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Title: Evaluating Coastal Protection Services Associated with Restoration Management of an Endangered Shorebird in Oregon, U.S.A.

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Sally D. Hacker

Coastal sand dunes and beaches offer a variety of ecosystem services such as coastal protection, sand stabilization, species conservation, and recreation. However, the management and balance of ecosystem services offered by dunes and beaches is challenging when ecosystem services interact across the landscape. Management focusing only on one ecosystem service may result in unintended consequences and trade-offs between other key services. Understanding the magnitude of the trade-offs and linkages between services provides a more holistic approach for reducing unintended consequences and maximizing function.

The degradation of habitats and land use changes associated with expanding human populations has resulted in the need for species conservation. However, species conservation techniques can sometimes have unintended consequences for other services. Given the mandate of the Endangered Species Act to restore habitat structure and function essential to endangered or threatened species, it becomes critical to evaluate the implications of species conservation management initiatives to reduce negative implications to other key services.

The coastal dune systems of the Pacific Northwest (PNW) are a prime example of how ecosystem services, such as species conservation and coastal protection, can interact with one another. Over the last 125 years in the Pacific Northwest (PNW), the intentional introduction of two non-native congeneric beach grasses (*Ammophila arenaria* and *A. breviligulata*) has increased coastal protection through the creation of foredunes, but also dramatically altered the dune ecosystem. Both invasive grasses build taller dunes that range from 3 – 18 m in height compared to the native grass, *Elymus mollis*. Increased foredune elevations generate greater coastal protection services that are increasingly important given sea level rise and extreme storm events on the PNW coast. However, the beach grasses have dramatically changed the beach/dune community, resulting in the decline of several native dune plants and animals.

One species that is negatively affected by the grass invasion is the Western snowy plover (*Charadrius nivosus nivosus)*, an endemic shorebird living on beaches and dunes in the Pacific Northwest. This shorebird was listed threatened under the Endangered Species Act in 1993 and a recovery plan was established that employed multiple recovery techniques. The most important part of the plan involves establishing habitat restoration areas (HRAs) where dunes are bulldozed, reducing dune elevations, burying the grass, and returning the dunes to an open shifting sand environment, historically preferred by the plover. Recent coastal hazards modeling revealed that the changes in beach and dune shape associated with plover restoration increases coastal exposure to flooding and erosion at certain locations along the

Oregon coast, particularly under projected climate change scenarios of sea level rise and extreme storms.

As part of future plover management, four critical habitat areas were proposed for Tillamook County, Oregon: Nehalem River Spit, Bayocean Spit, Netarts Spit, and Sand Lake South. Given the interest in plover habitat restoration in Tillamook County, this research project addresses the following questions: (1) What is the present day dune geomorphology and exposure to coastal hazards at four proposed critical habitat (PCH) areas in Tillamook County, Oregon; and (2) how do changes in beach geomorphology associated with different restoration scenarios alter coastal exposure today, under projected sea level rise and storm scenarios?

To address the coastal geomorphological impacts of HRA installation on the four proposed areas, multiple restoration scenarios that reduce foredune elevation were evaluated under present day sea level and potential future sea level rise and extreme storminess scenarios, using coastal exposure modeling techniques. The model projections provide site-specific information on the exposure of HRAs to overtopping under different restoration conditions.

We determined that exposure to flooding was dependent on proposed HRA site and restoration scenario, and was exacerbated by sea level rise and extreme storms. Empirical models projected the greatest flooding exposure would occur at Nehalem River Spit, followed by Netarts Spit, and then Bayocean Spit and Sand Lake South, which did not differ. Exposure to flooding at present day dunes was low across all sites, but with increasing exposure to flooding as foredune elevations were reduced to 6.0 m or below, as could happen with plover habitat restoration. Under present day water levels, restoring foredune elevations to 6.0 m or below would likely result in roughly 5 days of overtopping per year at Nehalem River Spit, Bayocean Spit, and Netarts Spit, and 4 days of overtopping at Sand Lake South. Flooding under various foredune restoration scenarios increased under higher sea level rise scenarios. Flooding exposure for the 6.0 m restoration scenario exceeded 10 days per year at Nehalem River Spit and 5 days per year at Bayocean Spit, Netarts Spit, and Sand Lake South.

Overall exposure to flooding under the extreme storm scenarios was dependent on proposed HRA site, restoration scenario, and increased wave conditions, such as wave height, period, and water level. Similar to the empirical model, flooding exposure under extreme storm scenarios increased when foredune elevations were reduced to 6.0 m or below, across all sites. The site with the greatest overall flooding exposure during extreme storms was Bayocean Spit. Flooding distance was dependent on restoration scenario and site while flooding duration was only dependent on restoration scenario. The 5.5 m restoration scenario under higher storm water levels resulted in one hour or more of flooding exposure at least one day per year at Nehalem River Spit, Netarts Spit, and Bayocean Spit. The overall likelihood of overwash extending to 150 m or more into the dune field during extreme storms was at least 5 days when selecting to reduce foredune to restoration elevations of 7.0 m or below across all sites. The effect of higher wave heights and greater wave periods was more important to overtopping distance than restoration scenario.

Learning from current plover management, combined with the coastal exposure analysis we conducted here, could enable managers to develop site-specific restoration plans that maximize plover recovery while minimizing coastal exposure. This research will give resource managers information on the coastal exposure associated with proposed HRAs and the foredune reduction scenarios they might want to employ at the different sites. It will allow them to identify the best restoration scenarios to maximum habitat restoration without compromising coastal protection, and thus balance some important services of dunes and beaches. Regardless of management objective, identifying the unintended consequences of restoration to key ecosystem services is necessary for the holistic management of our dynamic coasts, especially with projected sea level rise and the uncertainty of frequent and extreme storms.

Evaluating Coastal Protection Services Associated with Restoration Management of an Endangered Shorebird in Oregon, U.S.A.

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Lindsay J. Carroll, Author

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INTRODUCTION

Ecosystems provide multiple benefits to humans in the form of goods, services, and cultural benefits (MEA 2005). Ecosystems provide many marketable goods, such as produce, genetic material, fish, and lumber, and non-market services, such as water purification, climate regulation, habitat, flood control, biodiversity, and pollination (Heal et al. 2005, MEA 2005, Barbier et al. 2007, 2011, Bennet et al. 2009).

Recent research has focused on the linkages and interactions between key ecosystem services (Barbier et al. 2008, 2011, Bennet et al. 2009, Koch et al. 2009, Raudsepp-Hearne et al. 2010). Ecosystem service interactions can vary across both space and time, making the management and understanding of the linkages between services challenging (Farnsworth 1998, Heal et al. 2005, Bennet 2009). Management and decision making processes sometimes disregard non-linear relationships and interactions, and value one service over another (MEA 2005, Bennet et al. 2009, Barbier et al. 2011). In some cases, interacting services can be at odds with one another, as the optimization of one service results in the reduction of another, creating trade-offs (Heal et al. 2005, Rodriguez et al. 2006, Barbier et al. 2008, 2011, Halpern et al. 2008, Tallis et al. 2008). Understanding the magnitude of trade-offs and linkages between services provides a more holistic approach for reducing unintended trade-offs and maximizing function (Barbier et al. 2008, 2011, Koch et al. 2009).

Optimal ecosystem management is becoming increasingly important, as the demand for ecosystem services has grown with an increasing human population. Human-induced impacts are leading to overconsumption, habitat degradation, and a reduced ability for ecosystems to provide these key services (MEA 2005). The degradation of habitats and land use changes are contributing to reduced biodiversity and species conservation, both critical and often overlooked ecosystem services (Grundel and Pavlovic 2008, Isbell et al. 2015). Historically, the fundamental motivations and values of species conservation were linked to preservation of the intellectual, spiritual and aesthetic values of species (Ladle and Whittaker 2011, Ingram et al. 2012). Now, it is recognized that the overall function of ecosystems and ecosystem services depends on conservation of biodiversity (Schmid et al. 2009, Loreau 2010, Cardinale et al. 2011, Reich et al. 2012, Gamfeldt et al. 2013, Balvanera et al. 2014). Reduction in biodiversity in forest ecosystems can trickle down to affect other closely linked ecosystem services such as carbon storage, and forage and timber production (Isbell et al. 2015). Given the mandate for species conservation from the Endangered Species Act (USFWS 1993), it is important to take a more holistic view of conservation and address all management alternatives, to ensure that certain decisions do not have negative implications for other functions or services (Rodriguez et al. 2006, Lester et al. 2013).

Here we consider coupled coastal ecosystems, that of sandy beaches and dunes, where understanding the implications of conservation management can have important consequences for a number of high value ecosystem services. Sandy beaches and dunes offer key ecosystem services including shoreline protection through wave attenuation, sediment stabilization, habitat for flora and fauna, and recreational opportunities (Barbier et al. 2011). The ecosystem services provided by beaches and dunes are a major focus of coastal planners, resource managers, and coastal inhabitants as the impact of coastal development intensifies. Nearly one third of the world's population lives in coastal areas even though coastal areas are only 4% of Earth's total land area (MEA 2005, Barbier et al. 2008). In the United State, less than 10% of the land area (excluding Alaska) is coast even though 39% of the population lives on the coast (NOAA 2013). The interaction between humans and coastal ecosystems generates the need to evaluate the connections and potential trade-offs of essential ecosystem services to determine the best way to maximize coastal management.

Maximizing coastal protection becomes especially important given the predictions of sea level rise and potential increases in extreme storm events associated with climate change (Field 2012). Sand dunes and beaches are extremely important 'soft-defenses' as they serve as the first line of protection from extreme storms by mitigating and dissipating waves (Hanley et al. 2014). Historically, coastal communities often replaced these 'soft defenses' with 'hard' infrastructure such as seawalls and bulkheads in order to protect coastal infrastructure from flooding and erosion (Sterr 2008, Titus et al. 2009, Rozenqweig et al. 2011). However, given the costs of maintenance and increased erosion associated with 'hard' infrastructure, adaptive management strategies are incorporating plans to bolster coastal protection by restoring green infrastructure in the form of vegetated dunes (Spalding 2013). Given that climate change has the potential to cause detrimental effects to coastal systems, determining the coastal protective services provided by dunes and beaches becomes even more essential.

Here, we assess the changes in coastal exposure as a consequence of habitat restoration for the Western snowy plover (*Charadrius nivosus nivosus*), a federally listed threatened shorebird living on beaches and dunes in the Pacific Northwest. Historically, the beaches and dunes of the Pacific Northwest had little native vegetation and were n open, shifting sand environment. Over the last 125 years, two non-native beach grasses, *Ammophila arenaria* (European beach grass) and *Ammophila breviligulata* (American beach grass), were systematically planted along the Pacific coast to stabilize sand in this ecosystem. As a result of this stabilization, there were dramatic changes in coastal dune geomorphology and habitat for native species (Wiedemann and Pickart 1996, Zarnetske et al. 2010, Hacker et al. 2012). The invasive grasses create foredunes, vegetated linear hills of sand parallel to the shoreline, that range from 3–18 meters in height along the Pacific Northwest coast (Hacker et al. 2012). Besides stabilizing the sand, the foredunes provide substantial coastal protection from flooding and coastal erosion (Ruggiero et al. 2001, Barbier et al. 2011, Seabloom et al. 2013, Spalding et al. 2013, Hanley et al. 2014, Mull and Ruggiero 2014). However, with the addition of the non-native grasses, there have also been significant changes in the habitat value of Pacific Northwest dune ecosystems to native species (Wiedemann and Pickart 1996).

One species whose habitat was significantly impacted by the non-native grasses, and the foredunes they create, is the Western snowy plover. The Western snowy plover is endemic to all West Coast states and Mexico, utilizing the historically bare-sand habitat necessary for nesting and foraging (USFWS 2007). The birds nest in the open back beach habitat, as it allows them better views of aerial predators and decreases the chance of nest flooding from overwashing events by waves. The bare sandy habitat also provides the birds with easy access to the beach where they forage on marine and terrestrial invertebrates located in the lower intertidal zone of sandy beaches (USFWS 2007). Some sand-burrowing food sources of the plover are also found above the high tide line, and the rapid spread of the beach grasses may contribute to the loss of some plover food sources (Stenzel et al. 1981). A study conducted at dune sites in central California found that the presence of *A. arenaria* reduced the abundance and diversity of sand-burrowing arthropods, as *A. arenaria* roots densely packed sand and likely reduced the burrowing abilities of these invertebrates (Slobodchikoff and Doyen 1977).

The cumulative effects of reducing the access to food sources and the changes in back beach geomorphology resulted in the decline of snowy plovers along the Oregon, Washington, and California coasts. In 1993, the Western snowy plover was listed as federally threatened under the Endangered Species Act (USFWS 1993) and a habitat conservation plan was created with the goal of delisting the plover by 2047 (USFWS 2007). The plan focused on the reduction of human disturbance and the re-establishment of critical plover habitat through a variety of conservation initiatives along the West coast.

The plan incorporates multiple recovery strategies including habitat restoration, beach closures, and predator control during plover nesting season (USFWS 2007). Habitat restoration areas (HRAs) are sites where back beach habitat is restored by bulldozing the foredune, which levels the dune and removes beach grasses and associated plants (Zarnetske et al. 2010, Biel et al. in review). This open habitat provides nesting sites and easy beach access for the plovers to feed. In addition to restoration of the habitat, beach closures are used to limit recreational activities and reduce human disturbance during plover nesting periods. From March to September, sections of the beach above the high tide line extending into the dunes are fenced off to allow plover uninterrupted nesting opportunities.

Finally, lethal and non-lethal predator control has been used to reduce threats to nesting plovers. Predators of the plover include the gray fox (*Urocyon cinereoargenteus*), red fox (*Vulpes vulpes*), coyote (*Canis latrans*), raccoon (*Procyon lotor*), striped skunk (*Mephitis mephitis*), domestic dog (*Cannis domesticus*), mink (*Martes vision*), weasel (*Mustela spp.),* common raven (*Corvus corax*), common crow (*Corvus brachyrhynchos*), rodents, gulls, and raptors. Non-lethal management initiatives include beach litter control (i.e., food litter at beaches is an attractor of many avian predators), fencing, trapping, and relocating of unwanted predators, while lethal actions include addling the eggs of corvid and raptor predators (i.e., killing of chicks during development inside the egg), and culling of predators to decrease their population sizes (USFWS 2007).

There are ten habitat restoration areas (HRAs) for the Western snowy plover on the Oregon and Washington coasts (Baker Beach, Dunes Overlook, Coos Bay North Spit, Tahkenitch Creek, Ten-mile Creek, Bandon State Natural Area, New River, and Elk River, OR; Leadbetter Point, WA). In 2013, the plover breeding population size in Oregon was estimated at 206 breeding individuals, which was the highest on record since monitoring began in 1978 (OPRD 2013). However, the establishment of HRAs along the coast has led to some concerns about their influence on other native dune species. For example, repeated bulldozing of dunes can have negative effects on the re-establishment of endemic beach and dune plants (Zarnetske et al. 2010, Biel et al. in review).

Furthermore, because HRA establishment alters foredune geomorphology, HRAs have the potential to be more exposed to coastal flooding. Recent research by Biel and colleagues (in review) that modeled storm-induced coastal change showed that the degree to which HRAs are more vulnerable to flooding and dune retreat depended on location, geomorphology, and projected sea level rise. The analysis revealed site-specific vulnerability and trade-offs between coastal protection and plover population recovery. The removal of beach grass and the lowering of foredunes had a direct impact on increasing plover productivity, but lowering of foredunes subsequently increased HRA vulnerability to flooding and dune retreat.

When the current HRAs were originally established, the U.S. Fish and Wildlife Service (USFWS) and Oregon Parks and Recreation Department (OPRD) also proposed four additional sites in Tillamook County, Oregon, as potential restoration sites (Figure 1; USFW 2011). These sites, known as proposed critical habitat (PCH) areas, are locations where plovers historically nested and could be used to provide population connectivity between northern Oregon HRAs and the southern Washington HRA (Leadbetter Point). Recently, there has been interest in converting some of the four PCH areas in Tillamook County into HRAs. The goal of this research is to determine the exposure of proposed PCH areas to flooding especially under different foredune restoration and climate change scenarios. We ask the following questions: (1) What is the present day geomorphology and exposure to coastal hazards at four proposed PCHs in Tillamook County, Oregon; and (2) how do changes in beach geomorphology associated with different restoration scenarios alter coastal exposure today, under projected sea level rise, and various storm scenarios?

To evaluate the coastal exposure of the PCH areas along the Tillamook County coastline, we characterized cross-shore dune profiles to establish the present day geomorphology for all PCH locations. We then subjected various restoration and projected sea level rise scenarios to a total water level (TWL) modeling approach (Serafin and Ruggiero 2014) to determine the magnitude of dune overtopping under these scenarios and to optimize the design of HRAs in Tillamook County. Finally, we chose several restoration scenarios to which we applied a process based modeling approach known as XBeach (Roelvink et al. 2009) to determine storm-related overwash distance and duration in these proposed restoration areas.

MATERIALS AND METHODS

Study Sites

The research was conducted at four proposed critical habitat (PCH) areas for the Western snowy plover in Tillamook County, Oregon, identified by OPRD in their Habitat Conservation Plan (2010). The PCH areas are Nehalem River Spit, Bayocean Spit, Netarts Spit, and Sand Lake South (Figure 1; Appendix Table A1; Appendix Table B1). The selection of these areas by the USFWS and OPRD was based on both historical and current plover nesting areas as outlined in the report.

Characterization of Present Day Dune Geomorphology

Baseline geomorphology of the four PCH areas was quantified using beach and dune morphometrics extracted at five-meter resolution from a combined 2009/2011 Light Detection and Ranging (lidar) dataset (OR-DOGAMI 2009, USACE 2011). The shoreline (i.e., the horizontal location of mean high water (MHW)) of the 2011 LIDAR dataset was combined with the 2009 DOGAMI dataset, as the 2009 DOGAMI data did not adequately capture shoreline position but had full coverage of the foredunes. Cross-shore profiles were generated every 5 m (Nehalem River Spit = 720 profiles, Bayocean Spit = 608 profiles, Netarts Spit = 626 profiles, Sand Lake South = 488 profiles) from gridded lidar data. Key dune morphometrics including shoreline position, beach slope (tan (β), defined as the average beach slope between MHW and the foredune toe), foredune toe (d_t), foredune crest (d_c), and foredune height (d_h) were extracted using the methods of Mull and Ruggiero (2014) (Figure 2a).

Generation of Total Water Levels and Sea Level Rise Scenarios

To determine the amount of overtopping (i.e., instances when the water level exceeded the foredune crest elevation; Sallenger 2000) of foredune crest elevations at each site, we utilized a time series of wave and water levels from 1980 through 2012 (32 years). To make the time series representative of present day sea levels – that is, without the influence of recent historical sea level rise – sea level data was de-trended (subtracting the mean sea level rise trend from the dataset) such that the resulting mean sea level rise trend over the 32-year period was zero. The average sea level for the last 15 years of the dataset was calculated and added to the de-trended data such that the time series is representative of present day. This sea level time series was then combined with wave conditions and alongshore estimates of beach slope, to generate a present day total water level (TWL) time series (e. g., Sallenger 2000, Ruggiero et al. 2001, Serafin and Ruggiero 2014). Specifically, TWLs were calculated at each cross-shore location using,

$$TWL = MSL + \eta_A + \eta_{NTR} + R \qquad (1)$$

where MSL is mean sea level, η_A is the astronomical tide, η_{NTR} is the non-tidal residuals including storm surge, and R is a wave induced component, wave runup (Figure 2b). To estimate R, we used the empirical formula for the 2% exceedance percentile ($R_{2\%}$) established by Stockdon et al. (2006),

$$R_{2\%} = 1.1\left\{0.35\beta_f(H_0L_0)^{1/2} + \frac{[H_0L_0\left(0.563\beta_f^2+0.004\right)]^{1/2}}{2}\right\} \qquad (2)$$

where β_f is the beach slope, H_0 is the deep-water significant wave height, and L_0 is the deep-water wave length. In order to calculate an hourly TWL time series, measured water levels were extracted from the South Beach (SB) tide gauge station 9435380 operated by NOAA (data from 1967 – 2012) located off the central Oregon coast. Wave data was gathered from the National Data Buoy Center (NDBC) and the U.S. Army Corp of Engineers Wave Information Studies (WIS). We used stations located along the northern Oregon Coast (NDBC 46089, 46029, 46005, and WIS 81048). Buoys had multiple data ranges available, limiting the extent of data used. NDBC 46005 had the longest data range of 1984 – 2012, followed by NDBC 46029 (data range from 1984 – 2012) and NDBC 46089 (data range from 2004 –present). NDBC 46089 was selected as the primary buoy due to its proximity to the coast and optimal water depth where the data are not impacted by refraction and shoaling. Given the smaller data range of NDBC 46089, data from the surrounding buoys in the region were applied to complete the time series (Serafin and Ruggiero 2014).

