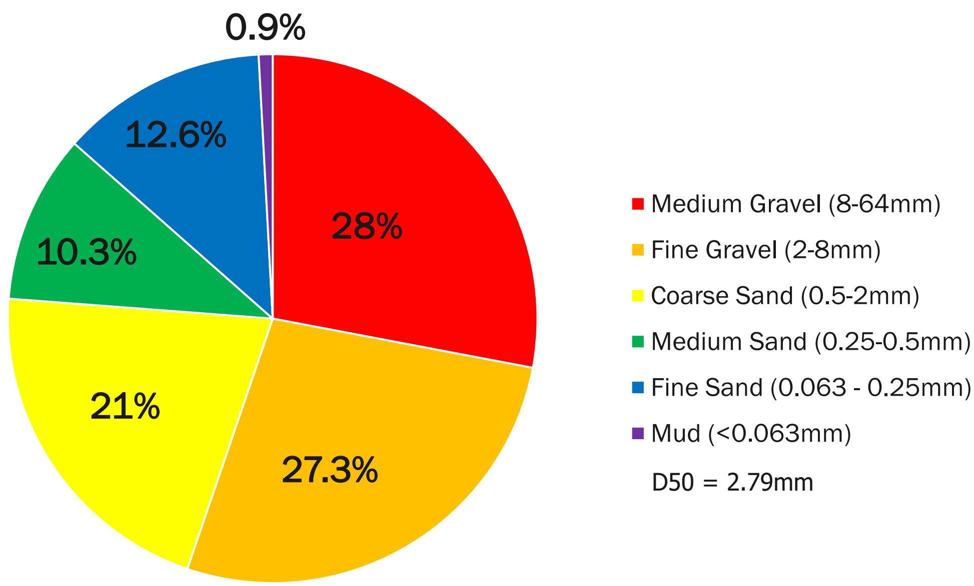


Figure 5. Grain size composition of a representative sample from channel pit CP1.

A



B

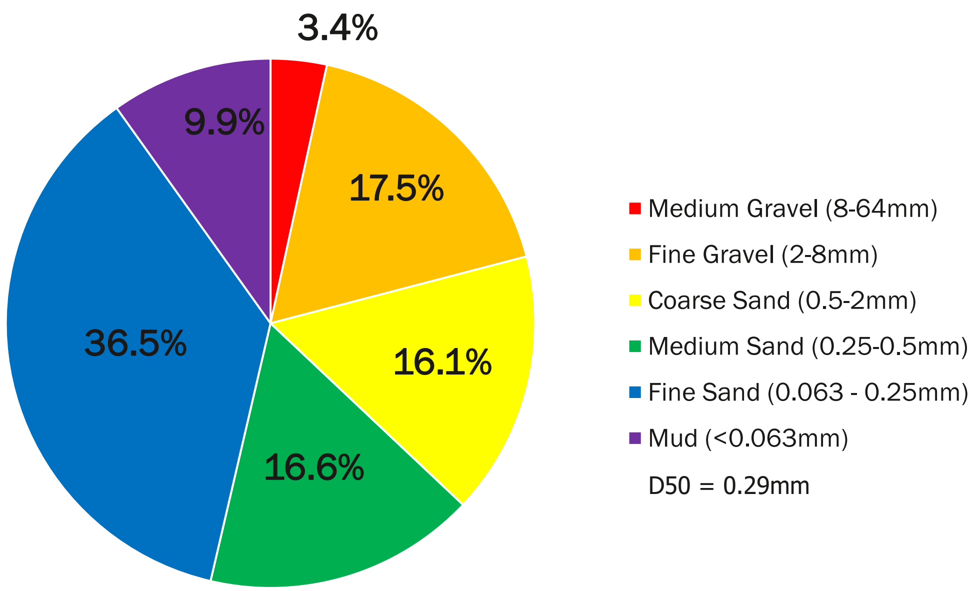


Figure 6. Grain size composition of representative samples from channel pit CP2 top (A) and CP2 bottom (B).

Appendices

Appendix 1. Bar Pit BP1 bucket contents.

BORE LOG

Site: Greenwood Beach
Location:
Sample/Pit ID: BP1

Date: 2/21/24
Driller: Paige Fernandez
Purpose: Fluvial Transport Buckets.

	Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
Surface	0.65 ↓		Sand, Pebbles, small shells. very few smaller gravel no gravel piled up on top	GW-BP1	
	0.25 ↓ 0.24		Thin layer of leaf debris		
	↓		Same as top layer		
Bottom of Bucket	0				

Appendix 2. Bar Pit BP1 bore log.

Appendix 3. Bar Pit BP2 bucket contents.

BORE LOG

Site: Greenwood Beach
Location:
Sample/Pit ID: BP2

Date: 2/21/24
Driller: Paige Fernandez
Purpose: Fluvial transport study

	Depth BGS Unit:	Symbol	Description	Sample ID	Analysis
Surface	0.62				
	↓		homogenous. Sand, small shells, pebbles + few gravels. little vegetation. ~~Some vegetation~~	GW-BP2	
Bottom of Bucket	0				

Appendix 4. Bar Pit BP2 bore log.

Appendix 5. Channel Pit CP1 bucket contents.

BORE LOG

Site: Greenwood Beach
Location:
Sample/Pit ID: CP1

Date: 2/21/24
Driller: Paige Fernandez
Purpose: Fluvial Transport Buckets.

Depth BGS Unit: ft.	Symbol	Description	Sample ID	Analysis
surface 0.8		Some gravel deposited on surface.		
↓		fairly homogenous small shell, sand, small pebbles. Some mud. ~~vegetation debris.~~ few gravel.	GW-CP1	
0.4				
↓		lots of vegetation debris. mud, bad smell. few gravel.		
bottom of Bucket. 0				

Appendix 6. Channel Pit CP1 bore log.

Appendix 7. Channel Pit CP2 bucket contents.

BORE LOG

Site: Greenwood Beach
Location:
Sample/Pit ID: CP2

Date: 2/21/24
Driller: Paige Fernandez
Purpose: Fluvial transport Buckets.

	Depth BGS Unit: ft	Symbol	Description	Sample ID	Analysis
Surface	0.7 ↓		sand, small shells, mixed size pebbles + gravel.	GW-CP2-1	
	0.6 ↓		Vegetation + mud. bad smell. 2 pieces of trash.		
	0.15 ↓		thick mud. Some veg but very little.	GW-CP2-2	
Bottom of Bucket	0				

Appendix 8. Channel Pit CP2 bore log.

Appendix H. Richardson Bay Wave Study Memorandum

WAVES ON BEACHES IN RICHARDSON BAY (MARIN COUNTY)

John Largier, Robin Roettger and Davis Kim
Coastal Oceanography Group
Bodega Marine Laboratory
University of California Davis

Summary

Wave measurements were obtained adjacent to beaches in Richardson Bay – and offshore at a mid-bay site unaffected by refraction and dissipation of waves over beach-adjacent shoals. Data were collected for a year to resolve seasonal differences as well as to identify wave events, when wave height and power significantly exceed modal conditions. We identify several events (5 in 2023) with wave heights exceeding ~0.2 m and wave power exceeding ~0.1 kW/m at study beaches. The dominant waves at Greenwood and Aramburu Beaches are high-frequency waves generated by local winds blowing over the waters in San Francisco Bay. Specifically southerly winds in winter are the strongest and benefit from the longest fetch to produce the biggest waves, which may exceed 0.3 m at the beaches. Westerlies in spring and summer are also important, with regular daily winds accounting for repeated afternoon wave events with wave heights of order ~0.1 m. Low-frequency ocean-generated swell is insignificant at these sites.

Introduction

Like many other major coastal cities (e.g., New York, Sydney, London, Shanghai), the metropolis surrounding San Francisco Bay is built around sheltered waters. The beaches in these estuaries and bays are often small and isolated – while not as iconic as open-ocean beaches in popular culture, they are valuable in supporting important ecosystem services in addition to recreational and economic benefits (Vila-Concejo et al., 2020). Specifically, beaches in estuaries and bays (BEBs) provide habitat and feeding areas for fish and birds, and protective buffers for wetlands and coastal development. Beach building processes are more complex in estuaries and bays owing to the important roles of river inflow and tidal currents in addition to wave forcing. While waves remain the essential factor in beach formation (i.e., deposits of sand above high-tide water levels), the wave field is not well documented in most bays and estuaries. This limits our ability to account for extant landforms and to forecast shoreline changes due to sea-level rise and/or local human-driven change including watershed management, shoreline development and offshore dredging. Depending on oceanographic conditions and the form of the bay, the dominant waves on BEBs may be locally wind-generated waves or they may propagate into the estuary/bay from open waters offshore of the mouth (i.e., swell). In addition to variations in wave height, there is considerable variation in wave frequency and orientation, interaction of waves with tidal currents, and local dissipation of wave energy over proximal tidal flats. Recent papers on waves in bays and estuaries include San Francisco Bay (Talke & Stacey 2003; Hanes &

Erikson 2013), Botany Bay (Rahbani et al 2022), and Tomales Bay (Winkler-Prins et al 2023), as well as a global review (Vila-Concejo et al 2024).

This study is focused on waves along the shorelines of Richardson Bay in Marin County, an embayment within the larger San Francisco Bay (Figure 1). In 2023, wave data were collected at Aramburu Beach and Greenwood Beach, sites of past and pending restoration. Wave data were also collected in the middle of the embayment to quantify wave energy offshore, without the influence of refraction and dissipation due to shoals adjacent to the beaches. These data are compared with data collected at an offshore buoy outside San Francisco Bay and data from a site off Marina Bay Beach in Richmond. The study period included several winter storm events, during which the biggest waves are observed.

The dominant waves at Greenwood and Aramburu Beaches are high-frequency waves generated by local winds blowing over the waters in San Francisco Bay. Low-frequency ocean-generated swell was insignificant at these sites and these waves are not considered important for beach processes in Richardson Bay. While the period of high-energy waves was always short (2-4 seconds), wave height and direction varied with local wind conditions. Three wave-generating wind states were identified: (i) NW winds that blow in from the ocean north of Mount Tamalpais during the spring-summer upwelling season, (ii) SW winds that blow over coastal hills south of Mount Tamalpais during the spring-summer upwelling season, and (iii) S and SE winds that blow up from Central Bay during the passage of winter storms. Due to the strength of the southerly winds and the longer fetch at this orientation, the biggest waves at Greenwood and Aramburu beaches are observed during these winter storms. Nevertheless, westerly winds in spring and summer can also produce significant waves, often with a marked day-night cycle that follows the strength of the sea-breeze wind cycle.

Approach and Methods

Study Site

Marin County includes the shorelines from Golden Gate Bridge to Petaluma River as well as shorelines along the open coast from Golden Gate Bridge to the mouth of the Estero Americano Estuary – including sheltered shorelines in Bolinas Lagoon and Tomales Bay. Attention here is on the waves within Richardson Bay and their impact on beaches along the north shore of the Bay. This area is exposed to strong S winds in winter and partially exposed to the strong NW winds that blow over the ocean in spring and summer. However, the spring/summer ocean winds can reach the Bay as NW winds blowing in from the Hwy-101 corridor, or as SW winds blowing over Marin Headlands while the sea breeze blows in through Golden Gate.

The study beaches are at the head of Richardson Bay, a sub-embayment of San Francisco Bay. The region experiences a Mediterranean climate with mild, wet winters and warm, dry summers. Following rain events, freshwater drains from the east slope of the Mount Tamalpais into Richardson Bay. Larger inflows of freshwater to San Francisco Bay from the Sacramento and San Joachin Rivers enter through Suisun Bay, far upstream of Richardson Bay. Richardson Bay is approximately 5 km long and 2 km wide at the mouth between the cities of Sausalito and Tiburon. The mouth of the bay opens southward towards the city of San Francisco, which lies 5km south across Central Bay. To the west, hills separate the bay from the open coast and to the east the Tiburon Peninsula separates the bay from the San Pablo Bay. Small-boat marinas line the western shore around Sausalito while tidal marshes and low-lying land is found along the northern shores of the Bay (where Greenwood and Aramburu Beaches are located).

Figure 1: Richardson Bay with Sausalito waterfront in lower left and Tiburon Peninsula in upper right. The white arrow indicates the orientation of winds with longest fetch (157.5°N). The red dots show the locations where sensors were installed (details in text and Table 1): Greenwood Beach (GRWB), Aramburu Beach (ARAM), sensor piling maintained by the National Estuarine Research Reserve (NERR), and Wave buoy (SOFAR Buoy). Also shown is a weather station (Onerain) and a short-term sensor deployed during a winter storm higher on Greenwood Beach (GRWB Bonus).

Mixed semi-diurnal tides in San Francisco Bay are typical of the west coast of the North America (Townsend, 2012). Water level data at Sausalito (Station 9614806) were collected by NOAA from February 1977 to November 1979 to provide tidal predictions for Richardson Bay. During the years of observations, the mean higher-high water level was 1.735m and the highest observed water level was 2.526m (9 January 1978), relative to the common datum of mean lower-low water level (MLLW; +0.17m NAVD88). Mean sea level was 0.935m above MLLW and the lowest observed water level was -0.827m (5 May 1977). The mean sea level in San Francisco Bay has risen at an average rate of 0.002m per year through the 20th century and is expected to rise faster in the 21st century. Models predict that sea level will rise between 0.3 and 2.0 meters by the end of the 21st century (i.e., 0.003 to 0.02m per year; Adusumilli et al., 2024). As much of the developed shoreline of the Bay lies close to high-tide water levels, flooding is expected to become worse with sea-level rise.

Sediment samples from Greenwood Beach show that the beach is composed of grain sizes between fine sand and fine gravel (0.063mm – 8mm). The degree of sorting varied across the beach, with samples ranging from poorly sorted to well sorted.

<u>Field Data</u>

Wave data were collected with 2Hz RBR*solo*^{3} pressure sensors deployed at shallow-water sites adjacent to the beaches of interest (Figure 1; Table 1). Wave data were also collected mid-bay by deploying a RBR*solo*^{3} pressure sensor on the NERR piling, and later through deploying a SOFAR wave buoy at the same mid-bay location (Figure 1). Most data were collected in 2023, but some data series started in November 2022 and other data series continued through January 2024. Deployment sites were selected in consultation with the County of Marin to characterize wave conditions in support of beach restoration projects.

Table 1: Sensor location data

Sensor Site	**Longitude**	**Latitude**	**Elevation** *(m NAVD88)*
Aramburu Beach	-122.499945	37.889680	0.57325
Greenwood Beach	-122.489571	37.893991	-0.50650
Greenwood Beach Bonus	-122.489617	37.893973	0.35600
NERR Piling	-122.487540	37.876692	0.356
SOFAR Buoy	-122.480800	37.874983	N/A

RBR*solo*^{3} pressure sensors were deployed for 1-2 months between field servicing. These sensors were secured to fixed structures on the mudflats adjacent to the beaches and on a piling maintained by the National Estuarine Research Reserve (NERR) in the middle of Richardson Bay. The precise elevation and position of each sensor was determined with a real-time kinematics (RTK) GPS (Table 1).

The RBR*solo*^{3} pressure sensor on the NERR piling was replaced by a SOFAR Spotter Buoy in March 2023 (Table 2). The buoy provided data on wave direction in addition to significant wave height and wave period that were obtained from the RBR*solo*^{3} pressure sensor. In addition, the

SOFAR Spotter Buoy provides estimates of wind speed and direction calculated from the wave data (however, the reliability of these wind estimates is not well documented for shallow/sheltered waters).

Table 2: Data availability for project sites

Sensor Site	Data Availability
Aramburu Beach	1/20/23-5/21/23 and 8/18/23-1/26/24
Greenwood Beach	11/23/22-10/14/23 and 10/26/23-12/11/23
Greenwood Beach Bonus	3/9/23-3/17/23
NERR Piling	12/20/22-1/21/23
SOFAR Buoy	3/1/23-1/26/24

Additional data are available from a prior deployment off Marina Bay Beach from April to June 2022 (Accordino 2023). In addition, a RBR*solo*[3] pressure sensor was deployed off the beach at Crissy Field in late 2023, but it was lost when buried by an unprecedented accretion of sand at the beach in early 2024.

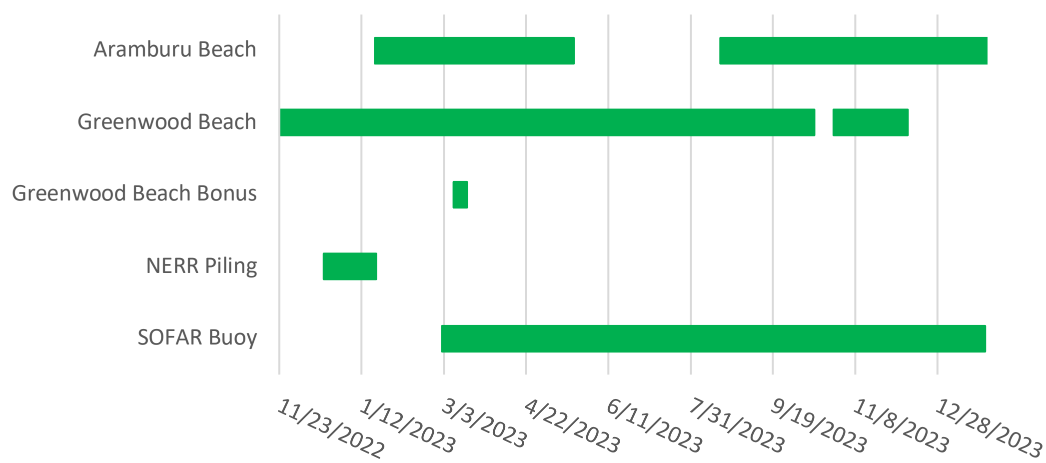


Figure 2: Graphic representation of data availability at each site.

<u>Additional Field Data</u>

In addition to in-water sensor data, atmospheric pressure data were obtained from the NOAA National Data Buoy Center (NDBC) station at Fort Point in San Francisco. These data are used to quantify fluctuations in sub-surface pressure data recorded on the RBR*solo*[3] sensors that are due to fluctuations in atmospheric pressure. Following Winkler-Prins et al (2023), this correction allows the RBR sub-surface pressure to be used as a precise and reliable measure of water surface elevation.

Wind data were downloaded from the OneRain station in Tiburon (Figure 1). Additional insight to wind conditions were obtained from the SOFAR Spotter buoy product and consumer products (e.g., Windy app).

Tidal fluctuations in water level were observed at NOAA stations at Fort Point, Alameda and Richmond in addition to observations from the RBR*solo*[3] pressure sensors.

Offshore wave data are available from buoys maintained by the Coastal Data Information Program (CDIP), specifically Buoy 142 on San Francisco Bay bar and Buoy 029 on the shelf edge west of Point Reyes (URL: *http://cdip.ucsd.edu*).

<u>Wave Data Analysis</u>

Water surface elevation data at 2Hz were obtained from the RBR*solo*[3] pressure data corrected for fluctuations in atmospheric pressure. These data were reduced to hourly water level and wave data through aggregation: hourly water level is given by the mean, and hourly wave height is determined as four times the standard deviation following the NDBC Nondirectional and Directional Wave Data Analysis Procedures (Earle, 2003). Significant wave height H_s is given as:

$$H_s = 4 * \sigma \qquad \textbf{Eq.1}$$

Standard deviation σ is calculated from hourly data after removing a linear trend due to tidal change as follows:

$$\sigma = \sqrt{\frac{\sum(d_{RBR} - d_{LI})^2}{N}} \qquad \textbf{Eq.2}$$

where d_{RBR} is measured depth, d_{LI} is linearly interpolated depth data, N is the number of data points in the hour.

To assess any residual influence of the tidal change in water level on the hourly calculation of standard deviations (after removing an hourly linear trend, as described above), the standard deviation was calculated from a smooth tidal signal with no high-frequency variability. Values are between 0 and 0.008 m (Figure 3), which is smaller than observed wave heights in general and an order of magnitude smaller than waves during the high-energy events that are the focus of this study. For comparison, the hourly standard deviation values calculated from water level measurements that include high-frequency variability have values between 0.007 and 0.058 m (Figure 3). Thus, we estimate the error in wave height estimates due to residual tidal influences to be less than 0.01 m.

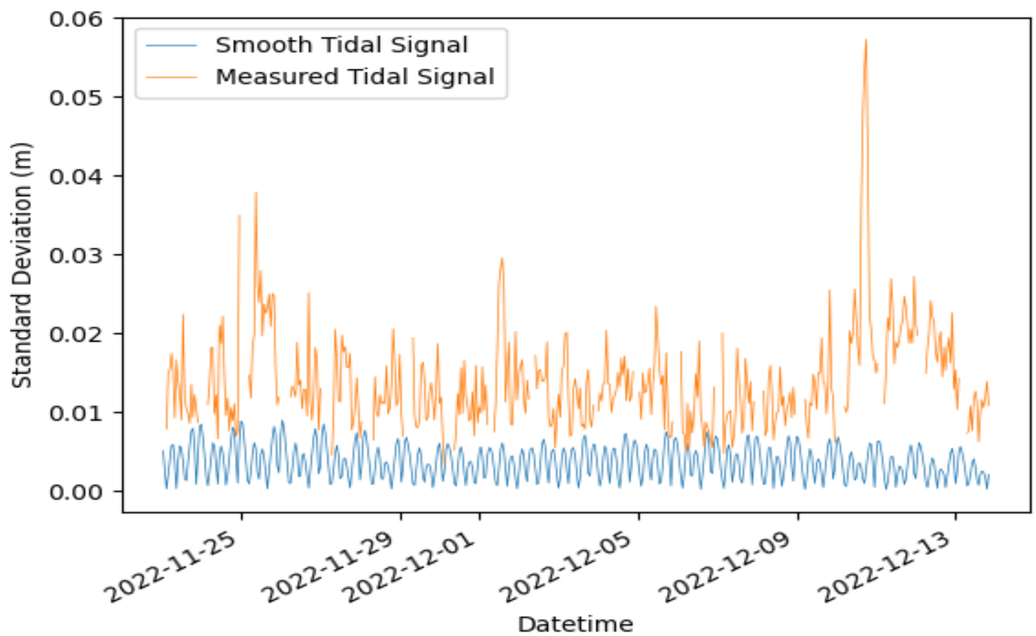


Figure 3: Hourly standard deviation in water level with hourly linear trend removed, calculated from a smooth tidal water level record (blue line) and from field-measured values that include high-frequency wave variability in water level (orange line). Data from Greenwood Beach.

At some sites wave measurements were not available at low tide as the pressure sensor was out of the water. Further, wave data calculated from the hourly standard deviation of pressure are not valid at times when the sensor was not persistently inundated for the entire hour. This includes periods when the sensor is in the swash zone, alternatively inundated and dry as waves run up the beach. To empirically assess when water level is too low, we plotted significant wave height against hourly average water depth at Greenwood Beach (Figure 4). Wave height values are clearly unreliable when water depths are less than 0.05 m and we thus use this as a cutoff to identify times of valid data (i.e., only treat wave heights as valid when water depth is more than 0.05 m).

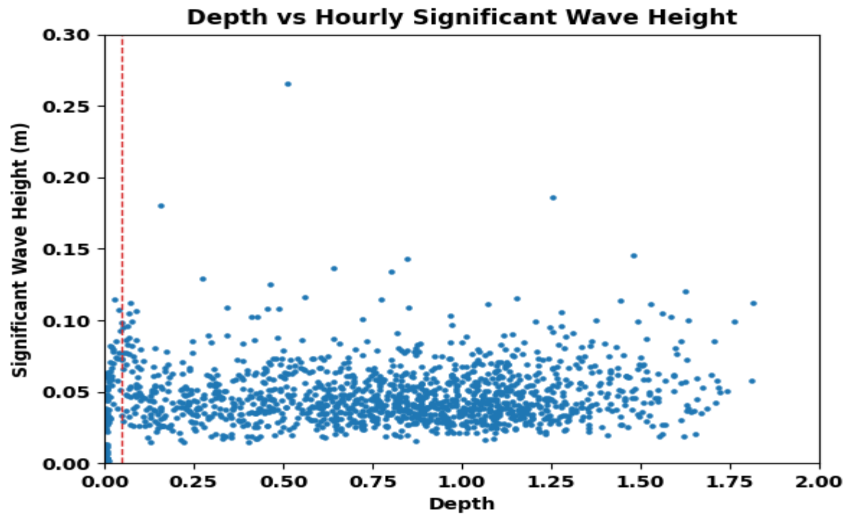


Figure 4: Hourly significant wave height versus hourly average water depth at Greenwood Beach (17 March to 21 May 2023). Red dashed line indicates a water depth of 0.05 m.

