

Humboldt Bay Trail Planning Study: Eureka to College of the Redwoods

Preliminary Flood Hazards, Sea Level Rise, and Tsunami Vulnerability Assessment

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1 INTRODUCTION

1.1 Study Purpose and Scope

The County of Humboldt (County) is preparing a planning study for the anticipated next major segment of the Humboldt Bay Trail (HBT), extending from the southern end of Eureka to College of the Redwoods (Project), with the support of RCAA, GHD, GRTA, and several others (Figure 1). This segment of the HBT will be an approximately 4.1 mile long paved, multi-use trail and will connect to a recently completed trail segment constructed by the City of Eureka near the Elk River Estuary. A significant length of the proposed HBT Project will be offset from the Humboldt Bay shoreline. However, two segments of the Project trail alignment run along the immediate shoreline of Entrance Bay and South Bay and represent the most vulnerable sections of trail to shoreline erosion from coastal flooding, waves and sea level rise.

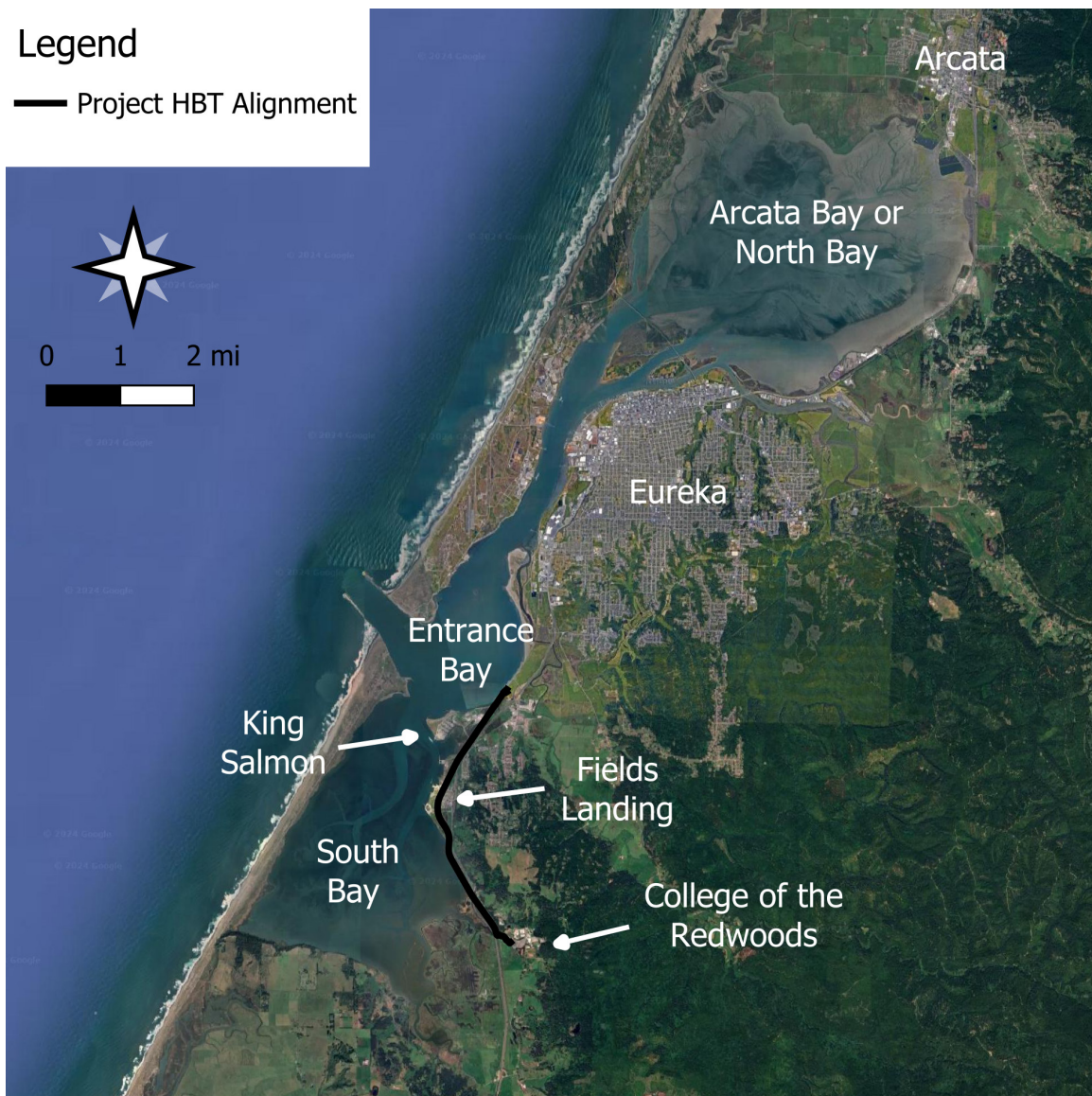


Figure 1. Vicinity map of Humboldt Bay and the proposed Project Humboldt Bay Trail (HBT) alignment.

Northern Hydrology and Engineering (NHE) was retained by the County to conduct a preliminary assessment of flood hazards and vulnerabilities for both current conditions and future conditions with sea level rise, and vulnerability associated with tsunami, to support the proposed HBT Project. The key components of this preliminary assessment are:

- Historical overview of shoreline changes and current conditions,
- Preliminary assessment of Humboldt Bay coastal hydrology, geomorphic processes, sea-level rise and tsunami vulnerability,
- Qualitative description of high-risk and low-risk sections of the proposed HBT alignment,
- Refined vulnerability analysis of the Entrance Bay RSP section and South Bay shoreline segments, and
- Recommendations for short-term and long-term options for sea-level rise adaptation.

This preliminary assessment focused on two key coastal flood scenarios for the proposed HBT alignment:

1. When the trail will be inundated from still water flooding caused by water levels in Humboldt Bay (wave effects are not considered).
2. When the trail will be overtopped by wave runup from locally generated wind-waves in Humboldt Bay or incident ocean waves entering Humboldt Bay through the bay entrance (includes still water levels and wave effects).

All sections of the proposed HBT trail are vulnerable to still water flooding. However, much of the HBT alignment is offset from the Humboldt Bay shoreline by 400 ft or more, and wave runup and overtopping is considered not significant at those locations as wave energy will be dissipated prior to reaching the trail grade. Only sections of the HBT alignment that are immediately adjacent to the shoreline will be assessed for wave overtopping in this preliminary assessment.

Results of the preliminary assessment are summarized in this report and were developed to support the initial planning and design phase of the Project and may need to be refined for future or final design phases and/or implementation. Information and data presented in the report are from publicly available sources, previous Humboldt Bay studies by NHE and other consultants, site data and imagery provided by the County, and site observations and additional analysis by NHE.

This analysis was conducted in SI units (e.g. water levels and wave height in meters (m), wind speed as meters per second (mps)), and only final tabulated results will be presented in English units. Water levels or water surface elevations are referenced to the North American Vertical Datum of 1988 (NAVD88).

1.2 Project HBT Description, Setting and Alignment

The proposed Project HBT 10% and 30% design plans (GHD, 2024a, 2024b and 2024c) and draft design criteria technical memo (GHD, 2023) were reviewed, and applicable information was integrated into this assessment. The proposed HBT alignment is approximately 21,840 ft (4.14 mi) long and located adjacent to or along the eastern shorelines of Humboldt Bay, specifically Entrance Bay and South Bay (Figure 1), and generally follows the existing railroad alignment and prism. Specifically, the proposed trail alignment will extend from the terminal end of a recently completed segment adjacent to Entrance Bay, run southwest and slightly inland of the shoreline to Fields Landing where it will gradually curve to the southeast staying inland of the shoreline. After passing through Fields Landing the alignment bends towards South Bay, and then runs southeast along the immediate South Bay shoreline before moving inland of the shoreline just before passing under Highway 101 and running towards College of the Redwoods.

For this study, the proposed Project HBT alignment has been divided into five trail segments (Figure 3), which are described from north to south as follows:

- Trail Segment 1 (TS-1) ties into the City of Eureka's existing Elk River Slough Trail segment and runs adjacent to the shoreline of Entrance Bay, but offset to the east of the railroad prism and shoreline rock revetment by 50+ ft. The proposed elevation of TS1 is 14 ft and the length is 1,373 ft (0.26 mi). [Sta 229+73 to 216+00]
- Trail Segment 2 (TS-2) has a total length of 11,500 ft (2.18 miles) and runs from TS-1 to the location south of Fields Landing where the trail runs adjacent to the shoreline of South Bay. Most of the TS-2 alignment is offset from the shoreline by a minimum distance of approximately 400 ft, except for small sections at the segment ends. Elevations of TS-2 range from 10.5 to 14 ft. Beginning at the TS-1 tie-in the TS-2 elevation transitions from 14 to 12 ft over 400 ft of trail length. The TS-2 elevation then transitions from elevation 12 to 10.5 ft over the next 2,600 ft (0.49 mi). The next 8,300 ft (1.57 mi) of TS-2 is at an elevation of 10.5 ft. The final 200 ft of TS-2 transitions from 10.5 to 11.5 ft elevation at the TS-3 tie-in. [Sta 216+00 to 101+00]
- Trail Segment 3 (TS-3) extends 4,100 ft (0.78 mi) southeast from the TS-2 segment at a constant trail elevation of 11.5 ft, except for the last 40 feet where the trail ramps up to elevation 12 ft. The entire TS-3 segment runs along the immediate shoreline of South Bay, and as will be discussed later, represents the most vulnerable section of the proposed HBT alignment to coastal erosion. The shoreline along the TS-3 reach consists of both RSP and natural shoreline sections. [Sta 101+00 to 60+00]
- Trail Segment 4 (TS-4) is the final trail segment along the railroad prism and continues 4,600 ft (0.87 mi) southeast from TS-3 segment. The initial about 1,420 ft of trail from TS-3 stays at a constant elevation of 12 ft, transitions from 12 ft to 8 ft over the next approximately 370 ft, and then stays at elevation 8 ft for approximately 1,840 ft. The final TS-4 section that follows the railroad prism is 970 ft long and transitions in elevation from 8 to 10 ft over its first 270 ft. Like TS-2, most of the TS-4 segment is offset from the South Bay shoreline by 400 ft or more. [Sta 60+00 to 14+00]
- Trail Segment 5 (TS-5) is the final approximately 1,300 ft (0.25 mi) of trail that leaves the railroad grade, runs east for a short distance, and then travels parallel to Tompkins Hill Road before crossing into the College of the Redwoods campus. Proposed elevations for TS-5 range from 7.3 to 14.8 ft. [Sta 14+00 to 1+00]

This report assesses the TS-1 to TS-4 portions of the proposed HBT but does not assess the inland TS-5 segment.

To support this preliminary assessment, the Humboldt Bay shoreline adjacent to the HBT alignment was split into the three shoreline reaches (Figure 3), designated as Shoreline Reach 1 (SR-1), Shoreline Reach 2 (SR-2), and Shoreline Reach 3 (SR-3). These shoreline designations will be used in later sections.

Most of the historic railroad prism of the proposed Project HBT alignment appears to have been constructed on the former low-lying grassland and tidal wetlands that historically fringed Entrance Bay and South Bay. The existing railroad grade is relatively low, with a typical elevation around 10 ft and ranging from 10 to 14 ft (NAVD88). Portions of the railroad prism, particularly along the immediate shoreline in TS-3 (Figure 3), show signs of ballast and fill erosion.

Legend

- Project HBT Alignment
- Project HBT Alignment
- Shoreline Reaches

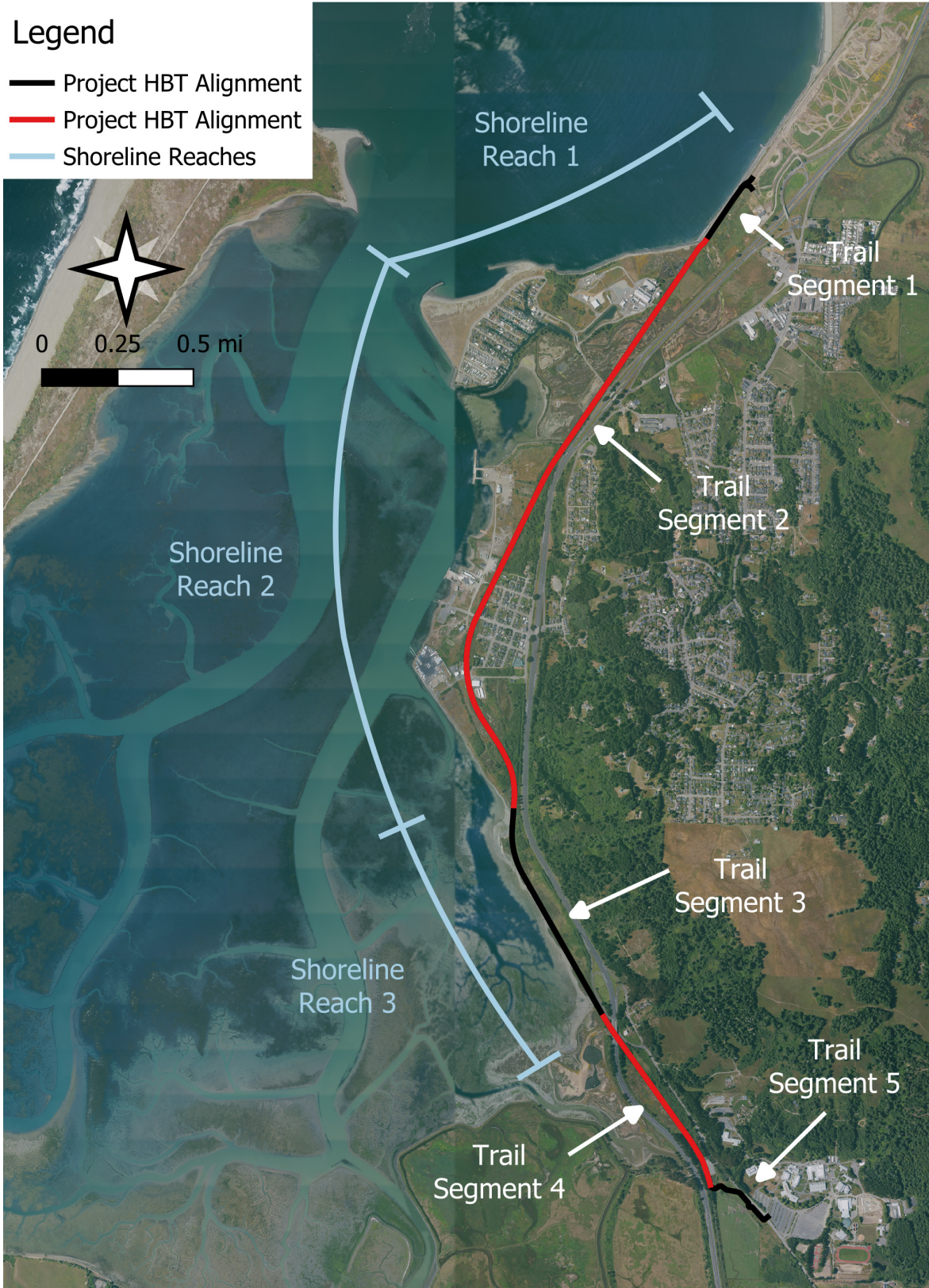


Figure 3. Proposed Project Humboldt Bay Trail (HBT) segments (Trail Segments 1, 2, 3, 4 and 5) and defined shoreline reaches (Shoreline Reach 1, 2, and 3) of the eastern Entrance Bay and South Bay shoreline.

2 PROJECT SETTING AND SHORELINE CONDITIONS

2.1 Physical and Geomorphic Setting

Humboldt Bay is a multi-basin, bar-built coastal lagoon located approximately 260 miles (418 km) north of San Francisco, California, is the second largest natural bay in California, and the only major harbor between San Francisco and Portland, Oregon (Costa and Glatzel 2002). Humboldt Bay consists of three basins, Arcata Bay (or North Bay), Entrance Bay and South Bay (Figure 1). North Bay is connected to Entrance Bay by a long narrow channel (North Bay Channel) that splits into multiple channels at the northern end, and South Bay and Entrance Bay are separated by a constriction between King Salmon and the South Bay spit. Humboldt Bay has a water surface area of approximately 25 mi² (65 km²) at high tide, 8 mi² (21 km²) at low tide, and about 70% of the bay is exposed tidal mudflat at low tide, with most of the mudflat contained in shallower North and South Bays (Costa and Glatzel 2002).

The region is known for its high erosion rates and fluvial sediment supply, which is generally attributed to a combination of unique land use, climate, geology and tectonics (Kelsey 1980; Mackey et al. 2011; Warrick et al. 2013). The current land cover is predominated by evergreen and mixed forest with the bulk of remaining land in a mixture of shrub and grassland. Principle land uses across the region consist of timber harvest, which peaked in the 1950s and 1960s, as well as cattle grazing that has remained relatively stable over time (Warrick et al. 2013). Although the region's climate is relatively moderate (cool temps with moderate precipitation of 30-40 inches/year), the wave climate is quite extreme with large frequent swells emanating from both the North and South Pacific (Wheatcroft and Borgeld 2000; Costa and Glatzel 2002; George and Hill 2008).

Humboldt Bay lies within the 42 mile (67 km) long Eureka littoral cell (ELC) which is bounded by Trinidad Head to the north and False Cape to the south (see Figure 19). The ELC has an approximate 4,520 mi² (11,700 km²) contributing watershed, and the two largest rivers (Eel River and Mad River) discharge directly into the ELC. In comparison, the Humboldt Bay watershed is relatively small at 223 mi² (578 km²). The four largest Humboldt Bay streams are Jacoby Creek and Freshwater Creek that discharge into North Bay, Elk River that discharges into the northern end of Entrance Bay, and Salmon Creek that discharges into South Bay.

The dominant forcing in Humboldt Bay are tides, followed by incident ocean waves that pass through the jetty into Entrance Bay, with wind and locally generated wind-waves having a secondary forcing in the shallow North and South Bays (Costa and Glatzel 2002). Due to the small watershed size and low freshwater flows, the circulation in Humboldt Bay is tidally dominated and the bay consists of well-mixed marine water. Seasonal estuarine conditions are generally associated with the sub-estuary regions of the bay tributaries (Costa and Glatzel 2002).

Much of the shoreline along the proposed Project HBT alignment consists of rock revetment (also called armoring or rock slope protection (RSP)), industrial and commercial wharfs and bulkheads, unfortified filled shoreline, and small sections of natural shoreline (Laird et al. 2013). Portions of the railroad prism, particularly along the immediate shoreline in TS-3 (Figure 3), show signs of ballast, fill and RSP erosion. Sections of the shoreline have a gravel/cobble beach often located immediately shoreward of the revetment toe, which consists of a thin layer of eroded railroad ballast or coarse fill materials overlying the mudflat.

2.1.1 Sediment Sources

Sediment sources to Entrance Bay include (1) littoral sediments from coastal beaches transported into the bay by waves and currents through the entrance, (2) locally generated littoral sediments from shoals, bottom sediment and the Elk River spit from wind, wave and current resuspension, scour and transport, (3) sediments delivered by Elk River, and (4) sediment eroded from the shoreline and adjacent bluffs by waves, although this sediment source is likely small today due to the shoreline armoring (Department of the Army 1957; Costa and Glatzel 2002). Review of imagery and field observations by NHE indicate that net long-shore transport appears to be northward towards the Elk River spit.

Sediment sources to South Bay include (1) sediments transported from Entrance Bay into South Bay by wind and tidal currents, (2) locally generated fine-grained sediments resuspended from the mudflats from wind-waves during wind events, and tidal current scour and transport, (3) sediments delivered by Salmon Creek, and (4) sediment eroded from the shoreline and bluffs by waves. Although portions of South Bay are armored, South Bay has the largest amount of natural shoreline and bluffs in Humboldt Bay (Laird 2013) that would be more vulnerable to erosion.

2.1.2 Longshore Transport

The net longshore transport or drift of sediment in Humboldt Bay is not well documented, although some historical accounts of littoral drift patterns in Entrance Bay exist, and the GHD et al. (2022) study discusses shoreline drift patterns along the eastern shoreline of North Bay. A study by the Department of the Army (1957) regarding the erosion of Buhne Point describes littoral transport in Entrance Bay from waves, both incident ocean waves entering the bay through the entrance and local wind-waves, and tidal currents. The continual erosion of Buhne Point and formation of Elk River Spit indicated northerly transport, while the continuous erosion of Buhne Spit and shoaling of Fields Landing Channel indicated southerly transport. The Department of the Army (1957) document did not describe the net longshore transport direction in Entrance Bay.

Today most of the easterly shoreline of Entrance Bay is armored with RSP and the erosion of Buhne Point and shoreline has decreased or stopped. NHE review of imagery from 1965 to 2022 shows persistent sediment accretion behind two groin features, indicated by the seaward offset of the shoreline, along the easterly shoreline in Entrance Bay located in Shoreline Reach 1 and adjacent to Trail Segment 1 (Figure 4). This accumulation of sediment on the south side of the groins also supports the conclusion that the net longshore transport along the easterly shoreline of Entrance Bay has been from south to north since at least 1965.

No longshore transport information was found for South Bay, and review of imagery did not indicate any obvious net shoreline drift direction. However, the easterly shoreline of South Bay (Shoreline Reach 3 in Figure 3) is perpendicular to the southerly wind directions (refer to Section 3.4), and this orientation indicates that shoreline drift likely occurs in both directions.

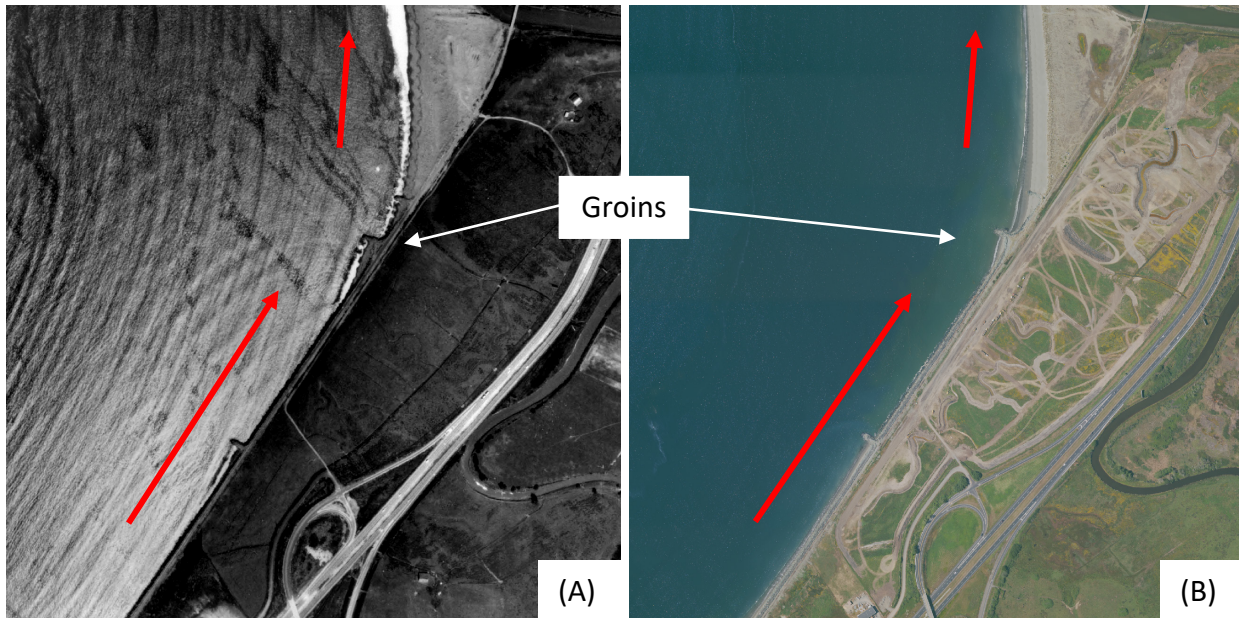


Figure 4. Easterly shoreline offset at groins in Entrance Bay on 1965 (A) and 2022 (B) aerial images indicating south to north net longshore transport or net drift directions (red arrows).

2.2 Topography and Bathymetry

Project area topography and bathymetry was defined by the 2020 USGS Coastal National Elevation Database (CoNED) 1-meter topobathymetric digital elevation model (TBDEM) for the Northern California Coast (2020 USGS CoNED DEM). The 2020 USGS CoNED DEM (or Project DEM) consists of multiple topographic and bathymetric data sets ranging in dates from approximately 1986 to 2019 that have been aligned vertically and horizontally to a common reference system (OCM Partners 2024).

Figure 5 shows the topography and bathymetry of the Project area in the vicinity of the proposed HBT alignment. Also provided are the proposed HBT trail segments and the shoreline reaches as previously defined (Figure 3).

According to the online metadata information (OCM Partners 2024), it appears that the topographic data surrounding Humboldt Bay relied on the City of Eureka 2019 Humboldt Bay LiDAR (24 September 2019 acquisition date). For this work, it was assumed that the City of Eureka 2019 Humboldt Bay LiDAR represents ground elevations in 2019 at the time of the acquisition and has not been adjusted for vertical land motion either before or after the acquisition date. This distinction is important when comparing ground elevations to observed or modeled water surface elevations, and when considering future sea-level change.

