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memorandum

date February 1, 2021

to Jeremy Svehla, PE (GHD)

from Robert (Bob) Battalio, PE and Louis White, PE

subject Conceptual Design for a Bayfront Horizontal Levee, Project 2 [Sea-Level Rise Adaptation Plan for Humboldt Bay Transportation Infrastructure (Phase 1), Task 4.2 (ESA Ref. #D201801130.00)]

1 Introduction and Purpose

This memorandum presents a conceptual design for a horizontal levee, also known as "Project 2" of the sea-level rise adaptation plan being prepared by the Humboldt County with the assistance of GHD. ESA prepared this conceptual design as a subcontractor to GHD.

This conceptual design will provide the basis for a benefit-cost analysis to be accomplished by economist Phil King Ph.D. The designs and economics analysis will inform the adaptation plan.

The geographic scope of the horizontal levee is 1.25 miles of the east shore of Arcata Bay between the Brainard and Bracut land areas west of Highway 101. The conceptual design consists of this description, including a plan and typical section, and engineer's estimates of likely construction quantities and costs. The purpose of the horizontal levee is to reduce flood and erosion hazards by dissipating waves generated in Arcata Bay, while providing ecological benefits with a nature-based design. The horizontal levee will protect the proposed Humboldt Bay Trail South (HBTS, Project 1) to be constructed on an out-of-service railway, and also reduce wave exposure to Highway 101 located slightly landward. The HBTS is also Project 1 of the Adaptation Plan being designed by GHD. Hence, Project 1 is assumed to be in-place and forms the landward boundary of the Project 2 horizontal levee.

ESA staff contributing to this memorandum are Louis White, PE (Project Manager and Engineer for ESA), Brent Davis, EIT (civil engineer) and Bob Battalio, PE (civil engineer). Internal quality control review was provided by Mark Lindley, PE (civil engineer).

2 Horizontal Levee Description

Horizontal Levee refers to an earth mass with a flatly sloped wet side that provides a landform that dissipates waves gradually, thereby reducing erosion potential and reducing the height of wave runup which would otherwise overtop the crest of the levee and cause dry-side flooding (ESA PWA and TBI 2013). A co-benefit of the horizontal levee is the ecological benefit of habitat that forms on the flat slope. Further, the flat slope crosses a range of elevations from tidal to upland, forming an "ecotone" that has greater ecological value than disjointed or isolated mono-type habitats. Also, the upland portions of the ecotone provide accommodation space for tidal wetlands to migrate to as sea-levels rise, thereby extending the functional life of hazard reduction and ecology improvement.

Horizontal levees have been constructed in the San Francisco Bay area. The term *horizontal levee* is used generically to refer to a relatively flat, vegetated earth slope fronting a flood barrier, and for the purposes of this memorandum we identify three major subtypes below: Tidal Bench, Horizontal Levee, and Living Levee. Note that sea-level rise adaptation is an evolving field, definitions are in flux, and terms sometimes have multiple meanings. Based on current usage, the term *horizontal levee* can have both a general and specific meaning.

2.1 Tidal Bench

A tidal bench is a relatively narrow section of flat slope ("bench") within the tidal range. The bench extends from low tide or site grade, whichever is higher, to an extreme high water such as the 10-year recurrence. The bench should be sloped no steeper than 7:1 (horizontal: vertical), providing a width of emergent vegetation not less than 30 feet to dissipate small, short-period wind waves without erosion: wider slopes that are flatter than 10:1 are strongly preferred. Additional bench width can be provided to accommodate erosion during extreme events. The additional cost of the earth is mitigated by avoiding rock slope protection or other armoring, although armoring may still be required above the bench to mitigate erosion during very high water levels (Newkirk and others 2018; ESA and others 2018). Tidal benches have been successfully constructed in the following San Francisco Bay projects: Warm Springs, Sonoma Baylands, Petaluma Marsh, Sears Point Wetland Restoration and Hamilton Wetlands Restoration Project.

2.2 Horizontal Levee

A horizontal levee is an expansion of the Tidal Bench to include wetland-upland transition and upland habitats, thereby creating an "ecotone" with much greater ecological benefits realized by any particular section (ESA and TBI, 2013). The upper slope also provides accommodation space for higher sea levels. Horizontal Levees have slopes flatter than 20:1, typically 30:1 to 50:1, and approaching horizontal were appropriate. Ecotones have been constructed at the Hamilton Wetland Restoration Project, Wildlife Corridor component, and at Sears Point Wetland Restoration. Extensive use of Horizontal Levees is proposed for the South San Francisco Bay Salt Ponds Wetlands Restoration Project (AECOM and others 2017) and the associated South Bay Shoreline Study (flood protection component with Federal participation, USACE and others 2015). A key feasibility factor is the sourcing, transporting, and placing the large volumes of required earth.

2.3 Living Levee

A Living Levee is a Horizontal Levee with treated wastewater irrigation that results in vertical accretion of fresh-brackish marsh while also removing nutrient loadings in the effluent. The concept was developed in the 2000s (PWA 2010) with a pilot project (ESA and Baye 2012) constructed in 2017 (Oro Loma Sanitary District and ESA 2015; Save the Bay 2017). There are multiple proposed living levee-horizontal levee projects planned in the San Francisco Bay area.

The selected concept for Project 2 of the Humboldt Bay Sea-level Rise Adaptation Project is a Horizontal Levee without the irrigated fresh-brackish marsh (aka living levee) component. However, the conceptual design does not preclude the addition of the living levee component.

3 Horizontal Levee Planning for Humboldt Bay

Wetland restoration and horizontal levee projects have been proposed in Humboldt Bay as a component of regional sediment and navigation dredging management, including the Project 2 location on the eastern Arcata Bay (ICF 2020; Trinity Associates 2019; SHN and others 2015; CSMW and MNE 2017).

The *Feasibility Study of Beneficial Reuse of Dredged Materials for Tidal Marsh Restoration and Sea Level Rise Adaptation* (SHN and others 2014) identified an ecotone dike with a slope of 10:1 from between elevations 2.75 to 9.75 feet with a width of approximately 120 feet. This study also identified tidal marsh restoration in the Project 2 location as desirable owing to historical losses of marsh in this area. One of the salt marsh restoration locations (SMR-LS-4) is the same location as Project 2: an estimated 36,000 to 110,000 cy is needed and likely to be supplied from marina dredging via hydraulic slurry pumped about 20,000 feet (about 4 miles). The study noted that the area is subject to wave-induced erosion and that fortification of the new marsh edge would likely be needed, and the possibility of using shell fish reefs consistent with a nature-based, living shoreline approach.

