City of Arcata Sea Level Rise Risk Assessment

April, 2018

CONTENTS

City of Arcata

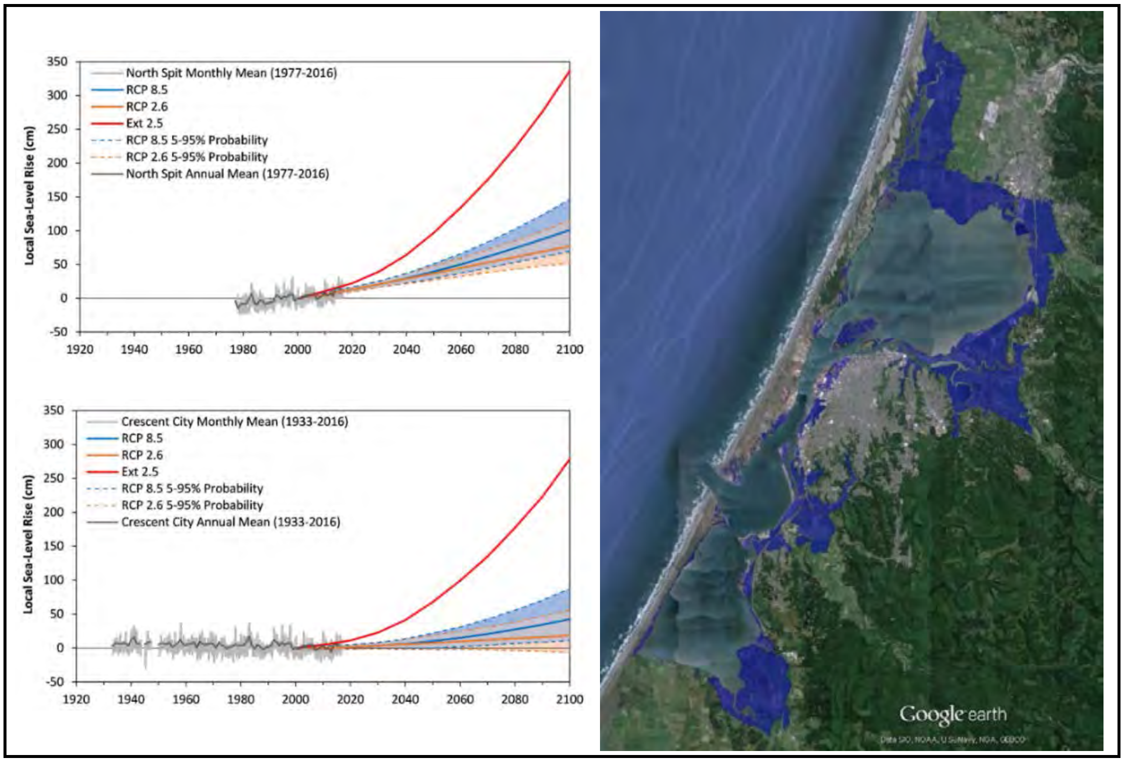
DRAFT Sea Level Rise Report Executive Summary

April 2018

The City of Arcata contracted with Jeff Anderson of Northern Hydrology Associates to provide background information on sea level rise science with focus on Humboldt Bay and the City of Arcata. The City also contracted with Aldaron Laird of Trinity Associates to provide natural habitat mapping and complete a vulnerability and risk assessment of assets at risk from sea level rise within the City of Arcata.

This document is a place holder for the Executive Summary that will be completed prior to the Study Session scheduled for Monday, April 30, 2018. The intent of the Executive Summary is to distill the complicated scientific information and concepts into plain language for the reader to better comprehend.

Sea-Level Rise in the Humboldt Bay Region



March 2018

Prepared for

City of Arcata
736 F Street
Arcata, CA 95521

Prepared by

Jeffrey K. Anderson
Northern Hydrology & Engineering
P.O. Box 2515
McKinleyville, CA 95519

Sea-Level Rise in the Humboldt Bay Region

Sea-level rise is one of the most evident and problematic consequences of global climate change. As the earth's climate warms, sea levels increase primarily from thermal expansion of a warmer ocean and melting land ice (NRC, 2012). In California, sea-level rise will threaten and directly affect vulnerable coastal ecosystems, bays and estuaries, coastal communities and infrastructure due to increased flooding, gradual inundation, and erosion of the coastal shorelines, cliffs, bluffs and dunes (Russell and Griggs, 2012). If sea level continues to rise at present rates, identified impacts could take decades or longer to occur. However, a troublesome aspect of climate change and the rapid warming of the earth's atmosphere and ocean is the potential for sea-level rise to accelerate to high rates over a short period of time, in which case the identified impacts could happen within a much shorter period (years to decades). Although there is uncertainty in the timing of sea-level rise and future impacts, society still needs to plan for, and adapt to higher sea levels.

The coasts of Humboldt and Del Norte Counties are experiencing the combined effects of global sea-level rise, regional sea-level height variability from seasonal to multidecadal ocean-atmosphere circulation dynamics (e.g. El Niño Southern Oscillation (ENSO)), and relatively large tectonic vertical land motions associated with the Cascadia subduction zone (CSZ) (Figure 1). These large tectonic motions along the southern CSZ create the highly variable and opposing sea-level trends observed between Humboldt Bay and Crescent City. Recent estimates of land subsidence by Patton et al. (2017) indicate that Humboldt Bay has the highest local sea-level rise rate in California, approximately two to three times higher than the long-term global rate. In contrast, the land in Crescent City (109 km north) is uplifting faster than long-term global sea level rise, which causes a negative or decreasing local sea-level rise rate.

Overview and Purpose

The purpose of this chapter is to provide an overview of global and regional sea-level rise, with an emphasis on physical processes locally affecting sea levels in the Humboldt Bay region, and provides an update to Chapter 2 of the Humboldt Bay: Sea Level Rise, Hydrodynamic Modeling, and Inundation Vulnerability Mapping report (NHE, 2015a). This overview relies on the past climate and sea-level change literature (e.g. NRC, 2012; IPCC, 2013; Church et al., 2013), the more recent sea-level science literature (e.g. Kopp et al., 2014; Kopp et al., 2015; Hall et al., 2016; Sweet et al., 2017; Griggs et al., 2017), the scientific and technical literature specific to the U.S. Pacific Northwest (PNW) coast (e.g. Burgette et al., 2009; Komar et al, 2011), and literature specific to the Humboldt Bay region (e.g. NHE, 2015a; Patton et al., 2017).

In 2017, the Ocean Protection Council (OPC) Science Advisory Team released its updated sea-level rise science report, titled Rising Seas in California: An Update on Sea-Level Rise Science (Griggs et al., 2017). The OPC report provides an update on the current state of sea-level rise science, along with a synthesis of the current scientific understanding of potential Greenland and

Antarctic ice sheet loss and implications for sea-level rise projections in California. The OPC report also provided probabilistic sea-level rise projections at three locations along the California coast (Crescent City, San Francisco, and La Jolla) based on the approach of Kopp et al. (2014).

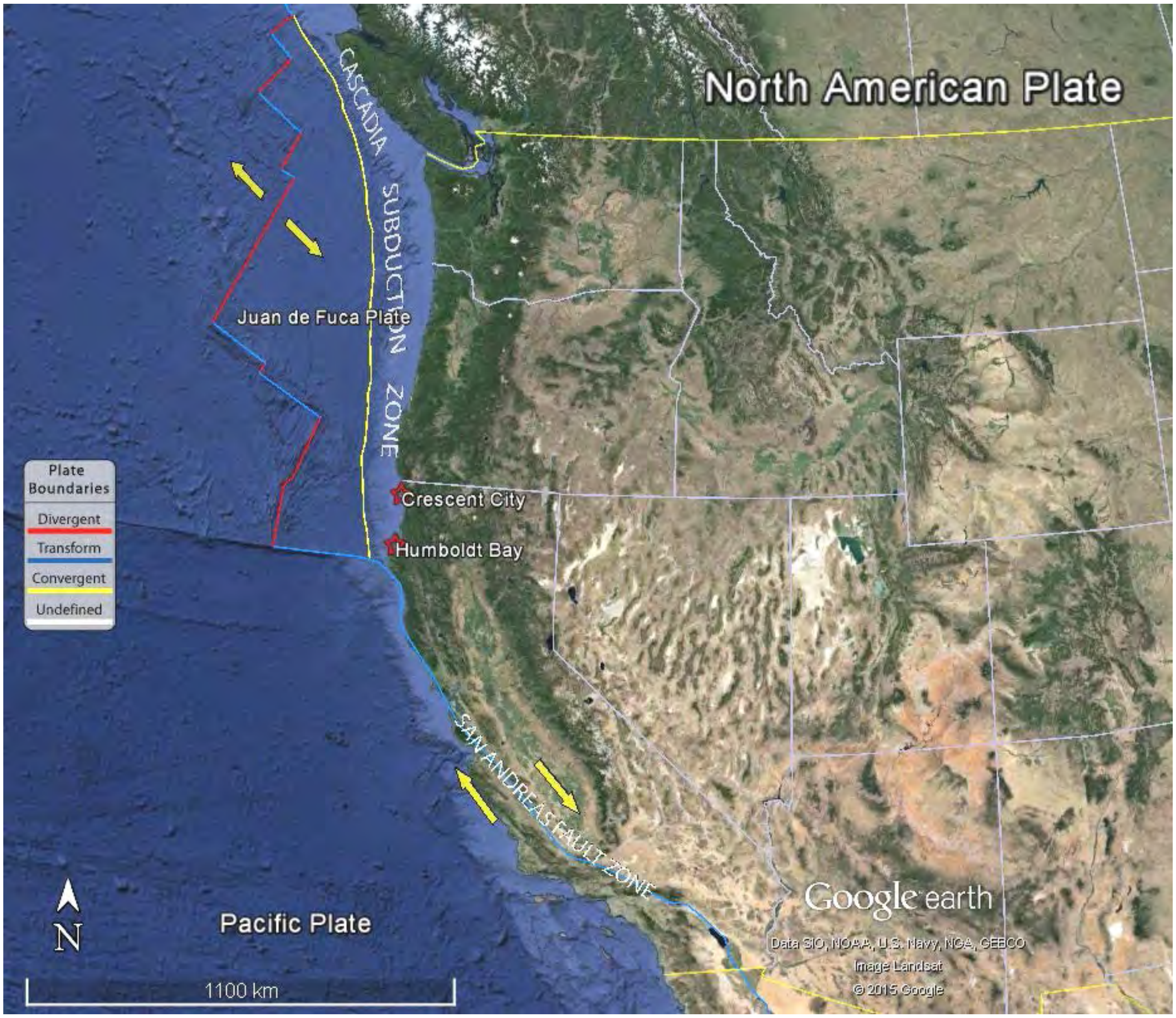


Figure 1. Tectonic plate boundaries along the U.S. west coast, and the location of Humboldt Bay and Crescent City relative to the Cascadia subduction zone. Tectonic boundary data downloaded from http://earthquake.usgs.gov/learn/kml.php.

The OPC (2017) report did not address local issues affecting sea-level rise in the Humboldt Bay region, or provide projections applicable for the region. A key purpose of this chapter is to provide probabilistic sea-level rise projections for the Humboldt Bay region based on the work of Kopp et al. (2014) and the local estimates of vertical land motion by Patton et al. (2017). The updated overview and probabilistic projections provides decision makers the most up-to-date and locally relevant information to support planning and developing adaptation strategies for sea-level rise in the Humboldt Bay region.

Global Climate System Change

In 2013, the IPCC completed its Fifth Assessment Report (AR5). The AR5 states that continued emissions of greenhouse gases (carbon dioxide, methane, and nitrous oxide) will cause changes in all components of the global climate system, affecting temperature and precipitation patterns, ocean temperatures and chemistry, ocean-climate variability, and sea-level rise. The AR5 reports (95% confidence) that human activity is the dominant cause of the observed global climate system warming since the mid-20th century (Figure 2), with the last three decades being successively warmer than any preceding decade since 1850. Furthermore, atmospheric concentrations of greenhouse gases have increased to levels unprecedented in at least the last 800,000 years. Carbon dioxide concentrations have increased by 40% since pre-industrial times, with the ocean absorbing about 30% of the emitted anthropogenic carbon dioxide (Figure 3), causing ocean acidification (IPCC, 2013). The AR5 concluded that limiting climate change will require substantial and sustained reductions of greenhouse gas emissions.

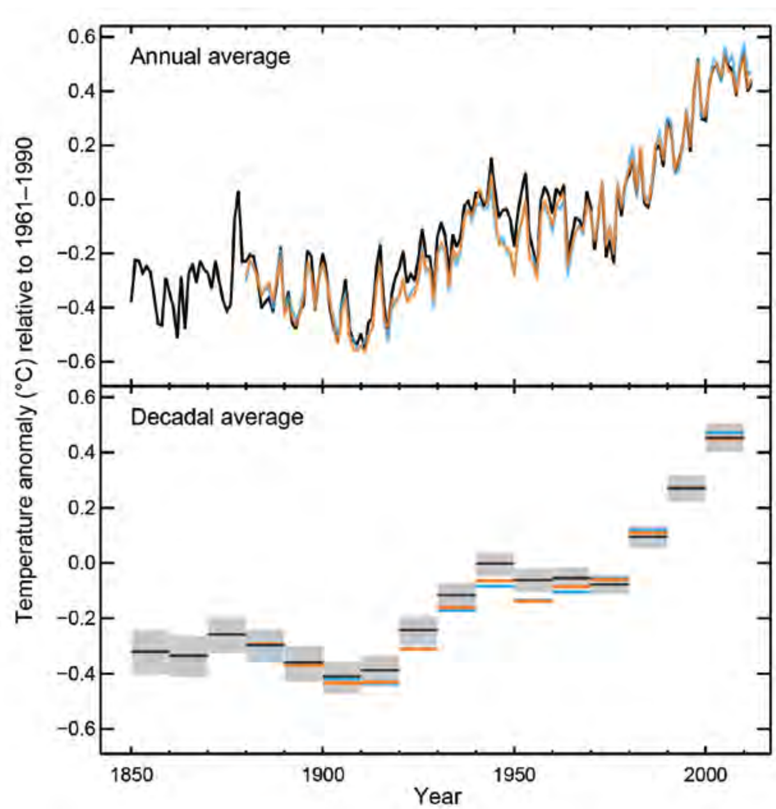


Figure 2. Observed 1850 to 2012 global mean combined land and ocean surface temperature anomalies (relative to the mean of 1961-1990) from three datasets. Top panel is the annual mean values, and bottom panel are the decadal mean values with uncertainty for one dataset (black). (Figure from IPCC, 2013)

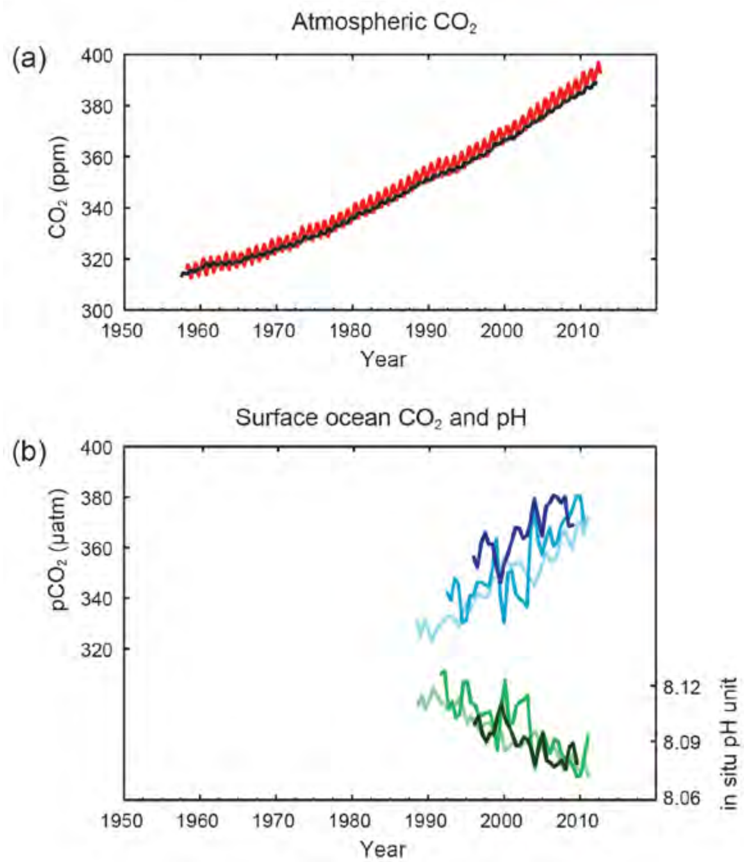


Figure 3. (a) Observed atmospheric carbon dioxide (CO_2) concentrations for Mauna Loa (red line) and South Pole (black line) since 1958. (b) Ocean surface observed partial pressure of dissolved CO_2 (blue lines), and in situ pH (green lines) which is an indicator of ocean acidification. Measurements from Atlantic Ocean (dark blue and dark green, and blue and green) and Pacific Ocean (light blue and light green). (Figure from IPCC, 2013)

Past and Present Sea-Level Rise

This section provides an overview of sea-level change associated with global mean sea-level (GMSL) rise, regional sea-level (ReSL) rise, and local sea-level (LSL) rise.

Global Mean Sea-Level

Global mean sea levels have been increasing since the last ice age about 20,000 years ago (Russell and Griggs, 2012; Kominz, 2001), although at relatively low rates (~ 0.1 mm/yr) over the last two millennia (NRC, 2012). There is high confidence, based on proxy records (e.g. salt marsh sediments) and instrumental sea-level data, that GMSL rise increased in the late 19th to early 20th century from relatively low rates over the previous two millennia to higher rates today (Church et al., 2013). The dominant contributors to GMSL rise over the last century are atmospheric and ocean warming, which increases ocean volume through ocean thermal expansion, and increases ocean mass from melting land ice and, to a lesser extent, land water storage and groundwater extraction (Rhein et al., 2013; Church et al., 2013).

Analysis of global tide gauge records dating back to the 1880s (Church and White, 2011), and the more recent satellite altimetry observations of sea surface change from 1993 to present (Beckley et al., 2010) clearly indicate that GMSL rise rates have increased since 1993 (Figure 4, Table 1). The tide gauge reconstructions by Church and White (2011) indicate that the rate of GMSL rise between 1901 to 1990 was 1.5 ± 0.2 mm/yr, and from 1901 and 2010 was 1.7 ± 0.2 mm/yr. The rate of GMSL rise measured by satellite altimetry from 1993 to 2016 is 3.4 ± 0.4 mm/yr (https://sealevel.nasa.gov, data accessed in September 2017), which is two times or more the tide gauge rates listed above. Recently, Hay et al. (2015) reanalyzed the tide gauge data using probabilistic techniques and estimated a GMSL rise rate of 1.2 ± 0.2 mm/yr from 1901 to 1990, which is lower than the Church and White (2011) estimate for the same period. This indicates that the increase in GMSL rates from 1993 to 2016 (altimetry rate of 3.4 ± 0.4 mm/yr) over the 1901 to 1990 rates is greater than previously thought (Hay et al., 2015). Although these methods result in different estimates of the rate of GMSL rise, they all indicate the same overall pattern of increased rates in recent decades.

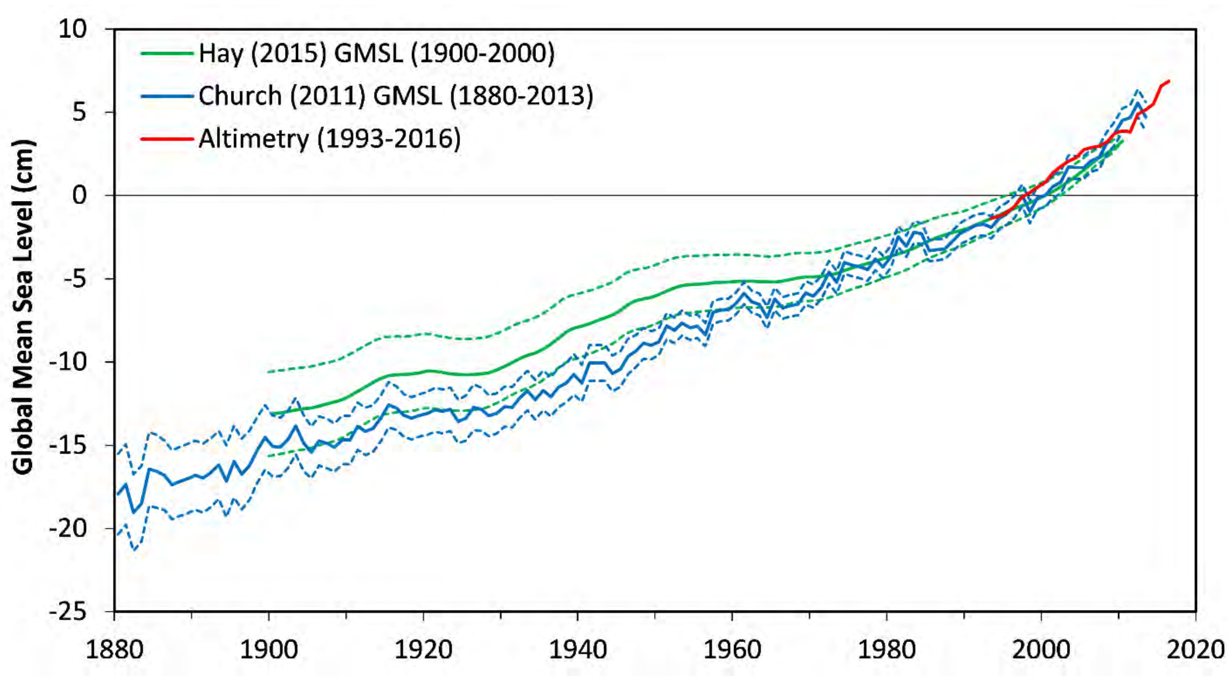


Figure 4. Yearly average reconstructed GMSL (blue line) for 1880 to 2013 of Church and White (2011) with one standard deviation uncertainty bounds (blue dashed line), data downloaded from http://www.cmar.csiro.au. Reconstructed GMSL (green line) for 1901 to 2010 of Hay et al. (2015) with one standard deviation uncertainty bounds (green dashed line), data downloaded with publication. Satellite altimeter data for 1993 to 2016 of Beckley et al. (2010), data downloaded at: https://sealevel.nasa.gov. All data relative to year 2000 baseline.

