Stinson Beach Integrated Flood Study

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1.0 - Introduction

This study evaluates the individual and combined effects of riverine, coastal, and groundwater flooding under existing and future sea level rise at the Golden Gate National Recreation Area's (GGNRA) Stinson Beach property (hereafter referred to as the GGNRA). This effort is intended to support development of a Stinson Beach Vulnerability Assessment to identify the most vulnerable facilities on site and to support site planning and adaptation. The GGNRA property is managed by the National Park Service (NPS) and consists of three parking lots, a restaurant concession, bathrooms, and other associated infrastructure. It is located near the town of Stinson Beach and lies between Easkoot Creek to the southeast and the Pacific Ocean to the northwest (Figure 1). Within the GGNRA and the community of Stinson Beach, riverine flooding from Easkoot Creek is a well-documented issue. The Federal Emergency Management Agency (FEMA) has conducted a flood hazard assessment for Easkoot Creek (FEMA, 2017) and OEI has previously conducted an alternatives analyses aimed at reducing flooding severity and frequency (OEI, 2013). Several other studies assessing flooding from Easkoot Creek, including those by Michael Love and Associates in 2009 and William Spangle and Associates in 1984 have also been conducted.

Currently, Easkoot Creek floods the GGNRA beginning at approximately the 5-year recurrence interval flood when the Marin County sediment detention basin is maintained to design specifications. The majority of overbank flows initiate at the sediment basin across from the Parkside Café, before flowing through the north parking lot and discharging to Bolinas Bay through a breach in the dunes. There is minor overbank flooding (left bank) just above the car bridge near the bus stop and in the north parking lot where the channel has aggraded. Park staff also report issues with shallow groundwater tables affecting buried infrastructure. Prior studies recommended managing flooding at the GGNRA by bypassing overbank flows originating across from the Parkside Café to the Pacific Ocean. Marin County constructed a sediment basin near this location in 2013 to help manage sediment and reduce aggradation of Easkoot Creek and associated flood impacts. The NPS is working with the Federal Highway Administration to design parking lot repairs planned for 2025. Preliminary designs include a bypass channel to capture high flows from Easkoot Creek flooding, though the final location of the bypass channel has not yet been determined.

The potential for coastal flooding from storm surge and sea level rise in the Stinson Beach area is well documented by the U.S. Geological Survey's (USGS) Coastal Storm Modeling System (CoSMoS). Groundwater emergence has also been studied at the statewide scale by the University of Arkansas (Befus et al., 2020). Results from both of these studies have been compiled through the Our Coast Our Future (OCOF) project, however these prior studies do not account for the role of riverine flooding of smaller drainages such as Easkoot Creek. Additionally, groundwater modeling conducted by Befus et al. (2020) did not account for local conditions such as streambed recharge from Easkoot Creek into the alluvial fan near the center of the GGNRA.

Figure 1: Site location and infrastructure overview map.

This study integrates riverine flooding impacts and examines local groundwater data to improve predictions of combined coastal, riverine, and groundwater flooding at the GGNRA. Details about coastal flooding were obtained directly from the CoSMoS model. Effects of riverine flooding were determined using a modified version of a hydraulic model of Easkoot Creek originally developed for the County of Marin Flood Control and Water Conservation District (OEI, 2013; OEI et al., 2013). This model was used to simulate a variety of discharges using coastal boundary conditions from the CoSMoS model. Separately, increases in the groundwater table predicted by Befus et al. (2020) were re-evaluated using observed water table elevations. Results from these analyses were then combined to create an estimate of flood depth, frequency, and duration from all three sources for a wide range of sea level rise scenarios. These scenarios were selected to be compatible with analyses conducted under County of Marin's CSMART program conducted for the nearby community of Stinson Beach. Results were compiled and used to identify specific infrastructure that will become vulnerable under each scenario to be used as part of a Stinson Beach Vulnerability Assessment and as a guide for future park development.

2.0 - Site Description & Characterization

The GGNRA Stinson Beach property is located on the outer coast of Marin County, immediately adjacent to the community of Stinson Beach. It is centered on an alluvial fan emanating from Mount Tamalpais and spans ~3,500 feet of shorefront. Easkoot Creek flows down this alluvial fan before turning sharply to the north at the park boundary and flowing to Bolinas Lagoon. Bolinas Lagoon is separated from Bolinas Bay by Stinson Spit which is immediately adjacent to the GGNRA. Although the GGNRA is the primary focus of this analysis, flooding at the GGNRA is influenced by hydraulic conditions in downstream portions of Easkoot Creek and in Bolinas Lagoon, therefore the study area has been extended to include these relevant areas.

Development at the GGNRA is centered around three parking lots. Within this report, these parking lots are referred to as the north, central, and south lots (Figure 1). The north parking lot is located immediately adjacent to private property and is separated from the Calle's neighborhood by a 1 to 2-ft tall dirt berm. The central parking lot is separated from the north lot by a small picnic area (north picnic/unimproved area) which is prone to flooding from Easkoot Creek. The central lot is separated from the south lot by another picnic area and adjacent low-lying unimproved lands (south picnic/unimproved area). Public restroom facilities are located near each of the three parking lots. The property also contains a restaurant concession located south of the central lot. Sanitary flows from the three bathrooms and restaurant are conveyed to a pump station located in the south picnic/unimproved area. Electric transmission lines are buried and connected to a series of meters in the central portions of the property.

Ongoing improvements are being made within the GGNRA to reduce the impacts of flooding from Easkoot Creek. A sedimentation basin was constructed in 2013 opposite the Parkside Café near the right-hand bend in the creek. This basin is designed to detain a portion of the sediment load originating from Mount Tamalpais, reducing sediment deposition in the lower reaches of Easkoot Creek. In addition to the sediment basin, channel aggradation is also managed by periodic localized dredging near the various bridges crossing the creek. As part of an upcoming parking lot rehabilitation project planned in conjunction with the Federal Highways Administration, the NPS is considering construction of a high-flow bypass channel extending from the sediment basin southwest through the dune field and discharging to Bolinas Bay. A preliminary design of a bypass channel was used in this analysis, though the final design and alignment of a future bypass channel is still being evaluated and is likely to change from that used here.

2.1 - Coastal Conditions

Tidal data is available from NOAA at the Point Reyes tide gage (9415020) from 1975 to present. Based on harmonic constituents derived from this data, the mean higher high water (MHHW) is estimated to be 5.74 ft NAVD 88. The great diurnal range is 5.77 ft and the highest astronomic tide is predicted to be 7.45 ft NAVD 88. The narrow entrance to Bolinas Lagoon slightly limits tidal fluctuations. Tides within Bolinas Lagoon were monitored by NOAA at the Bolinas Lagoon tide gage (9414958) from 2009 to 2017. Based on harmonic constituents derived from this data, the MHHW in Bolinas Lagoon is estimated to be 5.39 ft NAVD 88. The great diurnal range is 4.28 feet and the highest astronomical tide is predicted to be 6.60 ft NAVD 88.

Stinson Beach faces southwest and is somewhat sheltered by Duxbury Point. The highest waves and storm surges originate from the south leading to water surface elevations significantly higher than astronomic tides. The USGS's CoSMoS modeling predicts the total water elevation arising from tidal fluctuations, storm surge, and wave runup in the vicinity of the GGNRA to range from 11.9 ft during the 1-yr storm surge to 13.5-ft NAVD 88 during the 100-yr storm surge. Given that Bolinas Lagoon is largely sheltered from wave action, total water levels are significantly lower than in Bolinas Bay. Total water elevations in the southern portion of Bolinas Lagoon are estimated to range from 8.0 ft during the 1-yr storm surge to 8.9 ft NAVD 88 during the 100-yr storm surge.

Wave action significantly alters the shape of the beachfront. Higher wave power from winter storms typically results in beach erosion, which is replaced by longshore sediment transport during calmer months. Based on routine monitoring by NPS staff and others and a review of historical shorelines, beach width has been observed to fluctuate by up to 136 ft from season to season (ESA, 2021). The largest fluctuations typically occur during El Niño years when winter storm and associated waves are the strongest. Monitoring also shows that beach widths quickly recover, even after El Niño years. Previous studies have suggested that under existing sea level conditions most sand eroded during winter storms is stored in longshore bars from where it can readily replenish beaches. Permanent losses of sand to deep portions of Bolinas Bay are believed to be minimal (PWA, 2005).

A series of dunes currently protects facilities at the GGNRA from winter storms. As a result of rising sea levels, it is likely that these dunes will eventually retreat or disappear. The extent and pace of retreat is currently uncertain. A regional study predicted that 1.4 m of sea level rise would result in 300-600 ft of dune retreat in the vicinity of the GGNRA (PWA, 2009). A more local study was prepared for the Marin County Community Development Agency (ESA, 2021). This study estimated complete loss of the winter beach at the GGNRA when sea level rise reaches 1.4

to 2.4 m. The actual extent of dune retreat may also be heavily influenced by management decisions and the effects of existing park infrastructure. Despite the uncertainty, the magnitude of retreat indicated by these studies clearly indicates that this will become a major management issue at the GGNRA.

2.2 - Riverine Conditions

Easkoot Creek drains an approximately 1.6 mi^2 watershed discharging into Bolinas Lagoon. This watershed consists of steep, forested terrain along the seaward flank of Mount Tamalpais. Elevations range from sea level to ~2,100 ft and average annual precipitation ranges from 34 to 63 in/yr (PRISM, 2010). Storm hydrographs in this watershed are characteristically flashy with times of concentration of less than an hour. In support of a previous modeling effort, OEI and Robert Zlomke developed 2-, 10-, and 100-yr 24-hr design storms for Easkoot Creek (OEI, 2013; OEI et al., 2013). These were developed in HEC-HMS using a balanced storm approach. The HEC-HMS model represented infiltrative losses using the curve number method and transformed excess precipitation using a Clark Unit Hydrograph. Parameters for these models were calibrated to observed discharges at the NPS'S Easkoot Creek gage from two recent floods in December 2005 and January 2008.

The calibrated HEC-HMS model was re-run for this study to generate the 1- and 20-yr design storms needed to correspond to events simulated by the CoSMoS modeling. Peak discharges at Highway 1 range from 44 cfs for the 1-yr event to 471 cfs for the 100-yr event. Minor additional inflows occur within the modeled reach of Easkoot Creek between Highway 1 and Bolinas Lagoon. Flows are within ~90% of peak values for 2-3 hours and within 50% of peak values for 9-12 hours in the 20- and 100-yr events which is generally consistent with peak flow durations observed during the 2005 and 2008 floods. See OEI (2013) & OEI et al. (2013) for further description of model development.

In its present configuration, Easkoot Creek flows down an alluvial fan emanating from the flanks of Mount Tamalpais and then bends sharply to the northwest near the Parkside Café and NPS sediment basin, flowing along the eastern edge of the GGNRA and the Calle's neighborhood before discharging into Bolinas Lagoon (Figure 1). Maps prior to development of the Calle's neighborhood in the mid 1900's locate Easkoot Creek near its present alignment to a point just downstream of the present-day sharp bend. The historic channel then enters an area delineated as wetland/marsh and a small lake known as Poison Lake (Figure 2). Much of the current GGNRA land lies in the footprint of the former Poison Lake and marsh area. Since development of the area, the channel has been established and maintained by periodic dredging in an alignment running parallel to the beach and draining to Bolinas Lagoon

Issues with flooding are well documented along Easkoot Creek. Several studies have delineated the extent of flooding for current sea levels including a flood risk study by FEMA and a flood hazard evaluation prepared by OEI for the Marin County Water Conservation District in 2013. Based on hydraulic modeling performed by OEI, Easkoot Creek contains the 2-yr recurrence interval flood within the GGNRA but limited overbank flooding occurs on private property near

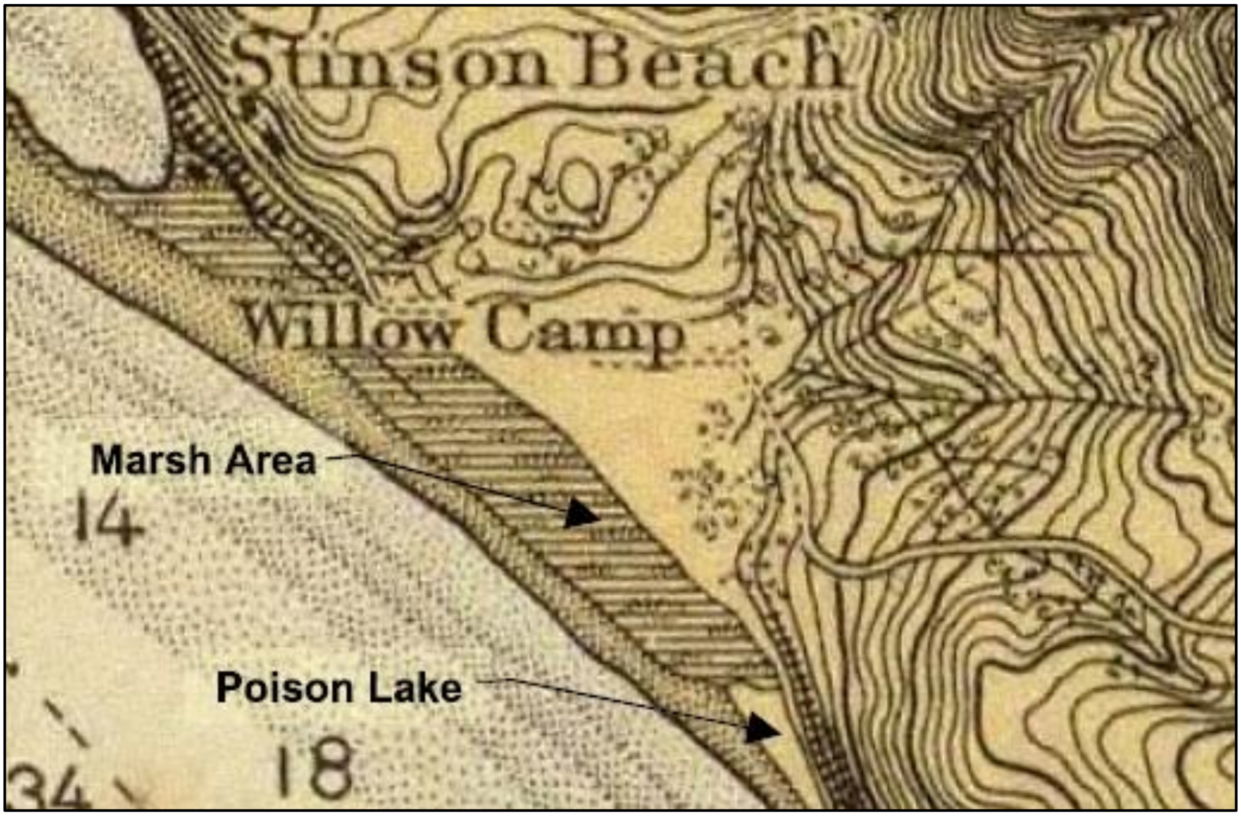

Figure 2: 1926 Coast and Geodetic Survey Chart of the Stinson Beach area.

Calle del Pinos and Calle del Recasa. At flows of 200-cfs or greater, roughly equivalent to the 5-yr recurrence interval flood event, flooding begins to occur on the GGNRA property adjacent to the Parkside Café. Flows overtop the left bank in two locations with overland flows flowing down Marine Way into the north parking lot. During the 10 to 100-yr recurrence interval events, flows breach the dunes near the north parking lot and flow into Bolinas Bay.

Overbank flows through the GGNRA limit flooding in the lowermost reach of Easkoot Creek. For the 100-yr recurrence interval event, up to 154 cfs is bypassed through the property into Bolinas Bay, roughly 31% of total discharge. The previous hydraulic modeling effort by OEI also identified factors contributing to flooding including low-set bridges, sedimentation, and the lack of a bypass channel. A previous sedimentation analysis estimated that flood events with a 10-year recurrence interval are likely to cause sediment deposition in lower Easkoot Creek on the order of 1,000 cubic yards or more with annual average sedimentation rates on the order of 125 to 160 cubic yards (OEI, 2013). To mitigate the effects of sedimentation, maintenance has been performed every 5-10 years. This has typically consisted of removing sediment near bridges. Since 2013, a portion of the sediment load has been captured by the sediment basin which was installed to limit deposition in lower reaches of Easkoot Creek. Marin County removes accumulated sediment from the sediment basin as needed based on comparison with design conditions. In 2014, the OEI model was used to assist in designing an optimal spill elevation for the sediment basin that was similar to bank elevations prior to basin construction.

2.3 - Hydrogeologic Conditions

The groundwater table is shallow across much of the GGNRA. Park staff report issues with buried infrastructure and seasonal/perennial groundwater discharge in topographic lows within the picnic/unimproved areas. The aquifer is located in a mixture of beach sands, buried wetlands materials, and alluvial fan materials from Easkoot Creek. The upper portions of the aquifer likely contain fill materials which may have greater clay content than the underlying native materials. A nearby hydrogeologic study reports that these unconsolidated materials are underlain by the Jurassic to Cretaceous-aged Franciscan Complex. The base of the unconsolidated materials is estimated to be ~32 m below sea level at the beachhead (Bergquist, 1978). Depths to bedrock in the vicinity of Easkoot Creek are significantly less with the contact between the unconsolidated deposits and the Franciscan occurring within 100-200 ft of the creek in the downstream reaches of the GGNRA. The hydraulic conductivity of the Franciscan materials is several orders of magnitude lower than the unconsolidated deposits and can be conceptualized as a separate bedrock aquifer. The shallow aquifer receives underflow from the adjacent bedrock aquifers of the Franciscan highlands (de Sieyes, 2011) and recharge from Easkoot Creek.

The unconsolidated deposits are described as primarily sandy materials by de Sieyes, which is consistent with materials described in geologic logs for shallow (~10 ft) monitoring wells in the south parking lot. Very shallow (5-ft) boreholes also indicate silty and clayey sand in the south parking lot as well as the north lot and entrance road area (YAI, 2020). Only one deeper (~50 ft) geologic log is available from a borehole in the vicinity of the pedestrian bridge. This log indicates layers of clay and silt alternating with layers of clayey sand. The upper portion of the sequence consists of ~10 ft of clay in contrast to shallow materials mapped at other locations. Given the location of this borehole near the center of the alluvial fan, it is likely that this area would contain a higher proportion of fine sediments compared to locations in the north and south lots.

The hydraulic conductivity of the unconsolidated aquifer has been previously estimated by de Sieyes (2007). Estimates are available from two approaches. Based on grain size distributions, hydraulic conductivity is estimated to be approximately 33 m/d after the method of Hazen. Estimates were also developed for 11 monitoring wells by comparing tidal fluctuations in Bolinas Bay to signals observed in these wells. Based on these measurements, the hydraulic conductivity of the unconsolidated material near Stinson Beach is approximately 5 m/d. These values are consistent with the predominantly sandy materials present in the north and south parking lots, however they are likely significantly higher than the silt and clay-dominated deposits near the center of the alluvial fan.

Groundwater levels have been monitored on the GGNRA at a network of 31 monitoring wells installed between 2003 and 2005. These wells are approximately 10 ft deep and are screened within the unconsolidated alluvial aquifer. A relatively dense network of wells was installed in the south parking lot and picnic area to observe groundwater levels in preparation for a potential wetland restoration project of Poison Lake. Monthly water surface elevations were collected in these monitoring wells intermittently from 2004 to 2011 by NPS staff and interns. Seasonal fluctuations are on the order of 2-3 ft. The highest water surface elevations are observed near the bend in Easkoot Creek, suggesting large losses into the alluvial fan at this location. After regular monitoring of the wells ceased in 2011, well heads have been buried, overgrown or otherwise lost and NPS staff are no longer able to monitor wells. See Section 5.1 for more detailed characterization of groundwater elevations and flowpaths.

3.0 - Combined Flooding Analysis

Within the GGNRA, flooding occurs from three main sources: riverine flooding from Easkoot Creek, coastal flooding from Bolinas Bay and Lagoon, and groundwater shoaling. Sea level is expected to increase the risk from all three flooding sources however each is controlled by a unique set of factors and risks will progress at different rates and at different times. To understand these complex flood hazard dynamics, flood conditions were estimated in response to sea level rises ranging from 0.5 to 2.0 m. This allows for a series of "snapshots" of flood risk as sea levels rise over time. Sea levels near Point Reyes are likely to rise by 0.5m (1.7 ft) by 2100 and possibly by up to 3.1m (10.3 ft) under the worst-case scenario (Kopp et al., 2014 and Sweet, et al., 2017).