The *Coastal Regional Sediment Management Plan for the Eureka Littoral Cell* (CSMW and MNE 2017) investigated beneficial reuse of sediment dredged for navigation, beneficial reuse “Schema 5” describes a horizontal levee in the same location as Project 2. The concept was about 150 feet wide, and requires 300,000 cubic yards of dredged material. Barriers would be constructed to facilitate sediment placement in the tidal waters, and hydraulic placement of fine sediment dredged from non-federal projects was considered the logical source.

Consistent with these prior studies, the *Humboldt Bay Trail South Sea-Level Rise Vulnerability and Adaptation Report* (ESA 2018) identifies a horizontal levee, marsh sills, and coarse sediment beaches among potential living shoreline – natural infrastructure approaches to mitigate the effects of sea-level rise. Project 1 addresses the same Trail, including the Project 2 location. The Trail exposure to waves and sea-level rise were addressed in this previous study, which also identified wave overtopping criteria for trail design, and are recommended for use as a basis for assessing the protective services benefits of Project 2 (see Wave Attenuation).

The Program Environmental Impact Report for Humboldt Bay Sediment Management (ICF 2020) identifies beneficial reuse of dredged material for sea-level rise adaptation as a desirable sediment management action. The program identifies both direct placement (from dredge site to beneficial reuse) as well as expansion of sediment processing sites. Direct placement is likely to require hydraulic slurry pumping of sediment for 2 to 4 miles.

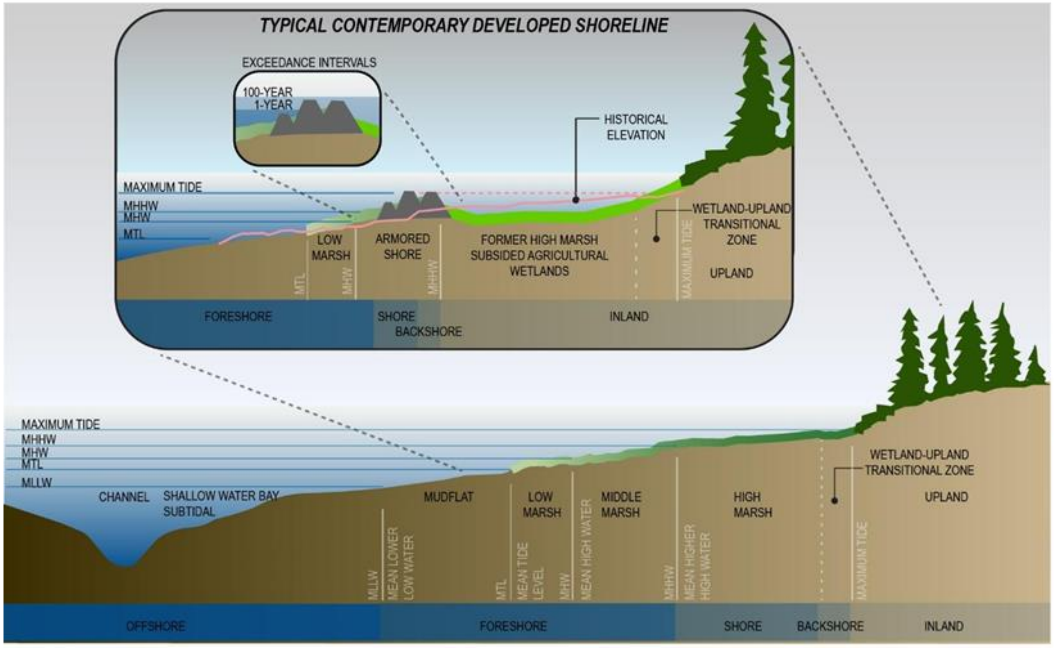
Sediment would be dried at the processing sites, and hence the sediment could be transported by truck or barge to beneficial reuse sites such as Project 2. This study focused on the dredging to maintain non-federal navigation depths to and at port-marina facilities. Maintenance dredging for these projects generate about 200,000 cubic yards of sediments mostly (85%) finer than sands every 7 to 10 years. Existing upland disposal – drying sites are discussed, including the potential for sediment storage on the order of 50,000 to 100,000 cubic yards of dried material (see Appendix B HBHRCD 2010 *Proposed Mitigated Negative Declaration for Humboldt Bay Upland Dredge Disposal Site* (Humboldt Bay Harbor, Recreation, and Conservation District 2010). Appendix A *Potential Beneficial Reuses of Dredged Sediment, Humboldt Bay* (Trinity 2019) provides additional information pertinent to Project 2, as discussed above for horizontal levees and below for ecology benefits.

4 Ecology and Habitats

Tidal and other wetlands were extensive in the vicinity of the project site prior to development (SHN and others 2015; Trinity 2019; Laird 2007). In particular, the marsh between Brainard and Bracut present in the 1870s mapping has eroded away (Laird 2007). The project area is primarily mudflats with some fringe salt marsh and seasonally varying patchy eelgrass nearshore and offshore of site[1]. Despite the value of mudflats, salt marsh and eelgrass, construction of a marsh in the Project 2 location can be considered restoration of historical habitat. Further, it is likely that the existing habitats will be degraded with sea-level rise owing to the increased depth of water and lack of higher ground to migrate into, and nature-based approaches to protect transportation assets are likely to have net ecological benefits relative to traditional shore armoring approaches. It is not known if mitigation for impacts to existing mudflats, salt marsh and eelgrass beds will be required.