Wave data may also be affected when the tide is high, and the pressure sensor is deeply submerged. The pressure signal due to the rise and fall of the water surface decreases with depth below the surface (Townsend 2012) and this attenuation with depth is quicker for higher frequency waves. It decreases exponentially with depth e^{-kz} where k is the wavenumber and z is the water depth. For high frequency waves, k is larger, and the attenuation is quicker. Winkler-Prins et al (2023) take a spectral approach to correcting wave energy across the frequency spectrum. Here we do not apply any corrections but point out that the highest frequency waves (periods of ~2 s) will show a severely reduced signal at the highest tides (estimate 15% true value when sensor depth ~2 m) but typical strong-wind waves with periods of ~3-4 s will show less reduction in signal (~40-50% true value). More typically high-tide water depths are of order 1 m, and high-frequency wave height estimates are ~60-70% true value. This effect is worst at Greenwood Beach where the pressure sensor was at the lowest elevation (Table 1): it was 0.67 m below MLLW and thus at a depth of 2.4 m at MHHW. At Aramburu, the pressure sensor was higher: 0.4 m above MLLW and thus at a depth of 1.3 m at MHHW. Also, at the NERR piling the sensor at 0.19 above MLLW was at a depth of 1.5 m at MHHW. To track variations in wave height without making detailed tidal corrections, we focus attention on the largest waves each day (using maximum, median and 90th percentile hourly wave values). This effect is not seen in data from the SOFAR buoy that measures waves by tracking the rise and fall of a buoy on the water surface.

Wave energy is related to the square of the wave height and wave power (the rate at which energy is propagated and delivered to the beach) can be calculated at shallow water sites following Davidson-Arnott (2009):

$$P_{ws} = \frac{1}{8}\rho g H_s^2 \sqrt{g d_{RBR}} \qquad \textbf{Eq.3}$$

where ρ is water density, H_s^2 is the significant wave height, g is gravitational acceleration, and d_{RBR} is the water depth at the RBR sensor.

Field Data Results

<u>Overview</u>

We tracked wave heights for a year at Greenwood and Aramburu Beaches and a third mid-bay site. Seasonal differences are evident with bigger waves in winter (Figure 5). In winter, the H_s mode is between 0.06 and 0.07 m and several events occur with H_s exceeding 0.15 m. In summer, the H_s mode is between 0.04 and 0.05 m and waves rarely exceed 0.10 m.

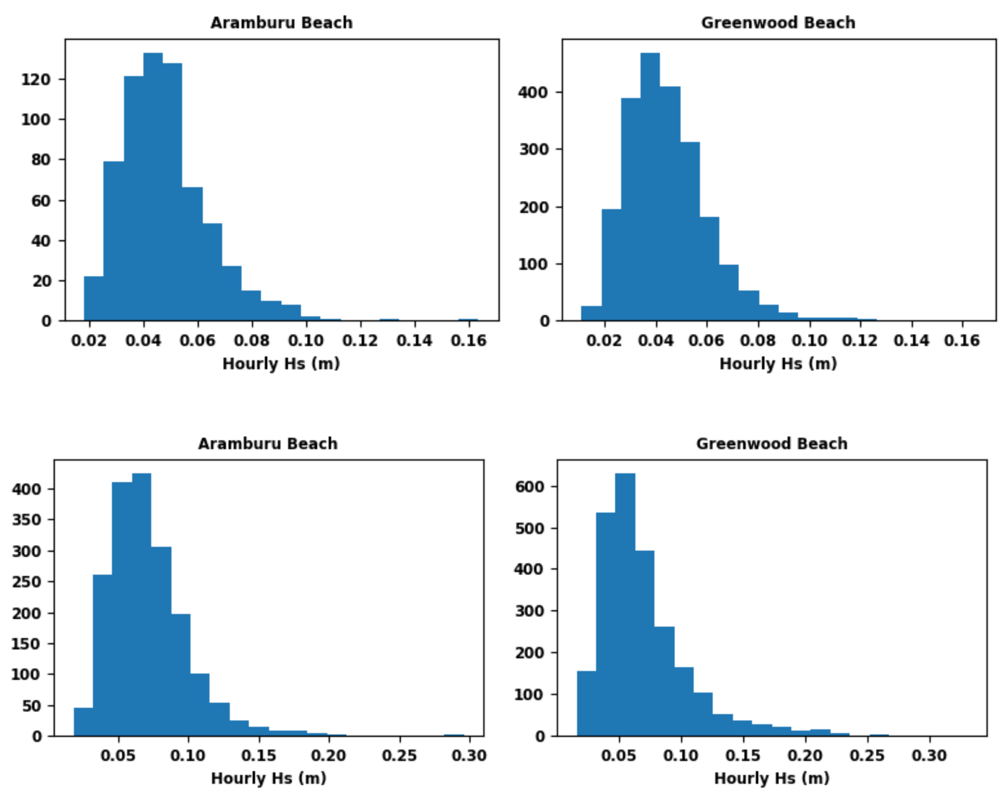


Figure 5: Distribution of wave heights observed at Aramburu and Greenwood Beach sites. Top panel for summer (May-August 2023) shows a mode between 0.04 and 0.05 m and few occurrences above 0.10 m. Bottom panel for winter (January-April 2023) shows a mode between 0.06 and 0.07 m and frequent events with wave heights greater than 0.15 m.

As outlined in Approach & Methods, we calculated water depth, wave height and wave power every hour (Figure 6). These data are plotted in parallel with local wind data, showing a strong association. Offshore ocean swell data are not included as we did not find a clear relation.

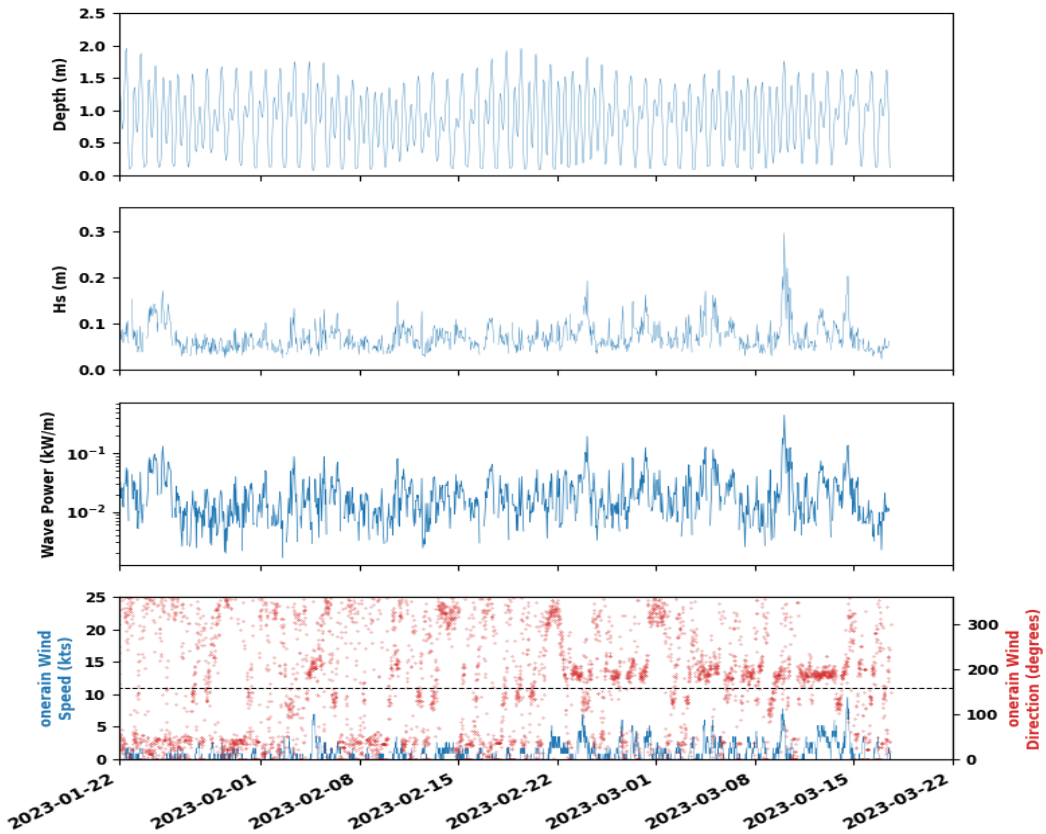


Figure 6: Hourly water depth and significant wave height at Greenwood Beach site from 22 January to 22 March 2023. Also shown are wave power (3rd panel; calculated from Equation 3) and wind speed and direction (4th panel; measured at OneRain site in Tiburon); the dashed black line in the bottom panel is the orientation of the longest fetch (157.5°; Figure 1).

During February and March 2023 at Greenwood Beach (Figure 6), water depth data show the pulsing of tides – both daily high and low tides and fortnightly spring and neap tides. Wave data show background/modal conditions (H_s ~ 0.05 m; P_{ws} ~ 10^{-2} kW/m) interrupted by several wave events that align with wind events. Most notable wind-wave events occur on 10 March (H_s ~ 0.25 m; P_{ws} ~ $50*10^{-2}$ kW/m; wind ~9 kts), 23 February (H_s ~ 0.20 m; P_{ws} ~ $20*10^{-2}$ kW/m; wind ~7 kts), and 14 March (H_s ~ 0.20 m; P_{ws} ~ $10*10^{-2}$ kW/m; wind ~10 kts). These are all southerly wind events. However, diurnal wind pulses and associated wave pulses are evident from 26 to 29 February and later in March – wave heights increase to 0.15 m daily at these times. Similar time series plots of all data are available in Appendix A, broken into 2-month segments.

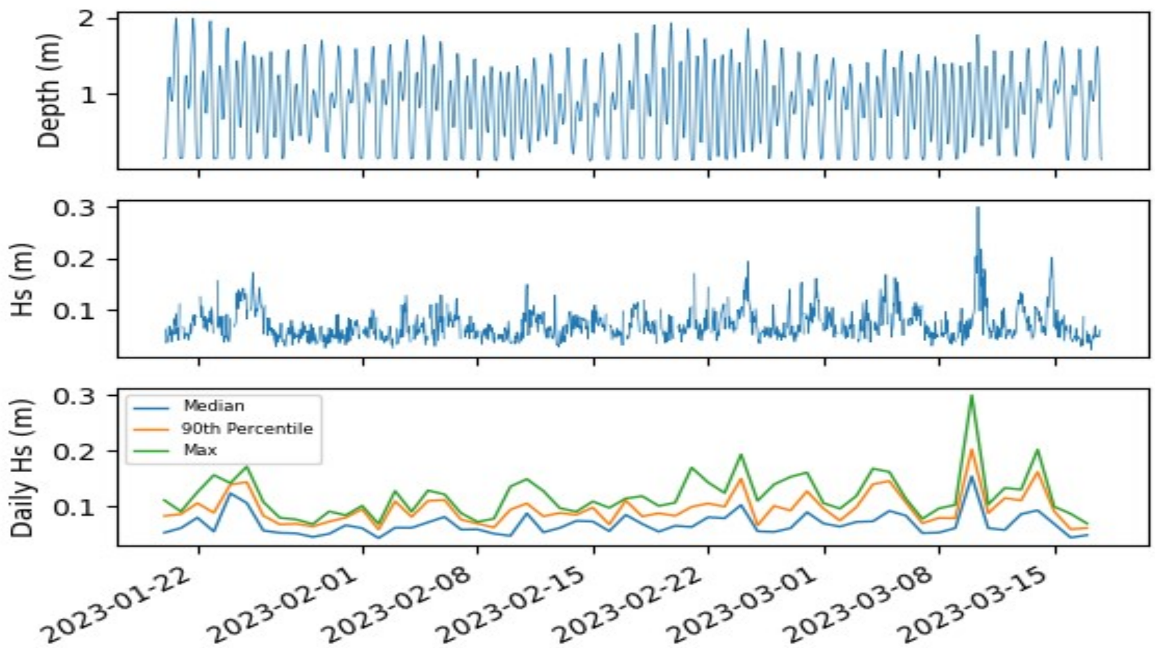


Figure 7: Hourly water level (top panel), hourly wave height (middle panel), and daily wave statistics (bottom panel) for Greenwood Beach from 20 January to 16 March 2023. In the bottom panel, daily maximum is green, daily 90-perecentile is orange, and daily median is blue.

Although not apparent in these time-series plots, there is a tidal variation in wave height consistent with the attenuation of the pressure signal at high tide when the pressure sensor is at a greater depth. While this tidal effect is weaker than wind-correlated variations in wave height, to preclude this artefact from further characterization of the wave field we focus attention on daily median, 90th-percentile and maximum values of the hourly wave height data (Figure 7). This allows us to compare waves across multiple field sites (e.g., Figure 8) and inspect the concurrence of wave events at Greenwood and Aramburu Beaches, which generally align with wave events observed at the mid-bay site. Similar time series plots are included in Appendix B.

Figure 8: Daily wave statistics for Aramburu Beach (top panel), Greenwood Beach (middle panel), and SOFAR Buoy (bottom panel) from 1 September to 31 December 2023. For each site, the daily maximum wave height is green, daily 90-perecentile wave height is orange, and daily median wave height is blue.

While the concurrence of wave events mid-bay and at the beaches is clear (Figure 8), typical values from the SOFAR buoy are larger than from the RBR pressure sensors. Modal wave height at the SOFAR buoy is 0.2 m and maximum wave heights are over 0.5 m – two to three times larger than values from beach sites and from the pressure sensor deployed on the NERR piling.

We will discuss this discrepancy further in the next section.

<u>Wave Events</u>

Monitoring waves over a full year allows insight to modal/background conditions and conditions during wave events, which are expected to be most important for beaches. Several events can be identified in the time series plots in Appendix B: 9 and 27 December 2022 (Figure B1), 4-14 January as well as 10, 14 and 21 March 2023 (Figure B3), 6 and 29 December 2023 (Figure B7), and 5 January 2024 (Figure B9). During each of these events, the daily maximum hourly wave height exceeds 0.20 m at Greenwood Beach and/or Aramburu Beach. These events are also apparent in time series plots in Appendix A, which show wind conditions. From these plots, it is apparent that these high-energy wave events deliver order 10^{-1}kW/m and align closely with southerly wind events with speeds of 5 knots or more. The importance of local wind forcing is corroborated by the dominance of short-period waves at the SOFAR buoy (dominant period of 3-4 s).

This association of energetic waves events with southerly winds is illustrated by looking more closely at data from Aramburu Beach during March 2023 (Figure 9). Strong southerly winds started around sunset on 9 March and persisted through the night, sustaining speeds of 7 knots for several hours over high tide. Wave H_s increased from ~0.1 to ~0.3 m shortly after midnight, corresponding to a 30-fold increase in wave power from ~0.01 to ~0.3 kW/m.

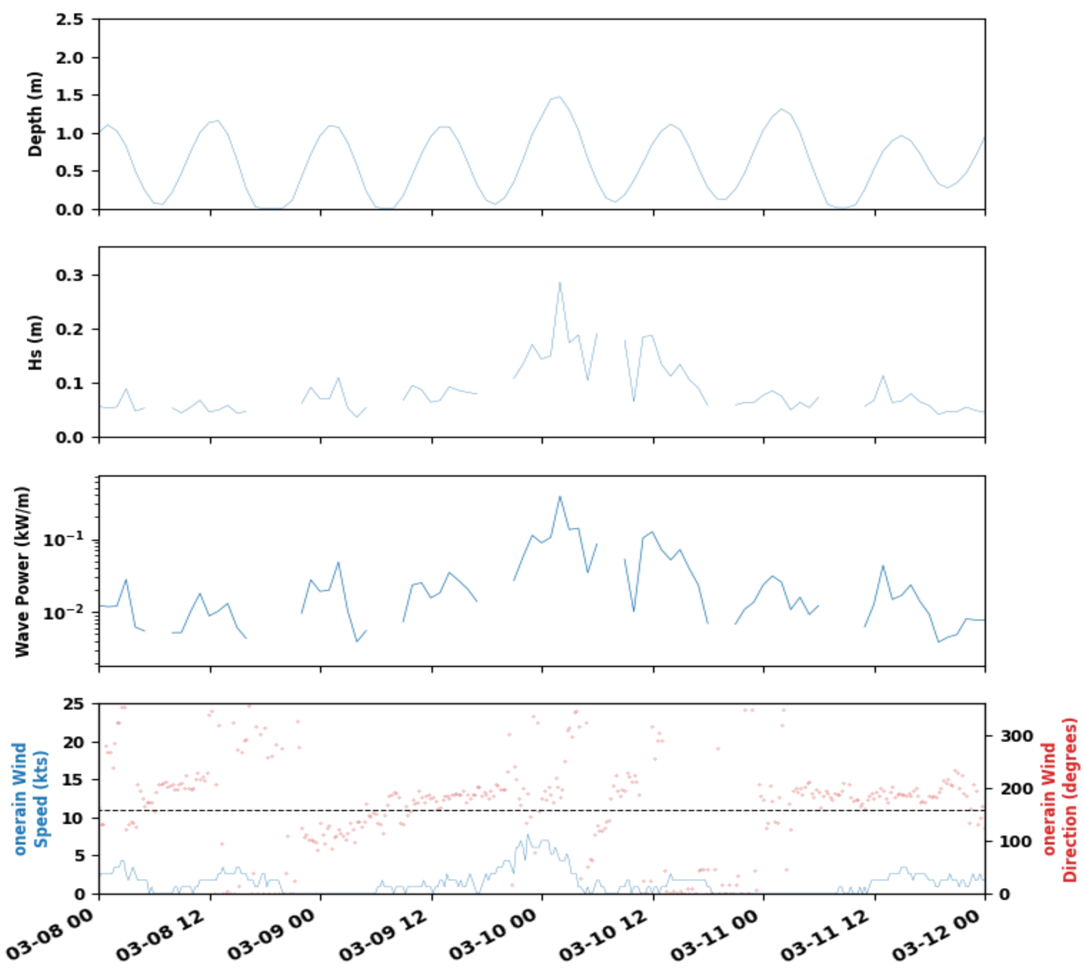


Figure 6: Hourly water depth (top panel), significant wave height (2nd panel) and wave power (3rd panel) at Aramburu Beach site for 8-11 March 2023. The bottom panel shows wind speed (blue line) and direction (red symbols), observed at the OneRain site; the black dashed line indicates the orientation of the longest fetch (157.5°; Figure 1).

Discussion

A full year of data at Greenwood Beach and Aramburu Beach in northern Richardson Bay provides a comprehensive view of wave energy. The most energetic waves occur during southerly winds in winter, accounting for significant wave heights that exceed 0.2 m and wave power that exceeds 0.1 kW/m several times a year. Some wave events persist for days (e.g., 4 to 14 January 2023) while others may only last an hour (e.g., 10 March 2023). Modal conditions are much less energetic with typical wave heights less than 0.05 m in summer only slightly bigger in winter (0.06 to 0.07 m). While there appear to be weak signals from ocean swell and infra-gravity waves, the peaks in these low-frequency signals are generally concurrent with and dominated by peaks in high-frequency waves generated by local winds. In summer as well, waves in Richardson Bay are dominated by local wind-generated waves. However, winds are from the west, weaker and short-lived. The prevailing winds offshore are northwesterlies and, when the marine atmospheric boundary layer is thick enough, they can crest the coastal hills and blow across Richardson Bay from the NW or the SW, apparent in the direction of waves observed at the SOFAR buoy. Often there is a marked diurnal cycle with stronger winds in the afternoon and associated increase in waves to ~0.06 m daily (e.g., Figure A9).

Similar dominance by high-frequency waves has been reported by Winkler-Prins et al (2023) for sites in Tomales Bay. Short-fetch, wind-generated waves exhibit periods of less than 4 seconds (typically 2-3 s but reaching 4 s during strong wind forcing). Other studies in Richmond Inner Harbor along the eastern shore of San Francisco Bay find similar wave conditions: Talke & Stacey (2003) and Accordino (2023). Winkler-Prins et al (2023) explored tidal signals in observed waves, highlighting four notable phenomena. Firstly, as noted previously (Jackson et al 2002; Vila-Concejo et al 2020), tidal fluctuations in water level alter the height and thus location on the beach where the wave energy is dissipated. Secondly, in the presence of low-tide mudflats off beaches in bays and estuaries, at low tide wave energy is fully dissipated before reaching the beach but at high tide wave energy is little dissipated. Thirdly, in the presence of extensive intertidal flats/shoals, the effective fetch is reduced at low tide, which in turn reduces the height and period of waves generated in the bay. Finally, the signal obtained by bottom-mounted pressure sensors is influenced by tidal height, precluding study of the highest frequency waves and requiring post-field data correction to account for attenuation of the pressure signal (as discussed above in the Approach and Methods section).

Of interest in Richardson Bay is the effect of waves on beaches. While we report wave power (i.e., the rate of delivery of wave energy to the beach), to understand the work done by these waves it is best to quantify the dissipation of energy between two sites across a beach. As waves shoal, they will slow down and amplify (increased energy density), following Dean & Dalrymple (1991): $A_2 = A_1 * sqrt(c_{g1}/c_{g2})$ where A is wave amplitude and c_g is the wave celerity at two sites. This appears to be the case during the brief deployment of two sensors at Greenwood Beach during the 10 March wave events (Figure A14). But shoaling waves will also lose energy through bed drag and viscous/turbulent effects in shallow water. It is this energy lost from the wave that does work on the sediment, potentially eroding/transporting or depositing sediment. Waves may thus grow in height as they shoal, dissipating most of their energy at the shoreline or they may dissipate more energy over the shoals and have little effect on the shoreline.

During this study we deployed a wave sensor offshore, in the middle of Richardson Bay, to obtain data on incident wave energy before it is refracted of dissipated by shoals adjacent to the beaches. Initially we deployed an RBR pressure sensor on a fixed piling at a similar depth to the sensor at Aramburu Beach and observed comparable H_s values during the wave events on 27 December 2023 and 4-14 January. Further, H_s distributions are similar at both sites (Figure B4), with a mode around 0.07 m for January 2023. However, wave height data provided by proprietary software for the SOFAR buoy appears to be a factor of 2 greater, e.g., the Aramburu mode ~0.06 m in September-December is similar to January but the SOFAR mode is ~0.15 m (Figure B8), which is 2½ times greater. A similar contrast is seen for data from January 2024 (Figure B10). By comparing maximum daily wave heights in specific events, it appears that the buoy yields H_s values that are 3 times that observed at the beach sites. This difference may be partly explained by the attenuation of the pressure signal with depth, by comparing daily maximum values that artefact should be avoided. Alternatively, the difference may be due to dissipation of wave energy between the buoy and the beach. However, given the difference between RBR data and buoy data at the same site, there also appears to be an important difference in the methods for obtaining H_s values.

While this discrepancy between buoy and pressure-sensor data prevents calculation of energy dissipation, it does not take away from the clear concurrence in wave events at all sites. Further, data from the SOFAR buoy allows more insight to wave period. Specifically, occasional low-frequency wave events are evident during calm (periods > 6 s and up to 20 s) with wave heights less than 0.1 m (corresponding to ~0.04 m equivalent at pressure sensors). Thus, comparable with Talke & Stacey (2003), it appears that some ocean swell does propagate into Richardson Bay, albeit very weak and unlikely to be important for beach processes. The insignificance of ocean swell in Richardson Bay is also supported by model studies (Hanes & Erikson, 2013) that show that less than 1% of ocean wave energy enters Richardson Bay, and then only for the optimal period and direction.