The current state of the science and uncertainty about emissions trajectories gives a wide range of predictions as to when a specific magnitude of sea level rise will occur. In acknowledgement of this uncertainty, California Coastal Commission's (CCC) updated 2018 Sea Level Rise Guidance (CCC, 2018) recommends setting statistical thresholds based on consequences and risk tolerance. Under the 'business as usual' RCP 8.5 emissions pathway, 0.5 meters of sea level rise should be planned for by 2050 assuming a Medium/High risk avoidance perspective (Kopp et al., 2014 and Sweet, et al., 2017). Sea level rise of 1.0 and 2.0 meters should be planned for by 2070 and 2100 respectively using these same emission pathway and risk avoidance assumptions.

For each sea level rise condition, flooding was considered for a range of storm surges and riverine discharges. In order to coordinate with vulnerability and adaptation assessments the County of Marin has commissioned for the nearby communities of Stinson Beach and Bolinas, this study has adopted a modified set of the scenarios used in the CSMART program (Table 1). Selection of these scenarios was based on State of California's updated 2018 Sea Level Rise Guidance and the availability of CoSMoS model outputs. Scenarios are also consistent with those used in the recent Stinson-Beach Nature-Based Adaptation Study (ESA, 2021). The CSMART scenarios included 0.25 and 3.0 m sea level rise conditions, however 3.0 m CoSMoS data is not available for the Stinson Beach area and some of the 0.25 m results available on the Our Coast Our Future (OCOF) application appear to contain invalid data, therefore we focused on sea level rises of 0, 0.5, 1.0, and 2.0 m. Several storm frequency/sea level rise combinations were included in addition to those used by CSMART to allow for a more comprehensive comparison and understanding of flood risk over time. In total the study includes 14 scenarios including most combinations of a 'no storm', 1-yr, 20-yr, and 100-yr recurrence interval event for the four sea level rise conditions (Table 1).

Table 1: Summary of storm frequencies and sea level rise scenarios evaluated in this study, 'CM' represents results taken directly from CoSMoS and 'CM/MF' represents results generated by a combination of CoSMoS and MIKE FLOOD.

		Recurrence Interval			
		No Storm	1-yr	20-yr	100-yr
Sea Level Rise (m)	0	CM	CM/MF	CM/MF	CM/MF
	0.5	CM	CM/MF	CM/MF	
	1	CM	CM/MF	CM/MF	CM/MF
	2	CM	CM/MF		CM/MF

The following sections describe the analytical approaches used to estimate riverine and coastal flooding (Section 4) and groundwater flooding (Section 5). Potential feedbacks between riverine/coastal flooding and groundwater flooding are discussed in Section 6 and estimates of flooding from individual sources were combined to develop a vulnerability assessment for park infrastructure in Section 7.

4.0 - Riverine and Coastal Flooding Analysis

The extent, duration, and frequency of riverine and coastal flooding at the GGNRA and adjacent lands is controlled by the combined impacts and interactions of riverine processes in Easkoot Creek and coastal processes in Bolinas Lagoon and Bolinas Bay. At current sea levels, the Stinson Beach property is above the extent of coastal storm surge and wave runup as well as the backwater formed in lower Easkoot Creek by Bolinas Lagoon. As sea levels rise, flooding by storm surge and wave action will begin to encroach on the site and backwater conditions will extend further upstream in Easkoot Creek leading to increased flood risks over time.

Hydraulic models were used to determine the extent, depth, and duration of flooding for the 14 scenarios described above in Section 3 (Table 1). For the 'no storm' scenarios, flows in Easkoot Creek are considered negligible and flooding is only a function of sea level, tidal fluctuations, and wave runup. Flooding from these sources alone has already been well studied by the CoSMoS model. For these scenarios, spatially distributed estimates of flood depth were accessed directly from the CoSMoS model via the OCOF website. For the remaining scenarios, additional hydraulic modeling was required to understand the interactions between coastal and riverine flooding. To this purpose, a hydraulic model of Easkoot Creek was developed using MIKE FLOOD. This model is a revised version of a hydraulic model of Easkoot Creek previously developed by OEI for Marin County Flood Control and Water Conservation District (OEI, 2013, OEI et al., 2013). It uses coastal boundary conditions from the CoSMoS model and synthetic inflow hydrographs to determine stillwater elevations over the course of a 24-hour storm.

Storm frequencies consider the joint probability of riverine discharges and storm surges. A study commissioned by Marin County's Community Development Agency found that the recurrence interval of storm surge and riverine flooding events may be considered statistically independent along the Pacific Coast of Marin County (Mouftakhari, 2018). These findings are statistically valid to the 5-15% confidence level. This is not to say that large precipitation events and large storm surge events do not frequently coincide, however the relatively short duration of peak discharges in a small stream like Easkoot Creek make the probability of coincident peak forcing relatively small. Additionally, the non-tidal residual (NTR) from even the largest storm surges along the Marin coastline are smaller than the diurnal range in Bolinas Bay. As a result, absolute stillwater elevations are driven more by the phase of the tide cycle, which is completely independent of riverine flooding, than they are by storm surge.

Because storm surge and riverine discharge are statistically independent, the simplified approach recommended by FEMA for compound flooding is valid for Easkoot Creek (FEMA, 2015). For the 20- and 100-yr scenarios, the hydraulic model was used to simulate two flooding conditions. In the first an extreme storm surge was paired with a non-extreme, annual recurrence interval riverine discharge. In the second, an annual storm surge was paired with an extreme riverine discharge. Results were post-processed by taking the maximum flood depth at each location from the two simulations. The annual event only required a single model run with both annual storm surge and annual riverine discharge.

The hydraulic modeling did not include wave runup, however a wave runup analysis was included as part of the CoSMoS modeling. To account for areas where wave runup generated flood extents greater than those determined from the combined riverine/storm surge modeling, the raw CoSMoS results were included in a final post-processing step. This step involved taking the maximum flood depth at each location from the final MIKE FLOOD maps and the original CoSMoS maps to derive a final flood map for each scenario.

4.1 - Model Development

The MIKE FLOOD model that was developed to evaluate scenarios that consider riverine flooding builds upon an earlier hydraulic model of Easkoot Creek developed by OEI for the Marin County Flood Control and Water Conservation District (OEI, 2013, OEI et al., 2013). This model was constructed using MIKE FLOOD, a program which allows for the dynamic coupling of 1-dimensional (1D) hydraulic models developed using MIKE 11 and 2-dimensional (2D) hydraulic models developed using MIKE 21 (DHI, 2022). Both components are designed to simulate free-surface flows in rivers, estuaries, and oceans using a finite-difference approximation to solve the Saint-Venant equations for unsteady flows. Additionally, MIKE 11 includes the ability to simulate the hydraulic effects of bridges and other structures using an energy equation approach. The models are accepted by FEMA for use in the National Flood Insurance Program and they have been applied in numerous studies around the world.

The general structure of the model used in this study is very similar to that of the previous hydraulic model. Flows within the banks of Easkoot Creek were represented using 1D cross-sections. This allows for channelized flows to be represented using detailed topography and for structure hydraulics to be simulated using well-established 1D energy formulations. All other areas were represented using a 2D flexible mesh. Key differences between this and the previous hydraulic model developed by OEI include updated topography, an expanded model domain including all NPS facilities, and updated boundary conditions reflecting projected sea level rises and storm surges. A detailed discussion of model construction is provided below.

4.1.1 – Model Domain

The model domain covers Easkoot Creek and adjacent floodplains from the Highway 1 crossing to the confluence with Bolinas Lagoon including the entire developed portion of the GGNRA (Figure 3). The model also includes the upper ~0.8 miles of Bolinas Lagoon, and the dune field, beach, and nearshore portions of Bolinas Bay extending ~600-700 ft offshore from the beachfront. Within Bolinas Lagoon the northwestern edge of the model domain was placed where the Lagoon becomes suitably wide, such that surcharges from Easkoot Creek (which are not represented in the CoSMoS model from which coastal boundary conditions were taken) do not appreciably affect water surface elevations or velocities. Within Bolinas Bay, the model boundary was placed at a location beyond the breaking zone for all scenarios.

4.1.2 – Model Topography

Topographic inputs were developed for three conditions: historic, existing, and future. The historic condition represents topography before construction of the sedimentation basin near the Parkside Café. The existing condition represents topography at the time of this study. The future condition represents one possible alignment of a future bypass channel between the north and south parking lots but does not include any grading proposed as part of parking lot reconfiguration. The NPS is in the process of finalizing a specific design for the bypass channel and parking lot configuration. Grading associated with parking lot changes is expected to be minimal, however the orientation of the bypass channel will likely be modified from the preliminary configuration simulated in this analysis.

In-channel topography is represented using a series of 1D channel cross-sections surveyed by OEI staff in 2011. Due to ongoing sedimentation, erosion, and sediment removal activities, the channel bed and cross sections change frequently. A comparison between historical channel profiles shows relatively similar bed conditions in 1979, 1999, and 2004. Between the 2004 and 2006 datasets about 2-ft of aggradation occurred which can be attributed to the December 2005

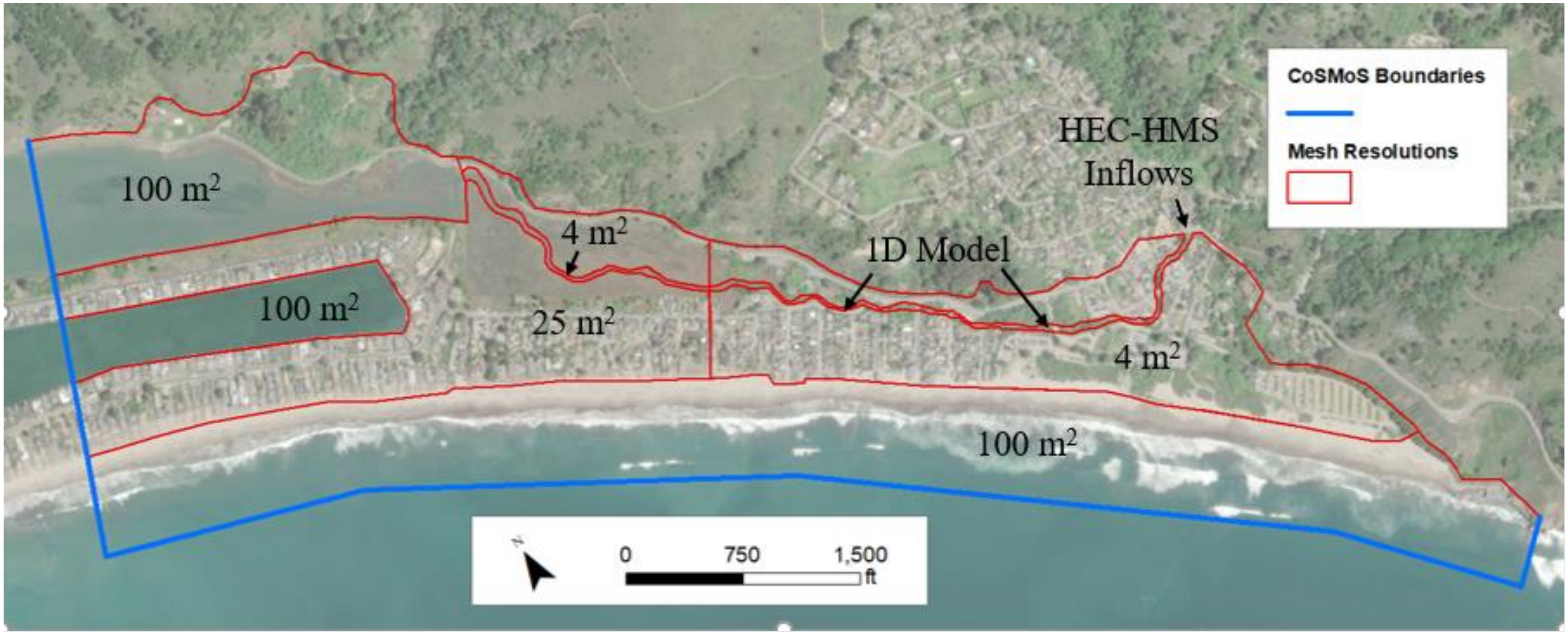

Figure 3: Extent of the hydraulic model domain, mesh resolution zones, and locations of boundary conditions applied from CoSMoS.

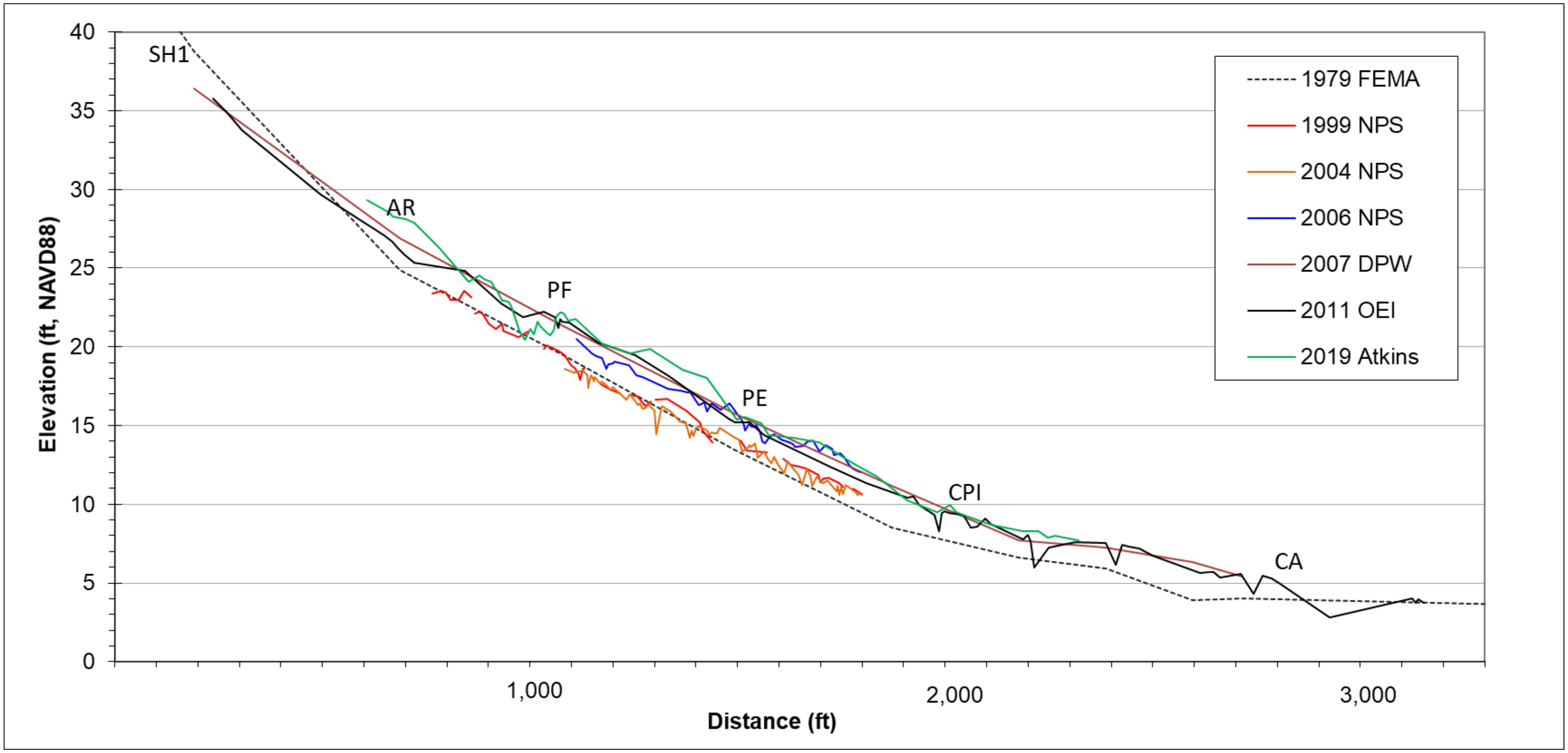

Figure 4: Longitudinal profiles of Easkoot Creek surveyed between 1979 and 2019. Select bridge crossings are denoted as: SH1-State Highway 1, AR-Arenal Ave., PF-Pedestrian Footbridge, PE-Park Entrance Rd., CPI-Calle del Pinos, and CA-Calle del Arroyo.

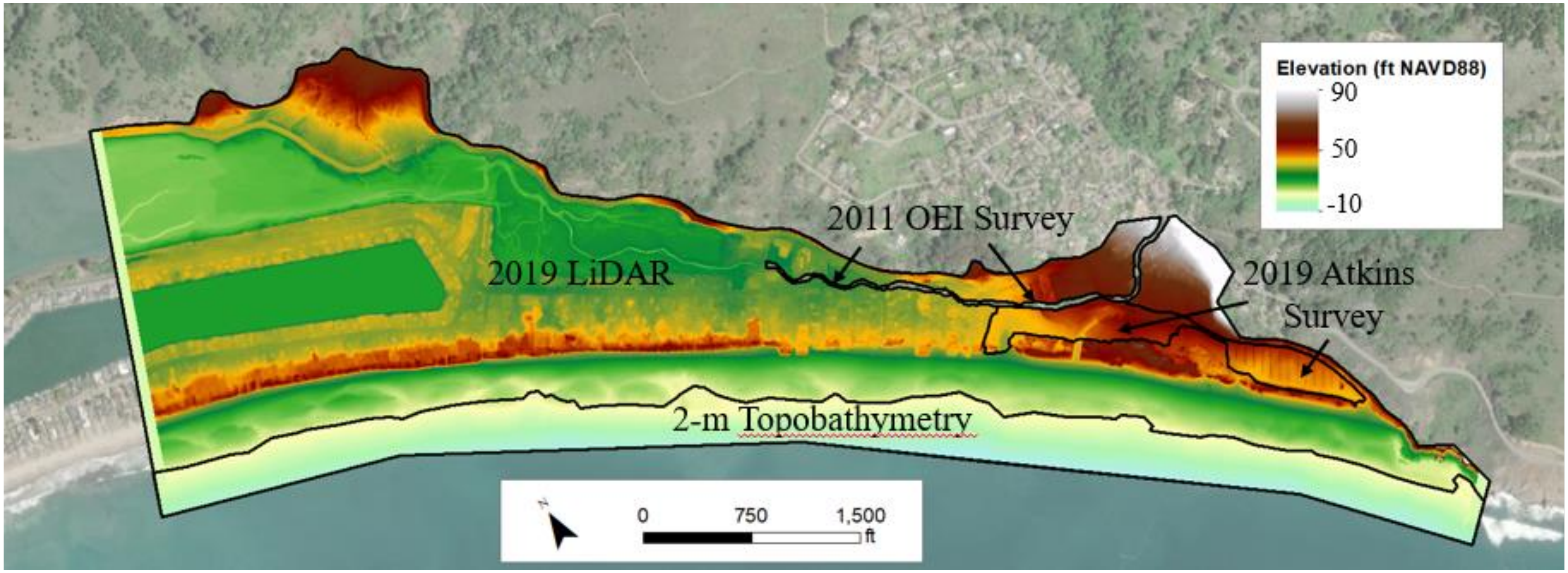

Figure 5: Digital terrain model used in the hydraulic model indicating data source areas.

flood (Figure 4). Bed conditions have since remained relatively constant as captured by the available data from 2006, 2011, and 2019. Given the general similarities between the most recent 2019 Atkins data and the 2011 OEI data, the 2011 data is expected to adequately represent current conditions, although there is some indication of localized aggradation since 2011 in the reach between the pedestrian bridge and the park entrance road bridge. Cross-sections are typically spaced at 10-30 m intervals with tighter spacing near bridges to adequately represent contractions and expansions. Twelve road and pedestrian bridges are included in the model using energy equations which include submergence and overtopping process formulations. Only the pedestrian bridge downstream of the sediment basin and the park entrance road bridge are located within the GGNRA. For more details on the bridge hydraulics please refer to OEI (2013). For the existing and proposed condition models, cross-sections were revised to match as-built plans for the sediment basin.