A conceptual profile of tidal ecotone in Arcata Bay is provided in Figure 1 (GHD and others 2020). The tidal elevations (datums) that correspond to the habitat elevation bands are provided in Table 1 (ESA 2018; NOAA *Tides and Currents* website North Spit Station 9418767; GHD and others 2020). Note that the closest primary tide gauge for which observations are available is located near the entrance to Humboldt Bay (North Spit Station 9418767), and the most recent projections are for the tidal epoch 1983-2001. However, the high tide elevations are known to be elevated in the north of Humboldt Bay (Arcata Bay) including at the project site (GHD and others 2020, Costa and Glatzel 2002, NHE 2015, NHE 2016). Consequently, tidal datums for the project site were extracted from the online tool VDATUM. A comparison of the tidal datums from VDATUM and published values for other locations in Arcata Bay (Samoa, Freshwater Slough and Mad River Slough) showed close agreement with the VDATUM values. These published values are all for the tidal epoch 1983-2001 and hence do not include sea-level rise to date. Consequently, the elevations were increased by 2.28 mm/yr (NHE 2015) for 30 years to approximate 2021 values. These adjusted tidal datum elevations are presented in Table 1 along with the published values for the North Spit Station for reference. Extreme high water values (e.g. 100-year) are from GHD and others 2020. We note that the high water levels for the project have been defined by GHD and others (2020), where MHHW at the project site was established at 7 feet NAVD by adjusting the North Spit elevation upward by 0.49 feet. The VDATUM output presents MHHW at elevation 6.8 feet NAVD at the project site. For purposes of this conceptual design the 6.8 feet NAVD from VDATUM and 7 feet NAVD from GHD and others (2020) are reasonably close. To compensate for uncertainty in the elevation of MHHW, we added additional volume of fill to be consistent with the higher tidal datums.

[1] Baseline Eelgrass Map, Humboldt Bay Harbor, Recreation and Conservation District: http://humboldtbay.org/eelgrass-distribution-map last visited December 2020.



Source: GHD and others 2020

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Figure 1
Tidal ecotone elevations and habitats

TABLE 1
ELEVATIONS, HABITATS AND SITE FEATURES

Elevation (feet NAVD)*	Condition or Datum	Habitat above	Vegetation above
11.5 [a]	--	Project 1 high grades - nominal	TBD
10.6 [a]	100-year still water	Upland	
9.9 [a]	10-year	Upland	
9.3 [a]	1 to 2 year	Wetland Upland Transition	TBD
6.8 [b] [6.5] [c]	MHHW	Middle and High Marsh	Pickleweed, salt grass, marsh rosemary, arrowgrass, Humboldt Bay owl's clover, Point Reyes bird's beak, invasive non-native cordgrass
6.1 [b] [5.8] [c]	MHW	Middle and High Marsh	Pickleweed, invasive non-native cordgrass
4.0 [d]	--	Site grade - nominal	Mudflat
3.3 [b] [3.4] [c]	MTL / MSL	Low Marsh	Mudflat, patchy eel grass

SOURCES:

a Extremes: GHD and others 2020
b Tidal datums: VDATUM at site adjusted for 30 years of sea-level rise @ 2.28 mm/yr from tidal epoch of 1983-2001 to 2020 approx.
c [Tidal datums]: NOAA NOS published for North Spit 9418767 tidal epoch 1983-2001
d Interpretation from mudflat topography, from Pacific Watershed Associates (2014)

5 Conceptual Design

This section presents a basis for the conceptual design of the Project 2 horizontal levee, a summary of the engineer's estimate of probable construction costs, and future opportunities for concept refinement. The horizontal levee was selected over tidal bench because it would be more effective for a longer term that includes accommodation space for sea-level rise. Also, a similar concept has been described for this same location by CSMW and MNE (2017).

5.1 Horizontal Levee Concept: Plan and Section

The conceptual design is depicted in Figure 2, and consists of three zones:

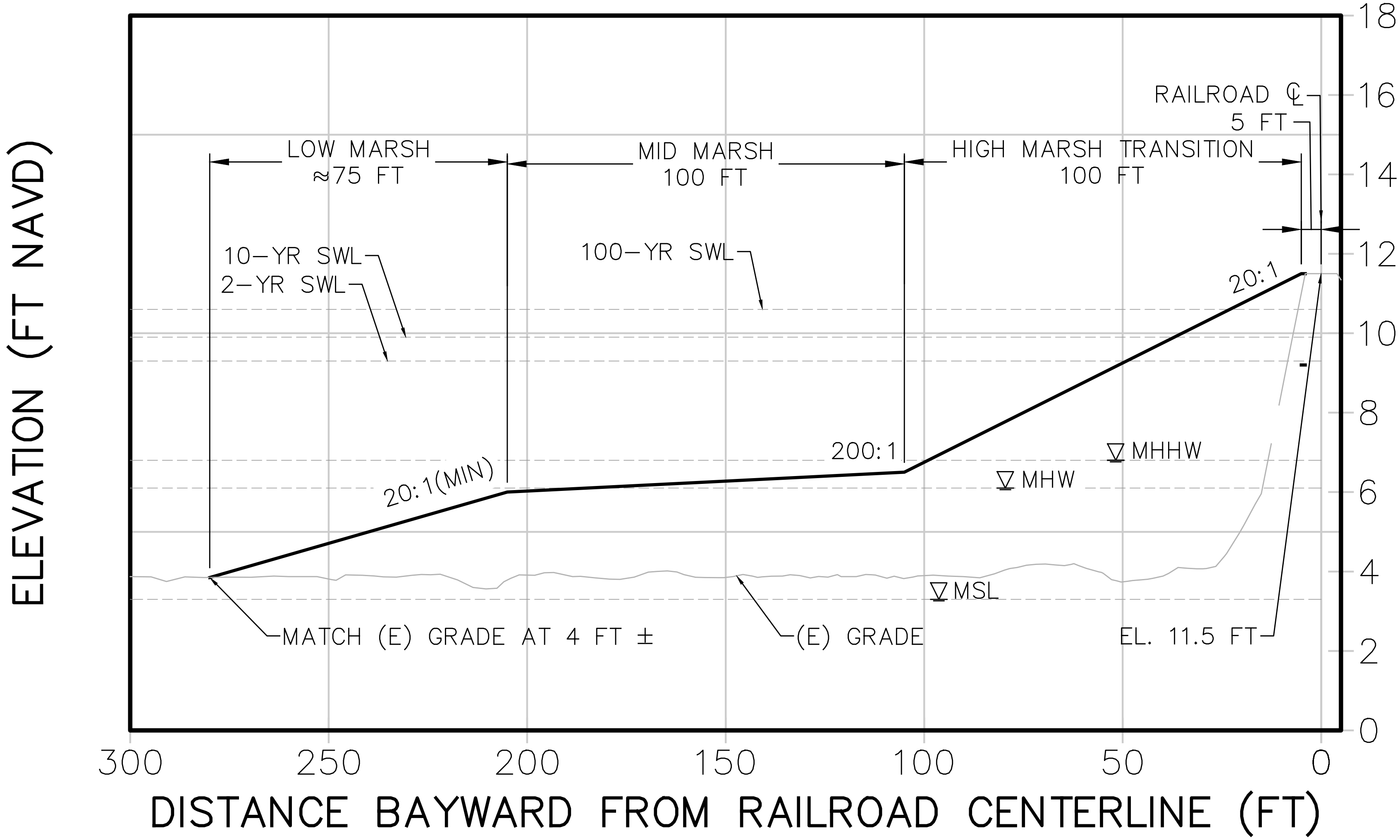
1. Low Marsh: A 75-foot wide slope at 20:1 (h:v). This is a transition from existing nominal mudflat elevation about +4' NAVD marsh grades to mid-marsh elevations. Coarse sediment, marsh sill or shellfish reefs could be included in this reach to mitigate wave action.
2. Mid Marsh: About 100 feet of nearly horizontal vegetated salt marsh extending from MHW to near-MHHW elevation (+6.5' NAVD). The 100-foot extent is a nominal dimension adequate to dissipate locally generated wind waves and runup during most tides. Channels and ponds can be expected to develop over time. Higher elevations may be desired for this mid marsh in order to be at or above MHHW and to compensate for relative sea-level rise, including long-term settlement resulting from fill placement. However, constructability may limit the fill thickness that can be practically achieved in this location.
3. High Marsh Transition: Approximately 100 feet of vegetated earth sloped at about 20:1, from MHHW to the Project 1 grade of 11.5' NAVD at the existing railroad. This flat slope is expected to dissipate wind waves incident during extreme high water levels, although some scarping and erosion can be expected during extreme events. Erosion will provide sediment to adjacent mid-marsh zones. A mix of mid- and high-marsh and upland vegetation will be planted. With sea-level rise, mid-marsh will migrate into this zone. Irrigation, rainfall-runoff erosion control, and access limitations will likely be required until vegetation establishes.