Wave data from the SOFAR buoy also shed light on the direction of waves in summer and spring, when westerly winds can generate significant waves in Richardson Bay with typical values of H_s ~ 0.25 m (~0.1 m equivalent at pressure sensors) and period 2-3 s. Two scenarios are observed: (i) waves with NW orientation associated with NW winds that blow in from the ocean north of Mount Tamalpais, and (ii) waves with SW orientation associated with SW winds that blow over low hills south of Mount Tamalpais.

The data reported from this field study provide a complete picture of waves in Richardson Bay, including seasonal variability. While these data allow assessment of the impact of waves on beaches in the Bay, a deeper understanding would require deployment of an array of sensors in place of a single sensor at a chosen beach site. By deploying multiple sensors along with sensors for fluid velocity and suspended sediment concentrations, a clearer view will emerge regarding specific places and times where wave energy is being dissipated and the consequent impact on sediment deposition, erosion and/or transport. In combination with more detailed field data, a computer model could provide insight to additional conditions prior to management decisions.

References

Accordino, M.F.M. (2023). *Studies on an Estuarine Beach: Short- and Long-term Morphological Change of Marina Bay Beach in San Francisco Bay*. MS Thesis, UC Davis, 117 pp.

Adusumilli, S., Barnard, P., Cayan, D., Engeman, L., Griggs, G., Hamlington, B., Hill, K., Landerer, F., Thompson, P. (2024). *California Sea Level Rise Guidance: 2024 Science and Policy Update.* California Sea Level Rise Science Task Force, California Ocean Protection Council, California Ocean Science Trust.

Davidson-Arnott, R. (2009). *An Introduction to Coastal Processes and Geomorphology.* Cambridge University Press.

Earle, M.D. (2003). *Nondirectional and Directional Wave Data Analysis Procedures*. National Data Buoy Center. https://www.ndbc.noaa.gov/wavemeas.pdf.

Hanes, D.M., Erikson, L.H. (2013). The significance of ultra-refracted surface gravity waves on sheltered coasts, with application to San Francisco Bay. *Estuarine Coastal and Shelf Science*, 133:129-126.

Jackson, N.L., Nordstrom, K.F., Eliot, I., Masselink, G. (2002). 'Low energy' sandy beaches in marine and estuarine environments: A review. *Geomorphology*. 48 (1–3): 147–162.

Townsend, D.W. (2012). *Oceanography and Marine Biology: An Introduction to Marine Science*. Sinauer Associates, Inc.

Talke, S.A., Stacey, M.T. (2003). The influence of oceanic swell on flows over an estuarine intertidal mudflat in San Francisco Bay. *Estuarine, Coastal and Shelf Science*. 58 (3): 541–554.

Rahbani, M., Vila-Concejo, A., Fellowes, T.E., Gallop, S.L., Winkler-Prins, L., Largier, J.L. (2022). Spatial patterns in wave signatures on beaches in estuaries and bays. *Geomorphology*. 398: 108070.

Vila-Concejo, A., Gallop, S.L., Largier, J.L. (2020). Sandy beaches in estuaries and bays. In *Sandy Beach Morphodynamics*, ed. D.W.T. Jackson and A.D. Short, 343–362. Elsevier.

Vila-Concejo A., Fellowes T.E., Gallop S., Alejo I., Angnuureng D.B., Benavente J., Bosma J.W., Brempong E.K., Dissanayake P., Gazi M.Y., González-Villanueva R., Guimarães R., Kennedy D.M., Largier J.L., van der Lugt M.A., Montes J., Orescanin M., Pattiaratchi C.B., Cajueiro Carneiro Pereira L., Marinho da Costa Pereira R.L., Price T., Rahbani M., del Río L., Rosenthal M., de Schipper M., Ton A.M., WinklerPrins L. and Chen Z. (2024). Morphodynamics and management challenges for beaches in modified estuaries and bays. *Cambridge Prisms: Coastal Futures*, 2, e11, 1–10

Winkler-Prins, L., Largier, J.L., Vila-Concejo, A., Gallop, S.L., Fellowes, T.E., Rahbani, M. (2023). Components and Tidal Modulation of the Wave Field in a Semi-enclosed Shallow Bay. *Estuaries and Coasts, doi.org/10.1007/s12237-022-01154-x*

Appendix A1: Wave Data at Aramburu Beach

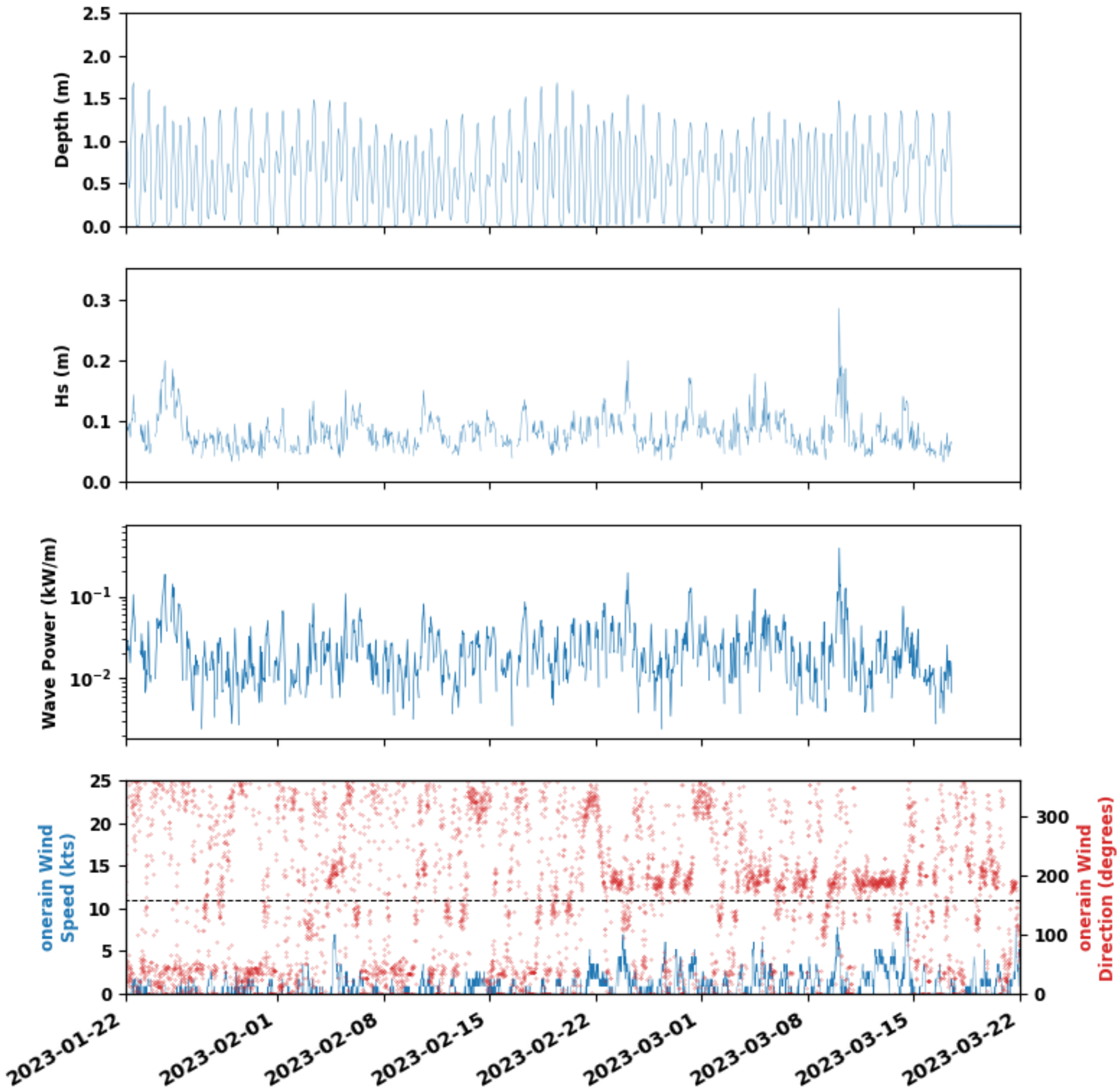


Figure A1a: Aramburu Beach data for 22 January to 22 March, 2023: Water depth, wave height, and wave power from RBR pressure data (top three panels); Wind speed and direction from OneRain site at Tiburon (bottom panel).

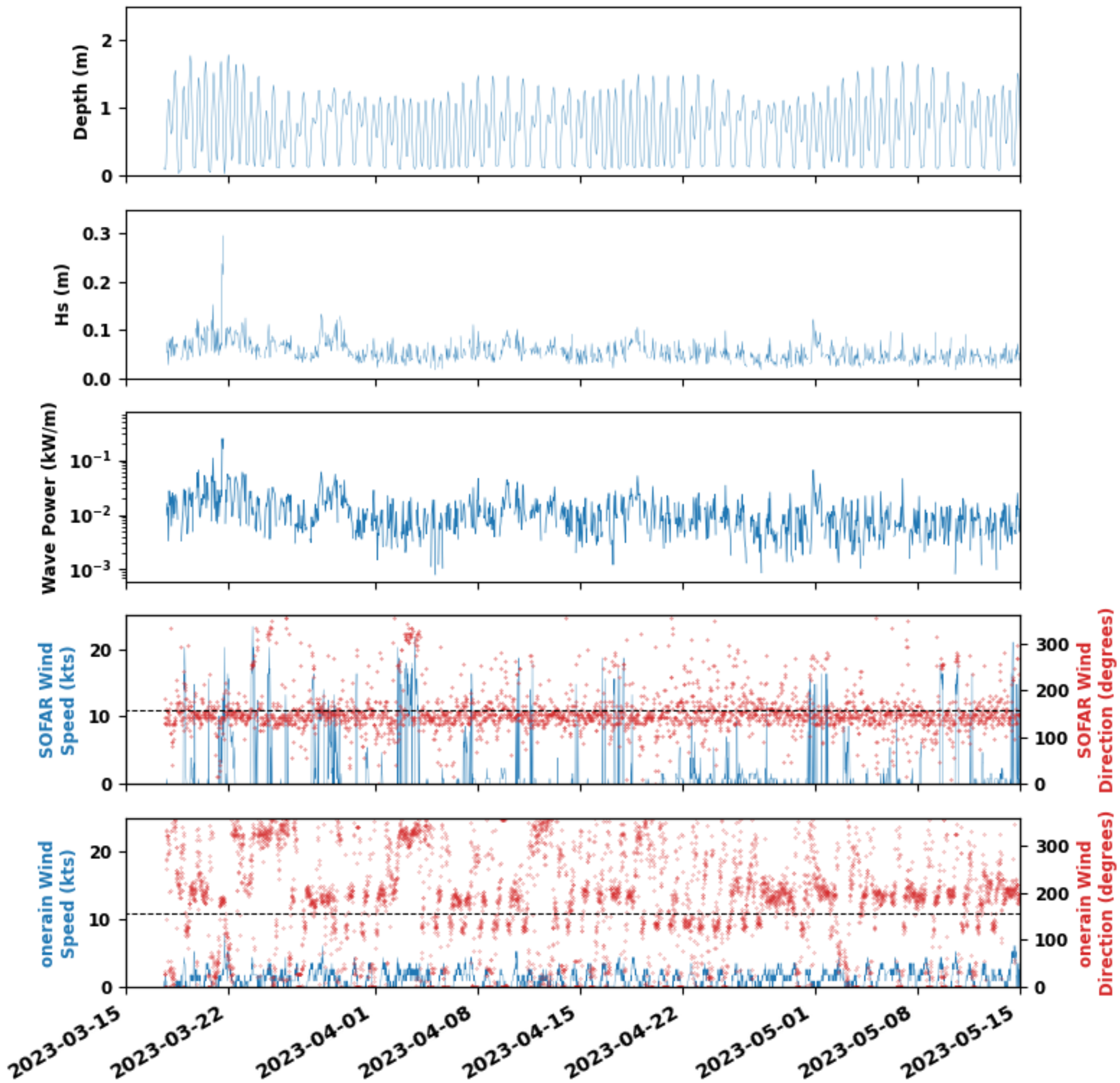


Figure A1b: Aramburu Beach data for 15 March to 15 May, 2023: Water depth, wave height, and wave power from RBR pressure data (top three panels); Wind speed and direction from OneRain site at Tiburon (bottom panel).

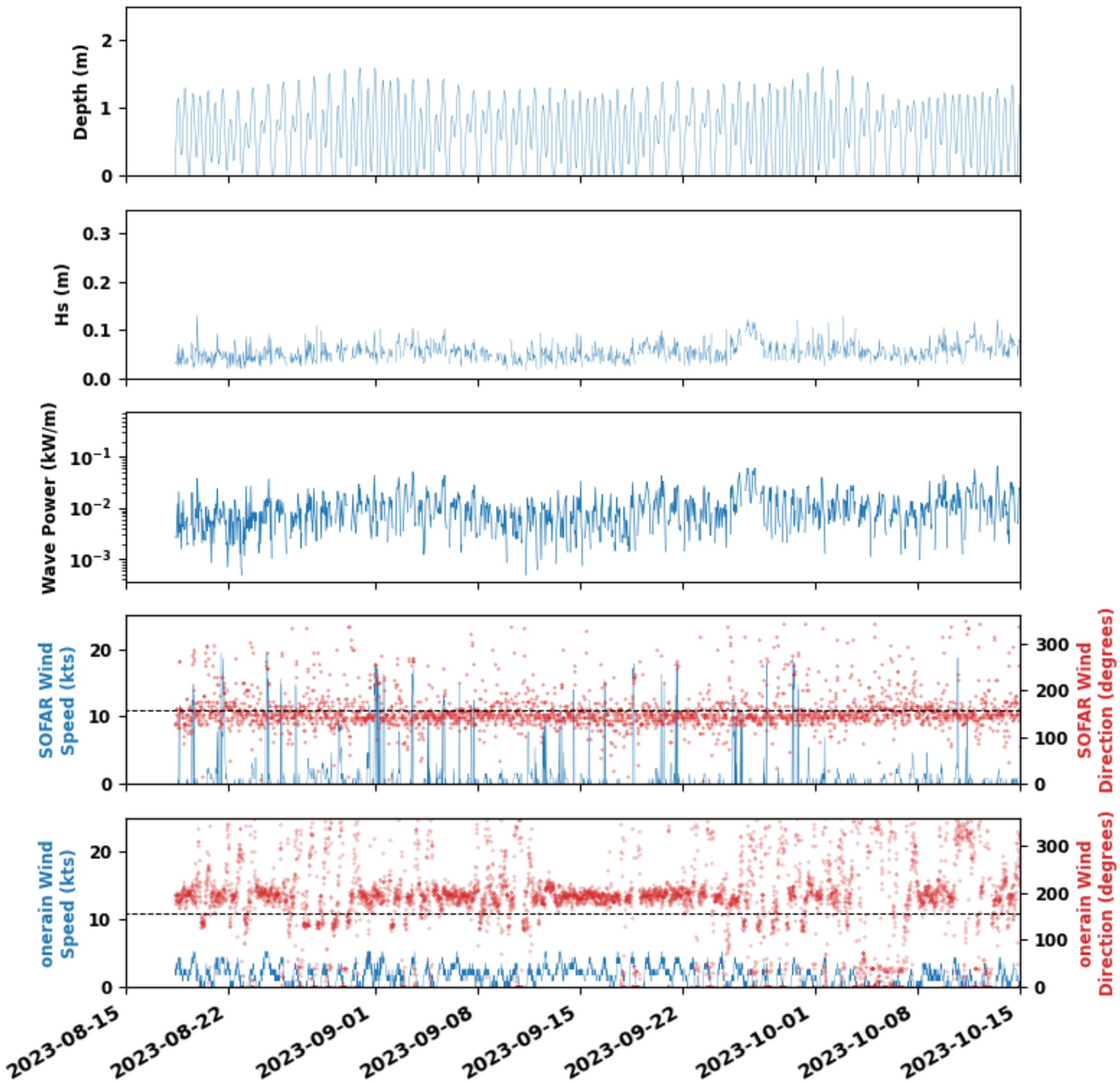


Figure A1c: Aramburu Beach data for 15 August to 15 October, 2023: Water depth, wave height, and wave power from RBR pressure data (top three panels); Wind speed and direction from OneRain site at Tiburon (bottom panel).

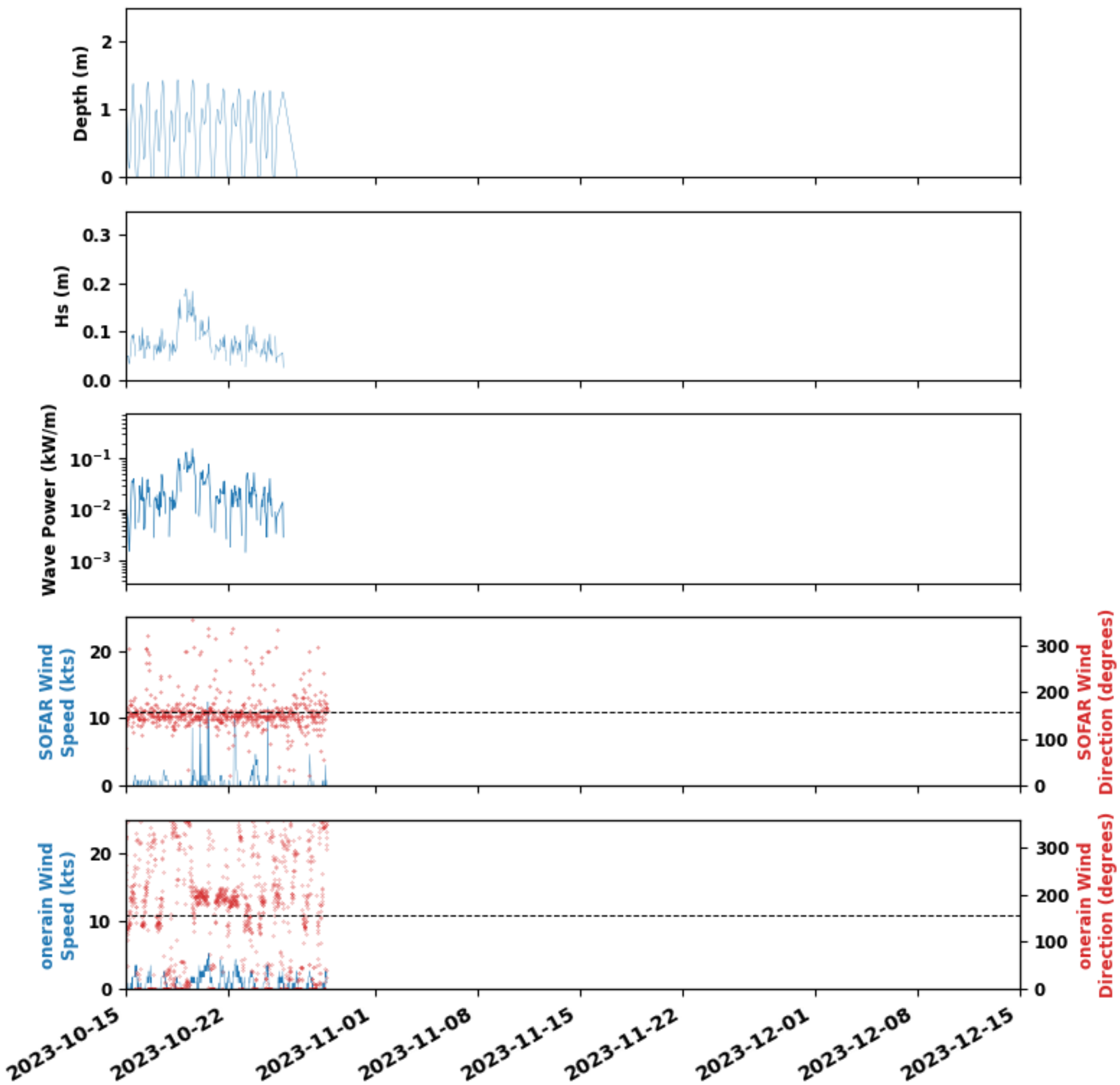


Figure A1d: Aramburu Beach data for 15 October to 15 December, 2023: Water depth, wave height, and wave power from RBR pressure data (top three panels); Wind speed and direction from OneRain site at Tiburon (bottom panel).

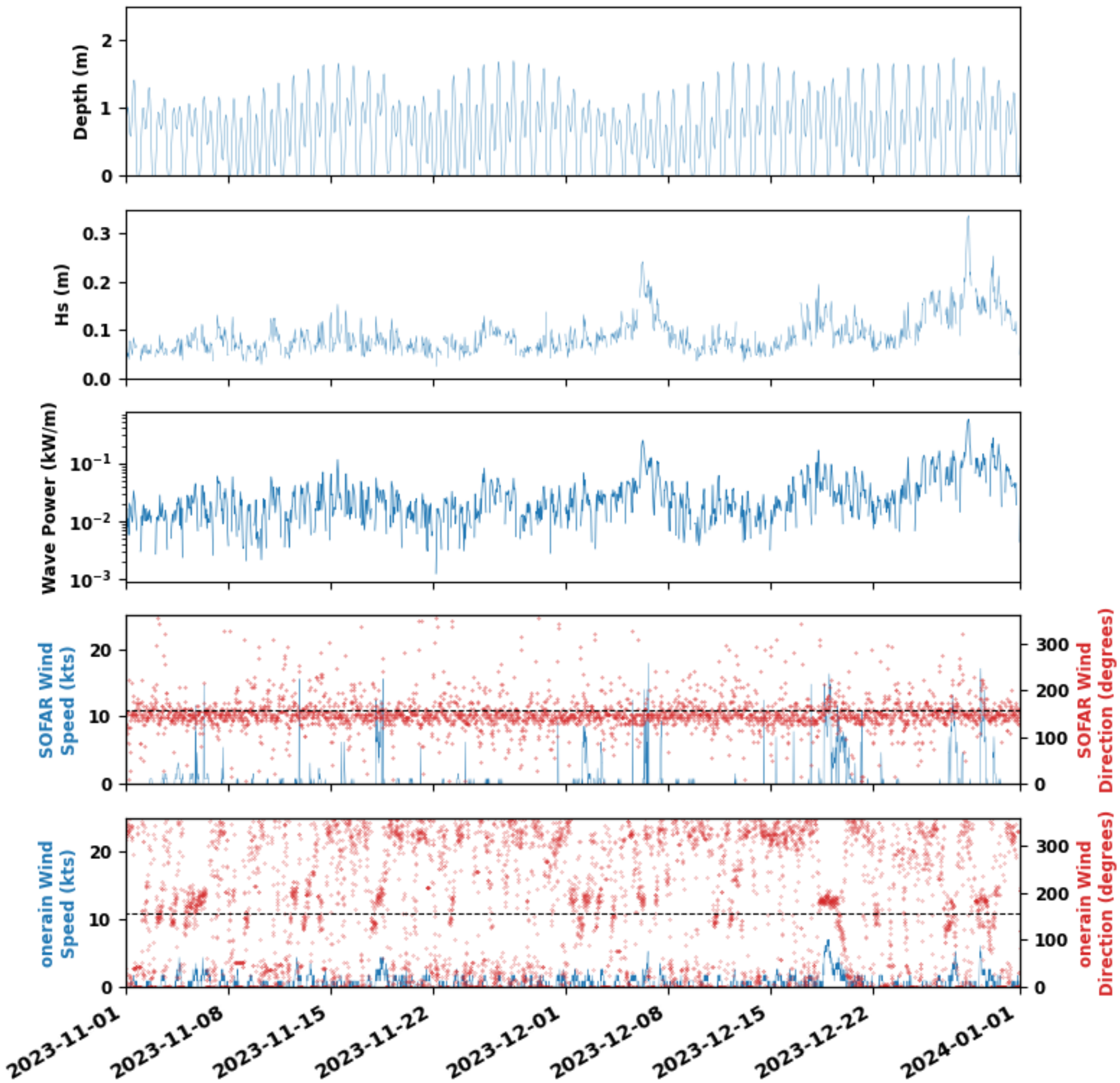


Figure A1e: Aramburu Beach data for 1 November 2023 to 1 January 2024: Water depth, wave height, and wave power from RBR pressure data (top three panels); Wind speed and direction from OneRain site at Tiburon (bottom panel).