Overbank topography used in the majority of the 2D portion of the hydraulic model is based on the 2019 Marin County QL1 LiDAR (QSI, 2019). This LiDAR has higher point density and greater vertical accuracy than the 2009 Golden Gate LiDAR used in the earlier version of this model (QSI, 2019) and comparisons to survey data indicate it described site conditions more accurately and in greater detail. Ground survey data collected by Atkins in 2019 was used in place of the LiDAR within the three parking lots and the riparian area near the sedimentation basin. Deep water bathymetry in Bolinas Bay, which was inaccessible to the LiDAR, was obtained from the 2-meter San Francisco Topobathymetric DEM (Figure 5). This bathymetric dataset was also used by CoSMoS and was selected to ensure topographic agreement between the two models where the CoSMoS model was used to drive boundary conditions. In the historic condition, the edges of the sediment basin included in the 2D component of the model were modified to represent topography before construction of the basin based on the 2011 OEI survey. In the future condition, overbank topography was revised to include the proposed bypass channel. A working version of bypass channel topography was provided by the FHWA for this purpose.

Floodplain topography was represented in the 2D component of the model using a flexible mesh. For areas where high resolution is required, such as the GGNRA and vicinity as well as the channel threads in the estuary near Bolinas Lagoon, the mesh was constructed at a 4 m^2 resolution. Other areas were represented using a 25-100 m^2 resolution mesh (Figure 3). This approach allowed for a detailed representation of topography where it is most needed without producing unmanageable computational times. Breaklines were added to ensure key topographic breaks such as the tops and bottom of banks, the berm along the northwest edge of the north parking lot, and the proposed bypass channel were accurately represented.

4.1.3 - Roughnesses

Historic condition hydraulic roughnesses are based directly on those used in OEI's 2013 hydraulic model. Within the channel, Manning's roughness coefficients were assigned to the left bank, channel bottom, and right bank on a reach-by-reach basis based on vegetation and substrate observations. Bank roughnesses varied from 0.09 in heavily vegetated reaches to 0.02 in concrete lined reaches while channel bottom roughnesses ranged from 0.03 to 0.06 depending on channel substrate conditions (OEI, 2013). Roughnesses were distributed on the floodplain based on major land use and vegetation types. The original 2013 distributions were extended to include additional areas of the model domain not included in the earlier effort (Figure 6). For the existing condition, in-channel hydraulic roughnesses were revised to reflect construction of the sedimentation basin. For the future condition, overbank hydraulic roughnesses were revised to reflect the proposed bypass channel and re-alignment of Marine Way in the immediate vicinity.

4.1.4 - Riverine Inflows

Riverine inflows were added at six locations within the model domain. The majority of inflows are received via Easkoot Creek at the upstream boundary of the model near Highway 1. The other five inflows are from smaller tributaries entering Easkoot Creek between Highway 1 and Bolinas Lagoon. Riverine inflows are based on two sources. Inflow hydrographs for the observed events used in model calibration were obtained from the NPS's Easkoot Creek (EK) gage. Inflow hydrographs for design storms used in future condition simulations were obtained from a previously developed HEC-HMS model of Easkoot Creek. This model was developed by OEI and Robert Zlomke for use in OEI's prior hydraulic model (OEI, 2013; OEI et al., 2013). A discussion of model construction and calibration can be found in the Riverine Conditions section of this report and in OEI (2013) and OEI et al. (2013). The model was initially run for the 24-hr 2-, 5-, 10-, and 100-yr recurrence interval storms. For consistency with the flooding scenarios considered by CSMART and CoSMoS, the HEC-HMS model was re-run for the 1- and 20-yr, 24-hour design storms. Discharge hydrographs used in each scenario are shown in Figure 7. The timing of peak riverine inflows was adjusted to correspond to the timing of peak coastal boundary condition water levels taken from CoSMoS (see below).

4.1.5 - Coastal Boundary Conditions

Along Bolinas Bay and Bolinas Lagoon, boundary conditions are driven by water surface elevation and current velocity timeseries. To make use of the spatially distributed model results available through CoSMoS, this boundary was subdivided into six segments, each capable of using separate timeseries. One was located within Bolinas Lagoon and the remaining five were located within Bolinas Bay.

For the December 2005 event used to calibrate the model, there is no interaction between flood flows from Easkoot Creek and water surface elevations in Bolinas Bay, however lower Easkoot Creek flows are controlled by water surface elevations in Bolinas Lagoon. Water surface elevations in Bolinas Lagoon were based on observed stillwater elevations at NOAA's Point Reyes tide gage (Station #9415020). NOAA's Bolinas tide gage, located within Bolinas Lagoon, was not active during this event, however a correlation was established between the two gages and used to develop an estimate of water surface elevations within Bolinas Lagoon (see OEI, 2013 for further details). Tidal velocities within Bolinas Lagoon were considered negligible.

For the sea level rise scenarios, boundary conditions are based on outputs from the USGS's CoSMoS model (Figures 8 & 9). Model outputs were available as hourly timeseries for 18 longshore profiles within OEI's model domain. Water surface and velocity timeseries were

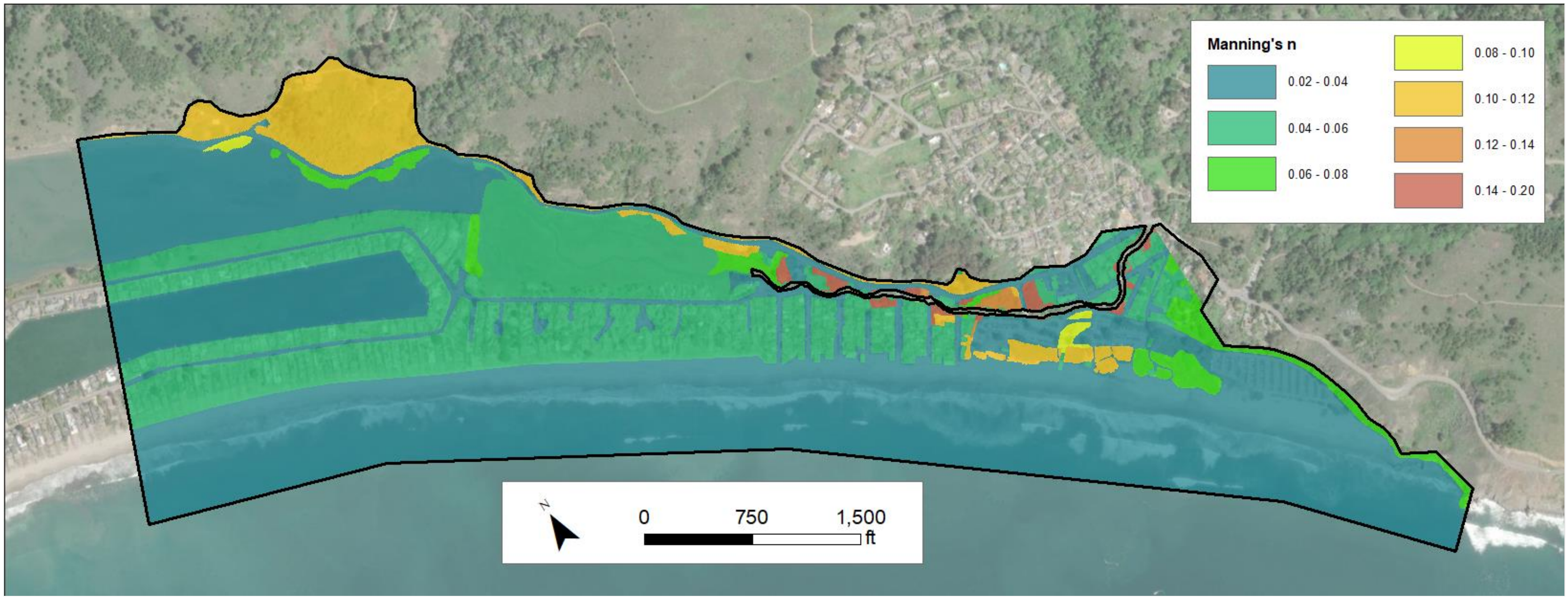

Figure 6: Manning's roughness coefficient (n) values used in 2D component of the hydraulic model.

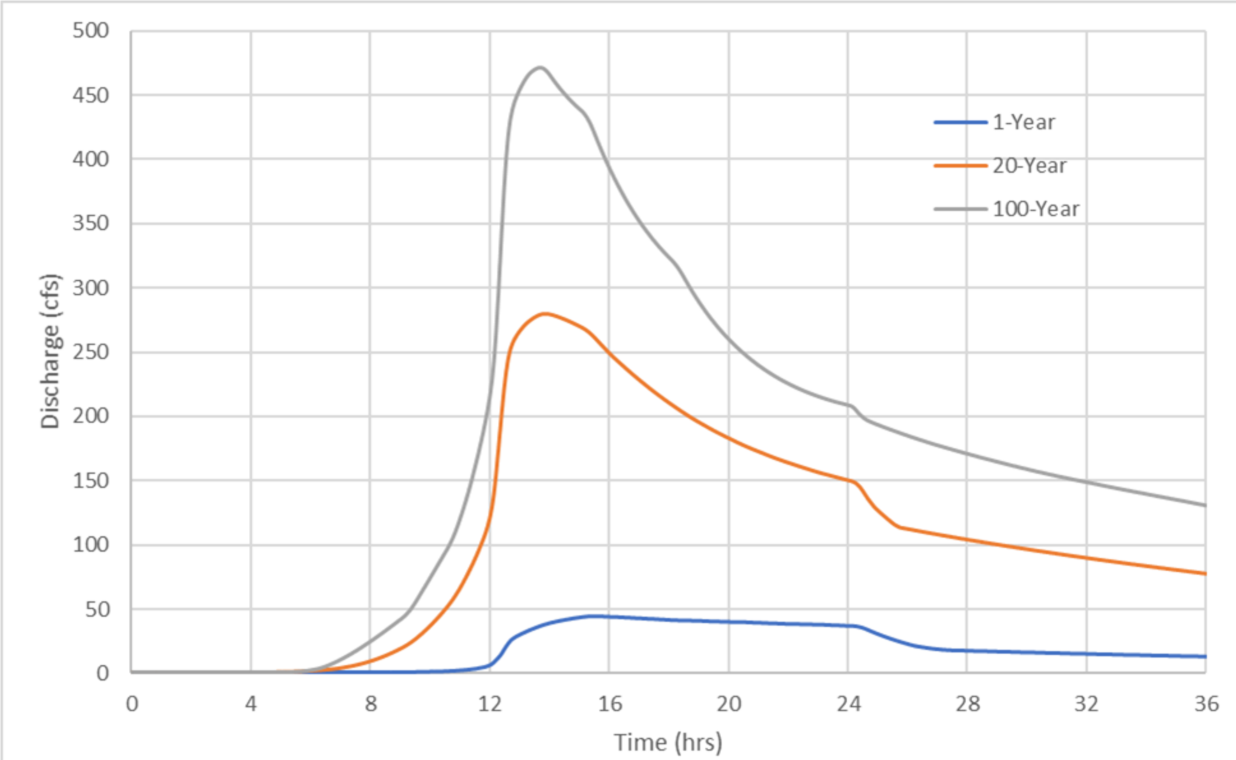

Figure 7: Design storm hydrographs used in the hydraulic model for Easkoot Creek at Hwy 1.

extracted from each profile where it intersected the model boundary. Timeseries from individual profiles were then averaged across each of the six boundary segments. Detailed water surface elevation and velocity timeseries were unavailable within Bolinas Lagoon. CoSMoS results accessed through the OCOF Hazard Map indicate that velocities within the relatively sheltered setting of Bolinas Lagoon are generally low except in scenarios with the most extreme combinations of sea level rise and storm surge. Therefore, velocities within Bolinas Lagoon were not considered in the model. Comparison of maximum stillwater elevations from the CoSMoS model show that water surface elevations are approximately 0.0-0.4 ft higher in Bolinas Bay than in Bolinas Lagoon in the absence of storms surge and between 0.4 and 0.6 ft lower during a range of winter storms. In the absence of detailed model results for Bolinas Lagoon, water surface elevations in Bolinas Lagoon were assumed to be the same as those described in the CoSMoS outputs for nearby areas of Bolinas Bay. In the long term, as Stinson Spit shrinks due to sea level rise, transfer between Bolinas Bay and Lagoon will be enhanced, leading to convergence of water surface elevations.

4.1.6 - Simulation Period

Each model scenario was simulated for a 24-hour period. This spans the typical observed duration of the storm hydrograph in Easkoot Creek and the daily tide cycles in Bolinas Bay and Bolinas Lagoon. The model was run using a 0.1-1.0 second timestep, satisfying the Courant condition at all locations

4.1.7 - Calibration

The hydraulic model is based directly on OEI's prior hydraulic model of Easkoot Creek. To a large degree, hydraulic roughnesses and other model parameters were already calibrated from this previous model. However, because the model uses new overland topography and a new, but similar, set of coastal boundary conditions, the calibration of the model was verified. Verification consisted of comparison of results to observed stage timeseries from the NPS's Easkoot Creek (EK) gage for the December 2005 flood event.

The initial model run (using previously calibrated hydraulic roughnesses from the original model) produced very similar water surface elevation results at the gauge location as the adequately calibrated previous model, therefore no further calibration adjustments were made. The model predicts the water surface elevations at the gauge location to within 0.4-ft throughout the 28-hr calibration period and captures the peak stage to within 0.1-ft (Figure 10). Floodplain elevations in the 2019 Marin County LiDAR are 0.1-0.5 ft higher than those used in the 2013 modeling in most locations. The slightly higher floodplain elevations resulted in less inundation during the revised December 2005 simulation compared to the 2013 results. The locations of over-bank flows and patterns of floodplain inundation are, however, generally similar between the two simulations and given the higher accuracy of the 2019 LiDAR compared to LiDAR used in the earlier study, the revised results are expected to be more accurate.

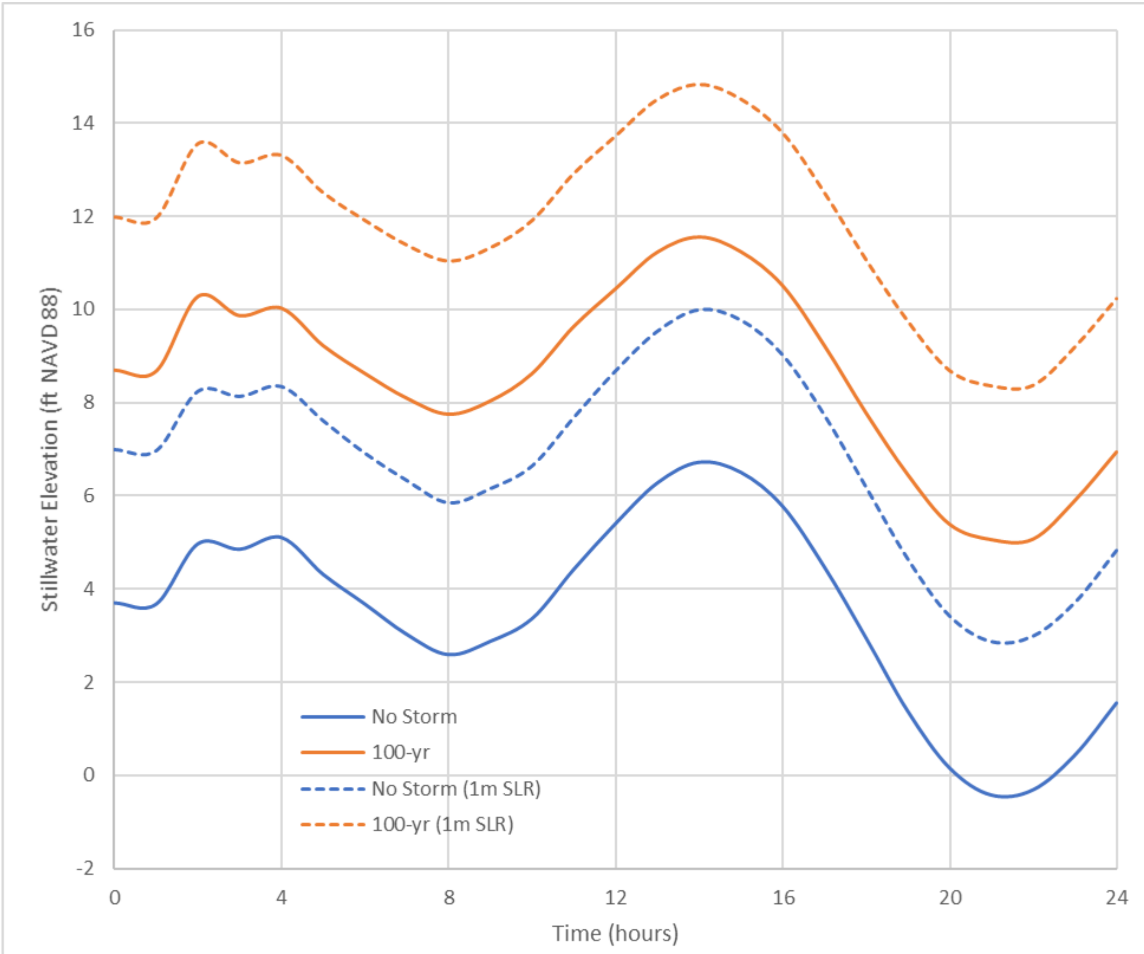

Figure 8: Spatially-averaged stillwater elevations from CoSMoS used as boundary conditions in the hydraulic model for select storm surge and sea level rise scenarios.

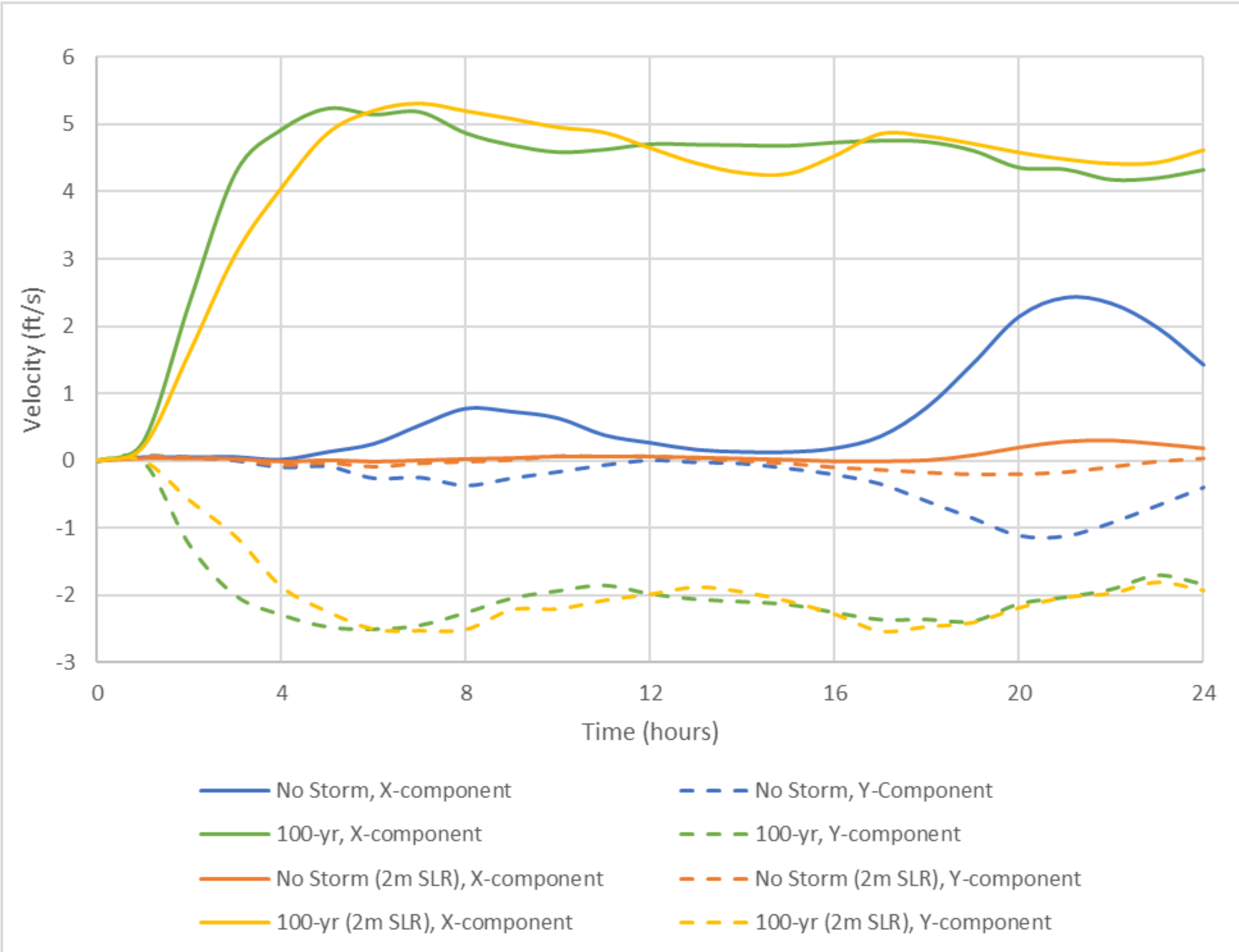

Figure 9: Spatially-averaged velocities from CoSMoS used as boundary conditions in the hydraulic model for select storm surge and sea level rise scenarios. Note the orientation of the velocity fields is accounted for by applying x and y velocity components with the sign convention being relative to the model grid orientation.