While flatter slopes can be used to increase constructed habitat and reduce the potential for wave-induced erosion, they would increase the footprint of the project, required fill volumes, displacement of existing habitat, and can affect construction feasibility. Slopes steeper than 7:1 are considered marginal, and 10:1 or flatter are recommended. Within these bookends (very flat or relatively steep), there are a range of potential geometries. This conceptual design provides one version without a rigorous evaluation of alternatives.

Constructability is an important consideration affecting design and further assessment is needed to refine the project geometry beyond the conceptual level of design. Key considerations include sediment sources (available volumes and rates, transport and placement), anticipated settlement, and environmental effects during construction. Regulatory constraints associated with conversion of mudflat to marsh may arise: This conceptual design presumes a self-mitigating project.

Alongshore variability is not addressed, but can be applied to potentially increase stability against sediment transport, direct and speed development of habitat structure, provide aesthetics and access opportunities, enhance adaptation and maintenance, and other potential project objectives. Further design and environmental review can address these issues.

An allowance in the engineer's estimate of likely construction costs (below) is provided for extension of three culverts that drain the backshore.



TYPICAL SECTION - EXAGGERATED VERTICAL SCALE

PROJECT 2 CONCEPT

SCALE:
HORIZ. 1"=40'
VERT. 1"=4'

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Figure 2
Conceptual horizontal levee section with three zones defined by elevation bands. Note that the vertical scale is exaggerated relative to the horizontal scale.

Figure 3 Plan and Section show the conceptual design to scale. The alongshore extent is approximately 6,600 feet, and the width of 275 feet is extended throughout this length, resulting in the following areas:

- Low Marsh: 11 acres
- Mid Marsh: 15 acres
- High Marsh Transition: 15 acres
- Total Footprint: 41 acres

Approximately 360,000 cubic yards of fill is required to achieve the neat line dimensions shown. This quantity estimate includes an allowance for additional volume to compensate for settlement (20%) and “losses” associated with densification and other factors encountered in earthwork (20%), resulting in a ~ 40% increase above the volume computed using the “neat” lines in the drawings. An additional foot of fill was added to the estimated construction quantities to compensate for long-term settlement and to allow for higher fill elevations owing to locally higher tidal datums. This increased volume is a better representation of the amount of earth that needs to be transported and placed to achieve the design. Additional fill placement may be required to compensate for additional long-term settlement following construction, but is not included in this estimate.

Use of dredged sediment from local non-federal navigation projects will require several decades to provide sufficient volumes. Hydraulic slurry transport and placement directly from the dredge sites or from drying facilities are likely means of earthwork given the difficult access conditions associated with the tidal portion of the Bay. Pumping distances of about 4 miles have been identified previously (SHN and others 2014; CSMW and MNE 2019). Use of dredged sand from federal projects could provide the required volumes in a much shorter time frame, based on the average annual dredge volumes of around 1,000,000 cubic yards. Sand can be used as a foundation element and covered with fines, as was done in the Hamilton Wetlands Restoration Project. Similar to the dredging from local non-federal navigation projects, the sand dredged by the USACE for federal projects would also require re-handling and long pumping distances. USACE hopper dredges do not have a pump-out capability, so either a hopper dredge would need to be retrofitted or other available commercial dredge vessels would be contracted and used.[2] There are multiple benefits with use of sand, primarily rapid dewatering and consolidation with little turbidity and limited subsequent consolidation of the sand with additional fill placement.

Based on the Hamilton Wetland Restoration Project (San Francisco Bay),[3,4] it appears that there are several feasible options for construction of the horizontal levee: The Hamilton project used a 5-mile-long hydraulic slurry delivery from a floating transfer station installed offshore, and placed sand and then mud to accomplish tidal marsh and upland habitats covering approximately 1,000 acres. An important difference, however, is that the Hamilton site was segregated from receiving waters (San Francisco Bay) by existing earth dikes, facilitating water and turbidity control measures.