We also computed TWLs for a subset of the profiles under two sea level rise (SLR) scenarios at proposed habitat restoration areas (pHRAs; see below for a description of these areas) within the four PCH areas. Medium and high regional SLR projections through 2100, published by the National Research Council (NRC 2012), were used to develop the two SLR scenarios used in this study. Projections through 2030 were selected as the most relevant to plover restoration and conservation planning, as plover habitat management plans will likely be revised in or around 2030. Projections of medium and high SLR by 2030 are 0.07 m, and 0.23 m, respectively. The SLR projections were added to the present day TWLs as part of the water level component and then compared to the foredune restoration scenarios to determine relative changes to overtopping hours (i.e., total hours foredune crest elevations were exceeded) at each pHRA (definition below) within the four PCH areas.

Generation of Restoration Scenarios

Dune restoration scenarios were developed in order to explore how the PCH areas might be impacted by overtopping as consequence of the reductions in dune height from restoration. The proposed methods include those applied to current HRAs: bulldozing the foredune to reduce its height and mechanically breaking up and burying the grass. The scenarios included the current foredune crest elevation, as well as five restoration conditions in which foredune crests are reduced to 9.0 m, 8.0 m, 7.0 m, 6.0 m, and 5.5 m NAVD88 (Figure 3). These foredune elevations were selected as they fall within the range of foredune crest reductions observed in existing HRAs along the southern Oregon and Washington coasts (Biel et al. in review). In addition, the restoration scenario reduction of 5.5 m was included to serve as a comparison to a vulnerability analysis conducted prior to the installation of the Elk River HRA located in southern Oregon (Allan 2004).

Analysis of Coastal Exposure Using Overtopping Modeling

Coastal Exposure at Proposed Critical Habitat (PCH) Areas

The overtopping at the four PCH areas were determined by comparing baseline foredune crest elevations from the profiles, as well as the five restoration scenario profiles (9.0 m, 8.0 m, 7.0 m, 6.0 m, and 5.5 m crest heights), to the estimated TWL values for those profiles under present day sea level. We computed two overtopping response variables from the profile data using MATLAB R2015a (MathWorks Natick, MA, USA). The first was the overtopping hours, where an overtopping hour was defined by any hour the estimated TWL exceeded the foredune crest elevation (Sallenger 2000). The second response variable was total overtopping days, quantified by estimating the number of unique days where overtopping occurred for a minimum of one hour.

Coastal Exposure at Proposed Habitat Restoration Areas (pHRAs)

In addition to quantifying the exposure of the entire extent of each PCH area, proposed habitat restoration areas (pHRAs) were delineated at each PCH area and were subjected to the overtopping analysis for different restoration and SLR scenarios. The dimensions and location of the pHRAs were established using information from the plover managers regarding best practices for HRA placement. Most HRAs were placed at the tip of spits (Figure 4), which are already characterized by lower foredune elevations due to greater overwash potential and reduced grass cover.

The dimensions and location of the Nehalem River Spit and Sand Lake South pHRAs mirrored boundaries pre-determined by Oregon Parks and Recreation Department (OPRD) in draft management and mapping plans (V. Blackstone, personal comm., September-November 2015). Dune morphometrics within the boundaries of the pHRAs were used for the site-specific pHRA analysis (Nehalem River Spit = 666 profiles and Sand Lake South = 294 profiles). For Netarts and

Bayocean Spits, one section was selected at the tip of each spit extending 1 km in length along the beach and resulting in 226 profiles (Figure 4).

The same response variables, overtopping hours per year and overtopping days per year, were computed for each of the pHRAs under the baseline foredune crest elevations from the profiles, as well as the five restoration scenario profiles (9.0 m, 8.0 m, 7.0 m, 6.0 m, and 5.5 m crest heights), under current SL and the two SLR (Medium and High) scenarios.

Analysis of Coastal Exposure Using Storm Scenario Analysis

A process-based numerical model, XBeach (Roelvink et al. 2009), was used to simulate dune overtopping distance (m) and duration (overtopping days per year) during storm events at the four pHRAs. The phase-averaged model solves two-dimensional, depth-averaged equations for wave propagation and has modules for simulating sediment transport and morphologic change due to waves and wave-driven circulation (not used in this study). XBeach has been widely used for a range of coastal applications, including infragravity generation (Pomeroy et al. 2012), overwash processes (McCall et al. 2010), dune erosion (de Winter et al. 2015), and wave run-up (Cohn and Ruggiero 2016), and has been extensively validated for storm-induced coastal change hazards (e.g., Bolle et al. 2011). For the application in this present study, a one-dimensional cross-shore XBeach model was applied to four-representative pHRA profiles for a range of environmental conditions (varying water levels, wave period, and wave height) and restoration scenarios (maximum dune crest elevations).

At each of the pHRA within the four PCH areas, five different cross-shore coastal profile configurations were assessed (Figure 5). Specifically, the restoration scenarios for the XBeach analysis included the current observed topographic profile as extracted from the 2009/2011 combined dataset and hypothetical transects for cases where the foredune crest was lowered to 7.0 m, 6.0 m, 6.5 m, and 5.5 m NAVD88. The 6.0 m and 5.5 m reduction scenarios were chosen based on the initial findings from the empirical TWL analysis. Preliminary XBeach runs revealed increased flooding exposure at the lower foredune elevations; therefore, two additional foredune reduction elevations (6.5 m and 7.0 m) were included in the full analysis. For each hypothetical reduction profile, random perturbations and a slope of 0.01 beginning at the dune crest was applied through the back of the profile to promote infiltration of water and limit the pooling of water in the backshore.

To generate a complete coastal profile from the inner shelf to the backshore, the topographic profiles were combined with measured summer 2011 nearshore bathymetry (~0m to -12 m NAVD88) collected with the OSU Coastal Profiling System (Ruggiero et al. 2005). For deeper water depths extending to 50 m NAVD88, bathymetric information was extracted from the NOAA Garibaldi 1/3 arc second Coastal Digital Elevation Model (Carnigan et al. 2009). These data were interpolated onto cross-shore grids for input into the XBeach model, with coarse resolution (40m) offshore and fine resolution (1m) in the inner surf zone and backshore.

Other boundary conditions for the model include a definition of the time-varying offshore wave characteristics and water levels. For the present study, the interest is in understanding the overtopping potential for a wide range of wave and water level conditions. Therefore, for this analysis, a single storm event cannot be prescribed at the offshore model boundary. Rather a generic storm hydrograph was deemed more appropriate and developed from measured wave and tide data.

To generate a generic storm, TWLs were calculated using the same hourly 32-year water level record utilized for the empirical model analysis (Figure 6). Across, the entire observed wave and tide record, the top five extreme TWL events per year were selected and averaged. Time series of wave height, wave period, and water level for the 191 events identified by this approach were normalized by the highest value of each parameter in each storm event to define a normalized 12 hour storm hydrograph (spanning 6 hours before and 6 hours after the peak TWL)(Figure 7). The 12 hour mean normalized hydrographs of wave height, wave period, and still water level and the mean of the un-normalized wave direction hydrograph were subsequently used to define the time evolution of offshore conditions for XBeach, including the ramp up and ramp down of wave energy during storms.

To determine the evolution of wave height (Hs), wave period (Tp), and water levels for each XBeach simulation, the normalized storm hydrographs were multiplied by a given maximum wave height, wave period, and water levels to create a synthetic storm event (Figure 8). Based on the observed 32-year historical environmental dataset, 54 sets of storm conditions with wave periods (ranging from 8 s to 24 s ($\Delta Tp = 2$ s) and wave heights ranging from 2 to 12 m ($\Delta Hs = 2$m). These conditions adequately cover the full range of wave conditions observed annually in the PNW. For input into XBeach, all wave conditions were defined by a JONSWAP spectrum in deepwater and shoaled to the -50 m contour using the Simulating Waves Nearshore Model (SWAN) (Booij et al. 1999).

Based on the extreme TWL events the average maximum storm still water level (SWL = MSL + Tide + η_{NTR}) was 2.9 m with a standard deviation of 0.3 m. Therefore, for analysis in XBeach three storm water level conditions were analyzed consisting of 2.6 m, 2.9 m, and 3.2 m, respectively. Each of the 54 wave conditions were run at these three water levels at each of the pHRAs among the four PCH areas for the five different site-specific restoration scenario profiles, resulting in a total number of 3,240 XBeach simulations. The model was run for 13-hours total allowing for 1-hour spin-up followed by the 12-hour storm hydrograph.

There are a wide variety of other optional inputs to XBeach; however, for this study, model default values were primarily used. Water infiltration was included in the model to limit ponding and allow for percolation of water into the sand. Although updates to morphology were not included for these simulations, the local grain size was an important parameter for infiltration. Median grain size (D50) sand was quantified for the four PCHs using sediment samples collected from Nehalem River Spit (240 mm), Netarts Spit (247 mm), and Sand Lake North (289 mm) (Appendix Table C1). Because grain size was not collected at Bayocean Spit, the grain size of Nehalem River Spit was used for this location given their proximity within the Rockaway littoral cell.

Water surface elevations and wave heights were stored every two seconds for the entire 12 hour storm for all 3,240 XBeach simulations. Output data was subsequently post-processed using MATLAB R2015a (MathWorks Natick, MA, USA) to estimate the number of days per year overtopping distance (m) and duration (hours per storm event) thresholds were reached for each model simulation.

Data Analysis

Statistical Analyses of Geomorphology and Overtopping

We used one-way analysis of variance (1-way ANOVA) to determine whether foredune geomorphology (beach slope and foredune height), TWL values (maximum and overall), and overtopping response variables (hours per year and days per year) varied among PCH areas using the statistical package R (R Core Team 2015). The variables “overtopping hours per year” and “overtopping days per year” were log transformed to meet assumptions of normality, and then back transformed for interpretation. As a result, the values are given as medians (± SE). Tukey post-hoc comparisons were conducted on significant variables to determine differences among PCH areas.

We used two-way analysis of variance (2-way ANOVA) to analyze overtopping hours per site and overtopping days per site as a consequence of pHRA and restoration scenario for each sea level rise (SLR) scenario. As above, the variables “overtopping hours per year” and “overtopping days per year” were log transformed and medians (± SE) are presented. When significant interactions were found, we used a Least Square Means (“lsmeans’) post-hoc test to compare levels within each main effect (Lenth 2015).

Data Analyses of Storm Scenarios

The probability of overtopping distance and duration thresholds associated with the storm scenario analyses were determined using the frequency of wave combinations (wave period and wave height) occurring annually off the Pacific Northwest coast. To calculate the wave frequencies, the daily maximum wave heights and periods were extracted from the historical TWL dataset. The probability of each daily wave height and period was calculated for the entire record. Given the storm scenarios used wave height and period combinations, wave period and wave height were assumed as independent variables; therefore, to determine the overall probability wave combinations occurring together, the individual wave height and period probabilities were multiplied. The resulting combined probability (% of the year of occurrence) was converted to wave days per year for interpretation.

The wave day frequencies were then used to calculate the overall likelihood of flooding reaching various distance and duration thresholds. The distance thresholds included whether overtopping during extreme storms reached either 50 meters or 150 meters or greater. The duration thresholds included whether flooding during extreme storms lasted for 1 to 2 hours or ≥ 2 hours. Overtopping was characterized by a minimum duration threshold of five minutes and minimum water level of 10 cm was applied in order to reduce the number of instances where water "barely" exceeded the foredune crest.

A 2-way ANOVA was used to determine the effect of pHRA and restoration scenario on the number of wave days per year that reached overtopping distances and duration thresholds during the extreme storm scenarios. When significance was found, we used a Least Square Means ("lsmeans') post-hoc test to compare levels within each of the factors (Lenth 2015). All of the wave days per year were presented with one standard error.

RESULTS

Characterization of Dune Geomorphology of Proposed Critical Habitat (PCH) Areas

Beach slope varied alongshore and among the PCH areas (Figure 9, Table 1). The PCH area with the steepest beach slope was Nehalem River Spit (average ± SE; 0.06 ± 0.0004) followed by Netarts Spit (0.05 ± 0.0005), and then Bayocean Spit (0.04 ± 0.0003) and Sand Lake South (0.04 ± 0.0006), which did not differ from one another (Table 1). At each site, the beach slope was shallowest at the tip of the spit, except for several profiles located at the tip of Nehalem River Spit (Figure 9). Using the Wright and Short (1984) morphodynamic classification of beaches, the beaches at the PCH sites can be characterized as intermediate beach states that range between dissipative and reflective states. Dissipative beaches have gentle gradients with wider surf zones and spilling breakers. Reflective beaches are steeper beaches often lacking a surf zone, where incident waves are breaking on the beach face reflecting wave energy backwards from the shoreline (Wright and Short 1984, Masselink et al. 2011). Dissipative beaches have gradual beach slopes where beach slopes range between 0.01 – 0.02, while reflective beaches are steeper with beach slopes ranging from 0.10 – 0.15.

The Iribarren number (ξ), which classifies wave breaker types on beaches using the relationship between beach slope, deep-water wave height, and wavelength, is also useful in beach classification (Komar 1998). Iribarren numbers were calculated using the average slopes (± 1 standard deviation) of the PCH areas and the average wave height and wavelength observed during the 32-year wave record. The resulting Iribarren numbers classify the breakers at Netarts Spit ($\xi = 0.43 \pm 0.08$), Bayocean Spit ($\xi = 0.40 \pm 0.03$), and Sand Lake South ($\xi = 0.36 \pm 0.12$) as spilling breakers ($\xi < 0.5$) that are associated with more dissipative beaches (Wright and Short 1984, Komar 1998). The Nehalem River Spit breakers ($\xi = 0.49 \pm 0.08$) can be classified as spilling to slightly plunging. Plunging breakers ($0.5 < \xi < 3.3$) are more characteristic of intermediate beaches. An important consideration is that beach slopes and beach states change throughout the year. The beach slopes used in this classification calculation were derived from lidar data flown in April of 2011 and serve as a snapshot in time.

Foredune crest elevations varied alongshore and among the PCH areas (Figure 9, Table 1). The average foredune crest elevation was highest at Netarts Spit (average ± SE; 10.8 ± 0.10 m), followed by Nehalem River Spit (10.2 ± 0.07 m), Sand Lake South (9.8 ± 0.07 m), and Bayocean (9.2 ± 0.03) (Table 1). While the foredune elevations varied alongshore, the foredune crest elevations were lowest at the tip of each spit (Figure 9).

Present Day Total Water Levels and Overtopping Exposure of PCH Areas

The total water levels (TWLs) varied alongshore and among the PCH areas (Figure 9, Table 1). The maximum TWLs for each profile are plotted in Figure 9. When we compared the maximum TWLs by PCH area, we found that Nehalem River Spit had the highest maximum TWL (average ± SE; 8.9 m ± 0.02 m), followed by

Netarts Spit (8.2 m ± 0.02 m), Sand Lake South (8.07 m ± 0.03 m), and Bayocean Spit (7.99 m ± 0.01 m) (Table 1). A comparison of the overall TWLs by site showed that Nehalem River Spit (average ± SE; 2.95 ± 0.005 m) had the highest value, followed by Netarts Spit (2.84 ± 0.006 m), Sand Lake South (2.79 ± 0.008 m), and then Bayocean Spit (2.78 ± 0.004 m), all of which did not differ (Table 1).

The overtopping hours per year projected for each of the PCH areas was low but varied alongshore and among the PCH areas (Figure 10, Table 2). Nehalem River Spit had the most overtopping hours (median ± SE; 0.05 ± 0.93 overtopping hours per year), followed by Sand Lake South (0.03 ± 0.93 overtopping hours per year) and Netarts Spit (0.02 ± 0.93 overtopping hours per year), which did not differ, and Bayocean Spit (0.003 ± 0.93 overtopping hours per year) had the least (Table 2). Moreover, the overtopping days per year were rare, with less than one day per year predicted for all sites under present conditions (Figure 11, Table 2). Overtopping days per year were greater at Nehalem River Spit (median ± SE; 0.14 ± 1.02 days), followed by Sand Lake South (0.12 ± 1.02 days) and Netarts Spit (0.12 ± 1.02 days), which did not differ, and Bayocean Spit (0.10 ± 1.02) had the least (Table 2).

Exposure of Proposed Habitat Restoration Areas (pHRA) Under Restoration and Sea Level Rise

For each sea level rise scenario, overtopping hours per year and days per year depended on both site (pHRA) and restoration scenario, and there was a site by restoration scenario interaction (Figure 12, Figure 13, Table 3, Table 4). Overall, flooding exposure increased when foredune elevations were reduced to 6.0 m or below across all sites and SLR scenarios. Under present day SL, restoring to 6.0 m resulted in the greatest exposure at Nehalem River Spit (median ± SE; 27.6 ± 1.12 overtopping hours per year), followed by Netarts Spit (13.4 ± 0.28 overtopping hours per year) and Bayocean Spit (13.4 ± 0.28 overtopping hours per year), which did not differ, and Sand Lake South (9.66 ± 0.76 overtopping hours per year) (Table 3). Restoring to 5.5 m generated the most overtopping at Nehalem River Spit (median ± SE 82.9 ± 2.4 overtopping hours per year), followed by Netarts Spit (52.2 ± 2.69 overtopping hours per year) and Bayocean Spit (53.8 ± 0.88 overtopping hours per year), which did not differ, and Sand Lake South (34.6 ± 2.04 overtopping hours per year) had the least (Table 3).

The overall exposure of the pHRAs, measured as overtopping hours per year, increased under the medium and high SLR scenarios (Figure 12, Table 3). Restoring to 6.0 m under the medium SL scenario generated the most overtopping exposure at Nehalem River Spit (median ± SE; 32.3 ± 1.26 overtopping hours per year), followed by Netarts Spit (19.0 ± 1.23 overtopping hours per year), Bayocean Spit (16.2 ± 0.32 overtopping hours per year), which did not differ, and Sand Lake South (11.4 ± 0.87 overtopping hours per year)(Table 3). Restoring to 5.5 m resulted in the greatest overtopping hours per year at Nehalem River Spit (median ± SE; 95.7 ± 2.66 overtopping hours per year), followed by Netarts Spit (61.8 ± 3.03 overtopping hours per year), Bayocean Spit (54.0 ± 0.88 overtopping hours per year), and Sand Lake South (41.0 ± 2.33 overtopping hours per year) (Table 3). For the same restoration scenario, increased water levels associated with the high SLR scenario generated the greatest overtopping hours per year at Nehalem River Spit (median ± SE; 136 ± 3.31

overtopping hours per year), followed by Netarts Spit (89.9 ± 3.94 overtopping hours per year) and Bayocean Spit (79.0 overtopping hours per year), which did not differ, and Sand Lake South (60.5 ± 3.12 overtopping hours per year)(Table 3). Even under the high SLR scenario, the flooding exposure remained low for the 7.0 m restoration scenario with the most overtopping hours per year at Nehalem River Spit (median ± SE; 3.96 ± 0.31 overtopping hours per year), followed by Netarts Spit (1.95 ± 0.23 overtopping hours per year), then by Bayocean Spit (1.51 ± 0.04 overtopping hours per year) and Sand Lake South (1.14 ± 0.14 overtopping hours per year), which did not differ (Table 3).

Overtopping days per year under the present SL and 6.0 m restoration scenario were greatest at Nehalem River Spit (median ± SE; 9.28 ± 0.26 overtopping days per year), followed by Netarts Spit (5.80 ± 0.29 overtopping days per year) and Bayocean Spit (5.08 ± 0.09 overtopping days per year), which did not differ, and Sand Lake South (3.97 ± 0.23 overtopping days per year) (Figure 13, Table 4). Restoring to 5.5 m increased exposure at Nehalem River Spit to 23.4 ± 0.46 overtopping days per year, 16.2 ± 0.62 overtopping days per year at Netarts Spit, 14.5 ± 0.19 overtopping days per year at Bayocean Spit, and 11.8 ± 0.52 overtopping days per year at Sand Lake South (Table 4). Increased water levels associated with the medium SLR scenario generated greater exposure at Nehalem River Spit (median ± SE; 10.8 ± 0.28 overtopping days per year), followed by Netarts Spit (6.82 ± 0.33 overtopping days per year), Bayocean Spit (5.86 ± 0.10 overtopping days per year), and Sand Lake South (4.51 ± 0.25 overtopping days per year) when selecting to restore to 6.0 m (Table 4). Selecting to restore to 5.5 m, resulted in the most flooding exposure at Nehalem River Spit (median ± SE; 26.9 ± 0.49 overtopping days per year), followed by Netarts (18.7 ± 0.68 overtopping days per year), Bayocean Spits (16.9 ± 0.22 overtopping days per year), and Sand Lake South (13.5 ± 0.58 days per year) with the lowest exposure (Table 4). For the same restoration scenario, the high SLR scenario increased the flooding exposure to 36.3 ± 0.56 overtopping days per year at Nehalem River Spit, 26.1 ± 0.81 overtopping days per year at Netarts Spit, 23.5 ± 0.30 overtopping days per year at Bayocean Spit, and 18.9 ± 0.73 overtopping days per year at Sand Lake South **(**Table 4**).**

Exposure of Proposed Habitat Restoration Areas (pHRAs) to Extreme Storms

Modeling the impacts of the various storm scenarios revealed that all the pHRAs experienced the greatest overtopping distances and durations when wave height, period, and still water levels were highest (Figure 14). The restoration scenarios with lower foredune elevations exhibited greater flooding distances and durations with the greatest flooding exposure at Bayocean Spit (Tables 5a, b). Overall flooding exposure during extreme storms was evaluated using overwash distance thresholds of 50 m and 150 m or more and duration thresholds of 1 hour and 2 hours or more. The probability of modeled wave height and period combinations occurring in one year (wave days per year) served as a proxy to determine the overall likelihood of overtopping events reaching or exceeding the distance and duration thresholds.