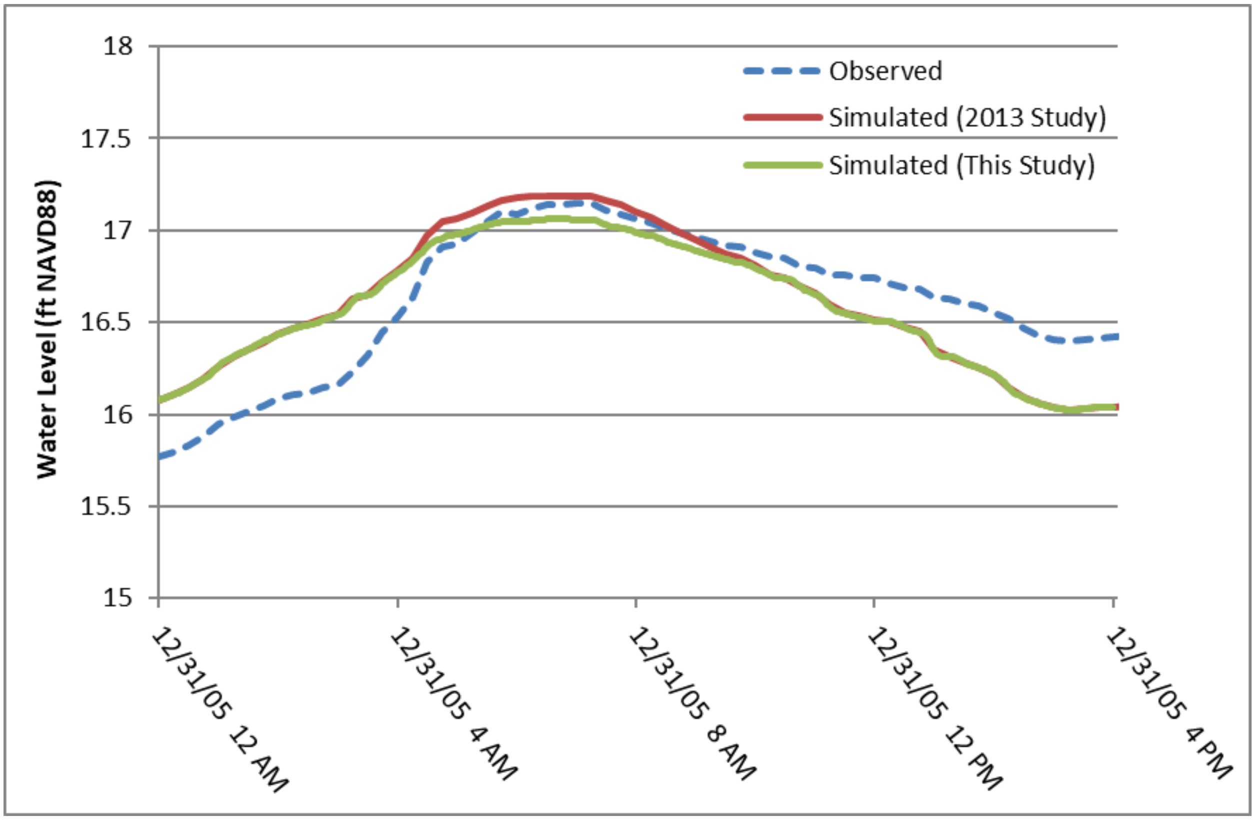

Figure 10: Comparison between simulated and observed stages at the NPS's Easkoot Creek gauging station during the December 2005 flood.

4.2 - Limitations

Future flooding is dependent on many complex and interdependent factors, all of which could not be fully represented in this model framework. As such, it is important to understand the limitations of this analysis. Most importantly, the hydraulic model assumes a static topography based on current conditions plus improvements the NPS is currently in the process of planning. This topography does not reflect long-term changes in dune position due to sea level rise or future managed retreat strategies. Nor does it include short term changes to dune position from erosion caused by individual storm events. Future iterations of the CoSMoS model will account for changes in shoreline position and dune retreat, however the currently available dataset assumes constant beach/dune morphology. In the absence of active management, significant dune retreat is expected to occur under future sea level rise conditions with a complete loss of the winter beach expected to occur under 1.4 to 2.4 m of sea level rise (ESA, 2021). Additionally, the model does not account for any responses to sea level rise implemented on nearby privately held lands. Additionally, the model does not account for changes in channel morphology resulting from sea level rise.

Another key limitation is uncertainty about future discharges. Riverine inflows do not account for future increases in precipitation intensity. The State of California is beginning to provide guidance for changes in 24-hour precipitation intensity (Agha Kouchak et al., 2018). However, floods in Easkoot Creek are driven by hourly and sub-hourly precipitation intensities. Changes in intensity at these shorter timescales is still an emerging area of research. Finally, peak riverine discharge was assumed to be coincident with peak tide. This is a simplifying assumption commonly applied in flood studies, however flooding will vary with the phase of the tide.

4.3 - Model Results

Under existing sea level conditions, no flooding occurs on the GGNRA in the combined riverine and coastal flooding 1-yr recurrence interval event or in the 'no storm' scenario (Figure 11). In the 20-yr event, overbank flows occur on both sides of the creek in the vicinity of the sediment basin and the Parkside Café. Most of the overbank flows occur on the left bank and with the proposed bypass channel in place, these flows are contained within the bypass channel and prevent flooding of the north parking lot (Figure 12). Without the bypass channel, these flows would inundate portions of the north parking lot. Overbank flows also occur in the Calles reaches in the 20-yr flood, however these flows do not impact the GGNRA due to the presence of the berm on the northwest side of the north parking lot. During the 100-yr flood, overbank flows at the sediment basin overwhelm the capacity of the bypass channel resulting in flooding of the north parking lot. Coastal storm surge and wave runup also inundate the lowest-lying portions of the north parking lot during the 100-yr coastal storm surge (Figure 13).

With 0.5 m of sea level rise, the GGNRA remains unimpacted by flooding during the 1-yr recurrence interval event and the 'no storm' scenario (Figure 14). In the 20-yr event, overbank flows in the vicinity of the sediment basin remain the same as they did with existing sea level conditions, however flooding in the Calles neighborhood increases dramatically. Storm surge and wave runup originating from Bolinas Bay also begin to impact the north parking lot and the southernmost area of the south parking lot (Figure 15). The 100-yr flood was not evaluated for the 0.5 m sea level rise condition.

With 1.0 m of sea level rise, the GGNRA is not impacted in the 'no storm' scenario, however impacts begin to occur during the 1-yr recurrence interval event with storm surge and wave runup originating from Bolinas Bay impacting portions of the north parking lot and the southernmost area of the south parking lot (Figure 16). Flows within Easkoot Creek remain contained in the vicinity of the sediment basin. During the 20-yr event, overbank flows in the vicinity of the sediment basin remain the same as they did with existing sea level conditions, however coastal storm surge and wave runup create more significant flooding in the north parking lot with floodwaters entering the parking lot and then flowing over lower portions of the berm separating the north lot from the Calles neighborhood. The southernmost area of the south parking lot is also impacted by coastal flooding (Figure 17). During the 100-yr flood, riverine and coastal flood processes begin to interact in the vicinity of the north parking lot with significant flooding of the parking lot to depths in excess of 4 ft in some areas and a fully-connected water surface across the berm between the Calles neighborhood and the north lot. A significant portion of the south parking lot also becomes inundated from coastal flooding during this event (Figure 17).

With 2.0 m of sea level rise, no impacts to the GGNRA occur during the ‘no storm’ scenario and flows in the vicinity of the sediment basin remained contained during the 1-yr recurrence interval event, however the entirety of the north parking lot and portions of the park entrance road are flooded from coastal storm surge and wave runup during the 1-yr storm (Figure 18). The berm between the north lot and the Calles neighborhood is fully overtopped and flood depths in excess of 4 ft occur throughout the central portions of the north lot. The direction of flow over the berm is primarily from the north parking lot towards the Calles, although the Calles are already inundated from direct coastal flooding by the time of berm overtopping. A significant portion of the south parking lot is also inundated during this event. The 20-yr flood was not evaluated for the 2.0 m sea level rise condition. During the 100-yr flood, significant interaction of riverine and coastal flood processes occurs resulting in flooding of the entirety of the north parking lot and portions of the park entrance road and central picnic area. The entirety of the south parking lot is also flooded during this event along with adjacent portions of the south picnic area. Flood depths exceed 4 ft in portions of both parking lots (Figure 19).

These results demonstrate that overbank flows in the vicinity of the sediment basin are not affected by sea level rise in the 0.5-2.0 m range. Comparison of longitudinal water surface profiles of Easkoot Creek indicate that backwater effects resulting from coastal storm surge originating from Bolinas Lagoon do not project far enough upstream to impact the hydraulics in the vicinity of the sediment basin (Figure 20). With 1 m of sea level rise backwater effects occur as far upstream as the Calles neighborhood and with 2 m of sea level rise, these effects extend onto the GGNRA property but only as far as a couple of hundred feet upstream of the park entrance bridge under the most extreme scenario (100-yr recurrence interval storm surge).

Given that coastal flooding does not impact the site during the ‘no storm’ scenario even with 2.0 m of sea level rise, flood durations during the various simulated events are expected to remain relatively short (hours). In other words, post-storm coastal water level conditions will continue to recede to levels at which flood waters at the GGNRA can readily drain away. More detailed flood duration analysis is not warranted given the lack of drainage impacts expected during even the most extreme 2.0 m sea level rise condition that was evaluated.

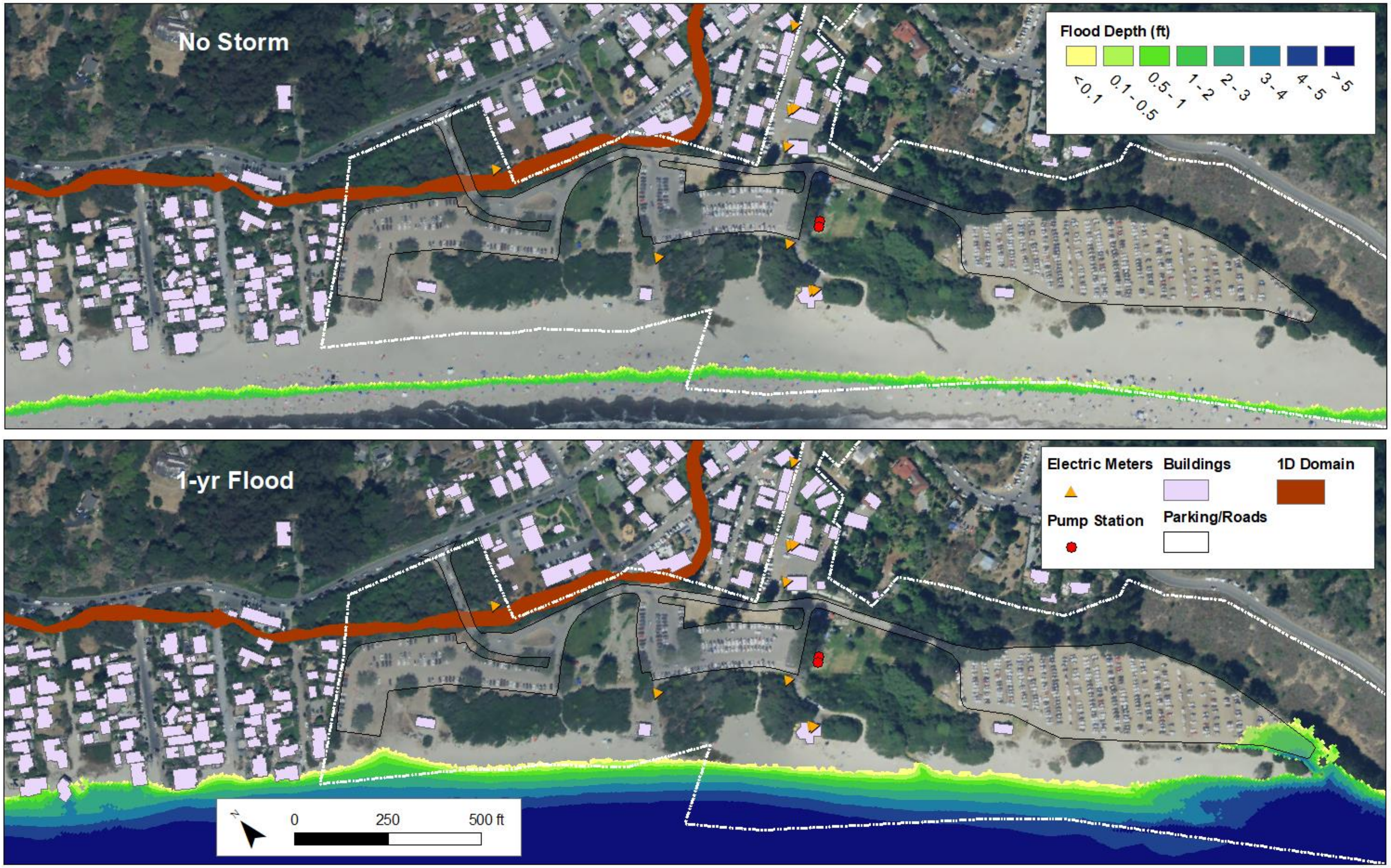

Figure 11: Combined coastal/riverine flooding for the 'no storm' (top) and 1-yr recurrence interval (bottom) storm events under existing sea level conditions.

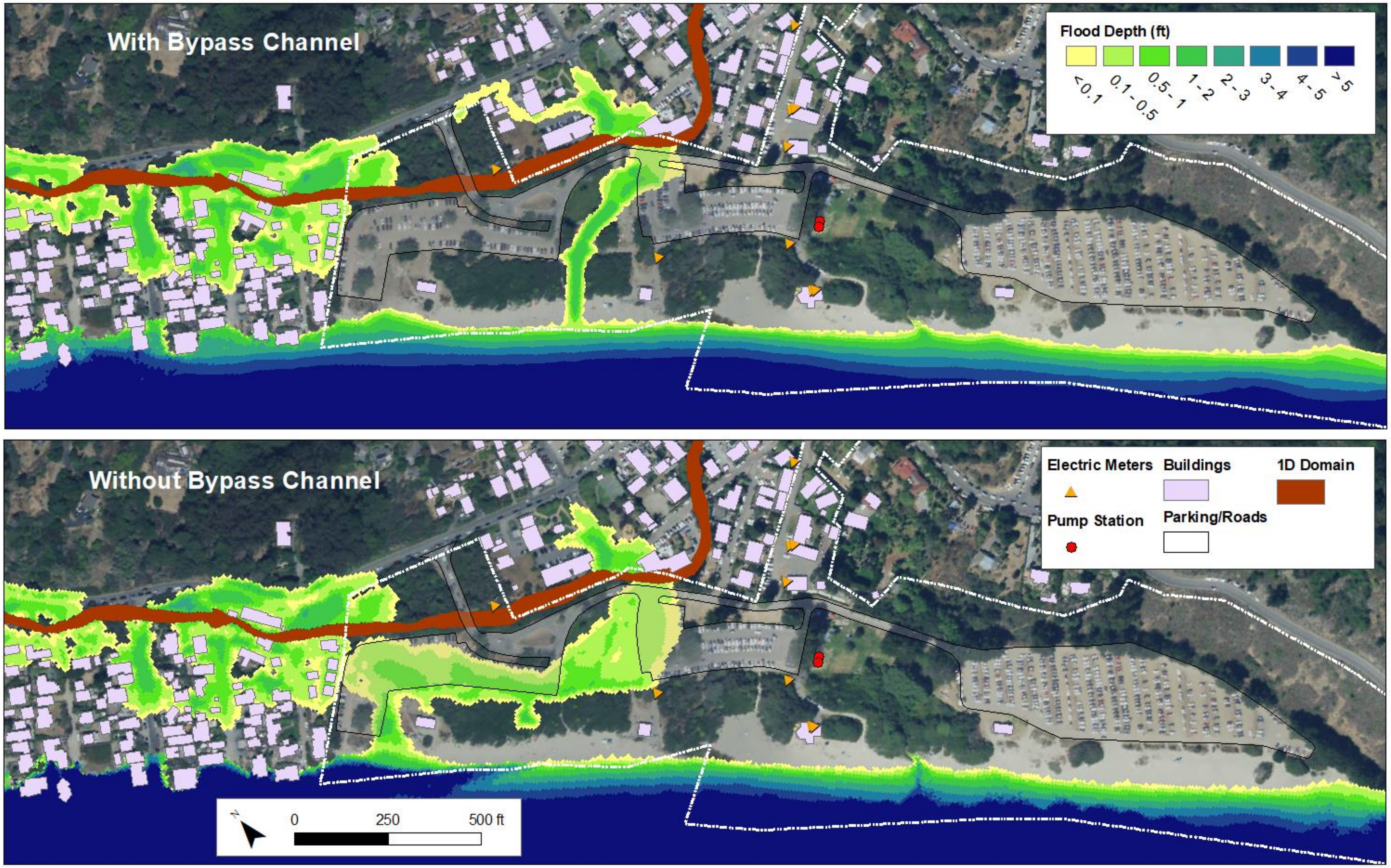

Figure 12: Combined coastal/riverine flooding for the 20-yr recurrence interval storm event under existing sea level conditions with (top) and without (bottom) the proposed bypass channel.

Figure 13: Combined coastal/riverine flooding for the 100-yr recurrence interval storm event under existing sea level conditions.

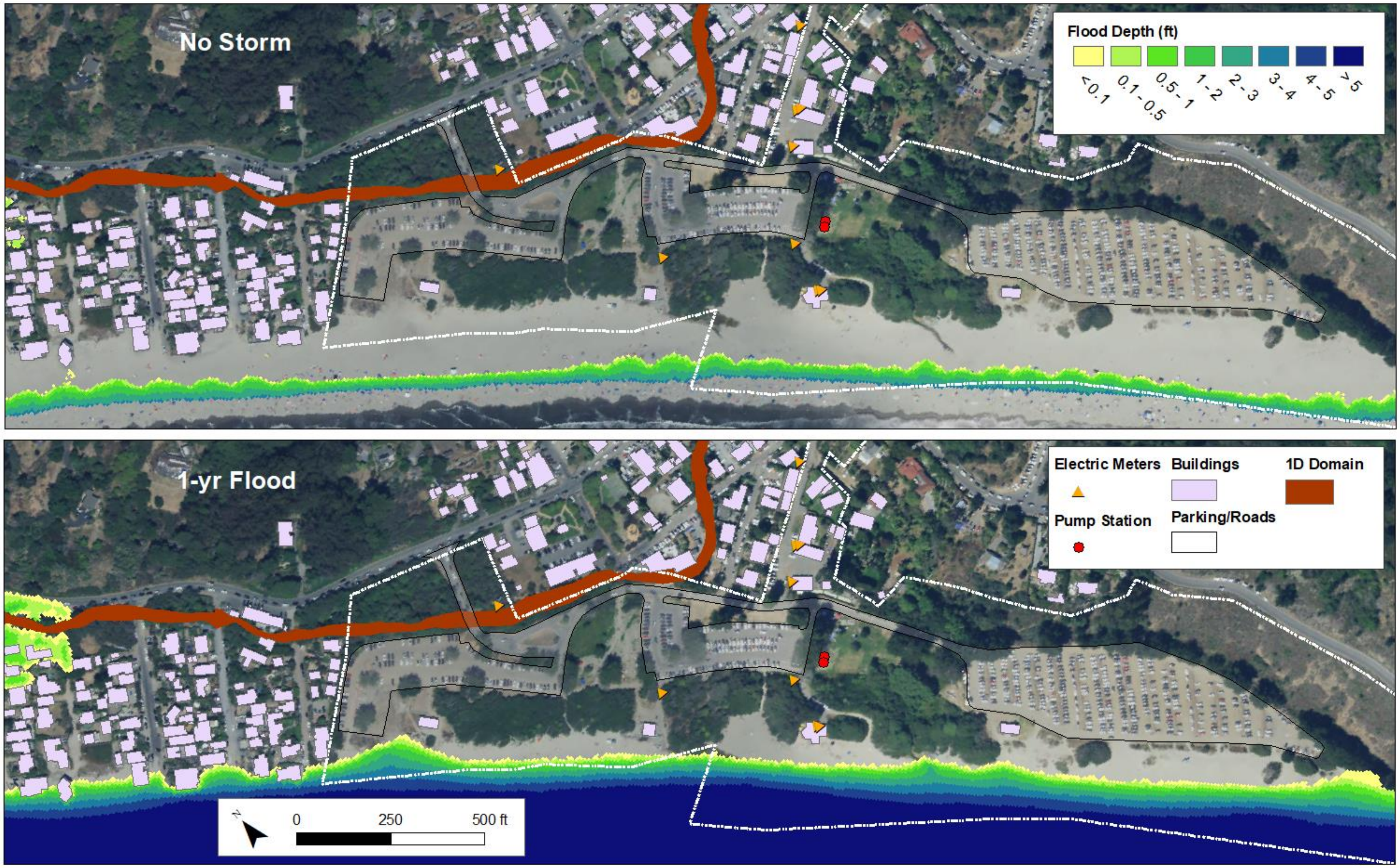

Figure 14: Combined coastal/riverine flooding for the 'no storm' (top) and 1-yr recurrence interval (bottom) storm events under the 0.5 m sea level rise condition.