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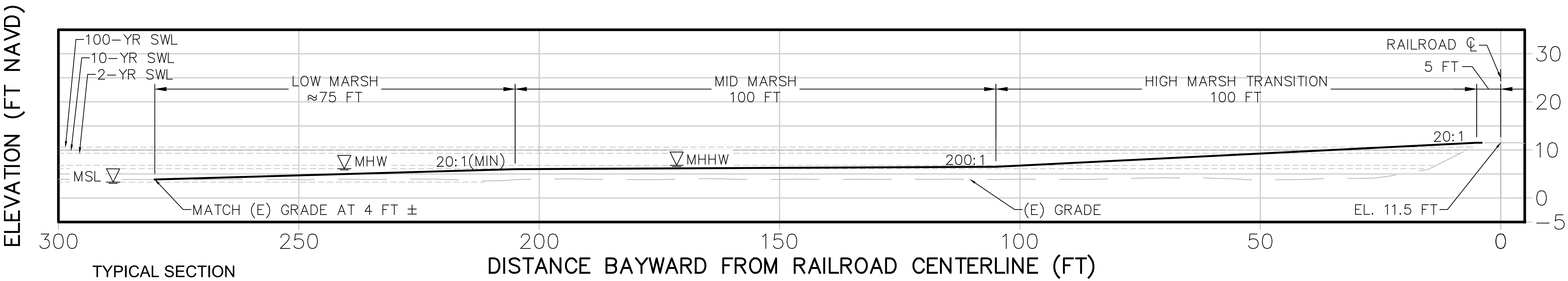
[2] USACE San Francisco District and City and County of San Francisco are pursuing a contract dredge to dredge the main shipping channel and pump directly to the shore at South Ocean Beach as part of the Ocean Beach Climate Change Adaptation Project: https://sfwater.org/index.aspx?page=1216

[3] https://www.spn.usace.army.mil/Missions/Projects-and-Programs/Projects-by-Category/Projects-for-Ecosystem-Restoration/Hamilton-Airfield-Wetland-Restoration/

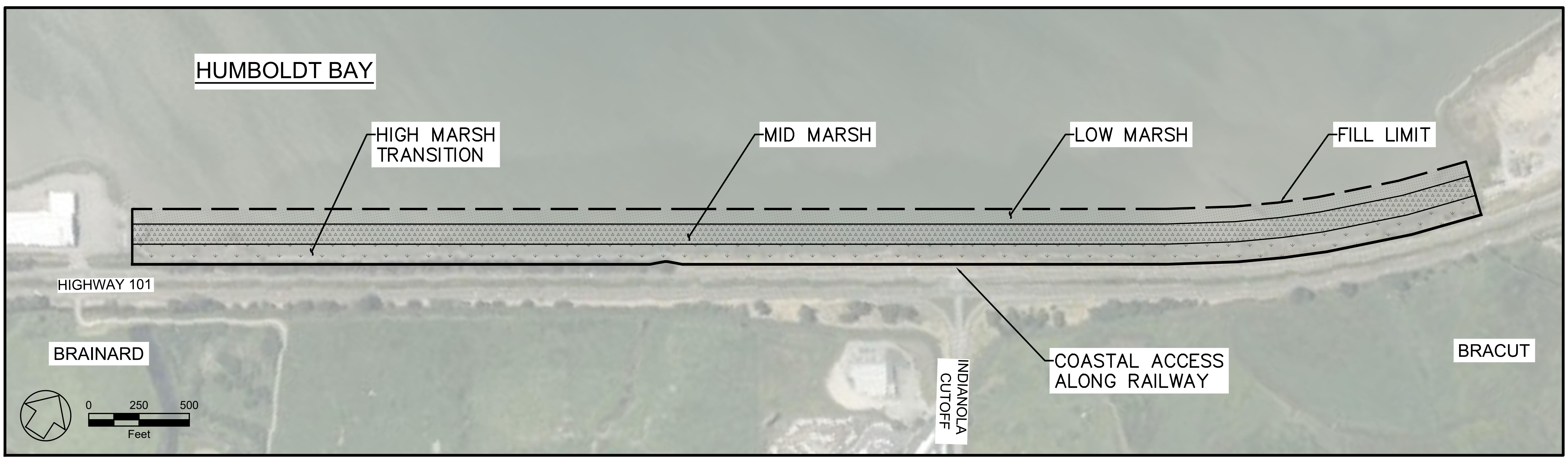
[4] https://scc.ca.gov/projects/san-francisco-bay/hamilton-wetlands-and-bel-marin-keys-unit-v-restoration/



TYPICAL SECTION

PROJECT 2 CONCEPT

SCALE:
HORIZ. 1"=20'
VERT. 1"=20'



PLAN OVERVIEW

PROJECT 2 CONCEPT

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Figure 3
Typical Section (top) and Plan Overview (bottom)
Project 2 Horizontal Levee

5.2 Engineer's Estimate of Probable Construction Costs

The concept-level engineer's estimate of likely construction costs is **$28,700,000**, which amounts to about $4,350 per foot, including a contingency of 30%. A $0.5M allowance for extension of three drainage culverts is included. This is a Class 5 to 4 Estimate, with an expected accuracy range of +70% to -40%. This order of magnitude estimate is intended to allow for cost comparison of alternatives. These cost estimates are intended to provide an approximation of total project costs appropriate for the conceptual level of design. These estimates are subject to refinement and revisions as the design is developed in future stages of the project. Please note that in providing estimates of likely construction costs, ESA has no control over the actual costs at the time of construction. The actual cost of construction may be impacted by the availability of construction equipment and crews and fluctuation of supply prices at the time the work is bid. ESA makes no warranty, expressed or implied, as to the accuracy of such estimates as compared to bids or actual costs.

5.3 Future Opportunities for Concept Refinement

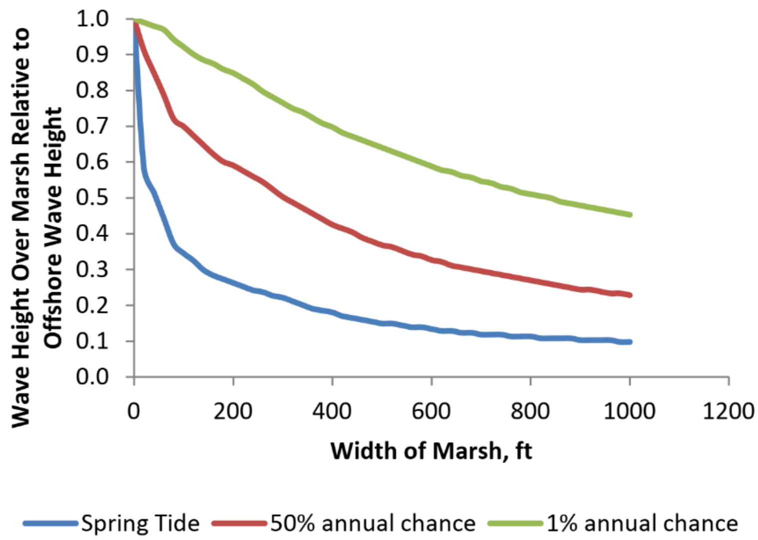
Planning and design phases subsequent to this conceptual design could consider exploring tradeoffs of the design objectives, as well as opportunities for refining the concept to scale down, phase, and/or value engineer the project to reduce the overall estimated cost. At this time, we have identified the following potential opportunities to refine the concept:

- Reduce plan extents of the project: assess whether the horizontal levee could extend from Brainard to Indianola Cutoff, or another intermediate point, rather than the full extent from Brainard to Bracut.
- Conduct a geotechnical study of the project to inform the design: include a specific task to assess settlement of the fill and subgrade, and whether opportunities exist to reduce the estimated amount of fill needed to construct the design cross-section.
- Phasing of project: consider how the project may be phased, and whether there are cost savings or geotechnical benefits associated with phasing construction over time.
- Consideration of a smaller placement footprint that would include a structural or coarse sediment toe.