Flooding exposure was greater when foredune elevations were reduced to 6.0 m or below. For the 2.6 m water level, overwash extent reached 50 m more often at Bayocean Spit (total days ± SE; 29.5 ± 2.8 wave days per year) followed by Netarts

Spit (12.6 ± 2.8 wave days per year), Nehalem River Spit (11.6 ± 2.8 wave days per year), and Sand Lake (10.6 ± 2.8 wave days per year), which did not differ (Figure 15; Table 6a). Increasing the water level to 3.2 m resulted in no difference in the number of wave days per year of overwash to 50 m or beyond. Comparing restoration scenarios within sites, the number of wave days per year the overwash distance reached 50 m or more was significantly greater when restoring dunes to 6.0 m or below compared to current conditions and reductions to 7.0 m (Table 6a).

Furthermore, the number of wave days per year the overwash distance reached 150 m or more was lower across all sites compared the 50 m threshold (Figure 15). For the 2.6 m storm water level, overwash was projected to reach 150 m or more at Bayocean Spit more often (total days ± SE; 6.6 ± 0.6 wave days per year) compared to Nehalem River Spit (2.9 ± 0.6 wave days per year), Netarts Spit (2.9 ± 0.6 wave days per year), and Sand Lake South (2.7 ± 0.6 wave days per year), which did not differ (Table 6b). Increasing the storm water levels to 2.9 m and 3.2 m resulted in a greater likelihood of overwash distance reaching 150 m or more at Bayocean Spit compared to Sand Lake South across all restoration scenarios, with no differences between the remaining sites (Table 6b). Finally, across all sites, there was no difference in the number of wave days per year the overwash was projected to reach 150 m or beyond for foredune reductions of 7.0 m or below.

While overwash distance was dependent on both restoration scenario and site, the overwash durations during extreme storm scenarios were only affected by restoration scenario (for storm water levels of 2.9 m and 3.2 m only) (Figure 16,

Table 7a). For the 2.6 m water level, there were no statistical differences between sites and restoration scenarios under the 1-hour duration threshold (Table 7a). Across all sites, increased storm water levels (2.9 m and 3.2 m) resulted in a significantly greater likelihood (greater than 5 days per year across sites) of overwash durations lasting for one hour or more under the 5.5 m restoration scenario, with no difference in overall likelihood between the other restoration scenarios (Table 7a). Furthermore, the overall likelihood of overwash duration exceeding 2 hours decreased. For all sites and storm water levels, the overall likelihood of overwash lasting 2 hours or more was greatest under the 5.5 m restoration scenario with no difference between the other restoration scenarios (Table 7b).

DISCUSSION

Coastal Geomorphology, Restoration Scenarios, and Sea Level Rise on Flooding Exposure of Habitat Restoration Areas

Our results showed that coastal exposure varied significantly among the proposed critical habitat (PCH) areas targeted for restoration of the federally listed Western snowy plover on beaches and dunes in the Pacific Northwest. Of the four proposed sites within Tillamook County in Oregon, our models showed that Nehalem River Spit would experience the most overtopping followed by Netarts Spit and then Bayocean Spit and Sand Lake South (Figures 10, 11). Restoration, sea level rise, and storm scenarios all exacerbated the exposure (Figures 12-16). Below we describe the factors affecting overtopping and flooding at the habitat restoration areas in more detail.

Coastal Geomorphology and Flooding Exposure

The differences in flooding exposure at the PCHs were the result of the variation in geomorphological conditions present at these sites. The average beach slope of Nehalem River Spit, the most exposed site, was the steepest compared to the other sites (Figure 9, Table 1). Beaches with steeper slopes experience higher run-up for the same wave conditions as beaches with more gradual slopes (Wright and Short 1985, Stockdon et al. 2006). Therefore, increased runup as a result of steeper beach slope is contributing to the increased overtopping exposure at Nehalem River Spit. In contrast, Bayocean Spit had the most gradual beach slope, contributing to lower projected total water levels (TWLs), overtopping, and overall exposure to flooding. Understanding the role of beach slope at potential habitat restoration areas (pHRAs) is pertinent to future plover management, as placement of HRAs on dissipative beaches could minimize coastal exposure, while still maintaining plover recovery (Biel et al. in review).

In addition to beach slope, foredune height is important to overtopping and flooding and thus coastal exposure. For example, at Sand Lake South, there were steeper beach slopes at the southern end of the spit that led to higher maximum TWLs. But here the foredunes were also taller resulting in reduced exposure to flooding at this site (Figure 9, Table 1). Our study, among others, confirms the importance of understanding the interaction between beach slope and foredune crest elevations is an important factor in determining the ultimate flooding potential of the different PCH areas (Biel et al. in review).

Furthermore, shoreline change rate is another important component of coastal geomorphology that contributes to overtopping and flooding exposure (Ruggiero et al. 2013). Locations where shorelines are building seaward (prograding) have lower coastal vulnerability compared to shorelines that are moving landward (eroding). Shoreline change in Oregon is influenced by sea level rise, increased wave heights, land uplift rates as a result of plate tectonics, and strong El Niño events (Ruggiero et al. 2013). Evaluations of the shoreline change rate of Tillamook County revealed that approximately 77% of the Tillamook County shoreline has eroded by an average of approximately 1.8 m per year from 2002 – 2011 (Ruggiero et al. 2013). Increased shoreline erosion results in narrower beaches making the Tillamook County PCH areas more susceptible to overtopping and flooding in the future.

Restoration Scenarios and Exposure to Flooding Under Present Day Conditions

Our modeling showed that the choice of restoration scenario made a big difference in the exposure to flooding at the different PCH areas. Overtopping at current foredune elevations was minimal; however, once elevations were reduced to 6.0 m, the overtopping days per year increased significantly (Figure 17). For all SLR scenarios, overtopping days per year associated with restoring to 5.5 m exceeded 10 days per year, across all sites. Restoring foredunes to 6.0 m, present day sea level generated 5 days or more of overtopping at Nehalem River Spit, Bayocean Spit, and Netarts Spit, but less than 5 days at Sand Lake South. The variation in vulnerability at these different elevations has management implications and should be considered when selecting restoration elevations for the proposed sites. In this example, a reduction to 6.0 m may generate ideal overtopping at Sand Lake South, but could lead to excessive overtopping at Nehalem River Spit, Netarts Spit, and Bayocean Spit. Therefore, the choice of restoration scenario should take into account the fact that sites vary in their exposure.

Habitat restoration conducted at Assateague Island, Maryland, intended to recover piping plovers, determined that one day of overwash per year maintained the bare, sandy habitat necessary for piping plover nesting (Schupp et al. 2013). In Tillamook County, at present day water levels, one day of overtopping or less occurred when selecting to reduce foredune elevations to 7.0 m (Figure 17). At present sea level, Sand Lake South experienced at least one day of overtopping at the 6.0 m restoration scenario. Therefore, if at least one day of overtopping per year is ideal to promote the bare, sandy habitat preferred by the plover, reductions between 6.0 m and 7.0 m would be necessary at the PCH areas in Tillamook County.

Considering previous research conducted prior to the implementation of an HRA at Elk River Spit in southern Oregon revealed that a foredune crest reduction to 5.5 meters would yield overtopping of 4 – 8% of the time (6 – 11.5 days) during the winter months (October – March), which was hypothesized to not compromise spit function (Allan 2004). However, reducing the dune elevations to approximately 4.5 meters would yield 15 – 25% more days (21 – 37.5 days) of overtopping per winter season with the likelihood of compromising plover habitat. Our analysis at present day water levels shows that the profiles within the PCH areas in Tillamook County could experience equivalent to greater exposure to flooding compared to Elk River, as the 5.5 m restoration scenario, generated 10 days of overtopping per year or more across all sites (Figure 17).

Sea Level Rise and Exposure to Flooding

We found that the effect of climate change in the form of sea level rise also had an effect on the overall exposure of the pHRAs within the PCH areas. We determined that the flooding of the current foredune elevations was minimal across all SLR scenarios. But, the combination of medium and high SLR scenarios and lower foredune crest elevations associated with some of the restoration scenarios yielded increased overtopping potential, across all sites. At lower foredune elevations, the Nehalem River Spit continued to have the most overtopping hours and days per year, followed by Netarts Spit, Bayocean Spit, and Sand Lake South (Figures 12, 13; Tables 3, 4). .

Comparing the median number of overtopping days per year expected across all sites, the medium SLR scenario resulted in similar overtopping days per year compared to the present day sea level. One difference was that under the 6.0 m restoration scenario the number of overtopping days per year increased to 10 days per year or more at Nehalem River Spit (Figure 17). At all other sites, reducing foredune elevations to 7.0 m or below generated the one day or less of overtopping per year that could promote the bare, sandy habitat preferred by the plover. Higher sea level also generated approximately one day of overtopping at foredune reductions of 7.0 m across all sites. Therefore, considering projected sea level rise, a more conservative restoration option would be to restore to 7.0 m.

Impacts of Extreme Storms on Coastal Exposure

In addition to comparing the likelihood of overtopping among sites, we also compared the distance and duration of flooding exposure during extreme storms to understand how extreme wave events would impact the entire extent of the pHRAs. The implication of extreme storm events on overtopping potential is critical, as storm frequency and the occurrence of extreme wave heights and periods have increased over the last several decades (Allan and Komar 2001, 2006, Graham and Diaz 2001, Menéndez et al. 2008). Overall, our results indicated that overtopping distances and durations were dependent on site, restoration scenario, and environmental conditions (wave height, wave period, and water level). The likelihood of overtopping occurring under current conditions was less than one day per year. However, when overtopping occurred, the extent of overtopping varied across sites. The average overtopping distances and durations during storms scenarios were greatest at Bayocean Spit, followed by Netarts Spit, Sand Lake South, and Nehalem River Spit (Table 5a).

The overtopping extent at present day conditions was likely influenced by geomorphology of the representative cross-shore profile used for the storm simulations (Figure 5). The current foredune elevation of the Bayocean Spit cross-shore profile was the lowest compared to the other sites resulting in greater overtopping exposure. In addition to foredune crest elevations, the topography and elevation of the backshore also likely influenced the extent and duration of overwash of the current foredunes. The presence of rolling dunes in the backshore likely caused temporary pooling of water (until removed through infiltration) and thus longer overwashing durations.

Similar to the empirical model results, lower foredune elevations, associated with greater foredune reductions, resulted in greater flooding durations and distances during storm scenarios. To give context to the overall likelihood of overtopping distances and durations being reached during extreme storms, we calculated the probability of storm scenario combinations occurring annually off of the PNW coast. Our analysis revealed that the number of wave days per year the sites experienced flooding for an hour or more depended on storm water level and restoration scenario (Figure 18a). Restoration elevations to 5.5 m generated an hour or more of flooding exposure at Bayocean Spit only. However, higher storm water levels increased the likelihood of one hour of flooding exposure to one day per year under the 5.5 m restoration scenario for Nehalem River Spit and Netarts Spit and more than 5 days per year at Bayocean Spit. Increased overall exposure (days per year) to flooding during extreme storms has management implications, as greater and longer flooding could cause increased erosion of critical plover habitat.

The number of wave days per year extreme storms generated overwash distances of 150 m or more was also dependent on site, restoration scenario, and extreme storm water levels (Figure 18b). Across all sites and storm water levels, the overall likelihood of overwash distances reaching 150 m or more was low. However, reductions to 7.0 m or less generated variable flooding exposure. For the average extreme storm water level (2.9 m), reductions to 7.0 m or below generated overwash of 150 m or more over 10 days per year at Bayocean Spit. The other sites became as equally exposed as Bayocean Spit to overwash distances of 150 m or more under increased storm water levels (3.2 m). We determined that higher wave height and period combinations were characteristic of overwash distances of 150 m or greater. The overall likelihood of occurrence was equal within the same site for all foredune reduction scenarios less than 6.5 m for Sand Lake South and 7.0 m for all other sites. Therefore, these results suggest that flooding distances of 150 m or more were a consequence of higher wave heights and periods and not foredune crest elevation. Seabloom et al. (2013) determined that increased storm intensity (wave height and period) caused greater flooding exposure, suggesting wave period as the primary component in contributing to flooding exposure.

Understanding the implications of elevated water levels and storminess is critical especially with projected sea level rise and increased storminess associated with climate change and El Niño events. For example, a strong winter storm during the 1997/1998 El Niño coincided with elevated mean water levels resulting in increased wave runup and thus greater erosion and overtopping of sections of the Netarts Spit (Revell et al. 2002). The increased water levels were likely due to tidal influence; however, the elevated water levels that generated the hot-spot erosion during that El Niño event could become the norm under projected sea level rise.

Modeling of existing HRAs along the southern Oregon and Washington coast has added to our knowledge about how pHRAs might respond to increased storm intensity. Flooding risk, dune retreat, and erosion were all explained by site-specific nearshore geomorphology, increased wave intensity, storm surge and dune height reductions due to restoration (Biel et al. in review). Existing HRAs along the

Southern Oregon Coast with foredune elevations of 7.0 m or greater had lower flooding risk and foredune retreat associated with increased storm intensity compared to locations with foredune elevations of less than 7 m. While overall exposure to flooding is site-specific, understanding the erosion and foredune retreat caused by certain levels of flooding at existing HRAs could serve as a proxy and enable managers to anticipate the likely foredune retreat associated with foredune crest reduction scenarios projected for the pHRAs in Tillamook County.

Implications to Plover Management and Trade-offs

Restoration of habitat for the Western snowy plover reduces dune height and beach grass cover. Habitat restoration conducted at Assateague Island, Maryland, intended to recover piping plovers, shows that areas with overwashing and greater shoreline erosion result in sparse vegetation, a desired habitat for plovers (Schupp et al. 2013). Simenstad et al. (2006) recognized that dynamic restoration planning that incorporates a range of natural disturbance such as overwashing is more likely to result in greater restoration success.

Overwash by ocean waves could serve as a natural alternative to reduce the re-growth and re-establishment of invasive beach grass (Pickart 1997; Zarnetske et al. 2010). Finding the amount of overwash to maintain an open sandy habitat for plovers could minimize the need for bulldozing maintenance and provide a better method to recover native dune plants. However, there is likely a balance between habitat restoration to promote overtopping and reductions in foredune profiles that could cause excessive flooding compromising plover habitat and coastal protection for humans.

Habitat restoration areas along the Pacific Northwest coast are examples of how foredune bulldozing is successfully removing the invasive beach grasses, restoring historical habitat conditions, and slowly recovering the Western snowy plover (Lafferty et al. 2006, Zarnetske et al. 2010, Biel et al. in review). However, an evaluation of multiple plover restoration methods, including the use of herbicides and hand pulling of grasses, showed that plovers positively respond to the removal of invasive grasses and were not necessarily dependent on specific management method (Zarnetske et al. 2010). The negative implications of bulldozing for native plants could be avoided if other alternatives such as the use of overwashing are employed. These findings highlight the importance of identifying restoration sites and methods that maximize plover productivity, discourage invasive beach grass regrowth, and avoid compromising coastal protection.

Biel et al. (in review) analyzed site-specific trade-offs between plover productivity, conservation of endemic dune plants, and coastal protection. They found that the extent of the coastal vulnerability varied significantly among the HRAs as a result of local beach and dune geomorphology and foredune restoration management. Plover productivity was positively influenced by predator management initiatives; productivity increased by an average of 1.8 fold across all sites except Coos Bay North Spit, where plover productivity increased by 1.1 fold. They also determined that invasive beach grass removal reduced native back dune plant richness by 84%, but did not change endemic plant richness. Finally, they found that the placement of HRAs on more gradually sloping beaches with wider beach width, as observed at

Leadbetter Point, Washington, resulted in a reduced trade-off of coastal protection while not reducing plover recovery compared to other sites.

The selection of foredune restoration scenarios is dependent on the overall management goal, which will likely be site-specific. In Tillamook County, the current restoration management goals identify Nehalem River Spit and Netarts Spit as potential locations for habitat restoration. Bayocean Spit and Sand Lake South are cited as “currently unoccupied” Recreation Management Areas where beach closures will be used to encourage nesting of plovers (ICF 2010). Our empirical analysis of overtopping predicted Nehalem River Spit and Netarts Spit to have greater flooding exposure relative to Sand Lake South and Bayocean Spit especially under foredune reductions to 6.0 m or below. If the overall management goal were to rely on bulldozing only with no overtopping, then restoring to 8.0 m would be appropriate for all sites.

Furthermore, given that previous research identified one overtopping event per year as sufficient for habitat maintenance, selecting to restore the foredune elevations to 7.0 m at Nehalem River Spit, Bayocean Spit, and Netarts Spit and 6.0 m at Sand Lake South would generate conservative flooding exposure (approximately 1 day or more of overtopping) within the pHRAs at the different PCH areas (Figure 17). These reductions could re-establish original dune function, as lower dune elevations prior to the beach grass invasion were maintained by intermittent overwash events during winter storms. However, considering SLR projections, more conservative foredune reductions would be optimal to reduce the trade-off of coastal protection services of the dunes. Finally, if the overall goal is to encourage greater overwash to reduce the re-growth of invasive grasses, restoring to 6.0 m could be the most appropriate. Restoring to 5.5 m resulted in greater than 10 overtopping days per year across all sties. While more modeling would be necessary to determine if 10 days of overtopping or more could compromise the spit, our results revealed the noticeable increase in overtopping days at lower foredune elevations. Excessive flooding could compromise and risk the plover habitat that management is intending to restore. Increased exposure could especially become problematic with increasing sea levels and storminess.

Applying the results of the storm analysis to these hypothetical restoration options, flooding during extreme storm events reached 150 m or more 10 days or less at lower storm extreme water levels (2.6 m), but greater than 10 days at higher storm water levels across all PCH areas in Tillamook County (Figure 18b). These flooding extents and frequencies should be considered when designing depth dimensions of future HRAs at the Tillamook County sites. Given salt water is used to reduce the regrowth of the invasive beach grass, an HRA depth of 150 m would likely be flooded enough to maintain the bare, sandy habitat necessary for plover productivity. However, as mentioned previously, more sophisticated modeling or ecological monitoring would be necessary to determine if 10 days or more of overwash associated with extreme storms could lead to geomorphological changes to the spits that could potentially risk the plover habitat or the coastal protective services of dunes.

Compromising coastal protection becomes more likely as projected SLR and stronger storms elevate water levels. These conditions could result in increased foredune erosion and habitat squeeze, which further reduces the coastal protection services of dunes (Everard et al. 2010). The location of the PCH sites on spits with estuaries located immediately behind limits the migration of open habitat inland. Lowering the foredune elevations will likely make the HRAs more susceptible to breaching and could increase the likelihood of overwashing and sand deposition into the estuary immediately behind the spit. For example, the HRA installed in 1998 at New River, Oregon, exhibited additional unintended reductions in foredune height as shown by surveys conducted in 2003 (U.S. BLM 2008). The lower elevations made the HRA susceptible to increased flooding, breaching, and sand deposition in sections of the New River channel located immediately behind the HRA. This example highlights the need to fully evaluate the trade-offs associated with foredune reduction scenarios, especially under increases in sea level, to ensure the function and integrity of adjacent ecosystems are not compromised.

Our research findings also highlighted the importance of understanding the geomorphology within a PCH area, particularly at the tip of spits. Our models showed that overtopping and flooding was greatest near the tips of spits compared to further down the beach (Figures 10, 11). Tips of spits are highly dynamic, as sand is deposited, transported, and eroded, sometimes in the matter of a single storm event. Strong storms, such as storms occurring during El Niño years, can cause the tips of spits to migrate. During the 1997/1998 El Niño, sand at the tip of the Netarts Spit migrated toward the inlet resulting in localized erosion south of the inlet (Revell et al. 2002). Although the dynamic nature of the tips of spits often produce low elevation and bare dunes, potentially ideal habitat for plovers, excessive overwash, breaching, and dune retreat as a result of scarping and erosion could be detrimental. Preliminary analysis of erosional impacts at Netarts Spit caused by storms during the 2015/2016 El Niño revealed that the dunes at the tip of the spit retreated approximately 30+ meters (Peter Ruggiero and Nick Cohn, unpublished data). In addition, spit orientation can be important when evaluating the potential exposure of proposed HRAs. During winter, strong waves in this region come from the southwest (Komar 1997) thus pHRAs on the tips of southerly oriented spits, such Nehalem River Spit, could likely be more vulnerable to flooding and erosion compared to spits oriented to the north (Bayocean Spit, Netarts Spit and Sand Lake South).