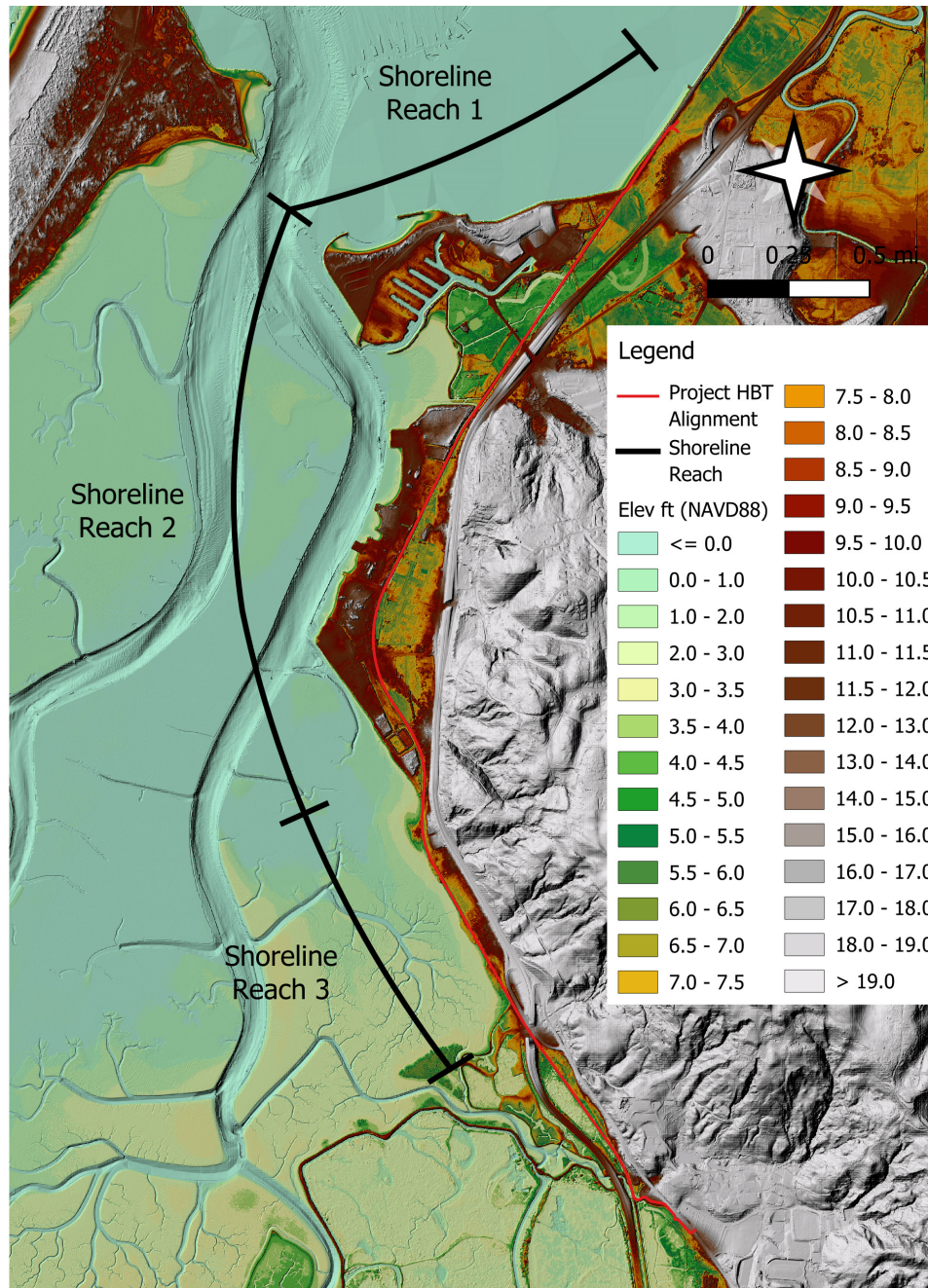


Figure 5. Project area topography and bathymetry in vicinity of proposed HBT alignment. The shoreline reaches and HBT alignment provided for reference. Topography and bathymetry based on 2020 USGS CoNED DEM.

2.3 Historical Shoreline Development and Change

This section provides a summary of the historical shoreline and railroad development in the general vicinity of the proposed Project HBT alignment based on review of a few key references. It is not intended to be a detailed description or timeline of historical development, which is beyond the scope of this work. Historic Humboldt Bay nautical charts are provided in this section to help visualize the shoreline development and changes. However, since the nautical charts were intended to document

changes to the bay for navigation purposes they appear to lag documenting land changes, such as the period documented for the railroad construction.

Figure 6 provides a side-by-side comparison of the 1851 Preliminary U.S. Coast Survey map, 1870 U.S. Coast Survey Map, 1894 U.S. Coast and Geodetic Survey Map, and 1916 U.S. Coast and Geodetic Survey Map. This figure is clipped to the vicinity of the proposed HBT alignment and shows the changes of the shoreline and land use over the approximate period of 1851 to 1916. The 1851 preliminary U.S. Coast Survey map is one of the earliest maps showing conditions at these locations of the bay prior to significant shoreline development. For reference, the proposed HBT alignment and shoreline reaches are provided on the 1870 map (Figure 6C).

Historically, Humboldt Bay was surrounded by extensive tidal marshes, slough channels and sandy shorelines. Review of Figure 6A and Figure 6B shows that tidal wetlands existed along the entire eastern shoreline of South Bay and wrapped behind Red Bluffs, and the eastern shoreline of Entrance Bay consisted of low-lying grassland. As documented by Laird et al. (2013), between the 1890s to 1910s approximately 90% of the Humboldt Bay tidal wetlands and associated bay shoreline were leveed to convert the marsh areas to agricultural uses or to construct the Northwest Pacific Railroad.

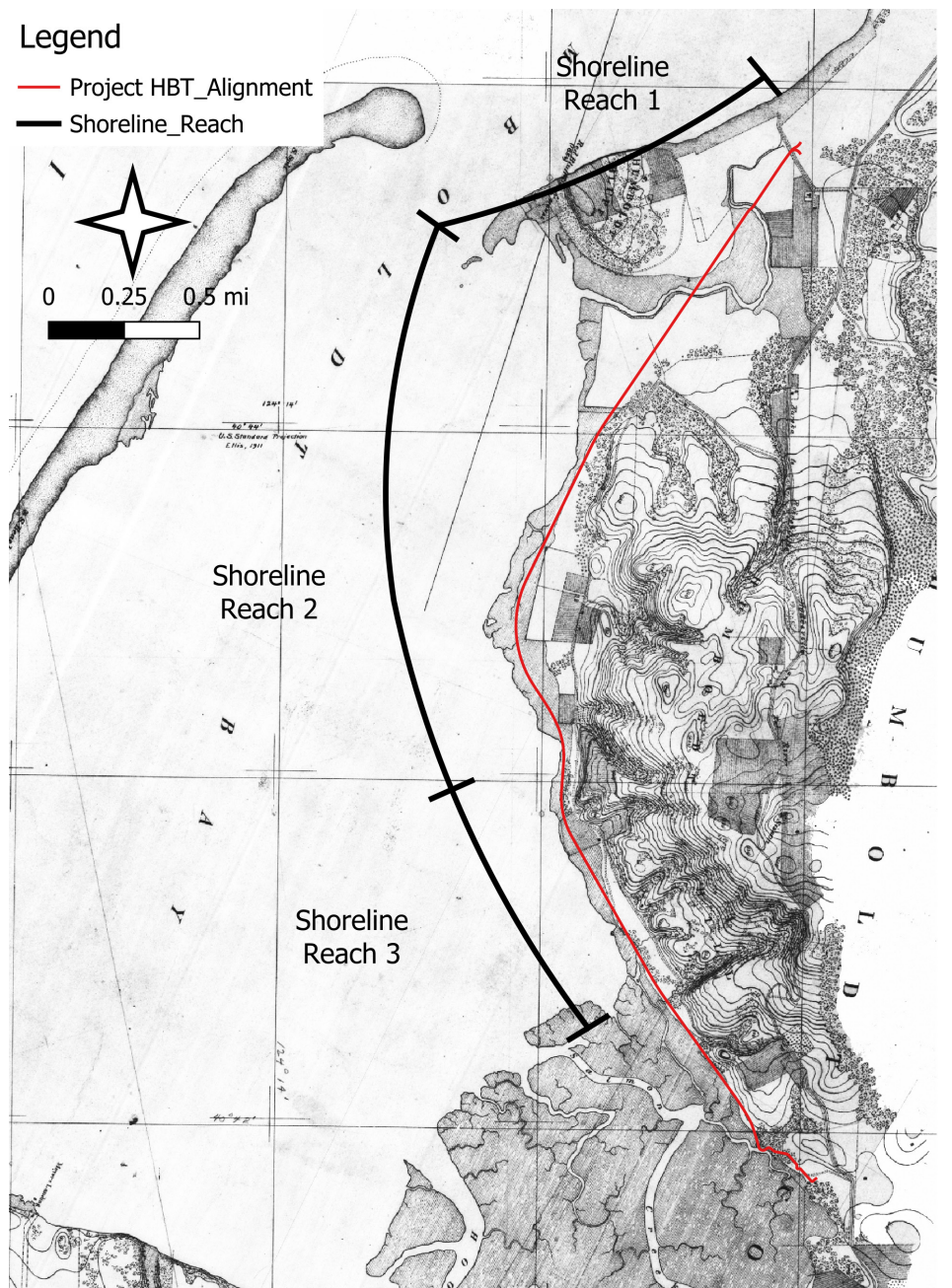
The 1851 preliminary map (Figure 6A) depicted tidal wetlands generally extending from the bay to the bottom of the hillslopes or bluffs all along Shoreline Reach 2 and 3. However, the 1870 map indicated tidal wetlands fringing the bay and transitioning to uplands with a brush or woodland pattern to the bottom of the bluffs. The 1870 tidal wetland and upland configuration better aligns with the present-day topography in Shoreline Reach 3 (Figure 5), where the shoreline between HWY101 (historic bluff edge) and the bay ranges in elevation between 6 to 12 ft, with much of this area at an elevation of 10 ft or greater.

Land use changes from the historic natural landscape to a developed condition are evident in Figure 6 along the HBT alignment shoreline and are generally indicated by the removal of the historic or natural map symbol pattern to agricultural/cultivated pattern or a blank or white fill pattern. Comparison of the 1851 (Figure 6A) and 1870 (Figure 6B) maps indicates that large portions of the tidal wetland and grassland had been converted to likely agricultural uses, although limited wetland conversion had occurred along the south-eastern shoreline of South Bay (Shoreline Reach 2 and 3). Since 1870 predates levee construction, most of the agricultural land in this area was offset from the shoreline by a strip of tidal wetland, with the agricultural land likely occupying the higher upland areas adjacent to the wetlands. A road had also been established at the base of the eastern hillslope, and it is interesting to note that in Shoreline Reach 3 a spur road extended to an outbuilding (rectangle with an X in the center) located at the closest point of the upland to the bay. Perhaps this building was a barn or boat access location, but another indication that the ground elevation at this location was likely higher than tidal marsh elevations (6 to 7 ft) that would have been tidally inundated often.

There was limited change along the shoreline between 1870 and 1894 (Figure 6C) except for establishment and expansion of Fields Landing, and the construction of the Fields Landing wharf. By 1916 (Figure 6D) Fields Landing and Fields Landing wharf, docks and bulwark had been significantly expanded, and the Northwest Pacific Railroad had been constructed through the area. All the land east of the railroad grade had been converted to agricultural or other land uses, indicating that the railroad grade was high enough to act as a levee from the bay. Most of the shoreline levee construction had been completed by 1914 and large sections of tidal wetland conversion are apparent at Hookton Slough and south of Point Humboldt (Buhne Point). Only small, fragmented sections of tidal wetland remained along the bay shoreline or between the railroad grade and the bay.



1851 Preliminary U.S. Coast Survey Map (A)



1870 U.S. Coast Survey Map (B)



1894 U.S. Coast and Geodetic Survey Map (C)



1916 U.S. Coast and Geodetic Survey Map (D)

Figure 6. Comparison of 1851 Preliminary U.S. Coast Survey map (A), 1870 U.S. Coast Survey Map (B), 1894 U.S. Coast and Geodetic Survey Map (C), and 1916 U.S. Coast and Geodetic Survey Map (D) for the proposed HBT alignment. The 1870 map (B) is georeferenced and the HBT alignment and shoreline reaches are shown for reference. Maps A, C and D are clipped to the approximate extents of Map B but are not scaled.

Review of imagery from 1941 to 1970 indicated that all the remaining tidal wetlands in Shoreline Reach 1 and 2 (see Figure 3) had been reclaimed for agricultural uses or filled for the expansion of the Fields Landing docks and waterfront infrastructure. Today, the only remaining tidal wetlands in the study area are small fringe wetlands seaward of the railroad grade primarily in Shoreline Reach 3 (see Figure 2 and Figure 3); which will be discussed in more detail later.

The following describes the settlement of the general Project area and is excerpted from a document by Van Kirk (1975). The first settlement on Humboldt Bay was Humboldt City located on Humboldt Point (Buhne Point today) in 1850 and can be seen on the 1851 map (Figure 6A). With the developments of Eureka and Union City (Arcata), Humboldt City did not establish itself as the packing trade supply center and was ultimately abandoned and became part of the H.H. Buhne dairy farm. The Fields Landing wharf was constructed in the 1860s to support local farmers, but the settlement of Fields Landing didn't develop until the 1880s, although the area had farms and scattered residences as can be seen in Figure 6B and Figure 6C. The Eel River and Eureka Railroad was established in Fields Landing during the 1880s, and in 1885 the Pacific Lumber Company extended the railroad from Alton to Fields Landing and constructed the large wharf at Fields Landing to ship lumber.

The community of King Salmon (Figure 1 and Figure 2) was constructed in the late 1940s as a fishing community, that today is a small unincorporated coastal community (Tuttle 2004; Kunkel 2019). In 1952, Pacific Gas and Electric (PG&E) bought the Buhne Point Ranch (Tuttle 2004) and began the construction of several power plants on the high ground of Buhne Point.

Construction of the Humboldt Bay jetties began in the 1890s, followed by reconstruction in the 1910s and 1920s, with subsequent periods of repairs from the 1930s to present (Tuttle 2004; Costa and Glatzel 2002). The orientation of Humboldt Bay and the alignment of the jetties focused wave energy into Entrance Bay, and much of the Entrance Bay shoreline, specifically the eastern shoreline from Buhne Spit to Elk River including Buhne Point, has seen extensive erosion. Beginning in the 1900s, various efforts were taken by the Northwest Pacific Railroad and PG&E to prevent shore erosion such as timber bulkheads, seawalls and revetment (Department of the Army 1957; Tuttle 2004). Today the entire shoreline from Elk River Spit to Buhne Spit and the shorelines surrounding King Salmon are protected by a series of rock revetments, seawalls, and breakwaters.

Since the railroad grade in Fields Landing was established in the 1880s, which predates the initial tidal wetland reclamation and leveeing efforts in the 1890s, it appears the historic railroad prism of the Project HBT alignment was constructed on the former low-lying grasslands and tidal wetlands that historically fringed Entrance Bay and South Bay, respectively (Figure 6). Along Trail Segment 1 and the northern portion of Trail Segment 2 (Figure 3) it appears that the railroad prism was constructed on the higher grassland north of Buhne Point. For the southern portion of Trail Segment 2, Trail Segment 3 and Trail Segment 4 (Figure 3), the railroad grade was likely constructed on the higher upland areas adjacent to the bay or by placing 2 to 4 ft of fill and/or granular ballast directly on the tidal wetlands. As mentioned previously, the railroad grade effectively formed a berm between the bay and reclaimed lands to the east.

Based on Ferndale Enterprise newspaper articles dating from 1900 to 1911 (Van Kirk 1998), levee construction of the Hookton Slough area by Z. Russ & Sons Co. occurred between about 1904 to 1911. This is likely the same general time frame for the levee construction and reclamation of the remaining tidal wetlands directly south of Buhne Point (see Figure 6C and Figure 6D). A Merle Shuster oblique aerial photo dated 1955 shows the dredger Jupiter working the shoreline near the recently completed wharf between Fields Landing and Buhne Point (Rhode, not dated). As mentioned above, review of aerial images shows that the last bit of shoreline reclamation and levee construction in this area occurred between 1965 and 1970.

It is not clear how the railroad grade along Shoreline Reach 3 and Trail Segment 3 was constructed on the seaward edge of the tidal wetland fringing South Bay, how extensive the levee system was on the seaward side of the tidal wetland, or how this area was protected from wave erosion. To provide some potential insight, a series of maps and images documenting key shoreline features and changes is provided in Figure 7 and summarized as follows:

- The 1940 Army Corps of Engineers map of South Bay (Figure 7A) shows that a levee existed along the bayside tidal wetland edge in the center of Shoreline Reach 3, but only at this location.
- The 1941 aerial image (Figure 7B) and 1948 Shuster oblique photo (Figure 7C) clearly show that this levee was eroding, likely due to wave erosion from locally generated wind-waves in South Bay. By approximately the 1970s to 1980s, the levee had completely eroded, and no evidence of the levee exists today (Figure 7D).
- A section of eroding natural shoreline directly adjacent to the railroad is apparent in Figure 7B and Figure 7C. Since this section of railroad is adjacent to some of the lowest land elevations in the area (Figure 5), the eroding shoreline is likely the last remnants of a tidal wetland fringe. The natural shoreline in this location has completely eroded, and today the shoreline is armored with rock and concrete revetments (Figure 7D).
- A series of borrow areas or pits are apparent at multiple locations in this reach (Figure 7B and Figure 7C). It is not clear exactly what these features were used for, but more than likely the excavated material was used for the railroad fill prism during initial construction or for repair. Most of these pit locations are adjacent to the higher upland areas, where material would have been better suited for railroad grade fill material than the wetland materials. It is possible that they were created by a dredger, but since they are fragmented and extensive levee construction was not done in this reach, they were more likely excavated with land or rail-based equipment.
- A few of these borrow areas still exist today (Figure 7D), although some have filled in with sediment and vegetation, or have been partially eroded away by the retreating shoreline.

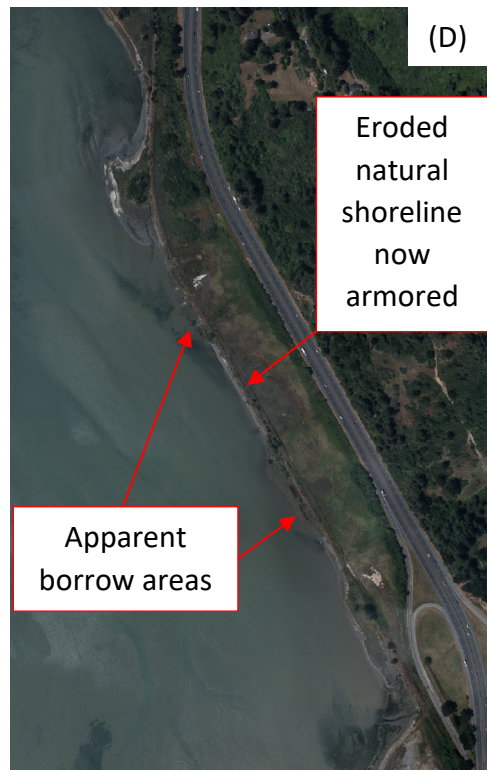
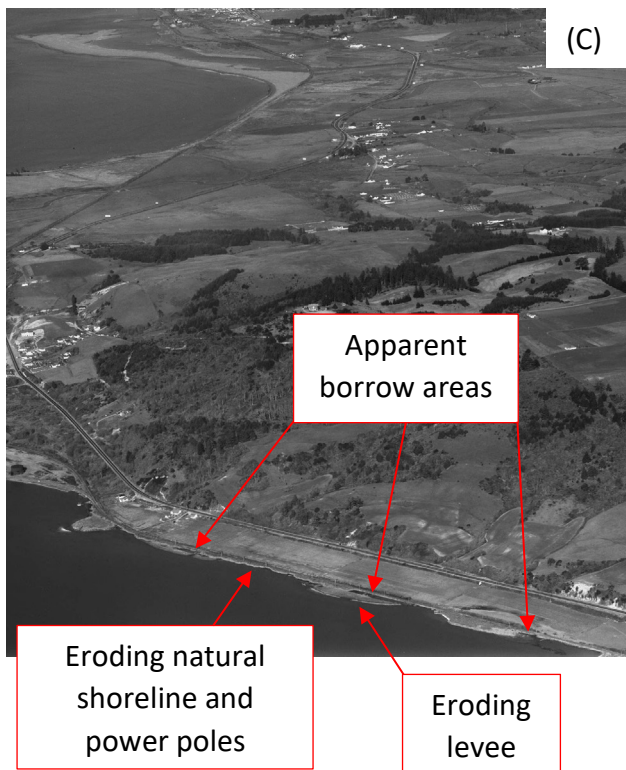
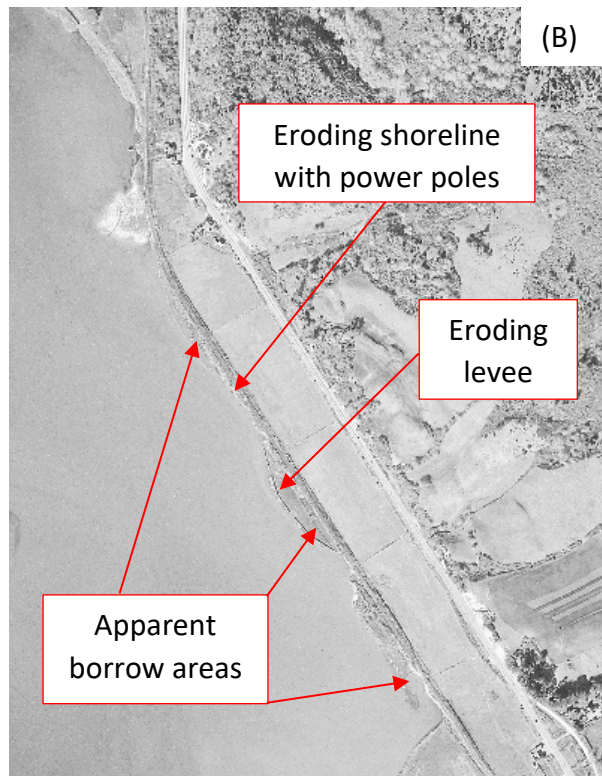
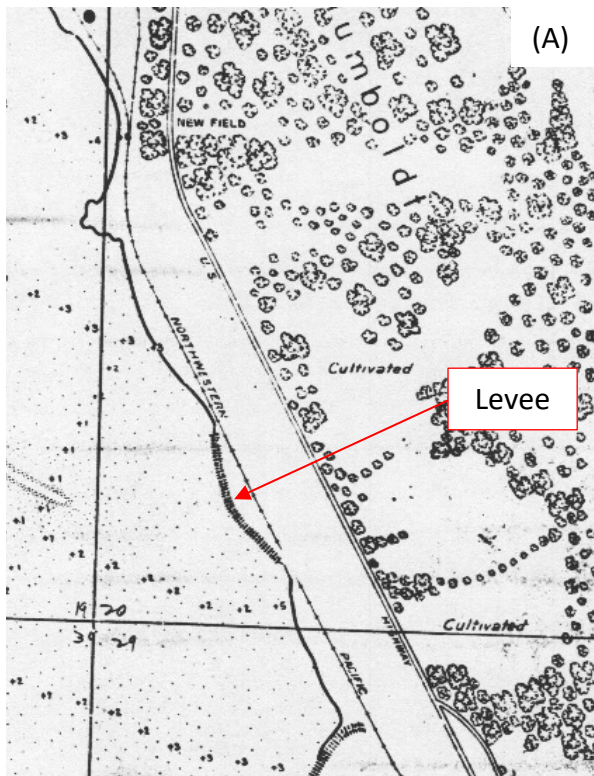


Figure 7. Comparison of 1940 U.S. Army Corps of Engineers map (A), 1941 aerial image (B), 1948 Merle Shuster oblique photo (C), and 2019 aerial image (D) for Shoreline Reach 3 and Trail Segment 3 of the proposed HBT alignment.

2.4 Existing Shoreline Condition

This section describes the existing condition of the three shoreline reaches (Shoreline Reach 1, Shoreline Reach 2, and Shoreline Reach 3) as previously defined (Figure 3). Existing conditions were based on review of recent aerial images, drone images of the HBT alignment provided by the County, and a site walk of Shoreline Reach 3.

2.4.1 Shoreline Reach 1

Shoreline Reach 1 extends along the eastern shoreline of Entrance Bay from south of Elk River spit to King Salmon (Figure 3 and Figure 5). As discussed previously, the entire shoreline is armored with rock revetments and seawalls from Elk River Spit to King Salmon, with dual rubble-mound breakwaters protecting the community of King Salmon. Design documents, as-built drawings, or other reports of the existing revetments and seawalls were not available, but information was available for the King Salmon shore protection (COE 1984, 1987a, 1987b).

The most critical length of shoreline in Shoreline Reach 1, as it relates to the proposed HBT alignment, is the 1,350-ft section adjacent to Trail Segment 1 (Figure 3). The remaining shoreline in Reach 1 is offset from the HBT alignment (Trail Segment 2) by more than 400 ft and will not be considered further in this study, as waves will be dissipated prior to reaching the railroad grade. Within Shoreline Reach 1, Trail Segment 1 will be analyzed for still water flooding and wave runup vulnerabilities, while Trail Reach 2 will only be analyzed for still water flooding vulnerability.

The shoreline along Trail Segment 1 consists of a sandy foreshore (beach face) backed by a rock revetment (Figure 8). Areas of the sandy beach contain gravel and small rock, likely material washed from the railroad prism and revetment. The foreshore is relatively narrow and slightly widens and gains elevation from north to south. Most of the foreshore is submerged during high tides. It is not clear the depth of the revetment toe embedment. The Project DEM shows the rock revetment toe ranging in elevation from 6 to 8 ft, with the revetment top at 12 ft. However, observations indicate the revetment rock extends well above 12 ft, and a FEMA (2014) cross-section (XS-76) at this location reports the revetment top at 17.65 ft.

In general, the rock revetment in Shoreline Reach 1 appears to be in reasonable condition. However, it is apparent that smaller rock is being dislodged from the revetment as rock is scattered seaward of the toe, and wave overtopping is displacing rock onto the railroad grade (Figure 9). Also, evidence of localized overwash erosion of the railroad grade material, likely caused by wave runup and overtopping flow, are apparent along back areas of the revetment (Figure 8B and Figure 9B). The locations of the overwash erosion may indicate low crest elevations of the rock revetment.