Table 1. Estimated GMSL rise rates and uncertainty range (90% confidence interval) for different time periods. Data from Church and White (2011), Hay et al. (2015), Rhein et al. (2013) and Beckley et al. (2010).

Time Period	GMSL Rise Rate and Uncertainty (mm/yr)	Source
1901 to 1990	1.5 [1.3 to 1.7]	Tide gauge reconstruction (Church and White, 2011)
1901 to 1990	1.2 [1.0 to 1.4]	Tide gauge reconstruction (Hay et al., 2015)
1901 to 2010	1.7 [1.5 to 1.9]	Tide gauge reconstruction (Church and White, 2011)
1993 to 2016	3.4 [3.0 to 3.8]	Satellite altimetry data (Beckley et al., 2017)

Regional Sea-Level Rise

As mentioned above, the dominant drivers to GMSL rise are thermal expansion of the ocean, increases in ocean mass from melting land ice, and to a lesser extent, changes in land water storage. However, the spatial or ReSL rise can differ from GMSL rise due to a range of factors such as ocean dynamics, climate variability, and sea-level fingerprints (Cayan et al., 2008; NRC, 2012; Church et al.,2013; Kopp et al., 2014; Kopp et al., 2015). Figure 5 shows the monthly mean LSL rise trends at three NOAA long-term (greater than 100-years) tide gauges located on relatively tectonically stable ground (Cayan et al., 2008; Burgette et al., 2009; Bromirski et al., 2011). The three sea-level rise trends are consistent, ranging from 1.94 to 2.15 mm/yr, with the average (2.0 mm/yr) representing an estimate of ReSL rise along the U.S. west coast. This rate is 18% greater than the 1901 to 2010 GMSL trend of 1.7 mm/yr (Table 1), implying that over the instrument period ReSL rise along the U.S. west coast has been greater than GMSL rise. The dominant factors affecting ReSL change along the U.S. west coast are summarized below.

Ocean Dynamics and Climate Variability. Non-uniform sea-level changes arise from ocean dynamics, circulation, heat content, and salinity differences due to freshwater (mass) inputs from ice loss, regional wind and current patterns, and coupled ocean-atmosphere processes from natural climate variability. The most important climate processes along the U.S. west coast affecting sea-level change are the seasonal cycle, ENSO, and the Pacific Decadal Oscillation (PDO) (Komar et al., 2011; Bromirski et al., 2011; NRC, 2012).

Seasonal coastal current and wind patterns (e.g. upwelling) produce variations in sea levels, known as the average seasonal cycle, due to ocean temperature and density changes (Zervas, 2009; Komar et al., 2011). ENSO causes seasonal to interannual timescale climate variability with more active winter storm periods and higher sea levels during the warmer El Niño phase, and lower levels during the cooler La Niña phase (Figure 6). The PDO is described as an interdecadal ENSO like pattern of climate variability in the Pacific Ocean with warm and cool phases (Figure 6) that shift on interdecadal timescales of about 20 to 30 years (Zhang et al., 1997; Mantua et al., 1997).

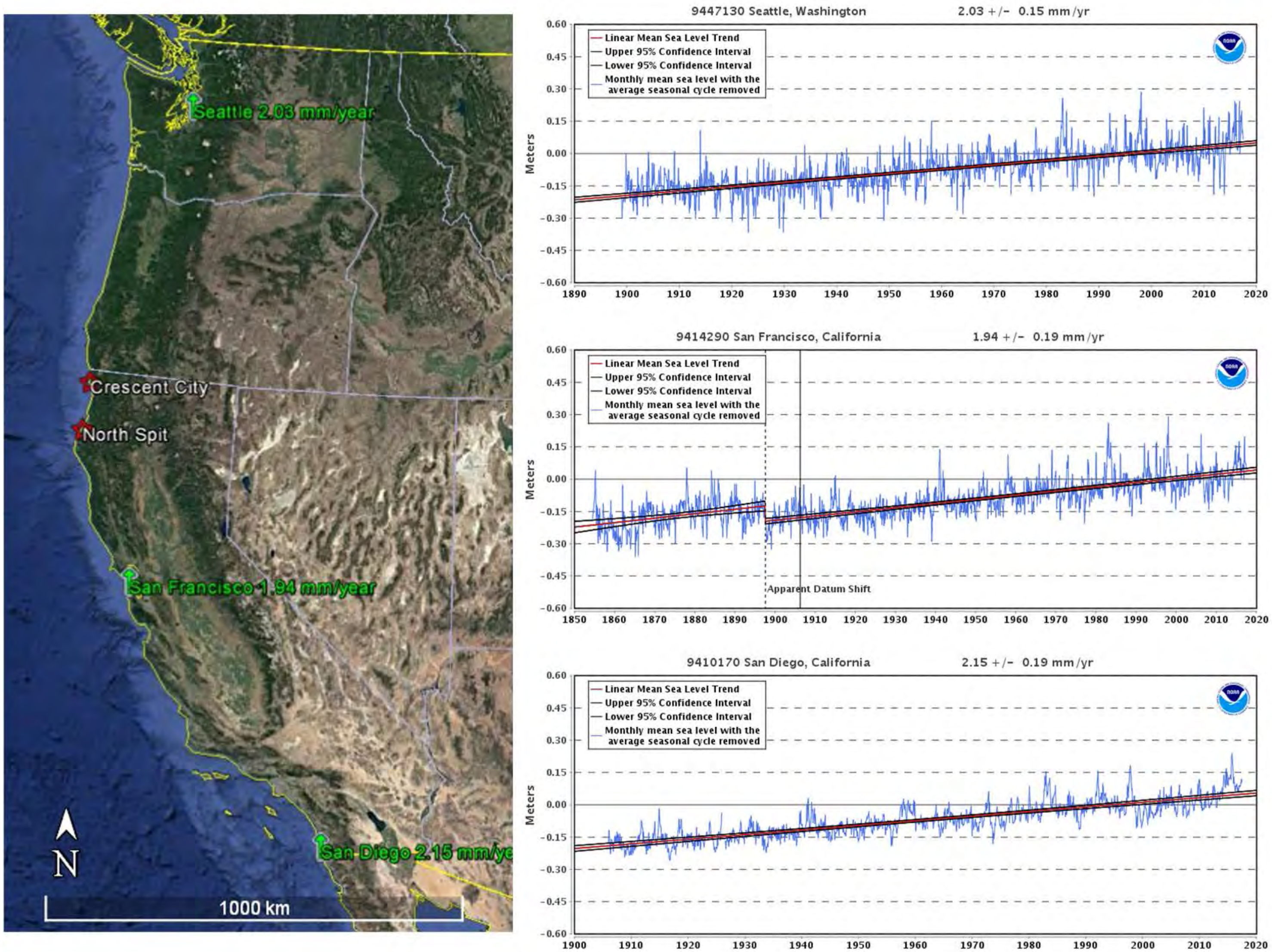


Figure 5. Observed monthly ReSL rise trends for NOAA tide gauge records for Seattle, San Francisco and San Diego. These tide gauge sites are located on relatively tectonically stable ground. Data and figures accessed on October 2017 at http://tidesandcurrents.noaa.gov.

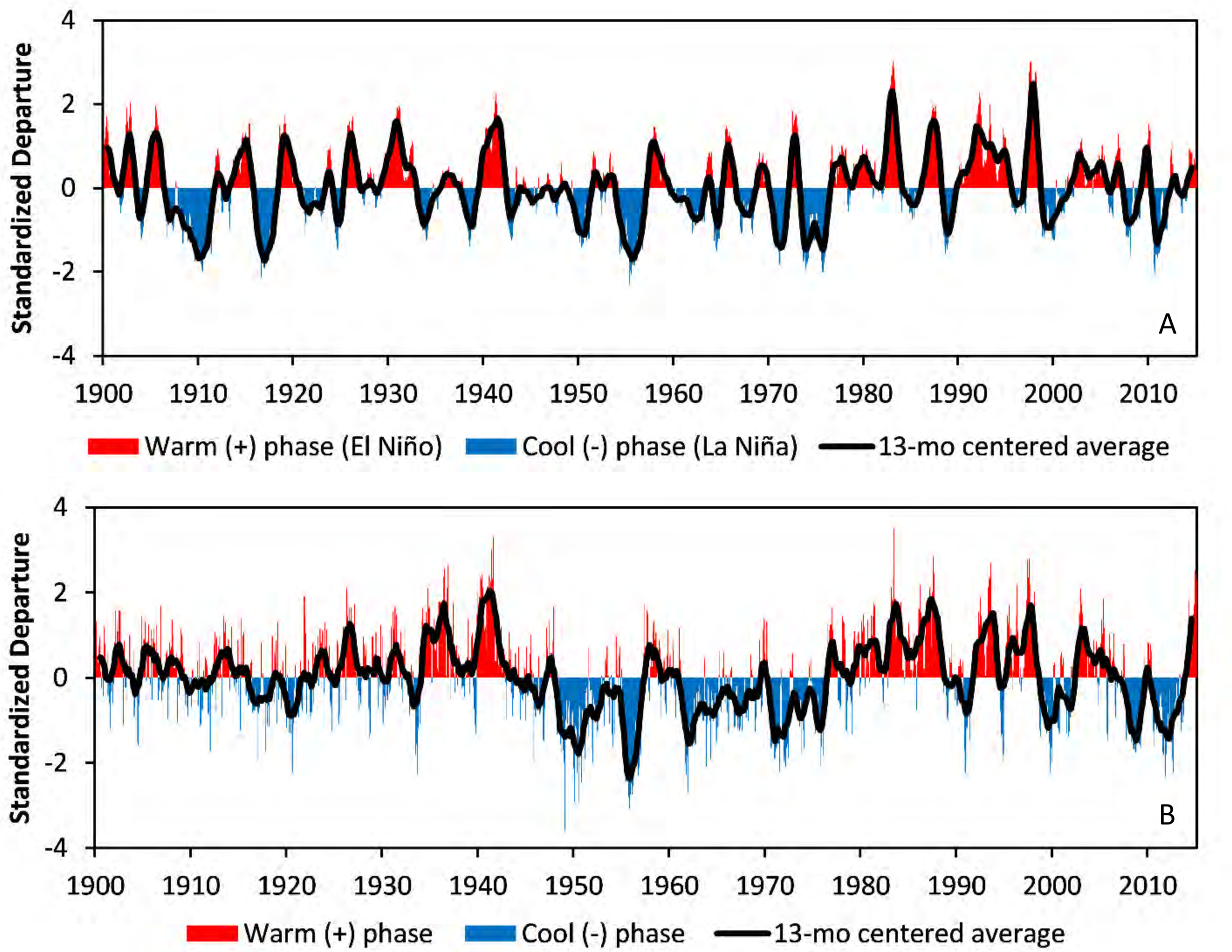


Figure 6. (A) Multivariate ENSO index (MEI), and (B) Pacific Decadal Oscillation (PDO) index from 1900 to March 2015. The black lines are 13-month centered average values. MEI index based on MEI.ext data from 1900 to 1949 (Wolter and Timlin, 2011), and MEI data from 1950 to March 2015 (Wolter and Timlin, 1993, 1998); MEI data downloaded from http://www.esrl.noaa.gov/psd/enso. PDO index data from 1900 to March 2015 (Mantua et al., 1997); PDO data downloaded from http://research.jisao.washington.edu/pdo. Refer to sources and links for details on how the MEI and PDO indexes were computed.

Bromirski et al. (2011) attributes suppression of the ReSL trend along the U.S. west coast since the 1980s (Figure 5) to changes in the wind stress curl associated with the PDO regime shift in the mid-1970s (Figure 6). Recently, Hamlington et al. (2016) noted an apparent PDO shift resulting in higher sea levels along the U.S. west coast over the last few years that could persist, leading to higher rates of sea-level rise, similar to the higher rates in the observational record.

Sea-Level Fingerprints. Changes to the Earth’s gravitational and deformational response to mass redistribution between the ocean and glaciers, ice caps and ice sheets (cryosphere) is known as sea-level or static-equilibrium fingerprints. As land ice melts, water enters the ocean raising

GMSL; however, a reduced gravitational pull on the ocean water also results from the decrease in ice mass. The overall net effect of these fingerprints is that ReSL will drop near the melting ice masses, and increase proportional to the distance from the ice masses.

Vertical land motion. Vertical land motion (VLM) is associated with tectonics, sediment compaction and/or subsidence, and glacial isostatic adjustment (GIA). GIA is the response of the Earth's surface to the retreat of the ice sheets during the last ice age. Regional and local VLM, such as tectonic land-level changes, can be much larger than those associated with GIA models (Zervas, 2009). Along the U.S. west coast, and in particular the CSZ, researchers have documented interseismic tectonic land-level rates from plate locking that are an order of magnitude greater than the global GIA rate (Mitchell et al., 1994; Burgette et al., 2009). Along the PNW coast, the tectonic land-level changes associated with the CSZ strongly affect regional and local sea-level changes (Komar, 2011).

Regional Sea-Level Rise along the Pacific North West Coast and Humboldt Bay Region

To infer VLM associated with tectonic uplift rates from LSL change at six NOAA tide gauge sites located between Crescent City, CA and Astoria, OR, Burgette et al. (2009) determined an average sea-level rise rate of 2.28 ± 0.20 mm/yr that represents an approximate 20th century ReSL rise rate for the PNW coast along the CSZ. As noted by Burgette et al. (2009), the 2.28 mm/yr ReSL rise rate compared well to the 1950 to 2000 GMSL reconstruction of Church and White (2006), which had trend slopes for grid points offshore of the CSZ of 2.2 ± 0.30 mm/yr. Komar et al. (2011) further assessed the 2.28 mm/yr ReSL rate by comparing LSL rates for the six CSZ tide gauge records to the benchmark and Pacific Northwest Geodetic Array Global Positioning System (GPS) data, and concluded that the rate is reasonable for the PNW coast. Finally, the NRC (2012) study determined an adjusted (for VLM and atmospheric pressure) sea level rise rate of 2.30 mm/yr for the Seattle tide gauge for the 1900 to 2008 period, which is also consistent with the 2.28 mm/yr ReSL rise rate.

The 2.28 mm/yr ReSL rise rate is 0.58 mm/yr greater (34% increase) than the 1901 to 2010 GMSL rate of 1.7 mm/yr (Table 1). This implies that natural climate variability (ENSO and PDO), ocean dynamic processes, and gravitational mass redistribution have produced a greater ReSL rise rate for the PNW coast relative to the GMSL rate for the same general period. The Burgette et al. (2009) rate of 2.28 mm/yr has been used by local researchers (e.g. NHE, 2015a; Patton et al., 2017) to represent historic ReSL rise rates for the Humboldt Bay region.

Past and Present Local Sea-Level Rise

Tide gauges measure local sea-level (LSL) change, which is the combined effects of sea-level change and VLM. The measured LSL change includes the same processes affecting ReSL patterns, and other short-term local processes such as wind waves, tides and hydrodynamic effects. As noted by Zervas (2009), VLM is responsible for most of the differences in LSL trends between regional tide observations. For example, although the Crescent City and North Spit tide gauges are only separated by 109 km (~68 mi), the LSL trends for these gauges are in opposing directions (Figure 7).

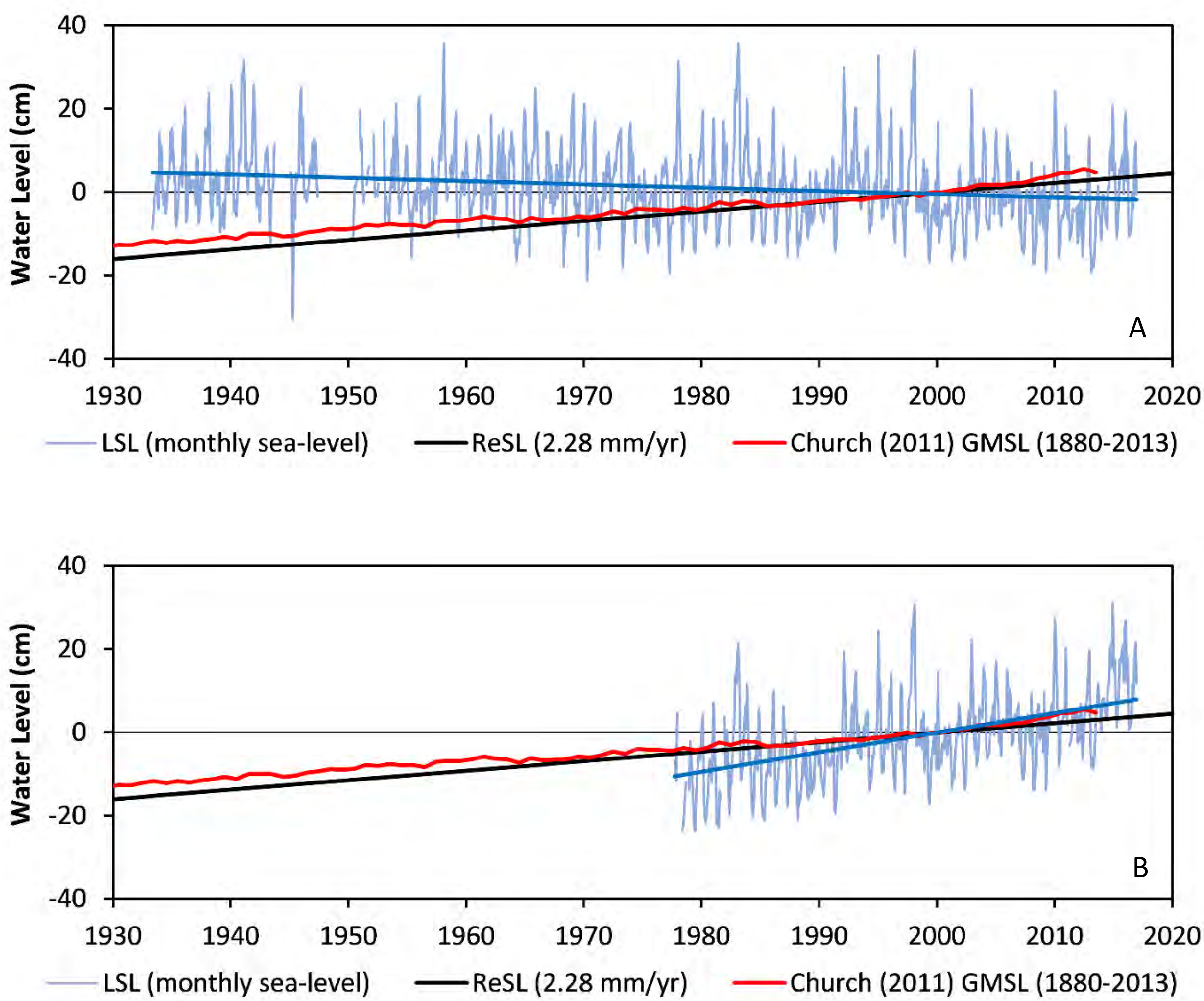


Figure 7. (A) LSL change for Crescent City tide gauge (1933 to 2016). (B) LSL rise for Humboldt Bay North Spit tide gauge (1977 to 2016). LSL changes (light blue lines) are monthly mean values, LSL trends (dark blue lines) are the linear regression on the monthly values, ReSL rise trend (black line) is the Burgette et al. (2009) ReSL rate of 2.28 mm/yr., GMSL rise trend (red line) is the Church and White (2011) reconstruction. All data relative to year 2000 baseline.

The downward LSL trend at Crescent City indicates this section of coast is emerging, with an uplift rate greater than the current GMSL and ReSL rise rates. In contrast, the North Spit LSL trend is greater than the GMSL or ReSL rates, indicating that Humboldt Bay is submergent, and in fact, has the highest LSL rise rate of any tide gauge in California. The relatively large oscillations in monthly LSL values around the trend line are due to short-term weather variability (e.g. storms), natural climate variability (e.g. ENSO and PDO), and the average seasonal cycle.

Local Sea-Level Rise and Vertical Land Motion Rates in the Humboldt Bay Region

The LSL rise rate at North Spit tide gauge is greater than both the GMSL and ReSL rise rates due to land subsidence in and around Humboldt Bay. To better understand how tectonic land motion affects LSL rates in Humboldt Bay, Cascadia Geosciences and partners received funding from the U.S. Fish & Wildlife Service (study plan at http://www.hbv.cascadiageo.org) to utilize tide gauge observations, benchmark level surveys, and GPS data to evaluate tectonic VLM and LSL rates in Humboldt Bay. The tide gauge analysis evaluated water level observations at the NOAA Crescent City tide gauge, and five NOAA tide gauge sites in Humboldt Bay, which include North Spit and four historic gauges located at Mad River Slough, Samoa, Fields Landing, and Hookton Slough (Figure 1, Figure 8).