Learning from current plover management, combined with the coastal exposure analysis we conducted here, could enable managers to develop site-specific restoration plans that maximize plover recovery while minimizing coastal exposure. The apparent trade-offs associated with plover recovery have both short-term and long-term consequences. Habitat creation through foredune reductions is intended to promote plover productivity and facilitate plover recovery in the short-term. However, management initiatives should consider the long-term implications of climate change and strong storms to coastal protection services, especially on the Pacific Northwest coast where storm frequency and intensity is increasing (Graham and Diaz 2001, Allan and Komar 2001, 2006, Menéndez et al 2008). Foredune reductions and bulldozing also have unintended long-term impacts to the re-growth of native plant species. Therefore, it becomes critical for future plover management initiatives to incorporate best-fit long-term alternatives that balance species conservation and coastal protection.

CONCLUSION

Our study evaluated how habitat restoration areas may differ in their exposure to coastal hazards as a result of foredune restoration elevation, site, and climate change. Selecting to not restore foredune habitat will likely have negative impacts on plover recovery. However, some sites and restoration scenarios may be better than others and, if planned with exposure to coastal flooding in mind, could avoid excessive overtopping and degradation of the habitat that managers intend to restore.

The linkages and potential tradeoffs of multiple ecosystem services in coastal systems is understudied and not well understood. Pacific Northwest beach and dune ecosystems provide a unique venue for analyzing these tradeoffs at the intersection of dune conservation and plover restoration priorities. While this work primarily focused on the coastal exposure associated with plover management, our results could serve as a basis for an ecosystem service valuation intended to explore the economic implications of restoration scenarios. Understanding the ecological and economic ramifications would enable resource managers to identify best-fit and cost-effective restoration scenarios while also balancing other key services.

Finally, our study supports the need for more holistic, ecosystem-based management approaches to coastal management. The one-size fits all management approach to habitat and species conservation is unable to balance site-specific trade-offs occurring between key ecosystem services. Most importantly, this work highlights that regardless of management objective, identifying the associated trade-offs between key ecosystem services and finding a balance that can maximize the potential of all services is critical for coastal management moving forward.

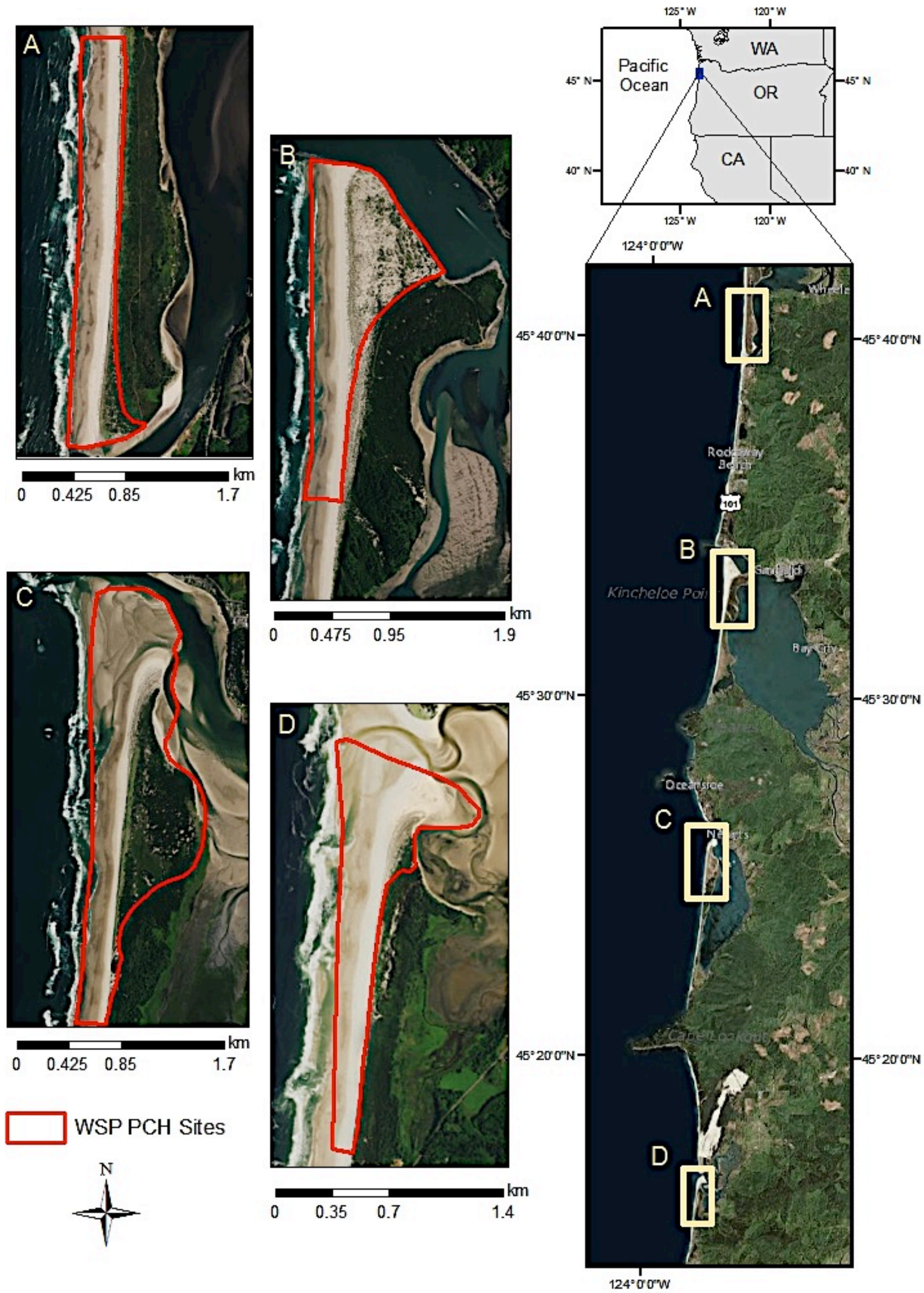


Figure 1. Map of proposed plover critical habitat (PCH) areas for the Western snowy plover (*Charadrius nivosus nivosus*) in Tillamook County, Oregon. From north to south: A.) Nehalem River Spit, B.) Bayocean Spit, C.) Netarts Spit, D.) Sand Lake South. For each PCH area, the flooding exposure analysis was confined to the red borders. See Appendix A and B or site descriptions locations.

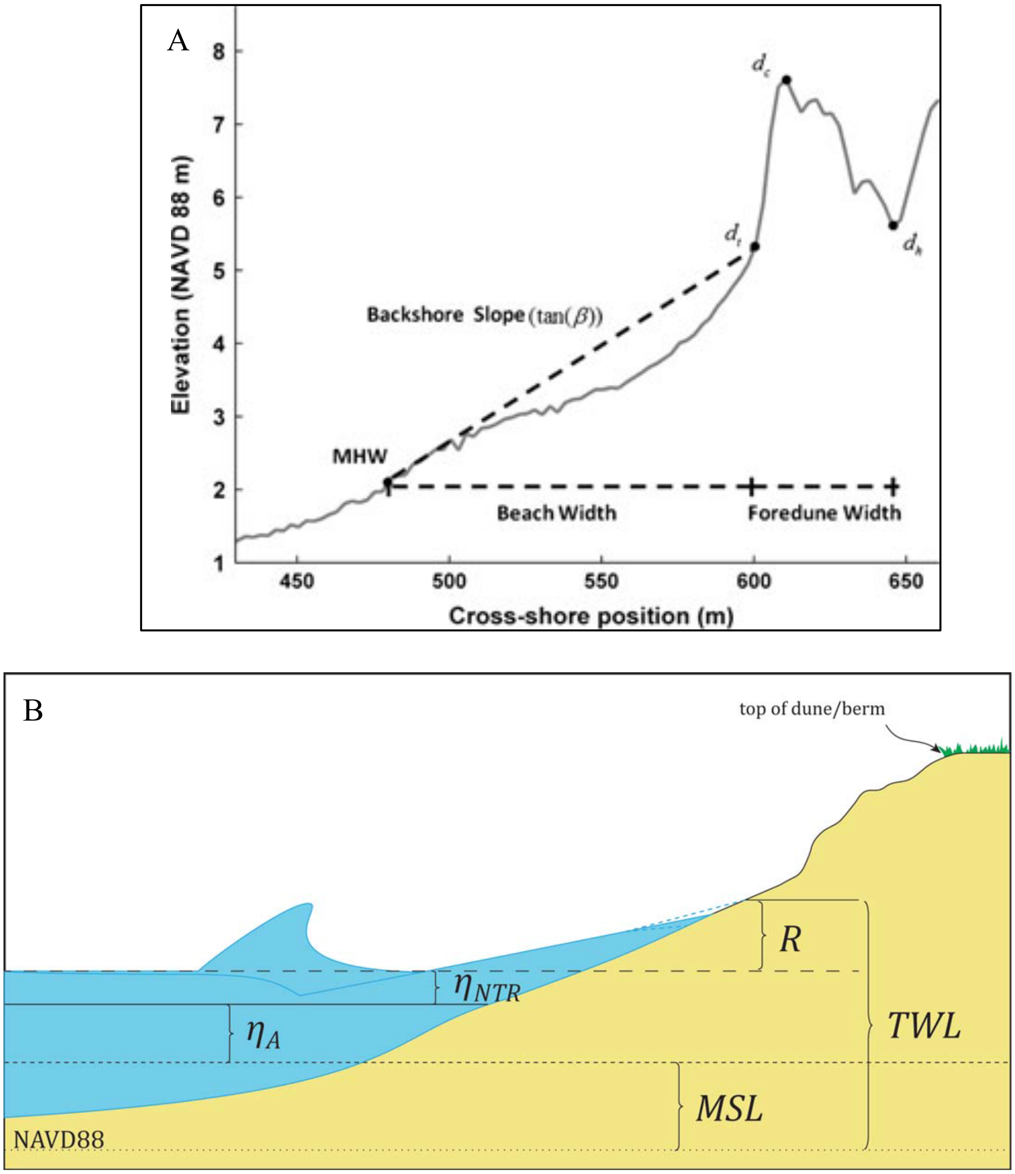


Figure 2. A.) An example of a dune topographical profile depicting the geomorphological data parameters extracted from 2009/2011 LIDAR dataset. Data parameters include mean high water (MHW), beach slope (tan (β)), dune toe (d_t), dune crest (d_c), and dune height (d_h). (adopted from Seabloom et al. 2013).
B.) Diagram of a sandy beach including parameters required for the calculation of total water levels (TWL). The TWL calculation combines mean sea level (MSL), astronomical tide (η_A), non-tidal residuals (η_{NTR}), and wave runup (R) (adopted from Serafin and Ruggiero 2014).

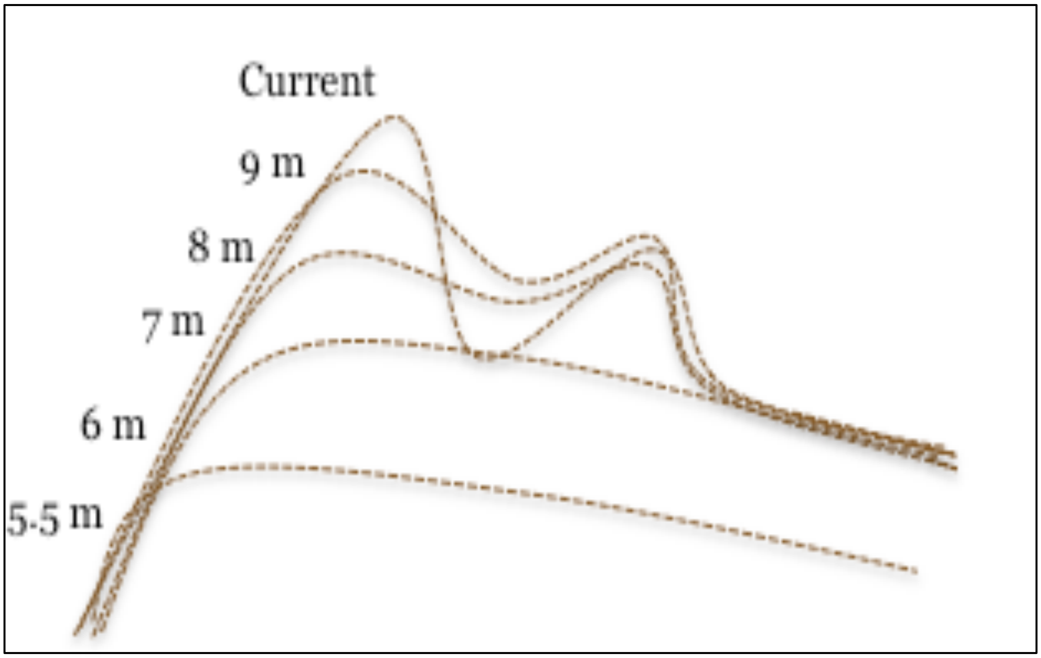


Figure 3. Illustration showing the restoration scenarios applied to the proposed critical habitat (PCH) areas in Tillamook County, Oregon. The scenarios included: (1) Current crest elevations and reductions to 9.0 m; 8.0 m; 7.0 m; 6.0 m; 5.5 m. Note this illustration is not drawn to scale.

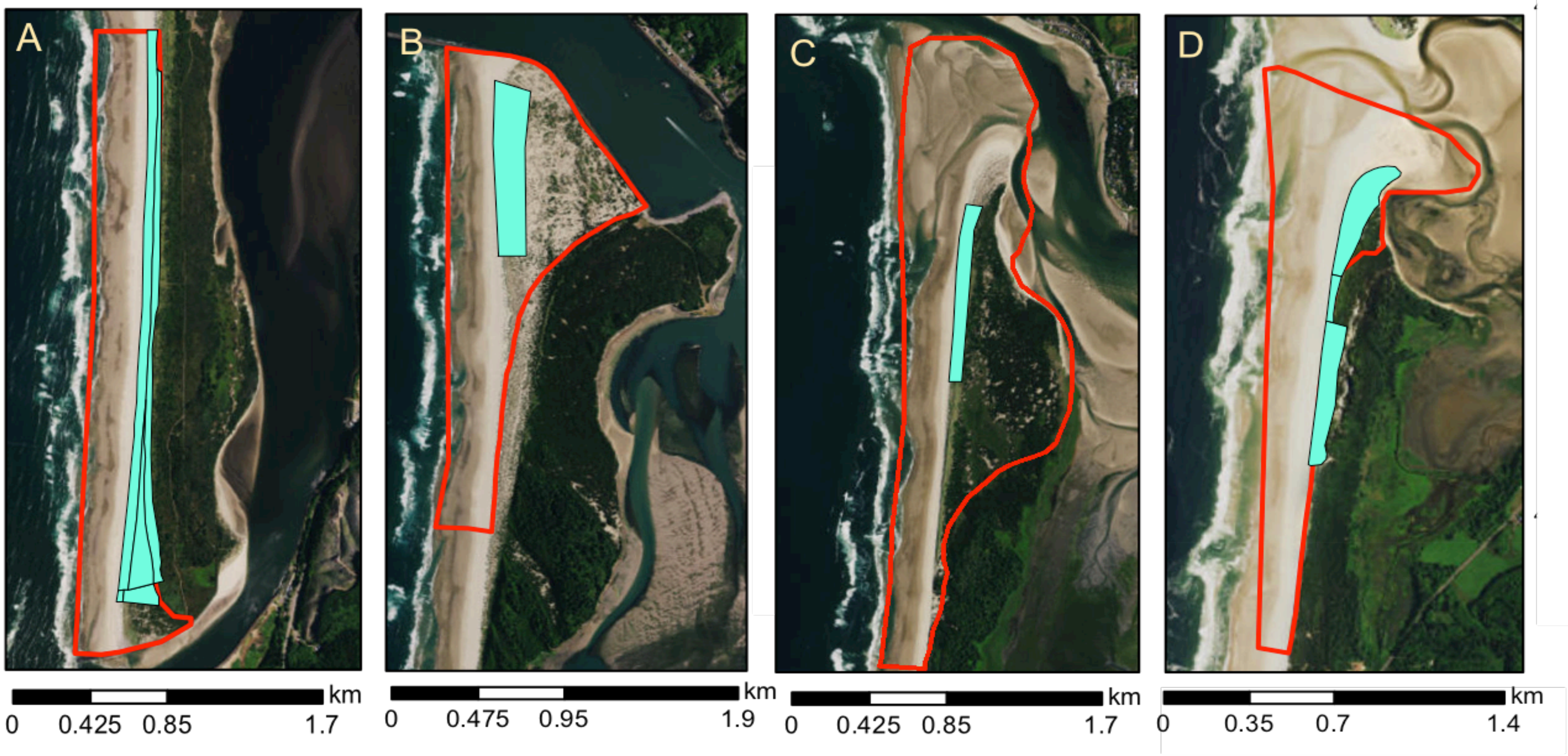


Figure 4. Map of proposed habitat restoration areas (HRAs) within the four proposed plover critical habitat (PCH) areas for the Western snowy plover (*Charadrius nivosus nivosus*) in Tillamook County, Oregon, A.) Nehalem River Spit, B.) Bayocean Spit, C.) Netarts Spit, D.) Sand Lake South. For each PCH area, the flooding exposure analysis at current conditions and present sea level was confined to the red borders. The pHRAs (indicated in light green) were established at the tip of the PCH areas, extending 1 km in length. The dune profiles from within these pHRA subsections were used to determine the overall flooding exposure under hypothetical restoration and sea level rise

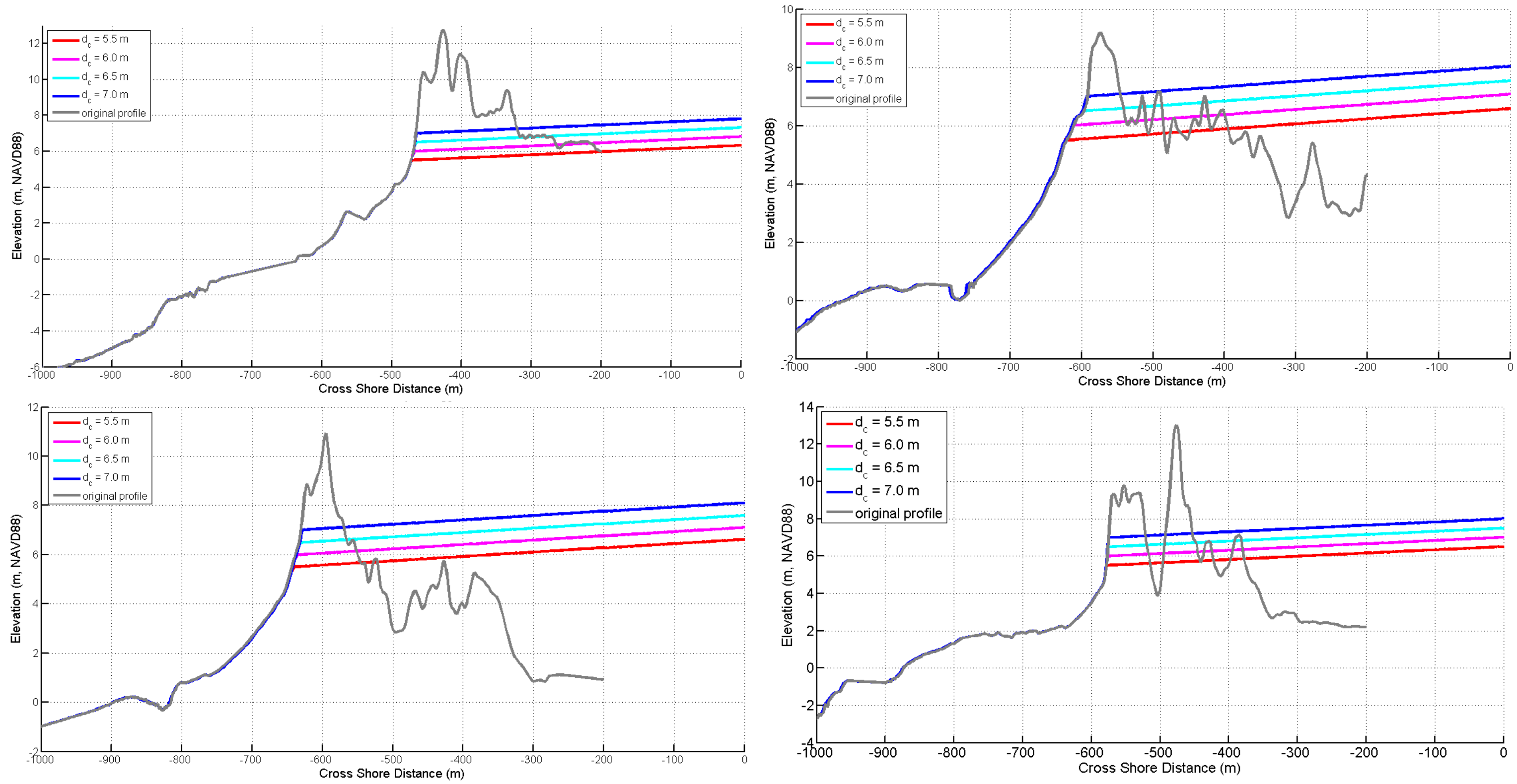


Figure 5. Cross-shore morphology used to characterize dune conditions for the XBeach model for storm analysis at Nehalem River Spit (upper left), Bayocean Spit (upper right), Netarts Spit (lower left), and Sand Lake South (lower right). Displayed is the current profile (black), reduction to 7.0 m (royal), reduction to 6.5 m (indigo), reduction to 6.0 m (pink), and reduction to 5.5 m (red).