The longevity of the revetment adjacent to Trail Segment 1 depends, at a minimum, on the following:

- Stability of the outer rock and erosion of the inner core material.
- The longevity of the sandy foreshore to protect against toe erosion and failure, which depends on the availability of nearshore sand, longshore transport processes, and the stability of the groins.
- Stability and erosion prevention of the material behind the levee.

No information on the design, maintenance or stability of this rock revetment was found to support this study, although that information likely exists. It is recommended that any recent information on this section of revetment be collected and reviewed. If information is not available, then it is recommended that an assessment/study of the current revetment condition be conducted, and a long-term monitoring and maintenance plan be developed.



Figure 8. 2022 aerial image of Trail Segment 1 & 2 within a portion of Shoreline Reach 1 (A); and 2023 oblique aerial view of Shoreline Reach 1 existing rock revetment along the proposed Trail Segment 1 (B), note the localized overwash erosion from wave runup and overtopping on the back area of the revetment. Drone image (B) provided by County of Humboldt.



(A)



(B)

Figure 9. 2023 oblique aerial view of Shoreline Reach 1 existing rock revetment and dislodged rock along beach and on top of railroad grade (A); and localized overwash erosion and washover fan of the railroad grade fill from wave runup and overtopping behind the revetment (B). Drone images provided by County of Humboldt.

2.4.2 Shoreline Reach 2

Shoreline Reach 2 extends from Buhne Spit at the northern end to the Fields Landing wharf and dock infrastructure at the southern end (Figure 3), which was quite extensive historically. Figure 10 shows a comparison of the 1970 aerial image, which was at the height of shoreline development in this area, and the condition of the shoreline today (2022 aerial image). The following describes the general condition of the shoreline today from north to south:

- Beginning at King Salmon, the shoreline consists of a rock breakwater, revetment, and groin to Fisherman's Channel at the southern end, which is defined by a seawall and rock armoring.
- Between Fisherman's Channel and the northerly Fields Landing wharf, the shoreline consists of an armored levee that was likely constructed in the early 1900s to reclaim the easterly tidal wetland area for agricultural purposes. Portions of the tidal wetland were filled to support commercial/industrial uses. It is not known when the rock revetment was added to the seaward side of the levee, but a later section documents shoreline erosion in this area. A breach exists at the southern end of the levee, and much of the former tidal wetland area is inundated at high tide. Today this former tidal wetland area sits idle.
- The remaining portion of Shoreline Reach 2 is the heavily developed shoreline of Fields Landing, which consists of a series of armored levees, wharfs, piers, rock revetments, concrete and wood seawalls and bulkheads, and small sections of natural shoreline. These natural shoreline features are located between armored sections of shoreline. This entire section of shoreline between the railroad grade and the bay consists of fill material placed on the historic tidal wetlands. The typical elevation of this shoreline is approximately 10 ft, and ranges between 9 to 13 ft (Figure 5).
- It is worth noting that much of the ground elevation of the King Salmon residential area east of the railroad grade is around 6 ft (Figure 5), which was the historic tidal wetland elevation.

Like most of Shoreline Reach 1, the HBT alignment is offset from the shoreline by more than 400 ft in Shoreline Reach 2. Since waves will be dissipated prior to reaching the railroad grade, Shoreline Reach 2 will not be assessed for wave effects in this study. Trail Segment 2 will be analyzed only for still water flooding vulnerability.

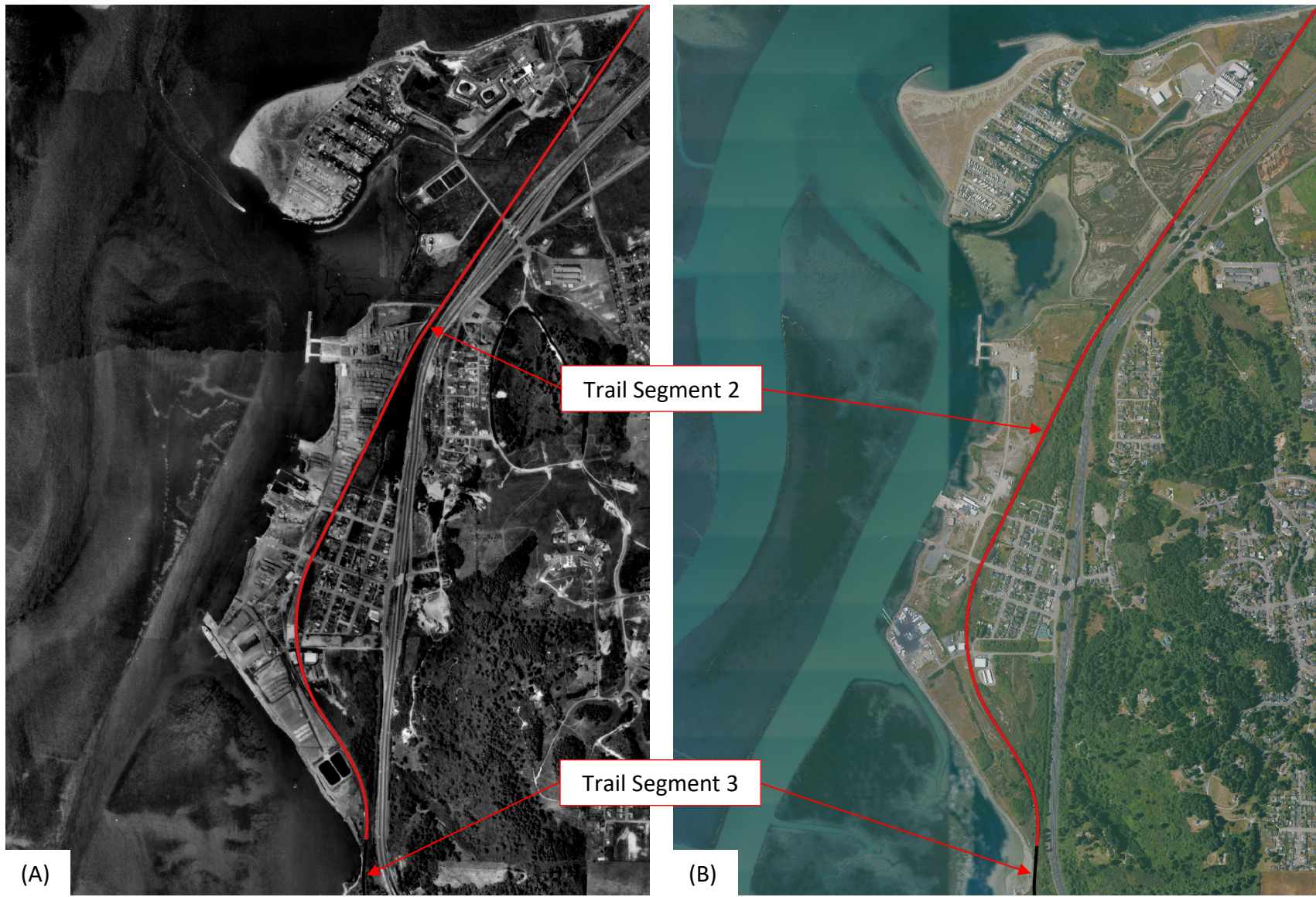


Figure 10. Comparison of aerial images of Fields Landing and the Fields Landing shoreline wharf and dock infrastructure and the King Salmon Development for 1970 (A) and 2022 (B) within Shoreline Reach 2 for Trail Segment 2.

2.4.3 Shoreline Reach 3

Shoreline Reach 3 begins at a slough channel along the southern end of the Fields Landing wharf and dock infrastructure and ends just prior to the HWY101 overcrossing (Figure 3, Figure 5 and Figure 11). Trail Segment 3 is the only HBT segment contained in Shoreline Reach 3, and the railroad grade runs adjacent to the easterly shoreline of South Bay. South Bay contains extensive mudflats that extend directly offshore of Shoreline Segment 3, while the shore edge consists of both natural tidal marsh scarps and armored shoreline segments (Figure 11). Low tides expose the mudflats, while the higher high tides inundate the fringe tidal marsh surfaces.

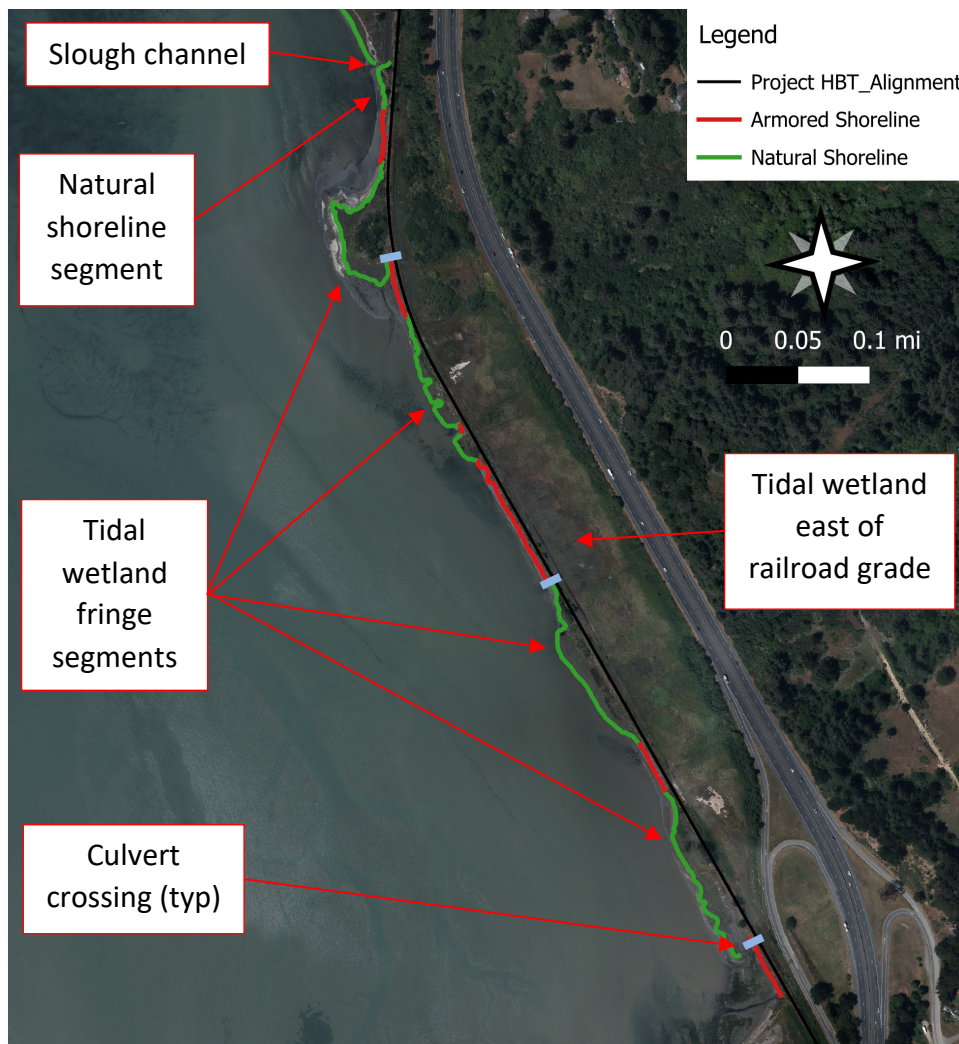


Figure 11. 2019 aerial image of Shoreline Reach 3 showing the HBT Trail Segment 3, natural tidal wetland and armored sections of shoreline, locations of three culvert crossings (blue line) through the railroad prism, and the tidal wetland area east of the railroad grade.

As mentioned in Section 2.3, it appears that the railroad grade was constructed on the tidal wetland and upland surfaces near the bay edge, but tidal wetland fringe remained between the shoreline and railroad grade. Over time the narrower sections of these fringe tidal wetlands eroded and today sections of the railroad grade are armored with rock and concrete revetments.

The following describes the general condition of the shoreline today in Shoreline Reach 3. This description is similar but differs slightly from the shoreline description provided by Laird et al. (2013).

- The northern end of Reach 3 contains a small section of natural shoreline at a typical elevation of 8 to 9 ft (Figure 5), that has eroded behind a failed wood bulkhead to its current location (Figure 12).
- Fringe tidal wetland areas occur at four locations along the shoreline (Figure 11) and have a typical elevation of about 7 ft, consistent with the MHHW elevation of 6.8 ft in South Bay (see Table 4), indicating that these small wetlands are keeping pace with sea-level rise. Each of the tidal wetland areas transition to a strip of vegetated upland that extends to the top of the railroad grade at an approximate 10-ft elevation. Figure 13 shows an oblique aerial view of the fringe wetlands along Reach 3.
- The fringe wetlands also contain the borrow areas or pits discussed in Section 2.3, and shown in Figure 14. The tidal wetland edge has eroded into some of these borrow pits as the wetland scarp erodes and retreats inland. The erosion of the borrow area shown in Figure 14 occurred between 2019 and 2022.
- Between the fringe tidal wetlands exist sections of armored railroad grade that make up the shoreline (Figure 11). The armoring consists of rock and concrete rubble revetments (Figure 14 and Figure 15).
- Two rock or concrete rubble groins were identified. It is not clear why groins were constructed at these locations.
- Portions of the railroad prism show signs of ballast and fill erosion, and sections of the low tide shoreline in front of the revetment consist of a thin layer of gravel/cobble beach overlying the mudflat (Figure 14 and Figure 15).
- The area east of the railroad between the railroad grade and HWY101 consists of tidal wetland areas that ranges in elevation from 6.5 to 7.5 ft in the center of Reach 3 that are surrounded by upland and transition areas up to an elevation of about 10.5 ft (Figure 14 and Figure 15).
- Three railroad grade culvert crossings with failed tide gates provide drainage from the easterly area into South Bay. The failed tide gates are providing a muted tidal inundation and tidal prism to the easterly tidal wetland areas (Figure 11, Figure 14 and Figure 15).
- Sections of the natural shoreline and railroad prism are showing recent signs of erosion (Figure 16). Erosion of the shoreline near the railroad grade occurred at the terminal end of the revetment and was apparent in the 2019 aerial, but the erosion into the railroad tracks (Figure 16) occurred between 2019 and 2023.

With Trail Segment 3 running along the immediate shoreline of South Bay within Shoreline Reach 3, it represents the most vulnerable section of the proposed HBT alignment to coastal erosion. Trail Segment 3 will be analyzed for vulnerability from both still water flooding and wave effects.

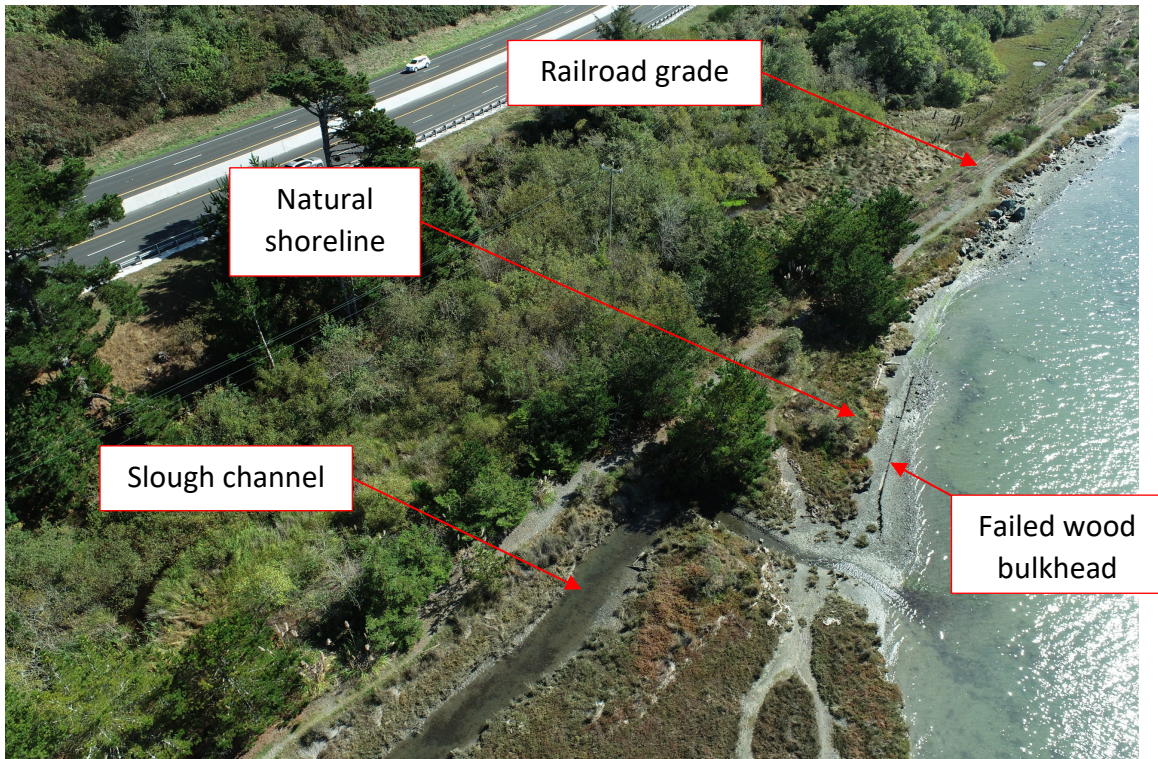


Figure 12. 2023 oblique aerial view looking south of the north end of Shoreline Reach 3 that shows natural section of shoreline that has eroded behind a failed wood bulkhead, and the slough channel separating Shoreline Reach 2 from Shoreline Reach 3 to the north. Drone image provided by County of Humboldt.

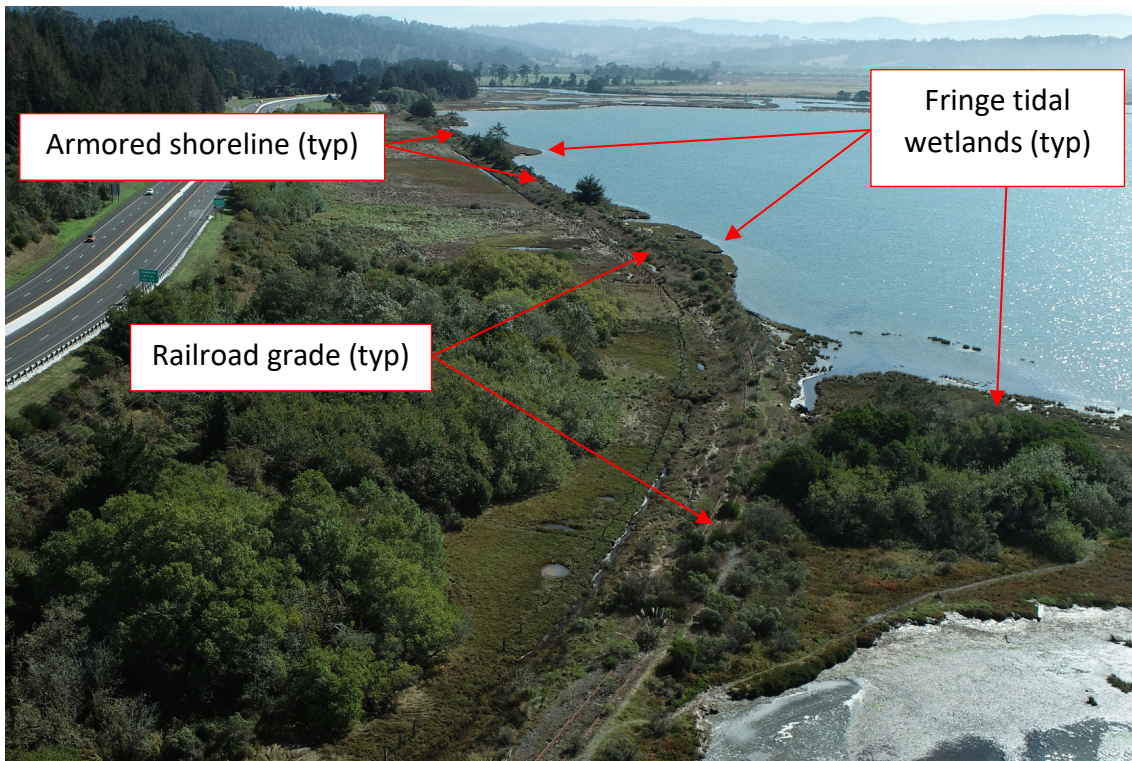


Figure 13. 2023 oblique aerial view looking south along Shoreline Reach 3 showing the fringe tidal wetland and armored shoreline sections bayward of the railroad grade. Drone image provided by County of Humboldt.

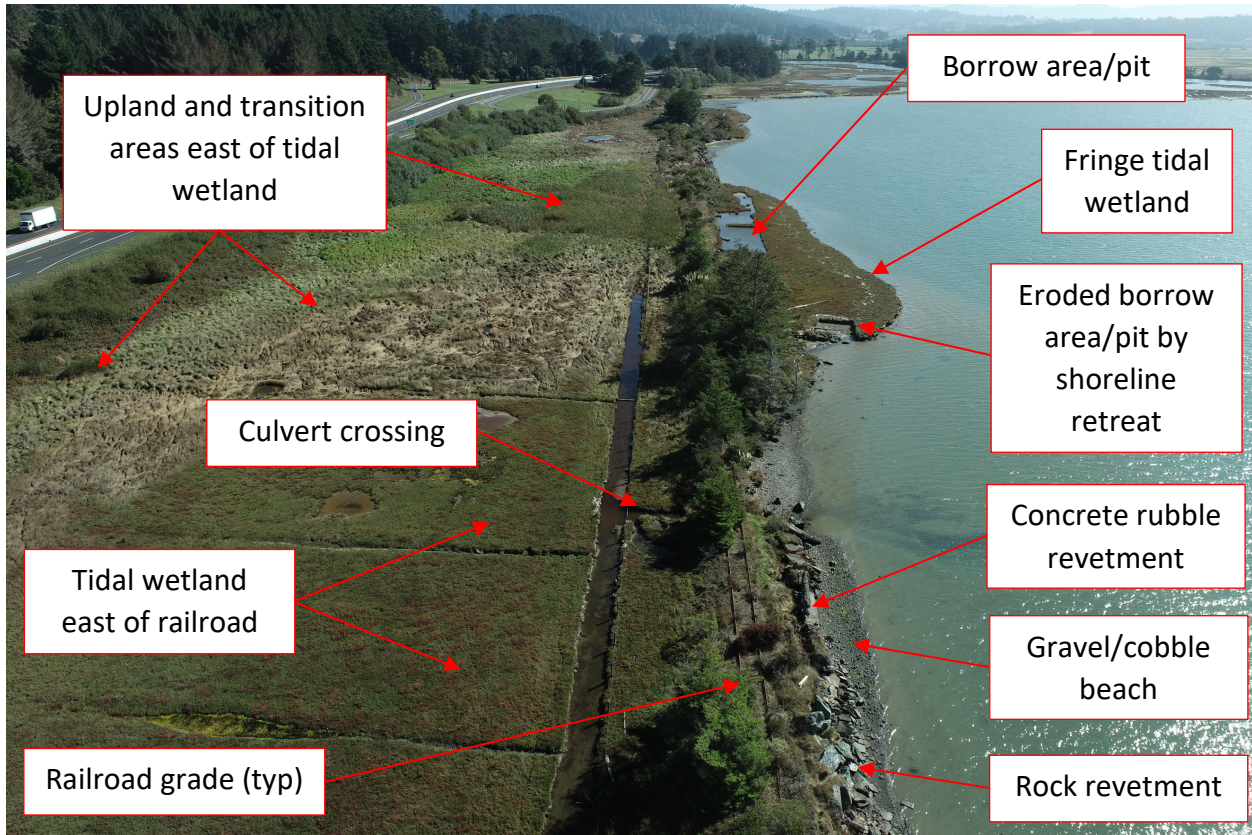


Figure 14. 2023 oblique aerial view looking south along Shoreline Reach 3 showing a fringe tidal wetland and borrow areas/pit, a borrow area eroded into by recent shoreline erosion and retreat (between 2019 and 2022), tidal wetland east of the railroad grade surrounded by upland area, culvert crossing through railroad prism, thin layer of gravel/cobble beach on top of mudflat from eroded railroad prism fill, and armored shoreline with rock and concrete rubble revetments. Drone image provided by County of Humboldt.

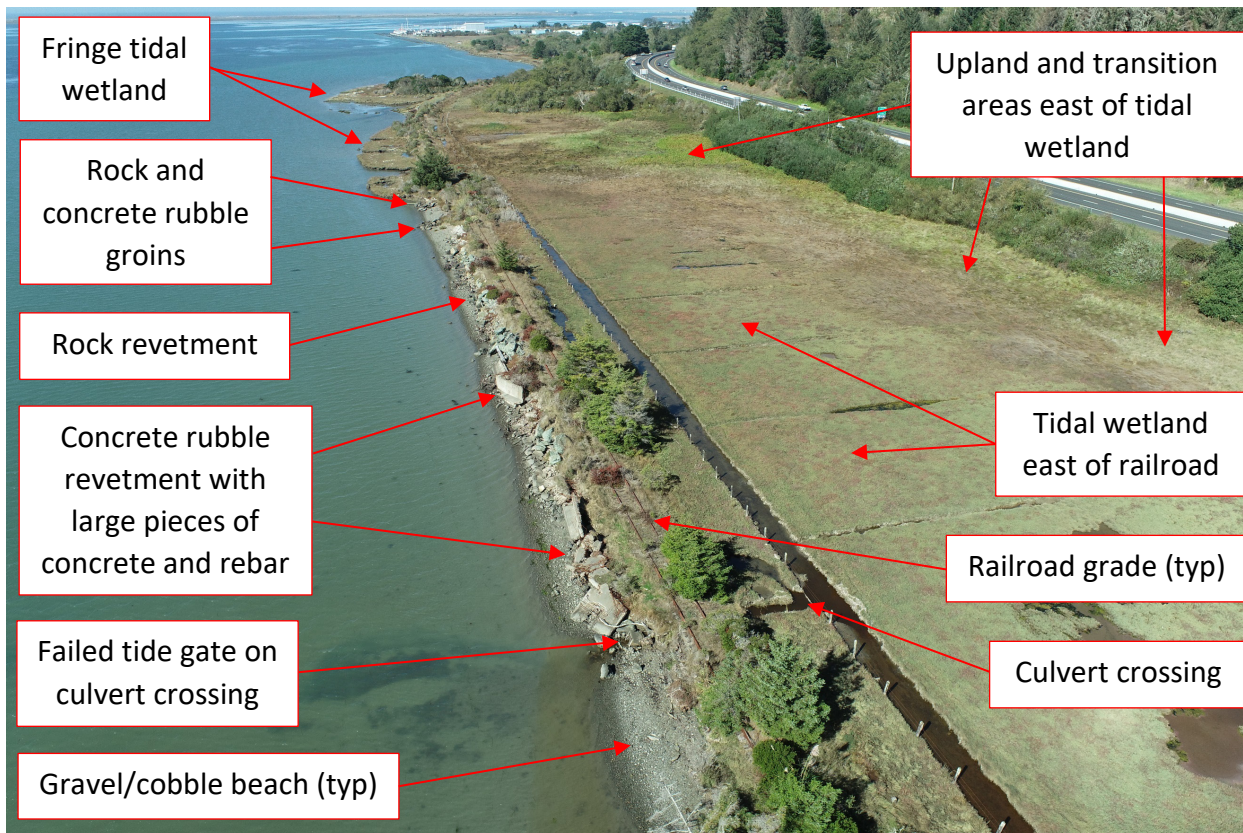


Figure 15. 2023 oblique aerial view looking north along Shoreline Reach 3 showing an armored section of shoreline with rock and concrete rubble revetments, tidal wetland east of the railroad grade surrounded by upland area, failed tide gate structure (door missing) on culvert crossing through railroad prism, thin layer of gravel/cobble beach on top of mudflat from eroded railroad prism fill, two small rock and concrete rubble groins at the north end armored shoreline, and large pieces of concrete and rebar rubble. Drone image provided by County of Humboldt.