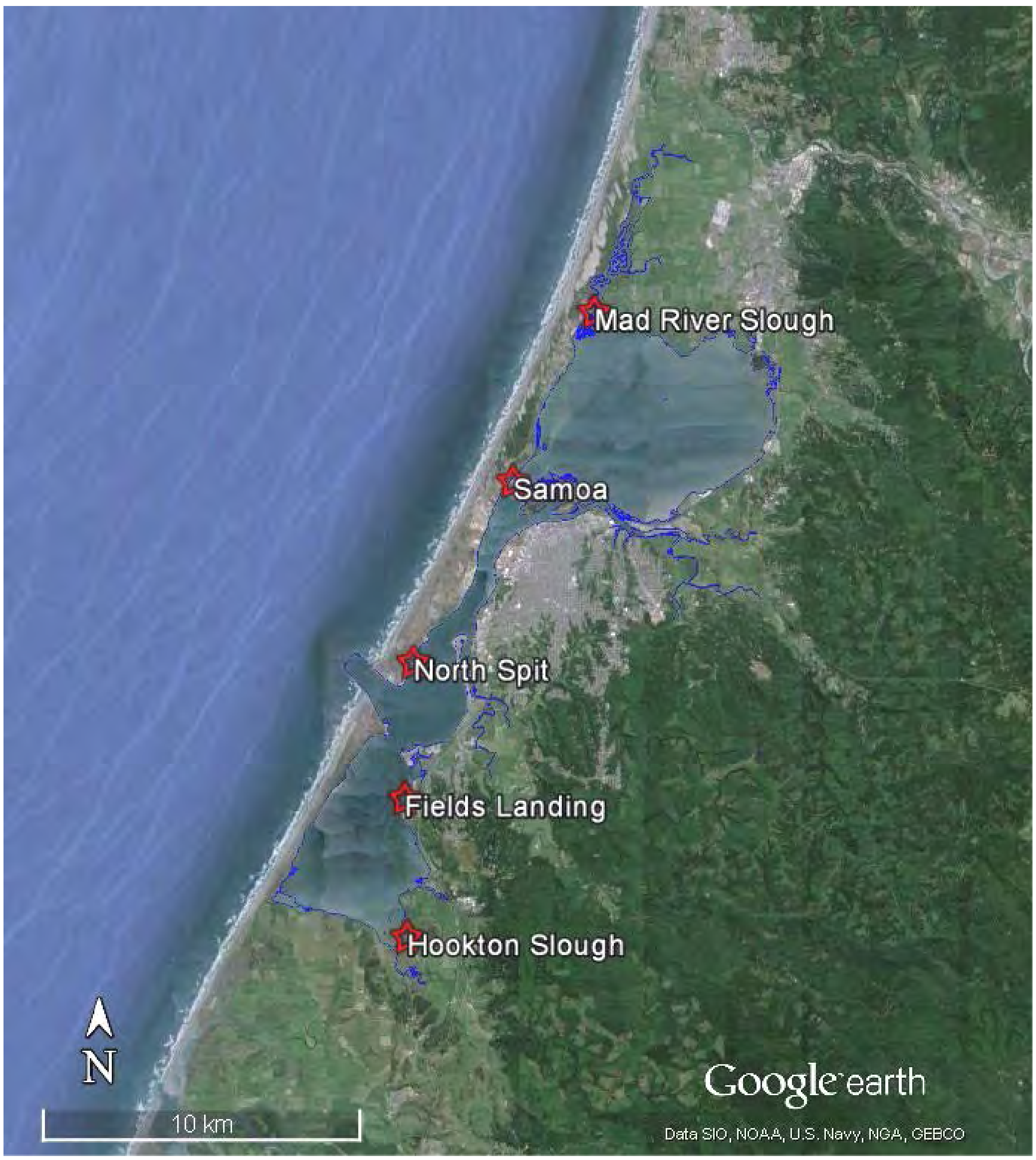


Figure 8. Five NOAA tide gauge locations in Humboldt Bay, and mean high water edge (blue line).

The tide gauge analysis relied on the long-term Crescent City (~84 years) and North Spit (40 years) tide gauges, and the general approach of Mitchell et al. (1994) and Burgette et al. (2009) to determine VLM and LSL rates at the other Humboldt Bay gauges, which all have record lengths less than 30 years and are considered too short to directly determine rates (Zervas, 2009). The analysis also relied on the 20th century ReSL rise rate (2.28 mm/yr) of Burgette et al. (2009).

Recently, NHE (in progress) updated the original VLM and LSL rate estimates of Patton et al. (2017) for the Crescent City and Humboldt Bay tide gauges using a weighted least squares adjustment approach as described by Ghilani (2010) (Table 2, Figure 9). The NHE update work is in progress, but reference to the Patton et al. (2017) work can be made for a general discussion of the tide gauge analysis methods and interpretation of results.

Table 2. Summary of LSL rise and VLM rates for Crescent City and the five Humboldt Bay tide gauges originally developed by Patton et al. (2017), and the weighted least square adjustment values recently developed by NHE (in progress). The weighted least square adjustment provides a mean and standard error (SE) for LSL rise and VLM. Positive VLM rates indicate upward land motion, and negative rates indicate downward motion.

	Patton et al. (2017) Values		Weighted Least Squares Adjustment (NHE, in progress)			
Tide Gauge Location	LSL Rise (mm/yr)	VLM (mm/yr)	LSL Rise (mm/yr)	SE (mm/yr)	VLM (mm/yr)	SE (mm/yr)
Crescent City	-0.97	3.25	-0.83	0.07	3.11	0.13
North Spit	4.61	-2.33	4.97	0.27	-2.69	0.25
Mad River Slough	3.39	-1.11	3.32	0.53	-1.04	0.27
Samoa	2.53	-0.25	2.93	1.14	-0.65	0.32
Fields Landing	3.76	-1.48	3.93	0.95	-1.65	0.41
Hookton Slough	5.84	-3.56	5.98	0.81	-3.70	0.41

The north to south down trending VLM gradient controls the LSL rate variation in Humboldt Bay, with the highest rate of VLM in south Humboldt Bay at the Hookton Slough tide gauge. The tectonic deformation in Humboldt Bay increases the LSL rates well above the long-term GMSL and ReSL rates of 1.7 and 2.28 mm/yr, respectively, with both the North Spit and Hookton Slough LSL rates being more than twice the ReSL rate. These higher LSL rise rates indicate that increases in the GMSL and ReSL will affect Humboldt Bay faster than other parts of U.S. west coast; and within the bay, the south end will be affected sooner than the north end.

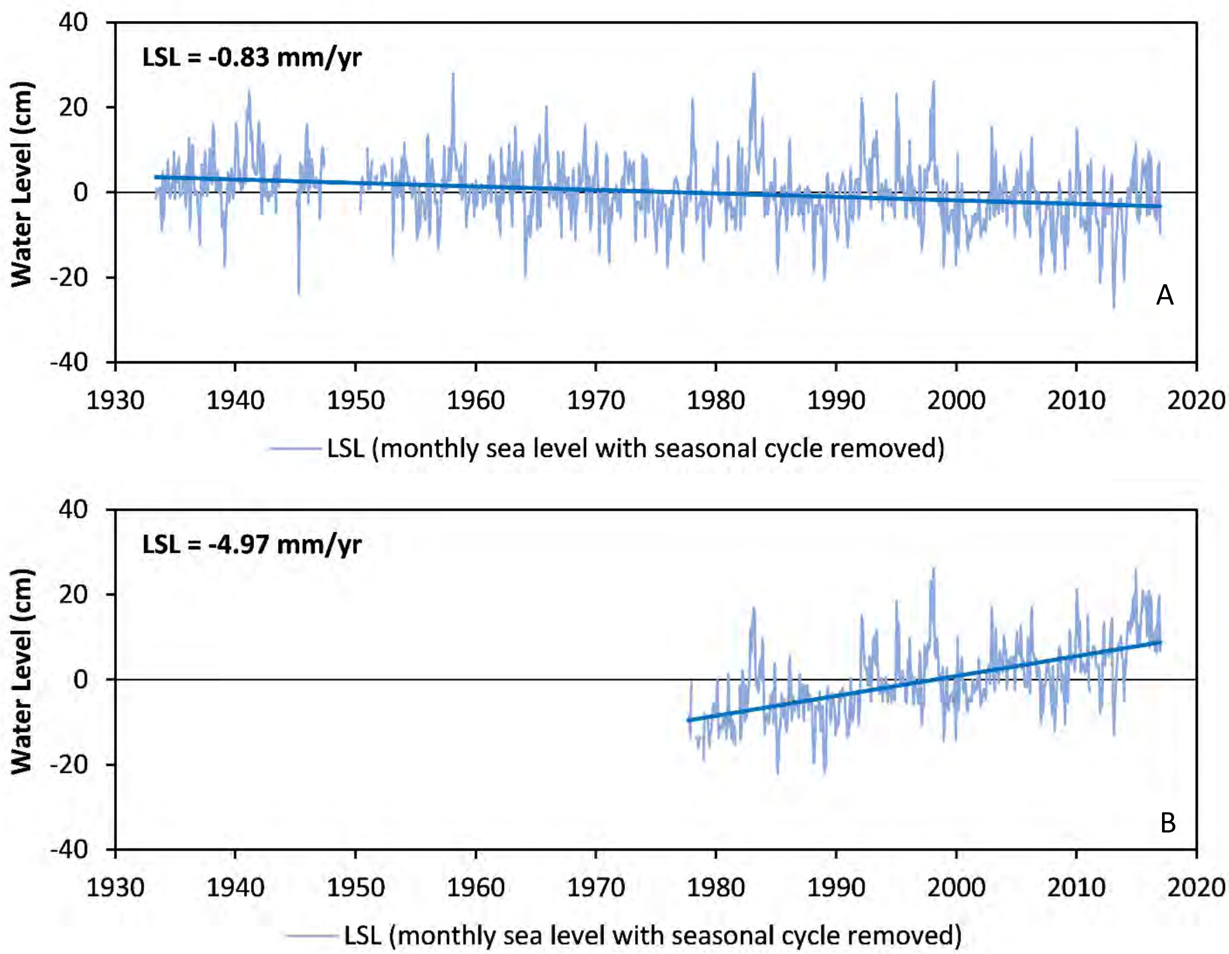


Figure 9. LSL rise trends for (A) Crescent City (1933 to 2016) and (B) North Spit (1977 to 2016) tide gauges using monthly mean sea levels with the average seasonal cycle removed.

Sea-Level Height Variability

Sea-level heights vary due to astronomical tides, storm surge, wind stress effects, changes in barometric pressure, seasonal cycles, and ENSO phases, which results in water levels reaching higher levels over longer time scales (Cayan et al., 2008; Knowles, 2010). Figure 10 shows the hourly water levels for the Crescent City tide gauge for the 1982-83 El Niño years, along with the mean sea level (MSL) and mean higher high water (MHHW) tidal datum, the mean monthly maximum water (MMMW), and the 10- and 100-yr extreme high-water level events.

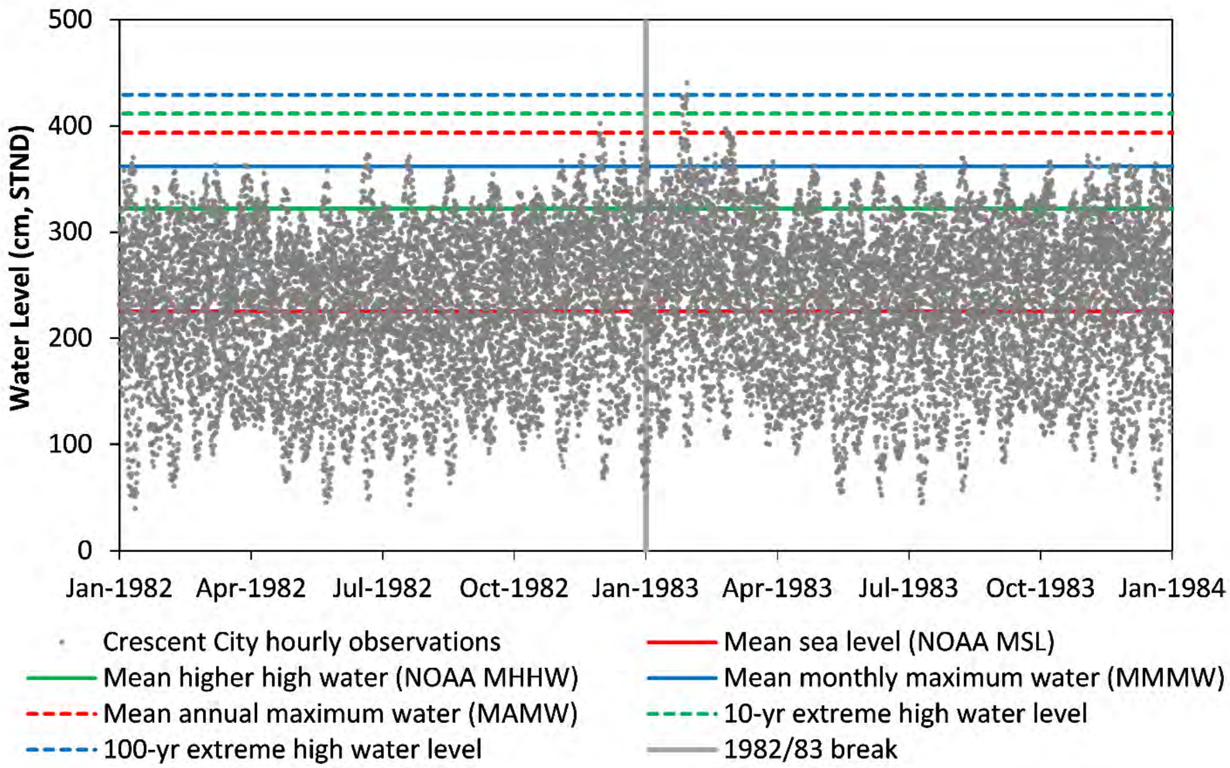


Figure 10. Crescent City tide gauge hourly water levels for 1982-83 El Niño years, with mean sea level (MSL), mean higher high water (MHHW), mean monthly maximum water (MMMW), mean annual maximum water (MAMW), and the 10- and 100-yr extreme high-water level events.

Most coastal damage to the U.S. west coast occurs when storm surge and high waves coincide with high astronomical tides and El Niño events (Cayan et al., 2008; NRC, 2012), which occurred during the winters of 1982-83 and 1997-98. For example, in late January 1983 a large El Niño driven storm coincided with higher than normal astronomical tides, and produced the highest water levels of record at the Crescent City tide gauge on 29 January 1983, exceeding the 100-year extreme exceedance probability event (Figure 10 and Figure 11). The peak hourly water level on 29 January 1983 was 66.2 cm (2.2 ft) higher than the astronomical high tide, and on 26 January 1983, the peak hourly water level was 84.0 cm (2.8 ft) above the astronomical high tide.

It is important to note that sea-level height variability is superimposed onto mean sea level (Cayan et al., 2008). Consequently, as sea-levels rise into the future, the water levels associated with sea-level height variability described above will also increase, and the incidence of extreme high-water levels will become more common (NRC, 2012).

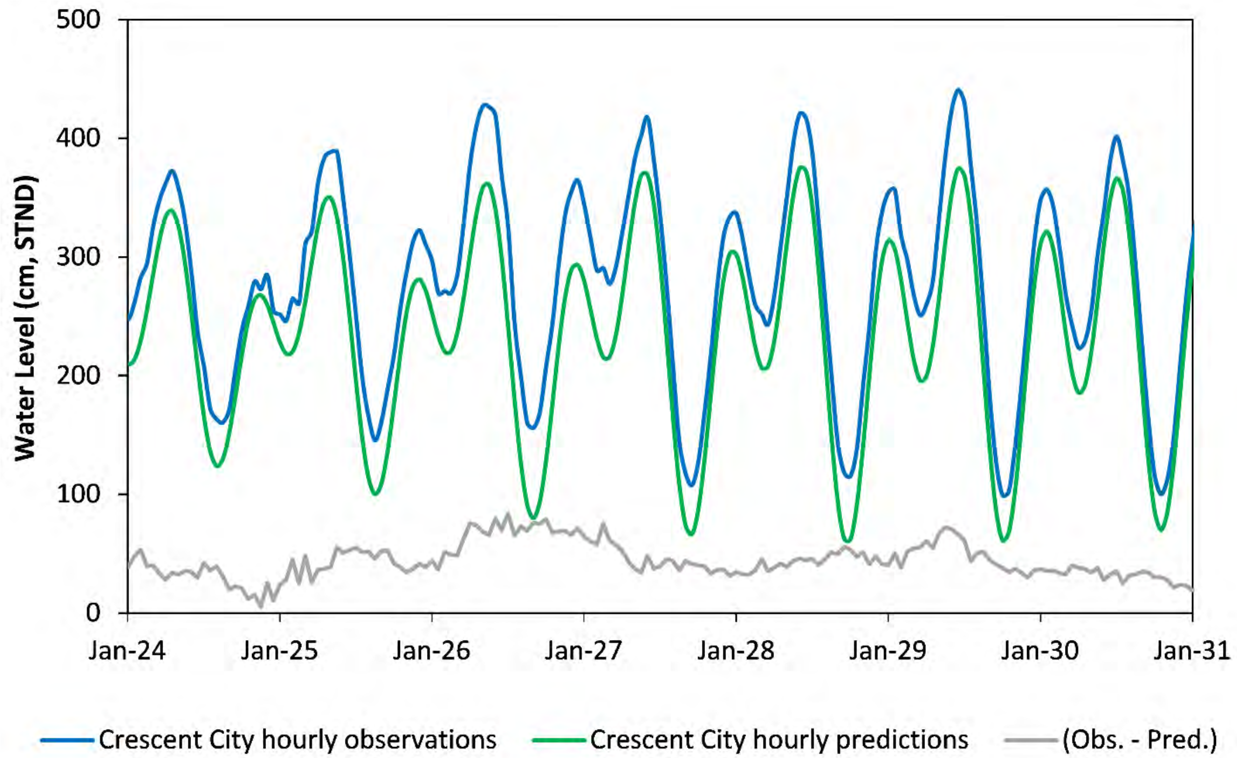


Figure 11. Crescent City tide gauge hourly water levels for January 1983 El Niño year. Blue line is observed water level, green line is astronomical tidal prediction, and grey line is observed minus predicted.

Projections of Sea-Level Rise

Observations provide unequivocal evidence that the climate system is warming and that GMSL has risen over the 20th century (NRC, 2012; IPCC, 2013), but projections of future sea-level rise, including global, regional and local estimates, are necessary to adequately assess and plan for potential impacts to coastal area. Sea-level rise projections generally depend on the understanding of contributions to sea-level change, the response of key geophysical processes, and assumptions regarding future warming of the climate system (NRC, 2012, Church et al., 2013). This section summarizes recent probabilistic projections of GMSL rise, and provides probabilistic estimates of LSL rise for the Humboldt Bay region based on the approach of Kopp et al. (2014).

The NRC (2012) report produced regional projections along the U.S. west coast for three scenarios (low, central and high), with the central or “mid-range” projection having the most weight. The NRC projections covered four regions (Seattle, Newport, San Francisco, and Los Angeles) that varied from the global average due to regional oceanic thermal expansion and dynamics, sea level fingerprint effects, and VLM, and represented the most comprehensive regional projections for the U.S. west coast at the time. Since the NRC (2012) report, significant effort and advances have been made in developing probabilistic projections of GMSL, ReSL and LSL rise (e.g. Church et al., 2013; Kopp et al., 2014; Grinsted et al., 2015).

The recently released OPC sea-level science update for California (Griggs et al., 2017) used the framework of Kopp et al. (2014) to determine probabilistic sea-level rise projections at three representative locations along the California coast (Crescent City, San Francisco, and La Jolla). Unfortunately, none of these locations adequately represent the high rates of LSL rise occurring in the Humboldt Bay region due to tectonically driven VLM.

The approach of Kopp et al. (2014) provides complete probability distributions for GMSL and LSL rise projections at a global network of tide gauge sites under three emission scenarios, RCP 2.6, RCP 4.5 and RCP 8.5 (discussed below). This approach develops individual probability distributions for the sea-level rise components of glacier/ice cap and ice sheet (Greenland and Antarctic) loss with fingerprint affects, oceanic processes (regional dynamic, thermal and steric effects), land water storage, and VLM from process-based model outputs and expert elicitation for the ice sheets. The GMSL and LSL probability distributions were determined by combining 10,000 Latin hypercube samples (a Monte-Carlo approach) from each individual component distribution. The Kopp et al. (2014) GMSL and LSL projections are available for download as supporting information, and include the Crescent City and North Spit tide gauges.

The IPCC AR5 adopted a set of greenhouse gas emission scenarios known as Representative Concentration Pathways (RCPs), which represent future emissions and concentrations of greenhouse gases, aerosols, and other climate drivers (Church et al., 2013). The RCPs (RCP 8.5, 6.0, 4.5 and 2.6) represent future radiative forcing by 2100 (e.g. RCP 8.5 is 8.5 W/m^2), and are dependent on various mitigation scenarios including implied policy actions, that have different targets in terms of greenhouse gas emissions and radiative forcing (IPCC, 2013). RCP 8.5 is a very high greenhouse gas emission scenario with high radiative forcing, and represents a future where there are no significant efforts to reduce emissions. RCP 2.6 represents an aggressive emission mitigation scenario leading to low radiative forcing, and requires net-negative global emissions in the last quarter of the 21st century. RCP 4.5 and 6.0 represent moderate emission mitigation scenarios. Kopp et al. (2014) only provides projections for RCP 2.6, 4.5 and 8.0, and notes that the sea-level rise projections for RCP 6.0 are similar to those for RCP 4.5.

As discussed in Griggs et al. (2017), recent work on Antarctic Ice Sheet modeling has identified modes of ice-sheet instability that could make extreme sea-level rise more likely than indicated in the Kopp et al. (2014) framework. Consequently, the OPC Science Advisory Team included the extreme sea-level rise scenario (GMSL rise of 2.5 m by 2100) of Sweet et al. (2016) with the Kopp et al. (2014) probabilistic projections. Consistent with Griggs et al. (2017), this extreme scenario (called the H++ scenario) was included in the Humboldt Bay region update, but was renamed the Ext 2.5 scenario to represent the Sweet et al. (2016) extreme GMSL rise of 2.5 m by 2100. The Sweet et al. (2016) scenario projections are also available as supporting information.