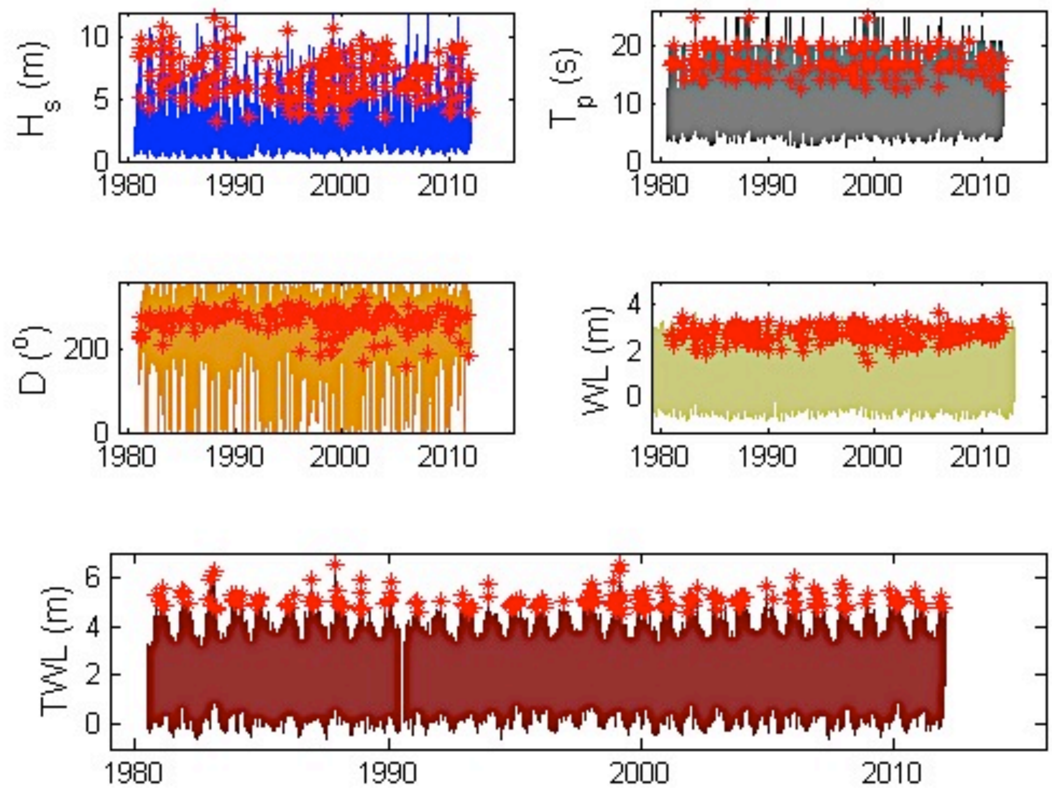


Figure 6. Parameterization of extreme total water level (TWL) events using the 32-year historical water level dataset. Environmental conditions that contributed to the overall TWL (lower panel) were wave height (H_s), wave period (T_p), wave direction (D°), and water levels (WL). The red asterisks pinpoint the environmental conditions associated the extreme water level events.

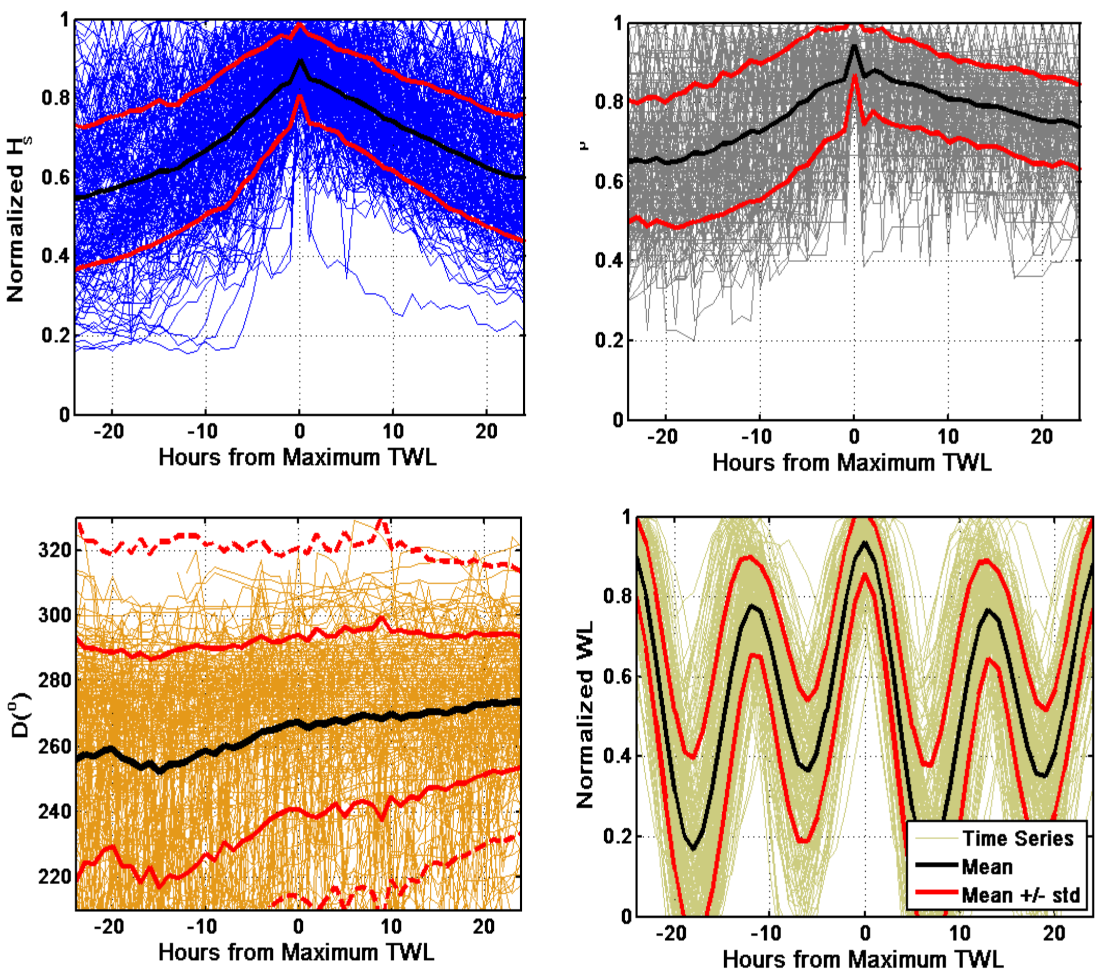


Figure 7. Time series of environmental wave (height (H_s), period (T_p), and direction (D°) and water level water level (WL) conditions associated with the 191 extreme storm events selected to represent the synthetic storm for the XBeach storm scenario analysis. Note that wave height, period, and water level were normalized.

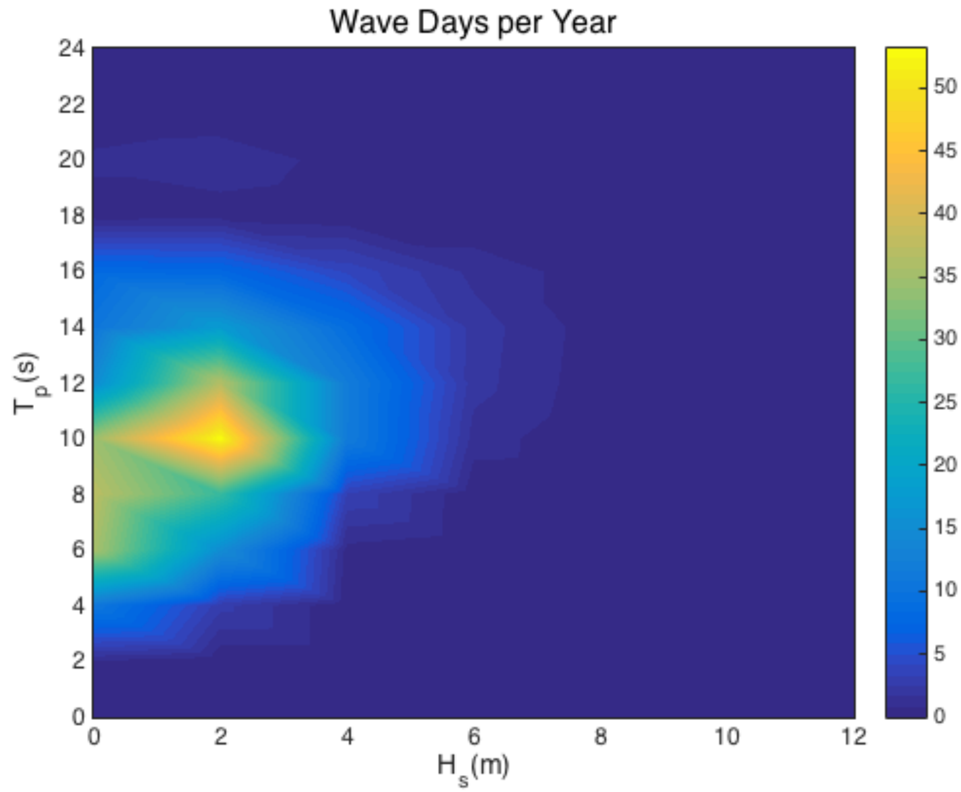


Figure 8. Wave day frequencies, independent of water level representative of annual observations of wave conditions off the Pacific Northwest Coast. The occurrence interval (days per year) was calculated using daily maximum wave height (*H_s*) and wave period (*T_p*) extracted from the 32 year historical TWL dataset.

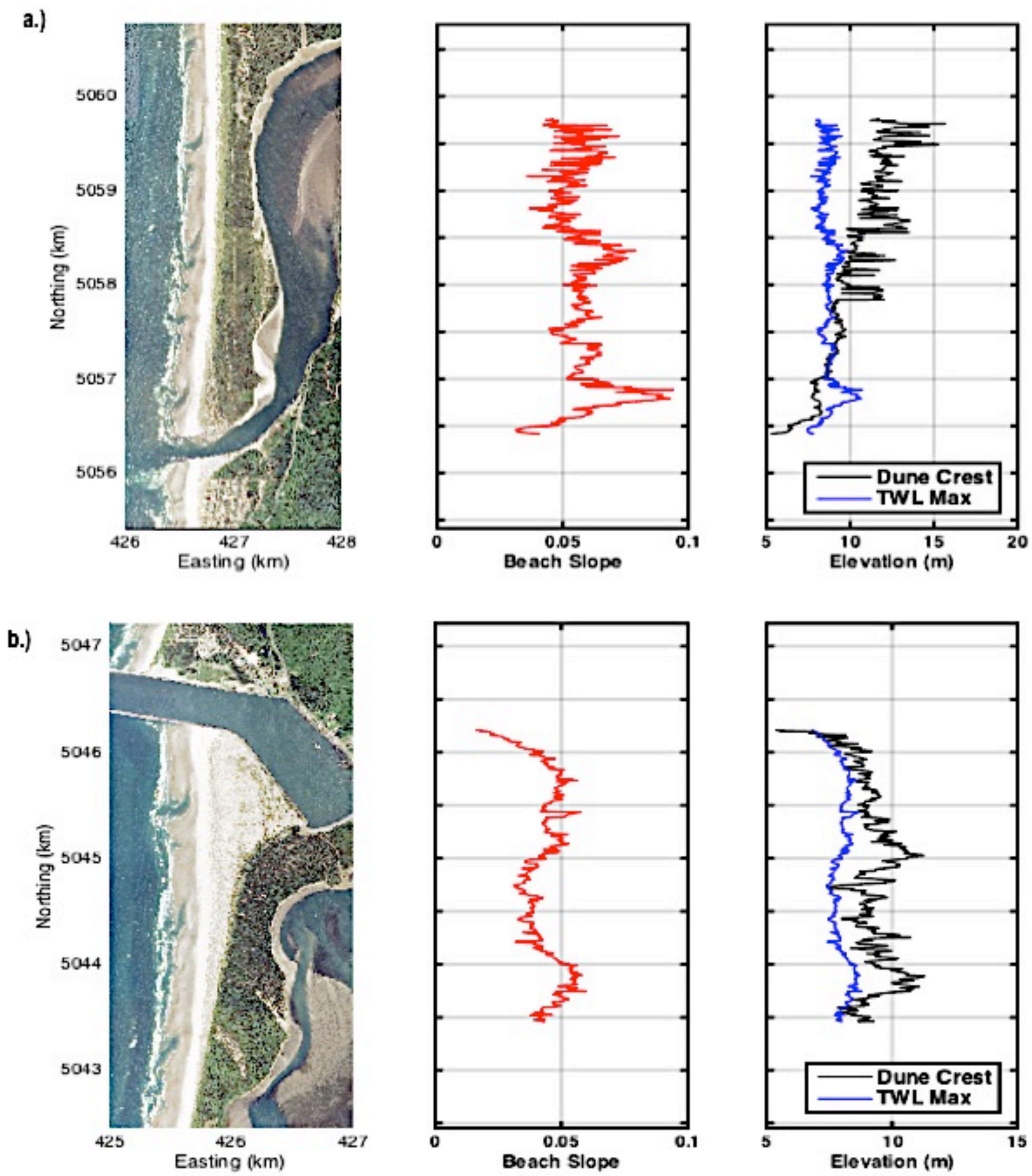
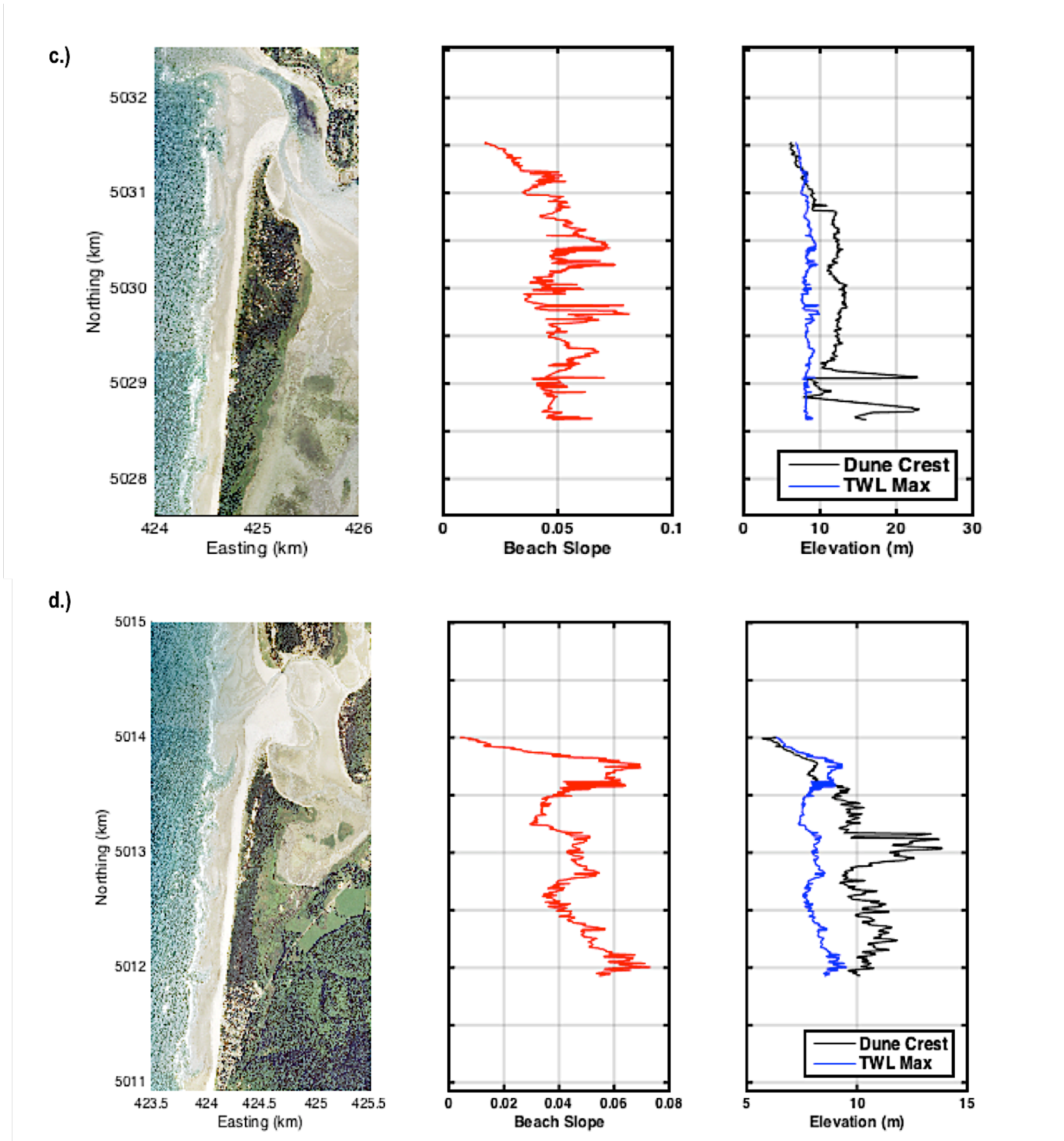


Figure 9. Current dune geomorphology (beach slope, foredune crest elevation) and maximum total water level (TWL) projected at A.) Nehalem River Spit, B.) Bayocean Spit, C.) Netarts Spit, and D.) Sand Lake South in Tillamook County, Oregon. Dune crest and beach slope elevations were extracted at 5m-resolution from a 2009/2011 lidar dataset (DOGAMI 2009, USACE 2011).