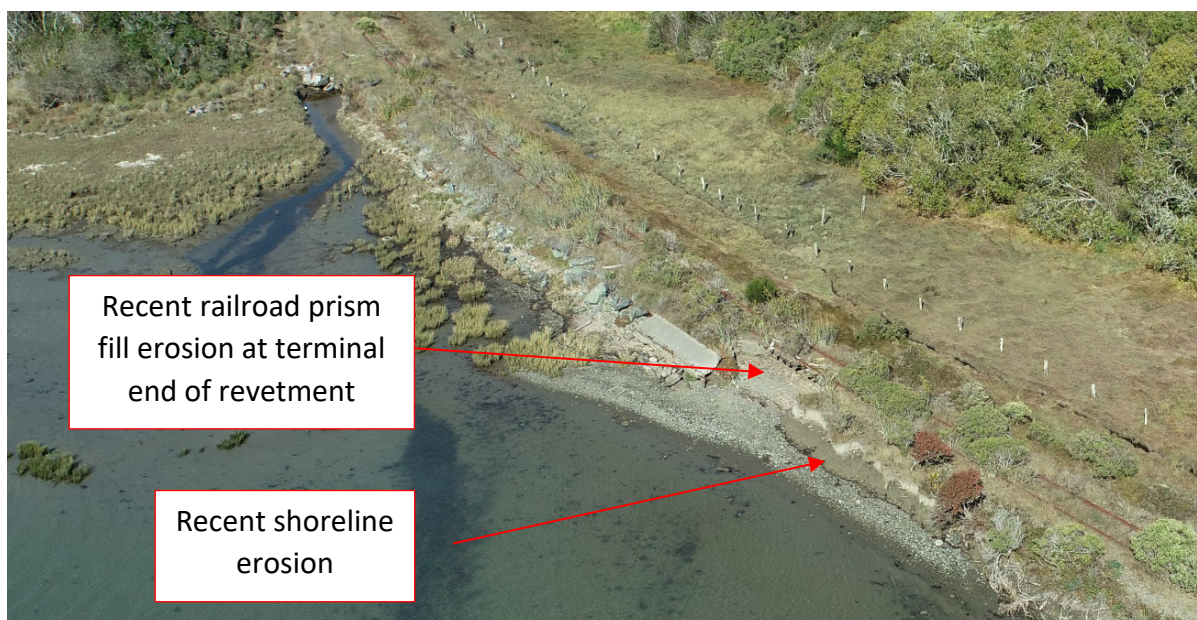


Figure 16. 2023 oblique aerial view looking east along Shoreline Reach 3 showing recent erosion of shoreline and railroad prism fill at terminal end of rock and concrete revetment. Drone image provided by County of Humboldt.

2.5 Shoreline Change and Trends

This section describes the shoreline changes that have occurred along the proposed HBT alignment. Most of the shoreline had been armored or developed by the 1950s, and with King Salmon being stabilized in the 1980s the shorelines in Shoreline Reach 1, 2 and 3 have been relatively stable since these dates.

2.5.1 Shoreline Reach 1

The historic erosion of the eastern shoreline of Entrance Bay, Buhne Point and Buhne Spit has been well documented (Department of the Army 1957; Bottin 1990; Tuttle 2004; Costa and Glatzel 2002). Erosion of the eastern shoreline of Entrance Bay initiated shortly after construction of the Humboldt Bay jetties began in the 1890s. As the jetties became longer, larger and more armored, and the entrance channel increased in depth, the wave energy entering Humboldt Bay intensified and erosion of Buhne Point and the eastern shoreline accelerated. Figure 17 is a 1955 U.S. Army Corps of Engineers map showing the eastern shoreline change of Entrance Bay from 1854 to 1926, and the location of the shoreline in 1955. Between 1854 to 1955 approximately 4,700,000 cubic yards of material were eroded from Buhne Point to south of Elk River Spit and the shoreline receded between 600 to 1,600 ft, or about 5.5 ft per year on average; and an additional 2,107,000 cubic yards of material was eroded from Entrance Bay between 1911 to 1955 (Department of the Army 1957). Littoral transport of the eroded sandy material was transported to the north and south and formed the Elk River and Buhne Spit areas, respectively.

Between the 1930s to 1950s over one mile of the eastern shoreline and Buhne Point was armored by the Northwest Pacific Railroad and PGE, and the shoreline erosion was significantly reduced. However, the reduction in eroded material from the armoring reduced the supply of littoral material transported to Buhne Spit and the northwest shoreline of King Salmon began to erode. In the 1980s the Corp of Engineers implemented the Buhne Point Shoreline Erosion Project which consisted of constructing two rock rubble-mound breakwaters along the eroded shoreline of King Salmon. This effectively armored the entire easterly shoreline of Entrance Bay, and Shoreline Reach 1 has been stable since the 1980s.

2.5.2 Shoreline Reach 2

Except for the Buhne Spit and King Salmon shoreline changes documented in Shoreline Reach 1, the remaining shoreline in Shoreline Reach 2 has remained relatively stable. As discussed in Section 2.3, construction of the Fields Landing wharf and tidal wetland filling began in the 1890s and continued through the 1960s and 1970s. Although the exact dates are not known, the levee construction and reclamation activities of the tidal wetland areas between Fields landing and Buhne Spit likely occurred during the early 1900s, and a 1940 Army Corps of Engineers map of South Bay (map not shown) shows the levees in this area completed.

Review of a 1919 Fields Landing Harbor Lines map (map not shown) shows that the high-water lines along the tidal wetland area between Fields Landing and Buhne Spit retreated about 60 to 80 ft from 1854 to 1919, or 0.9 to 1.2 ft per year. It is not clear if levees had been constructed in this area by 1919, but it appears that fringe wetlands were often left seaward of many levees in both South Bay and North Bay. In any case, the 0.9 to 1.2 ft per year rate can be used as an approximate estimate of tidal wetland erosion or retreat rates in this area. However, if a fringe wetland was left along these levees, this erosion rate could explain why no fringe wetland exists today and the levees are armored with a rock revetment.

Review of aerial images from the 1960s and 1970s to today show that the shoreline in Shoreline Reach 2 has been stable, except for small changes in the natural shoreline that exist between the armored segments of the Fields Landing wharf infrastructure.

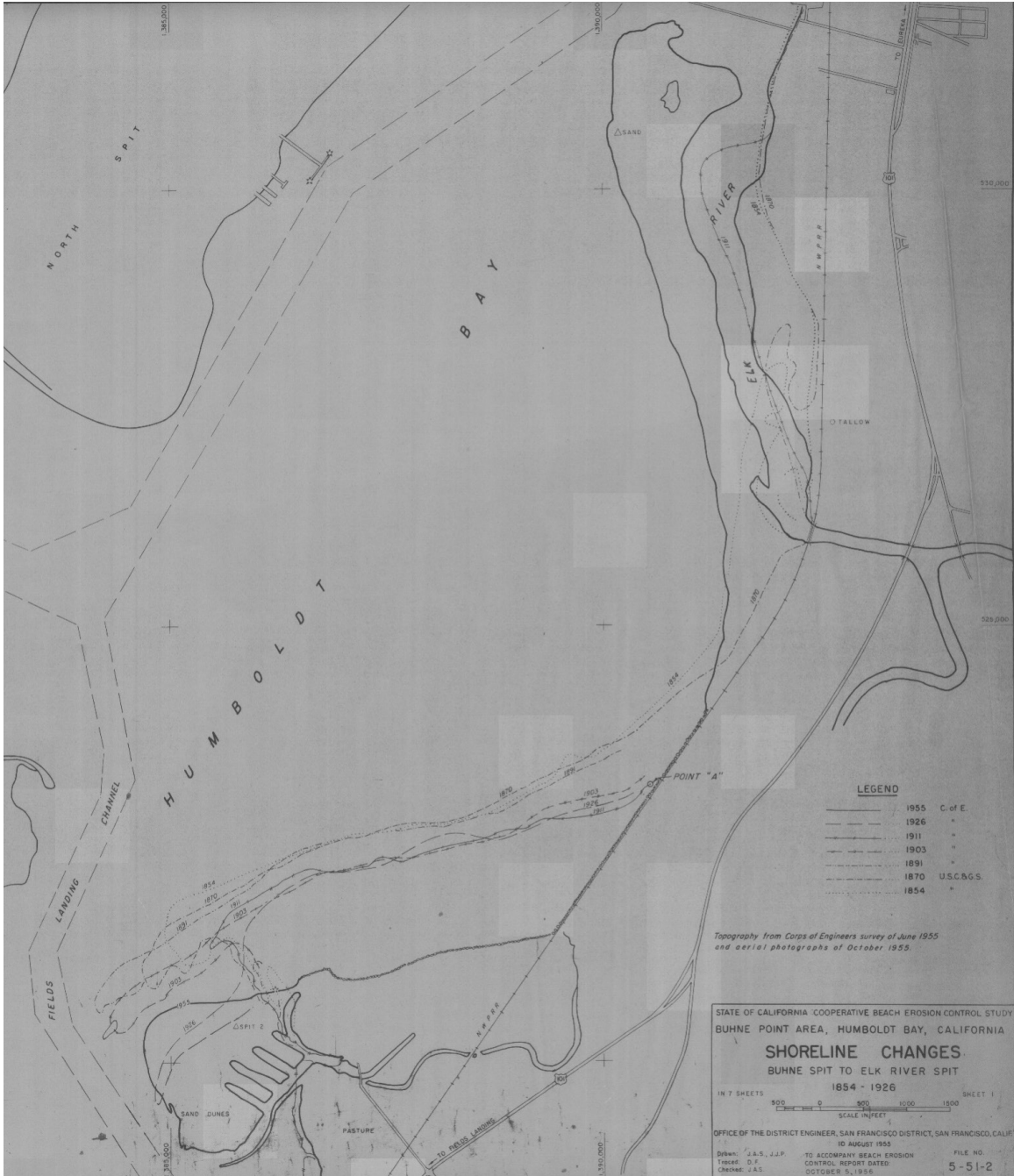


Figure 17. 1955 U.S. Army Corps of Engineers map showing shoreline changes of eastern Entrance Bay from 1854 to 1926, and the location of the shoreline in 1955. Note the shoreline armoring in 1955 that extends from the western edge of Buhne Point to the sound end of the Elk River spit.

2.5.3 Shoreline Reach 3

Today, Shoreline Reach 3 contains the only sections of natural shoreline that have not been significantly altered, in contrast to Shoreline Reach 1 and 2. These natural shorelines sections are vulnerable to wave erosion and retreat from locally generated wind waves in South Bay from southerly winds. The total length of natural shoreline in Shoreline Reach 3 was estimated at 1,390 m (4,561 ft or 0.86 mi) based on the 2019 aerial image.

Historical and recent shoreline change rates were estimated for the natural shoreline and tidal wetland segments by comparing shoreline position between historic and recent georeferenced aerial images. Shoreline change rates were estimated in Shoreline Reach 3 for three periods: (1) 1941 to 2019, (2) 1958 to 2019, and (3) 2019 to 2023.

The following describes the general steps of the shoreline change rate analysis.

1. For each aerial image (1941, 1958, 2019, and 2023) the apparent natural shoreline was digitized along the visible scarp/vegetation edge in each aerial image. The digitized shorelines from the 2019 image established the baseline extent of each natural shoreline segment.
2. The lengths of the 1941, 1953 and 2023 digitized shoreline segments were clipped to generally align with the 2019 baseline segments.
3. Transects 1 m (3.28 ft) on-center were created perpendicular to the 2019 shoreline segments.
4. The 2019 transects were then clipped to the corresponding 1941, 1958 and 2024 digitized shoreline segments, which represents the length of erosion or accretion that occurred at each transect for each image date relative to 2019. Separate erosion and accretion transect files were created for each of the three time periods (1941 to 2019, 1958 to 2019, and 2019 to 2024).
5. The percentage of eroding or accreting shoreline relative to the total natural shoreline was based on the number of erosion or accretion transects divided by the total number of transects.
6. The mean rates of erosion or accretion for each time period were determined using 10,000 bootstrap samples with replacement to estimate the mean and 95% confidence intervals (95% CI).

The estimated average shoreline erosion and accretion rates and lengths are summarized in Table 1, and Figure 18 shows the 1941, 1958, 2019 and 2023 digitized shoreline edges on the 2019 aerial image.

Table 1. Summary of mean shoreline change rates and 95% confidence intervals (CI) in Shoreline Reach 3.

Period	Number of Years	Percent (%) Shoreline Erosion	Percent (%) Shoreline Accretion	Erosion (ft/yr)		Accretion (ft/yr)	
				Mean Rate	95 % CI	Mean Rate	95 % CI
1941-2019	78	88.9	11.1	0.32	0.31 - 0.33	0.25	0.21 - 0.28
1958-2019	61	92.6	7.4	0.31	0.30 - 0.32	0.44	0.36 - 0.52
2019-2023	4	97.5	2.5	0.72	0.68 - 0.75	0.12	0.08 - 0.17

Results of the shoreline change rate analysis showed that 89 to 93% of the natural shoreline length was erosional, and 7 to 11% of the shoreline showed accretional patterns for the longer historical periods (1941-2019 and 1958-2019). For the recent period (2019-2023) most of the natural shoreline (98% of the length) shows signs of erosion, with only 2% of the shoreline length accreting.

Mean shoreline accretion rates for the three periods ranged from 0.1 to 0.4 ft/yr, and the associated 95% CI do not overlap indicating accretion rates differed for each period. It should be noted that the estimated accretion rates were more prone to digitizing error as there was not a clear demarcation of the accretion edge compared to the vegetation/scarp edge of the erosion edge.

The estimated mean shoreline erosion rate is higher (0.7 ft/yr,) for the more recent period compared to the historical period (0.3 ft/yr). Both historical values have similar mean rates and the 95% CIs overlap indicating no difference in the historical rates at the 95% level. However, the more recent rate 95% CI

does not contain the historical rates indicating these mean rates are different and that shoreline erosion rates have increased over time.



Figure 18. 2019 aerial image of Shoreline Reach 3 showing the digitized natural shoreline segments for 1941, 1958, 2019 and 2023. Most of the natural shoreline segments are tidal wetlands, except for the two north segments.

3 HUMBOLDT BAY COASTAL HYDROLOGY AND EXTREME HAZARDS

This section describes the coastal hydrology in Humboldt Bay related to the general Project site location. Figure 19 shows Humboldt Bay within the context of the Eureka Littoral Cell, and the locations of Humboldt Bay tidal stations and nearby weather stations.

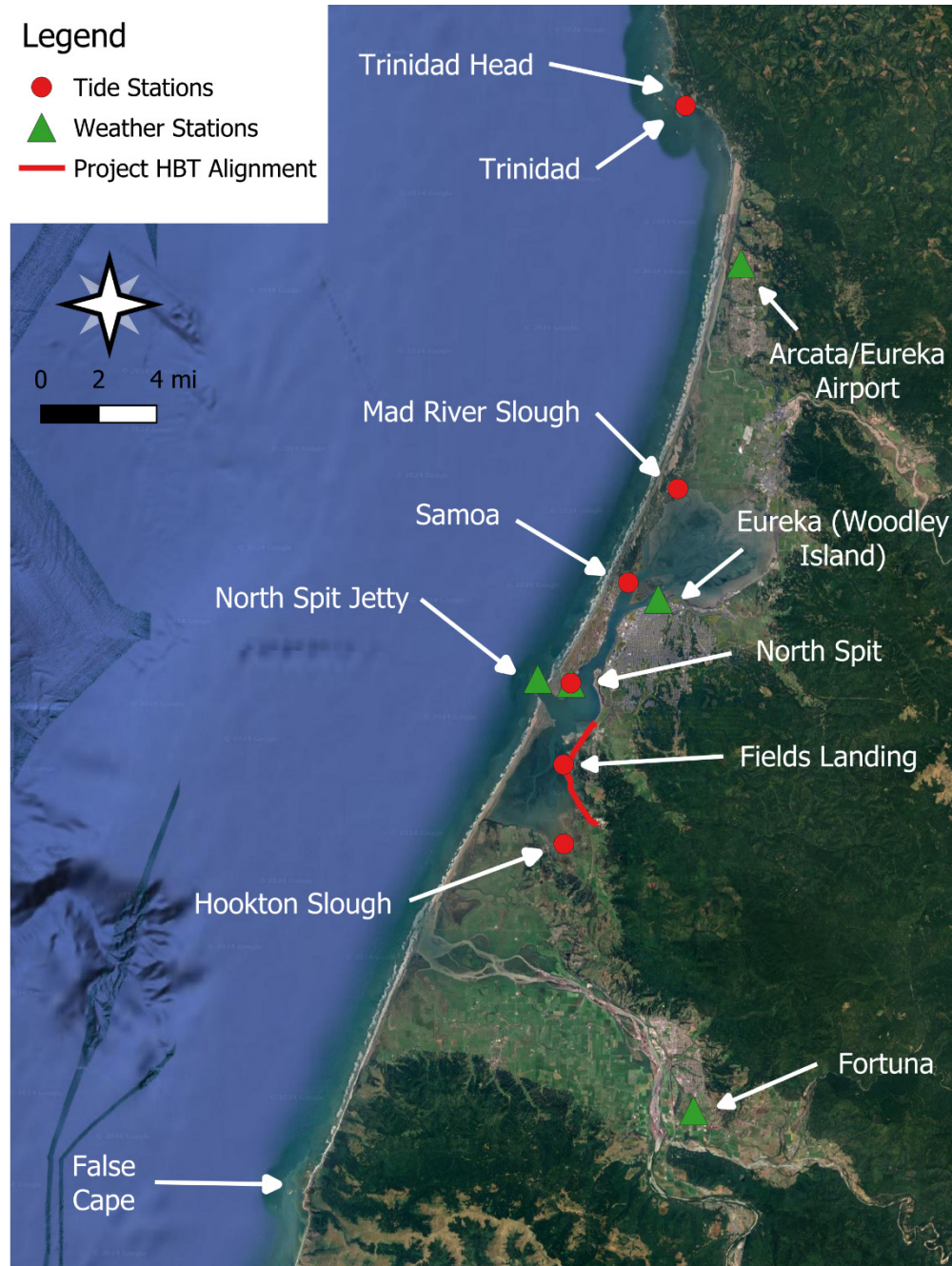


Figure 19. Location of NOAA tide stations in Humboldt Bay and Trinidad, weather stations in the Project vicinity, the extents of the Eureka Littoral Cell (Trinidad Head to the north and False Cape to the south), and the Project trail alignment. Crescent City tide station is located approximately 68 miles (109 km) north of the North Spit station.

3.1 Tide Levels and Tidal Datums

Humboldt Bay tides have a mixed semidiurnal pattern with two unequal high and low tides during each tidal (or lunar) day of duration 24 hours and 50 minutes. Continuous water level observations are available for the National Oceanic and Atmospheric Administration (NOAA) primary North Spit, CA tide station (Station ID: 9418767) with data spanning August 1977 to present. Tidal datums for the North Spit station and two secondary NOAA tide stations in South Bay, Fields Landing (Station ID: 9418723) and Hookton Slough, CA (Station ID: 9418686), are provided in Table 2 for the 1983-2001 tidal epoch. The location of the tidal stations relative to the Project trail alignment are shown in Figure 19.

Table 2. Tidal datums and water levels reported by NOAA for North Spit, Fields Landing and Hookton Slough tidal stations for the 1983-2001 tidal epoch; datums and elevations referenced to ft, NAVD88.

Description	Abbrev.	North Spit (NS) (ID: 9418767)	Fields Landing (FL) (ID: 9418723)	Hookton Slough (HS) (ID: 9418686) ¹
Highest Observed Water Level	HOWL	9.54	NA	NA
Highest Astronomical Tide	HAT	8.50	8.53	NA
Mean Higher High Water	MHHW	6.51	6.43	6.31
Mean High Water	MHW	5.80	5.72	5.58
Mean Tide Level	MTL	3.36	3.25	3.09
Mean Sea Level	MSL	3.36	3.25	3.13
Mean Low Water	MLW	0.91	0.79	0.60
North American Vertical Datum 1988	NAVD88	0.00	0.00	0.00
Mean Lower Low Water	MLLW	-0.34	-0.47	-0.63
Lowest Astronomical Tide	LAT	-2.74	-2.99	NA
Highest Observed Water Level	LOWL	-3.24	NA	NA
Diurnal Tidal Range (MHHW – MLLW)		6.86	6.90	6.94

¹ Hookton Slough elevations were referenced to MLLW and converted to NAVD88 using tidal benchmark K1087 (PID: LV0255) reported NGS NAVD88 elevation of 1.695 m (5.56 ft), and NOAA reported benchmark height above MLLW of 1.886 m (6.19 ft).

3.2 Sea-Level Change and Vertical Land Motion

Humboldt Bay has the highest rates of sea-level rise in California (NHE 2018). Recently, Patton et al. (2023) updated relative sea-level (RSL) and vertical land motion (VLM) rates and standard errors (SE) for the Crescent City and Trinidad tide stations, and five stations in Humboldt Bay (Figure 19 and Table 3). RSL rates were refined by combining the individual station rates and the difference in rates between stations in a weighted least squares adjustment. The VLM rates were resolved by subtracting the regional sea-level (ReSL) rate of 1.99 mm/yr for the Pacific Northwest region (Montillet et al. 2018) from the adjusted RSL rates. Within Humboldt Bay there is a significant north to south longitudinal gradient in RSL and VLM rates, with higher rates to the south. The North Spit (NS), Fields Landing (FL) and Hookton Slough (HS) sites in Table 2 correspond with those sites listed in Table 3.

Table 3. Tide station relative sea level (RSL) and vertical land motion (VLM) rates and standard errors (SE) from Patton et al. (2023); VLM determined by differencing RSL and the regional (or absolute) sea level (ReSL) rate of 1.99 ± 0.16 mm/yr (Montillet et al., 2018).

Station and Abbreviation	NOAA Station ID	Relative Sea-Level (RSL) (mm/yr)		Vertical Land Motion (VLM) (mm/yr)	
		Rate	SE	Rate	SE
Crescent City (CC)	9419750	-0.84	0.14	2.83	0.21
Trinidad (TR)	9419059	2.86	1.10	-0.87	1.11
Mad River Slough (MRS)	9418865	2.53	0.41	-0.54	0.44
Samoa (SO)	9418817	3.92	0.35	-1.93	0.38
North Spit (NS)	9418767	5.20	0.17	-3.21	0.23
Fields Landing (FL)	9418723	4.65	0.33	-2.66	0.37
Hookton Slough (HS)	9418686	6.64	0.65	-4.65	0.67

3.3 Estimated Extreme Water Levels and Tidal Datum Still Water Levels

The coastal still water levels for this analysis came from the 2D hydrodynamic model developed as part of the Humboldt Bay sea-level rise modeling and inundation vulnerability mapping project (NHE 2015). Estimates of Year 2023 extreme high-water levels were determined at representative grid cell locations along the three Project shoreline reaches (Figure 3). The maximum daily water elevation (NAVD88) for each day of the 100-yr simulation was extracted from the results database resulting in 36,525 daily values for each selected grid cell.

An estimate of the mean higher high water (MHHW) tidal datum, and the mean monthly maximum water (MMMW) and mean annual maximum water (MAMW) levels were determined from the 36,525 daily maximum values.

The extreme value analysis (EVA) was conducted on the daily maximum water levels at each grid cell using the peaks-over-threshold (POT) approach and Generalized Pareto Distribution (GPD). A theoretical definition, more detailed information, and an explanation of the parameter estimation process for the POT and GPD can be found in Coles (2001). The EVA and parameter estimation were conducted with the R package extRemes (Gilleland and Katz 2016). All model distribution parameters were estimated with the maximum likelihood estimation approach (Coles 2001). For this analysis, the threshold value was set to 97% of the maximum daily data. To satisfy the independence requirement of the EVA analysis, a de-clustering time of 3 days was used. Using these threshold and de-clustering values results in an approximate mean number of exceedances per year of 3.92, which is consistent with recommendations for regional and global extreme sea level analysis (Arns et al. 2017).