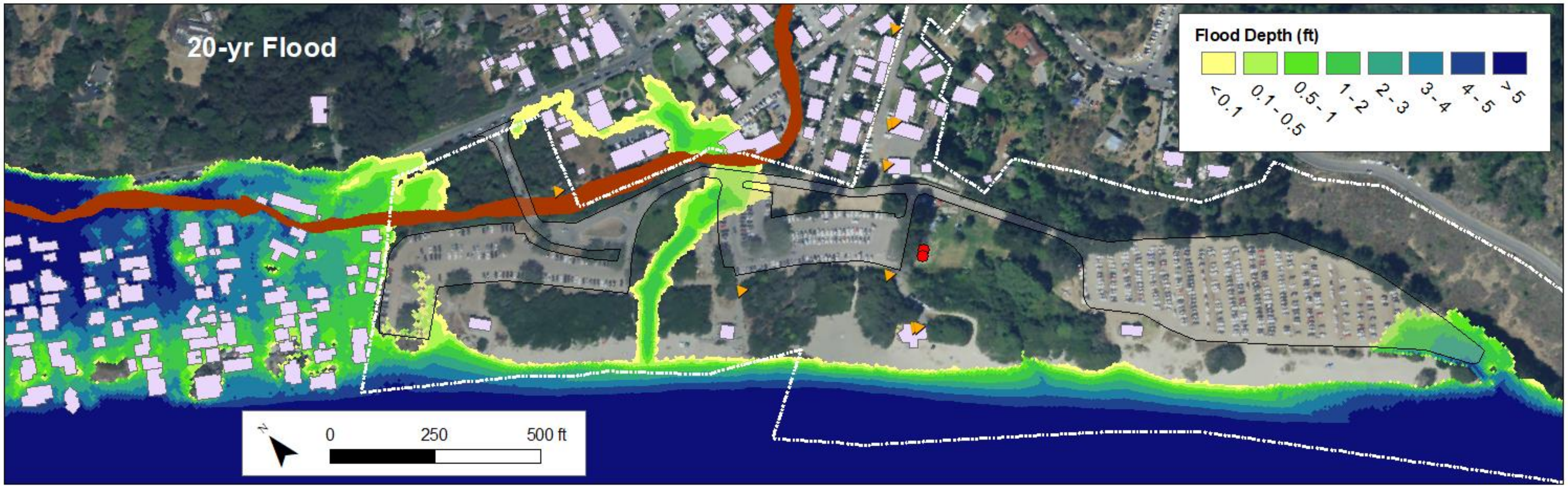

Figure 15: Combined coastal/riverine flooding for the 20-yr recurrence interval storm event under the 0.5 m sea level rise condition.

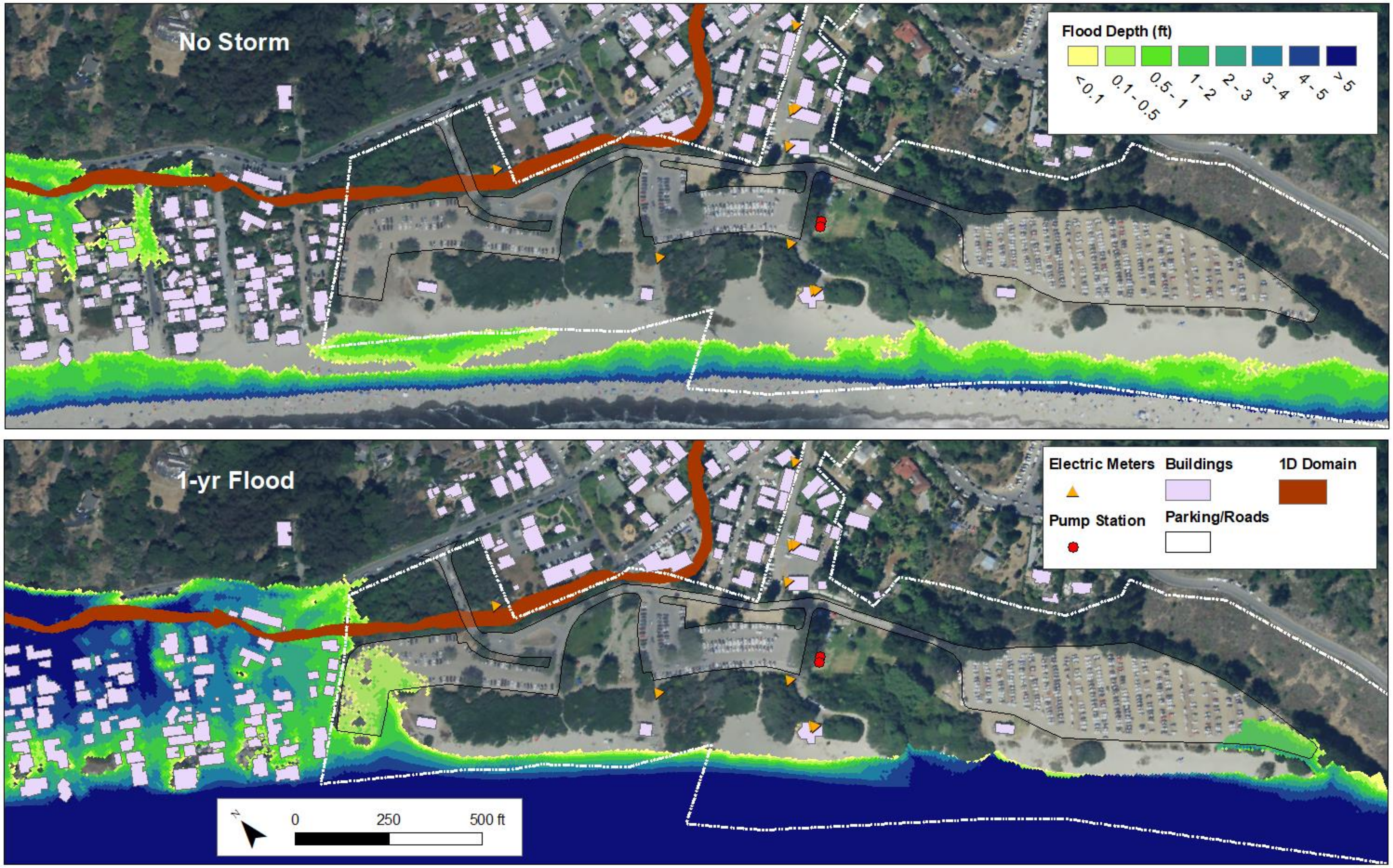

Figure 16: Combined coastal/riverine flooding for the 'no storm' (top) and 1-yr recurrence interval (bottom) storm events under the 1.0 m sea level rise condition.

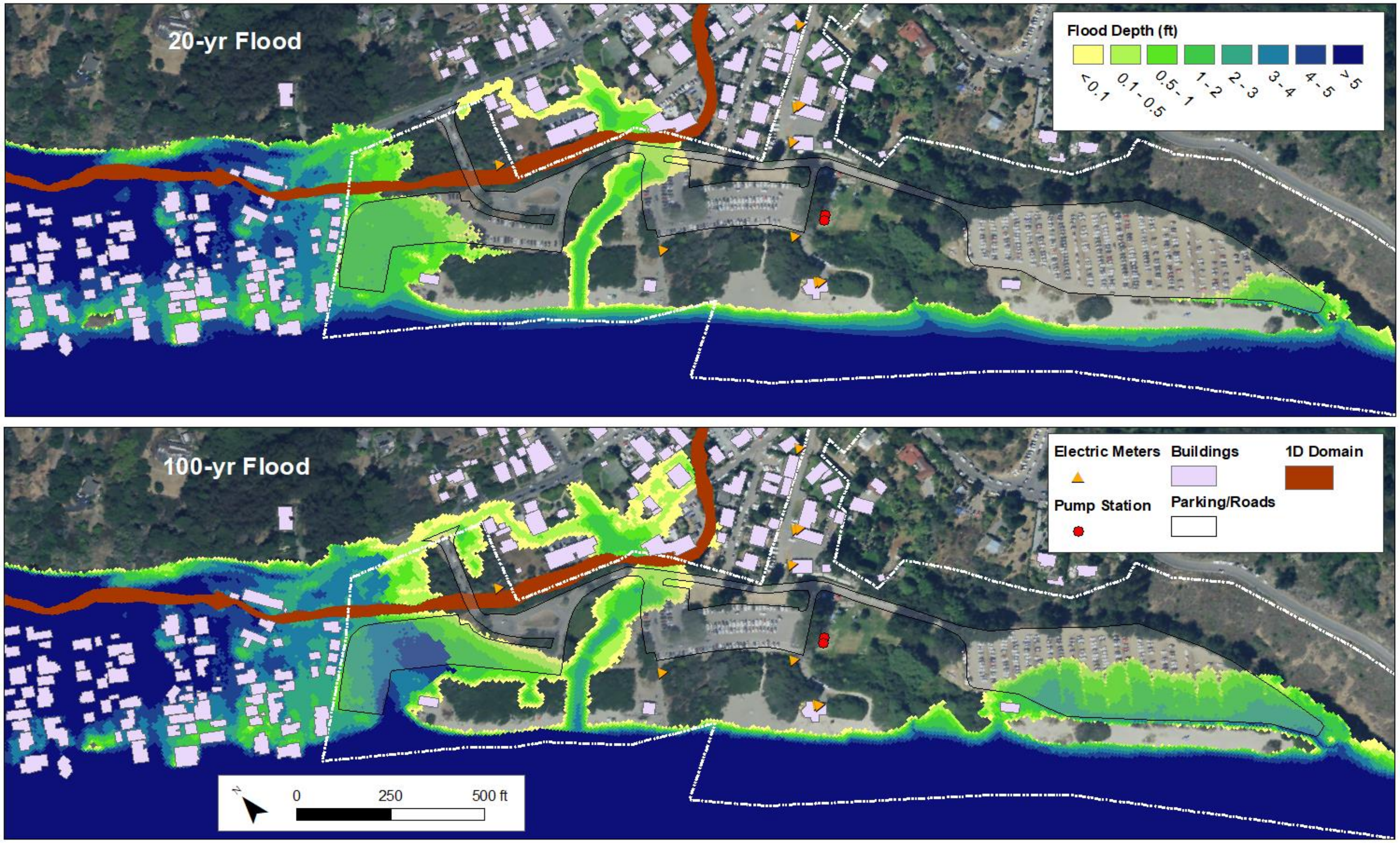

Figure 17: Combined coastal/riverine flooding for the 20-yr (top) and 100-yr recurrence interval (bottom) storm events under the 1.0 m sea level rise condition. Note that the dominant flow direction over the berm on the north edge of the north parking lot is from the GGNRA to the Calles.

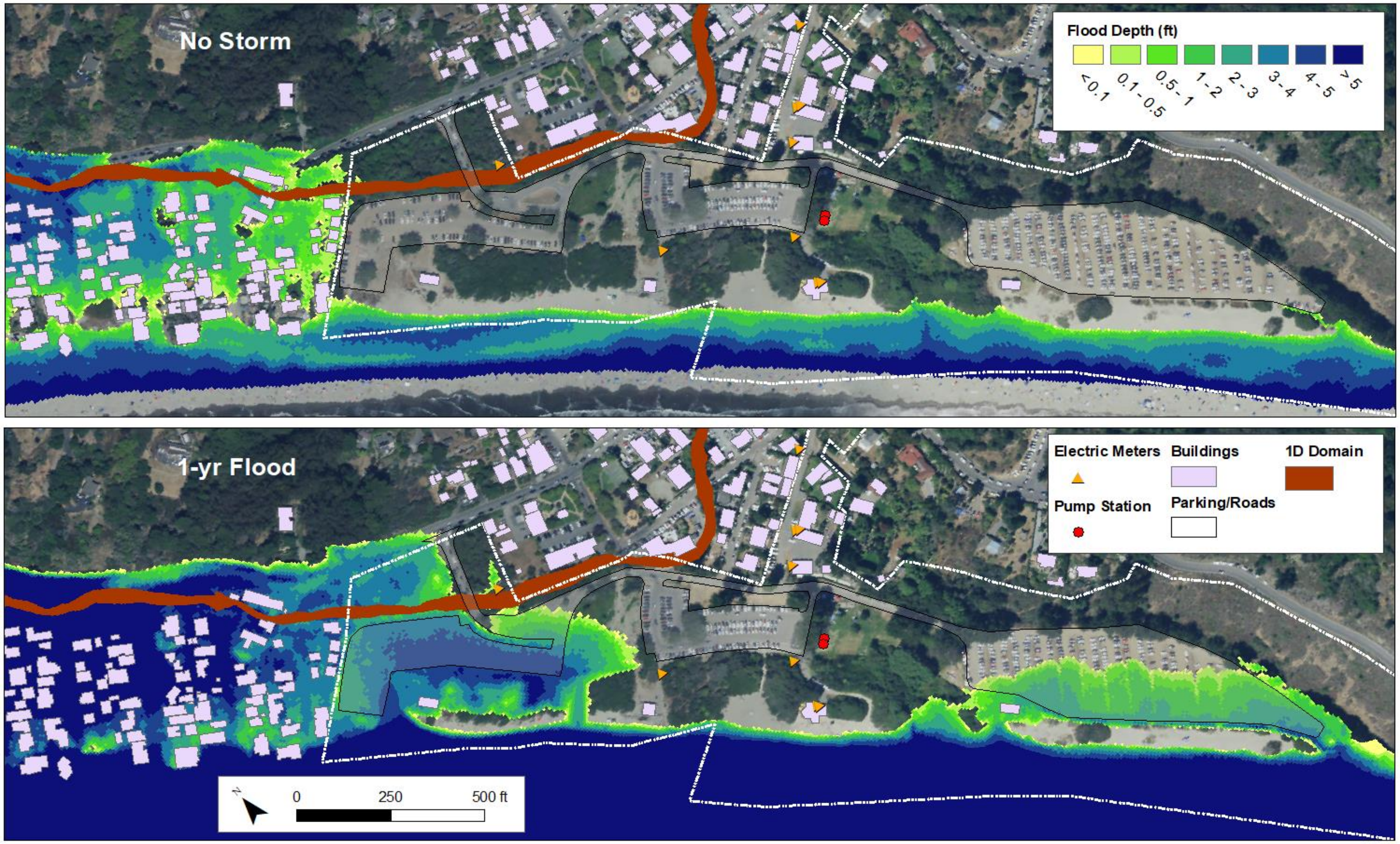

Figure 18: Combined coastal/riverine flooding for the 'no storm' (top) and 1-yr recurrence interval (bottom) storm events under the 2.0 m sea level rise condition. Note that the dominant flow direction over the berm on the north edge of the north parking lot is from the GGNRA to the Calles.

Figure 19: Combined coastal/riverine flooding for the 100-yr recurrence interval storm event under the 2.0 m sea level rise condition. Note that the dominant flow direction over the berm on the north edge of the north parking lot is from the GGNRA to the Calles.

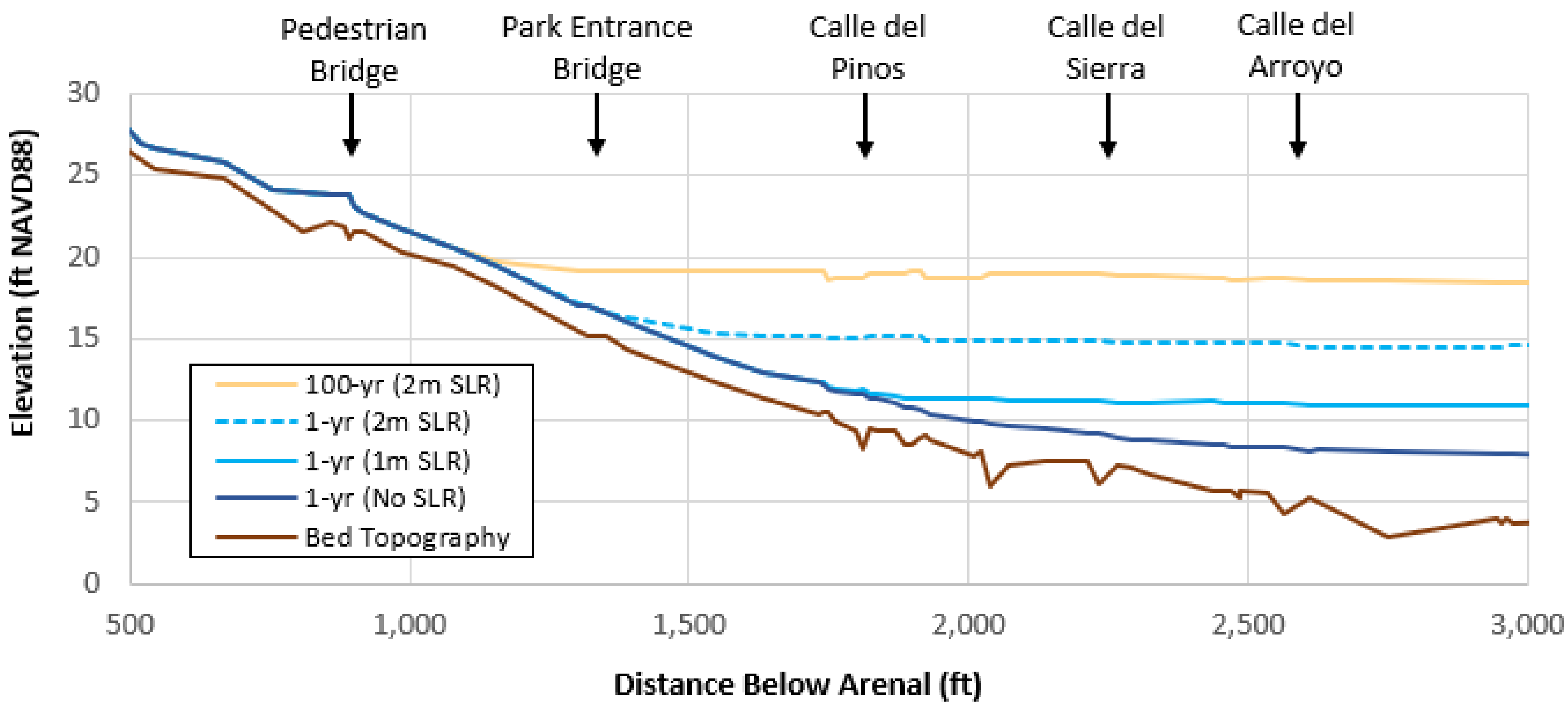

Figure 20: Water surface profiles of Easkoot Creek for selected storm event and sea level rise conditions

5.0 - Predicted Groundwater Emergence

In addition to impacts from coastal and riverine flood processes, increases in sea level may lead to long-duration flooding by raising the groundwater table above the land surface. The potential for groundwater emergence was assessed for the range of sea level rise scenarios considered in the study (0-2.0 m). As a first step, data from NPS monitoring wells was used to develop spatially distributed estimates of typical summer and winter groundwater table elevations. These were considered to represent the groundwater table in the absence of sea level rise. Predicted increases in groundwater elevations resulting from sea level rise based on the regional groundwater modeling work of Befus et al. (2020) were then used to adjust the existing groundwater elevations to account for changes in sea level.