The following sections summarize and provide updated sea-level rise projections for the Humboldt Bay region based on the probabilistic projections of Kopp et al. (2014) and the extreme scenario of Sweet et al. (2017), with the local estimates of VLM by Patton et al. (2017) and NHE (in progress) incorporated into the projections.

Global Mean Sea-Level Rise Projections

The GMSL rise projections of Kopp et al. (2014) for the RCP 8.5, RCP 4.5 and RCP 2.6 emission scenarios (Figure 12, Table 3, Table 4) are provided for consistency and comparison with the LSL projections for the Humboldt Bay region. Table 3 show the component contributions to GMSL rise at 2100 for the median (50% probability) and different probability ranges (e.g. 90 and 99% probabilities). The total GMSL median projections and probabilities for 2030, 2050, 2100, 2150 and 2200 are listed in Table 4, along with the Sweet et al. (2016) Ext 2.5 scenario.

It should be noted that the Ext 2.5 scenario, which has unknown probability, is somewhat consistent with the 99.9% probability of the RCP 8.5 projection (Table 4).

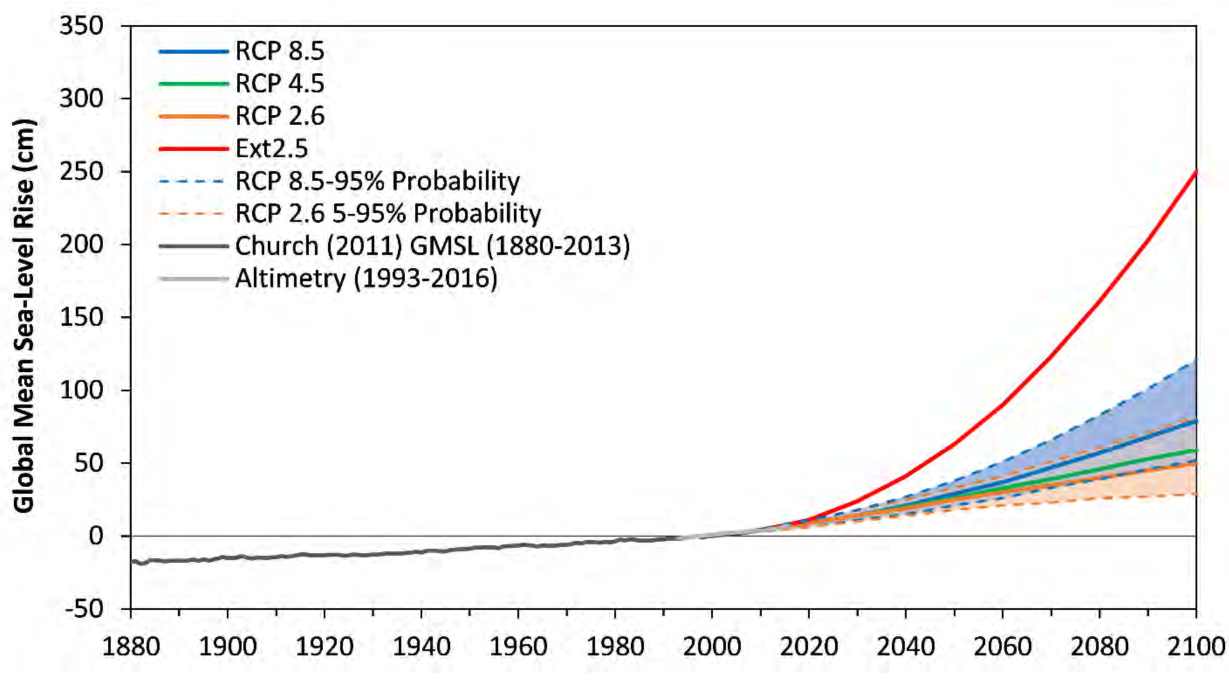


Figure 12. GMSL rise projections at Crescent City for RCP 8.5, RCP 4.5 and RCP 2.6 based on data from Kopp et al. (2014) and the Sweet et al. (2016) extreme scenario of 2.5 m of GMSL rise by 2100 (Ext2.5). The 5 and 95% probabilities are the shaded areas bounded by the dashed lines, and are only shown for RCP 8.5 and RCP 2.6. The reconstructed 1880 to 2013 GMSL curve is from Church et al. (2011). The 1993 to 2016 altimetry data is from Beckley et al. (2010), data downloaded at: https://sealevel.nasa.gov. All data relative to year 2000 baseline.

Table 3. GMSL rise component contributions at year 2100 of Kopp et al. (2014). Sea-level values are cm and ft above year 2000 baseline, probabilities are percent.[1]

	RCP 8.5					RCP 4.5					RCP 2.6				
	50	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**	**50**	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**	**50**	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**
Year 2100 – GMSL rise components (cm)															
GIC	18	14 to 21	11 to 24	7 to 29	< 30	13	10 to 17	7 to 19	3 to 23	< 25	12	9 to 15	7 to 17	3 to 20	< 25
GIS	14	8 to 25	5 to 39	3 to 70	< 95	9	4 to 15	2 to 23	0 to 40	< 55	6	4 to 12	3 to 17	2 to 31	< 45
AIS	4	-8 to 15	-11 to 33	-14 to 91	< 155	5	-5 to 16	-9 to 33	-11 to 88	< 150	6	-4 to 17	-8 to 35	-10 to 93	< 155
TE	37	28 to 46	22 to 52	12 to 62	< 65	26	18 to 34	13 to 40	4 to 48	< 55	19	13 to 26	8 to 31	1 to 38	< 40
LWS	5	3 to 7	2 to 8	0 to 11	< 10	5	3 to 7	2 to 8	0 to 11	< 10	5	3 to 7	2 to 8	0 to 11	< 10
Total	79	62 to 100	52 to 121	39 to 176	< 245	59	45 to 77	36 to 93	24 to 147	< 215	50	37 to 65	29 to 82	19 to 141	< 210
Year 2100 – GMSL rise components (ft)															
GIC	0.6	0.5 to 0.7	0.4 to 0.8	0.2 to 1.0	< 1.0	0.4	0.3 to 0.6	0.2 to 0.6	0.1 to 0.8	< 0.8	0.4	0.3 to 0.5	0.2 to 0.6	0.1 to 0.7	< 0.8
GIS	0.5	0.3 to 0.8	0.2 to 1.3	0.1 to 2.3	< 3.1	0.3	0.1 to 0.5	0.1 to 0.8	0.0 to 1.3	< 1.8	0.2	0.1 to 0.4	0.1 to 0.6	0.1 to 1.0	< 1.5
AIS	0.1	-0.3 to 0.5	-0.4 to 1.1	-0.5 to 3.0	< 5.1	0.2	-0.2 to 0.5	-0.3 to 1.1	-0.4 to 2.9	< 4.9	0.2	-0.1 to 0.6	-0.3 to 1.1	-0.3 to 3.1	< 5.1
TE	1.2	0.9 to 1.5	0.7 to 1.7	0.4 to 2.0	< 2.1	0.9	0.6 to 1.1	0.4 to 1.3	0.1 to 1.6	< 1.8	0.6	0.4 to 0.9	0.3 to 1.0	0.0 to 1.2	< 1.3
LWS	0.2	0.1 to 0.2	0.1 to 0.3	0.0 to 0.4	< 0.3	0.2	0.1 to 0.2	0.1 to 0.3	0.0 to 0.4	< 0.3	0.2	0.1 to 0.2	0.1 to 0.3	0.0 to 0.4	< 0.3
Total	2.6	2.0 to 3.3	1.7 to 4.0	1.3 to 5.8	< 8.0	1.9	1.5 to 2.5	1.2 to 3.1	0.8 to 4.8	< 7.1	1.6	1.2 to 2.1	1.0 to 2.7	0.6 to 4.6	< 6.9

[1]GMSL is global mean sea level; GIC is glaciers and ice caps; GIS is Greenland Ice Sheet; AIS is Antarctic Ice Sheet; TE is thermal expansion; LWS is land water storage; and RCP 8.5, RCP 4.5 and RCP 2.6 are greenhouse gas representative concentration pathways of AR5 (IPCC, 2013).

Table 4. GMSL rise projections of Kopp et al. (2014) and the extreme GMSL scenario (2.5 m of GMSL rise by 2100) of Sweet et al. (2016). Sea-level values are cm and ft above year 2000 baseline; probabilities are percent.[1]

	RCP 8.5					RCP 4.5					RCP 2.6					Ext 2.5
	50	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**	**50**	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**	**50**	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**	**50**
GMSL projections by year (cm)																
2030	14	12 to 17	11 to 18	8 to 21	< 25	14	12 to 16	10 to 18	8 to 20	< 20	14	12 to 16	10 to 18	8 to 20	< 20	24
2050	29	24 to 34	21 to 38	16 to 49	< 60	26	21 to 31	18 to 35	14 to 44	< 55	25	21 to 29	18 to 33	14 to 43	< 55	63
2100	79	62 to 100	52 to 121	39 to 176	< 245	59	45 to 77	36 to 93	24 to 147	< 215	50	37 to 65	29 to 82	19 to 141	< 210	250
2150	130	100 to 180	80 to 230	60 to 370	< 540	90	60 to 130	40 to 170	20 to 310	< 480	70	50 to 110	30 to 150	20 to 290	< 460	550
2200	200	130 to 280	100 to 370	60 to 630	< 950	130	70 to 200	40 to 270	10 to 520	< 830	100	50 to 160	30 to 240	10 to 500	< 810	970
GMSL projections by year (ft)																
2030	0.5	0.4 to 0.6	0.4 to 0.6	0.3 to 0.7	< 0.8	0.5	0.4 to 0.5	0.3 to 0.6	0.3 to 0.7	< 0.7	0.5	0.4 to 0.5	0.3 to 0.6	0.3 to 0.7	< 0.7	0.8
2050	1.0	0.8 to 1.1	0.7 to 1.2	0.5 to 1.6	< 2.0	0.9	0.7 to 1.0	0.6 to 1.1	0.5 to 1.4	< 1.8	0.9	0.7 to 1.0	0.6 to 1.1	0.5 to 1.4	< 1.8	2.1
2100	2.6	2.0 to 3.3	1.7 to 4.0	1.3 to 5.8	< 8.0	1.9	1.5 to 2.5	1.2 to 3.1	0.8 to 4.8	< 7.1	1.9	1.5 to 2.5	1.2 to 3.1	0.8 to 4.8	< 7.1	8.2
2150	4.3	3.3 to 5.9	2.6 to 7.5	2.0 to 12.1	< 17.7	3.0	2.0 to 4.3	1.3 to 5.6	0.7 to 10.2	< 15.7	3.0	2.0 to 4.3	1.3 to 5.6	0.7 to 10.2	< 15.7	18.0
2200	6.6	4.3 to 9.2	3.3 to 12.1	2.0 to 20.7	< 31.2	4.3	2.3 to 6.6	1.3 to 8.9	0.3 to 17.1	< 27.2	4.3	2.3 to 6.6	1.3 to 8.9	0.3 to 17.1	< 27.2	31.8

[1]GMSL is global mean sea level; RCP 8.5, RCP 4.5 and RCP 2.6 are greenhouse gas representative concentration pathways of AR5 (IPCC, 2013); and EXT2.5 is the extreme sea-level rise of 2.5 m of GMSL rise by 2100 of Sweet et al. (2016).

Local Sea-Level Rise Projections for the Humboldt Bay Region

As part of this work, NHE (in progress) updated and/or developed LSL rise probabilistic projections for the RCP 8.5, 4.5 and 2.6 emission scenarios at four sites in the Humboldt Bay region: Crescent City, North Spit, Mad River Slough and Hookton Slough. The three sites in Humboldt Bay (Figure 8) were selected to highlight how the north to south trending VLM gradient affects LSL rise projections.

To provide the LSL rise projections, the Kopp et al. (2014) and Sweet et al. (2016) Ext 2.5 projection data were obtained for the Crescent City and North Spit tide gauges. The VLM contributions to LSL rise for each Kopp et al. (2014) projection were removed (modified Kopp projections), and replaced with the VLM estimates of Patton et al. (2017) as modified by NHE (in progress). Following the same methodology of Kopp et al. (2014), the new VLM probability distributions were determined from 10,000 Latin Hypercube samples assuming a t-distribution with the mean and standard error for the components of the VLM estimates at each site. These VLM probability distributions were combined with the modified Kopp projections to determine LSL rise probabilistic projections for each site. A similar approach was followed for the Ext 2.5 scenario, with the Sweet et al. (2016) projections adjusted with the mean VLM estimate at each site.

For the LSL projections, VLM is configured as a contribution to LSL change. For example, the VLM at North Spit is negative (Table 2) indicating that the ground is moving downward. This downward land motion increases sea-level rise at North Spit, resulting in a positive LSL rise contribution, as reported in the LSL tables. The opposite occurs for Crescent City. Table 5 lists the VLM contributions to LSL change (mean and +/- 2 standard deviations) determined by Kopp et al. (2014) for Crescent City and North Spit, and the NHE (in progress) estimates for these two locations and the Mad River Slough and Hookton Slough sites. The locally generated VLM estimates are higher than those determined by Kopp et al. (2014), which will increase or decrease the updated LSL rates, depending on the site.

Table 5. VLM contributions to LSL change determined by Kopp et al. (2014) and by Patton et al. (2017) and NHE (in progress) used in the updated LSL probability projections for the Humboldt Bay region. VLMs are reported as mean and +/- 2 standard deviations (SD).

	VLM rate as contribution to LSL change (mm/yr)			
	Kopp et al. (2014)		Patton et al. (2017) and NHE (in progress)	
Tide Gauge Location	Mean	+/- 2 SD	Mean	+/- 2 SD
Crescent City	-2.63	0.30	-3.11	0.27
Mad River Slough			1.04	0.67
North Spit	1.64	0.76	2.69	0.53
Hookton Slough			3.70	1.31

The modified LSL projections for Crescent City and North Spit are shown in Figure 13. The 2100 component contributions to LSL rise for Crescent City, North Spit, Mad River Slough and Hookton Slough are provided in Table 6 for the median (50% probability) and different probability ranges (e.g. 90 and 99% probabilities). The total LSL median projection and probabilities at each site for 2030, 2050, 2100, 2150 and 2200 are listed in Table 7, along with the Sweet et al. (2016) extreme scenario (Ext 2.5).

Findings/Discussion

Comparing the 2100 projections for LSL within the Humboldt Bay region to GMSL (Table 3 and Table 6) show differences between GMSL and LSL rise components, and reveal important regional and local factors that affect LSL change compared to GMSL. Within the Humboldt Bay region oceanic dynamic processes appear to have a limited effect on increasing sea levels beyond GMSL projections, except for small increases for the lower RCPs. Contributions from the glaciers/ice caps and Greenland Ice Sheet are projected to be lower than global averages for all RCPs. The Antarctic Ice Sheet is projected to have only slight increases above the global average for the lower RCPs. However, unlike other portions of the U.S. west coast that are projected to have sea-level rise close to the global average (Kopp et al., 2014), the Humboldt Bay region has LSL projections well above the GMSL projections due to tectonically driven VLM.

Crescent City, which is uplifting, has LSL rise projections (50% probability of 0.42 m, 90% probability of 0.11 to 0.88) that are below GMSL projections (50% probability of 0.79 m, 90% probability of 0.52 to 1.21) under RCP 8.5 by 2100. However, North Spit is subsiding, and has LSL projections (50% value of 1.01 m, 90% probability of 0.69 to 1.46) that are above the GMSL projections by 2100 for RCP 8.5. Likewise, Mad River Slough and Hookton Slough also have LSL projections that are above the global average, with Hookton Slough having the highest rates, due to the north to south trending downward VLMs in Humboldt Bay.

It should be noted that up to 2050, differences between LSL projections are minimal between RCP emission scenarios, and the RCP 8.5 projections can just be used (Kopp et al., 2014; Griggs et al., 2017). After 2050, differences in projections begin to emerge due to emission scenarios.

One final note, large interannual monthly and annual mean sea-level variability as occurs in the Humboldt Bay region (Figure 13) can mask LSL rise over the near term (Kopp et al., 2014). The interannual variability also exceeds the uncertainty in projections (~90% probability) until about 2030 to 2040 for annual mean sea levels, and about 2040 to 2050 for monthly mean sea levels. During these timeframes, the interannual variability, either alone or in combination with the LSL rise projections, should be considered in decision making.

The key finding from the updated probabilistic LSL projections is that the tectonically driven VLM in Humboldt Bay creates the highest LSL rise rates in California. These higher LSL rates indicate that GMSL rise will impact Humboldt Bay faster than other parts of the U.S. west coast; and within the bay, the south end will be impacted sooner than the north end.

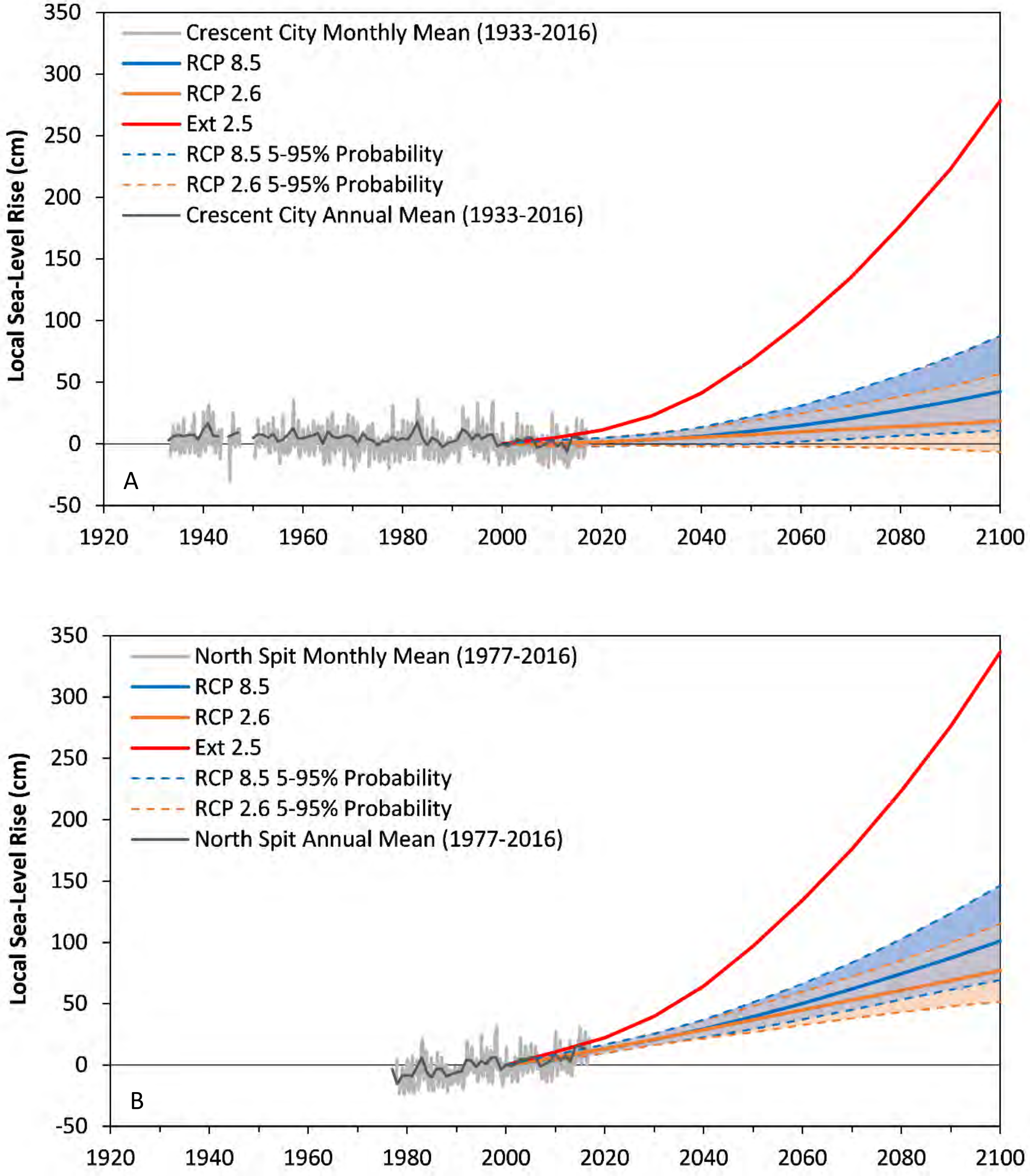


Figure 13. LSL rise projections at Crescent City (A) and North Spit (B) for RCP 8.5 and RCP 2.6 based on data from Kopp et al. (2014), the Sweet et al. (2016) extreme scenario of 2.5 m of GMSL rise by 2100 (Ext 2.5), and VLM contribution to LSL rise by Patton et al. (2017) and NHE (in progress). The 5 and 95 % probabilities are the shaded areas bounded by the dashed lines. The LSL curves are the annual and monthly mean sea levels for the 1933 to 2016 Crescent City data (NOAA 9419750), and the 1977 to 2016 North Spit data (NOAA 9418767), respectively. All data referenced to year 2000 baseline.