Results of the tidal datum and still water level EVA for the three Project shoreline reaches are provided in Table 4. Water levels were adjusted for sea-level rise to represent Year 2023 estimates using a ReSL value of 1.99 mm/yr. For comparison results for the North Spit tide station location are also provided.

Costa and Glatzel (2002) noted that tidal amplification and phase lag occur within the bay based on distance from the entrance. Based on the reported NOAA MHHW values (Table 2), tidal amplification is not occurring in South Bay, although the diurnal tidal range (difference between MHHW and MLLW) does increase with distance from the entrance or North Spit. However, the estimated (or modeled) MHHW tidal datum and other water levels (Table 4) does show the tidal amplification into South Bay as noted by Costa and Glatzel (2002). Although this discrepancy is not investigated further in this study, the mismatch in reported water levels (Table 2) may be due to the high and variable VLM rates (Table 3), and

the time periods and control stations used to determine tidal datums at the secondary (or subordinate) tide stations in Humboldt Bay for the current 1983-2001 tidal epoch.

Table 4. Summary of tidal datum and extreme value analysis (EVA) still water level results for the three Project shoreline reaches and North Spit tide station location for Year 2023. Water levels adjusted to Year 2023 using a ReSL value of 1.99 mm/yr.

Tidal Datum and Annual Exceedance Probability (%)	Annual Expected Number of Occurrences (#/yr)	Annual Average Recurrence Interval (yr)	Year 2023 Estimated Still Water Levels (ft, NAVD88)			
			Shoreline Reach 1	Shoreline Reach 2	Shoreline Reach 3	North Spit Location
MHHW			6.76	6.78	6.81	6.74
MMMW			8.04	8.06	8.11	8.01
MAMW			9.06	9.08	9.12	9.03
99.0	0.99	1.01	8.87	8.89	8.94	8.84
95.0	0.95	1.053	8.89	8.91	8.96	8.86
90.9	0.91	1.1	8.91	8.93	8.97	8.87
80.0	0.80	1.25	8.96	8.98	9.03	8.93
66.7	0.67	1.5	9.03	9.05	9.10	9.00
50.0	0.50	2	9.14	9.16	9.21	9.11
20.0	0.20	5	9.45	9.47	9.52	9.42
10.0	0.10	10	9.66	9.68	9.73	9.64
5.0	0.05	20	9.85	9.86	9.92	9.83
4.0	0.04	25	9.91	9.92	9.98	9.89
2.0	0.02	50	10.07	10.08	10.14	10.05
1.0	0.01	100	10.22	10.22	10.28	10.21
0.5	0.005	200	10.35	10.34	10.42	10.34
0.2	0.002	500	10.51	10.49	10.57	10.50

3.4 Winds

Humboldt Bay has distinct seasonal wind patterns, with winds normally from the north to northwest from March through October, and southeast to southwest winds from November to February (Costa and Glatzel 2002). Several weather stations exist in the Project vicinity with observed wind speed and direction data (Figure 19 and Table 5).

Hourly wind data for the stations listed in Table 5 were used to generate wind roses (Figure 20). The two land-based stations (Eureka/Arcata Airport and Fortuna) show an opposing northwest to southeast wind direction pattern, while the three stations located in Humboldt Bay (Eureka and North Spit) and nearshore (North Jetty Landing) show a stronger north to south pattern. This indicates that the topography of the easterly Northern Coast Range adjacent to Humboldt Bay may have a topographic steering effect on wind directions of the land-based stations.

Table 5. Weather stations in Project vicinity with wind speed and direction data. Arcata/Eureka Airport data downloaded from NOAA Integrated Surface Data (ISD) database; data for other stations from Iowa Environmental Mesonet of Iowa State University.

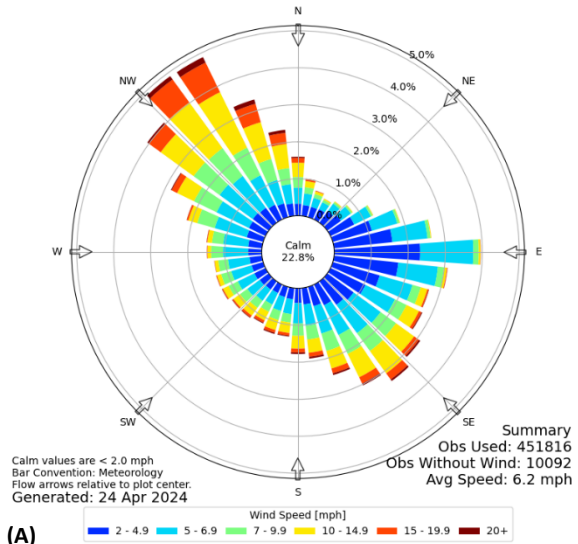
Station Name	Station ID	Coordinates	Elevation	Period of Record	Notes
Arcata/Eureka Airport	ACV	40.97811°N, 124.10861°W	66 m (217 ft)	1949 to present	Wind analysis
Fortuna	FOT	40.55390°N, 124.13270°W	112 m (369 ft)	2011 to present	Wind rose
Eureka (Woodley Island)	EKA	40.80970°N, 124.16030°W	18 m (599 ft)	1948 to 2022	Wind rose
North Spit (9418767)	HBVC1	40.76700°N, 124.21700°W	7.6 m (25.9 ft)	2016 to present	Wind rose
Samoa - North Jetty Landing	NJLC1	40.76890°N, 124.23890°W	6 m (20 ft)	2020 to present	Wind rose

An extreme 2-min wind speed and direction analysis was conducted by NHE for the Natural Shoreline Infrastructure project using the Arcata/Eureka Airport wind data (Appendix G, GHD et al. 2022). Reference to Appendix G can be made for a detailed discussion of the analysis methods and results.

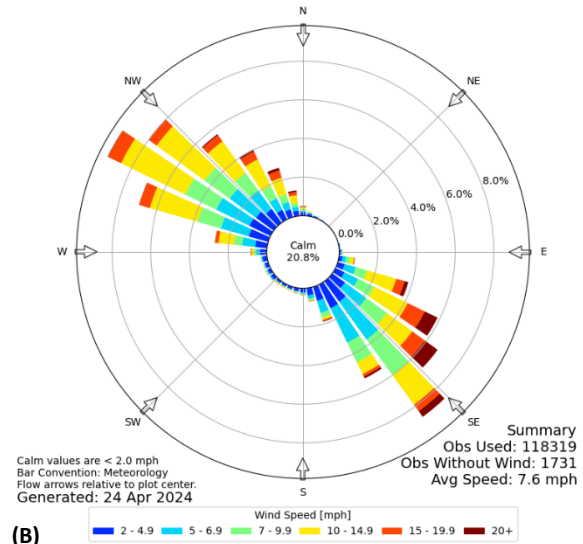
Peak 2-min wind speeds (assuming a Gumbel distribution) differ by wind direction in Humboldt Bay (Figure 21). The fastest wind speeds are from the east-southeast (112.5°) to north (360°) directions, with peak winds from easterly directions being much lower. Consistent with the Arcata/Eureka Airport wind rose (Figure 20) maximum peak winds appear to come from two dominant and opposing directions, southeast (135°) and northwest (315°). The extreme wind speed analysis was based on a GPD-POT approach and used the maximum daily 2-min wind speed neglecting wind direction. Consequently, the resulting extreme wind speeds are applicable for any wind direction from approximately 112.5° to 360°. Table 6 lists the estimated 2-min extreme wind speeds affecting the Project site.

Land Based Weather Stations

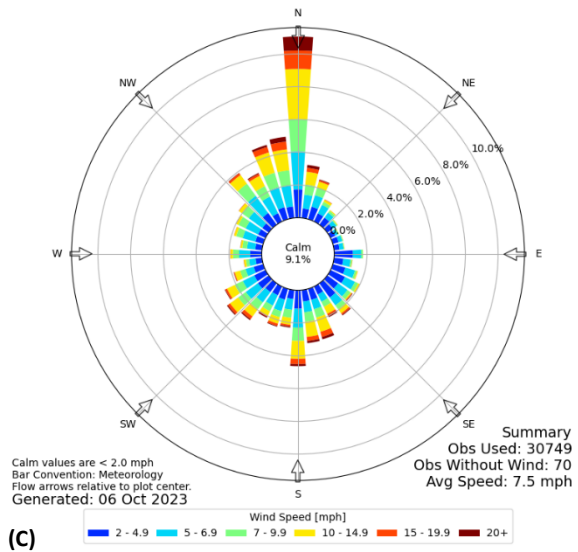
Windrose Plot for [ACV] ARCATA/EUREKA ARPT
Obs Between: 01 Jan 1970 01:00 AM - 23 Apr 2024 11:53 PM America/Los_Angeles



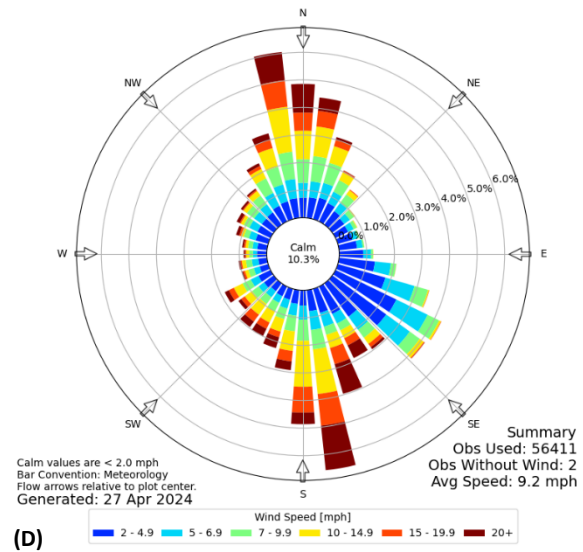
Windrose Plot for [FOT] Fortuna
Obs Between: 21 Sep 2011 09:55 PM - 24 Apr 2024 12:55 AM America/Los_Angeles



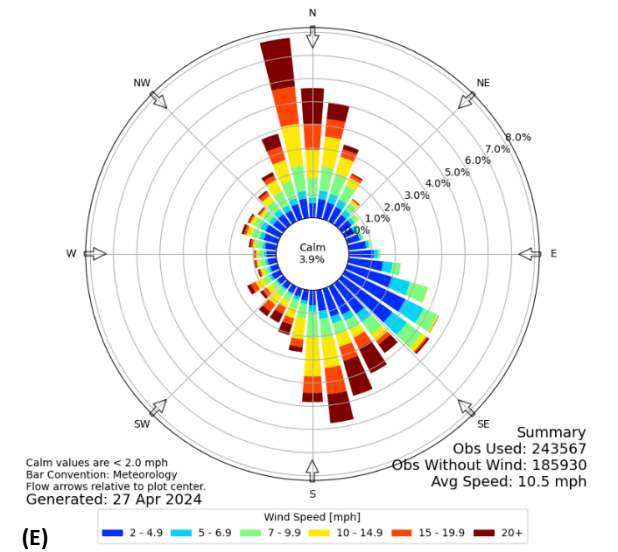
Windrose Plot for [EKA] EUREKA
Obs Between: 31 Dec 1972 04:00 PM - 14 Mar 2022 05:00 PM America/Los_Angeles



Windrose Plot for [HBYC1] North Spit CA - 9418767
Obs Between: 30 Aug 2016 11:36 AM - 07 Apr 2019 10:36 AM America/Los_Angeles



Windrose Plot for [NJLC1] Samoa - North Jetty Landing
Obs Between: 29 Jan 2020 10:12 AM - 30 May 2023 04:30 AM America/Los_Angeles



Humboldt Bay or Nearshore Weather Stations

Figure 20. Wind rose for Arcata/Eureka Airport (A), Fortuna (B), Eureka (C), North Spit (D) and North Jetty Landing (E). Plots generated from Iowa Environmental Mesonet of Iowa State University.

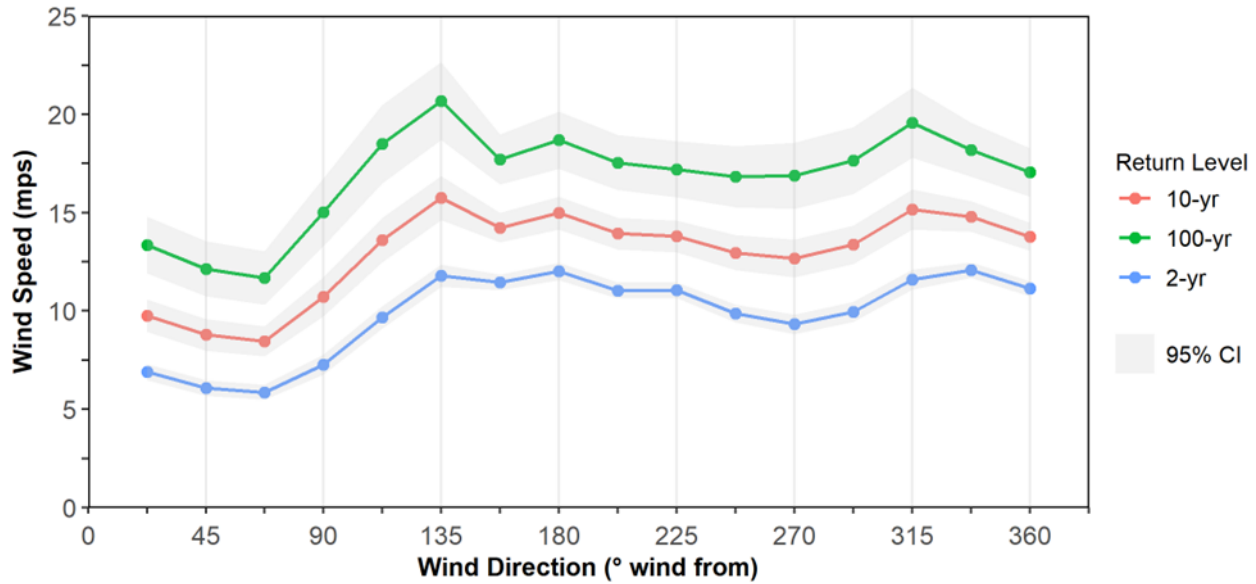


Figure 21. Peak 2-min wind speed estimates and 95% confidence intervals by wind direction from a Gumbel distribution for the 2-yr, 10-yr and 100-yr return levels (figure from Appendix G, GHD et al., 2022).

Table 6. Extreme 2-min wind speed estimates from the POT/GPD analysis of the Arcata/Eureka Airport data (Appendix G, GHD et al. 2022). Wind speeds have been adjusted to 2-min average duration and 10 m height.

Annual Exceedance Probability (%)	Annual Expected Number of Occurrences (#/yr)	Annual Average Recurrence Interval (yr)	Extreme 2-min Wind Speed (mps)		Extreme 2-min Wind Speed (mph)	
			Estimate	95% CI	Estimate	95% CI
~100	~1	~1	16.85	[15.90, 17.79]	37.7	[35.6, 39.8]
95.0	0.95	1.053	16.94	[15.98, 17.90]	37.9	[35.7, 40.0]
80.0	0.80	1.25	17.22	[16.22, 18.23]	38.5	[36.3, 40.8]
66.7	0.67	1.5	17.51	[16.46, 18.57]	39.2	[36.8, 41.5]
50.0	0.50	2	17.94	[16.82, 19.07]	40.1	[37.6, 42.7]
20.0	0.20	5	19.11	[17.69, 20.53]	42.7	[39.6, 45.9]
10.0	0.10	10	19.82	[18.11, 21.53]	44.3	[40.5, 48.2]
4.0	0.04	25	20.58	[18.38, 22.78]	46.0	[41.1, 51.0]
2.0	0.02	50	21.04	[18.39, 23.70]	47.1	[41.1, 53.0]
1.0	0.01	100	21.43	[18.25, 24.60]	47.9	[40.8, 55.0]
0.5	0.005	200	21.75	[17.97, 25.52]	48.6	[40.2, 57.1]
0.2	0.002	500	22.09	[17.38, 26.79]	49.4	[38.9, 59.9]

3.5 Wind-Waves for Shoreline Reach 3

3.5.1 Fetch Direction

Shoreline Reach 3 is the most vulnerable shoreline reach of the Project area and subject to incident wind-waves locally generated in South Bay from southerly winds. Fetch directions at 22.5° intervals along

Reach 3 are provided in Figure 22. Since waves in South Bay are fetch limited, the longest fetch length for a given constant wind speed will produce the largest wave heights. For this preliminary assessment, wind-wave heights and periods were estimated for winds from the west-southwest (247.5°) direction, which is the longest fetch with a length of 4.6 km (2.9 miles). It should be noted that the Reach 3 shoreline is approximately perpendicular to the maximum fetch direction.

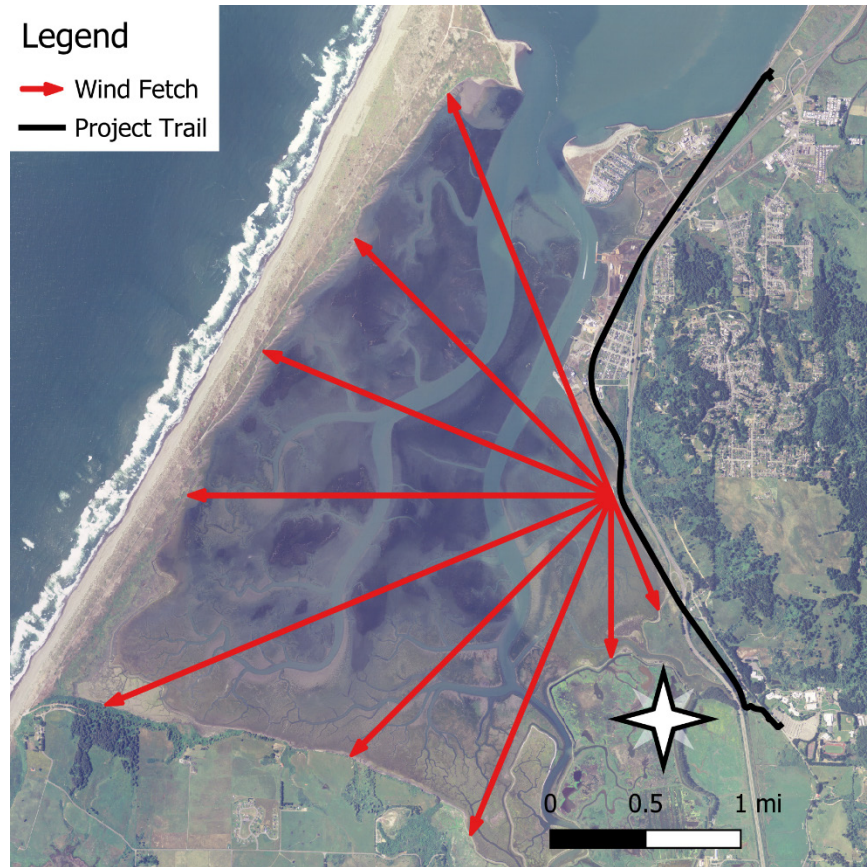


Figure 22. Fetch directions for Shoreline Reach 3 of the Project area in South Bay.

3.5.2 Estimated Wind-Wave Height and Period

Wave heights and periods were determined along the longest fetch direction for eight extreme wind speeds (95, 66.7, 50, 20, 10, 2 and 1% exceedance probability) outlined in Table 6. Fetch-limited peak wave heights and periods were estimated using the simplified procedures for wind adjustments and wave prediction outlined in CEM (2015). This procedure adjusts wind speeds to fetch-limited conditions by (1) adjusting wind speed for duration and fetch length, and (2) applying a 1.2 factor for overwater wind speeds for fetch lengths less than 16 km (~10 mi). The fetch lengths, adjusted wind speeds, and predicted peak wave heights and periods for the eight wind speeds are summarized in Table 7.

Table 7. Wind-wave analysis summary of adjusted wind speeds and predicted peak wind-wave heights and periods for eight extreme wind speeds for the Project site Shoreline Reach 3. Wave conditions are along longest fetch (west-southwest direction (247.5°), 4.632 km length) relative to the shoreline.

Annual Exceedance Probability (%)	Extreme 2-min wind speed (mps)	Adjusted Wind Speed (mps)	Adjusted Wind Speed (mph)	Peak Wave Height (m)	Peak Wave Height (ft)	Wave Period (s)
95	16.94	17.29	38.7	0.64	2.10	2.44
66.7	17.51	17.88	40.0	0.67	2.19	2.47
50	17.94	18.33	41.0	0.69	2.25	2.50
20	19.11	19.56	43.7	0.74	2.43	2.56
10	19.82	20.30	45.4	0.78	2.54	2.60
4	20.58	21.10	47.2	0.81	2.66	2.64
2	21.04	21.58	48.3	0.83	2.74	2.67
1	21.43	21.99	49.2	0.85	2.80	2.69

3.6 Estimated Wind Setup

Onshore directed winds can cause the build-up of water along the shoreline, resulting in a vertical increase in water surface elevation lasting on the order of several hours. The Humboldt Bay hydrodynamic model (Figure 23) developed as part of the Natural Shoreline Infrastructure project (GHD et al. 2022) was used to estimate wind setup at the Project site for various wind speeds and directions. Reference to the GHD et al. (2022) report can be made for a description of the hydrodynamic model setup and parameters.

The tidal open boundary condition (Figure 24) for the analysis consisted of a 10-day period from the 100-yr hourly sea level height series derived for the Crescent City tide station (NOAA Station ID: 9419750) as part of the Humboldt Bay sea-level rise vulnerability analysis (NHE 2015). The 10-day period spanned 22 to 31 January 1983, which was during the 1982-83 El Niño. During this 10-day period a large El Niño driven storm coincided with higher-than-normal astronomical tides producing the highest water levels of record at the Crescent City tide gauge. This 10-day tidal series contains a large tidal height range spanning mean higher high water (MHHW) to above the 1% annual chance extreme high-water level event. The wind speeds and directions were held constant for each 10-day simulation.

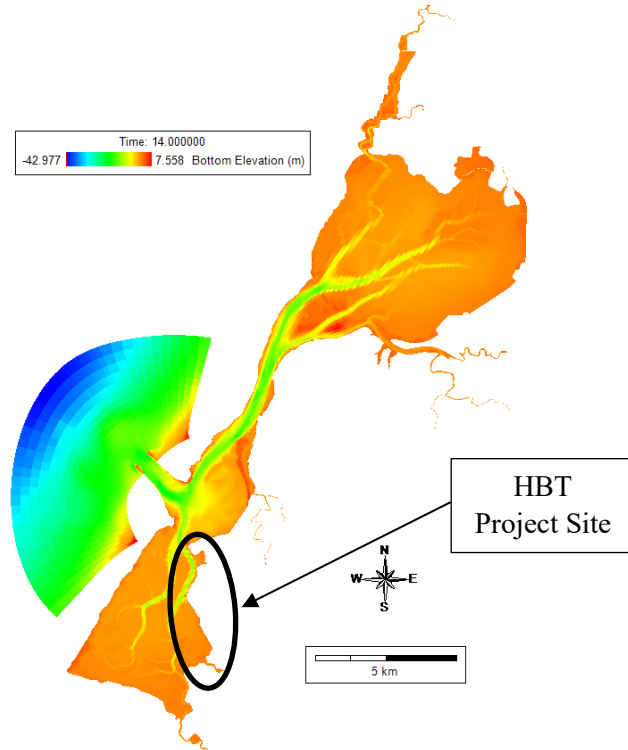


Figure 23. Humboldt Bay 3D circulation model domain. Bathymetry/topography based on grid cell elevations.

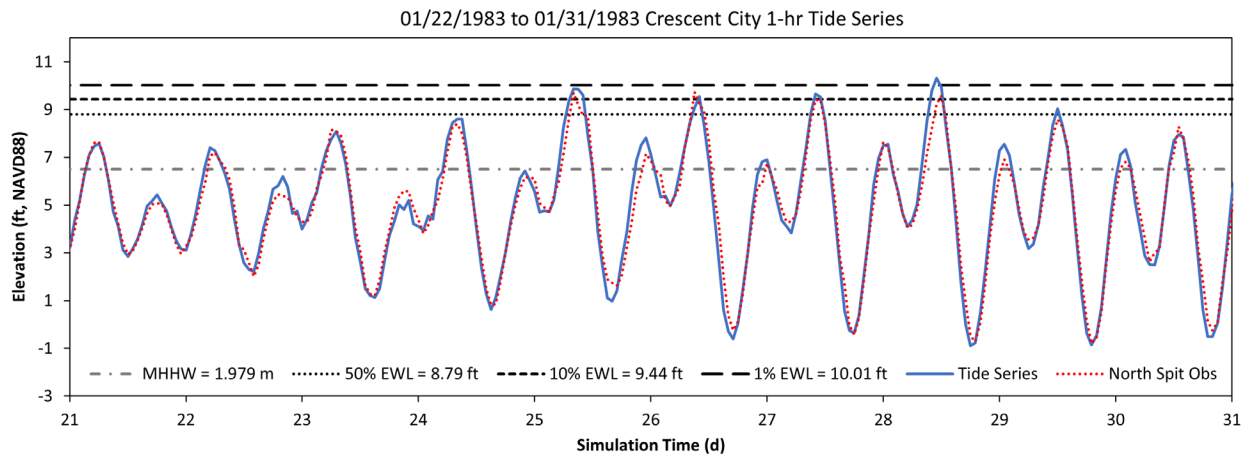


Figure 24. Tidal open boundary condition (blue line) used for the hydrodynamic model simulations. Tidal series based on Crescent City tide station (NOAA Station ID: 9419750). Observed North Spit tide station (NOAA Station ID: 9418767) observations (red dotted line) corrected for ~2.3 mm sea-level change from 1982 to 2012. MHHW is mean higher high water; #% EWL (e.g. 1% EWL) represents the #% annual chance extreme high-water level (e.g. 1% chance extreme high-water level).