5.1 - Existing Conditions

Groundwater elevation data was available at 31 wells distributed across the Stinson Beach property (Figure 21). Wells were monitored intermittently at monthly intervals by NPS staff and interns between 2004 and 2011, spanning a number of wet and dry winters. Development of water table elevations was limited by the quantity and quality of available measurements. The most significant limitation was collection frequency. The monthly observations collected are sufficient to capture seasonal trends but may omit short-term increases in the water table following large storms. Observations also show that fluctuations in groundwater elevations are complex and that there is not a single sampling day which yielded the highest or lowest water table elevations across the property. Rather, maximum and minimum elevations were observed at different days at different locations. Additionally, the dataset contains large amounts of missing data.

In light of these limitations, water surface elevations were developed for seasonally high (winter) and seasonally low (summer) conditions. Each surface is based on a single day from the monitoring record. For the winter conditions a day (February 18th, 2004) was selected where water surface elevations in each well were at or near their observed maximum. For summer conditions, a day (June 3rd, 2007) was selected where all wells were near their summer average over the monitoring period. Where records were missing from individual wells on these days, static water levels were estimated based on observed gradients to nearby wells observed during corresponding times of the year.

Spatially distributed estimates of water table elevations were developed by linearly interpolating static water levels between the monitoring wells. In many places, monitoring wells were located near, but not at the boundary of the study area. In such cases, the observed gradient between nearby wells was used to extend the coverage. In addition to monitoring wells, water levels in Easkoot Creek provide valuable information about groundwater elevations. In winter, monitoring wells near Easkoot Creek show static water levels very close to the thalweg. Therefore, the water table was assumed to be directly connected to Easkoot Creek and the thalweg of the creek was considered to provide a reasonable approximation of static water levels in the vicinity of the creek. In summer, static water levels are close to the thalweg of Easkoot

Creek upstream of the sedimentation basin but are several feet lower than the thalweg further downstream. Therefore, the thalweg of Easkoot Creek was only used as a summer water surface elevation upstream of the sedimentation basin. Further downstream the groundwater table was assumed to be disconnected from Easkoot Creek in the summer.

Both groundwater surfaces show similar flow patterns (Figure 21). The highest water surface elevations are present near the bend in Easkoot Creek. This is driven by large losses from Easkoot Creek into the alluvial fan and possibly also by the presence of fine-grained sediments. These losses result in a large groundwater mound near the central parking lot and in the unimproved area between the central and south parking lots. This mound is between 10 and 15 ft higher than the water table on comparable sections of the GGNRA to the north and south. The directions of groundwater flow radiate from this mound. In the vicinity of the mound, flowpaths are perpendicular to the beachfront and in the north and south lots, flowpaths are oriented approximately 45 degrees to the beachfront.

In the winter, shallow or emergent groundwater conditions exist across the majority of the GGNRA property (Figure 22). Emergent groundwater is mostly limited to the unimproved area between the central and south lots and to a lesser extent between the north and central lots. Groundwater is also emergent in portions of the south lot adjacent to the unimproved area. Very shallow (< 1 m) groundwater depths are present across large portions of the site. Following large storm events, short term increases in water table elevations could readily cause emergent groundwater in these areas. In the summer, groundwater elevations are 2-3 ft lower than winter elevations. Emergent groundwater persists only in a small low-lying portion of the unimproved area between the central and south lots (Figure 22). The extent of very shallow (depth <1 m) groundwater decreases to cover the two unimproved areas and adjacent portions of the three parking lots.

5.2 - Change in Groundwater Elevations

Predicted increases in groundwater elevations resulting from sea level rise are based on hydrogeologic modeling performed by the University of Arkansas (Befus et al., 2020). This modeling has been adopted by the CoSMoS project to identify areas at risk of groundwater shoaling along the entire coast of California.

Befus et al., 2020 estimated increases in groundwater tables using large-scale MODFLOW models of the entire California coastline representing the seaward flow of groundwater in response to a specified coastal water elevation. Models were run for both historic sea levels and a number of sea level rise scenarios. To facilitate the large scale of the modeling effort, these models were developed using a simplistic aquifer characterization with homogeneous hydrogeologic properties. Steady-state water tables were estimated assuming an annualized recharge rate, and the model does not account for streambed recharge, an important source of groundwater recharge at the Stinson Beach property. Because of these simplifications, these models are useful

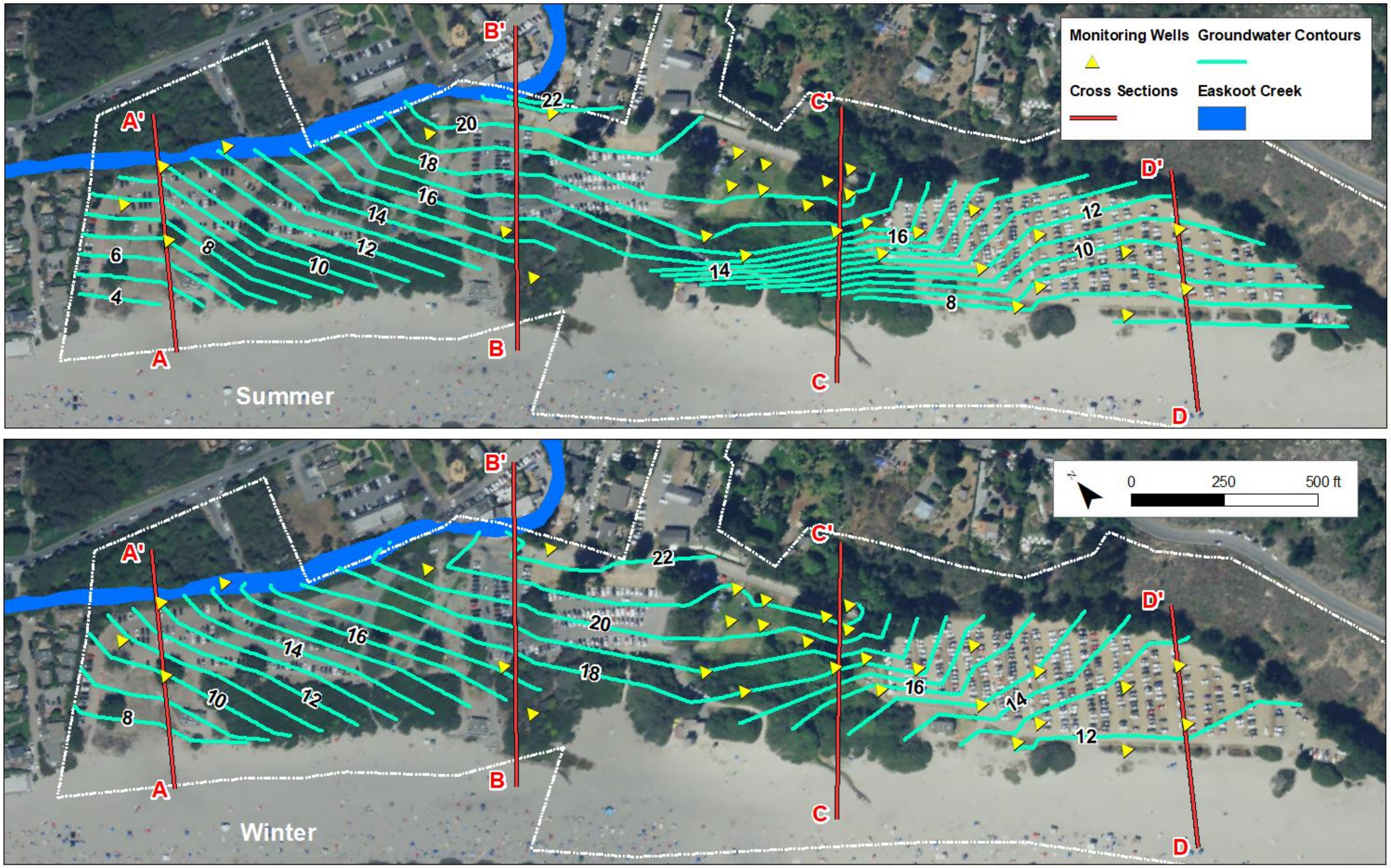

Figure 21: Representative summer (top) and winter (bottom) groundwater elevation contours under historic sea level conditions.

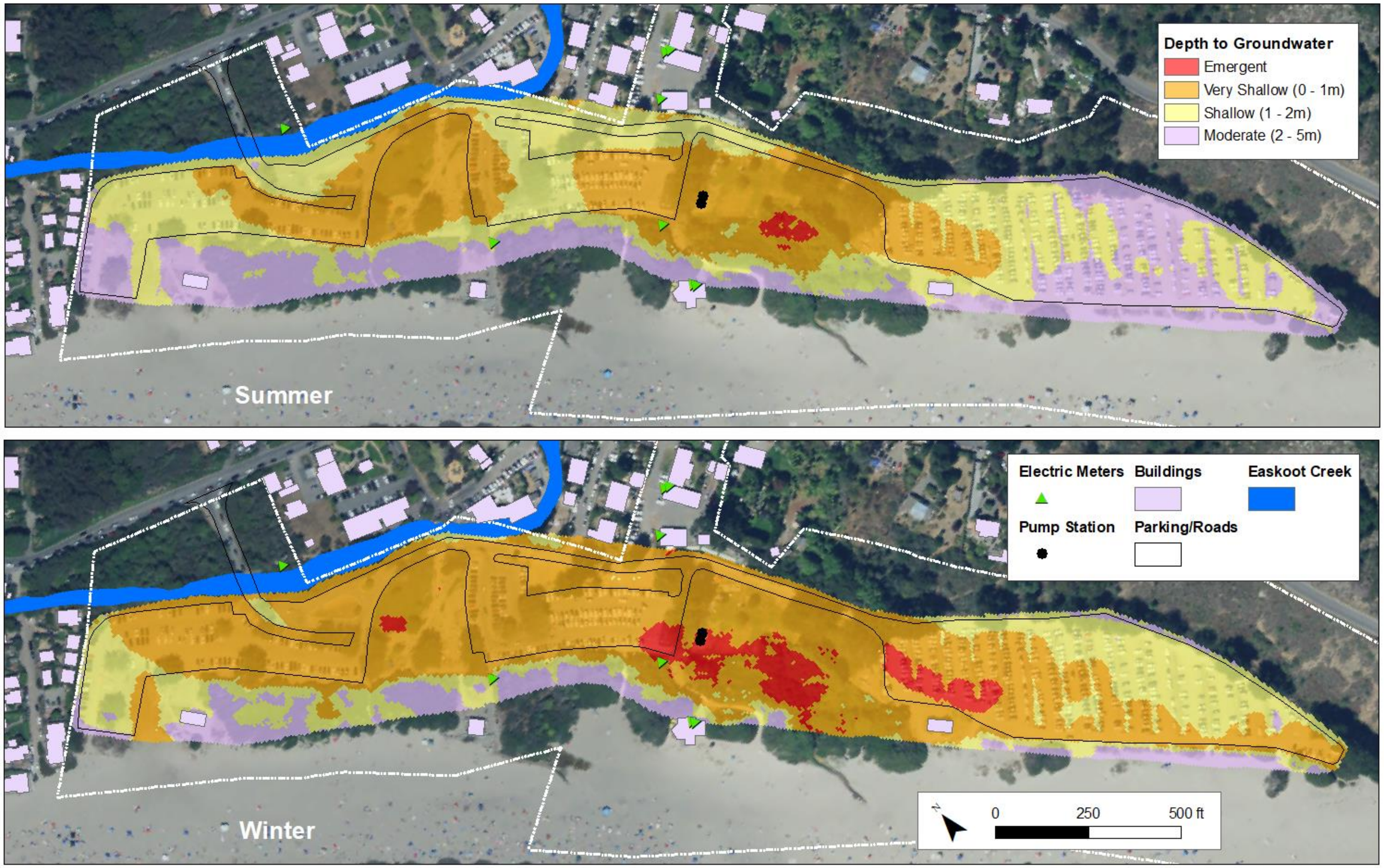

Figure 22: Representative summer (top) and winter (bottom) depths to groundwater under historic sea level conditions.

in estimating relative increases in groundwater elevations in response to specific increases in sea level, but do not accurately represent absolute static water levels at Stinson Beach.

Changes in groundwater elevation are available from several versions of the models developed by Befus et al. (2020). Different versions were developed based on different tidal boundary conditions and uniform hydraulic conductivities. Based on measured hydraulic conductivities from de Sieyes (2007 & 2011) and the sandy materials believed to be predominant at the GGNRA, model simulations conducted using a hydraulic conductivity of 10 m/d were determined to best represent overall site conditions. As discussed in Section 2.3, materials in the central portion of the property and the alluvial fan, likely contain higher proportions of fine-grained materials and simulations using a hydraulic conductivity of 0.1 or 1 m/d may be more appropriate in these areas. This is supported by static water level observations from the NPS monitoring network, where the 10 m/d model predictions best match the observed data at cross sections north and south of the fan, whereas the 1 m/d predictions best match observations from the central portion of the property (Figure 23). Another potentially significant factor contributing to elevated groundwater elevations near the alluvial fan is the presence of streambed recharge and subsurface underflow which is not accounted for in the Befus analysis.

The predictions of groundwater response to sea level rise in the GGNRA are very sensitive to the choice of hydraulic conductivity. At 1 m of sea level rise, results for 1 m/day hydraulic conductivity indicate ~0.2 m of groundwater elevation increase at the beachfront and <0.1 m near Easkoot Creek. Results for 1 m of sea level rise using 10 m/day hydraulic conductivity indicate ~0.7 m of groundwater elevation increase at the beachfront and ~0.6 m near Easkoot Creek. Given the uncertainty in the spatial and vertical extent of fine-grained deposits at the GGNRA, we focused on the 10 m/day version of the model which generated the largest groundwater level increases of the three available scenarios.

Predicted changes in static water levels were then added to the existing condition groundwater elevations developed by OEI to estimate future groundwater elevations. The results of this analysis differ from those shown in the Our Coast Our Future Hazard Map. This difference arises from the use of site specific, rather than modeled, initial groundwater elevations. The use of changes in groundwater elevation from the models developed by Befus et al. (2020) without re-running these models to account for different existing conditions poses a significant limitation to this approach. The approach may tend to over-predict groundwater shoaling since it does not account for the presence of drainage features such as Easkoot Creek and the proposed bypass channel that may limit groundwater elevation increases due to sea-level rise. However, this approach reflects the best use of available data without developing a site-specific hydrogeologic model of the site. For further discussion, refer to Section 5.4.

5.3 - Results

Based on observed water surface elevations and drillers logs from monitoring wells, surface expression of the static water table is not believed to be limited by fill material in the parking lots (Wagner and Inglis, 2004). Where emergent groundwater is predicted there will be obvious

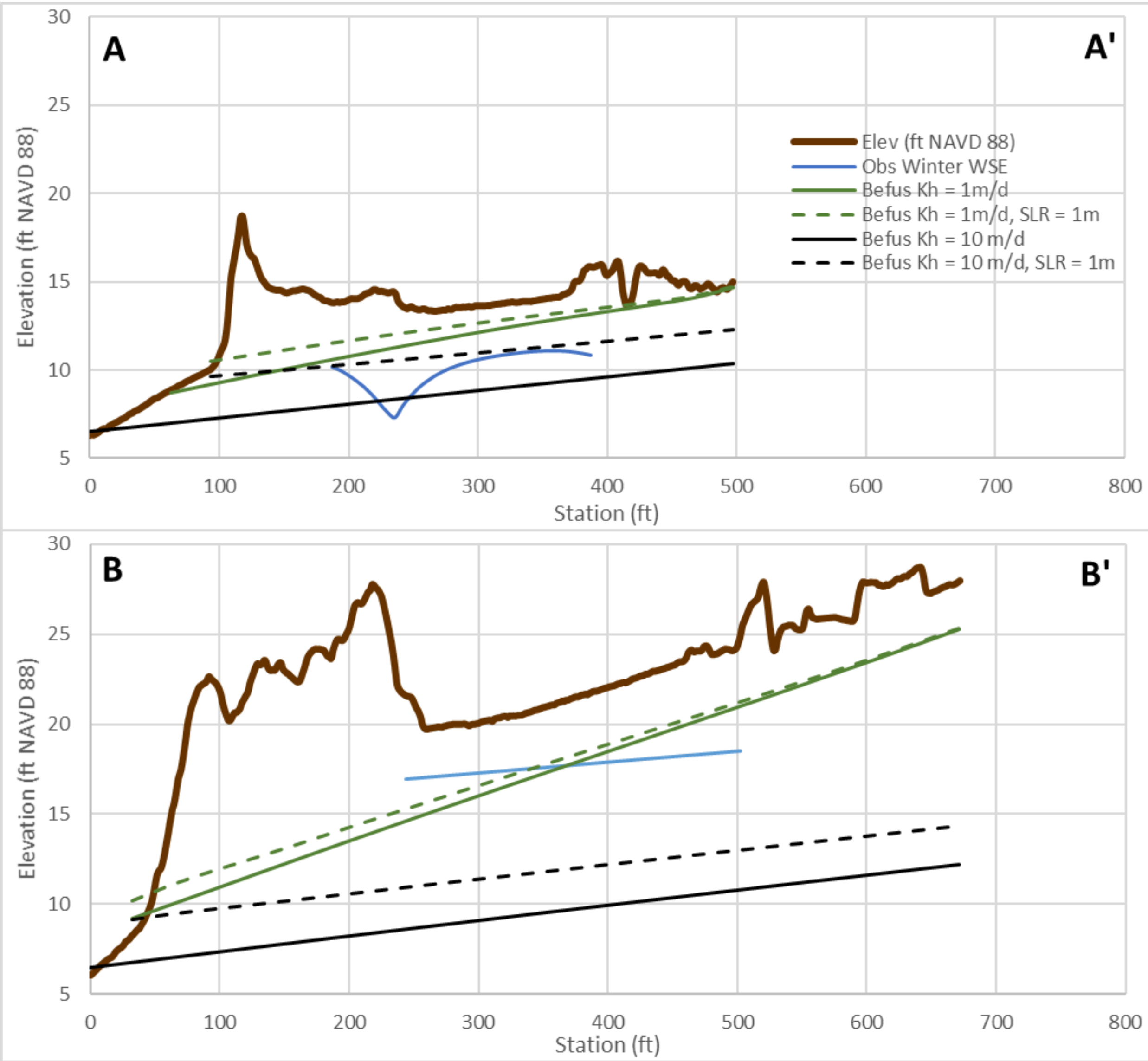

Figure 23: Observed representative water surface elevations from NPS monitoring wells versus water surface elevations predicted by Befus et al. (2020) for various hydraulic conductivity assumptions (see Figure 21 for cross section locations).