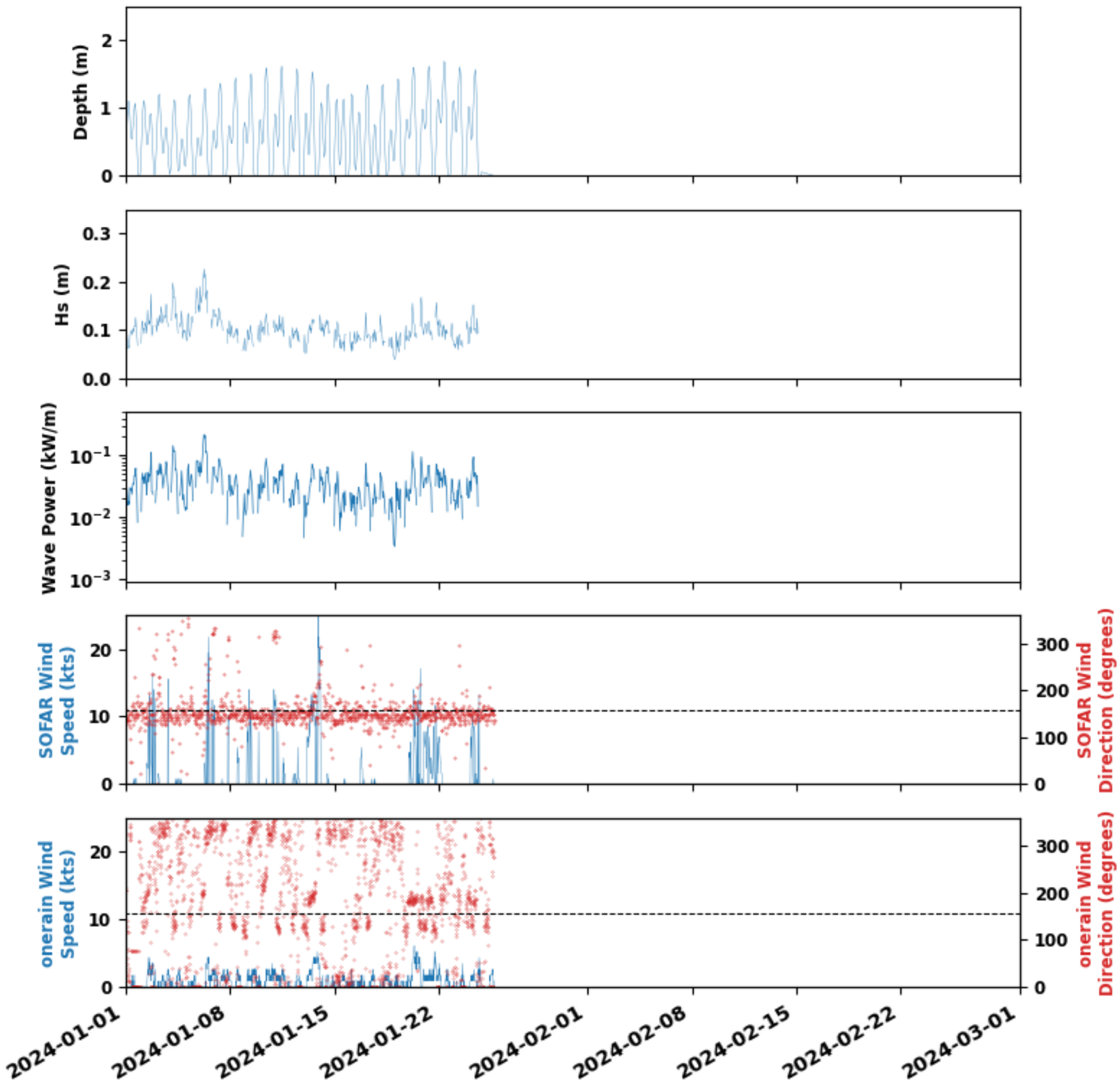


Figure A1f: Aramburu Beach data for 1 January to 1 March, 2024: Water depth, wave height, and wave power from RBR pressure data (top three panels); Wind speed and direction from OneRain site at Tiburon (bottom panel).

Appendix A2: Wave Data at Greenwood Beach

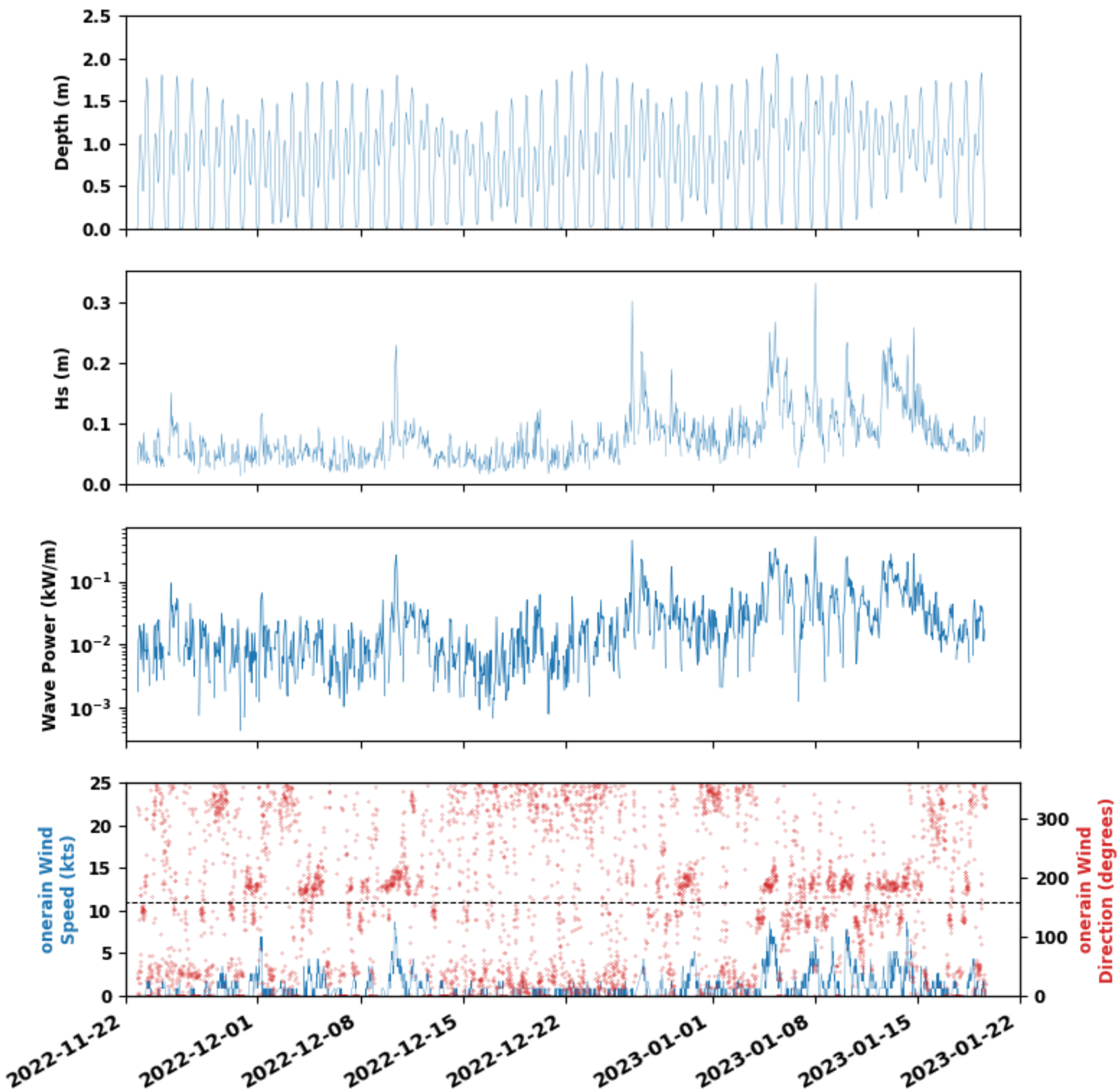


Figure A2a: Aramburu Beach data for 22 November 2022 to 22 January 2023: Water depth, wave height, and wave power from RBR pressure data (top three panels); Wind speed and direction from OneRain site at Tiburon (bottom panel).

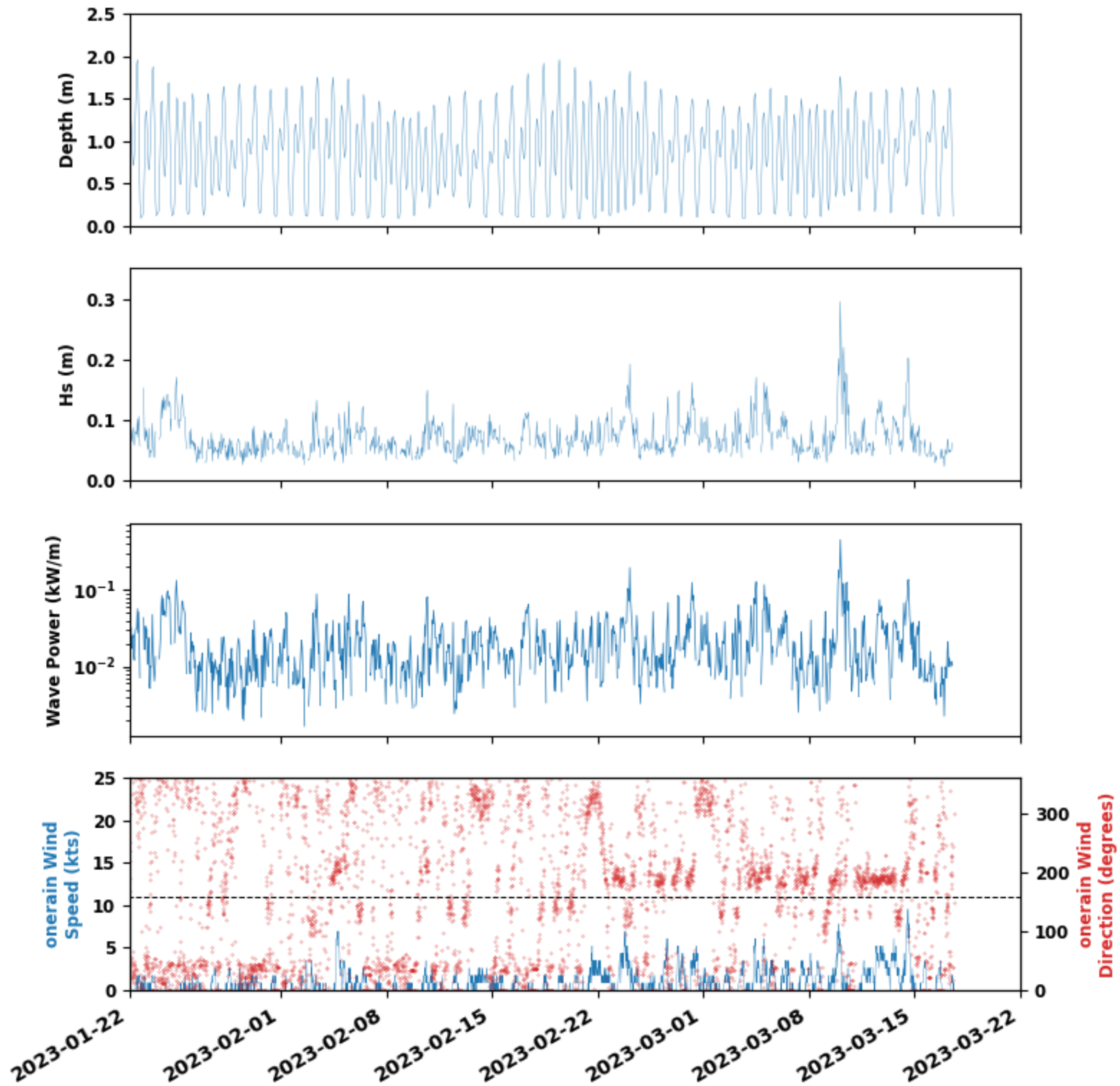


Figure A8: Greenwood Beach 2023-1-22 to 2023-03-22
depth, H_s, wave power, and wind plots

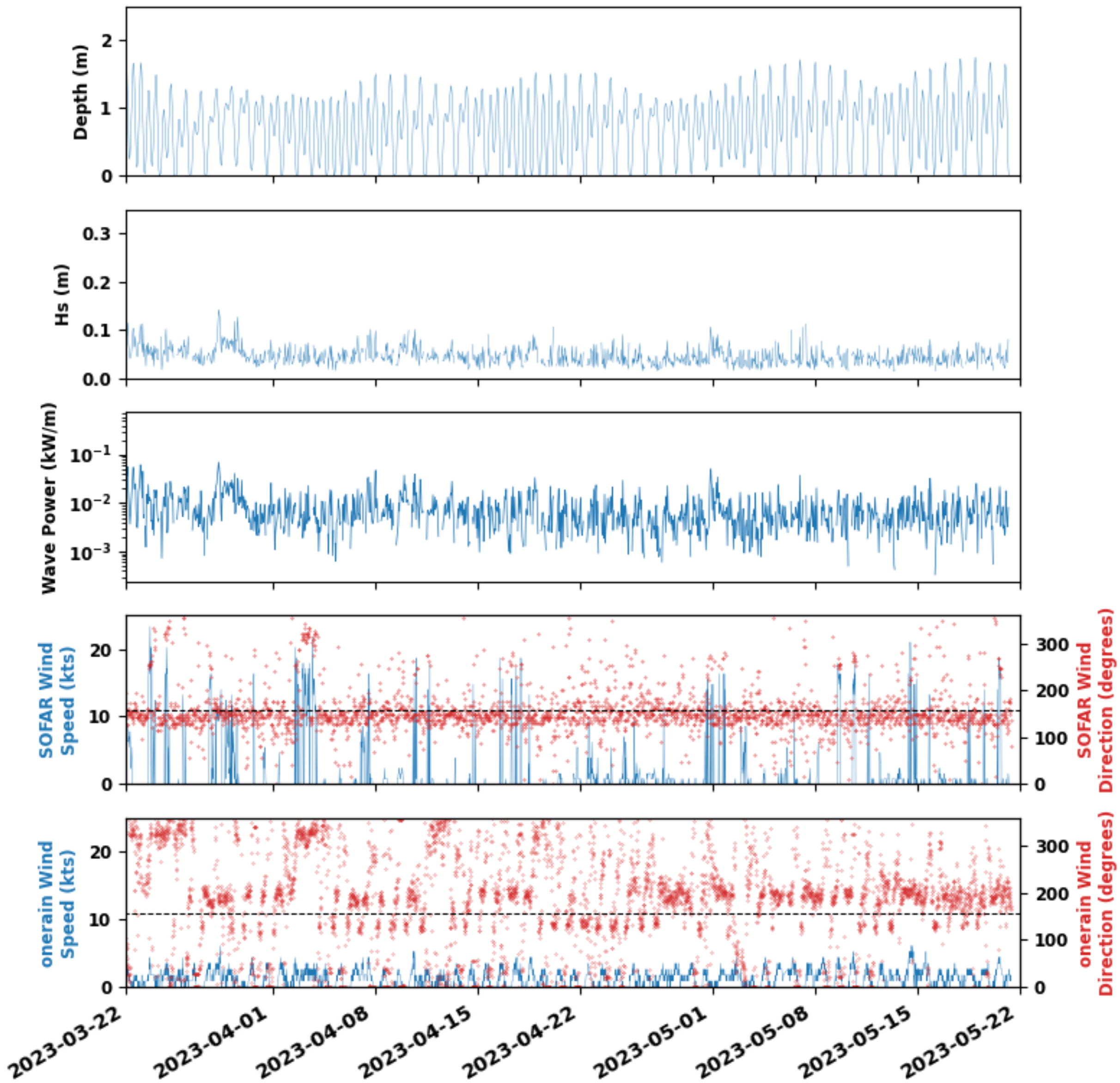


Figure A9: Greenwood Beach 2023-03-22 to 2023-05-22
depth, H_s, wave power, and wind plots

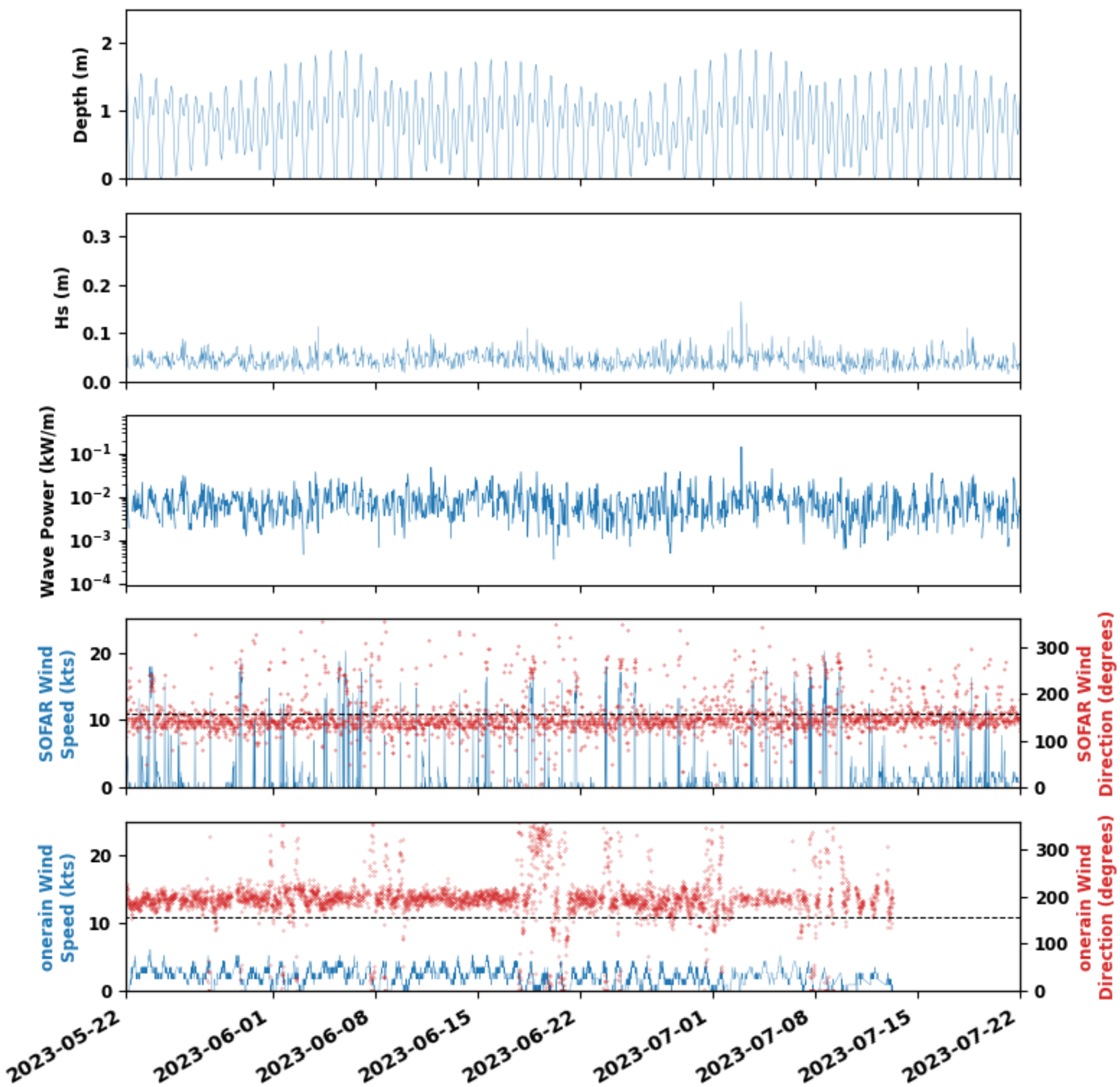


Figure A10: Greenwood Beach 2023-05-22 to 2023-07-22 depth, H_s, wave power, and wind plots

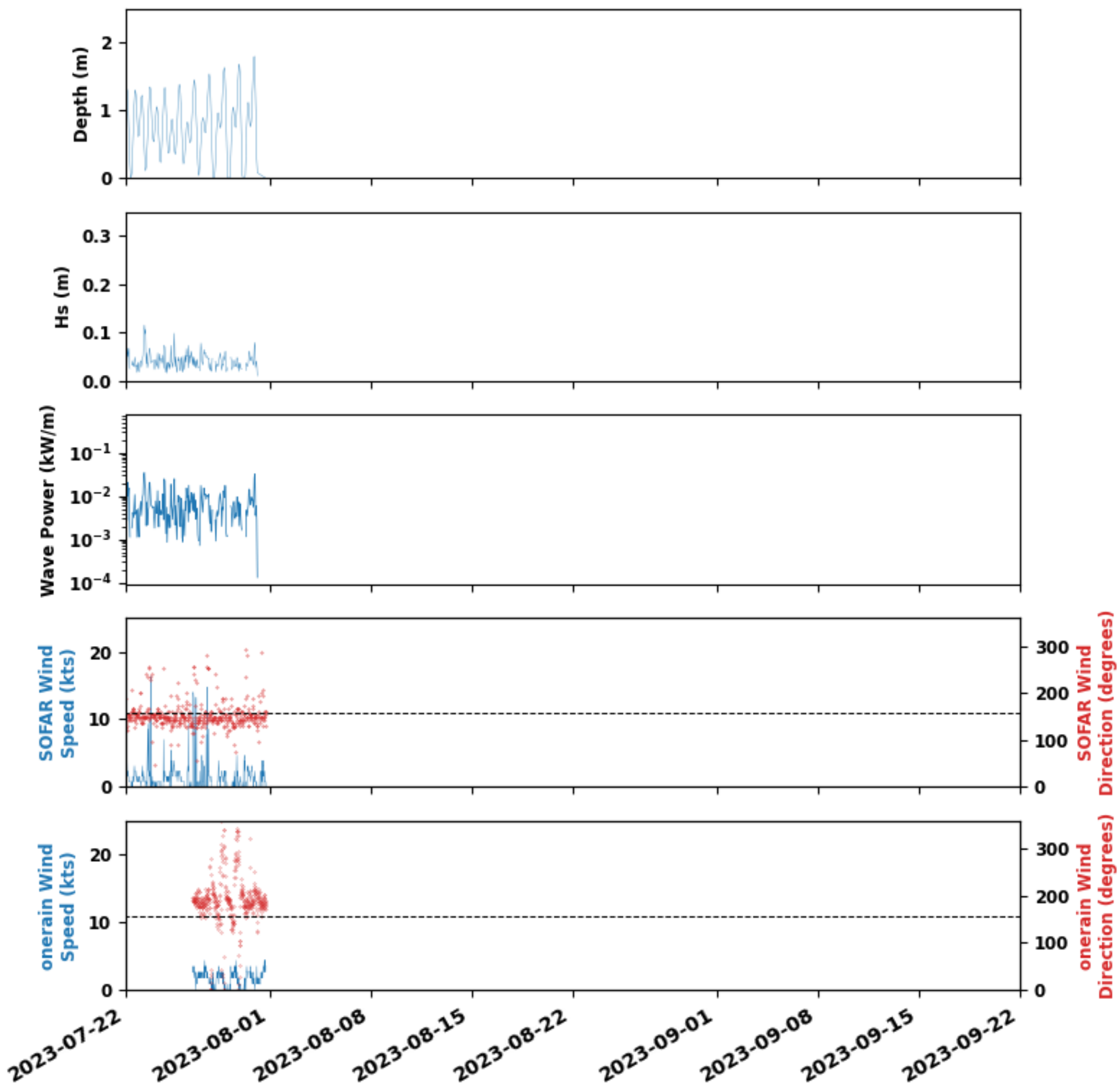


Figure A11: Greenwood Beach 2023-07-22 to 2023-09-22
depth, H_s, wave power, and wind plots