6 Wave Attenuation

The purpose of Project 2 is to dissipate waves, thereby reducing wave runup and augmenting the protective services of Project 1.

Prior study has indicated that tidal marsh dissipates wind waves, except when water levels are high enough to allow waves to pass over the vegetation. Wave attenuation by tidal salt marsh in San Francisco Bay, California is shown in Figure 4 (ESA PWA 2013; BCDC 2013). The "spring tide" is above the MHHW tidal datum, indicating that the proposed 100-foot width of mid-marsh would reduce incident wave heights to about 33% of their incident wave height (0.33 on the vertical axis), an attenuation of 67%. In addition, the upward sloping and vegetated high marsh transition would further dissipate waves and cause wave breaking at the spring tide water level. The horizontal levee can therefore be expected to eliminate waves at the spring tide level and below. At the 50% annual exceedance (2-year return period, red line), the wave height reduction over the 100-foot mid marsh would be only about 33%, but again the waves would dissipate across the vegetated high marsh transition and break before reaching the crest elevation of 11.5 feet NAVD. Note that these curves are for San Francisco Bay, most of which has a smaller tide range than Humboldt Bay.



Source: ESA PWA 2013; BCDC 2013.

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Figure 4
Wave height reduction by tidal salt marsh in San Francisco Bay, California as a function of marsh width and high water level.

Prior analysis for the HBTS (Project 1) provided coastal design criteria based on impacts of inundation to trail function and form (ESA 2018). The following Table 2 identifies barrier or rail prism elevations to achieve evaluation criteria for a range of sea levels. Project 1 has a barrier elevation of 11.5 feet NAVD, which meets all three criteria for existing conditions. Project 1 meets some of these criteria, but not all of them. Project 2 was configured to meet the rest of the criteria, in particular to dissipate wind waves and wave runup.

The criteria roughly correspond to a 2- to 10-year event (see ESA 2018). For example, the 100-year still water level is approximately 10.6 feet NAVD for existing conditions, and hence any sea-level rise would result in overtopping during that event.

Based on the expected effectiveness of tidal marsh at attenuating waves, the horizontal levee concept will dissipate waves and hence satisfy the other two criteria, which are associated with wave overtopping, for up to 2 to 3 feet of sea-level rise. The objective of Project 2 is to reduce the waves and the wave runup to near-zero for design conditions. For this concept development, we did not model the wave reduction, which would be accomplished during a subsequent analysis. The actual capacity to accommodate sea-level rise depends on the marsh response (i.e. future accretion) to sea-level rise and is further described below.

TABLE 2
SHORELINE CREST OR TRAIL OR BARRIER ELEVATIONS TO ACHIEVE EVALUATION CRITERIA FOR A RANGE OF SEA LEVELS

Evaluation Criteria	2018-2030 0 feet Sea-Level Rise	2050 1 foot Sea-Level Rise	2070[4] 2 feet Sea-Level Rise	2100 3 feet Sea-Level Rise
Usability[1] (Tidal Flooding)	9 feet NAVD	9 to 10 feet NAVD	10 to 11 feet NAVD	11+ feet NAVD
Usability[2] (Wave Overtopping)	9 feet NAVD	9 feet NAVD	10.8 feet NAVD	11.8 to 12.3 feet NAVD
Damages[3] (Wave Overtopping)	11.1 to 11.5 feet NAVD	12.1 to 12.5 feet NAVD	13.1 to 13.5 feet NAVD	14.1 to 14.5 feet NAVD

1 Elevations presented for usability associated with tidal flooding represent elevations that minimize average number of flood events and durations, but which may not altogether eliminate flood risk (see ESA 2018).
2 Usability associated with wave overtopping based on elevations where computed wave overtopping rate is less than 0.22 cfs/lf.
3 Damage threshold presented for lightly protected surfaces. Damages can be mitigated by including design measures to enhance stability.
4 2070 represents the end of the 50 year planning life for the project.

7 Response to Sea-Level Rise

Tidal marshes can rise with sea levels up to a maximum rate of potential vertical accretion. The rate depends primarily on the sediment supply and plant growth rates (GHD and others 2020). Depending on the sediment supply, the mid marsh component can be expected to withstand a foot or more of sea-level rise. Erosion of the high marsh transition may provide sediment to the mid marsh as sea-levels rise, and the mid marsh and low marsh can “move up” the horizontal levee. The low marsh may be difficult to maintain due to horizontal erosion, often called “marsh scarp” erosion, without armoring or increased sediment supply. Vegetation establishment is also important to erosion resistance. Sediment can also be placed on the marsh with “thin layer” placement techniques, such as spraying hydraulic slurry (Judge and others 2017).

8 Protective Services Benefit

We expect that Project 2 will provide protective services benefits by increasing the dissipation of waves and reducing wave runup and overtopping, and thereby avoiding damages associated with waves. Project 1 includes sufficient vertical fill to withstand static tidal water levels with up to three feet of sea-level rise, but Project 1 and other backshore assets would still be exposed to wave-induced flooding and loadings associated with waves and wave runup. This section describes how the horizontal levee can be designed to reduce wave damages to approximately zero for the proposed trail and the highway. Therefore, we are recommending that the Project 1 wave-induced damages would be computed, and the benefit of Project 2 is therefore the avoidance of those damages.

The preliminary coastal hazards and sea-level rise analysis of the HBTS identified three trail design criteria (ESA 2018), which are listed below, and correspond to the Evaluation Criteria in Table 2. These preliminary design criteria were developed using readily available guidance regarding the depth of still water and intensity of moving water (e.g., wave induced overtopping) on pedestrians and built surfaces, but are otherwise developed only for HBST at a preliminary level.