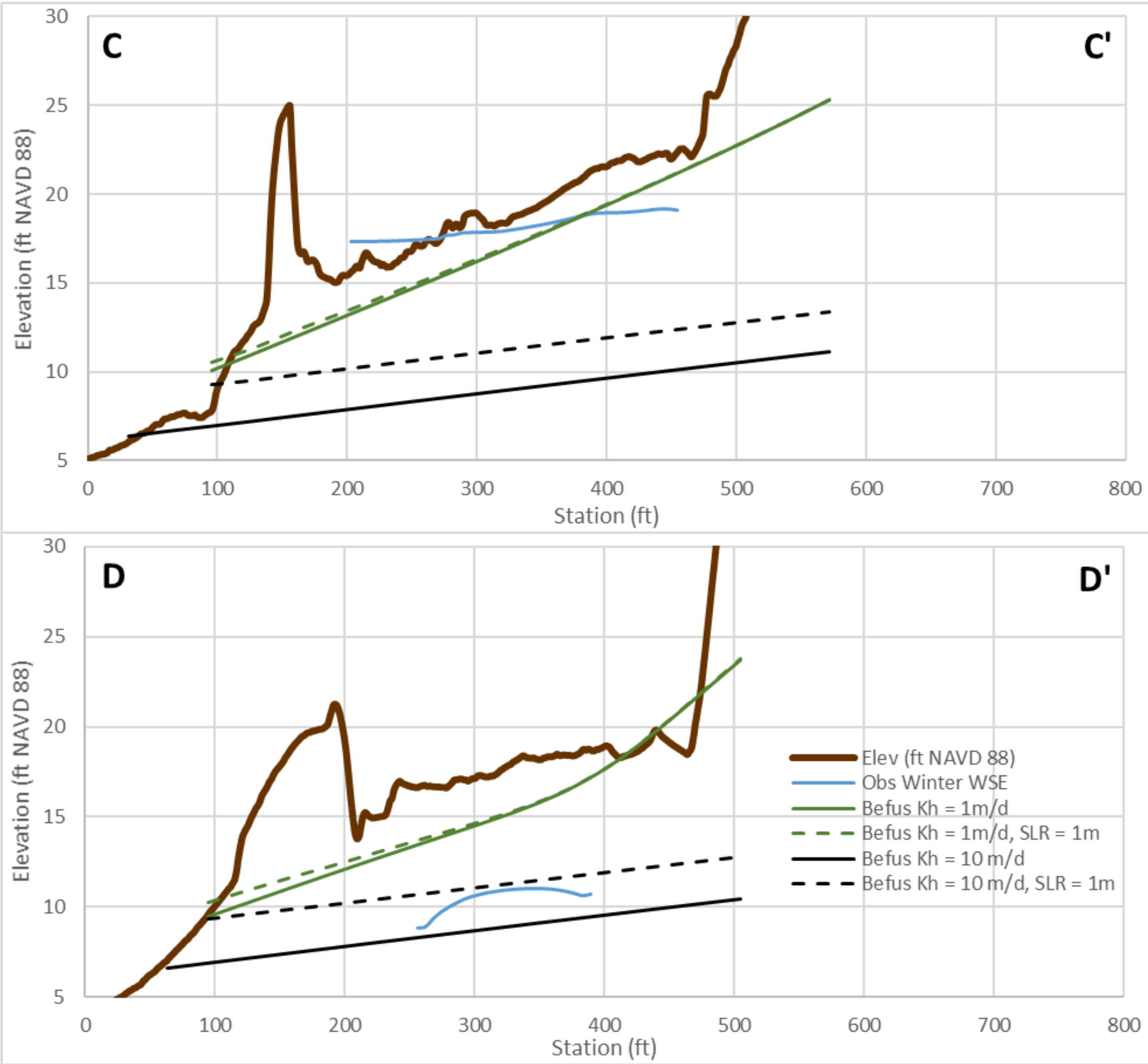

Figure 23: (continued).

impacts such as perennially wet ground, surface discharge, and changes in plant communities. Impacts to buried utilities, foundations, and plant communities may still occur where very shallow (<1 m depth) groundwater tables occur. The classification thresholds for groundwater depths were adopted from Hoover et al. (2017), a prior USGS study of groundwater shoaling along the California coast. Depths are based on the proposed condition topography developed for use in OEI's hydraulic model of Easkoot Creek (Section 4.1.2). This surface includes the proposed high-flow bypass channel but does not incorporate grading associated with parking lot realignment. However, it is assumed that any grading will be minimal and will not significantly change ground elevations.

With 0.5 m of sea level rise, emergent groundwater during winter occurs in portions of all three parking lots as well as the majority of the two picnic/unimproved areas between lots (Figure 24).

The footprint of emergent groundwater shrinks significantly during summer with only limited impacts to the parking lots. Very shallow (<1 m) groundwater tables occur in much of the remaining area of the GGNRA. In response to a 1.0 m rise in sea levels, the previous trends will intensify. Large portions of the three parking lots experience emergent groundwater during winter and perennial groundwater emergence occurs in portions of the central and south lots (Figure 25). A 2.0 m rise in sea levels may cause groundwater emergence across almost the entire property during winter. Emergent groundwater would persist year-round in the central parking lot and significant portions of the north and south lots (Figure 26).

5.4 - Limitations

The methodologies and results presented above are intended to provide a preliminary analysis of groundwater emergence using available data and previous regional modeling of sea level rise impacts. As such, there are several key limitations that must be considered when interpreting results for management decisions. These include but are not limited to:

- Existing condition water surface elevations are based on seasonal averages, not event maximums. In the days after a large rainfall event, water surface elevations may be significantly higher than estimated for winter conditions. While the soils will drain back to seasonal levels, shallow or emergent groundwater may be present in areas not shown in the days following such events.
- Changes in groundwater elevations are used directly from Befus et al. (2020) without correction for differences in existing conditions. Use of site-specific data for initial conditions may result in lower predictions of future groundwater elevations.
- Predictions of groundwater changes due to sea level rise are very sensitive to the choice of aquifer properties. We utilized the set of results that most closely matched available data which generates the largest predicted increases in elevations, however the presence of finer aquifer material in the central portion of the site may result in over-prediction of groundwater elevation increases in this area.
- The approach does not account for the role of drainage features in reducing groundwater elevations. Surface water/groundwater interaction between Easkoot Creek and the aquifer is an important process at the site, however neither the Befus et al. (2020) study nor this analysis directly considers these exchanges. Similarly, construction of the bypass channel may significantly alter subsurface drainage patterns near the north and south parking lots, however it is not directly considered in the future condition groundwater emergence mapping.
- The approach does not account for streambed recharge and subsurface inflows originating from the alluvial fan which may be substantial.
- Dune topography and position was assumed to be constant for this analysis, however without intervention dune retreat is expected to occur as sea levels rise, potentially altering subsurface drainage patterns.

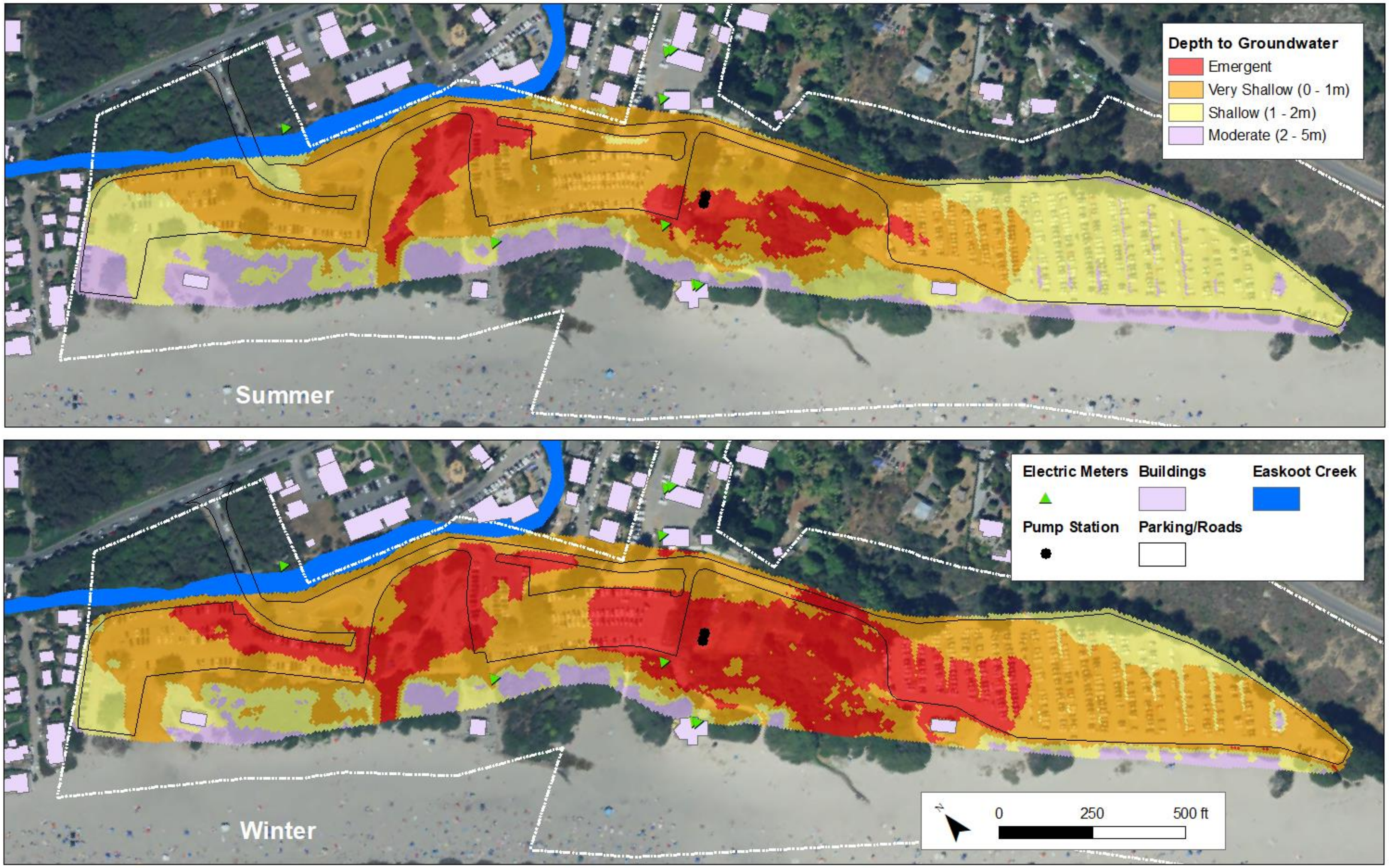

Figure 24: Estimated depths to representative summer (top) and winter (bottom) groundwater tables with 0.5 m of sea level rise assuming hydraulic conductivity of 10 m/day.

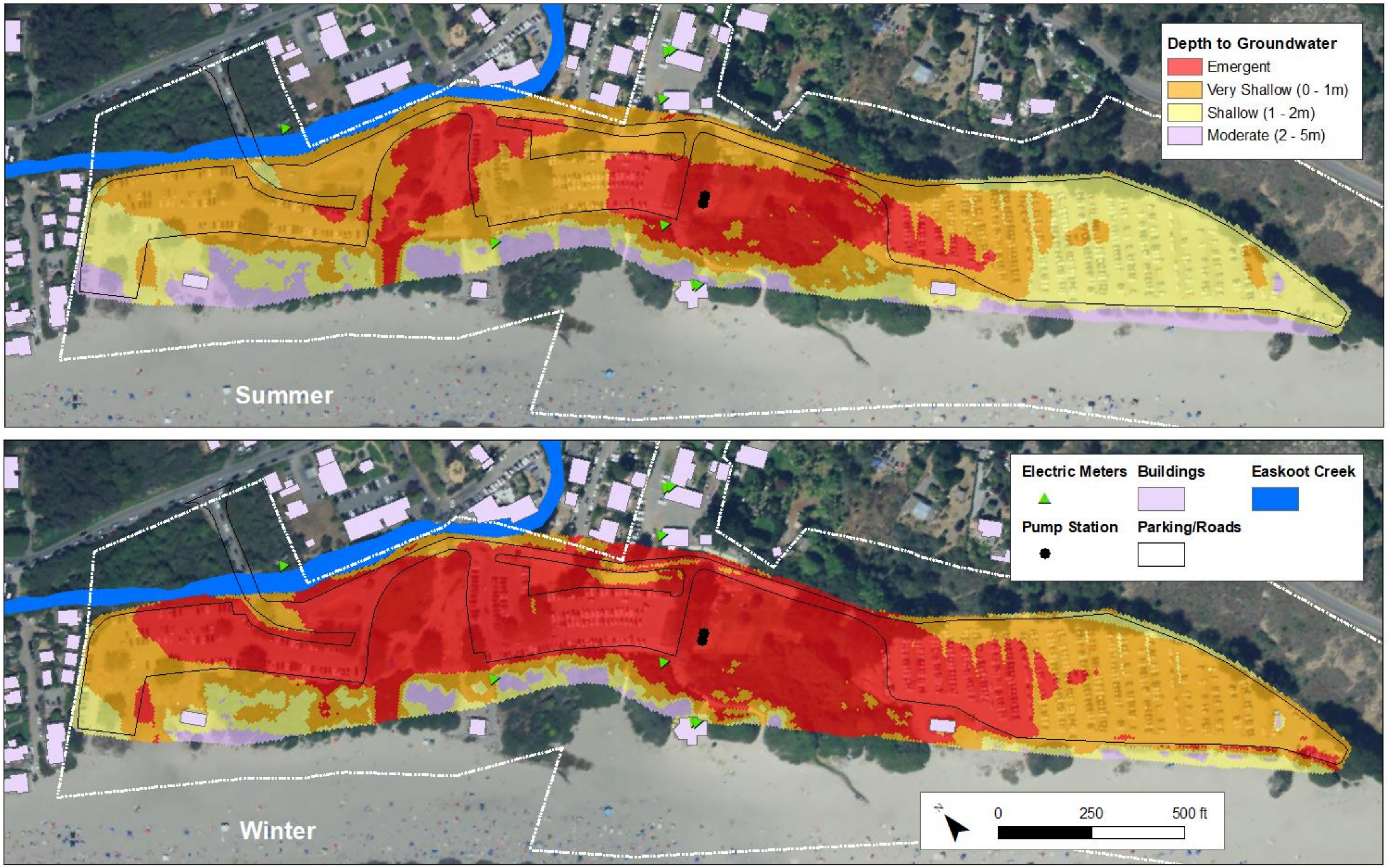

Figure 25: Estimated depths to representative summer (top) and winter (bottom) groundwater tables with 1.0 m of sea level rise assuming hydraulic conductivity of 10 m/day.

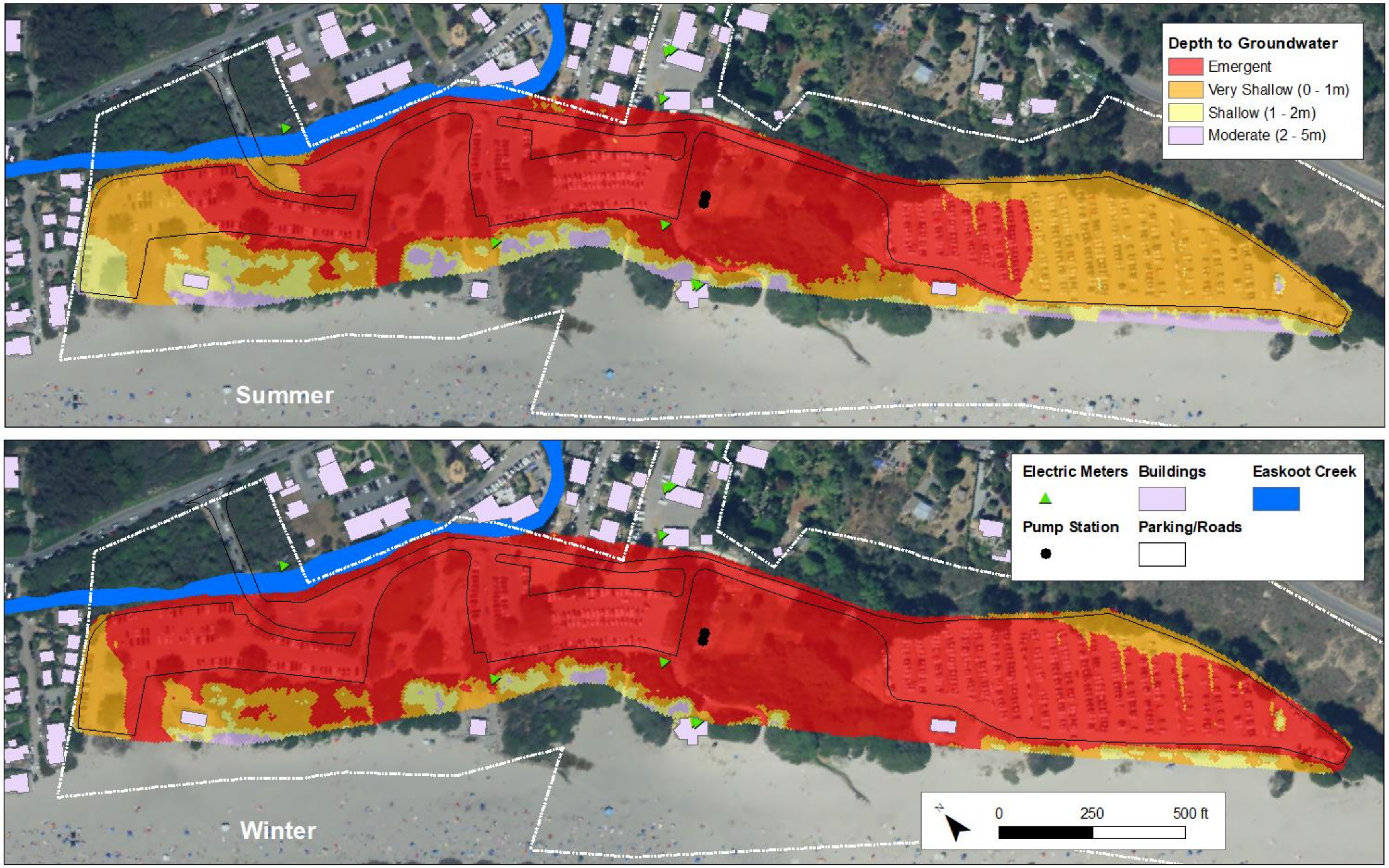

Figure 26: Estimated depths to representative summer (top) and winter (bottom) groundwater tables with 2.0 m of sea level rise assuming hydraulic conductivity of 10 m/day.

The results presented above represent the leveraging of best available existing data and regional studies. However, given the significant uncertainty regarding future groundwater elevations, we recommend additional data collection and analysis to better constrain the expected groundwater responses to rising sea levels. Existing monitoring wells should be re-occupied or new wells should be drilled and monitored regularly in areas of concerns. Drilling in areas lacking deeper subsurface information would allow for an improved understanding of the spatial distribution of coarse and fine sediments. Seepage runs could be conducted on Easkoot Creek to better constrain streambed infiltration rates. A site-specific surface water/groundwater model of the property would allow for a more accurate assessment of groundwater emergence. Such modeling should account for streambed recharge and groundwater underflow as well as the presence of drainage features such as the proposed bypass channel. The potential that excavation of the bypass channel would induce additional streambed losses in Easkoot Creek with associated impacts to salmonids could also be investigated using an integrated surface water/groundwater model.

6.0 – Coastal/Riverine & Groundwater Flooding Feedbacks

As sea levels rise, it is possible that coastal and riverine flood impacts may be exacerbated by the presence of expanded areas of groundwater emergence. The most likely impacts would be related to the proposed bypass channel and the potential for the capacity of the channel to decrease due to the presence of shallow groundwater. To examine this potential, we plotted the existing winter and summer groundwater elevations relative to the thalweg and banks of the proposed bypass channel. This comparison indicates that existing groundwater elevations are near the proposed thalweg elevation during summer and several feet above the thalweg during winter (Figure 27). With 1.0 m of sea level rise, groundwater elevations are projected to increase above the banks of the bypass channel. MHHW elevations at the outlet of the bypass channel remain below proposed thalweg elevations with 0.5 and 1.0 m of sea level rise and increase just above the thalweg with 2.0 m of sea level rise. These comparisons suggest that between storms, water in the bypass channel should remain able to readily discharge to Bolinas Bay under all but the most extreme sea level rise conditions. As discussed above in Section 5.4, the presence of the bypass channel is expected to act as a groundwater drain suppressing groundwater elevations below the projected levels in our analysis which does not consider the role of drainage features.

Nevertheless, given that existing groundwater elevations project above the thalweg of the bypass channel it is likely that groundwater shoaling may reduce the capacity of the bypass channel to convey flood flows from Easkoot Creek as sea levels rise. An additional version of the hydraulic model topography was generated by filling in the bypass channel to the elevations described by the existing condition winter groundwater elevations. This topography was evaluated for the 20-yr event with 1.0 m of sea level rise to better understand how combined coastal/riverine flooding at the site may increase due to reduced bypass capacity generated by groundwater encroachment. Results indicate that with groundwater encroachment, the bypass channel would cease to contain the 20-yr overbank flows from Easkoot Creek resulting in additional flooding of the north and central parking lots and the unimproved areas surrounding the bypass channel

(Figure 28). These results indicate flood extents similar to those generated using the existing conditions topography without the bypass channel.

As discussed in Section 5.4, the future condition groundwater elevation predictions contain a high degree of uncertainty. Given this uncertainty, the combined coastal/riverine flood predictions without groundwater encroachment were retained for the subsequent vulnerability assessment, however the above results demonstrate the potential for feedbacks between coastal/riverine flood processes and emergent groundwater. If a more detailed analysis of groundwater elevation increases due to rising sea levels is undertaken, predictions of future groundwater emergence can be used to update coastal/riverine flood simulations to account for these feedbacks. Although such feedbacks are primarily expected to influence the effectiveness of the bypass channel, the presence of emergent groundwater may also potentially exacerbate coastal/riverine flooding in other areas of the GGNRA. At the present time, groundwater flooding is, however, only considered as a separate flooding source.