Table 6. LSL rise component contributions at year 2100 for Humboldt Bay Region based on data (GIC, GIS, AIS, Ocean and LWS) from Kopp et al. (2014), and VLM contribution to LSL rise by Patton et al. (2017) and NHE (in progress). Sea-level values are cm and ft above year 2000 baseline; probabilities are percent.[1]

	RCP 8.5					RCP 4.5					RCP 2.6				
	50	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**	**50**	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**	**50**	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**
Crescent City, year 2100 – Sea-level rise components (cm)															
GIC	13	10 to 17	8 to 19	5 to 22	< 24	10	7 to 13	5 to 15	3 to 18	< 20	9	6 to 11	5 to 13	2 to 16	< 18
GIS	12	7 to 22	4 to 33	2 to 59	< 81	8	3 to 13	2 to 19	0 to 34	< 46	5	3 to 10	2 to 15	2 to 26	< 36
AIS	4	-8 to 18	-13 to 38	-15 to 110	< 183	6	-6 to 19	-10 to 39	-12 to 106	< 176	7	-4 to 20	-8 to 41	-11 to 112	< 185
Ocean	37	24 to 49	16 to 58	2 to 70	< 77	27	16 to 39	8 to 47	-4 to 59	< 64	22	12 to 32	6 to 39	-5 to 49	< 54
LWS	5	3 to 7	2 to 8	0 to 11	< 12	5	3 to 7	2 to 8	0 to 11	< 12	5	3 to 7	2 to 8	0 to 11	< 12
VLM	-31	-32 to -30	-33 to -29	-35 to -28	< -27	-31	-32 to -30	-33 to -29	-35 to -28	< -27	-31	-32 to -30	-33 to -29	-35 to -28	< -27
Total	42	23 to 65	11 to 88	-6 to 155	< 224	26	9 to 46	-2 to 65	-17 to 131	< 194	18	3 to 37	-7 to 57	-19 to 125	< 196
Mad River Slough, year 2100 – Sea-level rise components (cm)															
GIC	14	11 to 17	8 to 19	5 to 23	< 25	11	8 to 13	6 to 15	3 to 19	< 20	9	7 to 12	5 to 14	2 to 16	< 18
GIS	12	7 to 22	4 to 34	3 to 60	< 82	8	3 to 13	2 to 20	0 to 34	< 47	6	3 to 10	2 to 15	2 to 27	< 37
AIS	4	-8 to 18	-13 to 39	-16 to 110	< 184	6	-6 to 19	-10 to 39	-12 to 107	< 176	7	-4 to 20	-8 to 41	-11 to 112	< 186
Ocean	37	25 to 49	16 to 57	3 to 69	< 75	27	16 to 38	9 to 46	-4 to 58	< 63	22	13 to 31	6 to 38	-5 to 48	< 53
LWS	5	3 to 7	2 to 8	0 to 11	< 12	5	3 to 7	2 to 8	0 to 11	< 12	5	3 to 7	2 to 8	0 to 11	< 12
VLM	10	8 to 13	5 to 16	1 to 20	< 23	10	8 to 13	5 to 16	1 to 20	< 23	10	8 to 13	5 to 16	1 to 20	< 23
Total	85	65 to 108	53 to 130	36 to 197	< 268	68	51 to 88	39 to 108	23 to 173	< 242	61	45 to 79	35 to 99	21 to 168	< 242
North Spit, year 2100 – Sea-level rise components (cm)															
GIC	14	11 to 17	8 to 19	5 to 23	< 25	11	8 to 13	6 to 15	3 to 19	< 20	9	7 to 12	5 to 14	2 to 16	< 18
GIS	12	7 to 22	4 to 34	3 to 60	< 82	8	3 to 13	2 to 20	0 to 34	< 47	6	3 to 10	2 to 15	2 to 27	< 37
AIS	4	-8 to 18	-13 to 39	-16 to 110	< 184	6	-6 to 19	-10 to 39	-12 to 107	< 176	7	-4 to 20	-8 to 41	-11 to 112	< 186
Ocean	37	25 to 49	16 to 57	3 to 69	< 75	27	16 to 38	9 to 46	-4 to 58	< 63	22	13 to 31	6 to 38	-5 to 48	< 53
LWS	5	3 to 7	2 to 8	0 to 11	< 12	5	3 to 7	2 to 8	0 to 11	< 12	5	3 to 7	2 to 8	0 to 11	< 12
VLM	27	24 to 29	23 to 31	20 to 34	< 35	27	24 to 29	23 to 31	20 to 34	< 35	27	24 to 29	23 to 31	20 to 34	< 35
Total	101	81 to 124	69 to 146	53 to 215	< 287	85	67 to 104	56 to 124	41 to 190	< 252	77	62 to 95	52 to 115	39 to 183	< 253
Hookton Slough, year 2100 – Sea-level rise components (cm)															
GIC	14	11 to 17	8 to 19	5 to 23	< 25	11	8 to 13	6 to 15	3 to 19	< 20	9	7 to 12	5 to 14	2 to 16	< 18
GIS	12	7 to 22	4 to 34	3 to 60	< 82	8	3 to 13	2 to 20	0 to 34	< 47	6	3 to 10	2 to 15	2 to 27	< 37
AIS	4	-8 to 18	-13 to 39	-16 to 110	< 184	6	-6 to 19	-10 to 39	-12 to 107	< 176	7	-4 to 20	-8 to 41	-11 to 112	< 186
Ocean	37	25 to 49	16 to 57	3 to 69	< 75	27	16 to 38	9 to 46	-4 to 58	< 63	22	13 to 31	6 to 38	-5 to 48	< 53
LWS	5	3 to 7	2 to 8	0 to 11	< 12	5	3 to 7	2 to 8	0 to 11	< 12	5	3 to 7	2 to 8	0 to 11	< 12
VLM	37	32 to 42	28 to 46	16 to 59	< 73	37	32 to 42	28 to 46	16 to 59	< 73	37	32 to 42	28 to 46	16 to 59	< 73
Total	111	91 to 135	79 to 157	60 to 224	< 291	94	77 to 116	65 to 135	48 to 199	< 260	87	71 to 107	61 to 127	45 to 193	< 260

Table 6. Continued

	RCP 8.5					RCP 4.5					RCP 2.6				
	50	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**	**50**	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**	**50**	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**
Crescent City, year 2100 – Sea-level rise components (ft)															
GIC	0.4	0.3 to 0.6	0.3 to 0.6	0.2 to 0.7	< 0.8	0.3	0.2 to 0.4	0.2 to 0.5	0.1 to 0.6	< 0.7	0.3	0.2 to 0.4	0.2 to 0.4	0.1 to 0.5	< 0.6
GIS	0.4	0.2 to 0.7	0.1 to 1.1	0.1 to 1.9	< 2.7	0.3	0.1 to 0.4	0.1 to 0.6	0.0 to 1.1	< 1.5	0.2	0.1 to 0.3	0.1 to 0.5	0.1 to 0.9	< 1.2
AIS	0.1	-0.3 to 0.6	-0.4 to 1.2	-0.5 to 3.6	< 6.0	0.2	-0.2 to 0.6	-0.3 to 1.3	-0.4 to 3.5	< 5.8	0.2	-0.1 to 0.7	-0.3 to 1.3	-0.3 to 3.7	< 6.1
Ocean	1.2	0.8 to 1.6	0.5 to 1.9	0.2 to 2.3	< 2.5	0.9	0.5 to 1.3	0.3 to 1.5	0.0 to 1.9	< 2.1	0.7	0.4 to 1.0	0.2 to 1.3	-0.1 to 1.6	< 1.8
LWS	0.2	0.1 to 0.2	0.1 to 0.3	0.0 to 0.4	< 0.4	0.2	0.1 to 0.2	0.1 to 0.3	0.0 to 0.4	< 0.4	0.2	0.1 to 0.2	0.1 to 0.3	0.0 to 0.4	< 0.4
VLM	-1.0	-1.1 to -1.0	-1.1 to -0.9	-1.1 to -0.9	< -0.9	-1.0	-1.1 to -1.0	-1.1 to -0.9	-1.1 to -0.9	< -0.9	-1.0	-1.1 to -1.0	-1.1 to -0.9	-1.1 to -0.9	< -0.9
Total	1.4	0.7 to 2.1	0.4 to 2.9	-0.1 to 5.1	< 7.3	0.9	0.3 to 1.5	-0.1 to 2.1	-0.4 to 4.3	< 6.4	0.6	0.1 to 1.2	-0.2 to 1.9	-0.5 to 4.1	< 6.4
Mad River Slough, year 2100 – Sea-level rise components (ft)															
GIC	0.5	0.4 to 0.6	0.3 to 0.6	0.2 to 0.8	< 0.8	0.4	0.3 to 0.4	0.2 to 0.5	0.1 to 0.6	< 0.7	0.3	0.2 to 0.4	0.2 to 0.5	0.1 to 0.5	< 0.6
GIS	0.4	0.2 to 0.7	0.1 to 1.1	0.1 to 2.0	< 2.7	0.3	0.1 to 0.4	0.1 to 0.7	0.0 to 1.1	< 1.5	0.2	0.1 to 0.3	0.1 to 0.5	0.1 to 0.9	< 1.2
AIS	0.1	-0.3 to 0.6	-0.4 to 1.3	-0.5 to 3.6	< 6.0	0.2	-0.2 to 0.6	-0.3 to 1.3	-0.4 to 3.5	< 5.8	0.2	-0.1 to 0.7	-0.3 to 1.3	-0.3 to 3.7	< 6.1
Ocean	1.2	0.8 to 1.6	0.5 to 1.9	0.2 to 2.3	< 2.5	0.9	0.5 to 1.2	0.3 to 1.5	0.0 to 1.9	< 2.1	0.7	0.4 to 1.0	0.2 to 1.2	-0.1 to 1.6	< 1.7
LWS	0.2	0.1 to 0.2	0.1 to 0.3	0.0 to 0.4	< 0.4	0.2	0.1 to 0.2	0.1 to 0.3	0.0 to 0.4	< 0.4	0.2	0.1 to 0.2	0.1 to 0.3	0.0 to 0.4	< 0.4
VLM	0.3	0.2 to 0.4	0.2 to 0.5	0.1 to 0.7	< 0.8	0.3	0.2 to 0.4	0.2 to 0.5	0.1 to 0.7	< 0.8	0.3	0.2 to 0.4	0.2 to 0.5	0.1 to 0.7	< 0.8
Total	2.8	2.1 to 3.5	1.7 to 4.3	1.3 to 6.5	< 8.8	2.2	1.7 to 2.9	1.3 to 3.5	0.9 to 5.7	< 7.9	2.0	1.5 to 2.6	1.1 to 3.2	0.8 to 5.5	< 7.9
North Spit, year 2100 – Sea-level rise components (ft)															
GIC	0.5	0.4 to 0.6	0.3 to 0.6	0.2 to 0.8	< 0.8	0.4	0.3 to 0.4	0.2 to 0.5	0.1 to 0.6	< 0.7	0.3	0.2 to 0.4	0.2 to 0.5	0.1 to 0.5	< 0.6
GIS	0.4	0.2 to 0.7	0.1 to 1.1	0.1 to 2.0	< 2.7	0.3	0.1 to 0.4	0.1 to 0.7	0.0 to 1.1	< 1.5	0.2	0.1 to 0.3	0.1 to 0.5	0.1 to 0.9	< 1.2
AIS	0.1	-0.3 to 0.6	-0.4 to 1.3	-0.5 to 3.6	< 6.0	0.2	-0.2 to 0.6	-0.3 to 1.3	-0.4 to 3.5	< 5.8	0.2	-0.1 to 0.7	-0.3 to 1.3	-0.3 to 3.7	< 6.1
Ocean	1.2	0.8 to 1.6	0.5 to 1.9	0.2 to 2.3	< 2.5	0.9	0.5 to 1.2	0.3 to 1.5	0.0 to 1.9	< 2.1	0.7	0.4 to 1.0	0.2 to 1.2	-0.1 to 1.6	< 1.7
LWS	0.2	0.1 to 0.2	0.1 to 0.3	0.0 to 0.4	< 0.4	0.2	0.1 to 0.2	0.1 to 0.3	0.0 to 0.4	< 0.4	0.2	0.1 to 0.2	0.1 to 0.3	0.0 to 0.4	< 0.4
VLM	0.9	0.8 to 1.0	0.7 to 1.0	0.7 to 1.1	< 1.2	0.9	0.8 to 1.0	0.7 to 1.0	0.7 to 1.1	< 1.2	0.9	0.8 to 1.0	0.7 to 1.0	0.7 to 1.1	< 1.2
Total	3.3	2.7 to 4.1	2.3 to 4.8	1.9 to 7.0	< 9.4	2.8	2.2 to 3.4	1.8 to 4.1	1.5 to 6.2	< 8.3	2.5	2.0 to 3.1	1.7 to 3.8	1.4 to 6.0	< 8.3
Hookton Slough, year 2100 – Sea-level rise components (ft)															
GIC	0.5	0.4 to 0.6	0.3 to 0.6	0.2 to 0.8	< 0.8	0.4	0.3 to 0.4	0.2 to 0.5	0.1 to 0.6	< 0.7	0.3	0.2 to 0.4	0.2 to 0.5	0.1 to 0.5	< 0.6
GIS	0.4	0.2 to 0.7	0.1 to 1.1	0.1 to 2.0	< 2.7	0.3	0.1 to 0.4	0.1 to 0.7	0.0 to 1.1	< 1.5	0.2	0.1 to 0.3	0.1 to 0.5	0.1 to 0.9	< 1.2
AIS	0.1	-0.3 to 0.6	-0.4 to 1.3	-0.5 to 3.6	< 6.0	0.2	-0.2 to 0.6	-0.3 to 1.3	-0.4 to 3.5	< 5.8	0.2	-0.1 to 0.7	-0.3 to 1.3	-0.3 to 3.7	< 6.1
Ocean	1.2	0.8 to 1.6	0.5 to 1.9	0.2 to 2.3	< 2.5	0.9	0.5 to 1.2	0.3 to 1.5	0.0 to 1.9	< 2.1	0.7	0.4 to 1.0	0.2 to 1.2	-0.1 to 1.6	< 1.7
LWS	0.2	0.1 to 0.2	0.1 to 0.3	0.0 to 0.4	< 0.4	0.2	0.1 to 0.2	0.1 to 0.3	0.0 to 0.4	< 0.4	0.2	0.1 to 0.2	0.1 to 0.3	0.0 to 0.4	< 0.4
VLM	1.2	1.1 to 1.4	0.9 to 1.5	0.6 to 2.0	< 2.4	1.2	1.1 to 1.4	0.9 to 1.5	0.6 to 2.0	< 2.4	1.2	1.1 to 1.4	0.9 to 1.5	0.6 to 2.0	< 2.4
Total	3.6	3.0 to 4.4	2.6 to 5.2	2.2 to 7.4	< 9.6	3.1	2.5 to 3.8	2.1 to 4.4	1.8 to 6.5	< 8.5	2.8	2.3 to 3.5	2.0 to 4.2	1.6 to 6.3	< 8.5

[1]LSL is local sea level; VLM is vertical land motion contribution to LSL; GIC is glaciers and ice caps; GIS is Greenland Ice Sheet; AIS is Antarctic Ice Sheet; Ocean is ocean thermal, steric and dynamic contribution; LWS is land water storage; RCP 8.5, RCP 4.5 and RCP 2.6 are greenhouse gas representative concentration pathways of AR5 (IPCC, 2013).

Table 7. LSL rise projections for Humboldt Bay Region based on data from Kopp et al. (2014), the extreme GMSL scenario (2.5 m of GMSL rise by 2100) of Sweet et al. (2016), and VLM contribution to LSL rise by Patton et al. (2017) and NHE (in progress). Sea-level values are cm and ft above year 2000 baseline; probabilities are percent.[1]

	RCP 8.5					**RCP 4.5**					**RCP 2.6**					**Ext 2.5**
	50	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**	**50**	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**	**50**	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**	**50**
Crescent City LSL rise projections by year (cm)																
2030	3	1 to 6	-1 to 8	-4 to 11	< 14	3	0 to 6	-3 to 9	-6 to 13	< 15	3	1 to 6	-1 to 8	-4 to 12	< 14	23
2050	10	4 to 17	0 to 22	-6 to 33	< 50	9	3 to 15	-2 to 20	-8 to 30	< 46	8	2 to 14	-2 to 19	-8 to 30	< 47	68
2100	42	23 to 65	11 to 88	-6 to 155	< 224	26	9 to 46	-2 to 65	-17 to 131	< 194	18	3 to 37	-7 to 57	-19 to 125	< 196	279
2150	75	40 to 122	20 to 176	-2 to 333	< 507	43	10 to 84	-10 to 130	-35 to 288	< 452	25	-4 to 62	-17 to 111	-31 to 281	< 458	620
2200	118	54 to 205	19 to 305	-19 to 597	< 904	62	4 to 135	-28 to 220	-66 to 511	< 804	34	-18 to 102	-41 to 193	-63 to 505	< 810	1062
Mad River Slough LSL rise projections by year (cm)																
2030	16	13 to 19	11 to 21	9 to 24	< 26	16	12 to 19	10 to 22	6 to 25	< 28	16	13 to 19	11 to 21	8 to 25	< 27	35
2050	31	25 to 38	21 to 43	15 to 54	< 71	30	23 to 36	19 to 41	13 to 51	< 67	29	23 to 35	18 to 40	12 to 51	< 67	89
2100	85	65 to 108	53 to 130	36 to 197	< 268	68	51 to 88	39 to 108	23 to 173	< 242	61	45 to 79	35 to 99	21 to 168	< 242	320
2150	139	103 to 187	83 to 241	60 to 399	< 565	106	73 to 148	53 to 194	28 to 349	< 511	88	59 to 126	45 to 175	30 to 343	< 518	685
2200	203	138 to 290	102 to 392	64 to 684	< 993	146	87 to 219	54 to 304	17 to 598	< 891	118	66 to 187	41 to 279	20 to 586	< 887	1149
North Spit LSL rise projections by year (cm)																
2030	21	18 to 23	16 to 25	14 to 29	< 31	21	17 to 24	15 to 26	11 to 30	< 32	21	18 to 24	16 to 26	13 to 29	< 31	40
2050	40	33 to 46	29 to 51	24 to 62	< 80	38	32 to 44	28 to 49	22 to 60	< 74	37	31 to 43	27 to 48	21 to 59	< 74	97
2100	101	81 to 124	69 to 146	53 to 215	< 287	85	67 to 104	56 to 124	41 to 190	< 252	77	62 to 95	52 to 115	39 to 183	< 253	337
2150	163	127 to 211	107 to 265	85 to 427	< 597	131	97 to 173	77 to 219	53 to 379	< 547	112	84 to 150	70 to 200	54 to 365	< 547	710
2200	236	171 to 323	136 to 424	96 to 717	< 1024	178	120 to 252	88 to 337	48 to 625	< 922	150	99 to 219	76 to 310	52 to 617	< 927	1182
Hookton Slough LSL rise projections by year (cm)																
2030	24	21 to 27	19 to 29	15 to 33	< 36	24	20 to 27	17 to 30	13 to 34	< 37	24	21 to 27	18 to 30	14 to 34	< 37	43
2050	45	38 to 52	33 to 57	26 to 70	< 88	43	36 to 50	32 to 55	25 to 67	< 83	42	35 to 49	31 to 54	23 to 67	< 83	102
2100	111	91 to 135	79 to 157	60 to 224	< 291	94	77 to 116	65 to 135	48 to 199	< 260	87	71 to 107	61 to 127	45 to 193	< 260	347
2150	179	142 to 227	121 to 282	96 to 436	< 605	147	112 to 189	92 to 235	64 to 395	< 555	128	99 to 166	83 to 215	65 to 386	< 560	725
2200	256	191 to 345	154 to 445	114 to 741	< 1049	199	140 to 273	106 to 358	66 to 648	< 947	171	119 to 241	95 to 332	66 to 634	< 950	1202