Results of the wind setup analysis for different wind speeds and directions at the Project site are listed in Table 8. The wind setup results were extracted at the peak water level near day 25.36 of the simulation which represents the approximate 1% extreme high-water level. Results for the 20 mps (44.7 mph) wind speed, which is close to the 10% adjusted wind speed (Table 7) of 20.3 mps (45.4 mph), indicate that

southerly wind directions between 135° to 225° push water out of South Bay into North Bay creating negative wind setup values ranging from -0.05 to -0.14 m (-0.2 to -0.5 ft). Winds from the west to north (270° to 360°) push water towards the project site or out of North Bay into South Bay, resulting in positive wind setup values between 0.06 to 0.1 m (0.2 to 0.4 ft). Wind directions from the longest fetch (west-southwest direction (247.5°), 4.632 km length) produce small wind setup values between 0 to 0.01 m (0 to 0.03 ft) for wind speeds ranging from 5 to 25 mps (11 to 26 mph). In other words, conditions that produce the largest wind-waves and wave runup values along the most vulnerable shoreline (Reach 3) for the Project site produce negligible wind setup values.

Table 8. Summary of wind setup for various wind speeds and directions at the Project site Shoreline Reach 3. Still water levels were extracted at the approximate 1% extreme high-water level.

Wind Direction (from)	Wind Direction From (°)	Wind Speed (not adjusted) (mps)	Wind Speed (not adjusted) (mph)	~1% Still Water Level (m, NAVD88)	Wind Setup (m)	Wind Setup (ft)
No wind	No wind	20	44.7	3.053	0.000	0.00
East-Southeast	135.0	20	44.7	2.924	-0.129	-0.42
South-Southeast	157.5	20	44.7	2.910	-0.143	-0.47
South	180.0	20	44.7	2.923	-0.130	-0.43
South-Southwest	202.5	20	44.7	2.957	-0.096	-0.32
Southwest	225.0	20	44.7	3.006	-0.047	-0.16
West-Southwest	247.5	5	11.2	3.053	0.000	0.00
West-Southwest	247.5	10	22.4	3.055	0.002	0.01
West-Southwest	247.5	15	33.6	3.059	0.006	0.02
West-Southwest	247.5	20	44.7	3.062	0.008	0.03
West-Southwest	247.5	25	55.9	3.064	0.011	0.03
West	270.0	20	44.7	3.114	0.061	0.20
West-Northwest	292.5	20	44.7	3.151	0.098	0.32
Northwest	315.0	20	44.7	3.163	0.110	0.36
North-Northwest	337.5	20	44.7	3.156	0.103	0.34
North	360	20	44.7	3.131	0.078	0.26

3.7 Estimated R_{2%} Wave Runup for Trail Segment 3

Wave runup is the uprush of water caused by waves interacting with a beach, shoreline, or shoreline barrier. Wave runup for Trail Segment 3 along Shoreline Reach 3 was estimated following the EuroTop (2018) method, which is similar to the Technical Advisory Committee for Water Retaining Structures (TAW) method (van der Meer 2002), but with updated parameters. For this assessment, wave runup estimates were not determined for Trail Segment 1 in Shoreline Reach 1 but relied on the FEMA (2014) derived R_{2%} runup values that were used to determine total water levels described later.

The runup methodology was modified as in FEMA (2005) and used in the Natural Shoreline Infrastructure project (Appendix H, GHD et al. 2022). The approach in Appendix H is consistent with the approach used by FEMA (2014) to determine wave runup in Humboldt Bay where the shoreline is composed of a natural shoreline (without fringing tidal wetland) or shoreline structures. Reference to Appendix H (GHD et al. 2022), FEMA (2005) or FEMA (2014) can be made for more information regarding the wave runup methodology.

As noted in FEMA (2005 and 2014), the TAW (or EurOtop) runup equation is based on wave tank measurements which accounts for wave setup landward of the shoreline or structure toe, and FEMA (2005) recommends reducing the dynamic setup to account for this. Also, if the incident waves have not broken prior to reaching the structure toe, then wave setup is not included in the total runup, which is consistent with the approach used by FEMA (2014) for determining wave runup estimates in Humboldt Bay. For most water elevations listed in Table 4, the water depth at the toe of the shoreline or structure is greater than 0.78 times the wave height, indicating that waves have not broken prior to reaching the toe and wave setup was assumed zero. For runup estimates where the toe water depths were less than 0.78 times the wave height, static wave setup was determined using the Direct Integration Method (DIM) as described in FEMA (2005 and 2014), but the dynamic setup was assumed zero. Furthermore, wave runup estimates were based on the broken wave height determined as 0.78 time the toe water depth.

Based on the Project HBT 30% Plans (GHD, 2024c), three general trail sections are currently proposed to be constructed on top of the existing railroad grade along Shoreline Reach 3 (see Sheet G-003 of Project HBT 30% Plans). One section is for locations where a natural shoreline or tidal wetland exists between the bay and the trail, and two sections are proposed for locations where the existing railroad grade is the shoreline, and either protected by existing revetments or actively eroding. The three trail sections, which apply to this section ($R_{2\%}$ wave runup) and the later overtopping section, are briefly described as follows:

1. Section 1 is for portions of the trail that exist behind existing natural shoreline or fringe tidal wetland segments and will be constructed to elevation 11.5 ft, with no additional shoreline protection currently proposed. It is assumed that the natural shoreline or tidal wetland fringe will generally attenuate wave energy and prevent wave runup and overtopping.
2. Section 2 is the first option for portions of the trail where the railroad grade is actively eroding or currently protected by existing revetments of concrete rubble or poorly graded rock (riprap). The constructed revetment and trail will be at elevation 11.5 ft, and the revetment has a proposed slope of 1V:1.5H. This option also consists of constructing a natural sand/gravel beach (or coarse or shingle beach) in front of the rock revetment at an approximate slope of 1V:6.7H (~15%). The coarse beach will be dynamic, the beach profile will adjust to the largest incident waves, and if adequate material is available the beach crest can reach wave run-up levels (EurOtop, 2018). It is assumed that the coarse beach will ultimately adjust to the largest wave run-up values and naturally attenuate wave energy, runup and overtopping.
3. Section 3 is the second option for portions of the trail where revetment is proposed and consists of constructing the trail and revetment like Section 2 above, but instead of a coarse beach, this option proposes a 10-ft wide tidal wetland bench be constructed in the front the revetment at an average elevation of ~ 7.25 ft. The tidal wetland bench will have a rock armored toe for constructability and to prevent the wetland from eroding. Although the relatively narrow tidal wetland will provide some wave energy dissipation, it was assumed that the wetland bench will function as a submerged berm in front of the revetment, and the effect of a berm to reduce wave runup and overtopping were accounted for in the EurOtop (2018) equations.

For this assessment, wave runup and overtopping (to be discussed later) were only estimated for Shoreline Reach 3 assuming the Section 3 trail construction (i.e. trail, rock revetment and the 10-ft wide wetland bench). Wave runup and overtopping was not determined for the existing shoreline conditions. The wetland bench was treated as a submerged berm in the EurOtop (2018) equations which can reduce wave runup and overtopping. It was assumed that either the natural shoreline (Section 1) or coarse beach (Section 2) will attenuate wave energy and runup to values below the trail crest elevation, or to values

below the Section 3 estimates. At a minimum, the estimated wave runup and overtopping estimates represent a conservative upper limit for the natural shoreline or coarse beach.

Since runup estimates are along the longest fetch affecting Shoreline Reach 3, the R_{2%} wave runup values can be considered maximum values for each wind speed analyzed. Table 9 lists the wave runup estimates when the incident waves break prior to the toe of the structure, accounts for wave setup and breaking wave heights, and only applies to MHHW still water levels and higher wind speeds.

Table 10 lists the R_{2%} wave runup estimates for peak wind speeds at the Project site Shoreline Reach 3 when incident waves have not broken prior to reaching the structure toe and apply to higher water levels for most wind conditions.

Table 9. Summary of R_{2%} wave runup estimates for extreme wind speeds at Shoreline Reach 3. Runup estimates are for reported water levels (tidal datums), and account for wave breaking and setup. Wave conditions are along the longest fetch (west-southwest direction (247.5°), 4.632 km length) relative to the shoreline, a 1V:1.5H revetment slope, and a 10-ft wide wetland bench treated as a submerged berm.

Annual Exceedance Probability (%)	Annual Average Recurrence Interval (yr)	Applicable Still Water Level	Adjusted Wind Speed (mps)	Adjusted Wind Speed (mph)	Wave Runup - R _{2%} (m)	Wave Runup - R _{2%} (ft)
4	25	MHHW	21.10	47.2	1.529	5.02
2	50	MHHW	21.58	48.3	1.543	5.06
1	100	MHHW	21.99	48.3	1.556	5.10

Table 10. Summary of R_{2%} wave runup estimates for extreme wind speeds at Shoreline Reach 3. Runup estimates are maximum values for the reported still water levels (tidal datums or exceedance probabilities (EP)). Wave conditions are along the longest fetch (west-southwest direction (247.5°), 4.632 km length) relative to the shoreline, a 1V:1.5H revetment slope, and a 10-ft wide wetland bench treated as a submerged berm.

Annual Exceedance Probability (%)	Annual Average Recurrence Interval (yr)	Applicable Still Water Level	Adjusted Wind Speed (mps)	Adjusted Wind Speed (mph)	Wave Runup - R _{2%} (m)	Wave Runup - R _{2%} (ft)
95	1.053	>= MHHW	17.29	38.7	1.062	3.48
66.7	1.5	>= MHHW	17.88	40.0	1.108	3.63
50	2	>= MHHW	18.33	41.0	1.146	3.76
20	5	>= MHHW	19.56	43.7	1.246	4.09
10	10	>= MHHW	20.30	45.4	1.309	4.29
4	25	>= MMMW	21.10	47.2	1.377	4.52
2	50	>= MMMW	21.58	48.3	1.418	4.65
1	100	>= MMMW	21.99	49.2	1.453	4.77

3.8 FEMA Flood Hazard Maps

Much of the Project area is situated within a Federal Emergency Management Agency (FEMA) Special Flood Hazard Area for which 1% base flood elevations (BFE) have been determined from a detailed coastal flood hazard analysis for the open coast and Humboldt Bay (FEMA 2014 and 2018a). The Project area spans multiple flood zones, including VE and AE zones. VE zones are coastal areas subject to storm wave hazards and fast-moving water, where a BFE has been calculated through a detailed study. AE zones are used to depict inland areas subject to flooding and coastal areas subject to flooding where wave heights are less than three feet. The BFE represents the 1% total water level (TWL), which includes the still water elevation and increased elevation from wave setup and wave runup at the shoreline.

Figure 25 shows the proposed HBT alignment on Flood Insurance Rate Map (FIRM) map number 06023C1005G. Project HBT segments TS-2, TS-4, and TS-5 (see Figure 3) are behind levees, revetments or far enough inland from the shoreline that wave runup does not apply and are within an AE zone with a BFE of 10 ft (NAVD88). Trail segments TS-1 and TS-3 are situated near the boundary between VE and AE zones. For trail segment TS-1, the seaward side of the revetment is a VE zone with BFE of 18 ft and the landward side of the revetment is an AE zone with BFE of 10 ft. For trail segment TS-3, the seaward side of the revetment is a VE zone with BFE of 13 ft and the landward side of the revetment is an AE zone with BFE of 10 ft. A small section at the south end of TS-3 is in an AE zone with a BFE of 11 ft.

The preliminary 1% flood elevations determined in this work can be considered refinements to the FEMA 1% BFEs for the Project site. The preliminary 1% flood elevations are a composite water level estimate specific to the Project area consisting of coastal extreme high-water levels (e.g. storm surge), wind effects (wind setup), wave effects (e.g. wave runup), and projected sea-level rise adjustments.

3.9 Total Water Levels

3.9.1 Trail Segment 1 in Shoreline Reach 1 (Entrance Bay)

Total water levels (TWL) in Entrance Bay include incident ocean waves that enter Humboldt Bay through the entrance channel. Assessing wave propagation and wave effects in Entrance Bay was beyond the scope of this study, and instead the TWLs estimated by FEMA (2014) were used for the Trail Segment 1 shoreline. FEMA conducted a response-based 50-year hindcast of TWLs for two transects on the eastern shoreline of Humboldt Bay that included still water levels, storm surge, wave propagation into the bay, wave refraction, wave setup and wave runup. FEMA Transect 76 (Figure 25) is located just north of Trail Segment 1 and was used to represent TWLs along the shoreline revetment in Shoreline Reach 1.

FEMA only reported the 1% TWL for Transect 76 but did provide the 50-year hindcasted annual max TWL record, which was reported in ft (NAVD88) referenced to the 1983-2001 Tidal Epoch (TE). To provide additional TWL return levels, an EVA analysis was conducted on the 50-year annual maximum record using the Generalized Extreme Value (GEV) distribution. Table 11 provides the TWL for the 1983-2001 TE period and a Year 2023 TWL estimate that was adjusted for sea-level rise using a ReSL value of 1.99 mm/yr. For comparison the resulting 1% TWL for the 1983-2001 TE period is 18.05 ft, which is consistent with the 18.1 ft reported by FEMA for Transect 76.

Table 11. Total water level extreme value estimates from the GEV analysis of the FEMA response-based 50-yr total water level data for Transect 76 located in Shoreline Reach 3 just north of Trail Segment 1. Total water levels are provided for the 1983-2001 Tidal Epoch period and adjusted to Year 2023 using a ReSL value of 1.99 mm/yr.

Annual Exceedance Probability (%)	Annual Expected Number of Occurrences (#/yr)	Annual Average Recurrence Interval (yr)	1983-2001 Tidal Epoch Period Total Water Level Estimate (ft, NAVD88)	Year 2023 Total Water Levels	
				Estimate (m, NAVD88)	Estimate (ft, NAVD88)
~100	~1	~1	12.66	3.923	12.87
95.0	0.95	1.053	13.17	4.078	13.38
80.0	0.80	1.25	13.86	4.288	14.07
66.7	0.67	1.5	14.26	4.411	14.47
50.0	0.50	2	14.73	4.552	14.93
20.0	0.20	5	15.77	4.871	15.98
10.0	0.10	10	16.39	5.061	16.60
4.0	0.04	25	17.11	5.280	17.32
2.0	0.02	50	17.60	5.429	17.81
1.0	0.01	100	18.05	5.565	18.26
0.5	0.005	200	18.46	5.692	18.67
0.2	0.002	500	18.96	5.844	19.17

3.9.2 Trail Segment 3 in Shoreline Reach 3

The TWL for Trail Segment 3 in Shoreline Reach 3 was estimated along the longest fetch by combining still water, wind setup and the $R_{2\%}$ wave runup estimates. The estimated TWL applies to the proposed Section 3 trail construction (i.e. trail, rock revetment and the 10-ft wide wetland bench), and not existing conditions. Furthermore, these TWL estimates can be considered a conservative upper limit for the proposed natural shoreline or coarse beach portions of Trail Segment 3. Table 12 lists the estimated TWL for Trail Segment 3 for a range of water levels and the 1.05-yr, 2-yr, 10-yr and 100-yr wind conditions.

Table 12. Total water level estimates for Trail Segment 3 in Shoreline Reach 3 for different tidal datum and extreme coastal flood event levels and wind speeds; also provided are still water, wind setup and R_{2%} wave runup estimates. Wave conditions are for the longest fetch (west-southwest direction (247.5°), 4.632 km length) relative to the shoreline, a 1V:1.5H revetment slope, and a 10-ft wide wetland bench treated as a submerged berm.

Tidal Datum and Extreme Flood Event	Wind Speed from WSE (247.5°)	Still Water Level (m, NAVD88)	Wind Setup (m)	R _{2%} Runup (m)	Total Water Level	
					Estimate (m, NAVD88)	Estimate (ft, NAVD88)
MHHW	95% EP (1.05-yr RI)	2.072	0.007	1.127	3.206	10.52
MHHW	50% EP (2-yr RI)	2.072	0.008	1.220	3.299	10.82
MHHW	10% EP (10-yr RI)	2.072	0.009	1.391	3.472	11.39
MHHW	1% EP (100-yr RI)	2.072	0.009	1.556	3.637	11.93
MMMW	95% EP (1.05-yr RI)	2.466	0.007	1.091	3.564	11.69
MMMW	50% EP (2-yr RI)	2.466	0.008	1.180	3.653	11.99
MMMW	10% EP (10-yr RI)	2.466	0.009	1.356	3.830	12.57
MMMW	1% EP (100-yr RI)	2.466	0.009	1.510	3.985	13.08
95% EP (1.05-yr RI)	95% EP (1.05-yr RI)	2.725	0.007	1.062	3.794	12.45
95% EP (1.05-yr RI)	50% EP (2-yr RI)	2.725	0.008	1.146	3.878	12.72
95% EP (1.05-yr RI)	10% EP (10-yr RI)	2.725	0.009	1.309	4.042	13.26
95% EP (1.05-yr RI)	1% EP (100-yr RI)	2.725	0.009	1.453	4.188	13.74
66.7% EP (1.5-yr RI)	95% EP (1.05-yr RI)	2.768	0.007	1.062	3.837	12.59
66.7% EP (1.5-yr RI)	50% EP (2-yr RI)	2.768	0.008	1.146	3.922	12.87
66.7% EP (1.5-yr RI)	10% EP (10-yr RI)	2.768	0.009	1.309	4.086	13.40
66.7% EP (1.5-yr RI)	1% EP (100-yr RI)	2.768	0.009	1.453	4.231	13.88
50% EP (2-yr RI)	95% EP (1.05-yr RI)	2.801	0.007	1.062	3.870	12.70
50% EP (2-yr RI)	50% EP (2-yr RI)	2.801	0.008	1.146	3.955	12.98
50% EP (2-yr RI)	10% EP (10-yr RI)	2.801	0.009	1.309	4.119	13.51
50% EP (2-yr RI)	1% EP (100-yr RI)	2.801	0.009	1.453	4.264	13.99
20% EP (5-yr RI)	95% EP (1.05-yr RI)	2.898	0.007	1.062	3.966	13.01
20% EP (5-yr RI)	50% EP (2-yr RI)	2.898	0.008	1.146	4.051	13.29
20% EP (5-yr RI)	10% EP (10-yr RI)	2.898	0.009	1.309	4.215	13.83
20% EP (5-yr RI)	1% EP (100-yr RI)	2.898	0.009	1.453	4.360	14.31
10% EP (10-yr RI)	95% EP (1.05-yr RI)	2.961	0.007	1.062	4.030	13.22
10% EP (10-yr RI)	50% EP (2-yr RI)	2.961	0.008	1.146	4.115	13.50
10% EP (10-yr RI)	10% EP (10-yr RI)	2.961	0.009	1.309	4.279	14.04
10% EP (10-yr RI)	1% EP (100-yr RI)	2.961	0.009	1.453	4.424	14.51
4% EP (25-yr RI)	95% EP (1.05-yr RI)	3.035	0.007	1.062	4.104	13.47
4% EP (25-yr RI)	50% EP (2-yr RI)	3.035	0.008	1.146	4.189	13.74
4% EP (25-yr RI)	10% EP (10-yr RI)	3.035	0.009	1.309	4.353	14.28
4% EP (25-yr RI)	1% EP (100-yr RI)	3.035	0.009	1.453	4.498	14.76
2% EP (50-yr RI)	95% EP (1.05-yr RI)	3.084	0.007	1.062	4.153	13.63
2% EP (50-yr RI)	50% EP (2-yr RI)	3.084	0.008	1.146	4.238	13.90
2% EP (50-yr RI)	10% EP (10-yr RI)	3.084	0.009	1.309	4.402	14.44
2% EP (50-yr RI)	1% EP (100-yr RI)	3.084	0.009	1.453	4.547	14.92
1% EP (100-yr RI)	95% EP (1.05-yr RI)	3.128	0.007	1.062	4.197	13.77
1% EP (100-yr RI)	50% EP (2-yr RI)	3.128	0.008	1.146	4.282	14.05
1% EP (100-yr RI)	10% EP (10-yr RI)	3.128	0.009	1.309	4.446	14.59
1% EP (100-yr RI)	1% EP (100-yr RI)	3.128	0.009	1.453	4.591	15.06

3.10 Wave Overtopping

Wave overtopping was estimated to assess trail usability and damage and was a key component in the preliminary vulnerability assessment for the proposed HBT alignment. Wave overtopping occurs when the wave runup elevation exceeds the shore or barrier crest elevation. Overtopping is generally quantified as the overtopping flow rate in cubic meters per second per meter (cms/m) or cubic feet per second per linear foot (cfs/ft) of shoreline. Three types of wave overtopping can exist: green water, splash, and spray overtopping (FEMA, 2018b). Green water overtopping occurs when waves break onto or over the shore barrier and the overtopping volume is relatively continuous. Splash overtopping occurs when waves break seaward of the shore barrier face, or where the shore barrier is high in relation to the wave height, and overtopping is a concentrated stream of water droplets. Spray overtopping is generated by the action of wind on the wave crests and does not represent a significant source of flooding.

The wave overtopping rate was estimated using EurOtop II (2018) equations, the still water and wave conditions previously determined above, the shoreline structure, and the available freeboard between the structure crest and still water or dynamic water level. The EurOtop (2018) equations for overtopping rate include contributions from green water and splash overtopping, but not spray overtopping.

Wave overtopping rates were only determined for Trail Segment 1 in Shoreline Reach 1 and Trail Segment 3 in Shoreline Reach 3. Given the horizontal distance from the shoreline, Trail Segments 2, 4 and 5 are not affected by wave runup or overtopping, only still water flooding.

3.10.1 Trail Segment 1 in Shoreline Reach 1 (Entrance Bay)

FEMA (2014) estimated an overtopping rate of 0.01 cfs/ft for the 1% annual chance TWL at FEMA Transect 76, but did not provide overtopping rates for other flood frequency levels. To provide more detailed overtopping information for Trail Segment 1 in Shoreline Reach 1, wave data from the FEMA (2014) study for Transect 76 and updated still water levels were used to provide a range of overtopping rates. The following wave data and shoreline revetment structure information for FEMA Transect 76 were used in the EurOtop (2018) overtopping equations for armored rubble slopes:

- Maximum wave height = 7.6 ft (2.31 m),
- Average wave period = 12.9 s,
- Revetment structure crest elevation = 17.7 ft, NAVD88 (5.68 m, NAVD88),
- Revetment structure toe elevation = 6.6 ft, NAVD88 (2.00 m, NAVD88),
- Revetment slope = 0.47 (1V:2.1H), and
- Assumed revetment crest width of 6 ft (1.83 m).

Table 13 provides a detailed summary of overtopping rates for Trail Segment 1 in Shoreline Reach 1 for a range of water levels and wind speeds. To support the preliminary HBT vulnerability assessment overtopping rates were also provided for sea level rise increases of 0.24 m (0.8 ft), 0.43 m (1.4 ft) and 0.95 m (3.1 ft). The results are evaluated in Table 16.

Table 13. Overtopping rates for Trail Segment 1 in Shoreline Reach 1 for different tidal datum and extreme coastal flood event levels, and the maximum wave height (H_{mo}) and average peak period (T_p) from the FEMA (2024) 50-yr wave hindcast data for FEMA Section 76 for existing conditions (Year 2023), and 0.24 m, 0.43 m and 0.95 m of SLR. Wave conditions are assumed normal to the shoreline, a 1V:2.1H revetment slope, and a crest elevation of 17.6 ft, NAVD88.

Tidal Datum and Extreme Flood Event	50-yr Wave Hindcast Data for FEMA Section 76	Year 2023		SLR 0.24 m (0.8 ft)		SLR 0.43 m (1.4 ft)		SLR 0.95 m (3.1 ft)	
		q (cms/m)	q (cfs/ft)	q (cms/m)	q (cfs/ft)	q (cms/m)	q (cfs/ft)	q (cms/m)	q (cfs/ft)
MHHW	Max H_{mo} , Avg T_p	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0000	0.000
MMMW	Max H_{mo} , Avg T_p	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0002	0.002
95% EP (1.05-yr RI)	Max H_{mo} , Avg T_p	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0037	0.040
66.7% EP (1.5-yr RI)	Max H_{mo} , Avg T_p	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0053	0.058
50% EP (2-yr RI)	Max H_{mo} , Avg T_p	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0070	0.075
20% EP (5-yr RI)	Max H_{mo} , Avg T_p	0.0000	0.000	0.0000	0.000	0.0001	0.001	0.0144	0.155
10% EP (10-yr RI)	Max H_{mo} , Avg T_p	0.0000	0.000	0.0000	0.000	0.0002	0.002	0.0220	0.237
4% EP (25-yr RI)	Max H_{mo} , Avg T_p	0.0000	0.000	0.0000	0.000	0.0004	0.005	0.0347	0.373
2% EP (50-yr RI)	Max H_{mo} , Avg T_p	0.0000	0.000	0.0001	0.001	0.0008	0.008	0.0458	0.493
1% EP (100-yr RI)	Max H_{mo} , Avg T_p	0.0000	0.000	0.0001	0.001	0.0012	0.013	0.0578	0.623

It should be noted that the existing condition overtopping rates for Shoreline Reach 1 are low (<0.01 cfs/ft), consistent with the FEMA (2024) estimate of 0.01 cfs/ft. However, these estimates are for only one cross-section along the shoreline (FEMA Transect 76), which had a rock crest elevation of 17.7 ft. As discussed in Section 2.4.1, the rock revetment has locations of wave overtopping that displaced smaller rock onto the landward railroad grade, and the railroad grade shows signs of overwash erosion. This indicates that sections of the rock revetment likely have crest elevations below 17.7 ft, and the overtopping rates in Table 13 may not be representative of the entire revetment.

3.10.2 Trail Segment 3 in Shoreline Reach 3

Wave overtopping rates were determined for Trail Segment 3 in Shoreline Reach 3 using the EurOtop (2018) overtopping equations for armored rubble slopes. Similar to the $R_{2\%}$ wave runup estimates, the overtopping rates were determined along the longest fetch for Shoreline Reach 3, and for the proposed Section 3 trail construction (i.e. trail, rock revetment and the 10-ft wide wetland bench) only. The overtopping rates can be considered a conservative upper limit for the proposed natural shoreline or coarse beach portions of Trail Segment 3. Table 14 lists the estimated overtopping rates for Trail Segment 3 for a range of water levels, the 1.05-yr, 2-yr, 10-yr and 100-yr wind conditions, and for existing Year 2023 sea levels and SLR increases of 0.24 m (0.8 ft), 0.43 m (1.4 ft) and 0.95 m (3.1 ft). These results are evaluated in Table 18.