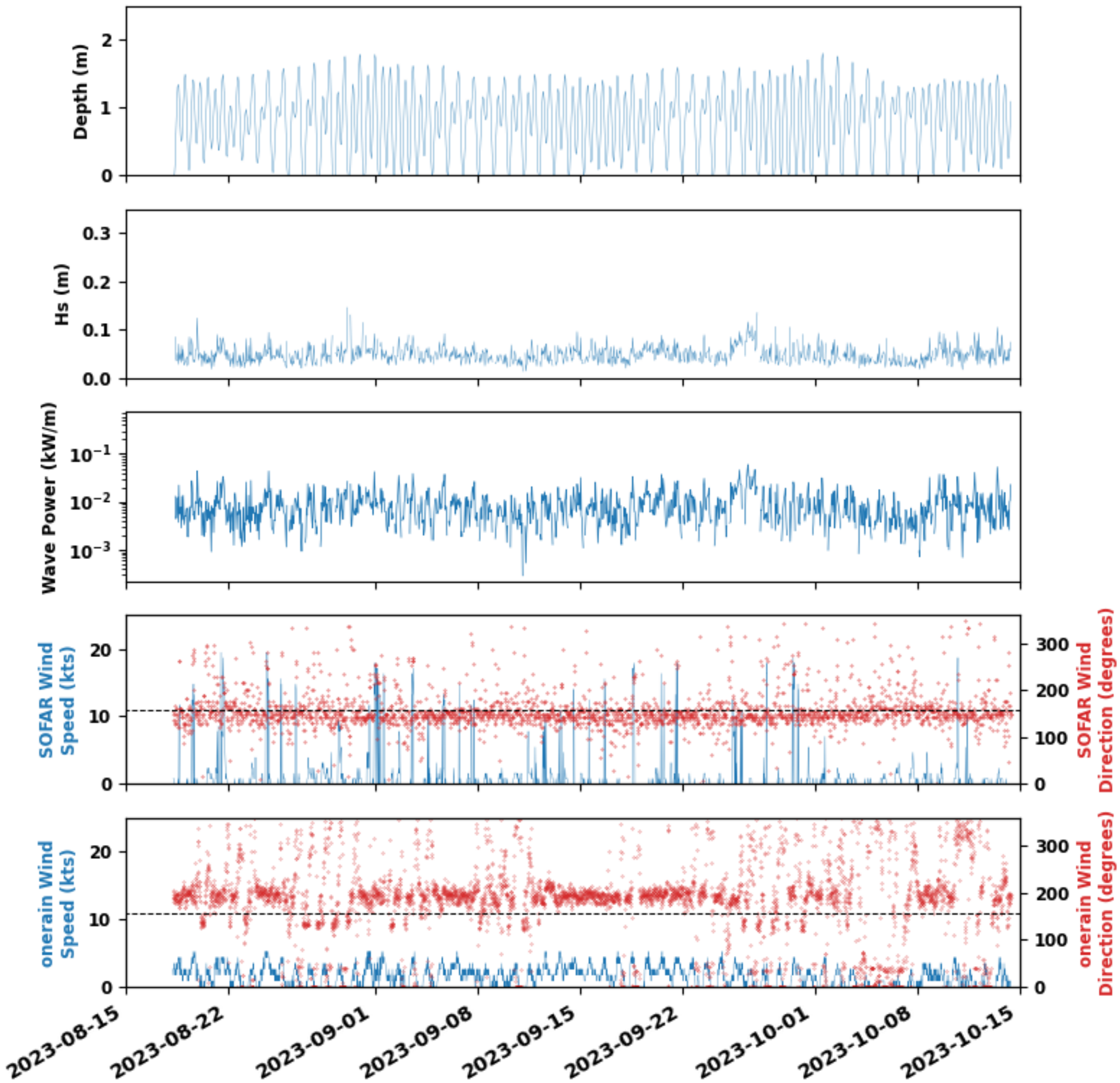


Figure A12: Greenwood Beach 2023-08-15 to 2023-10-15 depth, H_s, wave power, and wind plots

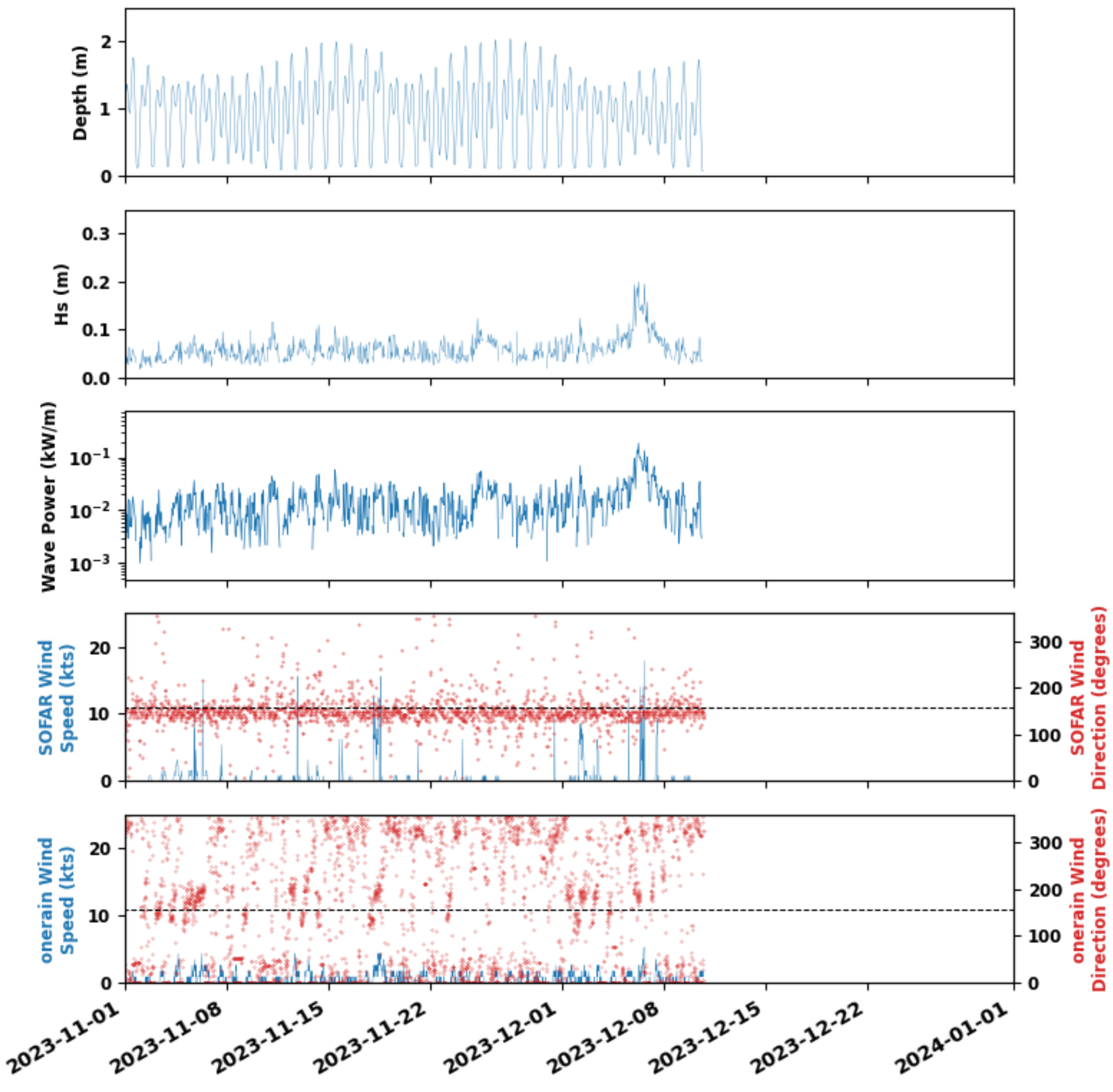


Figure A13: Greenwood Beach 2023-11-01 to 2024-01-01
depth, H_s, wave power, and wind plots

Greenwood Beach Bonus

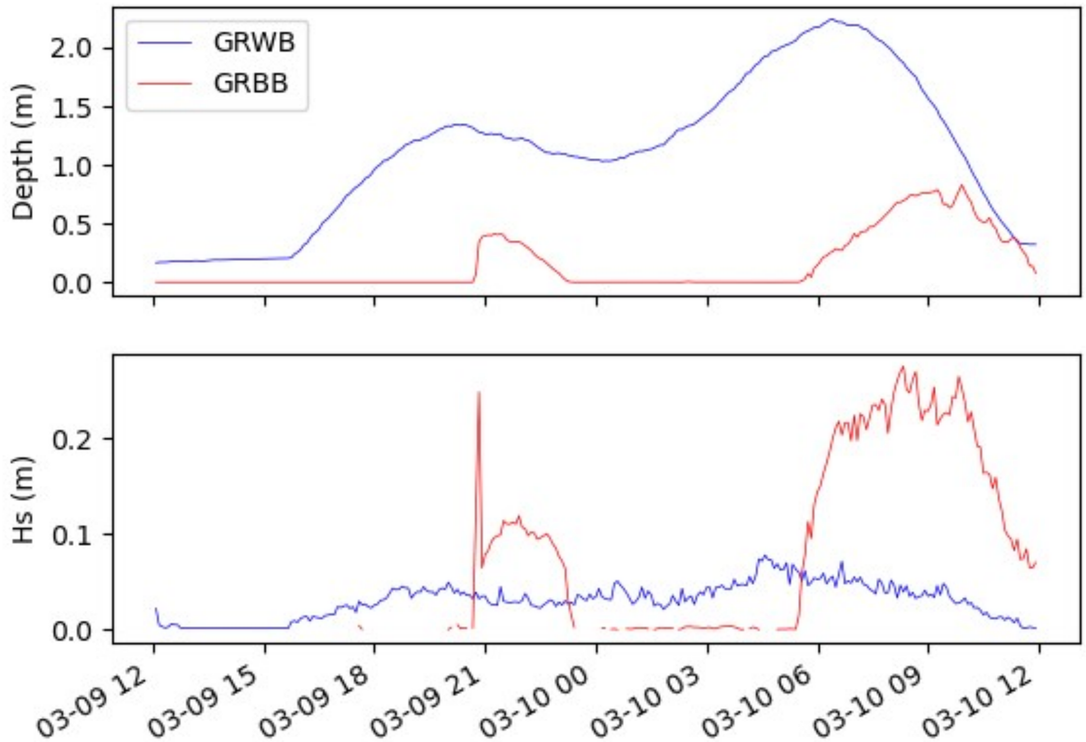


Figure A14: Greenwood Beach and Greenwood Beach Bonus sensor comparison

NERR Piling

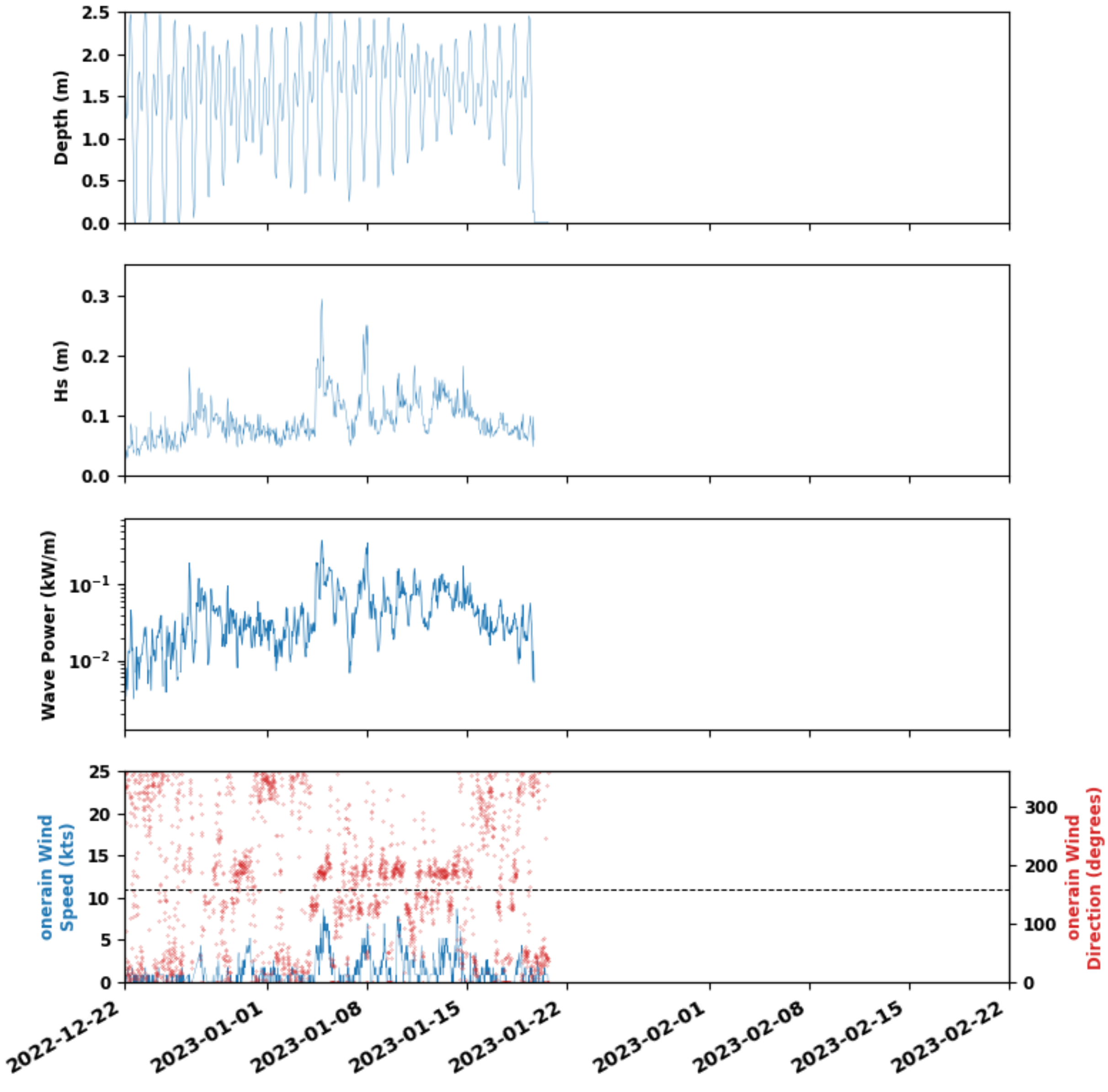


Figure A15: NERR Piling 2022-12-22 to 2023-2-22
depth, H_s, wave power, and wind plots