Table 7. Continued

	RCP 8.5					RCP 4.5					RCP 2.6					Ext 2.5
	50	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**	**50**	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**	**50**	**17 to 83**	**5 to 95**	**0.5 to 99.5**	**99.9**	**50**
Crescent City LSL rise projections by year (ft)																
2030	0.1	0.0 to 0.2	0.0 to 0.3	-0.1 to 0.4	< 0.4	0.1	0.0 to 0.2	-0.1 to 0.3	-0.2 to 0.4	< 0.5	0.1	0.0 to 0.2	0.0 to 0.3	-0.1 to 0.4	< 0.5	0.7
2050	0.3	0.1 to 0.5	0.0 to 0.7	-0.2 to 1.1	< 1.7	0.3	0.1 to 0.5	-0.1 to 0.7	-0.2 to 1.0	< 1.5	0.2	0.1 to 0.5	-0.1 to 0.6	-0.2 to 1.0	< 1.5	2.2
2100	1.4	0.7 to 2.1	0.4 to 2.9	-0.1 to 5.1	< 7.3	0.9	0.3 to 1.5	-0.1 to 2.1	-0.4 to 4.3	< 6.4	0.6	0.1 to 1.2	-0.2 to 1.9	-0.5 to 4.1	< 6.4	9.1
2150	2.5	1.3 to 4.0	0.7 to 5.8	0.1 to 10.9	< 16.6	1.4	0.3 to 2.8	-0.3 to 4.3	-0.9 to 9.4	< 14.8	0.8	-0.1 to 2.0	-0.5 to 3.6	-0.9 to 9.2	< 15.0	20.4
2200	3.9	1.8 to 6.7	0.6 to 10.0	-0.3 to 19.6	< 29.7	2.0	0.1 to 4.4	-0.9 to 7.2	-1.9 to 16.8	< 26.4	1.1	-0.6 to 3.4	-1.3 to 6.3	-1.9 to 16.6	< 26.6	34.8
Mad River Slough LSL rise projections by year (ft)																
2030	0.5	0.4 to 0.6	0.4 to 0.7	0.3 to 0.8	< 0.9	0.5	0.4 to 0.6	0.3 to 0.7	0.2 to 0.8	< 0.9	0.5	0.4 to 0.6	0.4 to 0.7	0.3 to 0.8	< 0.9	1.1
2050	1.0	0.8 to 1.2	0.7 to 1.4	0.6 to 1.8	< 2.3	1.0	0.8 to 1.2	0.6 to 1.3	0.5 to 1.7	< 2.2	0.9	0.7 to 1.1	0.6 to 1.3	0.5 to 1.7	< 2.2	2.9
2100	2.8	2.1 to 3.5	1.7 to 4.3	1.3 to 6.5	< 8.8	2.2	1.7 to 2.9	1.3 to 3.5	0.9 to 5.7	< 7.9	2.0	1.5 to 2.6	1.1 to 3.2	0.8 to 5.5	< 7.9	10.5
2150	4.5	3.4 to 6.1	2.7 to 7.9	2.1 to 13.1	< 18.5	3.5	2.4 to 4.9	1.7 to 6.4	1.1 to 11.5	< 16.8	2.9	1.9 to 4.1	1.5 to 5.7	1.1 to 11.2	< 17.0	22.5
2200	6.6	4.5 to 9.5	3.3 to 12.9	2.4 to 22.4	< 32.6	4.8	2.9 to 7.2	1.8 to 10.0	0.8 to 19.6	< 29.2	3.9	2.2 to 6.1	1.4 to 9.2	0.8 to 19.2	< 29.1	37.7
North Spit LSL rise projections by year (ft)																
2030	0.7	0.6 to 0.8	0.5 to 0.8	0.5 to 0.9	< 1.0	0.7	0.6 to 0.8	0.5 to 0.9	0.4 to 1.0	< 1.1	0.7	0.6 to 0.8	0.5 to 0.8	0.5 to 1.0	< 1.0	1.3
2050	1.3	1.1 to 1.5	1.0 to 1.7	0.8 to 2.0	< 2.6	1.2	1.0 to 1.4	0.9 to 1.6	0.8 to 2.0	< 2.4	1.2	1.0 to 1.4	0.9 to 1.6	0.7 to 1.9	< 2.4	3.2
2100	3.3	2.7 to 4.1	2.3 to 4.8	1.9 to 7.0	< 9.4	2.8	2.2 to 3.4	1.8 to 4.1	1.5 to 6.2	< 8.3	2.5	2.0 to 3.1	1.7 to 3.8	1.4 to 6.0	< 8.3	11.0
2150	5.4	4.2 to 6.9	3.5 to 8.7	3.0 to 14.0	< 19.6	4.3	3.2 to 5.7	2.5 to 7.2	1.9 to 12.4	< 17.9	3.7	2.8 to 4.9	2.3 to 6.5	1.9 to 12.0	< 17.9	23.3
2200	7.7	5.6 to 10.6	4.5 to 13.9	3.5 to 23.5	< 33.6	5.8	3.9 to 8.3	2.9 to 11.1	1.9 to 20.5	< 30.3	4.9	3.2 to 7.2	2.5 to 10.2	1.9 to 20.2	< 30.4	38.8
Hookton Slough LSL rise projections by year (ft)																
2030	0.8	0.7 to 0.9	0.6 to 1.0	0.5 to 1.1	< 1.2	0.8	0.7 to 0.9	0.6 to 1.0	0.5 to 1.1	< 1.2	0.8	0.7 to 0.9	0.6 to 1.0	0.5 to 1.1	< 1.2	1.4
2050	1.5	1.2 to 1.7	1.1 to 1.9	0.9 to 2.3	< 2.9	1.4	1.2 to 1.6	1.0 to 1.8	0.9 to 2.2	< 2.7	1.4	1.2 to 1.6	1.0 to 1.8	0.8 to 2.2	< 2.7	3.3
2100	3.6	3.0 to 4.4	2.6 to 5.2	2.2 to 7.4	< 9.6	3.1	2.5 to 3.8	2.1 to 4.4	1.8 to 6.5	< 8.5	2.8	2.3 to 3.5	2.0 to 4.2	1.6 to 6.3	< 8.5	11.4
2150	5.9	4.7 to 7.4	4.0 to 9.3	3.4 to 14.3	< 19.8	4.8	3.7 to 6.2	3.0 to 7.7	2.4 to 13.0	< 18.2	4.2	3.2 to 5.5	2.7 to 7.1	2.3 to 12.7	< 18.4	23.8
2200	8.4	6.3 to 11.3	5.1 to 14.6	4.1 to 24.3	< 34.4	6.5	4.6 to 9.0	3.5 to 11.8	2.5 to 21.2	< 31.1	5.6	3.9 to 7.9	3.1 to 10.9	2.4 to 20.8	< 31.2	39.4

[1]LSL is local sea level; RCP 8.5, RCP 4.5 and RCP 2.6 are greenhouse gas representative concentration pathways of AR5 (IPCC, 2013); and Ext 2.5 is the extreme 2.5 m of GMSL rise by 2100 of Sweet et al. (2016).

City of Arcata Local Sea-Level Rise Data and Information

This section provides data and information specific to the northern portion of Humboldt Bay (North Bay) that is more applicable for the City of Arcata sea-level rise planning and decision-making efforts. Information presented in this section relies on the modeling and analysis work conducted by NHE for the Humboldt Bay: Sea Level Rise, Hydrodynamic Modeling, and Inundation Vulnerability Mapping report (NHE, 2015a). Modeling and analysis results were used to produce inundation vulnerability maps of areas surrounding Humboldt Bay vulnerable to inundation from existing and future sea levels, along with bay-wide spatial data of average water levels of mean higher high water (MHHW), mean monthly maximum water (MMMW), and mean annual maximum water (MAMW), and extreme high-water level events (e.g. 100-yr flood level).

As part of the modeling and mapping work, a two-dimensional hydrodynamic model was developed and used to predict water levels within the existing shoreline of Humboldt Bay for five sea-level rise scenarios: year 2012 existing sea levels and half-meter sea-level rise increments of 0.5, 1.0, 1.5 and 2.0 m. The hydrodynamic model was forced by a 100-yr long hourly sea-level height series. Each model simulation produced 100-years of 15-minute predicted water levels at each model grid in the bay. Estimates of average high-water levels (e.g. MHHW) and annual exceedance probabilities of extreme high-water levels (e.g. 100-yr flood) were determined at each model grid cell for each of the five sea-level rise scenarios.

It should be noted that the open ocean boundary condition for the model accounts for sea-level height variability from astronomical tides, and the effects of wind, sea-level pressure, and El Niño variability (NHE, 2015a). However, the effects of internally generated wind waves on predicted water levels in Humboldt Bay were not assessed. The extreme high-water level elevations presented in the NHE (2015a) report do not represent what FEMA defines as the 1% annual base flood elevation, which includes wave effects. The water levels presented in the NHE (2015a) report correspond more closely to what FEMA defines as still water elevations.

In 2015, with funding from the City of Arcata, NHE (2015b) developed an Excel application that allows users to extract estimated average water levels and annual exceedance probabilities of extreme high-water levels at any hydrodynamic model grid cell in Humboldt Bay. The application also allows the user to interpolate a specific sea-level rise value, within the range of sea-level rise scenarios (year 2012 to 2.0 m), from the extracted grid cell water levels using spline interpolation. This application is used here to provide water-level elevations specific to the City of Arcata for the updated probabilistic LSL rise projections.

Sea-Level Rise Projections

The probabilistic LSL rise projections for Mad River Slough (Table 6 and Table 7) and the VLM estimate for Mad River Slough of 1.04 ± 0.67 mm/yr (Table 2) are the most appropriate for the City of Arcata to use in their sea-level rise planning and decision making efforts.

The half-meter sea-level rise scenarios (0.5, 1.0, 1.5 and 2.0 m) modeled in the NHE (2015a) study were not tied to any sea-level rise projection timeline. However, the scenarios were developed in the context of published sea-level rise projections (e.g. NRC, 2012) available at the time of that work, which resulted in the 2.0 m maximum scenario. Figure 14 shows the five sea-level rise scenarios compared to the probabilistic LSL rise projections for Mad River Slough for RCP 8.5, 4.5 and 2.6 (50% probability, and 90% probabilities for RCP 8.5 and 2.6). The half-meter sea-level rise scenarios cover most of the LSL projections range for Mad River Slough, except for the Ext 2.5 scenario which crosses the 2.0 m scenario line around 2080. Review of Table 7 also shows that the 99.9% probability value (268 cm) at 2100 for RCP 8.5 also exceeds the 2.0 m scenario. As noted by Griggs et al. (2017), sea-level rise is not currently following the Ext 2.5 scenario or extreme probabilistic projections; however, current modeling and research indicates the possibility of extreme sea-level rise by the end of this century.

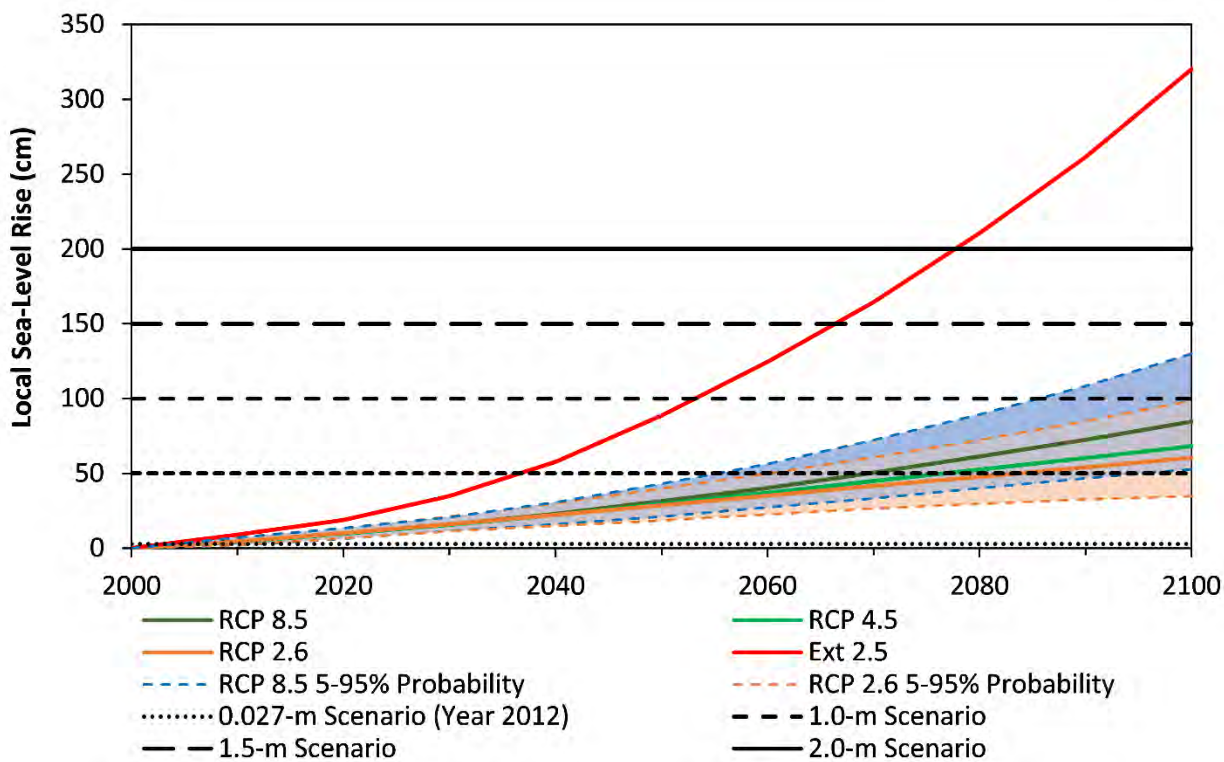


Figure 14. Humboldt Bay half-meter sea-level rise scenarios modeled in the NHE (2015a) study compared to the LSL rise projections at Mad River Slough for RCP 8.5, RCP 4.5 and RCP 2.6. The 5 and 95 % probabilities for RCP 8.5 and RCP 2.6 are the shaded areas bounded by the dashed lines. All data is referenced to year 2000 baseline.

Predicted Water-Level Elevations at the Arcata Marsh & Wildlife Sanctuary

Water-level elevations at the Arcata Marsh & Wildlife Sanctuary for the five sea-level rise scenarios (year 2012 existing sea levels and 0.5, 1.0, 1.5 and 2.0 m) were generated from model predictions that specifically apply to the City of Arcata (Table 8). It should be noted that modeled water-levels varied less than 1-cm between Jacoby Creek and Mad River Slough, except for MHHW estimates which varied up to 100 cm depending on whether the grid cell was on a mud flat or tidal wetland. Results presented here were extracted from a grid cell over mud flat near the Arcata Marsh & Wildlife Sanctuary, and can be used to represent water levels at most locations of interest for the City of Arcata. However, if MHHW elevations near a specific tidal wetland is of interest, it may be necessary to extract that water level from the nearest tidal wetland grid cell, depending on the need.

To support more specific sea-level rise planning and decision making efforts for the City of Arcata, the Excel application was used to provide the 50% probability (median) and 95% probability water-level elevations at 2030, 2050 and 2100 for RCP 8.5 (Table 9) at the Arcata Marsh & Wildlife Sanctuary. As discussed earlier, the large interannual monthly and annual mean sea-level variability that occurs in the Humboldt Bay region (Figure 1) can mask near term LSL rise. For the 2030 and 2050 projections in Table 9, it will be necessary to consider the effects of interannual variability, either alone, or in combination with the LSL projections.

Effects of LSL Rise on Predicted Water-Levels

The LSL projections estimate how mean sea levels will change as GMSL increases. However, extreme sea-level events are the cause of most damage to the California coast (Cayan et al., 2008; NRC, 2012), making it critical to understand the effects of sea-level rise on extreme events. Figure 15, which shows predicted water levels at the Arcata Marsh & Wildlife Sanctuary, demonstrates the importance of considering extreme events when planning for sea-level rise, compared to using average tidal levels such as MHHW. For example, the 100-yr extreme event is approximately 2 meters higher than mean sea level, 1 meter higher than MHHW, and 0.4 meters higher than MAMW. Furthermore, the 2-yr extreme event is approximately equal to MAMW, and the 1-yr event is only slightly greater than MMMW, showing how, on average, the more frequent extreme events are related to average water levels in the bay near the City of Arcata.

Figure 16 shows the predicted extreme high water level events for year 2012 existing sea levels, and the half-meter increment sea-level rise scenarios of 0.5, 1.0, 1.5 and 2.0-m relative to year 2000 at the Arcata Marsh & Wildlife Sanctuary. Over time, sea-level rise increases the extreme high water events. Furthermore, as sea-levels rise, the frequency of inundation of fixed water-levels increases. For example, the 1.1-yr extreme event under the 0.5-m sea-level rise scenario relative to year 2000, is approximately equal to the 100-yr event today, which is consistent with other parts of Humboldt Bay (NHE, 2015a) and in San Francisco Bay (Knowles, 2009).

To better understand how sea-level rise effects water levels, a frequency analysis was conducted for the predicted water levels at the Arcata Marsh & Wildlife Sanctuary that assessed the number

Table 8. Tidal levels and annual extreme high-water level probability estimates near Arcata Marsh & Wildlife Sanctuary for year 2012 existing sea levels and the 0.5, 1.0, 1.5 and 2.0-m sea-level rise scenarios (NHE, 2015a). Water levels are from 2D model predictions (NHE, 2015a). Water-level elevations are in cm and ft (NAVD88).[1]

Parameter	Return Interval (yr)	Year 2012	0.5 m Scenario	1.0 m Scenario	1.5 m Scenario	2.0 m Scenario
Elevations in cm (NAVD88)						
MHHW		216	264	315	364	414
MMMW		257	305	357	407	457
MAMW		288	336	387	437	486
1.01-yr	1.01	264	313	364	414	463
1.1-yr	1.1	272	321	372	421	471
1.5-yr	1.5	281	330	380	430	480
2-yr	2	286	335	385	435	485
5-yr	5	298	347	397	446	496
10-yr	10	305	354	404	453	503
25-yr	25	314	362	412	462	511
50-yr	50	320	368	418	467	517
100-yr	100	325	374	424	473	523
500-yr	500	337	385	435	484	535
Elevations in ft (NAVD88)						
MHHW		7.1	8.7	10.3	12.0	13.6
MMMW		8.4	10.0	11.7	13.3	15.0
MAMW		9.4	11.0	12.7	14.3	15.9
1.01-yr	1.01	8.7	10.3	11.9	13.6	15.2
1.1-yr	1.1	8.9	10.5	12.2	13.8	15.5
1.5-yr	1.5	9.2	10.8	12.5	14.1	15.7
2-yr	2	9.4	11.0	12.6	14.3	15.9
5-yr	5	9.8	11.4	13.0	14.6	16.3
10-yr	10	10.0	11.6	13.2	14.9	16.5
25-yr	25	10.3	11.9	13.5	15.1	16.8
50-yr	50	10.5	12.1	13.7	15.3	17.0
100-yr	100	10.7	12.3	13.9	15.5	17.2
500-yr	500	11.0	12.6	14.3	15.9	17.5

[1]MHHW is mean higher high water, MMMW is mean monthly maximum water, MAMW is mean annual maximum water.

Table 9. Tidal levels and annual extreme high-water level probability estimates near Arcata Marsh & Wildlife Sanctuary for updated probabilistic LSL projections for 2030, 2050 and 2100 for RCP 8.5. Water levels are provided for 50% (median) and 95% probabilities. Water levels are from 2D model predictions (NHE, 2015a). Water-level elevations are in cm and ft (NAVD88).[1]

Parameter	Return Interval (yr)	2030		2050		2100	
		50%	95%	50%	95%	50%	95%
Elevations in cm (NAVD88)							
MHHW		229	234	245	257	299	345
MMMW		270	275	286	298	341	387
MAMW		302	307	317	329	372	417
1.01-yr	1.01	278	283	293	306	349	394
1.1-yr	1.1	286	291	301	314	356	402
1.5-yr	1.5	295	300	310	323	365	410
2-yr	2	300	305	315	328	370	415
5-yr	5	312	317	327	339	382	426
10-yr	10	319	324	334	347	389	433
25-yr	25	328	333	343	355	397	442
50-yr	50	334	339	349	361	403	448
100-yr	100	339	344	354	367	409	453
500-yr	500	350	356	366	378	420	465
Elevations in ft (NAVD88)							
MHHW		7.5	7.7	8.0	8.4	9.8	11.3
MMMW		8.9	9.0	9.4	9.8	11.2	12.7
MAMW		9.9	10.1	10.4	10.8	12.2	13.7
1.01-yr	1.01	9.1	9.3	9.6	10.0	11.4	12.9
1.1-yr	1.1	9.4	9.5	9.9	10.3	11.7	13.2
1.5-yr	1.5	9.7	9.8	10.2	10.6	12.0	13.5
2-yr	2	9.8	10.0	10.3	10.8	12.1	13.6
5-yr	5	10.2	10.4	10.7	11.1	12.5	14.0
10-yr	10	10.5	10.6	11.0	11.4	12.8	14.2
25-yr	25	10.7	10.9	11.3	11.7	13.0	14.5
50-yr	50	10.9	11.1	11.4	11.8	13.2	14.7
100-yr	100	11.1	11.3	11.6	12.0	13.4	14.9
500-yr	500	11.5	11.7	12.0	12.4	13.8	15.2

[1]MHHW is mean higher high water, MMMW is mean monthly maximum water, MAMW is mean annual maximum water.

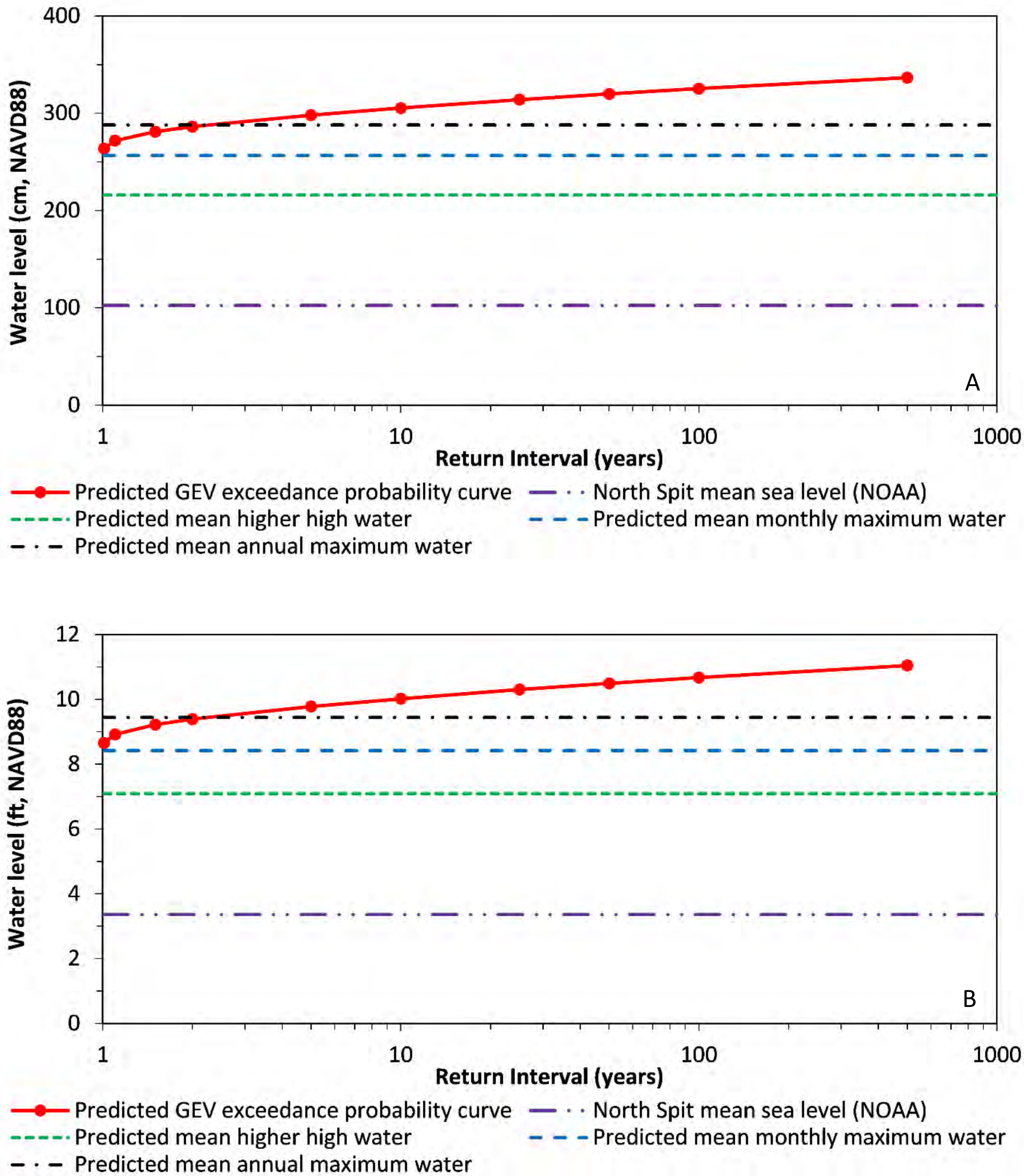


Figure 15. Humboldt Bay year 2012 existing sea-level scenario water levels near Arcata Marsh & Wildlife Sanctuary in units of cm (A) and ft (B). The generalized extreme value (GEV) probability curve, mean higher high water, mean monthly maximum water, and mean annual maximum water are from 2D model predictions (NHE, 2015a). Mean sea level is for North Spit tide gauge (1983-2001 National Tidal Datum Epoch). Water-level elevations in cm and ft (NAVD88).