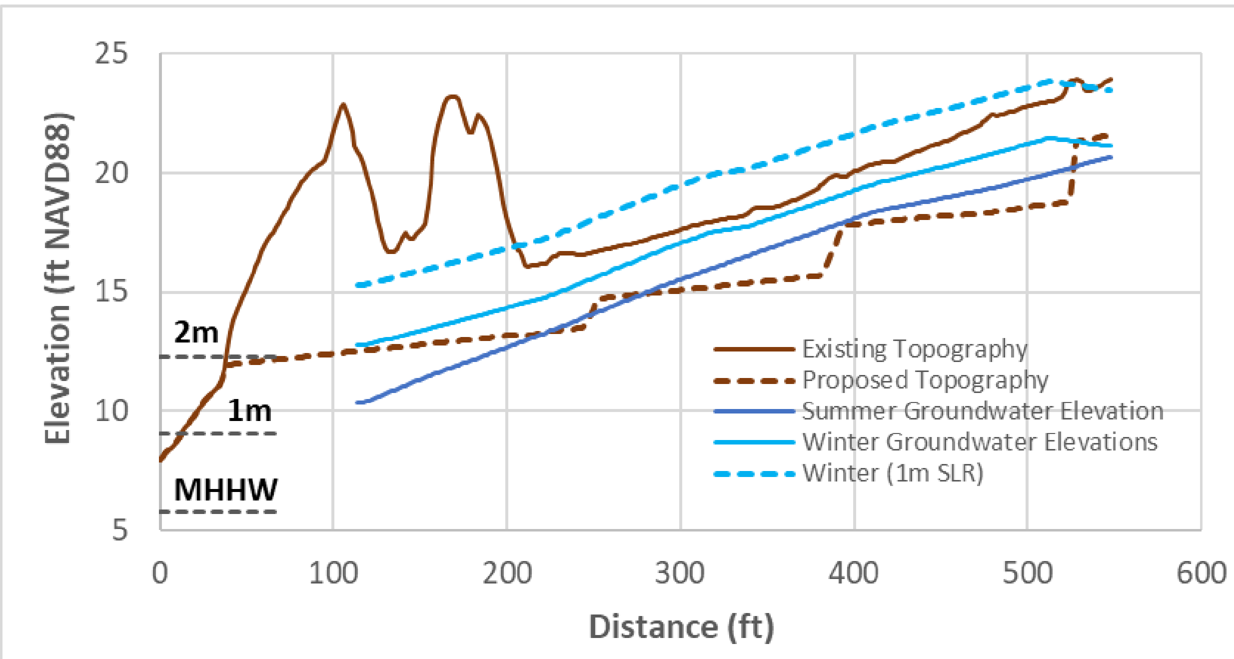

Figure 27: Longitudinal profile of the proposed bypass channel compared to water surface elevations under existing and future sea level conditions.

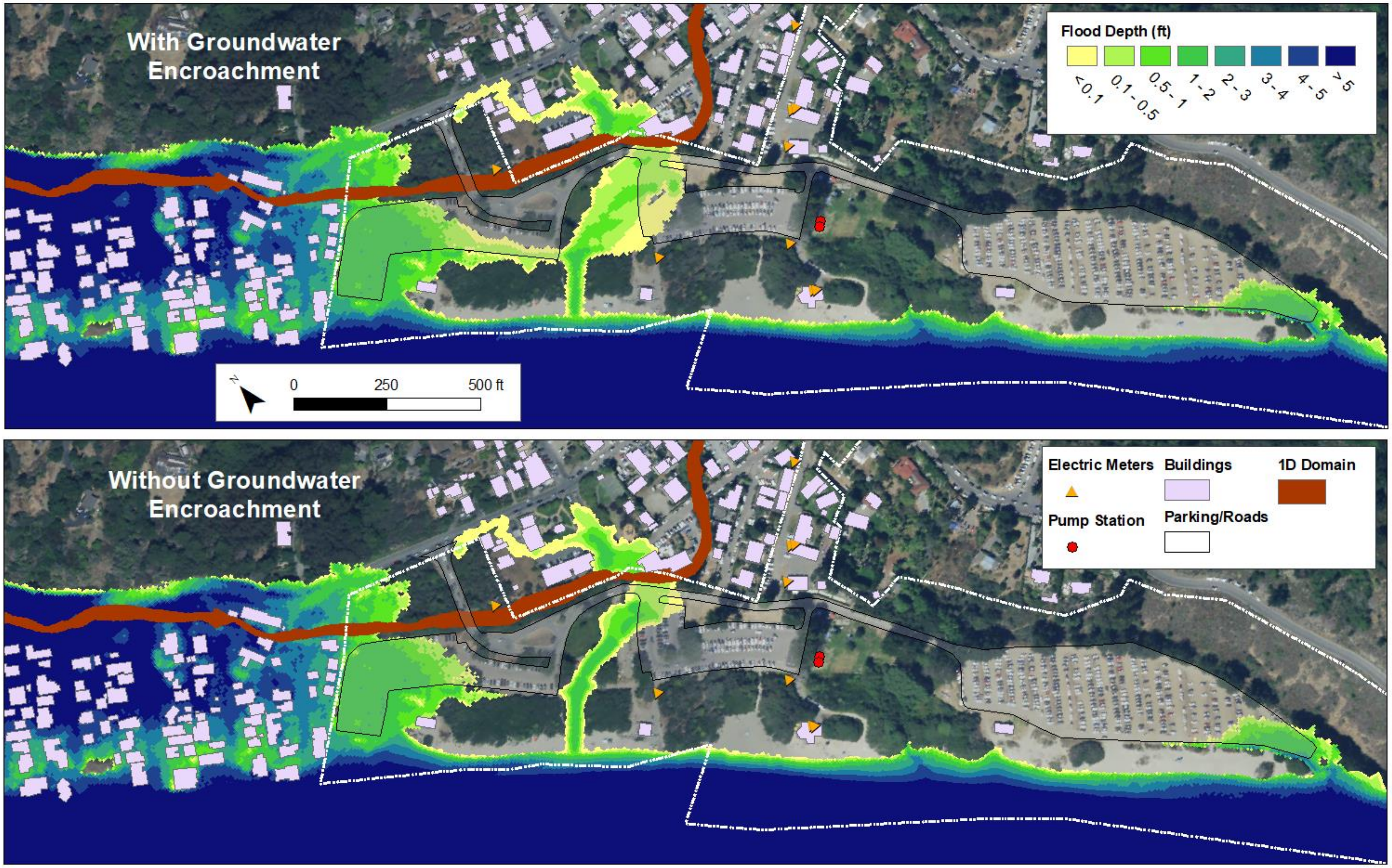

Figure 28: Combined coastal/riverine flooding for the 20-yr recurrence interval event with 1.0 m of sea level rise accounting for reduced bypass capacity due to groundwater encroachment (top) and without consideration of emergent groundwater (bottom).

7.0 - Vulnerability Assessment

A vulnerability assessment was performed for key areas and critical infrastructure at the GGNRA including the various parking lots, bathrooms, and electric meters, as well as the septic pump station. Of the three parking lots, the central lot is the most resilient to flooding (Figure 29). Under existing sea level conditions, the north and central parking lots are subject to coastal/riverine flooding during the 100-yr event, and the central and south lots may also be subject to flooding from emergent groundwater. With 0.5 m of sea level rise, the north and south lots will become subject to coastal/riverine flooding during the 20-yr event, and the central lot will remain subject to flooding during the 100-yr event. With 1.0-2.0 m of sea level rise, the north and south lots will become subject to flooding during the 1-yr event, and the central lot will remain subject to flooding during the 100-yr event. All three lots may also be subject to flooding from emergent groundwater for sea level rises of 0.5-2.0 m (Figure 29).

Of the three bathrooms, the central bathroom is the most resilient to flooding owing to its sheltered location behind sand dunes and away from flood flow paths originating from Easkoot Creek (Figure 30). Under existing sea level conditions, the three bathrooms are not subject to flooding over the range of simulated events. With 0.5 m of sea level rise, the south bathroom is subject to flooding during the 100-yr event. With 1.0 m of sea level rise, the north bathroom is subject to flooding during the 20-yr event, and the south bathroom remains subject to flooding during the 100-yr event. With 2.0 m of sea level rise, both the north and south bathrooms will become subject to flooding during the 1-yr event. The south bathroom may also be subject to flooding from emergent groundwater for sea level rises of 0.5-2.0 m (Figure 30).

None of the electric meters or the wastewater pump station are subject to coastal/riverine flooding over the range of simulated storm events and sea level rise conditions (Figure 31). The central electric meter located near the south edge of the central parking lot as well as the wastewater pump station may be subject to flooding from emergent groundwater under existing sea level conditions and such flooding should be expected to increase in frequency and duration as sea levels rise (Figure 31).

As discussed in Section 5.4, the groundwater analysis contains a high degree of uncertainty. Additionally, the degree to which operation of the electric meters and the wastewater pump station are impacted by the presence of shallow or emergent groundwater is dependent on the specific designs of these features which were not considered in detail. Nevertheless, the central electric meter and the wastewater pump station appear to be the most vulnerable facilities at the GGNRA with possible impacts from groundwater flooding occurring even under existing sea level conditions. Such flooding is predicted to be seasonal under current conditions but may become perennial with as little as 0.5 m of sea level rise. The central and south parking lots are also particularly vulnerable to flooding from emergent groundwater and the south bathroom may begin to experience impacts from groundwater with as little as 0.5 m of sea level rise. With

1.0 m of sea level rise, the most vulnerable facilities subject to impacts from coastal/riverine flooding include the north and south parking lots which may become impacted during relative frequent events such as the 1-yr flood as well as the north bathroom which may become subject to flooding during the 20-yr event.

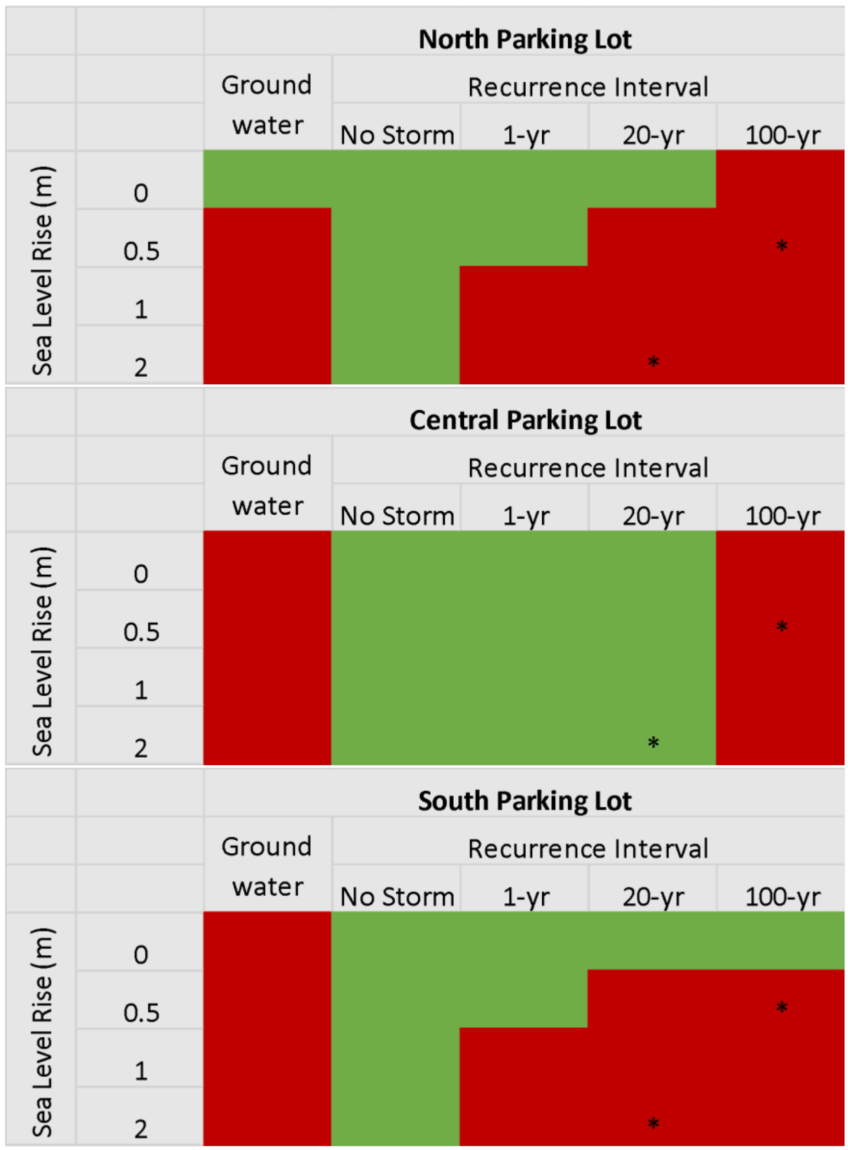

Figure 29: Flood risk matrix for the three parking lots at the GGNRA. Green indicates unimpacted and red indicates impacted. Events denoted with the * symbol were inferred from CoSMoS results and other events.

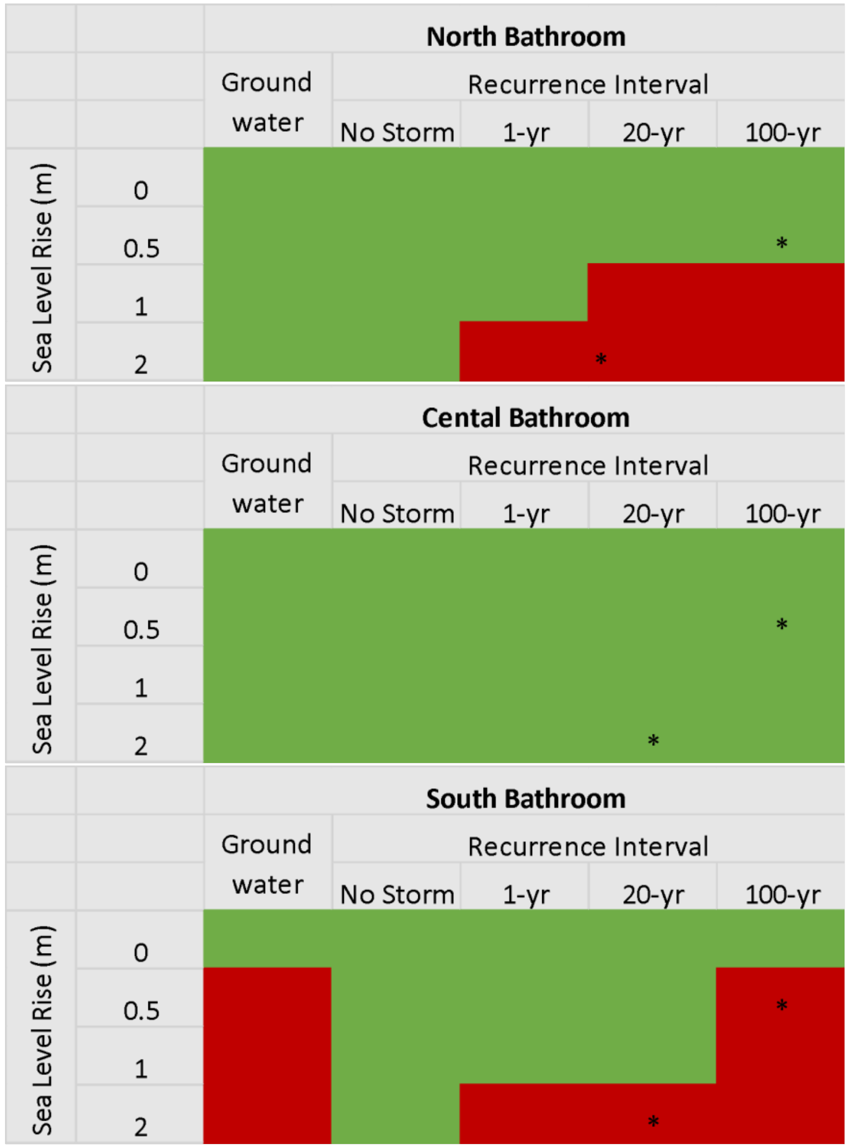

Figure 30: Flood risk matrix for the three bathrooms at the GGNRA. Green indicates unimpacted and red indicates impacted. Events denoted with the * symbol were inferred from CoSMoS results and other events.

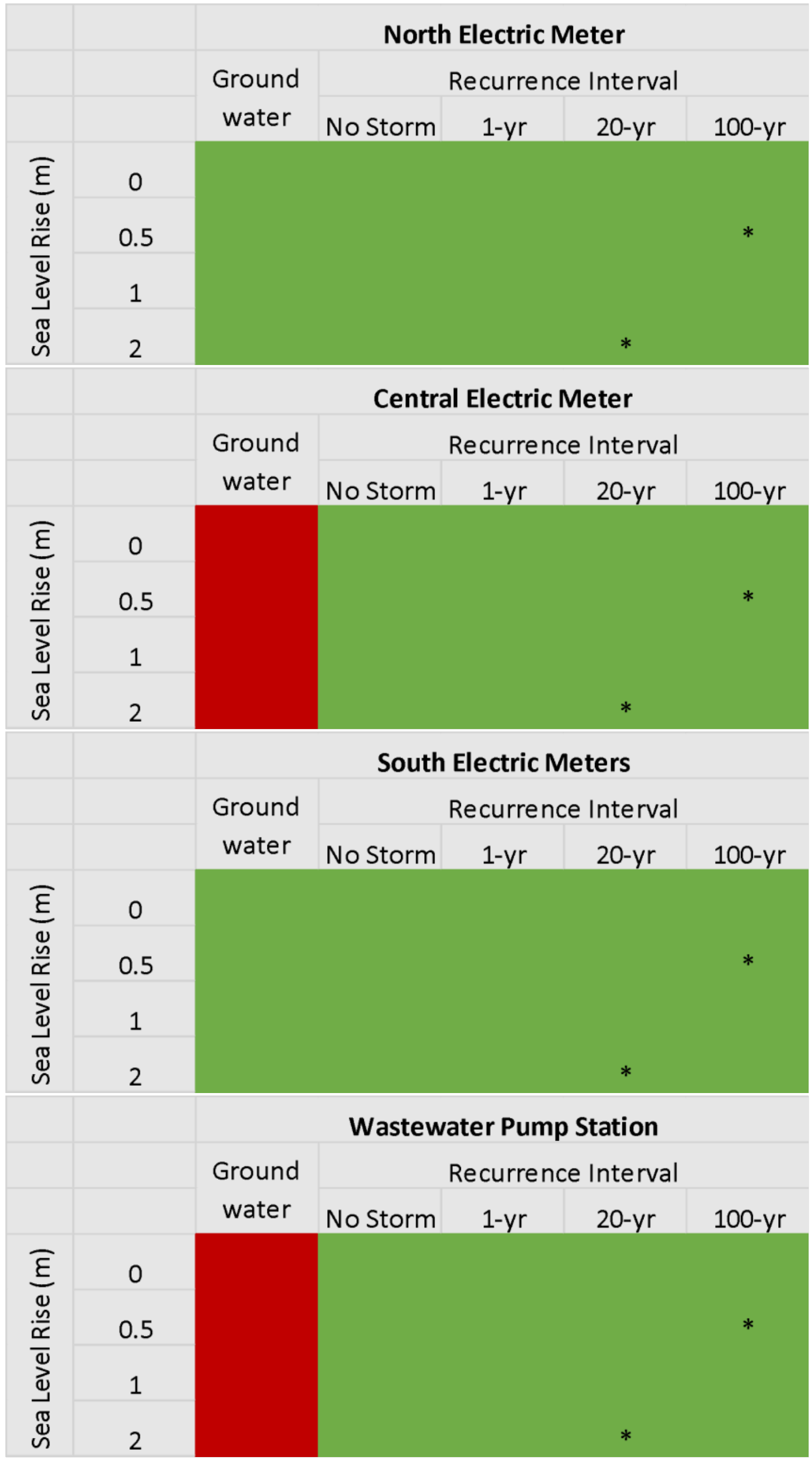

Figure 31: Flood risk matrix for the electric meters and wastewater pump station at the GGNRA. Green indicates unimpacted and red indicates impacted. Events denoted with the * symbol were inferred from CoSMoS results and other events.

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