Figure 9 (Continued)



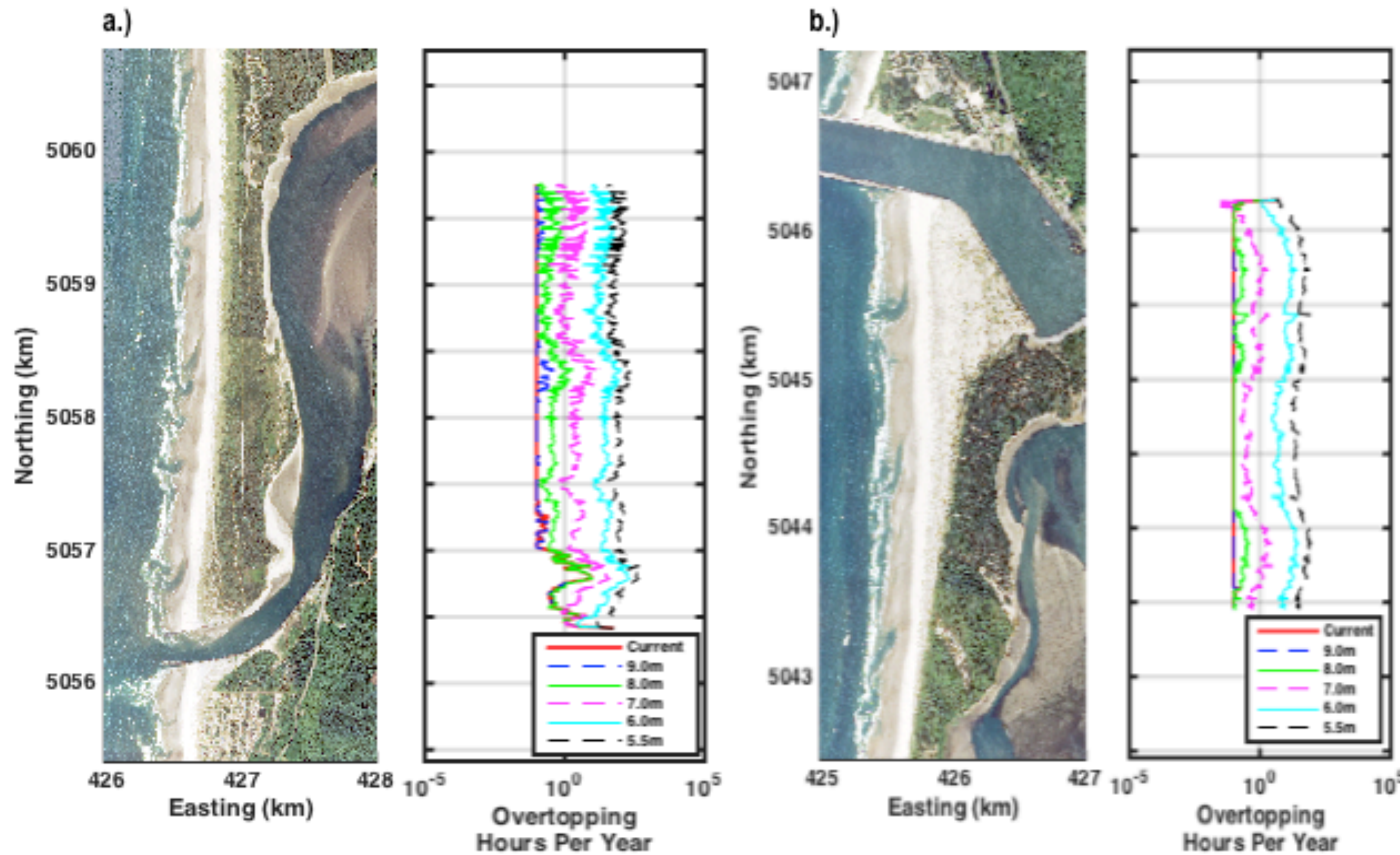
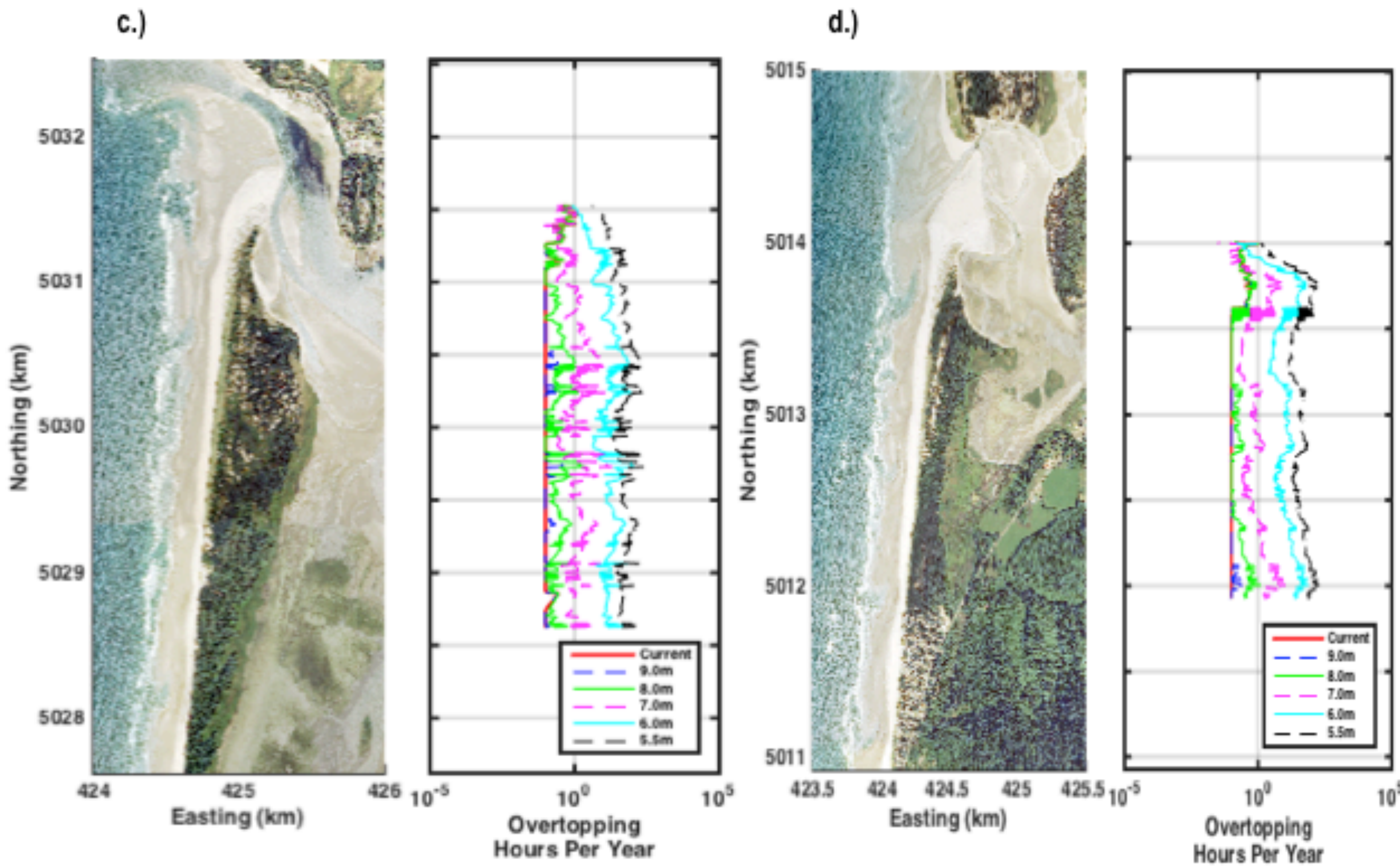


Figure 10. Overtopping hours per year calculated for alongshore profiles under current and restored scenarios at the PCH areas. The PCH areas include: (a.) Nehalem River Spit, (b.) Bayocean Spit, (c.) Netarts Spit, and (d.) Sand Lake South in Tillamook County, Oregon. Overtopping is given for present day elevations (red) and the following foredune restoration reductions to: 9.0 m (light blue), 8.0 m (pink), 7.0 m (lime green), 6.0 m (black), and 5.5 m (royal blue).

Figure 10 (Continued)



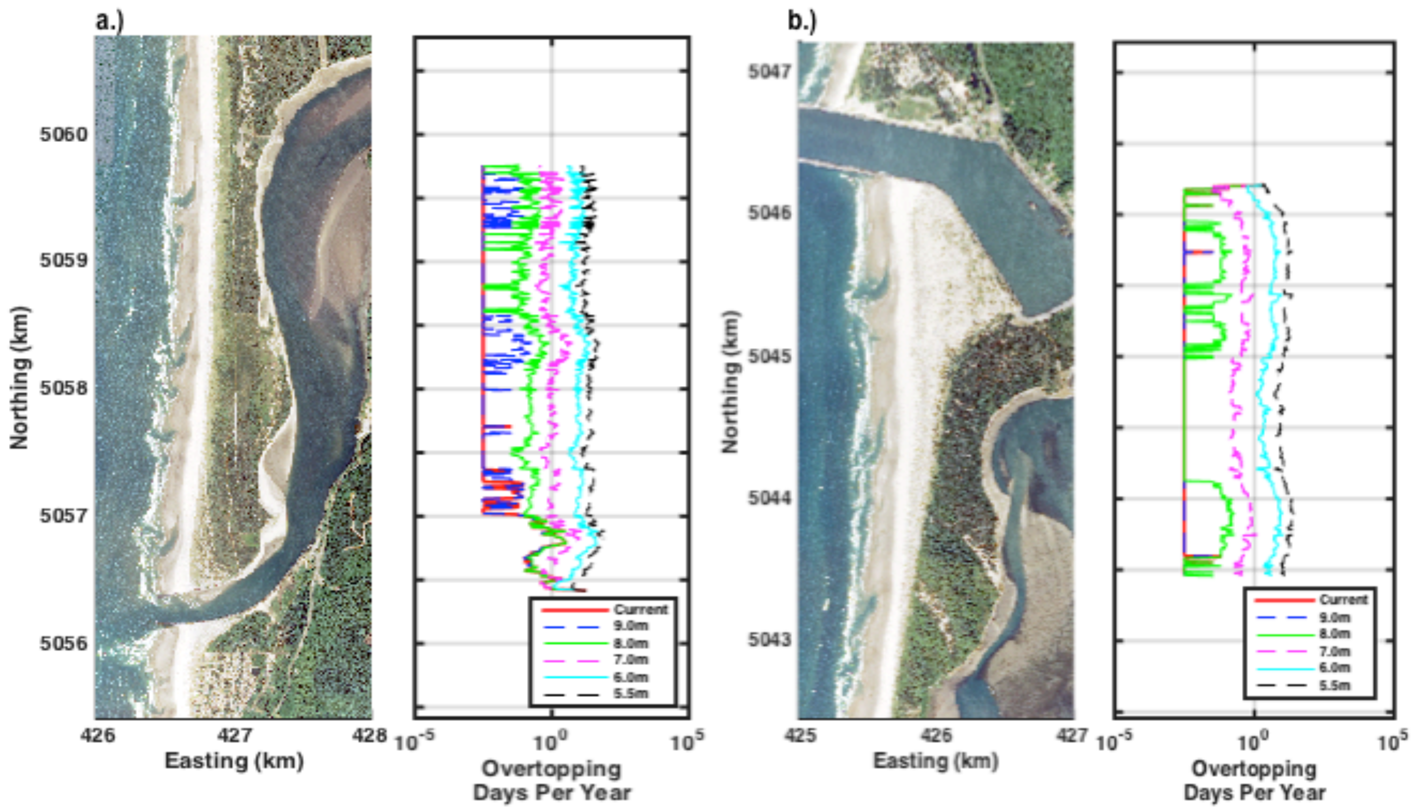
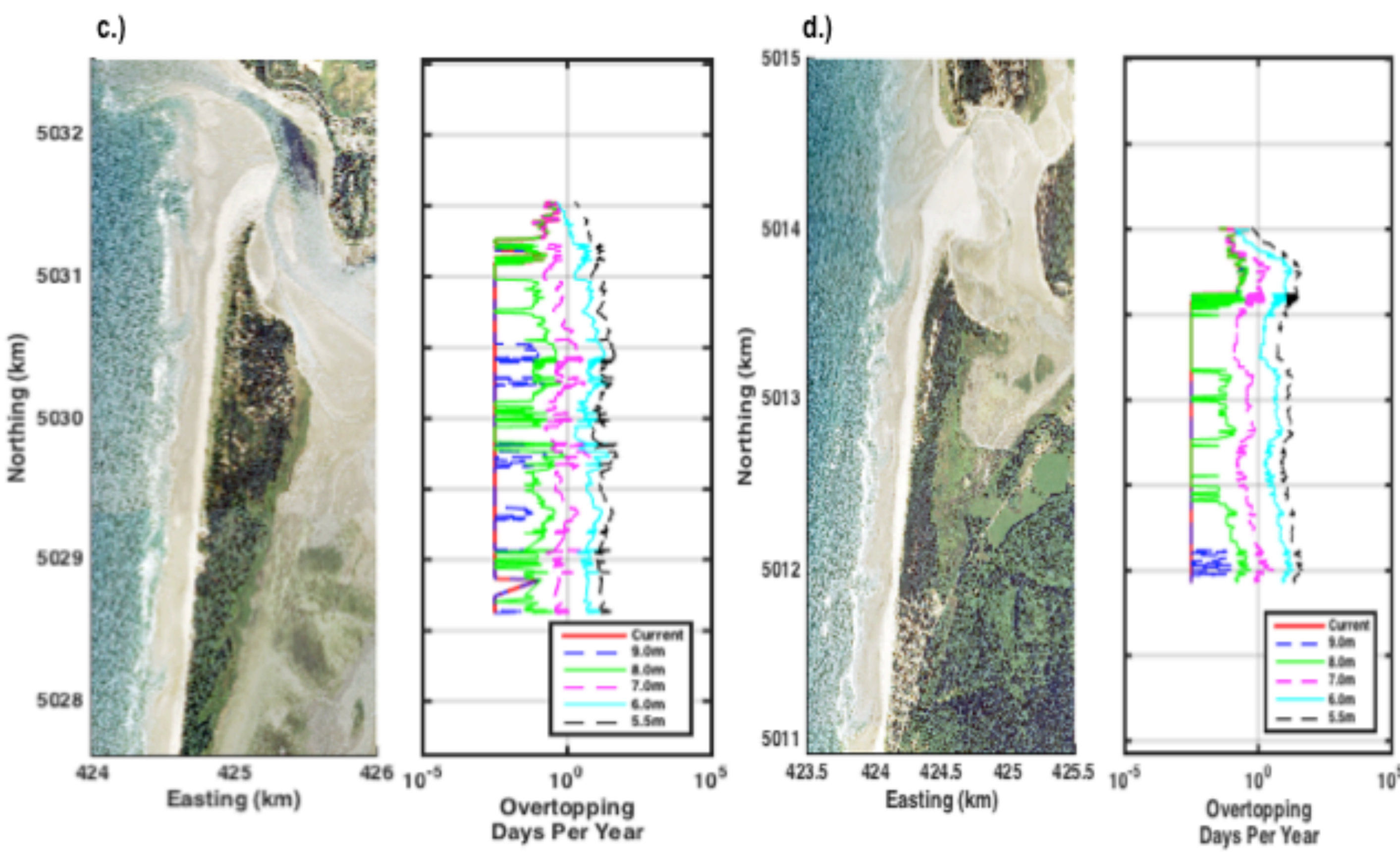


Figure 11. Overtopping days per year calculated for alongshore profiles under current and restored scenarios at the PCH areas. The PCH areas include: (a.) Nehalem River Spit, (b.) Bayocean Spit, (c.) Netarts Spit, and (d.) Sand Lake South in Tillamook County, Oregon. Overtopping is given for present day elevations (red) and the following foredune restoration reductions to: 9.0 m (light blue), 8.0 m (pink), 7.0 m (lime green), 6.0 m (black), and 5.5 m (royal blue).

Figure 11 (Continued)



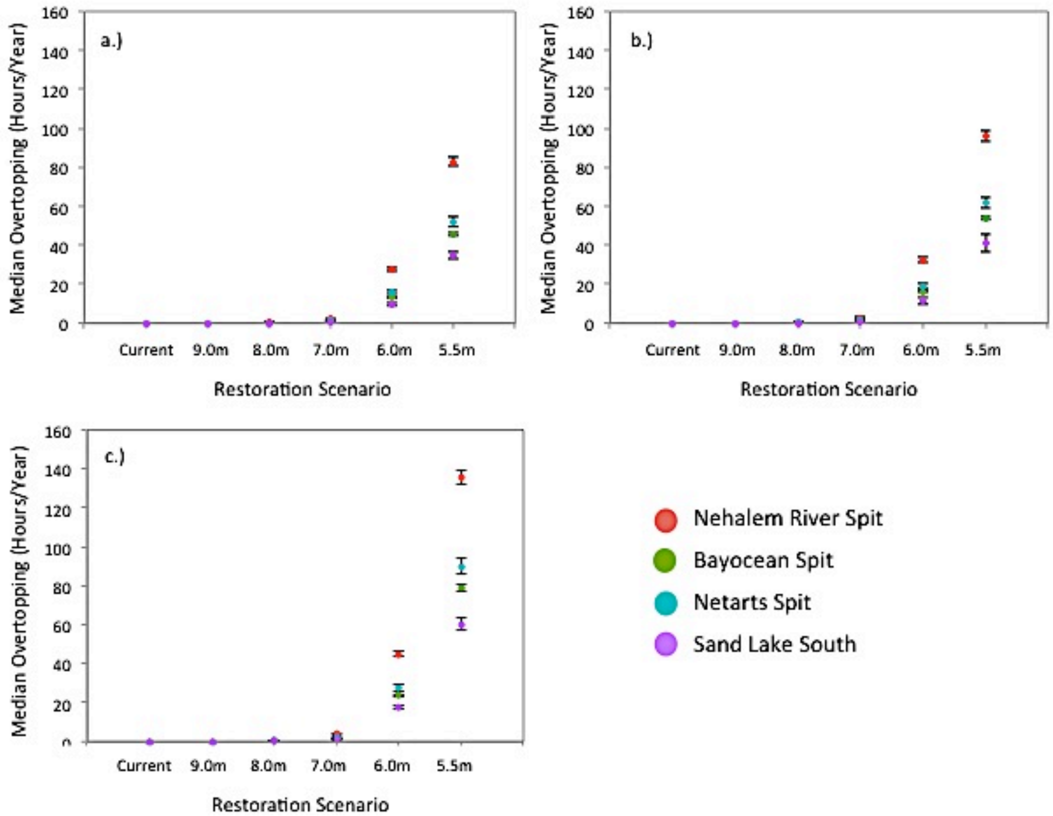


Figure 12. Median (± SE) overtopping hours per year for all proposed habitat restoration areas (pHRAs) under different restoration and sea level rise scenarios. Plots are (A.) present day sea level (SL) and (B.) medium sea level rise scenario (SLR), and (C.) high SLR scenarios for Nehalem River Spit (red), Bayocean Spit (green), Netarts Spit (Blue), and Sand Lake South (purple).

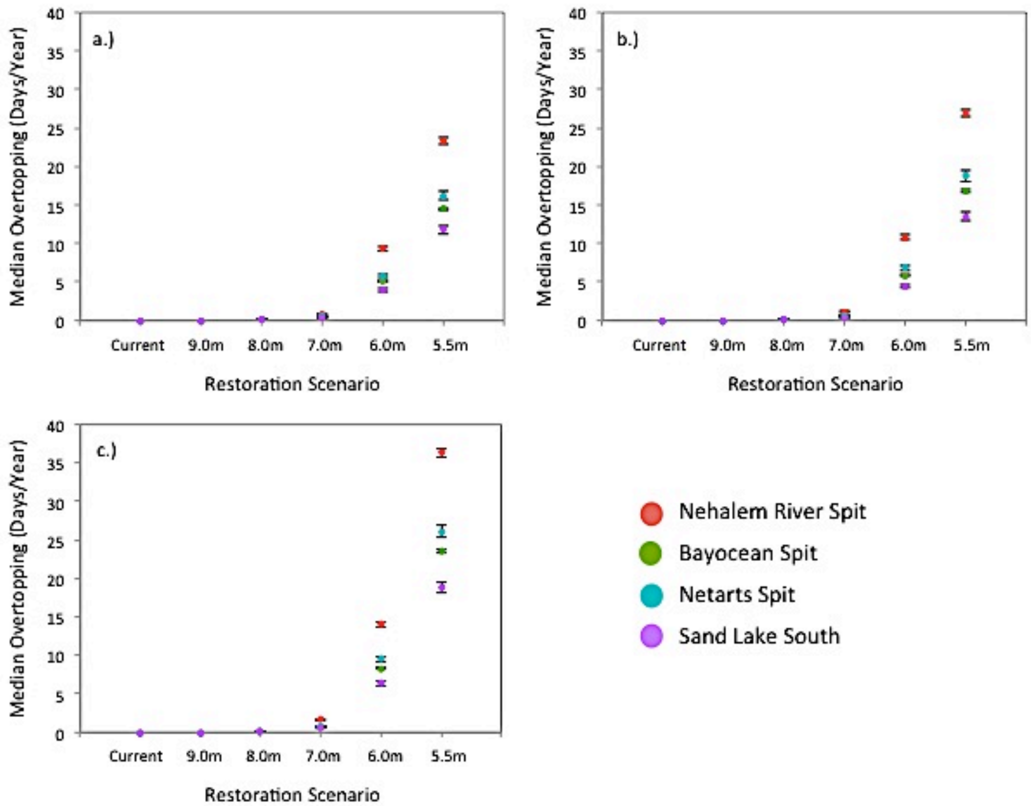


Figure 13. Median (± SE) overtopping days per year for all proposed habitat restoration areas (pHRAs) under different restoration and sea level rise scenarios. Plots are (A.) present day sea level and (B.) medium sea level rise scenario, and (C.) high sea level rise scenarios for Nehalem River Spit (red), Bayocean Spit (green), Netarts Spit (Blue), and Sand Lake South (purple).