SOFAR Buoy

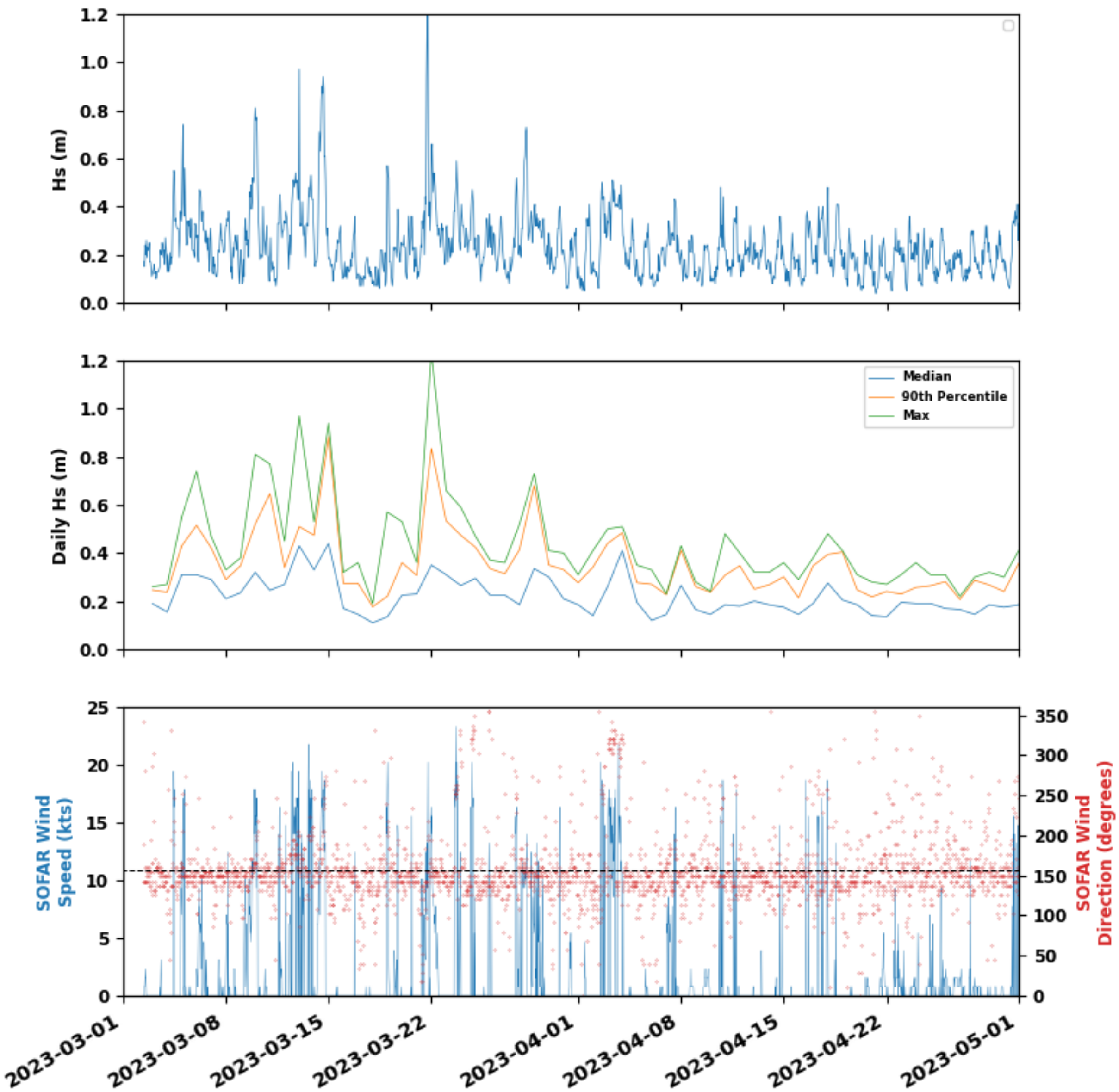


Figure A16: SOFAR Buoy 2023-03-01 to 2023-5-01
H_s, daily H_s, and wind plots

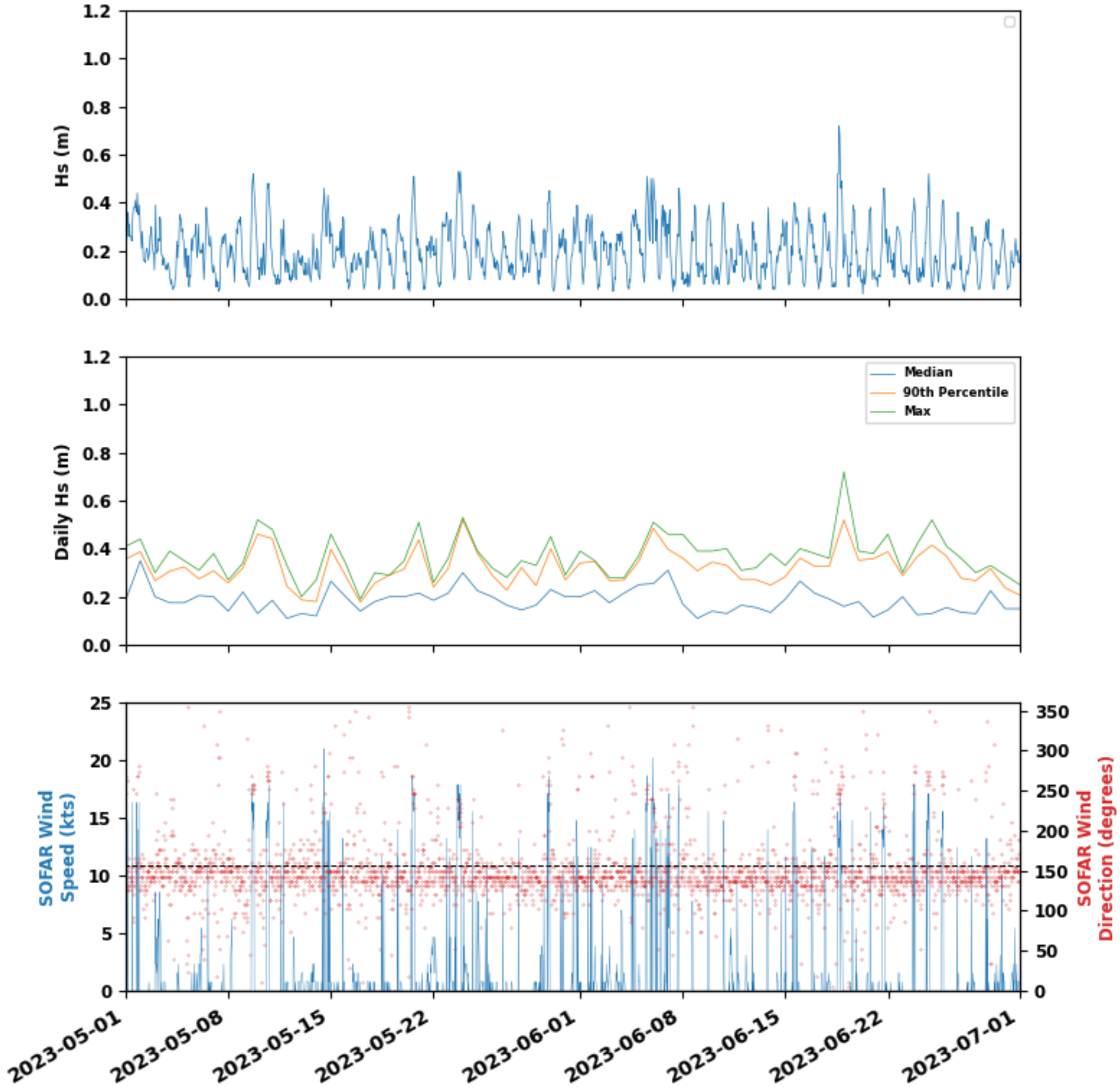


Figure A17: SOFAR Buoy 2023-05-01 to 2023-7-01
H_s, daily H_s, and wind plots

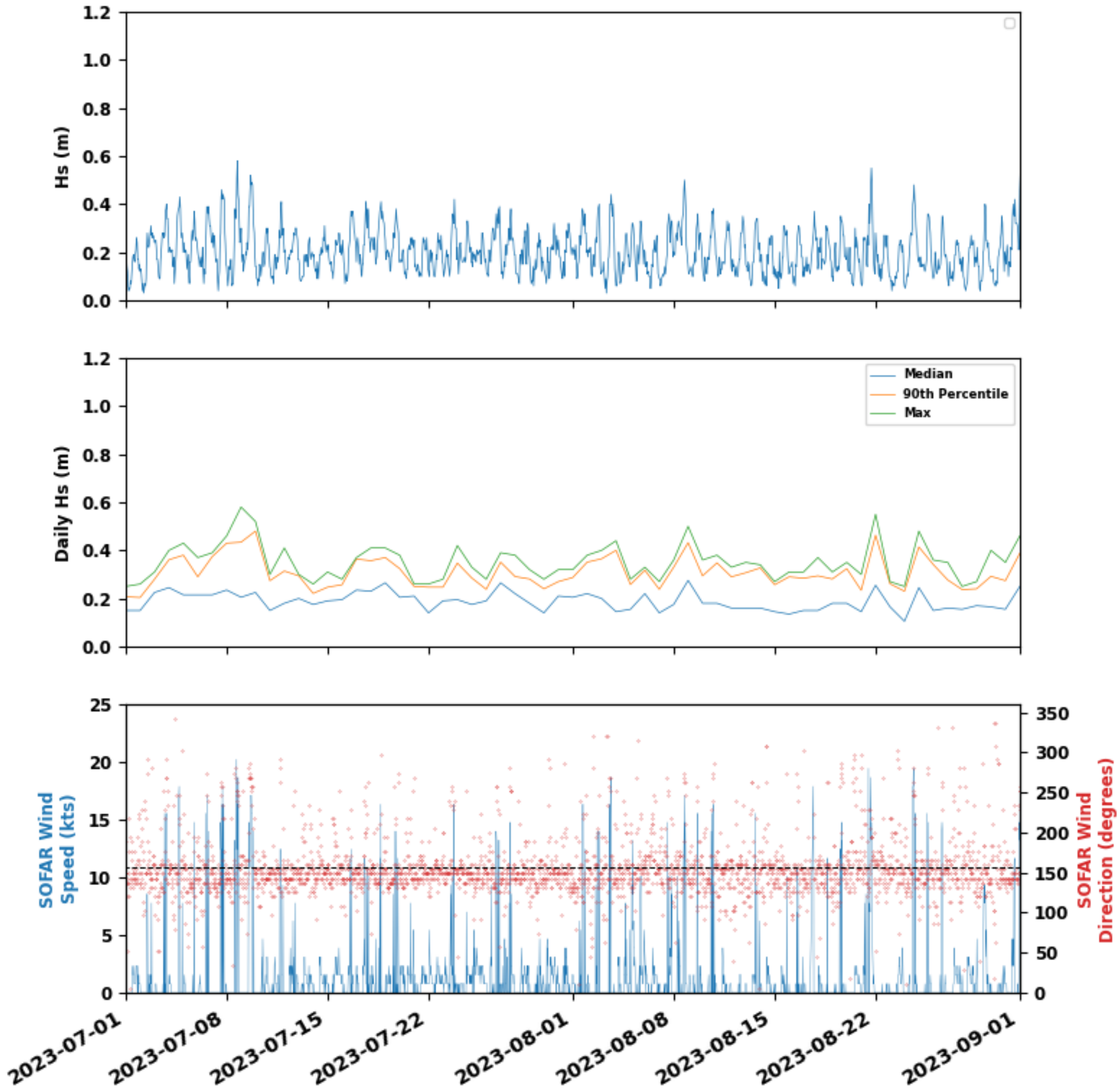


Figure A18: SOFAR Buoy 2023-07-01 to 2023-9-01
H_s, daily H_s, and wind plots

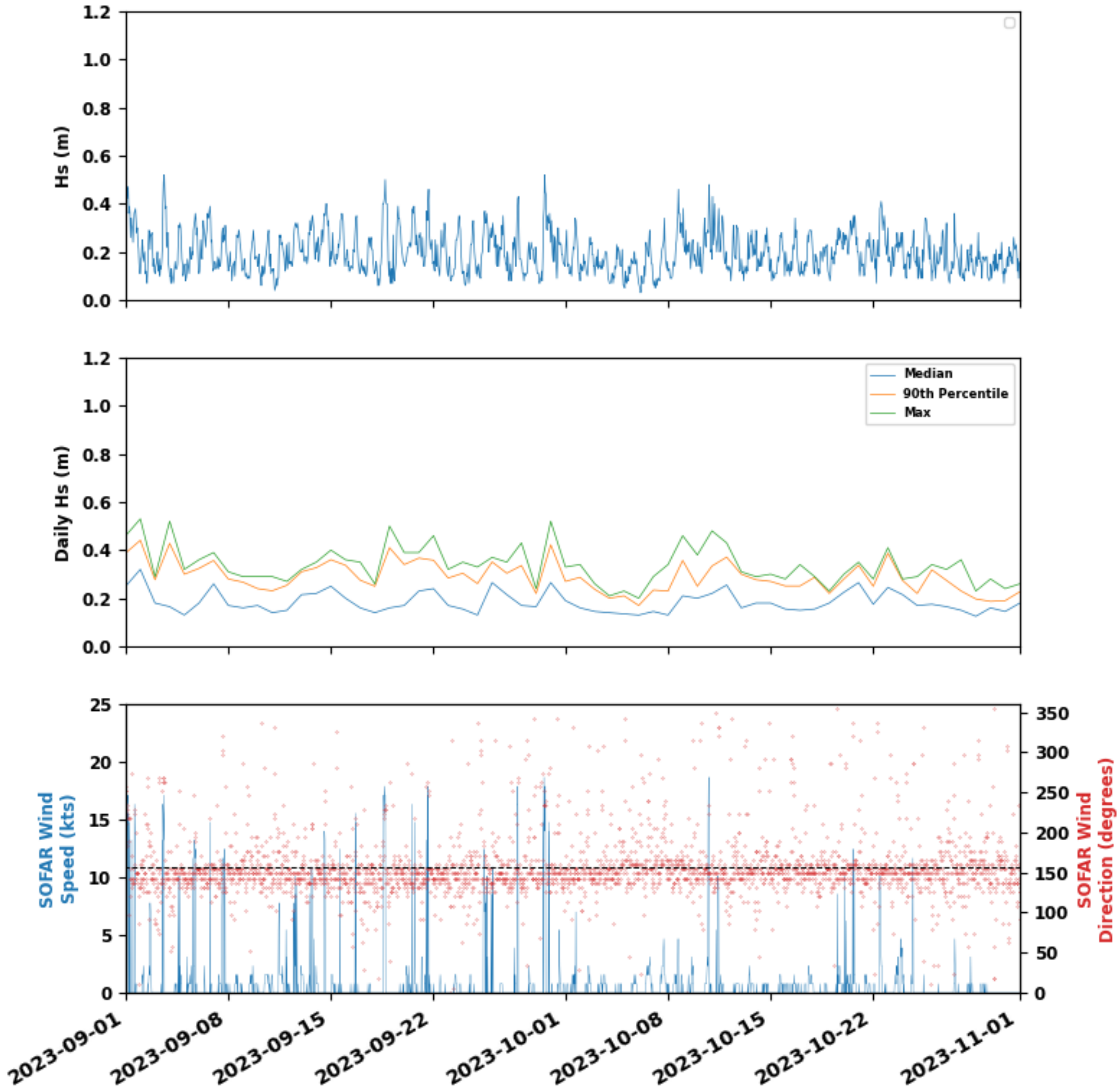


Figure A19: SOFAR Buoy 2023-09-01 to 2023-11-01
H_s, daily H_s, and wind plots

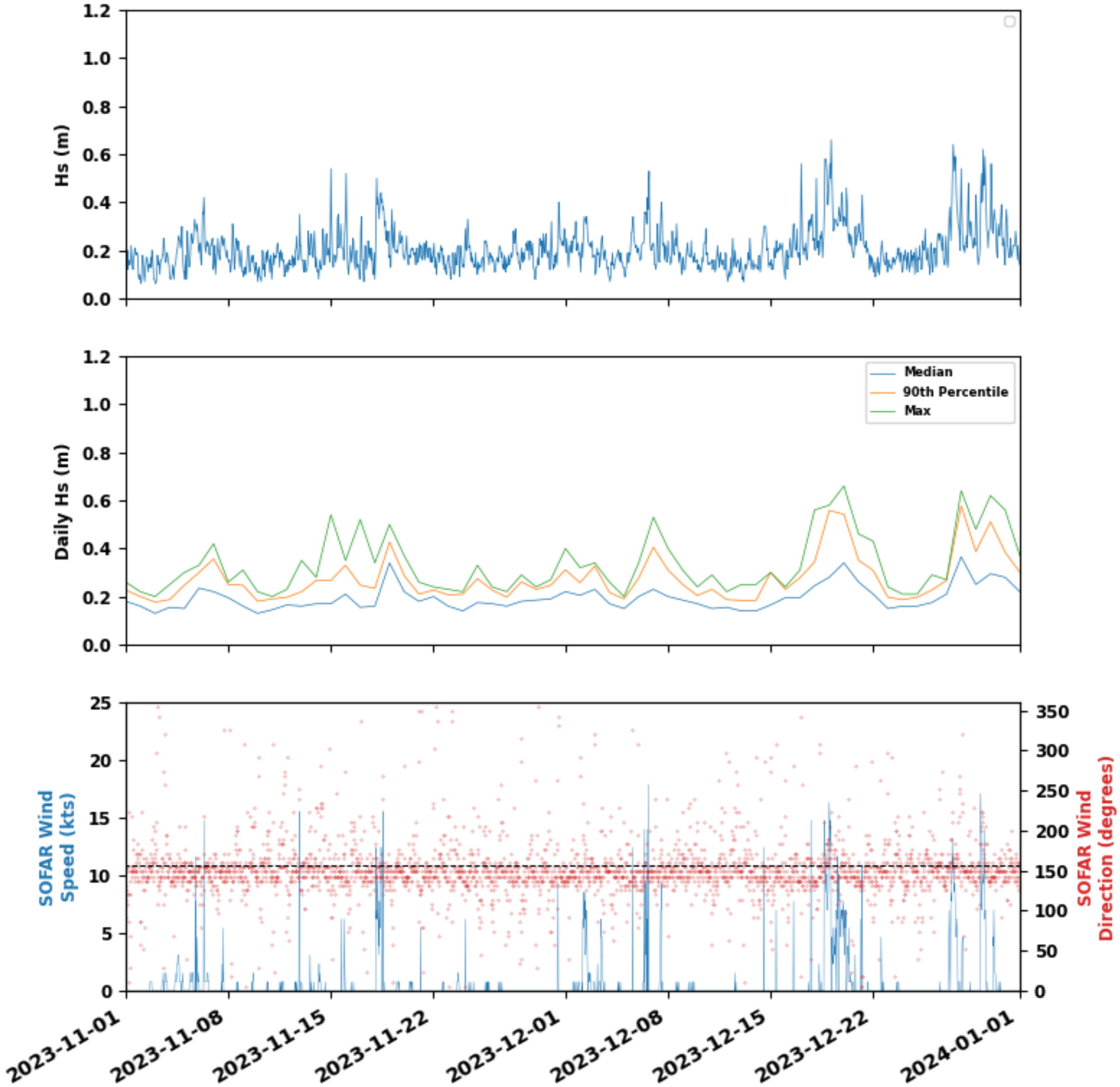


Figure A20: SOFAR Buoy 2023-11-01 to 2024-01-01
H_s, daily H_s, and wind plots

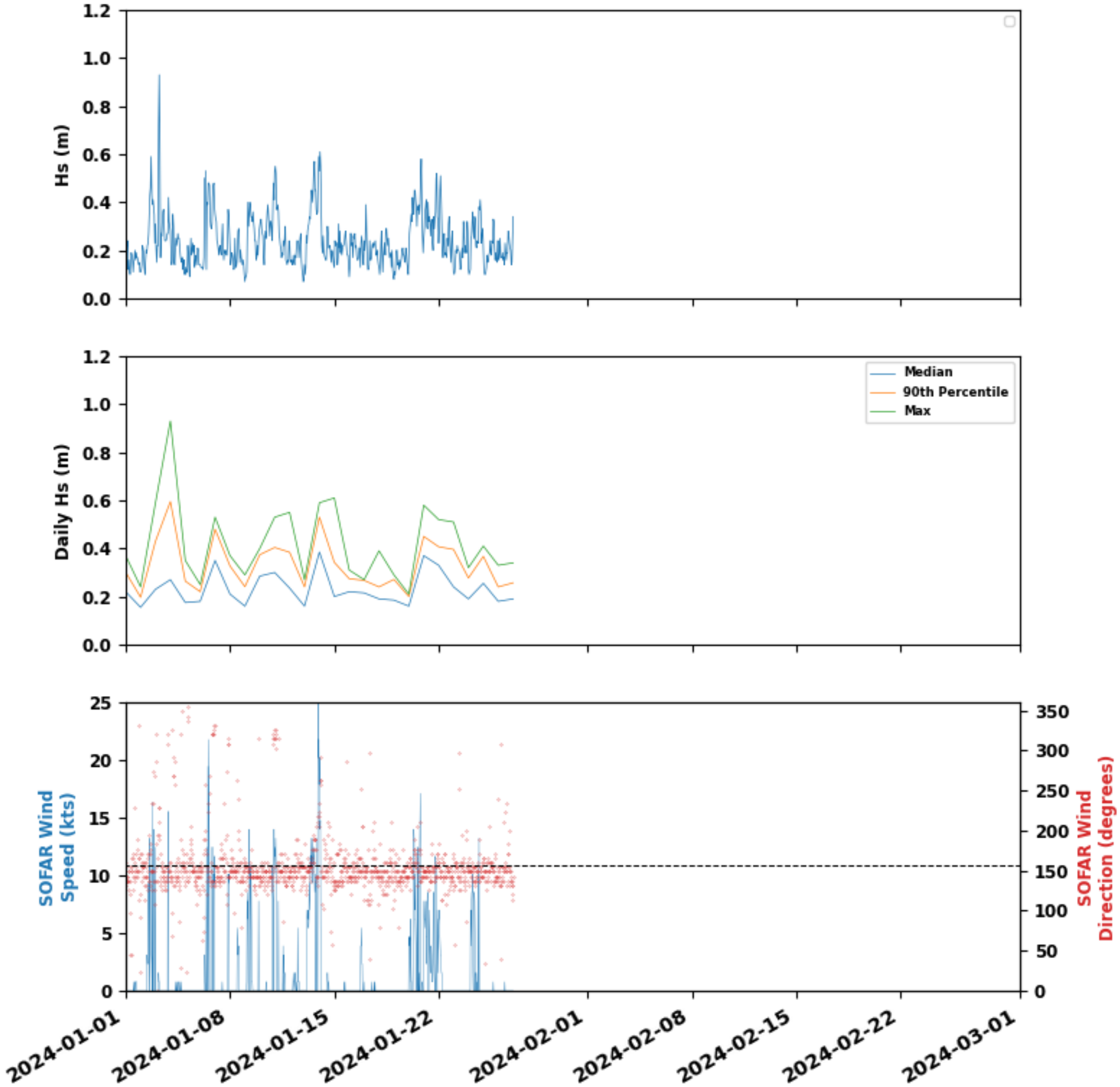


Figure A21: SOFAR Buoy 2024-01-01 to 2024-03-01
H_s, daily H_s, and wind plots

Appendix B: RBR Sensor and SOFAR Buoy Summary Plots

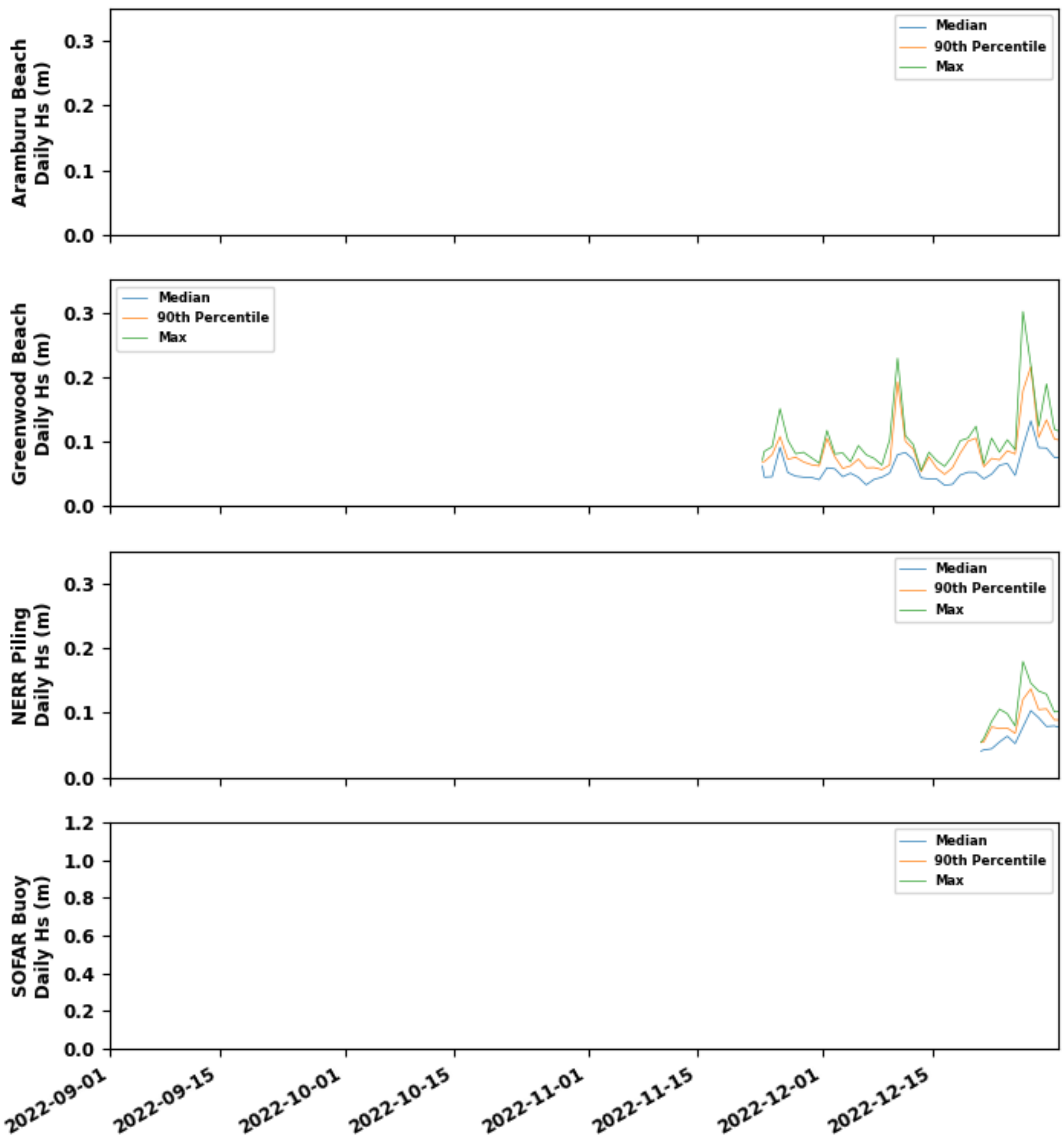


Figure B1: Aramburu Beach, Greenwood Beach, NERR Piling, SOFAR Buoy 2022-09-01 to 2022-12-31 daily H_s summary plots

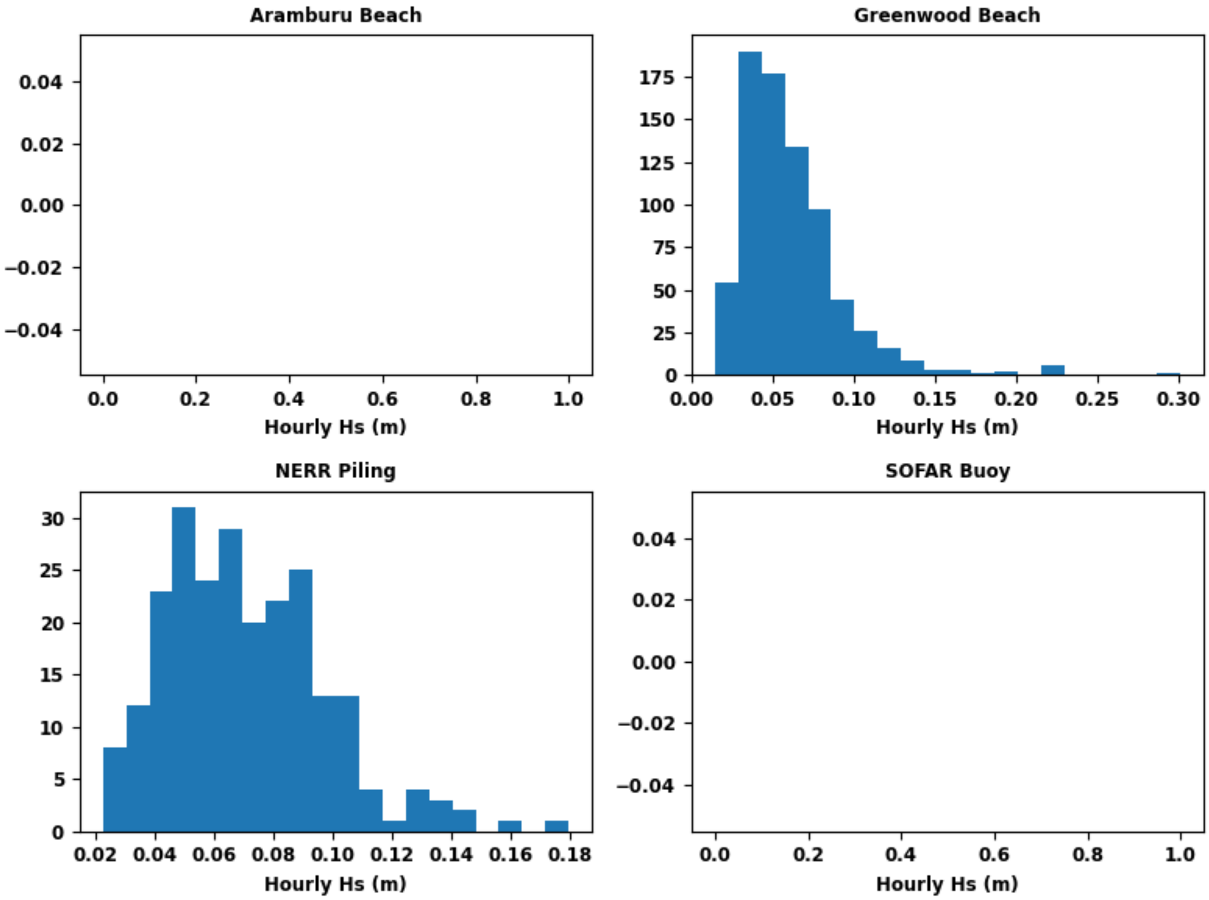


Figure B2: Aramburu Beach, Greenwood Beach, NERR Piling, SOFAR Buoy 2022-09-01 to 2022-12-31 hourly H_s histograms

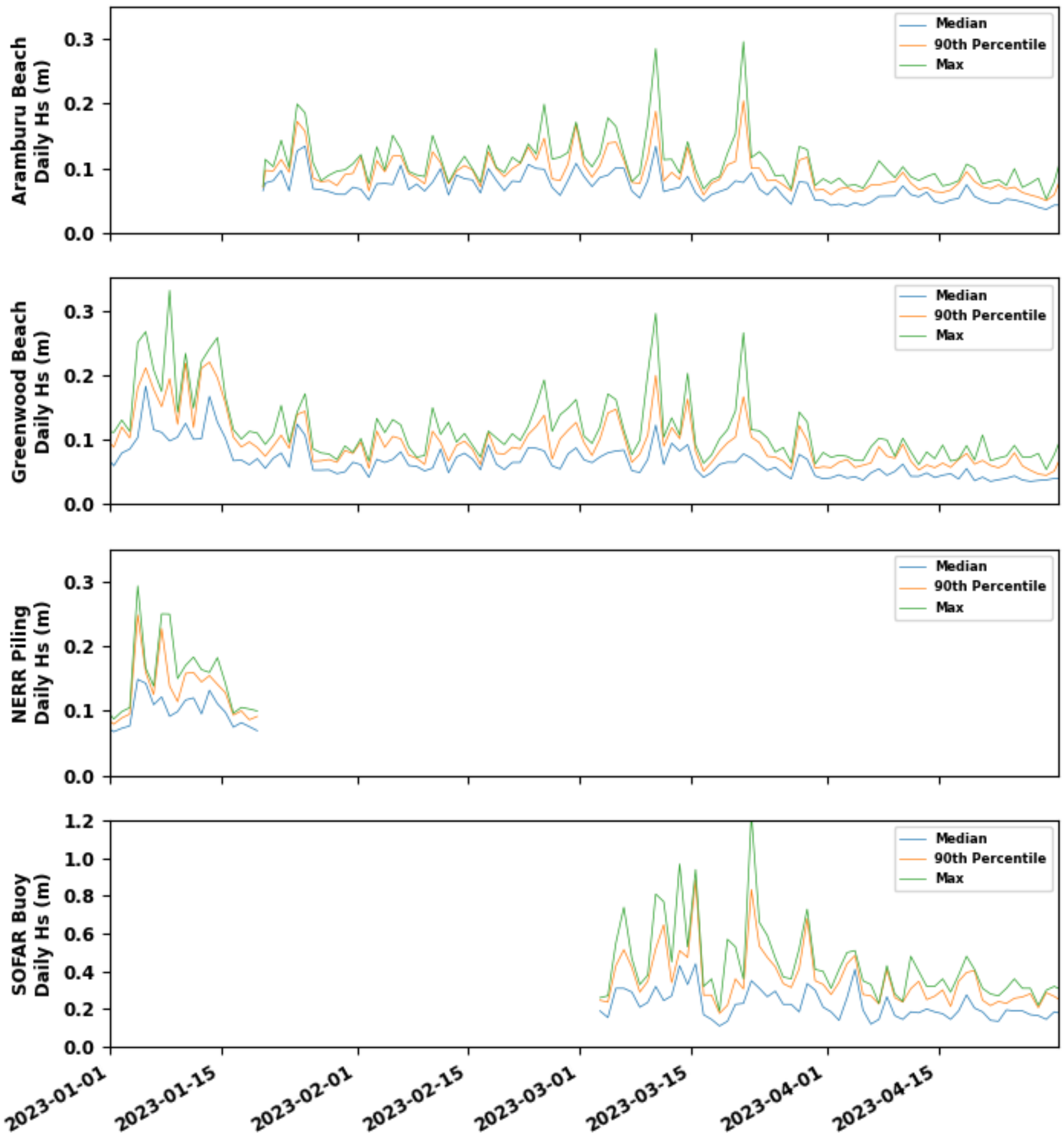


Figure B3: Aramburu Beach, Greenwood Beach, NERR Piling, SOFAR Buoy 2023-01-01 to 2023-04-30 daily H_s summary plots