1. **Trail Usability (Still Water Flooding):** Nuisance flooding inhibits trail usability when tidal flooding results in at least 0.5 feet of inundation over the potential trail finished grade elevation

2. **Trail Usability (Wave Overtopping):** Wave overtopping could inhibit trail usability by creating potentially unsafe conditions. Trail usability as a result of wave overtopping is evaluated using the threshold of wave overtopping rate of 0.22 cfs/lf as published by EuroTop 2016 (van der Meer et al. 2016).

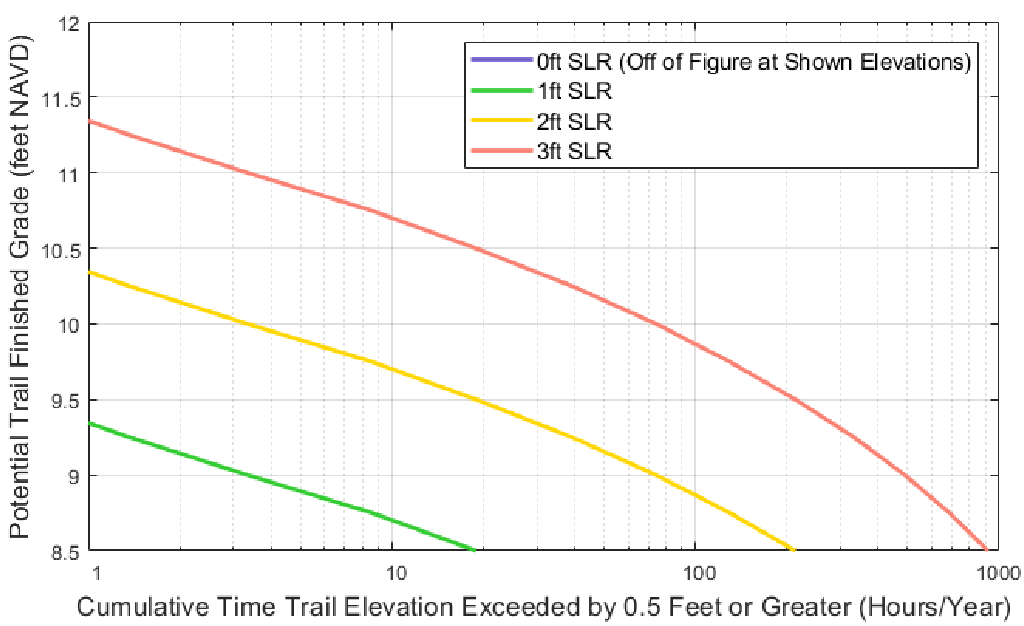
3. **Trail Damage from Wave Overtopping:** Damages to the trail are evaluated using the thresholds of wave overtopping rates published by EuroTop 2007 (Pullen et al. 2007) for two types of damage (see Section 4.4.2 for discussion on tolerable discharges of wave overtopping):

    a. Damage to lightly-protected surfaces resulting when wave overtopping rates exceed 0.54 cubic feet per second per linear foot of shore (cfs/lf)

    b. Damage to trail pavement when wave overtopping rates exceed 2.2 cfs/lf

As discussed previously, Project 1 elevation is above the level of overtopping for existing conditions, and above the still water flooding elevation for up to 3 feet of sea-level rise. Therefore, the trail criteria listed above are not met for wave overtopping when sea levels rise. Hence, the benefit of Project 2 is to eliminate these future overtopping damages by way of dissipating incoming waves prior to reaching the HBTS. Therefore, the benefit of Project 2 is this prevention of overtopping and associated damages, and the task is therefore to estimate these avoided damages.

The extent to which the Project 1 flooding and overtopping criteria are exceeded can be computed, and the following three graphs address the three criteria. Figure 5 shows the hours per year that a given trail elevation is inundated for existing tides and with 1, 2 and 3 feet of sea-level rise. It can be seen that the Project 1 elevation of 11.5 is not exceeded. Hence, exceedance of this design criterion is not expected.



Source: ESA 2018

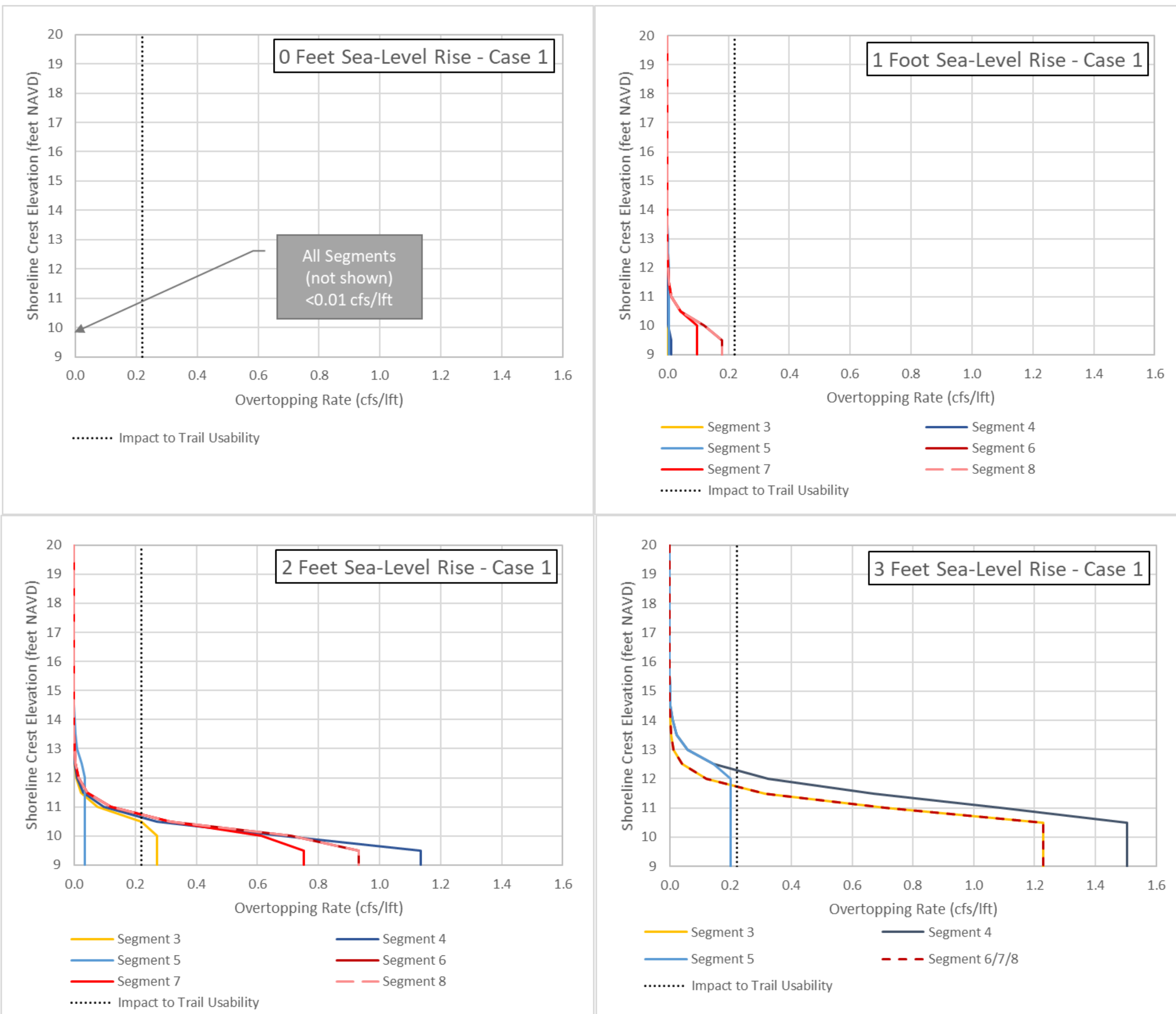
D181130.00 – Humboldt Bay SLR Adaptation