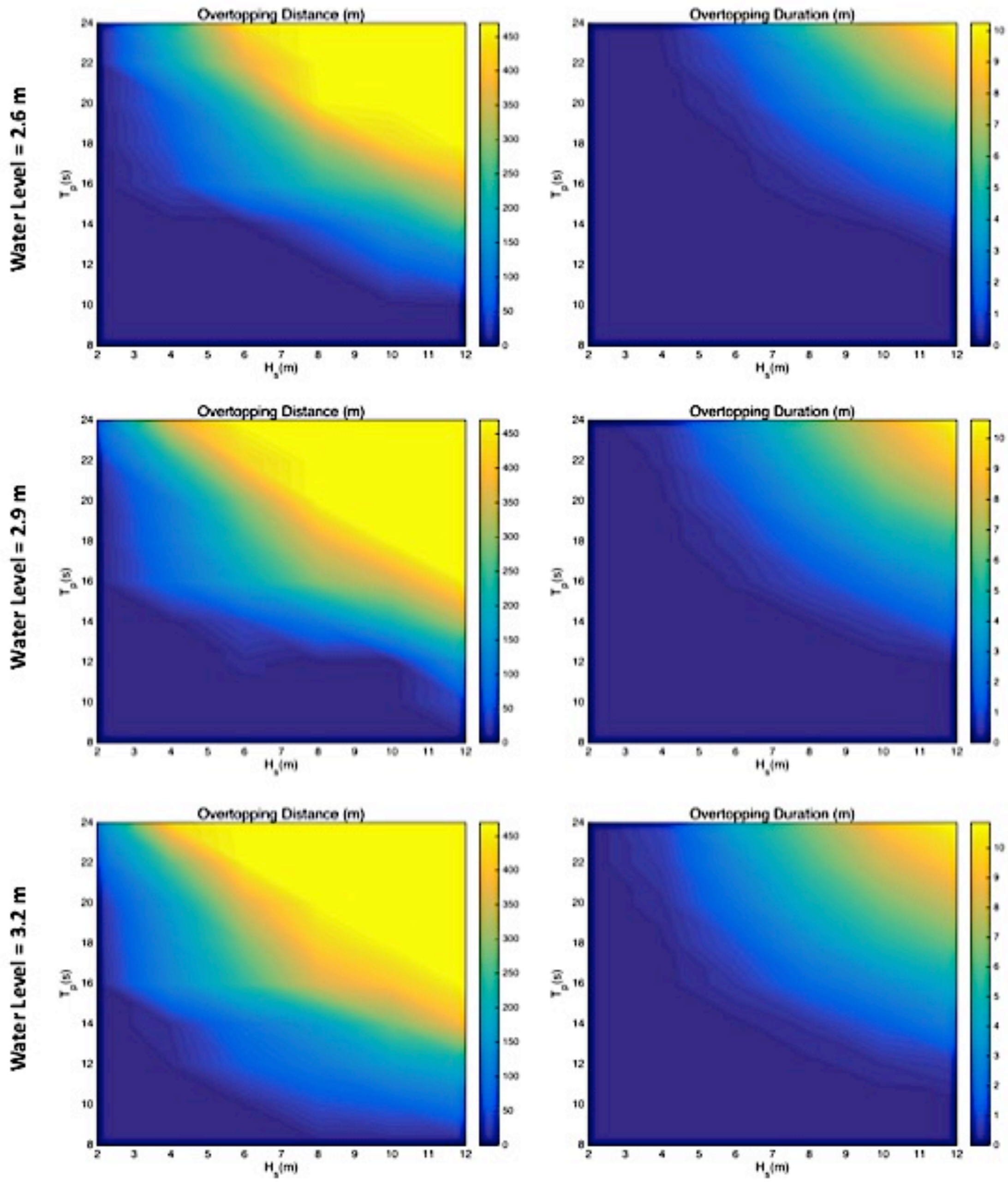


Figure 14. Example of overtopping distance (m) and duration (hours) associated with average storm water levels (2.9 m), one standard deviation below (2.6 m) and above (3.2 m) for the 5.5 m restoration scenario at Nehalem River Spit. Results are a result of the XBeach analysis where the y-axis represents the wave height (*Hs*) while the x-axis represents wave period (*Tp*).

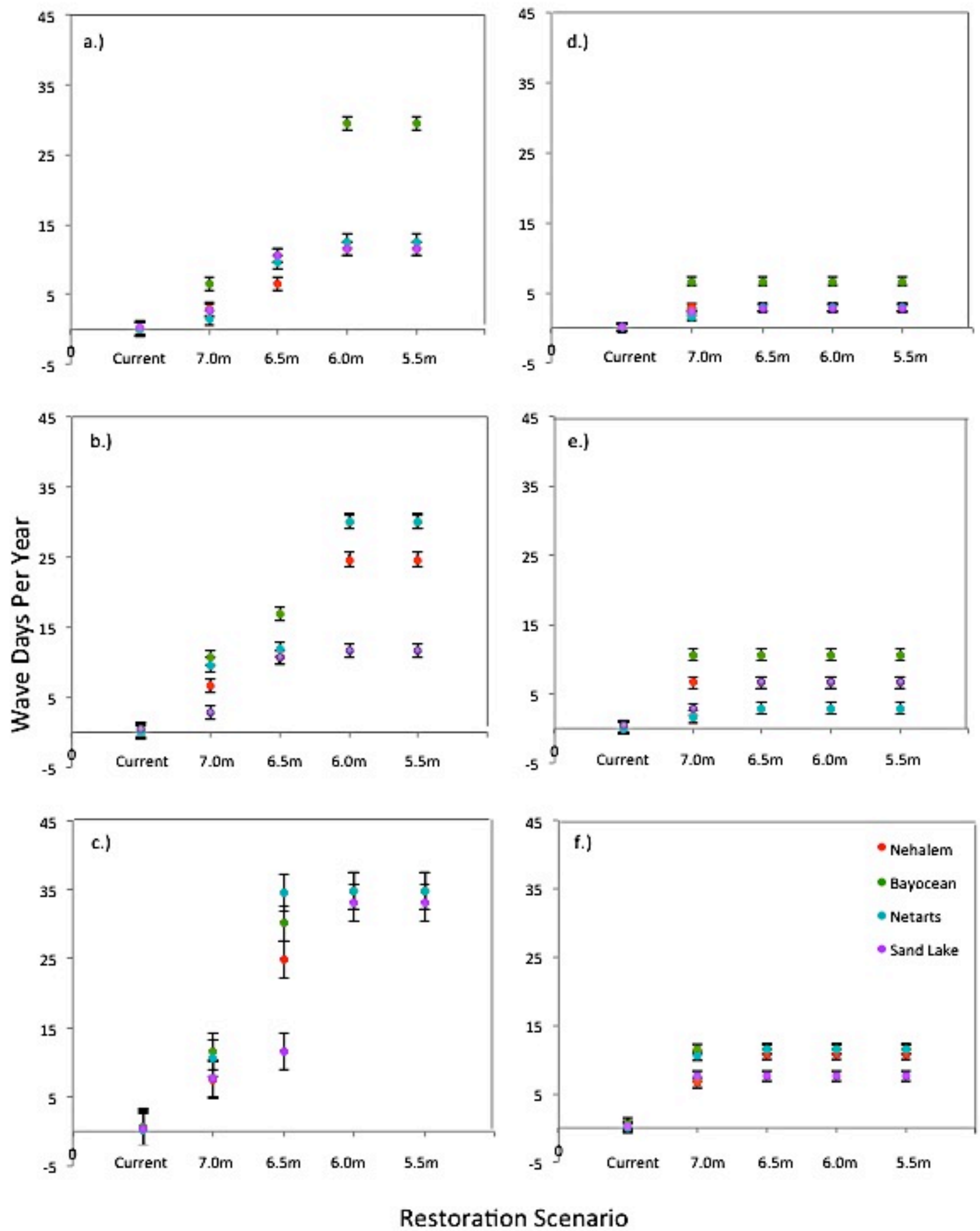


Figure 15. Overtopping (days per year) for various distance thresholds under five restoration scenarios (current, 7.0 m, 6.5 m, 6.0 m, and 5.5 m) and three extreme storm water levels (2.6 m, 2.9 m, and 3.2 m) at the four proposed critical habitat (PCH) areas: Nehalem River Spit (red), Bayocean Spit (green), Netarts Spit (Blue), and Sand Lake South (purple). Overtop distance thresholds included the number of days where water levels: exceeded 50m or greater (a-c), and reached 150 m or greater (d-f) for each extreme storm water level, 2.6 m (a and d), 2.9 m (b and e), and 3.2 m (c and f). Error bars reflect one standard error.

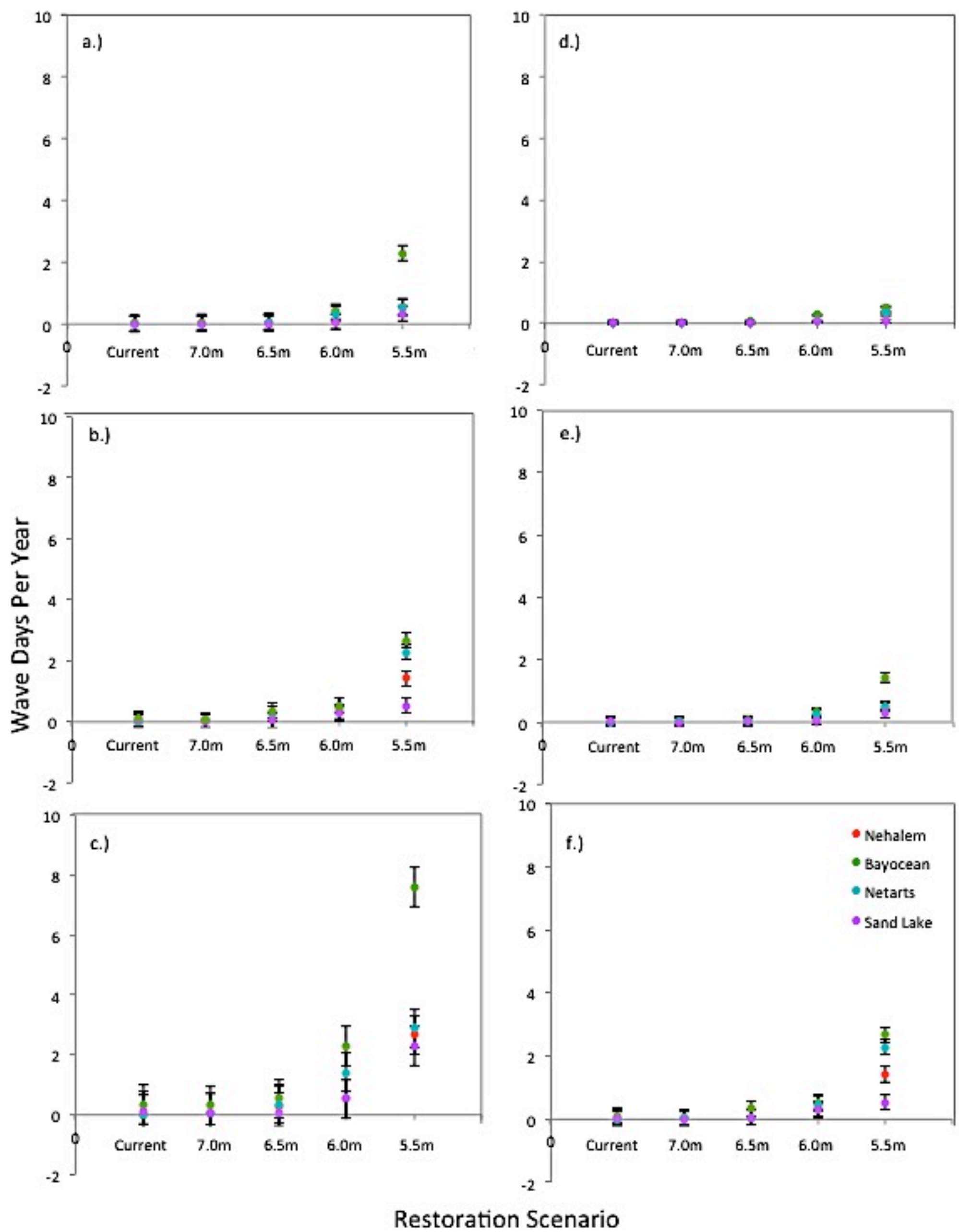


Figure 16. Overtopping (days per year) for two duration thresholds under five restoration scenarios (current, 7.0 m, 6.5 m, 6.0 m, and 5.5 m) and three extreme storm water levels (2.6 m, 2.9 m, and 3.2 m) at the four proposed critical habitat (PCH) areas: Nehalem River Spit, Bayocean Spit, Netarts Spit, and Sand Lake South. Overtop duration thresholds included the number of days where overtopping duration lasted for a maximum of 1 hour (a-c) and 2 hours or more (d-f) for each extreme storm water level, 2.6 m (a and d), 2.9 m (b and e), and 3.2 m (c and f). Error bars reflect one standard error.

Present SL	Restoration Scenario					
Site	Current	9 m	8 m	7 m	6 m	5.5 m
Nehalem						
Bayocean						
Netarts						
Sand Lake						
Medium SL	Restoration Scenario					
Site	Current	9 m	8 m	7 m	6 m	5.5 m
Nehalem						
Bayocean						
Netarts						
Sand Lake						
High SL	Restoration Scenario					
Site	Current	9 m	8 m	7 m	6 m	5.5 m
Nehalem						
Bayocean						
Netarts						
Sand Lake						

Figure 17. Summary of overtopping days per year for each foredune restoration scenario at the four proposed habitat restoration areas (pHRAs) located in the four proposed critical habitat (PCH) areas in Tillamook County. Sites in include Nehalem River Spit, Bayocean Spit, Netarts Spit, and Sand Lake Spit. Median overtopping days per year were characterized by blue (< 1 day/year), green (≥ 1 day/year), yellow (≥ 5 days/ year), and red (≥ 10 days/ year).

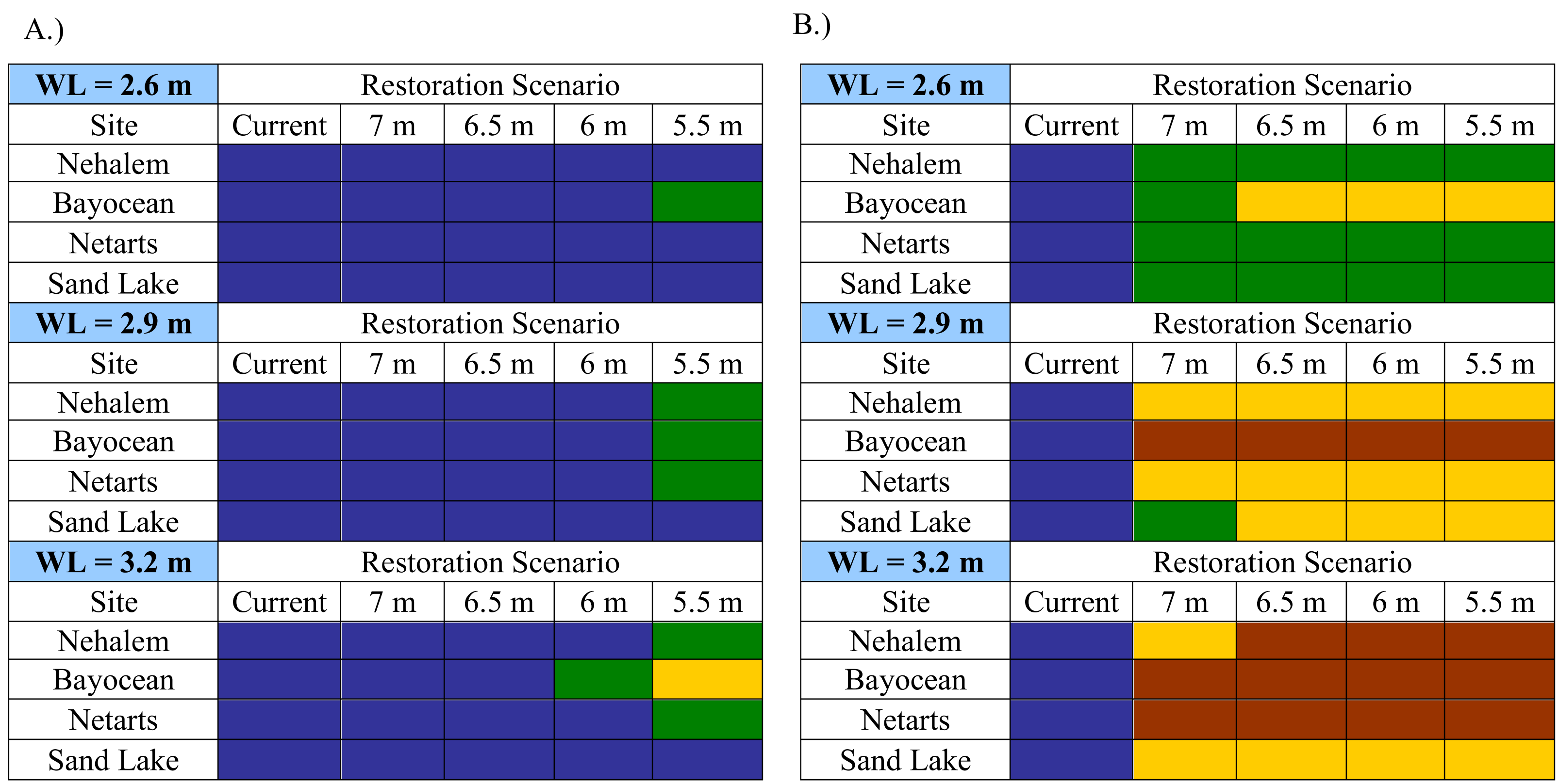


Figure 18. Summary of the overtopping days per year of flooding duration and distance during extreme storms each foredune restoration scenario and storm water level (2.6 m, 2.9 m, and 3.2 m) at the four proposed habitat restoration areas (pHRAs) located in the four proposed critical habitat (PCH) areas in Tillamook County. Sites in include Nehalem River Spit, Bayocean Spit, Netarts Spit, and Sand Lake Spit. (A.) The median number of days per year flooding during extreme storms that lasted for one hour or more; (B.) The median number days per year flooding extended to 150 m or more. Overtopping days per year were characterized by blue (< 1 day/year), green (≥ 1 day/year), yellow (≥ 5 days/ year), and red (≥ 10 days/ year).

Table 1. One-way analysis of variance (ANOVA) for the effect of proposed critical habitat (PCH) area on dune geomorphology and total water levels (TWL) at the four PCH areas in Tillamook County, Oregon: Nehalem River Spit (NRS), Bayocean Spit (BS), Netarts Spit (NS), and Sand Lake South (SLS). Dune geomorphological parameters (beach slope and foredune crest elevation) and total water levels (maximum and overall) served as the response variables and site was used as the fixed effect. Tukey HSD post hoc tests were utilized to determine the differences between sites. Levels of significance are indicated using the following: ns = no significant difference; *p < 0.05; **p < 0.01; ***p < 0.001.

Response	df	Sum of Squares	Mean of Squares	*F* (p)	Tukey HSD (site)
Beach Slope	3	0.078	0.026	243.6 (***)	NRS > NS > BS = SLS
Foredune Crest Elevation	3	823.0	274.4	82.82 (***)	NS > NRS > SLS > BS
Maximum TWL	3	197.8	65.94	250.0 (***)	NRS > NS > SLS = BS
Overall TWL	3	12.61	4.204	250.0 (***)	NRS > NS > SLS = BS

Table 2. One-way ANOVA results for the effect of proposed critical habitat (PCH) area on overtopping hours per year and overtopping days per year at current foredune elevations among the four PCH areas in Tillamook County, Oregon: Nehalem River Spit (NRS), Bayocean Spit (BS), Netarts Spit (NS), and Sand Lake South (SLS). Overtopping hours and overtopping days were the response variables and site was the fixed effect. Lsmean post hoc tests were utilized to determine the differences between sites. Levels of significance are indicated using the following: ns = no significant difference; *p < 0.05; **p < 0.01; ***p < 0.001.

Response	df	Sum of Squares	Mean of Squares	*F* (p)	Lsmean (Site)
Overtopping Hours per Year	3	54.7	18.2	40.3 (***)	NRS > SLS = NS >BS
Overtopping Days per Year	3	31.4	10.4	39.1 (***)	NRS > SLS = NS >BS

Table 3. Two-way analysis of variance (ANOVA) for restoration scenario and proposed habitat restoration area (pHRA) on total overtopping hours per year at the four proposed critical habitat (PCH) areas in Tillamook County, Oregon. The overtopping hours per year under present sea level (SL), medium sea level rise (SLR), and high SLR scenarios were the response variables while restoration scenario (1 = current dune elevation; 2 = reduction to 9.0 m; 3 = reduction to 8.0 m; 4 = reduction to 7.0 m; 5 = reduction to 6.0 m; 6 = reduction to 5.5 m) and pHRA (Nehalem River Spit (NRS); Bayocean Spit (BS); Netarts Spit (NS); and Sand Lake South (SLS)) served as the fixed effects. Lsmean post hoc tests were used to examine the differences between restoration scenarios and sites. Levels of significance are indicated using the following: ns = no significant difference; *p < 0.05; **p < 0.01; ***p < 0.001.