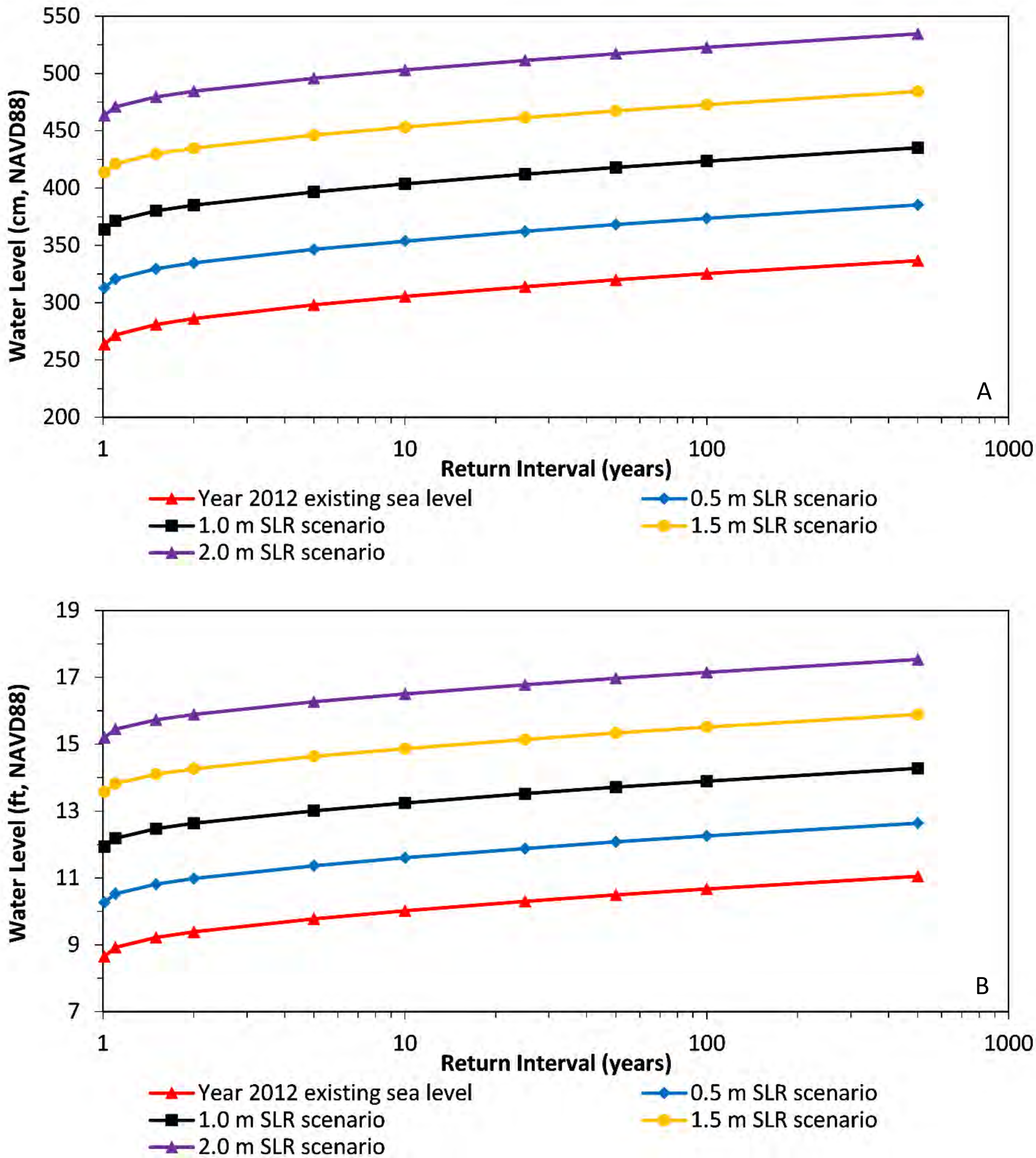


Figure 16. Annual extreme high-water level exceedance probability curves near Arcata Marsh & Wildlife Sanctuary in units of cm (A) and ft (B) for year 2012 existing sea levels and the 0.5, 1.0, 1.5 and 2.0-m sea-level rise scenarios relative to year 2000. All generalized extreme value (GEV) exceedance probability curves are from the 2D model predictions (NHE, 2015a). Water-level elevations are in cm and ft (NAVD88).

of days water levels exceeded year 2012 values for each half-meter sea-level rise scenario (Table 10). As sea-levels increase, the number of days that a current extreme water level is exceeded also increases. For example, the 2-year extreme event (approximately equivalent to MAMW) increases from about 1 day per year today to 67 days per year with 0.5 meters of LSL rise, to 319 days per year for 1 meter of LSL rise, and daily at 1.5 meters. For the 100-yr event, which occurs well below 1 day per year today, will be exceeded 6 days per year with 0.5 meters of LSL rise, about 118 days per year with 1 meter of LSL rise, and will be exceeded almost daily after 1.5 meters of LSL rise.

Table 10. Modeled water-level exceedances above year 2012 base levels near Arcata Marsh & Wildlife Sanctuary for year 2012 existing sea levels and the 0.5, 1.0, 1.5 and 2.0-m sea-level rise scenarios (NHE, 2015a). Water levels are from 2D model predictions (NHE, 2015a). Water-level elevations in cm and ft (NAVD88).[1]

Year 2012		Number of days that Year 2012 base value is exceeded				
Return Interval (yr)	Base Value (cm, NAVD88)	Year 2012	0.5 m Scenario	1.0 m Scenario	1.5 m Scenario	2.0 m Scenario
1.1	272	5	130	351	365	365
1.5	281	2	87	334	365	365
2 (~MAMW)	286	1	67	319	365	365
5	298	0	32	270	365	365
10	305	0	18	231	363	365
25	314	0	9	180	360	365
50	320	0	6	146	354	365
100	325	0	3	118	346	365

To help put this into perspective, since 1912 Humboldt Bay has seen approximately 50 cm of sea-level rise using the North Spit LSL rise rate of 5.0 mm/yr applied over 100 years. Therefore, what was a 100-yr extreme event in 1912 is today about the 1-yr event, or about the monthly average high tide (Figure 15). Using the Hookton Slough LSL rate of 6.0 mm/yr, it would only take approximately 83 years for the 100-yr event to equal the 1-yr event. For Mad River Slough, it would take about 150 years due to the lower LSL rise rate of 3.3 mm/yr. This helps to explain why many Humboldt Bay levees are currently so vulnerable to overtopping by high water level events (Laird, 2013), as many of the bay's levees were constructed in the early 1900s.

Sea-Level Rise Effects on Groundwater and Drainage (An Overview)

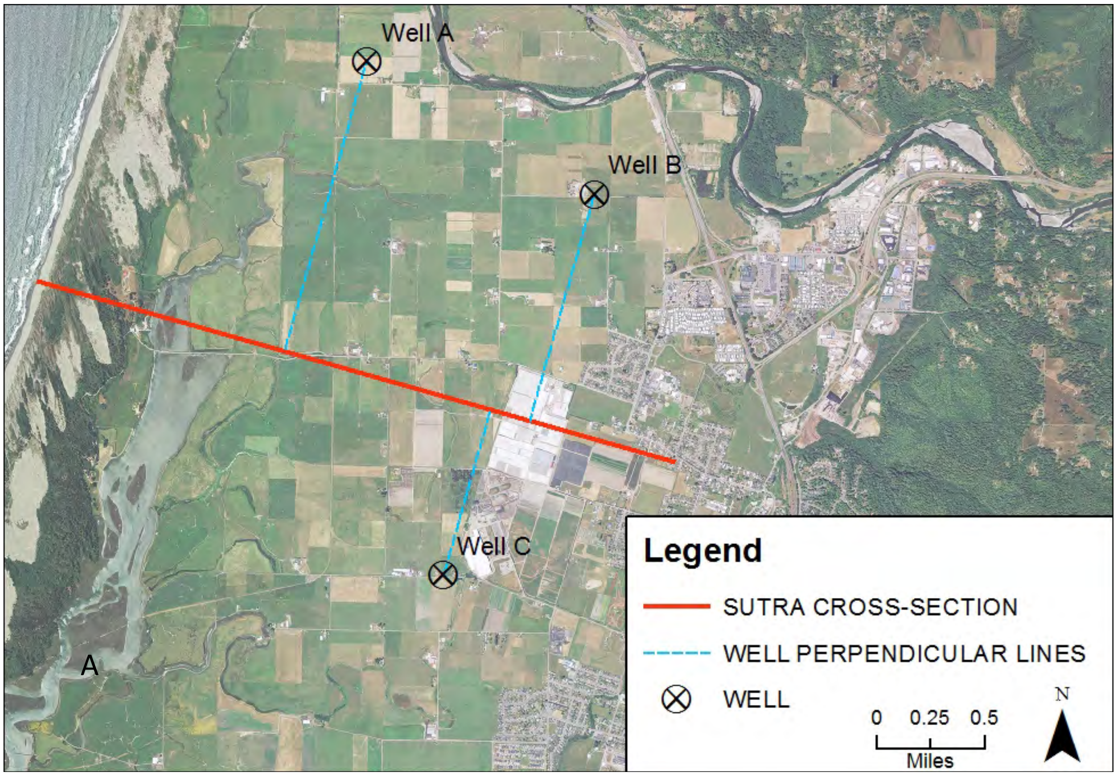
The focus of most sea-level rise research, and vulnerability and planning studies has been on the impacts of inundation from rising sea levels and higher storm surge. Groundwater inundation and emergence, or the increase in water table elevation and corresponding decrease in vadose zone thickness, also threatens low-lying coastal communities as sea-levels rise (Walter et al., 2016; Bjerklie et al., 2012; Hoover et al., 2017). Limited research or consideration has been given to the effect that rising sea-levels will have on groundwater levels, and likewise the impact that elevated groundwater levels will have on coastal communities. The purpose of this section is to provide a brief overview of sea-level rise effects on groundwater and drainage, and to illustrate, based on existing literature, how rising groundwater levels could affect low lying areas in the City of Arcata.

A common assumption in many groundwater assessments is that the groundwater elevation at the ocean edge is at mean sea level (Turner et al., 1997). However, research has shown that the action of tidal oscillations, waves and wave runup can cause fluctuating groundwater levels and a net super-elevation (increase) of the groundwater surface above mean sea level at the ocean boundary in unconfined coastal aquifers (Turner et al., 1997; Rotzoll and El-Kadi, 2008; Monachesi and Guarracino, 2011; Maréchal, n.d.). Similar to considerations for interannual monthly and annual sea-level variability, the effects of elevated groundwater levels above mean sea level will also need to be considered for sea-level rise planning.

Studies, although somewhat limited, have been carried out to analyze the effects of sea-level rise on groundwater elevations in coastal environments and communities. For example, Rotzoll and Fletcher (2012) estimated inundation in Honolulu, HI, and showed that the areal extents of predicted inundation more than doubled when groundwater inundation was combined with the effects of direct sea-level inundation alone. Habel (2016), using a quasi three-dimensional groundwater flow model (MODFLOW) showed that a 1-meter increase in sea level resulted in continuous or episodic flooding throughout most of the study area in Honolulu, HI.

Analyses regarding the effects of sea-level rise on groundwater levels specific to the Arcata-area were carried out by Willis (2014) and Hoover et al. (2017). Willis (2014), used the USGS SUTRA (Saturated-Unsaturated Transport) model to develop a conceptual numerical groundwater model to analyze the potential effects of sea-level rise on the water table in a representative two-dimensional cross-section of the Eureka-Arcata coastal plain (Figure 17). Results of the conceptual model indicate that sea-level rise could increase the degree of saltwater intrusion, and shift the location of the maximum hydraulic head westward (towards the ocean), with more pronounced effects occurring with greater degrees of sea-level rise (Figure 17). Furthermore, the effects of increased groundwater extraction rates and/or decreased recharge rates would increase the degree of saltwater intrusion within the aquifer. Willis (2014) emphasized that the model was a conceptual simulation model, and was not fully calibrated or validated, due to data and budget limitations. It was recommended that additional data collection and studies be carried out to more accurately assess the effects of sea-level rise on groundwater levels within the Eureka-Arcata Plain.

Hoover et al. (2017) assessed the spatial effects of sea-level rise on groundwater emergence in a low-lying area of Arcata (same general area as Willis (2014) study) and two other California



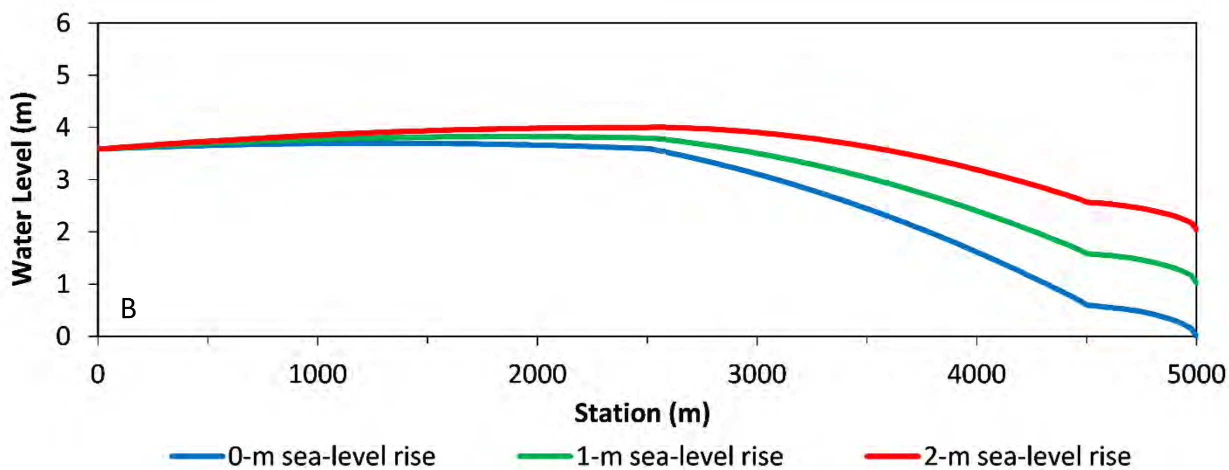


Figure 17. Location of conceptual groundwater model cross-section in Eureka-Arcata Plain and location of three Department of Water Resources wells (A), and groundwater level (hydraulic head) response of 0-, 1- and 2-meters of sea-level rise (B). Figures from Willis (2014).

coastal sites. Using a groundwater surface generated from groundwater elevation data obtained from three wells and topographic data developed using high-resolution digital elevation models (DEMs), Hoover et al. (2017) assessed the vulnerability of the Arcata region to sea-level rise driven groundwater emergence and shoaling with future sea-level rise scenarios of 1 and 2 meters (Figure 18). The analysis predicted 27% and 73% of the study area to be inundated from emergent groundwater with 1 and 2 meters of sea-level rise, respectively, compared with a 2.7% areal inundation for 2011 existing conditions. Due to the simplicity of the modeling approach, and since the effects of groundwater extraction and tidal forcing were neglected, these results were thought to be conservative, but informative, estimates of the actual areal extents of sea-level driven groundwater inundation (Hoover et al., 2017).

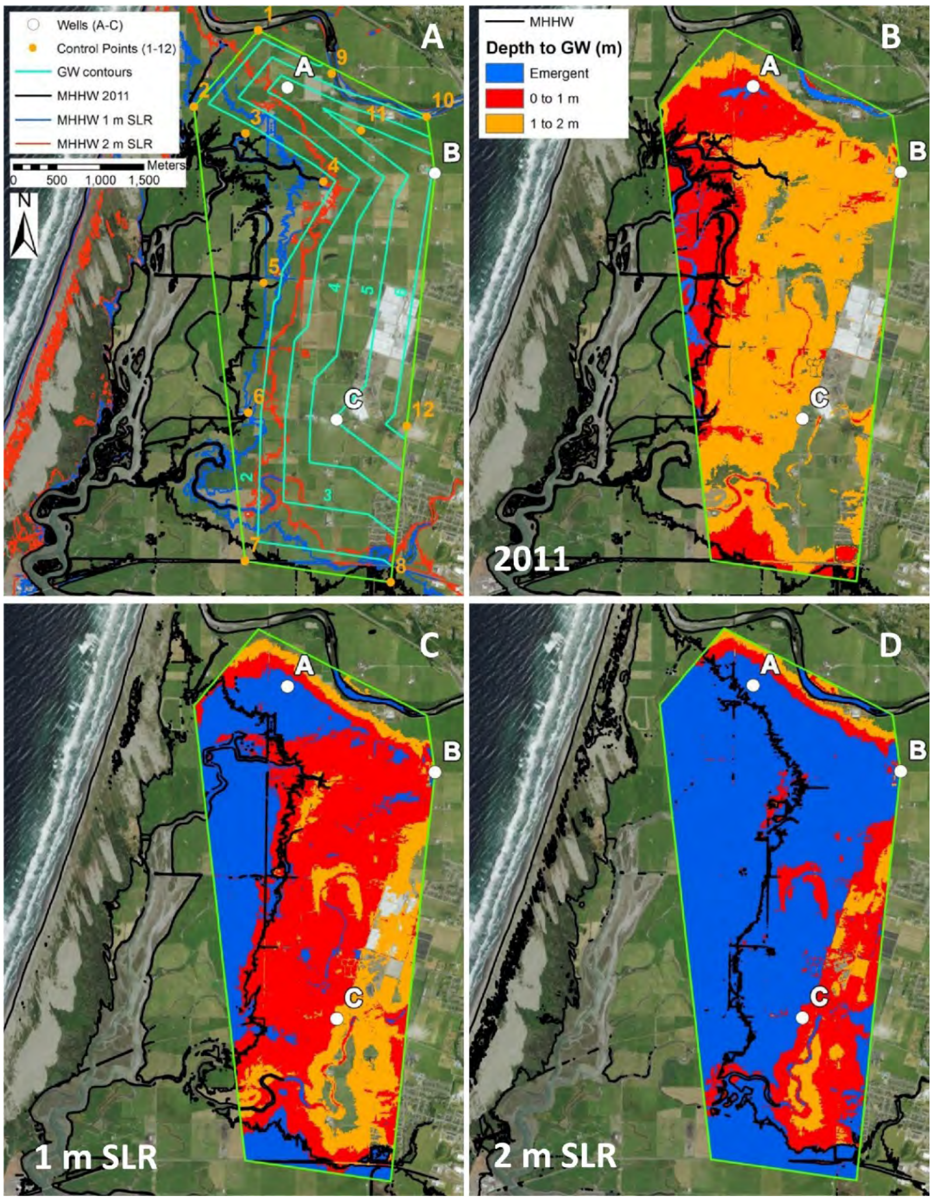


Figure 18. Sea-level rise driven groundwater emergence/shoaling in Arcata study area. Overview map showing well and boundary control point locations, resulting groundwater contours, and extent of inundation by present day MHHW, and 1 and 2 m increases (A). Calculated depths to groundwater for present-day conditions (B). Depth to groundwater for 1-m sea-level rise (C). Depth to groundwater for 2-m sea-level rise (D). Figure from Hoover et al. (2017).

As sea-level rise continues into the future, increases in groundwater levels within unconfined coastal aquifers can be expected, with potential adverse impacts to low-lying communities (Walter et al., 2016; Hoover et al., 2017). The degree of sea-level rise related groundwater inundation may vary substantially between different regions along the California coast. Since a significant amount of land near Arcata, CA is situated at elevations below 3 m (NAVD88), and typical MHHW levels range between 1.6 m and 2.0 m (NAVD88) throughout the California coast, Arcata was identified as "potentially vulnerable to sea-level rise driven groundwater emergence and shoaling" (Hoover et al., 2015).

Following is a brief list of potential impacts to low-lying areas of Arcata due to increased groundwater levels and inundation from sea-level rise:

- Rising groundwater levels can inundate and flood low-lying areas within Arcata, even if those areas are protected from surface water inundation by levees.
- Increased groundwater levels could impact current agricultural land and practices, and change/alter existing vegetation communities.
- Rising groundwater levels can alter surface water drainage patterns, impact existing stormwater drainage infrastructure, and limit the ability of low-lying areas to drain.
- Rainfall runoff and infiltrative characteristics of existing areas will change as groundwater levels increase. For example, unpaved areas that currently produce limited runoff due to infiltration of rainfall could generate more runoff as groundwater levels rise and infiltration capacity lessons. This type of rainfall/runoff response would create more runoff than currently exists from these low-lying areas, further impacting downstream stormwater infrastructure.
- Existing stormwater mitigation measures, such as detention and infiltration basins, swales, pervious pavements, etc., would become less effective as groundwater rises and infiltration capacity is reduced.
- Rising groundwater levels can increase Infiltration & Inflow into existing wastewater collection systems due to increased hydraulic head.
- Increased groundwater levels could impact existing residential and commercial onsite wastewater treatment and disposal systems in rural low-lying areas.