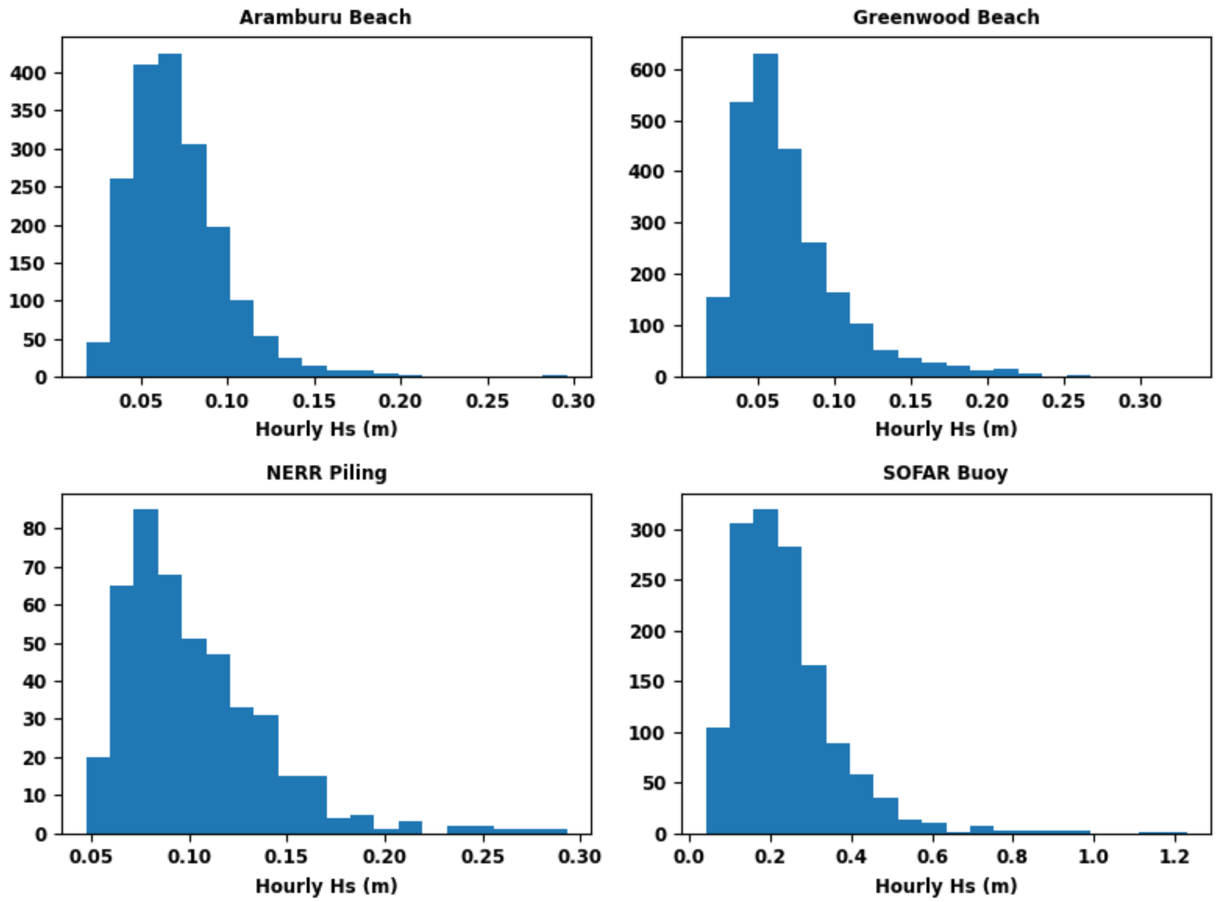


Figure B4: Aramburu Beach, Greenwood Beach, NERR Piling, SOFAR Buoy
2023-01-01 to 2023-04-30 hourly H_s histograms

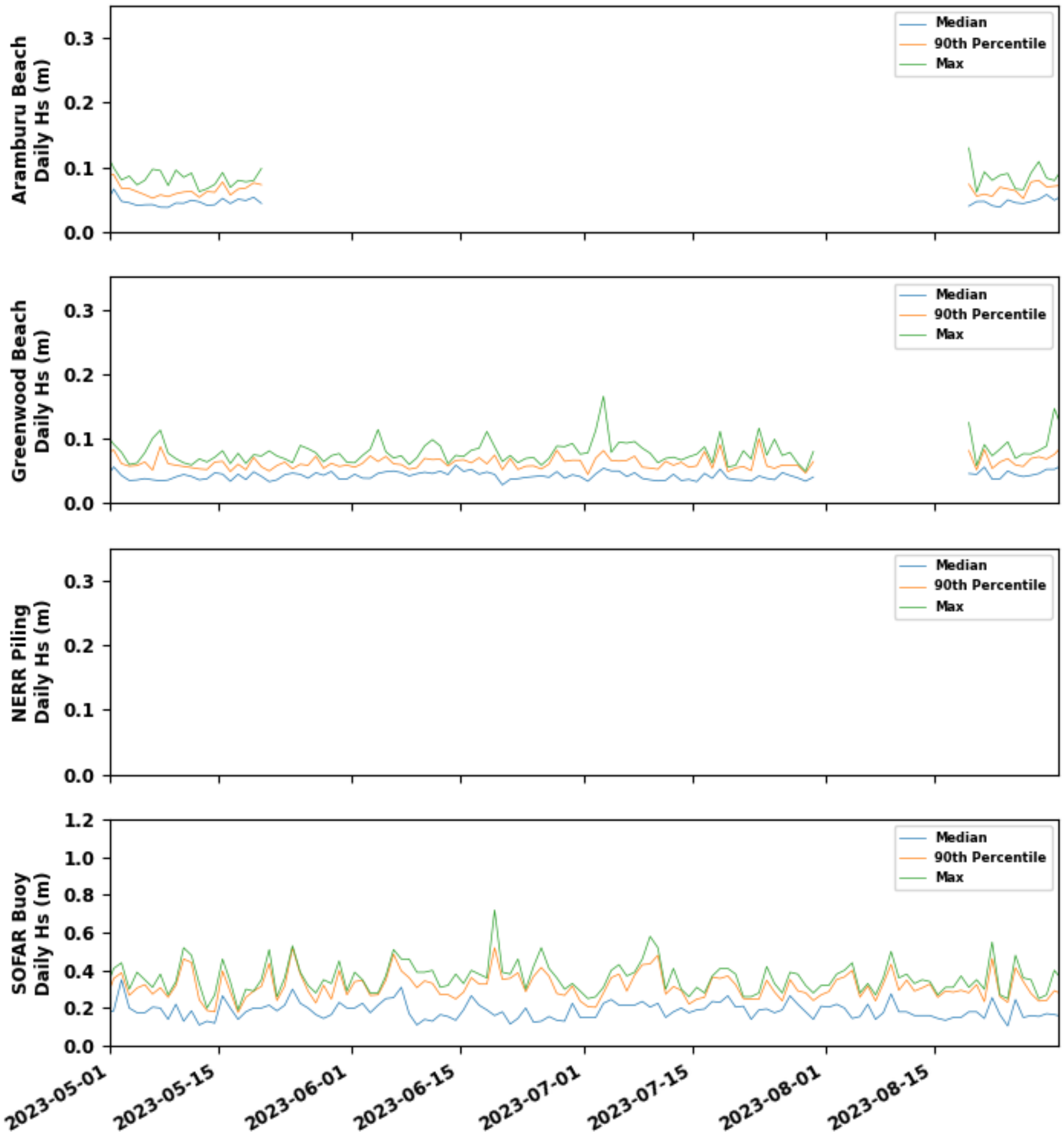


Figure B5: Aramburu Beach, Greenwood Beach, NERR Piling, SOFAR Buoy 2023-05-01 to 2023-08-31 daily H_s summary plots

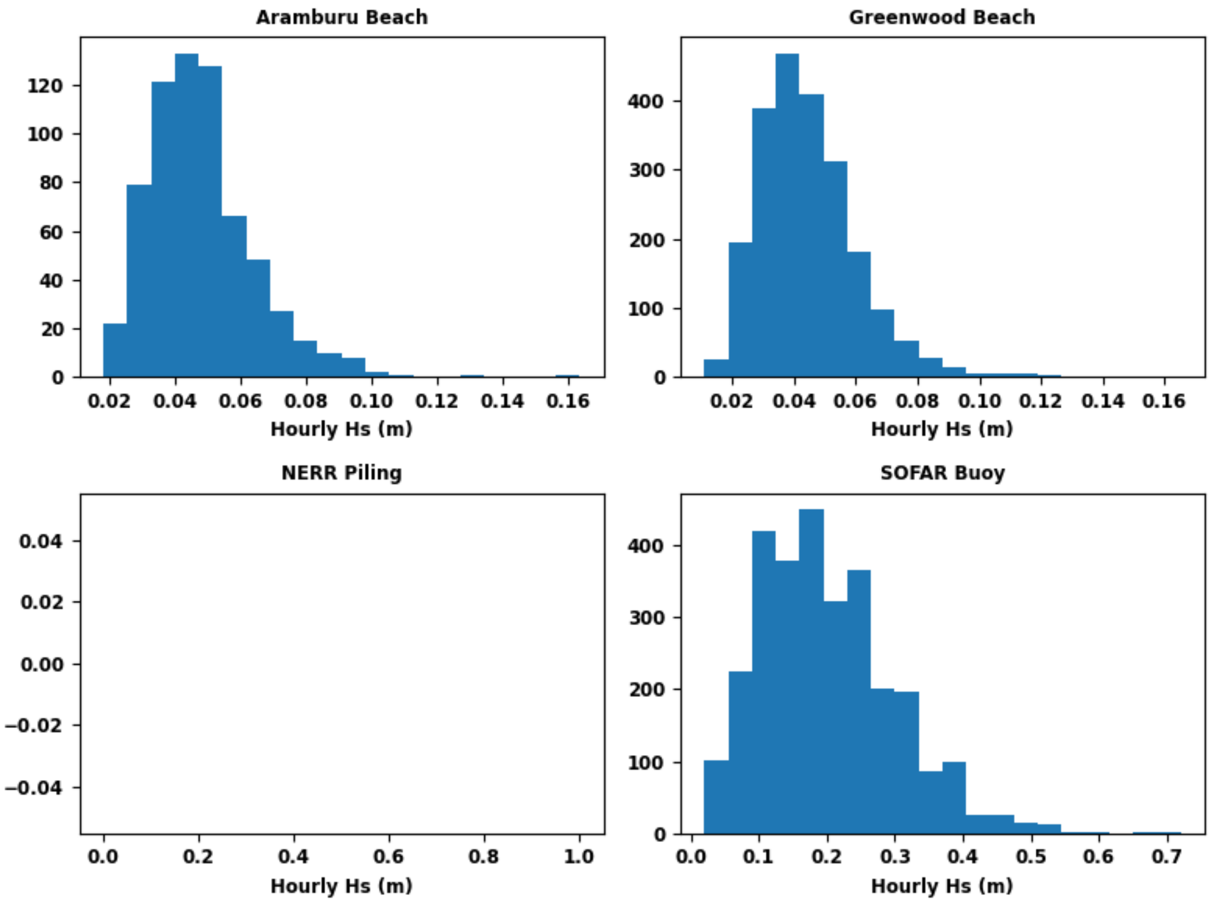


Figure B6: Aramburu Beach, Greenwood Beach, NERR Piling, SOFAR Buoy 2023-05-01 to 2023-08-31 hourly H_s histograms

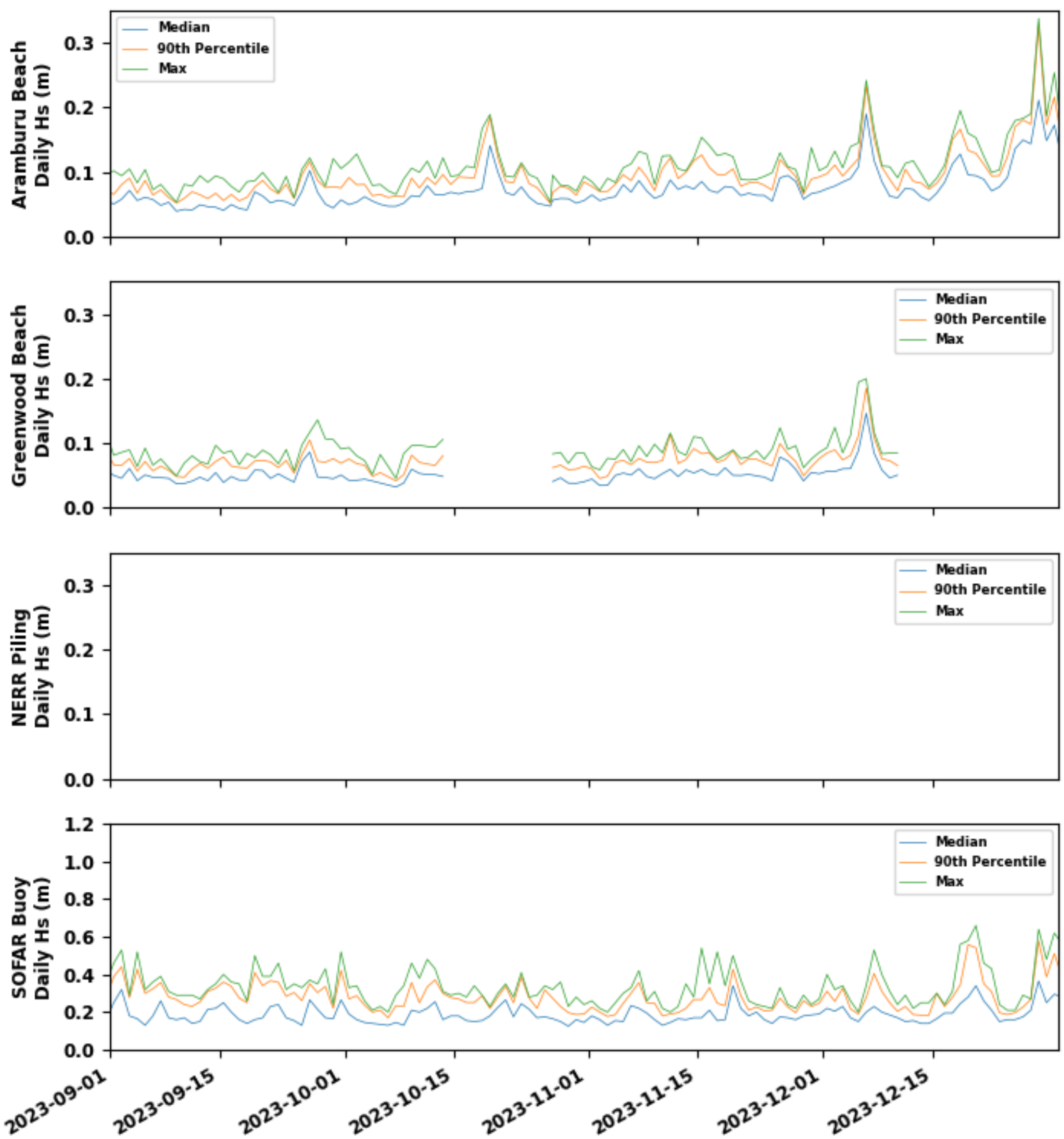


Figure B7: Aramburu Beach, Greenwood Beach, NERR Piling, SOFAR Buoy 2023-09-01 to 2023-12-31 daily H_s summary plots

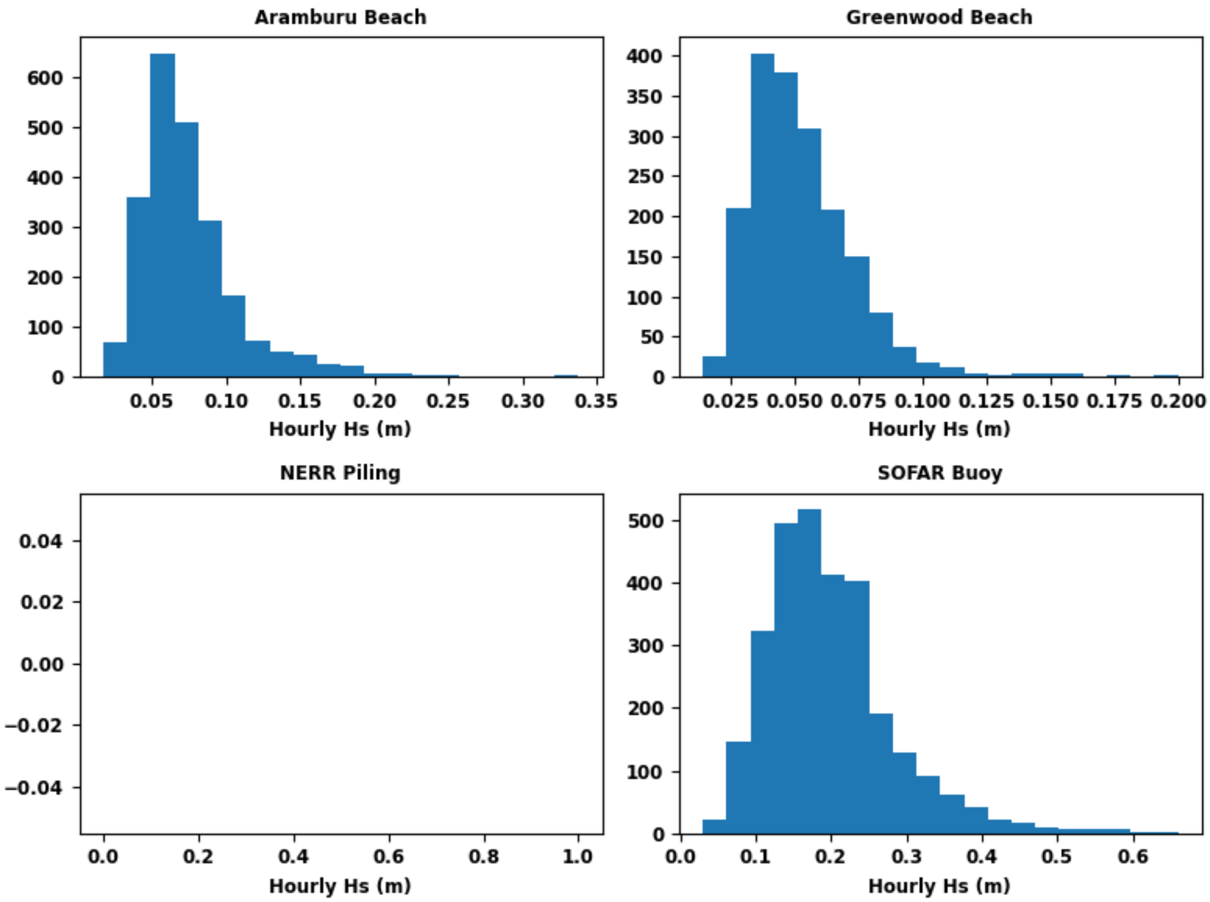


Figure B8: Aramburu Beach, Greenwood Beach, NERR Piling, SOFAR Buoy 2023-09-01 to 2023-12-31 hourly H_s histograms

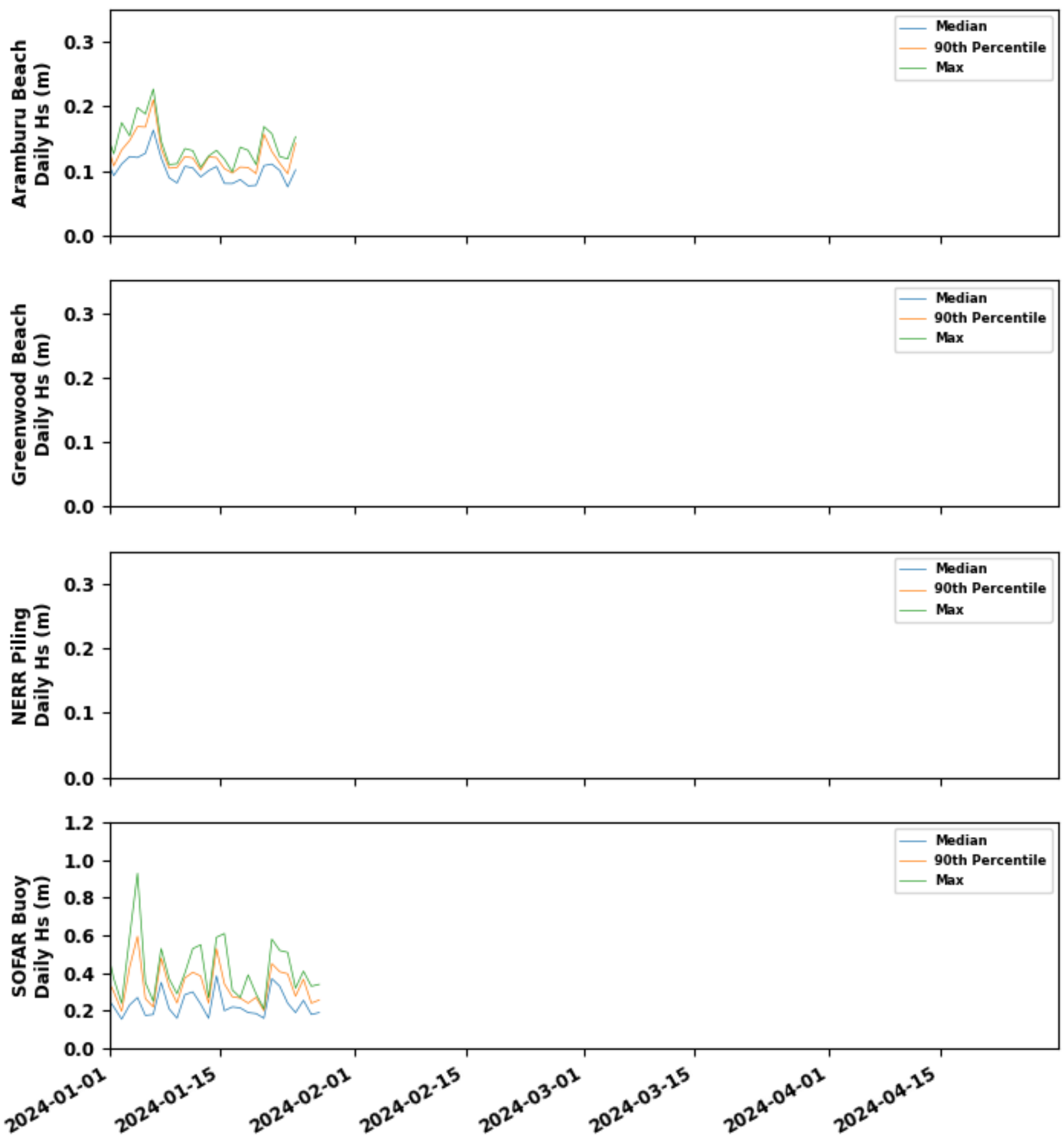


Figure B9: Aramburu Beach, Greenwood Beach, NERR Piling, SOFAR Buoy 2024-01-01 to 2024-04-30 daily H_s summary plots