Response	Fixed Effects	df	Sum of Squares	Mean of Squares	*F* (p)	Lsmean (Restoration Scenario)	Lsmean (Site)
Overtopping Hours Per Year: Present SL	*Restoration Scenario*	5	4.83e+4	9.66e+3	1.97e+4 (***)	1: SLS > NRS > NS = BS 2: SLS = NRS > NS > BS	NRS: 6 > 5 > 4 > 3 > 2 > 1
	Site	3	837	279	571 (***)	3: NRS > NS > BS = SLS 4: NRS > NS > BS = SLS	BS: 6 > 5 > 4 > 3 > 2 = 1 NS: 6 > 5 > 4 > 3 > 2 > 1
	*Restoration Scenario*Site*	15	397	54.1	54.1 (***)	5: NRS > NS = BS > SLS 6: NRS > NS = BS > SLS	SLS: 6 > 5 > 4 > 3 > 2 = 1
Overtopping Hours Per Year: Medium SLR	*Restoration Scenario*	5	5.03e+4	1.01e+4	2.01e+4 (***)	1: SLS > NRS > NS = BS 2: SLS = NRS > NS > BS	NRS: 6 > 5 > 4 > 3 > 2 > 1
	Site	3	836	279	556 (***)	3: NRS > NS > BS > SLS 4: NRS > NS > BS = SLS	BS: 6 > 5 > 4 > 3 > 2 = 1 NS: 6 > 5 > 4 > 3 > 2 > 1
	*Restoration Scenario*Site*	15	387	26.0	51.5 (***)	5: NRS > NS = BS > SLS 6: NRS > NS = BS > SLS	SLS: 6 > 5 > 4 > 3 > 2 = 1
Overtopping Hours Per Year: High SLR	*Restoration Scenario*	5	5.51e+4	1.10e+4	2.08+4 (***)	1: SLS > NRS > NS = BS 2: NRS > SLS > NS > BS	NRS: 6 > 5 > 4 > 3 > 2 > 1
	Site	3	828	276	522 (***)	3: NRS > NS = BS > SLS 4: NRS > NS > BS = SLS	BS: 6 > 5 > 4 > 3 > 2 = 1 NS: 6 > 5 > 4 > 3 > 2 > 1
	*Restoration Scenario*Site*	15	360	24.0	45.4 (***)	5: NRS > NS = BS > SLS 6: NRS > NS = BS > SLS	SLS: 6 > 5 > 4 > 3 > 2 = 1

Table 4. Two-way analysis of variance (ANOVA) for restoration scenario and proposed habitat restoration area (pHRA) on total overtopping days per year at the four proposed critical habitat (PCH) areas in Tillamook County, Oregon. The overtopping days per year under present sea level (SL), medium sea level rise (SLR), and high SLR scenarios were the response variables while restoration scenario (1 = current dune elevation; 2 = reduction to 9.0 m; 3 = reduction to 8.0 m; 4 = reduction to 7.0 m; 5 = reduction to 6.0 m; 6 = reduction to 5.5 m) and pHRA (Nehalem River Spit (NRS); Bayocean Spit (BS); Netarts Spit (NS); and Sand Lake South (SLS)) served as the fixed effects. Lsmean post hoc tests were used to examine the differences between restoration scenarios and sites. Levels of significance are indicated using the following: ns = no significant difference; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

Response	Fixed Effects	df	Sum of Squares	Mean of Squares	*F* (p)	Lsmean (Restoration Scenario)	Lsmean (Site)
Overtopping Days Per Year: Present SL	*Restoration Scenario*	5	3.20e+4	6.39e+3	2.10e+4 (***)	1: SLS = NRS > NS = BS 2: SLS = NRS > NS = BS	NRS: 6 > 5 > 4 > 3 > 2 = 1
	Site	3	519	173	567 (***)	3: NRS > NS > SLS = BS 4: NRS > NS > BS = SLS	BS: 6 > 5 > 4 > 3 > 2 = 1 NS: 6 > 5 > 4 > 3 > 2 = 1
	*Restoration Scenario*Site*	15	254	17.0	55.8 (***)	5: NRS > NS = BS > SLS 6: NRS > NS > BS > SLS	SLS: 6 > 5 > 4 > 3 > 2 = 1
Overtopping Days Per Year: Medium SLR	*Restoration Scenario*	5	3.34e+4	6.69e+3	2.13e+4 (***)	1: SLS = NRS > NS = BS 2: SLS = NRS > NS = BS	NRS: 6 > 5 > 4 > 3 > 2 = 1
	Site	3	517	172	551 (***)	3: NRS > NS > SLS = BS 4: NRS > NS > BS = SLS	BS: 6 > 5 > 4 > 3 > 2 = 1 NS: 6 > 5 > 4 > 3 > 2 = 1
	*Restoration Scenario*Site*	15	249	17.0	53.0 (***)	5: NRS > NS > BS > SLS 6: NRS > NS > BS > SLS	SLS: 6 > 5 > 4 > 3 > 2 = 1
Overtopping Days Per Year: High SLR	*Restoration Scenario*	5	3.69e+4	7.38e+3	2.25+4 (***)	1: SLS = NRS > NS = BS 2: NRS = SLS > NS > BS	NRS: 6 > 5 > 4 > 3 > 2 > 1
	Site	3	522	174	531 (***)	3: NRS > NS > SLS = BS 4: NRS > NS > BS = SLS	BS: 6 > 5 > 4 > 3 > 2 = 1 NS: 6 > 5 > 4 > 3 > 2 > 1
	*Restoration Scenario*Site*	15	234	16.0	47.6 (***)	5: NRS > NS > BS > SLS 6: NRS > NS > BS > SLS	SLS: 6 > 5 > 4 > 3 > 2 = 1

Table 5a. Summary of average and maximum overtopping distance (m) projected for the average storm water level for current dune height and each foredune restoration scenario (reduction to 7.0 m, reduction to 6.5 m, reduction to 6.0 m, and reduction to 5.5 m) at the four proposed critical habitat (PCH) areas: Nehalem River Spit, Bayocean Spit, Netarts Spit, and Sand Lake South.

	Nehalem River Spit		Bayocean Spit		Netarts Spit		Sand Lake South	
Restoration Scenario	Avg. (SE)	Max.	Avg. (SE)	Max.	Avg. (SE)	Max.	Avg. (SE)	Max.
Current Elevation	23.3 (±3.9)	46.0	139 (±31.6)	371	88.2 (±13.7)	137	44.8 (±8.6)	80.0
7.0 m Reduction	261 (±35.5)	464	302 (±39.2)	592	290 (±42.7)	628	281.7 (±40.5)	572
6.5 m Reduction	271 (±33.1)	464	308 (±39.2)	597	313 (±41.7)	631	285.9 (±39.8)	575
6.0 m Reduction	278 (±30.5)	467	336 (±37.0)	612	309 (±40.2)	635	322.0 (±38.7)	575
5.5 m Reduction	289 (±29.7)	470	342 (±37.0)	623	336 (±38.0)	640	304.6 (±37.1)	577

Table 5b. Summary of average and maximum overtopping duration (hours per storm event) projected for the average storm water level for the current dune height and each foredune restoration scenario (reduction to 7.0 m, reduction to 6.5 m, reduction to 6.0 m, and reduction to 5.5 m) at the four proposed critical habitat (PCH) areas: Nehalem River Spit, Bayocean Spit, Netarts Spit, and Sand Lake South.

Restoration Scenario	Nehalem River Spit		Bayocean Spit		Netarts Spit		Sand Lake South	
	Avg. (SE)	Max.	Avg. (SE)	Max.	Avg. (SE)	Max.	Avg. (SE)	Max.
Current Elevation	0.015 (±0.006)	7.553	0.258 (±0.095)	9.556	0.070 (±0.037)	6.637	0.088 (±0.036)	9.332
7.0 m Reduction	0.400 (±0.135)	6.713	0.503 (±0.148)	6.887	0.506 (±0.164)	6.867	0.359 (±0.130)	5.480
6.5 m Reduction	0.533 (±0.157)	7.916	0.638 (±0.168)	8.086	0.650 (±0.189)	7.941	0.523 (0.164)	6.897
6.0 m Reduction	0.662 (±0.171)	9.209	0.860 (±0.199)	9.194	0.853 (±0.219)	9.227	0.745 (0.200)	8.305
5.5 m Reduction	0.810 (± 0.18)	10.61	1.11 (±0.227)	10.732	1.033 (±0.237)	10.45	0.939 (0.225)	9.654

Table 6a. Two-way analysis of variance (ANOVA) for restoration scenario and site on wave days per year a distance threshold of 50 m or more was reached during extreme storm scenarios at the four proposed critical habitat (PCH) areas in Tillamook County, Oregon. Total wave days per year under three difference extreme storm water levels (2.6 m, 2.9 m, and 3.2 m) were the response variables while restoration scenario (1 = current dune elevation; 2 = reduction to 9.0 m; 3 = reduction to 8.0 m; 4 = reduction to 7.0 m; 5 = reduction to 6.0 m; 6 = reduction to 5.5 m) and site (Nehalem River Spit (NRS); Bayocean Spit (BS); Netarts Spit (NS); and Sand Lake South (SLS)) served as the fixed effects. Lsmean post hoc tests were used to examine the differences between restoration scenarios and sites. Levels of significance are indicated using the following: ns = no significant difference; *p < 0.05; **p < 0.01; ***p < 0.001.

Response	Fixed Effects	df	Sum of Squares	Mean of Squares	*F* (p)	Lsmean (Restoration Scenario)[1]	Lsmean (Site)[1]
Wave Days per Year: 2.6 m	*Restoration Scenario*	4	848	212	11.1 (***)	1: BS > NS, NRS, SLS 2: BS > NS, NRS, SLS 3: BS > NS, NRS, SLS 4: BS > NS, NRS, SLS 5: BS > NS, NRS, SLS	NRS, NS and SLS: 1 < 4, 5; 2 < 4, 5; 4 > 2, 1; 5 > 2, 1 BS: 1 < 3, 4, 5; 2 < 4, 5; 4 > 2, 1; 5 > 2, 1
	Site	3	284	95.5	4.96 (*)		
Wave Days per Year: 2.9 m	*Restoration Scenario*	4	1756	439.0	25.10 (***)	1: BS > SLS; NS > SLS 2: BS > SLS; NS > SLS 3: BS > SLS; NS > SLS 4: BS > SLS; NS > SLS 5: BS > SLS; NS > SLS	NRS, BS, NS, and SLS: 1 < 3, 4, 5 2 < 4, 5 3 > 1 5 > 1, 2 4 > 1, 2
	Site	3	310.1	103.4	5.91 (*)		
Wave Days per Year: 3.2 m	*Restoration Scenario*	4	3739	934.9	53.56 (***)	1: BS = NS = NRS = SLS 2: BS = NS = NRS = SLS 3: BS = NS = NRS = SLS 4: BS = NS = NRS = SLS 5: BS = NS = NRS = SLS	NRS, BS, NR, and SLS: 1 < 3, 4, 5 2 < 3, 4, 5 3 > 1, 2 4 > 1, 2 5 > 1, 2
	Site	3	103	34.3	1.965 (ns)		

[1] Only statistically significant relationships from the lsmeans post hoc are displayed.

Table 6b. Two-way analysis of variance (ANOVA) for restoration scenario and site on wave days per year a distance threshold of 150 m or more was reached during extreme storm scenarios at the four proposed critical habitat (PCH) areas in Tillamook County, Oregon. Total wave days per year under three difference extreme storm water levels (2.6 m, 2.9 m, and 3.2 m) were the response variables while restoration scenario (1 = current dune elevation; 2 = reduction to 9.0 m; 3 = reduction to 8.0 m; 4 = reduction to 7.0 m; 5 = reduction to 6.0 m; 6 = reduction to 5.5 m) and site (Nehalem River Spit (NRS); Bayocean Spit (BS); Netarts Spit (NS); and Sand Lake South (SLS)) served as the fixed effects. Lsmean post hoc tests were used to examine the differences between restoration scenarios and sites. Levels of significance are indicated using the following: ns = no significant difference; $*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

Response	Fixed Effects	df	Sum of Squares	Mean of Squares	*F* (p)	Lsmean (Restoration Scenario)[1]	Lsmean (Site)[1]
Wave Days per Year: 2.6 m	*Restoration Scenario*	4	42.53	10.63	13.31 (***)	1: BS > SLS, NS, NRS 2: BS > SLS, NS, NRS 3: BS > SLS, NS, NRS 4: BS > SLS, NS, NRS 5: BS > SLS, NS, NRS	NRS, BS, NS, and SLS: 1 < 2, 3, 4, 5
	Site	3	36.43	12.14	15.21 (***)		
Wave Days per Year: 2.9 m	*Restoration Scenario*	4	203.2	50.79	28.03 (***)	1: BS > NRS, SLS; NS > SLS 2: BS > NRS, SLS; NS > SLS 3: BS > NRS, SLS; NS > SLS 4: BS > NRS, SLS; NS > SLS 5: BS > NRS, SLS; NS > SLS	NRS, BS, NS, and SLS: 1 < 2, 3, 4, 5
	Site	3	53.78	17.93	9.89 (**)		
Wave Days per Year: 3.2 m	*Restoration Scenario*	4	42.53	10.63	13.31 (***)	1: BS > SLS, NRS 2: BS > SLS, NRS 3: BS > SLS, NRS 4: BS > SLS, NRS 5: BS > SLS, NRS	NRS, BS, NS, and SLS: 1 < 2, 3, 4, 5
	Site	3	36.43	12.14	15.21 (***)		

[1] Only statistically significant relationships from the lsmeans post hoc are displayed.

Table 7a. Two-way analysis of variance (ANOVA) for restoration scenario and site on wave days per year a duration threshold of 1 hour or more was reached during extreme storm scenarios at the four proposed critical habitat (PCH) areas in Tillamook County, Oregon. Total wave days per year under three difference extreme storm water levels (2.6 m, 2.9 m, and 3.2 m) were the response variables while restoration scenario (1 = current dune elevation; 2 = reduction to 9.0 m; 3 = reduction to 8.0 m; 4 = reduction to 7.0 m; 5 = reduction to 6.0 m; 6 = reduction to 5.5 m) and site (Nehalem River Spit (NRS); Bayocean Spit (BS); Netarts Spit (NS); and Sand Lake South (SLS)) served as the fixed effects. Lsmean post hoc tests were used to examine the differences between restoration scenarios and sites. Levels of significance are indicated using the following: ns = no significant difference; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Response	Fixed Effects	df	Sum of Squares	Mean of Squares	F (p)	Lsmean (Restoration Scenario)	Lsmean (Site)
Wave Days per Year: 2.6 m	*Restoration Scenario*	4	2.423	0.605	3.852 (ns)	1: BS = NS = NRS = SLS 2: BS = NS = NRS = SLS 3: BS = NS = NRS = SLS 4: BS = NS = NRS = SLS 5: BS = NS = NRS = SLS	NRS: 5 = 4 = 3 = 2 = 1 BS: 5 = 4 = 3 = 2 = 1 NR: 5 = 4 = 3 = 2 = 1 SLS: 5 = 4 = 3 = 2 = 1
	Site	3	0.713	0.238	1.511 (ns)		
Wave Days per Year: 2.9 m	*Restoration Scenario*	4	8.109	2.027	12.88 (***)	1: BS = NS = NRS = SLS 2: BS = NS = NRS = SLS 3: BS = NS = NRS = SLS 4: BS = NS = NRS = SLS 5: BS = NS = NRS = SLS	NRS, BS, NR and SLS[1]: 5 > 4, 3, 2, 1
	Site	3	0.955	0.319	2.023 (ns)		
Wave Days per Year: 3.2 m	*Restoration Scenario*	4	40.54	10.13	9.465 (**)	1: BS = NS = NRS = SLS 2: BS = NS = NRS = SLS 3: BS = NS = NRS = SLS 4: BS = NS = NRS = SLS 5: BS = NS = NRS = SLS	NRS, BS, NR and SLS[1]: 5 > 4, 3, 2, 1
	Site	3	8.28	2.76	2.577 (ns)		

[1] Only statistically significant relationships from the lsmeans post hoc are displayed.

Table 7b. Two-way analysis of variance (ANOVA) for restoration scenario site on wave days per year a duration threshold of 2 hours or more was reached during extreme storm scenarios at the four proposed critical habitat (PCH) areas in Tillamook County, Oregon. Total wave days per year under three difference extreme storm water levels (2.6 m, 2.9 m, and 3.2 m) were the response variables while restoration scenario (1 = current dune elevation; 2 = reduction to 9.0 m; 3 = reduction to 8.0 m; 4 = reduction to 7.0 m; 5 = reduction to 6.0 m; 6 = reduction to 5.5 m) and site (Nehalem River Spit (NRS); Bayocean Spit (BS); Netarts Spit (NS); and Sand Lake South (SLS)) served as the fixed effects. Lsmean post hoc tests were used to examine the differences between restoration scenarios and sites. Levels of significance are indicated using the following: ns = no significant difference; *p < 0.05; **p < 0.01; ***p < 0.001.

Response	Fixed Effects	df	Sum of Squares	Mean of Squares	*F* (p)	Lsmean (Restoration Scenario)	Lsmean (Site)[1]
Wave Days per Year: 2.6 m	*Restoration Scenario*	4	0.255	0.064	8.511 (**)	1: BS = NS = NRS = SLS 2: BS = NS = NRS = SLS 3: BS = NS = NRS = SLS 4: BS = NS = NRS = SLS 5: BS = NS = NRS = SLS	NRS, BS, NS, and SLS: 5 > 3, 2, 1
	Site	3	0.062	0.021	2.768 (ns)		
Wave Days per Year: 2.9 m	*Restoration Scenario*	4	1.253	0.313	6.689 (**)	1: BS = NS = NRS = SLS 2: BS = NS = NRS = SLS 3: BS = NS = NRS = SLS 4: BS = NS = NRS = SLS 5: BS = NS = NRS = SLS	NRS, BS, NS, and SLS: 5 > 3, 2, 1
	Site	3	0.280	0.093	1.989 (ns)		
Wave Days per Year: 3.2 m	*Restoration Scenario*	4	8.312	2.078	12.87 (***)	1: BS = NS = NRS = SLS 2: BS = NS = NRS = SLS 3: BS = NS = NRS = SLS 4: BS = NS = NRS = SLS 5: BS = NS = NRS = SLS	NRS, BS, NS, and SLS: 5 > 4, 3, 2, 1
	Site	3	0.888	0.296	1.833 (ns)		

[1] Only statistically significant relationships from the lsmeans post hoc are displayed.

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APPENDICES

Appendix A. Site Descriptions for Proposed Critical Habitat (PCH) Areas

Table A1. Proposed critical habitat locations for Western snowy plover in Tillamook County, Oregon (listed north to south).

Critical Habitat Location	Total (acres)	Federal Land (acres)	State Land (acres)	Other Land (acres)	Historical Breeding Site (Y/N)	Breeding at Time of 1993 Listing (Y/N)	Manager/ Owner
Nehalem River Spit	299	0	299	0	Y	N	OPRD
Bayocean Spit	367	279	0	88	Y	Y	ACOE
Netarts Spit	541	0	541	0	Y	N	OPRD
Sand Lake South	200	0	0	200	Y	N	USFWS
Totals	1407	279	840	288	Y	-	-

OPRD (Oregon Parks and Recreation Department; ACOE (Army Corps of Engineers); USFWS (U.S. Fish and Wildlife Service)

Appendix B. Site Locations for Proposed Critical Habitat (PCH) Areas

Table B1. Northing and Easting coordinates (Universal Transverse Mercator (UTM)) for the northern and southern

	Proposed Critical Habitat Sites				Proposed Habitat Area			
	Northern Boundary		Southern Boundary		Northern Boundary		Southern Boundary	
Site	Northing (m)	Easting (m)	Northing (m)	Easting (m)	Northing (m)	Easting (m)	Northing (m)	Easting (m)
Nehalem River Spit	5059758.3	426863.3	5056414.8	426667.0	5059758.8	426863.3	5056684.2	426685.2
Bayocean Spit	5046209.0	425897.6	5043456.3	425777.6	5046062.3	425849.1	5045064.2	425839.9
Netarts Spit	5031527.8	425188.7	5028620.7	424709.4	5031264.6	424990.6	5030262.7	424862.6
Sand Lake South	5014002.8	424567.5	5011928.8	424183.1	5014005.6	424587.7	5012746.5	424271.3

Appendix C. Sand Grain Size Table

Table C1. Sand Grain Size (D50 and D90) for Netarts Spit, Nehalem River Spit, and Sand Lake South in Tillamook County, Oregon, used for XBeach model parameterization. Sand samples were collected during the summer of 2012 (R. Biel, S. Hacker, and P. Ruggiero, unpublished data).

Location (Transect)	D50 (ϕ)	D90 (ϕ)
Netarts (CL01)	1.80	2.375
Netarts (CL02)	2.06	2.47
Netarts (CL03)	2.20	2.47
Netarts Average	**2.02**	**2.44**
Nehalem (NB03)	1.95	2.45
Nehalem (NB04)	2.17	2.50
Nehalem Average	**2.06**	**2.475**
Sand Lake (SL01)	1.75	2.15
Sand Lake (SL02)	1.83	2.375
Sand Lake (SL03)	1.79	2.20
Sand Lake Average	**1.79**	**2.24**