Figure 5
Cumulative amount of time that trail is inundated by 0.5 foot

Criterion 2 is addressed in Figure 6, with the dotted vertical line indicating the 0.22 cfs/ft threshold of trail usability impact. For this Project 2 location, which corresponds to Segments 7 and 8 in the graphs, wave overtopping threshold of 0.22 cfs/ft is exceeded only after 3 feet of sea-level rise.

Criterion 3 is addressed in Figure 7, the lower threshold for trail damage, 0.55 cfs/ft, is exceeded for sea-level rise over one foot.

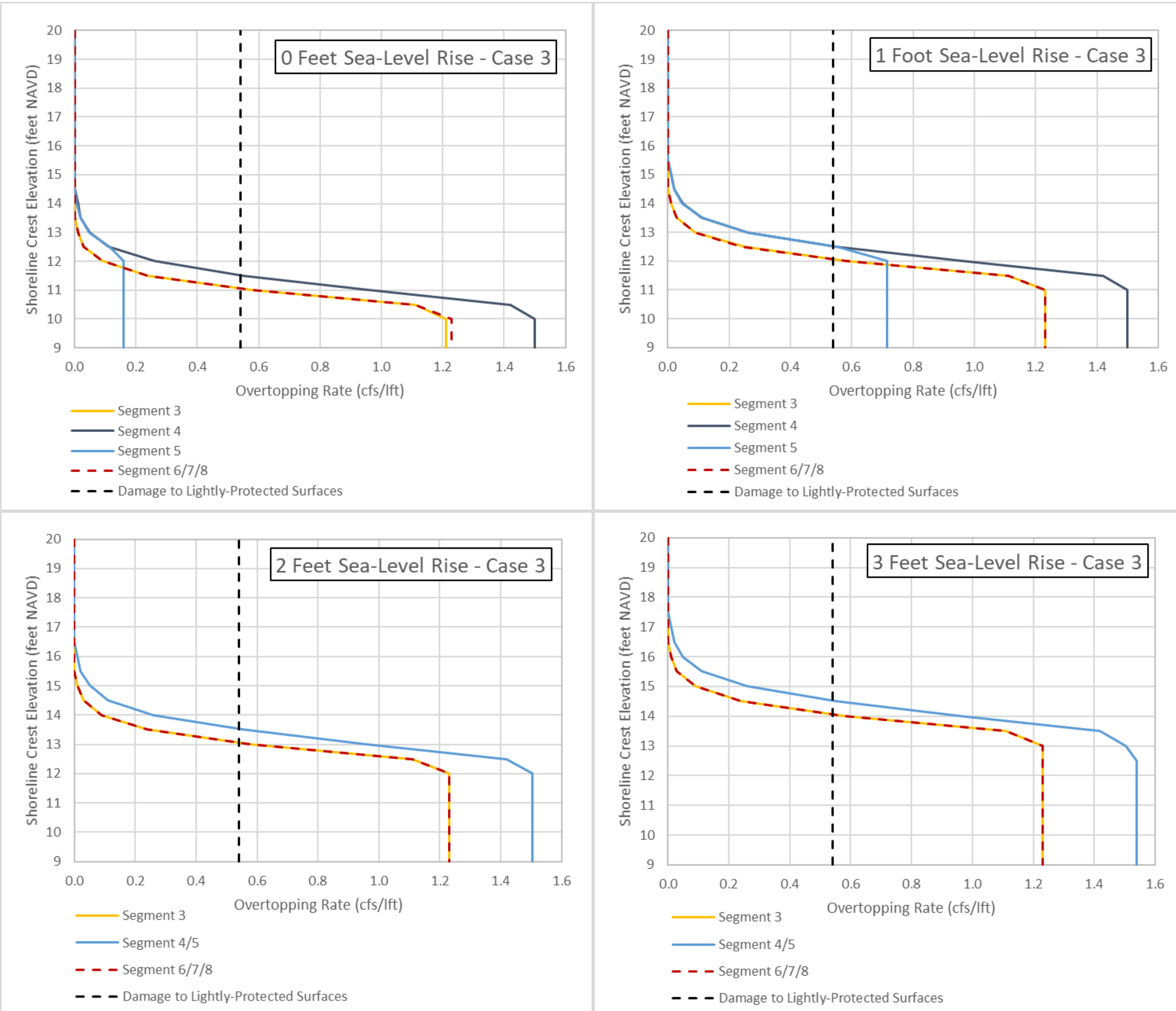
The overtopping criteria exceedances in Figures 6 and 7 can be associated with trail damages and used in the economics analysis. The overtopping rates can also be used to assess potential damages to Highway 101 and other assets landward of the trail.



Source: ESA 2018

D181130.00 – Humboldt Bay SLR Adaptation

Figure 6
Wave Overtopping Rates for Case 1 as a Function of Potential Trail Finished Grade by Shore Segment with Sea-Level Rise



Source: ESA 2018

D181130.00 – Humboldt Bay SLR Adaptation

Figure 7
Wave Overtopping Rates for Case 3 as a Function of Potential Trail Finished Grade by Shore Segment with Sea-Level Rise

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