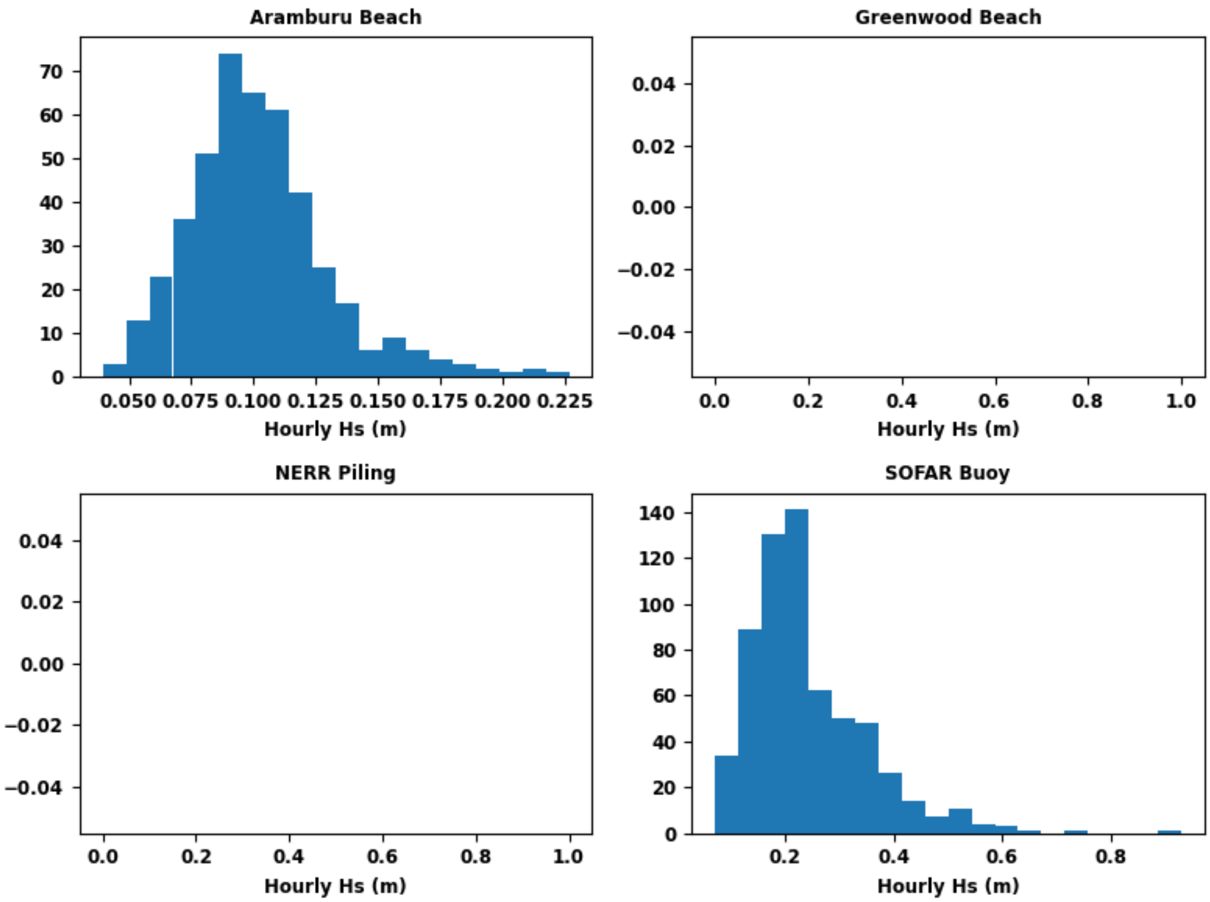


Figure B10: Aramburu Beach, Greenwood Beach, NERR Piling, SOFAR Buoy 2024-01-01 to 2024-04-30 hourly H_s histograms

Appendix I. Preliminary Benthic Macroinvertebrate Investigation Memorandum

Preliminary Benthic Macroinvertebrate Investigation

Geana Ayala 8/9/22

The Greenwood Beach Restoration Project aims to reduce shoreline erosion, enhance beach habitats, and improve sea level rise resilience at Greenwood Beach in Blackies Pasture, Tiburon. The aim of this survey was to survey the benthic macroinvertebrate community to understand current shorebird foraging opportunities offshore of Greenwood Beach.

Data collection:
Six sediment cores were collected parallel to the shoreline at Greenwood Beach at six pre-determined locations (Figure 1). GPS coordinates were sent via a kmz file and opened on the Google Earth app on a smartphone. The site was accessed at a -1.6 ft tide around 9 am on 6/17/22. However, at 12:40 pm when the tide was about +1.75 ft the survey points were still accessible. For future collection, accessing at a + 1.5 ft tide would work.

Each core was collected by pushing a 5 cm diameter PVC pipe to a depth of 10 cm. A rubber stopper was placed on the top of the PVC to create a suction and the core contents were placed into a plastic bag and stored on ice. A photo was taken of the sample location *in-situ* (Figure 2) and approximate GPS locations (Table 1) were taken using the Google Earth app on a smartphone.

Lab processing:
In the lab, the cores were rinsed of all mud and debris and passed through a 1 mm sieve to collect invertebrates. Invertebrates were fixed in 70% ethanol and identified to taxonomic order. After invertebrates were counted, they were dried at 50 °C to a constant mass and weighed. When invertebrates are fixed in ethanol, it is common to us dry weights for biomass estimates.

Results:
Seven taxonomic groups were identified in all the cores (Table 2). The most abundant invertebrate was Veneroida (Bivalvia), a clam. It was present in all cores with the highest abundance in BI-4 with 70 individuals present (Figure 4). BI-4 also had the highest total abundance of invertebrates (Figure 3 & Figure 7). The invertebrate biomass that contributed most were also Veneroida (Figure 5 & Figure 6). This makes sense as these clams have a hard shell.

Species richness was similar across all cores (Figure 7). Simpson Diversity index measurements were more variable across all cores. Simpson Diversity index is a measure of dominance and species richness. Total abundance was also variable across the cores, with the highest total abundance in BI-4 (n = 129) and lowest total abundance in BI-2 (n=31).

Tables and Figures

collection site	collection date	sample ID	latitude	longitude
Greenwood Beach	6/17/22	BI-1	37°53'42"N	122°29'24"W
Greenwood Beach	6/17/22	BI-2	37°53'42"N	122°29'23"W
Greenwood Beach	6/17/22	BI-3	37°53'42"N	122°29'22"W
Greenwood Beach	6/17/22	BI-4	37°53'42"N	122°29'19"W
Greenwood Beach	6/17/22	BI-5	37°53'41"N	122°29'18"W
Greenwood Beach	6/17/22	BI-6	37°53'41"N	122°29'22"W

Table 1. GPS points of core locations.

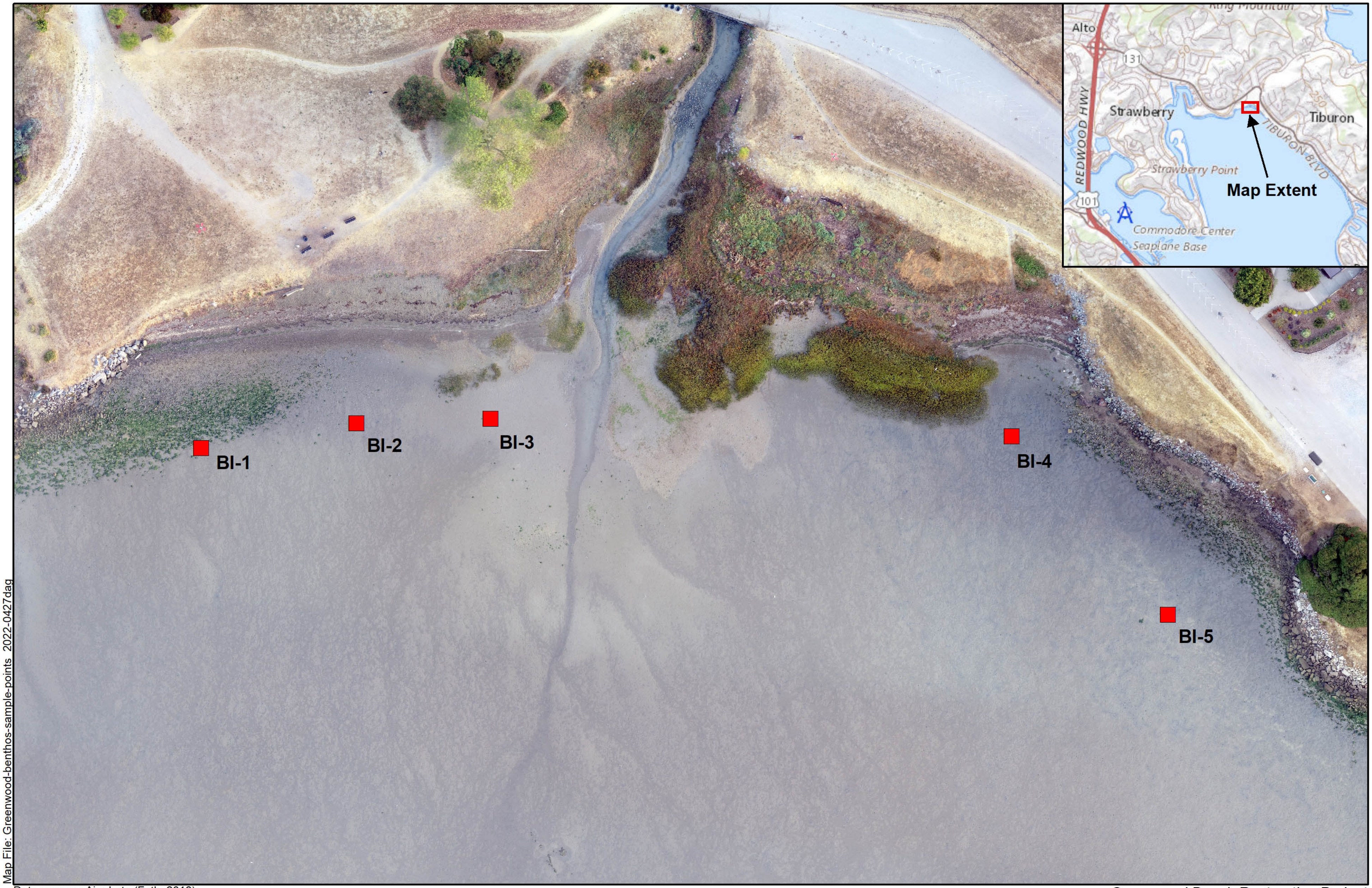
Greenwood Beach 6/17/22

	order ID	invertebrate count	invertebrate biomass (g)
BI-1			
	Veneroida (Bivalvia)	39	0.3134
	Gammarid Amphipoda	33	0.0085
	Polychaetea	13	0.0036
	Oligochaeta	4	0.01
BI-2			
	Veneroida (Bivalvia)	23	0.216
	Gammarid Amphipoda	3	0.002
	Nematoda	3	1E-04
	Oligochaeta	2	0.0062
BI-3			
	Veneroida (Bivalvia)	42	0.3816
	Polychaetea	19	0.0236
	Oligochaeta	2	0.0007
	Stylommatophora (Gastropoda)	1	0.0662
BI-4			
	Veneroida (Bivalvia)	70	0.6213
	Gammarid Amphipoda	53	0.0098
	Decapoda	1	0.026
	Polychaetea	5	0.0021
BI-5			
	Veneroida (Bivalvia)	45	0.4631
	Gammarid Amphipoda	24	0.0113
	Polychaetea	4	0.0017
BI-6			
	Veneroida (Bivalvia)	52	0.6
	Polychaetea	4	0.0062
	Oligochaeta	3	0.0077

Table 2. Invertebrate abundances and biomass (g) for all samples collected.

sample ID	Species Richness	Simpson Diversity	Total Abundance
BI-1	4	0.647	89
BI-2	4	0.427	31
BI-3	4	0.480	64
BI-4	4	0.535	129
BI-5	3	0.509	73
BI-6	3	0.216	59

Table 3. Species richness, Simpson Diversity index, and total abundance of invertebrates.



Map File: Greenwood-benthos-sample-points 2022-0427daq

Data sources: Air photo (Foth, 2018);
data (GillenH2O, 2022)

1:900 (1" = 75' at letter size)

0 37.5 75 ft

Greenwood Beach Restoration Project

Figure 1

Greenwood Beach
Benthic Macroinvertebrate Sampling Locations

Gillenwater GillenH2O Consulting

Figure 2. Photos of cores *in-situ*.

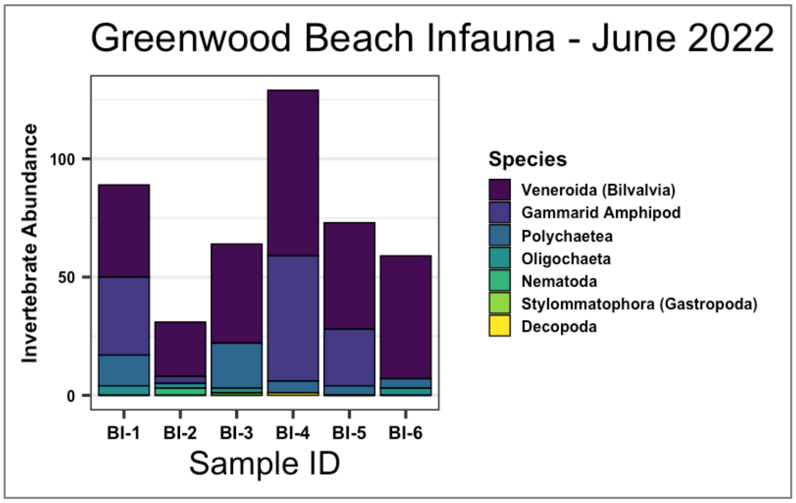


Figure 3. Total invertebrate abundances.

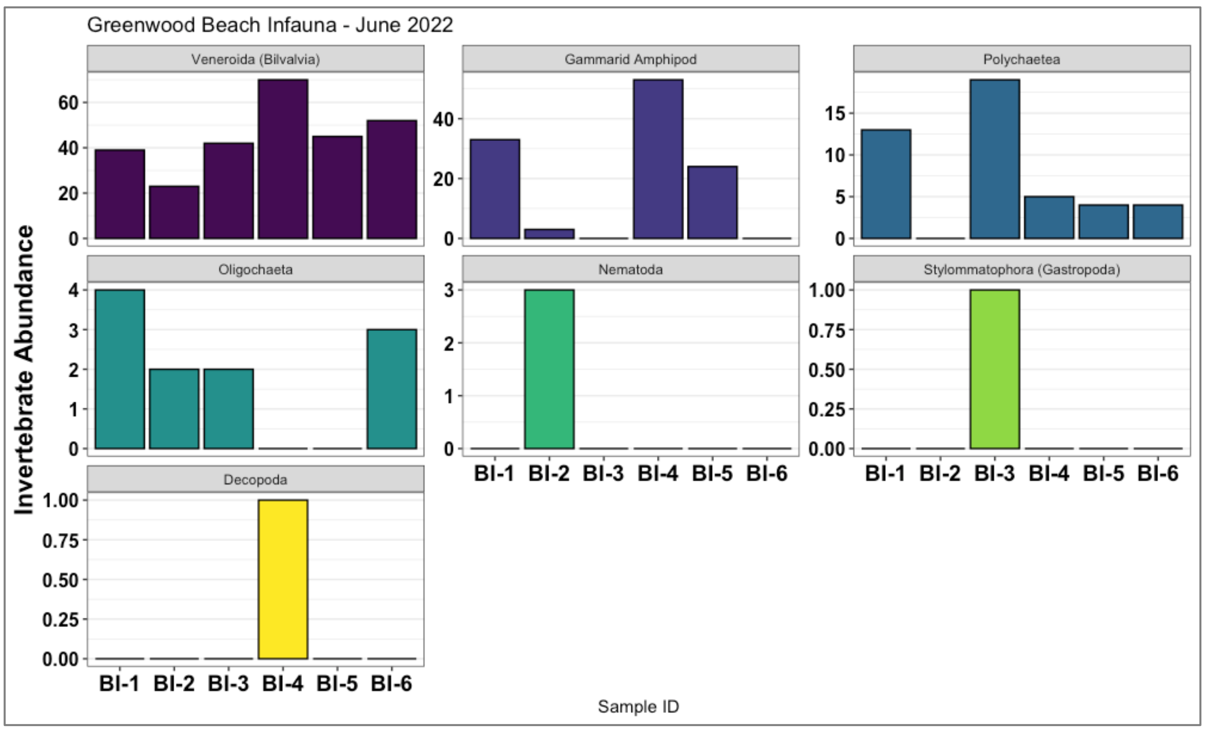


Figure 4. Total invertebrate abundances separated out by taxonomic group.

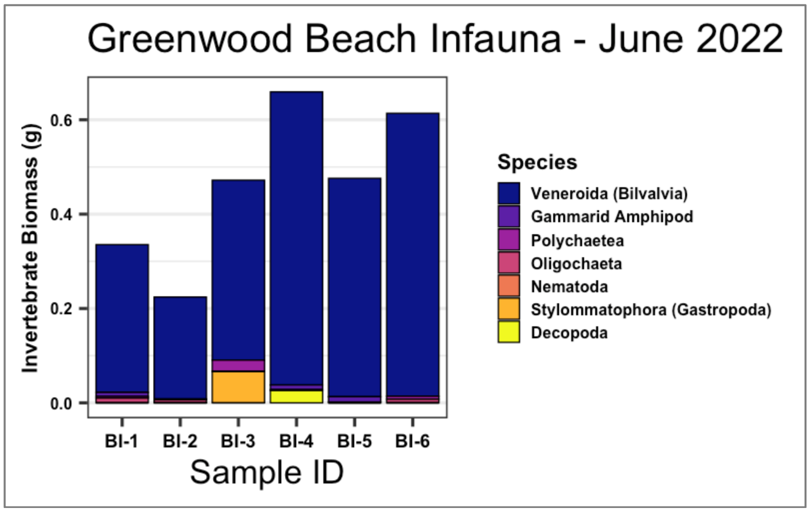


Figure 5. Total invertebrate biomass in grams.

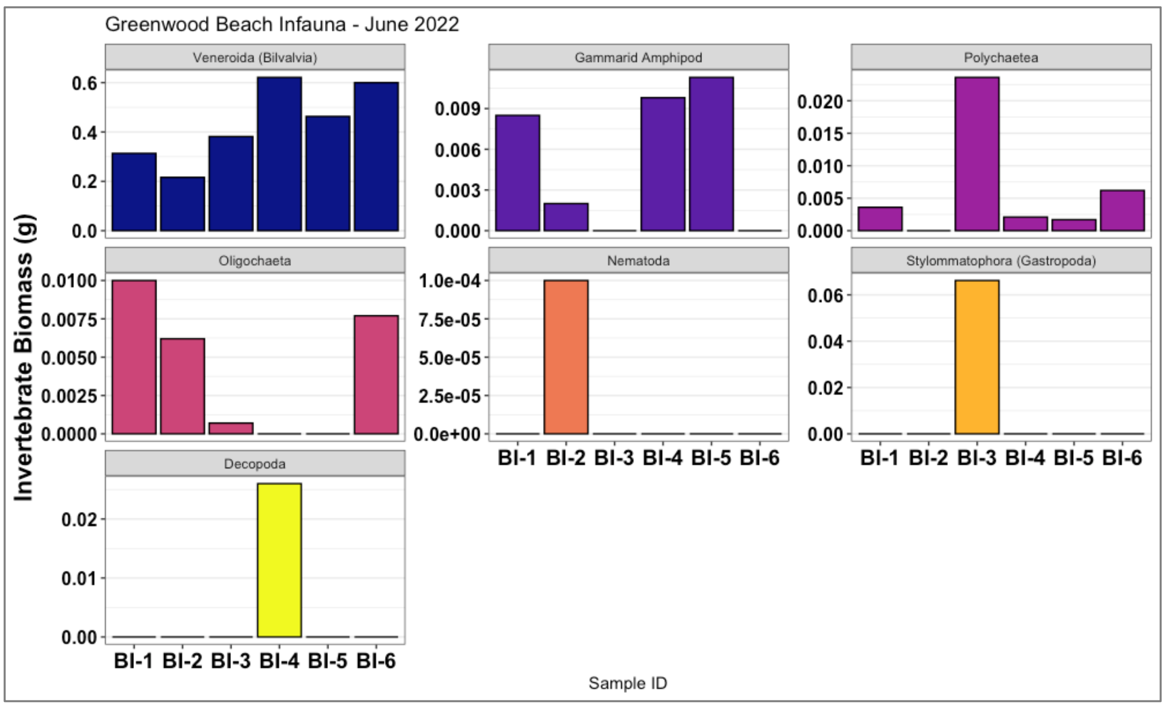


Figure 6. Total invertebrate biomass in grams separated out by taxonomic group.

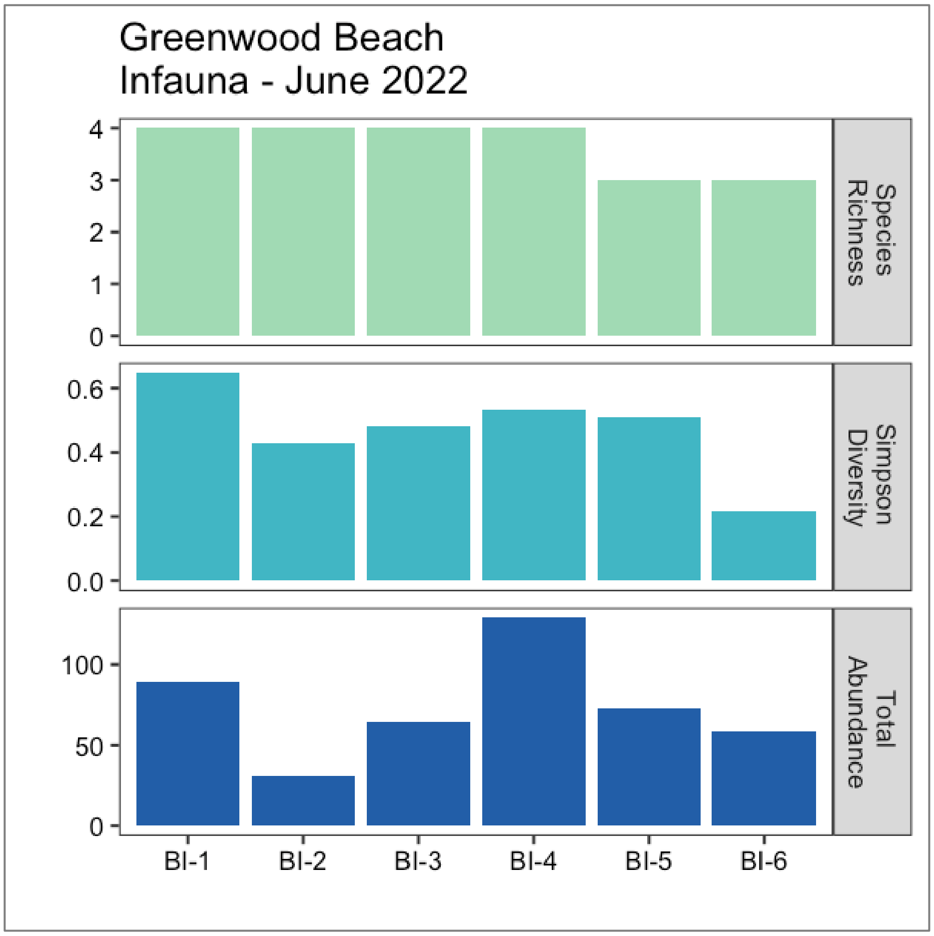


Figure 7. Species richness, Simpson diversity index, and total abundance of invertebrates.