Table 14. Overtopping rates for Trail Segment 3 in Shoreline Reach 3 for different tidal datum and extreme coastal flood event levels and wind speeds for existing conditions (Year 2023), and 0.24 m, 0.43 m and 0.95 m of SLR. Wave conditions are along the longest fetch (west-southwest direction (247.5°), 4.632 km length) relative to the shoreline, a 1V:1.5H revetment slope, and a 10-ft wide wetland bench treated as a submerged berm.

Tidal Datum and Extreme Flood Event	Wind Speed from WSE (247.5°)	Year 2023		SLR 0.24 m (0.8 ft)		SLR 0.43 m (1.4 ft)		SLR 0.95 m (3.1 ft)	
		q (cms/m)	q (cfs/ft)	q (cms/m)	q (cfs/ft)	q (cms/m)	q (cfs/ft)	q (cms/m)	q (cfs/ft)
MHHW	95% EP (1.05-yr RI)	0.0000	0.000	0.0000	0.000	0.0002	0.002	0.0058	0.062
MHHW	50% EP (2-yr RI)	0.0000	0.000	0.0001	0.001	0.0003	0.003	0.0091	0.097
MHHW	10% EP (10-yr RI)	0.0000	0.000	0.0003	0.004	0.0011	0.012	0.0186	0.200
MHHW	1% EP (100-yr RI)	0.0005	0.005	0.0009	0.010	0.0025	0.027	0.0313	0.337
MMMWW	95% EP (1.05-yr RI)	0.0001	0.001	0.0007	0.008	0.0026	0.028	0.0454	0.489
MMMWW	50% EP (2-yr RI)	0.0002	0.003	0.0013	0.014	0.0042	0.046	0.0594	0.639
MMMWW	10% EP (10-yr RI)	0.0008	0.009	0.0035	0.038	0.0095	0.103	0.0927	0.998
MMMWW	1% EP (100-yr RI)	0.0019	0.020	0.0068	0.074	0.0168	0.181	0.1287	1.386
95% EP (1.05-yr RI)	95% EP (1.05-yr RI)	0.0008	0.009	0.0043	0.046	0.0129	0.139	0.1005	1.081
95% EP (1.05-yr RI)	50% EP (2-yr RI)	0.0015	0.016	0.0069	0.074	0.0188	0.203	0.1235	1.329
95% EP (1.05-yr RI)	10% EP (10-yr RI)	0.0040	0.043	0.0147	0.158	0.0348	0.375	0.1743	1.877
95% EP (1.05-yr RI)	1% EP (100-yr RI)	0.0081	0.087	0.0254	0.273	0.0544	0.585	0.2259	2.432
66.7% EP (1.5-yr RI)	95% EP (1.05-yr RI)	0.0011	0.012	0.0056	0.060	0.0164	0.176	0.0576	0.620
66.7% EP (1.5-yr RI)	50% EP (2-yr RI)	0.0020	0.022	0.0088	0.095	0.0234	0.252	0.0665	0.716
66.7% EP (1.5-yr RI)	10% EP (10-yr RI)	0.0051	0.055	0.0182	0.196	0.0420	0.452	0.1990	2.142
66.7% EP (1.5-yr RI)	1% EP (100-yr RI)	0.0100	0.108	0.0307	0.330	0.0641	0.690	0.2549	2.744
50% EP (2-yr RI)	95% EP (1.05-yr RI)	0.0014	0.015	0.0069	0.074	0.0196	0.211	0.0721	0.776
50% EP (2-yr RI)	50% EP (2-yr RI)	0.0025	0.027	0.0106	0.114	0.0276	0.297	0.0832	0.895
50% EP (2-yr RI)	10% EP (10-yr RI)	0.0061	0.066	0.0214	0.230	0.0482	0.519	0.1045	1.124
50% EP (2-yr RI)	1% EP (100-yr RI)	0.0118	0.127	0.0353	0.380	0.0725	0.780	0.2795	3.008
20% EP (5-yr RI)	95% EP (1.05-yr RI)	0.0027	0.029	0.0122	0.131	0.0315	0.339	0.1193	1.284
20% EP (5-yr RI)	50% EP (2-yr RI)	0.0045	0.048	0.0179	0.192	0.0426	0.459	0.1376	1.481
20% EP (5-yr RI)	10% EP (10-yr RI)	0.0102	0.110	0.0333	0.359	0.0699	0.753	0.1729	1.861
20% EP (5-yr RI)	1% EP (100-yr RI)	0.0185	0.199	0.0523	0.563	0.1007	1.083	0.2032	2.187
10% EP (10-yr RI)	95% EP (1.05-yr RI)	0.0041	0.044	0.0173	0.187	0.0416	0.447	0.1546	1.664
10% EP (10-yr RI)	50% EP (2-yr RI)	0.0066	0.071	0.0247	0.266	0.0549	0.591	0.1785	1.921
10% EP (10-yr RI)	10% EP (10-yr RI)	0.0142	0.153	0.0439	0.472	0.0869	0.935	0.2242	2.413
10% EP (10-yr RI)	1% EP (100-yr RI)	0.0246	0.265	0.0667	0.718	0.1219	1.312	0.2635	2.836
4% EP (25-yr RI)	95% EP (1.05-yr RI)	0.0065	0.070	0.0254	0.273	0.0542	0.583	0.1993	2.145
4% EP (25-yr RI)	50% EP (2-yr RI)	0.0101	0.108	0.0350	0.377	0.0700	0.753	0.2300	2.476
4% EP (25-yr RI)	10% EP (10-yr RI)	0.0204	0.219	0.0591	0.636	0.1068	1.150	0.2890	3.110
4% EP (25-yr RI)	1% EP (100-yr RI)	0.0339	0.365	0.0868	0.934	0.1463	1.575	0.3396	3.656
2% EP (50-yr RI)	95% EP (1.05-yr RI)	0.0087	0.094	0.0321	0.345	0.0601	0.647	0.2309	2.486
2% EP (50-yr RI)	50% EP (2-yr RI)	0.0132	0.142	0.0433	0.466	0.0769	0.828	0.2665	2.869
2% EP (50-yr RI)	10% EP (10-yr RI)	0.0257	0.277	0.0709	0.763	0.1159	1.247	0.3348	3.604
2% EP (50-yr RI)	1% EP (100-yr RI)	0.0416	0.448	0.1019	1.097	0.1572	1.692	0.3935	4.236
1% EP (100-yr RI)	95% EP (1.05-yr RI)	0.0113	0.121	0.0389	0.418	0.0666	0.717	0.2605	2.803
1% EP (100-yr RI)	50% EP (2-yr RI)	0.0167	0.179	0.0517	0.556	0.0844	0.908	0.3006	3.235
1% EP (100-yr RI)	10% EP (10-yr RI)	0.0314	0.338	0.0824	0.887	0.1252	1.348	0.3776	4.064
1% EP (100-yr RI)	1% EP (100-yr RI)	0.0496	0.534	0.1164	1.253	0.1682	1.810	0.4438	4.777

3.11 Tsunami

Tsunamis are long ocean waves typically caused by displacement of the ocean bottom that are usually associated with large earthquakes but can also be caused by landslides and volcanic eruptions. The most extreme hazards likely faced by the Pacific Northwest, including Northern California, would be a Cascadia Subduction Zone earthquake and the resulting tsunami (Komar 2013). Tsunami depth and runup estimates for the Project site were determined using the American Society of Civil Engineers (ASCE) Tsunami Hazard Tool (ASCE Tsunami Design Geodatabase Version 2022-1.0) as part of the ASCE 7-22 design standards. The Tsunami Hazard Tool visually provides tsunami runup data points and the 3-ft inundation depth line. However, the Tool is designed to provide this information at specific locations for structure design purposes and does not readily provide supporting information for large areas.

Figure 26 provides a screen capture of the Tsunami Hazard Tool for the proposed Project HBT alignment. The entire HBT alignment is within the tsunami inundation zone and seaward of the 3-ft inundation depth line, indicating that the trail will have tsunami depths greater than 3-ft deep. It should be noted that this also applies to Fields Landing, King Salmon, and large sections of HWY 101. Thus, the proposed HBT would have comparable tsunami risks to existing residential areas and transportation infrastructure.

The tsunami runup elevation point is the approximate location where the runup elevation estimate intersects the ground topography and is landward of the entire HBT alignment. Runup estimates are highly variable and depend on the tsunami depth and topography at or near the runup elevation point. As mentioned before, continuous tsunami runup estimates are not readily obtained from the Tsunami Hazard Tool.

For reference a range of approximate runup estimates adjacent to each HBT segment is provided below:

- Trail Segment 1 (TS-1): tsunami runup elevation range = ~ 25 to 29 ft (NAVD88)
- Trail Segment 2 (TS-2): tsunami runup elevation range = 13 to 40 ft (NAVD88)
- Trail Segment 3 (TS-3): tsunami runup elevation range = 24 to 50 ft (NAVD88)
- Trail Segment 4 (TS-4): tsunami runup elevation range = 10 to 42 ft (NAVD88)
- Trail Segment 5 (TS-5): tsunami runup elevation range = 10 to 32 ft (NAVD88)

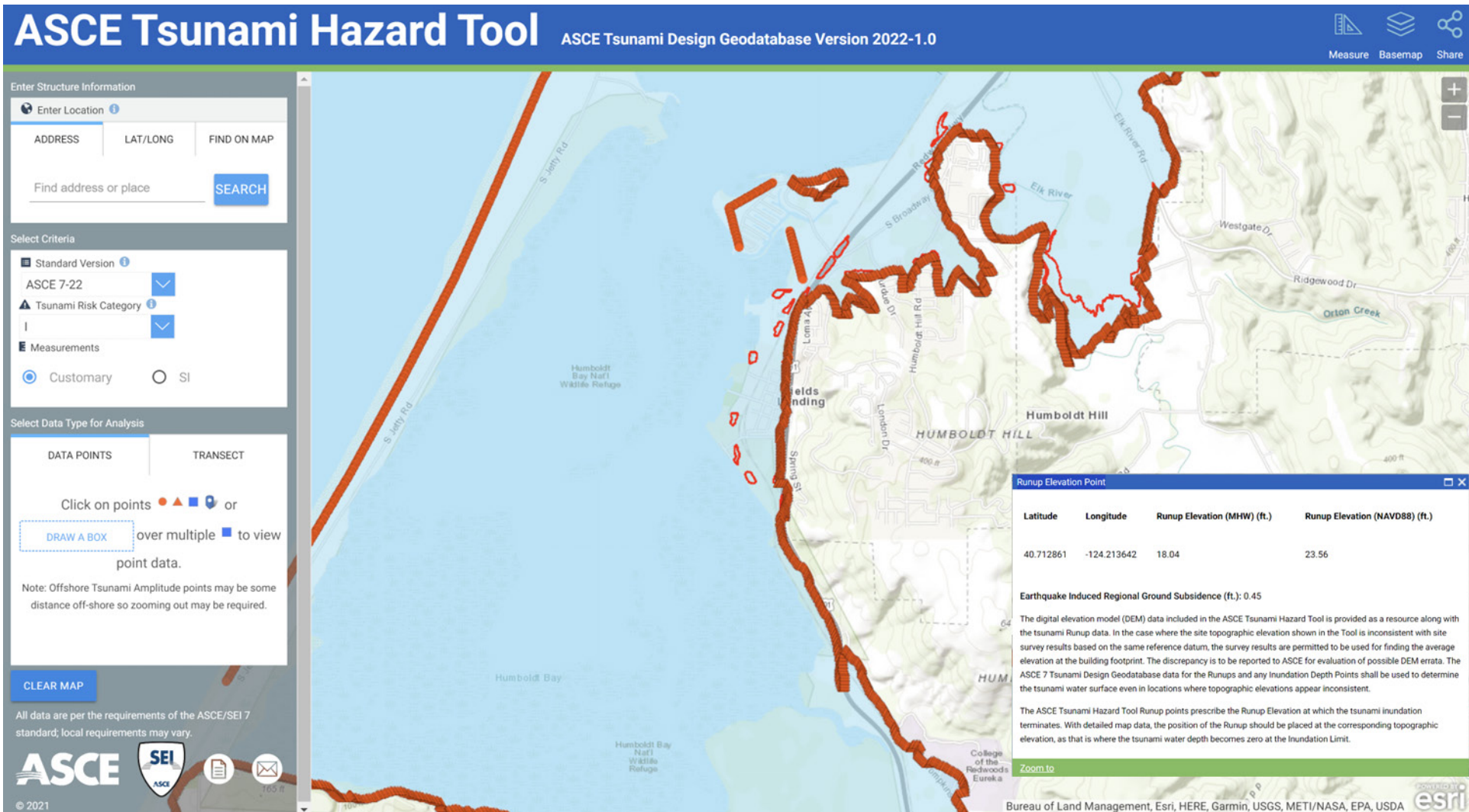


Figure 26. Screen capture of the American Society of Civil Engineers (ASCE) Tsunami Hazard Tool (ASCE Tsunami Design Geodatabase Version 2022-1.0) for ASCE 7-22 design standards, showing tsunami depth and runup locations for the proposed Humboldt Bay Trail (HBT) Project alignment from Eureka and College of the Redwoods. The inset shows the Runup Elevation Point information for a selected point in HBT trail segment 3 (TS-3) reach which has a tsunami runup elevation of 23.6 ft (NAVD88).

4 PRELIMINARY VULNERABILITY ASSESSMENT

A preliminary vulnerability assessment was conducted for the proposed HBT Project to address vulnerabilities from tsunamis, coastal erosion, and coastal flooding for current sea-level, and how these vulnerabilities change with sea level rise. For this assessment changes in HBT flooding vulnerability were assessed for SLR increases of 0.24 m (0.8 ft), 0.43 m (1.4 ft) and 0.95 m (3.1 ft). These SLR increases were taken from the California Sea Level Rise Guidance (2024) Intermediate Sea Level Scenario for California (Intermediate Scenario). Although the Intermediate Scenario assigns future dates to each SLR increase, the actual date when these increases will occur is not known. How local VLM increases the relative sea-level (RSL) rates in the vicinity of the HBT and shortens the timing of each Intermediate Scenario SLR increase into the future is addressed at the end of this section.

The coastal flooding vulnerability to the HBT is only assessed for Trail Segments 1, 2, 3, and the 1,400-foot section of Trail Segment 4 closest to Humboldt Bay and north-west of the Highway 101 overpass. As previously described, two types of coastal flooding are addressed in this vulnerability assessment. All sections of the HBT are subject to still water flooding, but only Trail Segment 1 and 3, which are immediately adjacent to the Humboldt Bay shoreline, are vulnerable to wave overtopping. It should be noted that the EurOtop (2018) wave overtopping methodology accounts for the effects of still water flooding.

Two types of erosion are evaluated in this vulnerability assessment. Coastal erosion is defined as erosion of the HBT section from direct wave attack and/or tidal/wind-driven currents and can result in large trail failures that would require major repairs. This type of coastal erosion is assessed in the coastal erosion vulnerability section. Potential damage or erosion to HBT surfaces from still water flooding or wave overtopping are addressed in the coastal flooding vulnerability section. This type of trail erosion or damage will likely require minor repairs for infrequent or shallow depth events. However, if the frequency and/or inundation depths of the flooding or overtopping increases then major damage and repairs to the HBT could occur.

The lowest trail elevation in each HBT segment is used to assess flood thresholds. For still water flooding, the following trail useability and damage thresholds are assumed:

- No useability or trail impact: < 0.25 ft above trail elevation
- Trail use compromised, no damage: 0.25 ft to < 0.5 ft above trail elevation
- Trail closed, minor damage: 0.5 ft to < 1 ft above trail elevation
- Trail closed, major damage: \geq 1 ft above trail elevation

The wave overtopping thresholds are based on criteria established in the EurOtop (2018) manual and are generally the same trail useability and damage thresholds used in the ESA (2018) and NSI (2022) studies. Wave overtopping thresholds are as follows:

- No useability or trail impact: < 0.22 cfs/ft
- Trail useability compromised, no damage: 0.22 to < 0.53 cfs/ft
- Trail closed, damage to lightly protected surfaces: 0.53 to < 2.2 cfs/ft
- Trail closed, damage to Promenade/Trail Pavement: \geq 2.2 cfs/ft

4.1 Tsunami Vulnerability

The entire proposed HBT alignment is within the 3-ft or greater tsunami inundation zone and therefore currently vulnerable to tsunamis, and future sea level rise will increase the tsunami inundation depths. As mentioned earlier the tsunami vulnerability also applies to Fields Landing, King Salmon, large sections of HWY 101, and sections of HBT previously or currently constructed. Thus, the proposed HBT would have comparable tsunami risks to existing residential areas and transportation infrastructure.

4.2 Coastal Erosion Vulnerability

Only Trail Segments 1 and 3 are vulnerable to coastal erosion from direct wave attack or currents. Most of Trail Segments 2 and 4 are over 400-ft inland from the Humboldt Bay shoreline and it was assumed that these segments are not vulnerable to coastal erosion.

4.2.1 Trail Segment 1

Trail Segment 1 is offset from the shoreline by 50+ feet to the east. As long as the existing rock revetment along Shoreline Reach 1 remains intact, the vulnerability from coastal erosion to Trail Segment 1 is non-existent too low. However, if the rock revetment or a section of revetment fails from increasing sea levels and/or increased wave activity in Entrance Bay, then the sections of Trail Segment 1 behind the revetment failures could be subject to direct coastal erosion.

4.2.2 Trail Segment 3

Trail Segment 3 is located immediately adjacent to the South Bay shoreline in Shoreline Reach 3 and is the most vulnerable section of the proposed HBT to coastal erosion. As described in Section 2, the sections of remnant tidal wetland fringe and/or natural shoreline seaward of the existing railroad grade are attenuating wave energy and erosion of the railroad grade at these locations are currently not occurring. Between the fringe tidal wetlands, the railroad grade is armored with rock or concrete rubble revetments that make up the immediate shoreline, and in locations where the revetment is intact the railroad grade is not eroding. However, in locations where the tidal wetland fringe has eroded, or the revetments have been out flanked, the existing railroad grade is actively eroding from direct wave attack.

Two general types of trail construction are proposed for Trail Segment 3. In locations where a natural shoreline or fringe tidal wetland exists the HBT will be constructed with no additional shoreline protection currently proposed. In locations where the existing railroad grade is eroding or has rock or concrete rubble revetments, the proposed HBT will be constructed with new/upgraded rock revetment.

As long as the existing tidal wetland fringe and natural shoreline segments, and the proposed rock revetments along Shoreline Reach 3 remain intact, the vulnerability from coastal erosion to Trail Segment 3 is non-existent too low. However, if the natural shoreline erodes or sections of the revetments fail over time from sea level rise and/or increased wave activity in South Bay, then sections of Trail Segment 3 could be subject to direct coastal erosion.

As described in Section 2.5.3, the natural shoreline or tidal wetland fringe in Shoreline Reach 3 are showing signs of edge erosion and retreat. Historical shoreline erosion rates have been about 0.3 ft/yr, but the more recent rate has increased to 0.7 ft/yr. Given that locations of the existing railroad grade are showing signs of erosion in locations where the natural shoreline has eroded back to the railroad prism, it is recommended in future design efforts to consider adding rock revetment to sections of Trail Segment 3 where the existing fringe wetland is relatively narrow in anticipation of ongoing shoreline erosion.

Another action to consider is adding a sand/gravel beach to the shoreline edge or scarp of the existing tidal wetland fringe to slow or prevent future erosion of the natural shorelines in Shoreline Reach 3.

4.3 Coastal Flood Vulnerability

This section describes coastal flooding from still water or wave overtopping to Trail Segments 1, 2, 3 and the north-west 1,400 feet of Trail Segment 4.

4.3.1 Trail Segment 1

Trail Segment 1 is vulnerable to both still water flooding to the trail grade and wave overtopping of the rock revetment. Since the rock revetment along Shoreline Reach 1 is porous and constructed higher than the backshore and offset section of the proposed trail (Figure 8 and Figure 9), Trail Segment 1 is vulnerable to still water flooding above the proposed trail elevation of 14 ft, NAVD88.

For SLR increases of 0.8 ft, 1.4 ft and 3.1 ft, Trail Segment 1 is not vulnerable to still water flooding as all flood levels are below the proposed trail elevation of 14 ft (Table 15).

Table 15. Trail Segment 1 vulnerability from still water flooding for a trail threshold elevation of 14 ft (NAVD88) for existing conditions (Year 2023), and 0.8 ft, 1.4 ft, and 3.1 ft of SLR increase.

Tidal Datum and Extreme Flood Event	Threshold (ft, NAVD88)	Still Water Level (ft, NAVD88)			
		Year 2023	0.8 ft SLR	1.4 ft SLR	3.1 ft SLR
MHHW	14.0	6.76	7.56	8.16	9.86
MMMW		8.04	8.84	9.44	11.14
95% EP (1.05-yr RI)		8.89	9.69	10.29	11.99
50% EP (2-yr RI)		9.14	9.94	10.54	12.24
10% EP (10-yr RI)		9.66	10.46	11.06	12.76
1% EP (100-yr RI)		10.22	11.02	11.62	13.32
No impact: < 0.25 ft above trail elevation					
Trail use compromised, no damage: 0.25 ft to < 0.5 ft above trail elevation					
Trail closed, minor damage: 0.5 ft to < 1 ft above trail elevation					
Trail closed, major damage: >= 1 ft above trail elevation					

Table 16 summarizes the Trail Segment 1 useability and damage vulnerability from wave overtopping of the rock revetment along Shoreline Reach 1 with a revetment crest elevation of 17.7 ft, NAVD88. Results indicate that the vulnerability to Trail Segment 1 from wave overtopping for a range of water and flood levels is low for current conditions and SLR increases of 0.8 and 1.4 ft. For 3.1 ft of SLR the vulnerability to wave overtopping is also low for the more frequent coastal flood events, but has compromised trail use for the 10% exceedance probability (EP) coastal flood event, and potential damage to lightly protected surfaces for the 1% EP event.

It was assumed for this vulnerability assessment that wave overtopping of the rock revetment along Shoreline Reach 3 will directly affect Trail Segment 1. Since the trail is proposed to be offset from the rock revetment, minor amounts of wave overtopping may be accommodated by the ground surface between the revetment and trail. However, as previously mentioned sections of the revetment likely have crest elevations lower than the 17.7 ft threshold, and the vulnerabilities in Table 16 may not be representative of the entire revetment and Trail Segment 1.

Table 16. Trail Segment 1 vulnerability from wave overtopping for a revetment crest elevation of 17.7 ft (NAVD88) for existing conditions (Year 2023), and 0.8 ft, 1.4 ft, and 3.1 ft of SLR increases.

Tidal Datum and Extreme Flood Event	Threshold (ft, NAVD88)	Wave Overtopping Rate, q (cfs/ft)			
		Year 2023	0.8 ft SLR	1.4 ft SLR	3.1 ft SLR
MHHW	17.6	0.00	0.00	0.00	0.00
MMMW		0.00	0.00	0.00	0.00
95% EP (1.05-yr RI)		0.00	0.00	0.00	0.04
50% EP (2-yr RI)		0.00	0.00	0.00	0.08
10% EP (10-yr RI)		0.00	0.00	0.00	0.24
1% EP (100-yr RI)		0.00	0.00	0.00	0.62
No impact: 0-0.22 cfs/ft					
Trail Usability Compromised, no damage: 0.23 - 0.53 cfs/ft					
Trail closed, damage to Lightly Protected Surfaces: 0.54-2.1cfs/ft					
Trail closed, damage to Promenade/Trail Pavement: 2.2+ cfs/ft					

4.3.2 Trail Segment 2

Trail Segment 2 is only vulnerable to still water flooding as most of the trail is more than 400 ft from the shoreline and will not be affected by wave conditions. The trail elevation in Trail Segment 2 ranges between 10.5 and 14 ft (NAVD88), and the lowest elevation of 10.5 ft will be used as the flood threshold. Table 17 summarizes the vulnerability to Trail Segment 2 from still water flooding. For existing sea levels and 0.8 ft of SLR the trail is not vulnerable to flooding, except for the 1% EP flood event when trail use may be compromised. With 1.4 ft of SLR, the trail is not vulnerable to flooding for the typical daily tide levels and more frequent flood events; but trail use is compromised for the 50% EP event, closed with minor damage for the 10% EP event, and closed with major damage for the 1% event. With 3.1 ft of SLR, the trail is not inundated for only the typical daily tide levels (e.g. MHHW) but is routinely inundated with over 1 foot of water multiple times each year and for all annual flood events.

Table 17. Trail Segment 2 vulnerability from still water flooding for a trail threshold elevation of 10.5 ft (NAVD88) for existing conditions (Year 2023), and 0.8 ft, 1.4 ft, and 3.1 ft of SLR increases.

Tidal Datum and Extreme Flood Event	Threshold (ft, NAVD88)	Still Water Level (ft, NAVD88)			
		Year 2023	0.8 ft SLR	1.4 ft SLR	3.1 ft SLR
MHHW	10.5	6.78	7.58	8.18	9.88
MMMW		8.06	8.86	9.46	11.16
95% EP (1.05-yr RI)		8.91	9.71	10.31	12.01
50% EP (2-yr RI)		9.16	9.96	10.56	12.26
10% EP (10-yr RI)		9.69	10.48	11.08	12.78
1% EP (100-yr RI)		10.22	11.02	11.62	13.32
No impact: < 0.25 ft above trail elevation					
Trail use compromised, no damage: 0.25 ft to < 0.5 ft above trail elevation					
Trail closed, minor damage: 0.5 ft to < 1 ft above trail elevation					
Trail closed, major damage: >= 1 ft above trail elevation					

4.3.3 Trail Segment 3

Trail Segment 3 in Shoreline Reach 3 is located immediately adjacent to the South Bay shoreline and vulnerable to both still water flooding and wave overtopping. The elevation of the proposed trail and revetment crest elevation are the same at 11.5 ft, NAVD88) and represents the threshold for Trail Segment 3. Both still water and wave overtopping rates for Trail Segment 3 are included in the EurOtop (2018) overtopping equations, so only one vulnerability analysis was needed for this trail segment. Table 18 summarizes the vulnerability to Trail Segment 3 from still water flooding and wave overtopping.

Table 18. Trail Segment 3 vulnerability from combined still water flooding and wave overtopping for a trail and revetment crest threshold elevation of 11.5 ft (NAVD88) for existing conditions (Year 2023), and 0.8 ft, 1.4 ft, and 3.1 ft of SLR increases.

Water Level	Wind Speed from WSE (247.5°)	Wave Overtopping Rate, q (cfs/ft)			
		Year 2023	0.8 ft SLR	1.4 ft SLR	3.1 ft SLR
MHHW	95% EP (1.05-yr RI)	0.00	0.00	0.00	0.06
MHHW	50% EP (2-yr RI)	0.00	0.00	0.00	0.10
MHHW	10% EP (10-yr RI)	0.00	0.00	0.01	0.20
MHHW	1% EP (100-yr RI)	0.00	0.01	0.03	0.34
MMMW	95% EP (1.05-yr RI)	0.00	0.01	0.03	0.49
MMMW	50% EP (2-yr RI)	0.00	0.01	0.05	0.64
MMMW	10% EP (10-yr RI)	0.01	0.04	0.10	1.00
MMMW	1% EP (100-yr RI)	0.02	0.07	0.18	1.39
95% EP (1.05-yr RI)	95% EP (1.05-yr RI)	0.01	0.05	0.14	1.08
95% EP (1.05-yr RI)	50% EP (2-yr RI)	0.02	0.07	0.20	1.33
95% EP (1.05-yr RI)	10% EP (10-yr RI)	0.04	0.16	0.37	1.88
95% EP (1.05-yr RI)	1% EP (100-yr RI)	0.09	0.27	0.59	2.43
50% EP (2-yr RI)	95% EP (1.05-yr RI)	0.02	0.07	0.21	0.78
50% EP (2-yr RI)	50% EP (2-yr RI)	0.03	0.11	0.30	0.90
50% EP (2-yr RI)	10% EP (10-yr RI)	0.07	0.23	0.52	1.12
50% EP (2-yr RI)	1% EP (100-yr RI)	0.13	0.38	0.78	3.01
10% EP (10-yr RI)	95% EP (1.05-yr RI)	0.04	0.19	0.45	1.66
10% EP (10-yr RI)	50% EP (2-yr RI)	0.07	0.27	0.59	1.92
10% EP (10-yr RI)	10% EP (10-yr RI)	0.15	0.47	0.93	2.41
10% EP (10-yr RI)	1% EP (100-yr RI)	0.26	0.72	1.31	2.84
1% EP (100-yr RI)	95% EP (1.05-yr RI)	0.12	0.42	0.72	2.80
1% EP (100-yr RI)	50% EP (2-yr RI)	0.18	0.56	0.91	3.24
1% EP (100-yr RI)	10% EP (10-yr RI)	0.34	0.89	1.35	4.06
1% EP (100-yr RI)	1% EP (100-yr RI)	0.53	1.25	1.81	4.78
No impact: 0-0.22 cfs/lf					
Trail Usability Compromise, no damage: 0.23 - 0.53 cfs/lf					
Trail closed, damage to Lightly Protected Surfaces: 0.54-2.1cfs/lf					
Trail closed, damage to Promenade/Trail Pavement: 2.2+ cfs/lf					

For existing sea levels, the trail is not vulnerable to flooding except for the most extreme flood and wind wave events that may occur jointly, when trail use may be compromised. With 0.8 ft of SLR, the trail is

not vulnerability to flooding for the daily tide levels under any extreme wind event, but trail useability becomes compromised for most flood events occurring with most extreme wind conditions. At the 1% EP flood event the trail is closed with minor damage when this flood event occurs with most extreme wind events. For 1.4 ft of SLR trail use is not vulnerable for the typical daily tides and any extreme wind event, but trail use becomes compromised under the more frequent flood events when combined with most extreme wind events. Trail use is closed with minor damage for the 10% and 1% EP flood events when combined with the extreme wind events. With 3.1 ft of SLR, trail use is not compromised only for typical daily tide levels (e.g. MHHW) under any extreme wind event. However, trail use is compromised or closed with minor damage multiple times each year and for the more frequent flood events when combined with all extreme wind events. For the 10% flood event the trail is closed with minor damage when occurring with the more frequent extreme wind events, and the trail is closed with damage for the 10% flood event occurring with the most extreme wind events and for the 1% flood events under any extreme wind event.

4.3.4 Trail Segment 4

Only the first 1,400 ft of Trail Segment 4 is assessed for vulnerabilities from still water flooding. Like Trail Segment 2, this trail segment is located away from the shoreline and will not be affected by wave conditions. The trail elevation threshold for Trail Segment 4 is 12 ft (NAVD88). Table 19 summarizes the vulnerability to Trail Segment 4 from still water flooding. For existing sea levels, and with 0.8 ft and 1.4 ft of SLR the trail is not vulnerable to flooding. With 3.1 ft of SLR the trail use is not compromised for the daily tide levels and the most frequent flood event. For the 50% flood event trail use becomes compromised. At the 10% and 1% flood event the trail is closed with minor to major damage, respectively.

Table 19. Trail Segment 4 vulnerability from still water flooding for a trail threshold elevation of 12 ft (NAVD88) for existing conditions (Year 2023), and 0.8 ft, 1.4 ft, and 3.1 ft of SLR increases.

Tidal Datum and Extreme Flood Event	Threshold (ft, NAVD88)	Still Water Level (ft, NAVD88)			
		Year 2023	0.8 ft SLR	1.4 ft SLR	3.1 ft SLR
MHHW	12.0	6.81	7.61	8.21	9.91
MMMW		8.11	8.91	9.51	11.21
95% EP (1.05-yr RI)		8.96	9.76	10.36	12.06
50% EP (2-yr RI)		9.21	10.01	10.61	12.31
10% EP (10-yr RI)		9.73	10.53	11.13	12.83
1% EP (100-yr RI)		10.28	11.08	11.68	13.38
No impact: < 0.25 ft above trail elevation					
Trail use compromised, no damage: 0.25 ft to < 0.5 ft above trail elevation					
Trail closed, minor damage: 0.5 ft to < 1 ft above trail elevation					
Trail closed, major damage: >= 1 ft above trail elevation					

It should be noted that lower elevation sections of Trail Segment 4 exist to the south-east towards College of the Redwoods. These sections of lower trail elevations may be more vulnerable to still water flooding than described in Table 19 if coastal flood waters can back flood into these areas. This type of flooding was not analyzed for Trail Segment 4.

4.4 Future Dates of SLR and Timing Effects of VLM

Although the actual future dates when the SLR increases of 0.8 ft, 1.4 ft, and 3.1 ft are not known, the Intermediate Scenario for California (California Sea Level Rise Guidance, 2024) assigns dates to these SLR increments. By linking the SLR increases to the Intermediate Scenario for California, these SLR values can generally be considered regional sea level rates for this assessment. Furthermore, local VLM increases the RSL rates in the vicinity of the proposed HBT which shortens the timing of each SLR increase and effectively changes the future dates associated with the Intermediate Scenario. The downward VLM rates of 2.66 and 4.65 mm/yr (Table 3), associated with Fields Landing and Hookton Slough respectively, approximately bracket the proposed HBT location and will be used for this assessment.

Figure 27 shows the timing and future dates of the Intermediate Scenario referenced to the Year 2000, with the regional SLR increases of 0.8 ft, 1.4 ft, and 3.1 ft indicated on the plot. RSL curves are generated by adding the 2.66 and 4.65 mm/yr VLM to the Intermediate Scenario and are also included in Figure 27, along with the same SLR increment levels plotted on each RSL curve. As can be seen, the effect of VLM changes the timing and future dates when each of the SLR increases occur.

Table 20 summarizes the future dates associated with the SLR increases of 0.8 ft, 1.4 ft, and 3.1 ft linked to the Intermediate Scenario, and how these future dates change with RSL by adding VLM rates of 2.66 and 4.65 mm/yr to the Intermediate Scenario. For example, under the Intermediate Scenario a 1.4 ft regional SLR increase will occur in 2070. However, VLM shortens the timing when the 1.4 ft SLR increase occurs. For a 2.66 mm/yr VLM rate, the 1.4ft SLR increase will occur 15 years earlier around 2055, and the 4.65 mm/yr VLM rate further shortens the timing to 24 years resulting in a 1.4 ft SLR increase occurring in 2046.

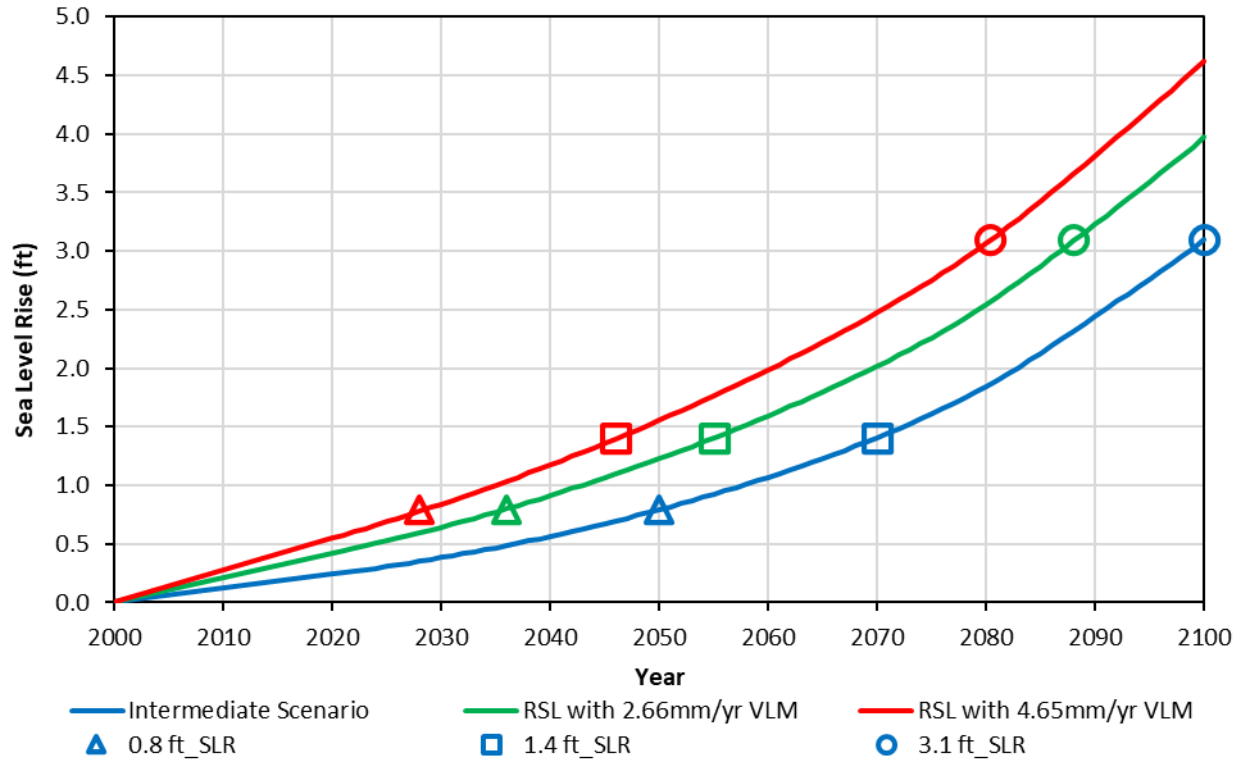


Figure 27. California Sea Level Rise Guidance (2024) Intermediate Sea Level Scenario for California (Intermediate Scenario) and the relative sea level (RSL) curves generated by adding 2.66 mm/yr vertical land motion (VLM) (for Fields Landing) and 4.65 mm/yr VLM (for Hookton Slough) to the Intermediate Scenario. All curves have a Year 2000 baseline. The 0.8 ft sea level rise (SLR) increase (triangle symbol), 1.4 ft SLR increase (square symbol), and 3.1 ft SLR increase (round symbol) represent the same water levels, and the color of the symbols represent how the dates change based on each sea-level curve.

Table 20. Change in timing and future dates for sea level rise (SLR) increases of 0.8 ft, 1.4 ft and 3.1 ft associated with the California Sea Level Rise Guidance (2024) Intermediate Sea Level Scenario for California (Intermediate Scenario) and the relative sea level (RSL) curves generated by adding 2.66 mm/yr vertical land motion (VLM) (for Fields Landing) and 4.65 mm/yr VLM (for Hookton Slough) to the Intermediate Scenario.

SLR Increases (ft)	Year Associated with Intermediate Scenario for California	Year Associated with RSL Curve with 2.66 mm/yr VLM added to Intermediate Scenario	Year Associated with RSL with 4.65 mm/yr VLM added to Intermediate Scenario
0.8	2050	2036	2028
1.4	2070	2055	2046
3.1	2100	2088	2080

5 RECOMMENDATIONS

The following recommendations are provided as the proposed HBT advances into the future.

- **Prioritize assessing and maintaining the revetment along Trail Segment 1.** No information on the design, maintenance or stability of the rock revetment in Trail Segment 1 was found, although that information likely exists. It is recommended that any recent information on this section of revetment be collected and reviewed. If information is not available, then it is recommended that an assessment/study of the current revetment condition be conducted, and a long-term monitoring and maintenance plan be developed. There may be a need to supplement localized areas of the revetment to maintain minimum elevations.
- **Utilize the best available data and analytical methods in future work.** As part of the Caltrans Highway 101 Corridor Project, Cal Poly Humboldt and NHE are developing a robust approach/methodology to simulate a 74-yr 1-hr water level and wind wave record at any location in Humboldt Bay. The water level record includes tide levels + storm surge + wind setup. The wind wave record includes wave height, period and direction. From this information a 74-yr 1-hr record of wave runup, total water level, and wave overtopping rates can also be determined at any location in Humboldt Bay. Using the 74-yr 1-hr records, extreme value analysis using GEV or GPD/POT methodologies can be used to determine extreme frequency analysis for water levels, wave conditions, and total water levels. This new approach provides a robust methodology for determining extreme water levels and wind-wave conditions that simultaneously occur and will be far superior compared to the additive approach used in this assessment. At a minimum it is recommended that the wave runup, total water level, wave overtopping and HBT vulnerability assessment be updated in a future design phase with results from this new approach, especially for Trail Segment 3 and Shoreline Reach 3.
- **Utilize the USGS CoSMos results in future work.** In a future design phase, it is recommended that the wave runup, total water level, and wave overtopping analysis for Trail Segment 1 along Shoreline Reach 1 be updated with the recently released USGS CoSMos results.
- **Consider the trade-offs of increasing the design elevation of the trail.** Raising the elevation of the trail in certain areas, especially Trail Segment 3 and portions of Trail Segment 2, could reduce flood vulnerability. The flood resilience benefits of raising the trail elevation by various increments (0.5 ft, 1.0 ft, 1.5 ft., etc.) in key areas should be weighed against trade-offs including cost and wetland impacts in order to optimize the value of the project. Increasing the trail elevation would also help to offset the increased RSL rates and shortened timing of SLR caused by higher VLM rates for the proposed HBT alignment, compared to previously constructed sections of the HBT where VLM rates are lower. Thus, balancing the future timing of SLR vulnerabilities for the entire HBT.
- **Plan for increasing erosion along Trail Segment 3.** The existing natural shoreline or tidal wetland fringe in Shoreline Reach 3 are showing signs of edge erosion and retreat. Historical shoreline erosion rates have been about 0.3 ft/yr, but the more recent rate has increased to 0.7 ft/yr. Future design phases should consider adding a sand/gravel or shingle beach to the shoreline edge or scarp of the existing tidal wetland fringe to slow or prevent future erosion of the natural shorelines in Trail Segment 3. Given that locations of the existing railroad grade are showing signs of erosion in locations where the natural shoreline has eroded back to the railroad prism, it is recommended in future design efforts to consider adding rock revetment to sections of Trail

Segment 3 where the existing fringe wetland is relatively narrow in anticipation of ongoing shoreline erosion. The increasing rate of erosion represents an urgency to provide stewardship and/or protection of the existing fringe wetlands before they disappear.

- **Include Trail Segment 4 in future assessment work.** In a future design phase, it is recommended that a flood vulnerability assessment be conducted for the remaining section of Trail Segment 4 not assessed in this study.

6 REFERENCES

- Arns, A., T. Wahl, I.D. Haigh, J. Jensen, and C. Pattiaratchi. (2013). Estimating extreme water level probabilities: A comparison of the direct methods and recommendations for best practice. *Coastal Engineering*, Volume 81, 51-66.
- Bottin, R.R. Jr. 1990. Case Study of a Successful Beach Restoration Project. *Journal of Coastal Research*, Vol. 6, No. 1, pp. 1-14.
- California Sea Level Rise Guidance: 2024 Science and Policy Update. 2024. California Sea Level Rise Science Task Force, California Ocean Protection Council, California Ocean Science Trust.
- Coastal Engineering Manual (CEM). 2015. Chapter 2, Meteorology and Wave Climate. U.S. Army Corps of Engineers. Washington D.C. EM 1110-2-1100 (Part II).
- Coles, S. 2001. An introduction to statistical modeling of extreme values. Springer-Verlag, London.
- Costa, S.L. and K.A. Glatzel. 2002. Humboldt Bay, Entrance Channel Report 1: Data Review. Report ERDC/CHL CR-02-1. U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS.
- Department of the Army. 1957. Appendix VI, Humboldt Bay (Buhne Point), Calif. Beach Erosion Control Study. Letter from the Chief of Engineers, Department of the Army, Dated July 24, 1957. United States Government Printing Office, Washington.
- Environmental Science Associates (ESA). 2018. Sea level Rise Vulnerability and Adaptation Report, Humboldt Bay Trail South. Report Prepared by ESA for County of Humboldt, Under Contract with GHD, June 2018.
- EurOtop, 2018. Manual on wave overtopping of sea defenses and related structures. An overtopping manual largely based on European research, but for worldwide application. Van der Meer, J.W., Allsop, N.W.H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P. and Zanuttigh, B., www.overtopping-manual.com.
- Federal Emergency Management Agency (FEMA), 2005. Final Draft Guidelines for Coastal Flood Hazard Analysis and Mapping for the Pacific Coast of the United States. Joint Project by FEMA Region IX, FEMA Region X, and FEMA Headquarters. FEMA Region IX, Oakland, CA.
- Federal Emergency Management Agency (FEMA), 2014. Intermediate Data Submittal #3: Nearshore Hydraulics, Humboldt County, California. Prepared for FEMA Region IX. Prepared by Baker AECOM.
- Federal Emergency Management Agency (FEMA), 2018a. Flood Insurance Study (FIS), Humboldt County and Incorporated Areas. Revised FIS dated 21 June 2017 with Corrected Reprint dated 31 August 2018.
- Federal Emergency Management Agency (FEMA), 2018b. Guidance for Flood Risk Analysis and Mapping Coastal Wave Runup and Overtopping. Guidance Document 89, February 2018.
- George, D.A. and P.S. Hill. 2008. Wave climate, sediment supply and the depth of the sand-mud transition: A global survey. *Marine Geology* 254, 121-128.

- GHD Inc., Northern Hydrology & Engineering, and Conor Shea. 2022. Natural Shoreline Infrastructure in Humboldt Bay for Intertidal Coastal Marsh Restoration and Transportation Corridor Protection: Draft 50% Design Report. Prepared for Humboldt County Department of Public Works. Draft report and appendices available at <https://humboldt.gov.org/2487/Sea-Level-Rise>.
- GHD Inc. (GHD). 2023. Humboldt Bay Trail Planning Study: Eureka to College of the Redwoods, Technical Memorandum - Draft. Prepared for Humboldt County Department of Public Works. GHD, Eureka, CA. Dated 11/7/2023.
- GHD Inc. (GHD). 2024a. Humboldt Bay Trail Planning Study: Eureka to College of the Redwoods, 10% Design Plans. Prepared for Humboldt County Department of Public Works. GHD, Eureka, CA. Dated 2/2/2024.
- GHD Inc. (GHD). 2024b. Humboldt Bay Trail Planning Study: Eureka to College of the Redwoods, Trail Profile, Interim Draft. Prepared for Humboldt County Department of Public Works. GHD, Eureka, CA. Dated 2/15/2024.
- GHD Inc. (GHD). 2024c. Humboldt Bay Trail Planning Study: Eureka to College of the Redwoods, 30% Design Plans. Prepared for Humboldt County Department of Public Works. GHD, Eureka, CA. Dated 9/20/2024.
- Gilleland, E. and R.W. Katz. 2016. extRemes 2.0: An Extreme Value Analysis Package in R. *Journal of Statistical Software*, 72(8), 1-39. doi:10.18637/jss.v072.i08.
- Kelsey, H. M. 1980. A sediment budget and an analysis of geomorphic process in the Van Duzen River basin, north coastal California, 1941–1975. *Geological Society of America Bulletin*, 91(4_Part_II), 1119-1216.
- Komar, P.D., J.C. Allan and P. Ruggiero. 2013. U.S. Pacific Northwest Coastal Hazards: Tectonic and Climate Controls. Chapter 21 in *Coastal Hazards*, Coastal Research Library 6, C.W. Finkl (Editor). Springer Science+Business Media Dordrecht.
- Kunkel, K. 2019. Exploring Community Knowledge and Perceptions of Flooding and Sea-Level Rise in King Salmon, California. Master's Thesis. Environmental Systems: Energy, Technology and Policy, Cal Poly Humboldt. Available at: <https://digitalcommons.humboldt.edu/etd/341>.
- Laird, A., Powell, B. and J.K. Anderson. 2013. Humboldt Bay Shoreline Inventory, Mapping and Sea level Rise Vulnerability Assessment. Humboldt Bay Sea Level Rise Adaptation Planning Project, Phase 1. Prepared for the California State Coastal Conservancy.
- Mackey, B. H. and J.J. Roering. 2011. Sediment yield, spatial characteristics, and the long-term evolution of active earthflows determined from airborne LiDAR and historical aerial photographs, Eel River, California. *Bulletin*, 123(7-8), 1560-1576.
- Montillet, J.-P., Melbourne, T. I. and W. M. Szeliga. 2018., GPS vertical land motion corrections to sea-level rise estimates in the Pacific Northwest. *Journal of Geophysical Research: Oceans*, 123(2), 1196–1212.
- Northern Hydrology and Engineering (NHE). 2018. Sea-Level Rise in the Humboldt Bay Region, Update 2: December 2018. Partial funding for document preparation by the City of Arcata. NHE, McKinleyville, CA. Report available at <http://www.coastalecosystemsinstitute.org>.
- OCM Partners. 2024. 1986 -2019 USGS CoNED Topobathy DEM (Compiled 2020): Northern California. Available at: <https://www.fisheries.noaa.gov/inport/item/62987>.

- Patton, J. R., Williams, T.B., Anderson, J.A., Hemphill-Haley, M., Burgette, R.J., Weldon, R. II, McPherson, R.C., and T.H. Leroy. 2023. 20th to 21st Century Relative Sea and Land Level Changes in Northern California: Tectonic Land Level Changes and their Contribution to Sea-Level Rise, Humboldt Bay Region, Northern California in *Tektonika*, v. 1, no. 1, <https://doi.org/10.55575/tektonika2023.1.1.6>.
- Rhode, J. Not Dated. The Humboldt Bay Area 1946-1955: A Decade of Development & Disturbance. Presentation. Available at: <https://cdm16166.contentdm.oclc.org/digital/collection/shuster>.
- Tuttle, D.C. 2004. History of Major Developments on Humboldt Bay. Proceedings of the Symposium: Current Perspectives on the Physical and Biological Processes of Humboldt Bay. Schlosser, S.C. and Rasmussen, R. (Editors). Publication No. T-063.
- U.S. Army Corps of Engineers (COE). 1984. Buhne Point, Humboldt Bay, California Design for the Prevention Shoreline Erosion Demonstration Project; Hydraulic and Numerical Model Investigations. Technical REprot cERC-84-5. Department of the Army, Waterways Experiment Station, Corps of Engineers, Vicksburg, MS.
- U.S. Army Corps of Engineers (COE). 1987a. Buhne Point Shoreline Erosion Demonstration Project; Final Main Report. San Francisco and Los Angeles District of Corps of Engineers. San Francisco, CA.
- U.S. Army Corps of Engineers (COE). 1987b. Buhne Point Shoreline Erosion Demonstration Project; Final Appendices Vol. II, E. San Francisco and Los Angeles District of Corps of Engineers. San Francisco, CA.
- van der Meer, J.W. (2002). Technical Report: Wave Run-up and Overtopping at Dikes. Technical Advisory Committee for Water Retaining Structures, Delft, Netherlands.
- Van Kirk, S. 1975. Fields Landing-Buhne's Point Research. Letter to Don Tuttle, dated 10 April 1975.
- Van Kirk, S. 1998. Land Uses on Humboldt Bay Tributaries (Salmon Creek, Elk River, Freshwater Creek and Jacoby Creek). Newspaper articles compiled in Kris Humboldt Bay. Available at: https://www.krisweb.com/krihumboldtby/krisdb/html/krisweb/humbay_historic/bayfish2.htm.
- Warrick, J. A., Madej, M. A., Goñi, M. A. and R.A. Wheatcroft. 2013. Trends in the suspended-sediment yields of coastal rivers of northern California, 1955–2010. *Journal of hydrology*, 489, 108-123.
- Wheatcroft, R.A. and J.C. Borgeld. 2000. Oceanic flood deposits on the norther California shelf: large-scale distribution and small-scale physical properties. *Continental Shelf Research* 20, p. 2163–2190.