Glossary

AIS	Antarctic Ice Sheet
AR5	IPCC Fifth Assessment Report
CG	Cascadia Geosciences
CSZ	Cascadia subduction zone
DEM	digital elevation model
ENSO	El Niño Southern Oscillation
GIA	glacial isostatic adjustment
GIC	glaciers and ice caps
GIS	Greenland Ice Sheet
GMSL	global mean sea level
GPS	global positioning system
IPCC	Intergovernmental Panel on Climate Change
LSL	local sea-level
LWS	land water storage
MAMW	mean annual maximum water
MEI	multivariate ENSO index
MHHW	mean higher high water
MMMW	mean monthly maximum water
MSL	mean sea level
NAVD88	North American Vertical Datum of 1988
NHE	Northern Hydrology and Engineering
NOAA	National Ocean and Atmospheric Administration
OPC	Ocean Protection Council
PDO	Pacific Decadal Oscillation
PNW	U.S. Pacific Northwest
RCP	representative concertation pathway
ReSL	regional sea-level
TE	thermal expansion
USGS	United States Geological Survey
VLM	vertical land motion

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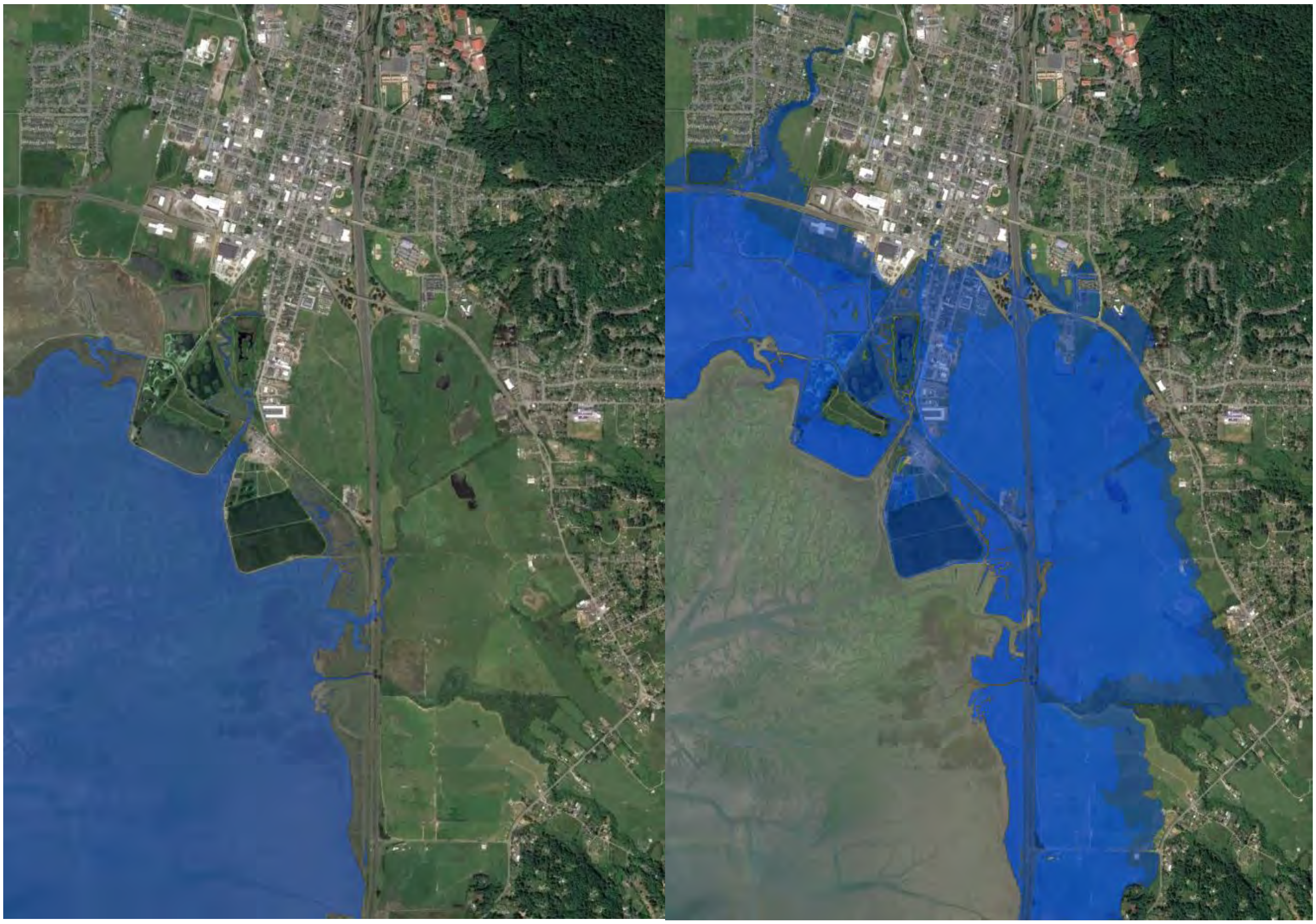
City of Arcata



Current Tidal Inundation Areas versus Potential Tidal Inundation Areas (Stillwater) with 4.6 feet (1.5 meters) of Sea Level Rise

Sea Level Rise Vulnerability Assessment

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CITY OF ARCATA

Local Coastal Program

Sea Level Rise
Vulnerability Assessment

Prepared By

Aldaron Laird
Trinity Associates

February 2018

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Sea level rise vulnerability assessments and adaptation planning on Humboldt Bay have been greatly enabled by the research and engineering of Jeff Anderson of Northern Hydrology and Engineers. Combined with the equally valuable research by geologist at Cascadia Geosciences, planners now have the tools to educate the public, agencies, and decision-makers about sea level rise on Humboldt Bay.

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Glossary

Numerous technical terms are defined upfront for the reader, to enable a greater understanding of the material presented in this report. This report relies in part on terms and definitions that were derived from the California Coastal Commission (Commission) Sea Level Rise Policy Guidance (2015).

Adaptation: Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which minimizes harm or takes advantage of beneficial opportunities.

Adaptive capacity: The ability of a system to respond to climate change (including climate variability and extremes), moderate potential damages, take advantage of opportunities, and cope with the consequences.

Backwater or Backwater flooding: Upstream flooding caused by downstream conditions such as channel restriction or high tide blocking high river flows from entering estuaries.

Coastal-dependent development or use: Any development or use which requires a site on, or adjacent to, the sea to be able to function at all.

Coastal resources: A general term used throughout the Guidance to refer to those resources addressed in Chapter 3 of the California Coastal Act, including beaches, wetlands, agricultural lands, and other coastal habitats; coastal development; public access and recreation opportunities; cultural, archaeological, and paleontological resources; and scenic and visual qualities.

Development: On land, in or under water, the placement or erection of any solid material or structure; discharge or disposal of any dredged material or of any gaseous, liquid, solid, or thermal waste; grading, removing, dredging, mining, or extraction of any materials; change in the density or intensity of use of land, including, but not limited to, subdivision pursuant to the Subdivision Map Act (commencing with Section 66410 of the Government Code), and any other division of land, including lot splits, except where the land division is brought about in connection with the purchase of such land by a public agency for public recreational use; change in the intensity of use of water, or of access thereto; construction, reconstruction, demolition, or alteration of the size of any structure, including any facility of any private, public, or municipal utility; and the removal or harvesting of major vegetation other than for agricultural purposes, kelp harvesting, and timber operations which are in accordance with a timber harvesting plan submitted pursuant to the provisions of the Z'berg-Nejedly Forest Practice of 1973 (commencing with Section 4511).

Environmentally Sensitive Habitat Area (ESHA): Any area in which plant or animal life or their habitats are either rare or especially valuable because of their special nature or role in an ecosystem and which could be easily disturbed or degraded by human activities and developments.

Erosion: The wearing away of land and removal of shoreline, beach or sand dune sediments by wave action, high tides, tidal currents, and overtopping shoreline structures such as dikes.

Flood (or Flooding): Refers to normally dry land becoming temporarily covered in water, either episodically (*e.g.*, storm or tsunami flooding) or periodically (*e.g.*, tidal flooding). Annual king tides are an example of tidal flooding of lands normally not covered by daily or monthly high tides. Coastal Hazard planning generally addresses episodic 100-year floods that have 1% probability of occurring in any year but like all floods are unpredictable as to when they might occur. Floods do recede, and flooded lands generally do dry out again.

Inundation: Inundation as used in this report is a form of tidal flooding. Inter-tidal areas are those lands above the lowest tide and below the highest tide elevations that periodically experience tidal inundation. Areas that are below the lowest tide elevation are submerged lands, and thus are permanently inundated. Tidal inundation datums are generally described as to their frequency of occurrence and elevation, such as daily mean low or high water (MLW and MHW); mean monthly and mean annual maximum high water are additional tidal datums (MMMW and MAMW). Tidal inundation is very predictable. Tide charts are published each year that identify when, and how low or high, the tides are expected reach common daily tidal datums: mean lower low water (MLLW), MLW, MHW, and mean higher high water (MHHW). Inundation maps used in this report depict areas that could be inundated by MMMW under various sea level rise scenarios, absent storm surge or wind wave conditions.

Mean sea level: The average relative sea level over a period, such as a month or a year, long enough to average out transients such as waves and tides.

Relative sea level: Combination of regional sea level measured by a tide gauge and vertical land motion trends of the land upon which the gauge is situated.

Risk: Commonly considered to be the combination of the likelihood of an event and its consequences – *i.e.*, risk equals the probability of climate hazard occurring multiplied by the consequences a given system may experience.

Sea level: The height of the ocean relative to land; tides, wind, atmospheric pressure changes, heating, cooling, and other factors cause sea level changes.

Sea level change/sea level rise: Sea level can change, both globally and locally, due to (a) changes in the shape of the ocean basins, (b) changes in the total mass of water and (c) changes in water density. Factors leading to sea level rise under global warming include both increases in the total mass of water from the melting of land-based snow and ice, and changes in water density from an increase in ocean water temperatures and salinity changes. Relative sea level rise occurs where there is a local increase in the level of the ocean relative to the land, which might be due to ocean rise and/or land level subsidence.

Sea level rise impact: An effect of sea level rise on the structure or function of a system.

Sensitivity: The degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. The effect may be direct (*e.g.*, a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (*e.g.*, climatic or non-climatic stressors may cause people to be more sensitive to additional extreme conditions from climate change than they would be in the absence of these stressors).

Shore protection: Structures or sand placed at or on the shore to reduce or eliminate upland damage from wave action or flooding during storms.

Shoreline protective devices: A broad term for constructed features such as seawalls, revetments, riprap, earthen berms, cave fills, and bulkheads that block the landward retreat of the shoreline and are used to protect structures or other features from erosion and other hazards.

Shoreline vulnerability rating: A quantitative measure of vulnerability that uses combinations of shoreline attributes (cover type and relative elevation to modeled MMMW) to rank shoreline segment's vulnerability to erosion and/or overtopping due to extreme tides, storm surges, and sea level rise. (Laird and Powell 2013).

Still water level: The elevation that the surface of the water would assume if all wave action was absent.

Storm surge: A rise above normal water level on the open coast due to the action of wind stress on the water surface. Storm surge resulting from a hurricane also includes the rise in water level due to atmospheric pressure reduction as well as that due to wind stress.

Subsidence: Sinking or down-warping of a part of the earth's surface; can result from seismic activity, changes in loadings on the earth's surface, fluid extraction, or soil settlement.

Tectonic: Of or relating to the structure of the earth's crust and the large-scale processes that take place within it.

Tidelands: Lands which are located between the lines of mean high tide and mean low tide.

Vulnerability: The extent to which a species, habitat, ecosystem, or human system is susceptible to harm from sea level rise impacts. More specifically, the degree to which a system is exposed to, susceptible to, and unable to cope with, the adverse effects of sea level rise, and tidal extremes.

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Sea Level Rise Vulnerability Assessment Methods

The City of Arcata's approach to assessing vulnerability to sea level rise in its planning jurisdiction is to identify the effects of specific water elevations, such as the mean monthly maximum water (MMMW) tidal datum. Because the uncertainty of sea level rise projections for any planning horizon generates an ever-increasing range of water levels over time, more confidence is provided to the public by the City's focus on the effects of specific water level increases, rather than when those increased levels may occur. This is a departure from the California Coastal Commission's (Commission) 2015 Sea Level Rise Policy Guidance and the January 2017 Memorandum summarizing steps for conducting sea level rise vulnerability assessments. The Commission recommends that sea level rise exposure scenarios associated with specific planning horizons based on high sea level rise projections should be considered for vulnerability assessments and adaptation planning. Projections based on low or high greenhouse gas emissions and contributions from melting ice are constantly being revised, ever upward. While the Commission does encourage utilizing specific water elevations in addition to planning horizons to reduce concerns over uncertainty of sea level rise projections, particularly for planning horizons after 2050. The City believes that it is more prudent to focus its sea level rise vulnerability assessment and adaptation planning based on the best available science and engineering and rely on specific increases in water elevations, and not a range of sea level rise projections.

All surface elevations in this report are North American vertical datum of 1988 (NAVD 88) and measured at the North Spit tide gauge (National Oceanic and Atmospheric Agency (NOAA) Station 9418767). California planners, and engineers, and scientists often use different units of measure. Sea level rise planning documents generally refer to sea level rise in feet (ft.), while engineers/scientists who create sea level rise models and maps are likely to use meters (m). To facilitate the public's use of information presented in this report, it relies on English units of measure (feet) and offers metric conversions.

This report uses two approaches to address sea level rise on Humboldt Bay:

1) shoreline elevation profile, and
2) inundation modeling and mapping.

A shoreline elevation profile, utilizing the baseline MMMW elevation of 7.7 ft., was used to identify shoreline segments that are vulnerable to sea level rise, in one-foot increments (Laird and Powell 2013). Sea level rise vulnerability assessment efforts on Humboldt Bay have selected the MMMW as a baseline because it correlates well with the current upper boundary of tidal vegetation on the shoreline.

Hydrodynamic modeling and inundation vulnerability mapping prepared for Humboldt Bay by Northern Hydrology and Engineering (NHE) depicts and quantifies areas that are potentially vulnerable to being inundated, with the assumption that shoreline structures (dikes) are absent or not functioning, by specific water elevations, including:

- MMMW (7.7 ft.),
- mean annual maximum water (MAMW) (8.8 ft.),
- MMMW+0.5-meter (M) (9.3 ft.),
- MMMW+1.0 M (11.0 ft.), and
- MMMW+1.5 M (12.6 ft.) (NHE 2015).

The inundation maps depict still water conditions, with no wave run-up or storm surge incorporated.

NHE's inundation maps of Humboldt Bay are the best maps available and are used as the basis for identifying areas that are potentially vulnerable to sea level rise and quantifying impacts for purposes of this report. For example, they are used to visually depict the extent of tidal inundation from sea level rise absent the effects of protective barrier-like structures such as dikes and road grades, commonly referred to as a "bathtub model". The integrity of the entire protective shoreline in a common hydrologic unit needs to be maintained to prevent inundation of the low-lying areas behind the shoreline, not just the shoreline in front of an asset. A single breach would cause the inundation of the entire hydrologic unit and all assets residing behind that common shoreline. With six feet of sea level rise, 92% of the current artificial shoreline would be overtopped; the low-lying land behind artificial shorelines would be inundated.

Executive Summary

With three feet of sea level rise, the most critical and vulnerable asset in the City of Arcata is its wastewater collection system and treatment facility, including the Arcata Marsh. The City is not sustainable if its wastewater infrastructure is compromised. The risk to wastewater infrastructure is ongoing. Based on existing conditions, exposure of wastewater infrastructure will become critical due to the combination of two feet of sea level rise and king tides that could result in three feet of sea level rise for several days a year.

Humboldt Bay will expand in response to three feet of sea level rise while the available footprint for urban development and open space areas used for agriculture and wildlife will decrease. The majority of the City is not directly vulnerable to sea level rise. However, vulnerable areas include the former tidelands south of Samoa Boulevard and west of Old Arcata Road that were isolated from Humboldt Bay in 1890, including associated infrastructure and land uses.

Other assets located in these vulnerable areas include Highways 101 and 255, industrial and residential property, Pacific Gas and Electric's gas lines and electrical transmission structures, optical fiber lines, the Humboldt Bay Trail, and the Bayside Wildlife reserve. Likewise, the City of Eureka's municipal water transmission line, which traverses vulnerable former tidelands within the City of Arcata, and is also a critical, at-risk asset.

Today, there are approximately 52 miles of shoreline on Humboldt Bay that form a barrier protecting nearly 10,000 low-lying acres from tidal inundation. A New Year's Eve 2005 king tide and storm surge caused sea levels to rise 1.8 feet, the highest water level ever recorded on Humboldt Bay. The Governor responded by declaring a State of Disaster (Figure 1). King tides could reach 2005 levels on an annual basis with just one foot of sea level rise. With three feet of sea level rise, roughly 35 miles of barrier shoreline (58% of the artificial shoreline) could be overtopped. Approximately 10,000 acres of agricultural land, Highways 101 and 255, municipal water and wastewater lines, electrical distribution infrastructure, gas lines, and optical fiber communications lines could all become tidally inundated if tidal waters on Humboldt Bay rise three feet. The current mean annual maximum tide (MAMW) of 8.8 ft.—king tides— would become equivalent to daily mean high tide (MHW) with three feet of sea level rise.

Figure 1. New Year's Eve 2005 king tide with dikes filled to overtopping in Arcata.

The effects of three feet of sea level rise in the City's Local Coastal Program (LCP) planning area would be significant. Roughly 3.4 miles (49%) of the shoreline in the City would be overtopped. The shorelines on Butcher Slough and Gannon Slough would be overtopped and substantial tidal inundation of the City's Waste Water Treatment Facility (Treatment Plant) and Arcata Marsh and Wildlife Sanctuary (Arcata Marsh), as well as the residential, industrial properties, and agricultural lands south of Samoa Boulevard would occur.

With three feet (1.0 M) of sea level rise, nearly 684 acres (78%) of the agricultural lands, 249 acres (84%) of the natural resource lands, 29 acres (37%) of the public facilities, 63 acres (46%) of the industrial property, and 21 acres (15%) of the residential area in the City's LCP planning area would become tidally inundated.

Most of the City's streets south of Samoa Boulevard would become tidally inundated with three feet (1.0 M) of sea level rise, as would the Bayside Cutoff. Highway 101, as it traverses Arcata Bay and Highway 255 on the Mad River Bottom adjacent to the City, would be tidally inundated. Roughly 1.4 miles of railroad and the recently constructed Humboldt Bay Trail would become tidally inundated.

Approximately 2.6 miles of municipal water transmission lines and one pump station, 3.7 miles of sewer lines and one lift station, 2.8 miles of gas lines, and nine electrical transmission towers and 30 transmission poles would be tidally inundated.

There are 1,639 acres of environmentally sensitive habitat (ESHA) in the City's LCP planning area, including open water, eelgrass, mudflats, salt marsh and seasonal freshwater wetlands (pasture). With three feet (1.0 M) of sea level rise, tidal inundation would expand mud flats by 735 acres and salt marsh by 261 acres; seasonal freshwater wetlands would shrink by 393 acres. Eelgrass habitat, currently a valuable habitat on Humboldt Bay, could expand by 62 acres.

While it is necessary to locate and assess individual assets in areas vulnerable to sea level rise, to do so is not a complete vulnerability assessment by itself. Assets do not exist in a vacuum. Assets are intricately linked to and served by multiple regional assets, including municipal water, wastewater, electricity, natural gas, optical fibers, local streets and Highway 101. Focusing on just one asset or one location would omit the inter-connectedness of other related assets and their vulnerabilities. For example, even if all the residences in the vulnerable area south of Samoa Boulevard had livable floor elevations above the 100-year sea level rise projection, they would still be vulnerable and at risk when local streets and utilities become tidally inundated.

Unique to the north coast region of California, relative sea level rise (a combination of vertical land motion trends and regional sea levels) projections and potential inundation maps have been developed for Humboldt Bay. Both tools have informed the preparation of this vulnerability assessment report. The City's sea level rise planning work is building on previous regional vulnerability assessments and adaptation planning efforts as well as state guidance.

Based on available tidal inundation maps (NHE 2015), this report emphasizes impact assessment for specific water elevations [1.1 ft. (MAMW), 1.6 ft. (0.5 M), 3.3 ft. (1.0 M) and 4.9 ft. (1.5 M)] relative to various assets, rather than assessing a range of potential sea level rise projections for specific planning horizons (2030, 2050, and 2100). This report focuses on informing the public, agencies, and decision-makers about where, what, and how a particular level of sea level rise could have impacts, regardless of when that sea level rise level might occur.

Sea levels on Humboldt Bay currently vary by three feet: daily MHW is 5.8 ft. and MAMW is 8.8 ft. Sea levels on Humboldt Bay tend to be highest in the winter months when king tides provide real time examples of the impacts of one or more feet of sea level rise. Despite the conclusions of recent federal and state sea level rise reports (NRC 2012 and Griggs 2017), Humboldt Bay has the highest rate of sea level change on the west cost of the United States, rising 18 inches over the last century. Local geologists and engineers have studied regionally specific vertical land motion (Patton 2017) and tidal modeling (NHE 2015); these studies and models are the technical basis for this vulnerability assessment.

The primary near-term sea level rise impacts to the assets within the City's LCP planning area are shoreline erosion and the resultant tidal inundation due to extreme tidal events and storms. Long-term impacts include backwater flooding (a result of downstream blockage from higher tides), rising groundwater and salt water intrusion. Because, in the long-term, sea level rise would be compounded by rising groundwater and would likely overcome barrier-like shoreline structures, Humboldt Bay would expand and reclaim thousands of acres of former tidelands.

The next step in planning for sea level rise is to develop adaptation policies and measures. The City of Arcata is preparing adaptation polices for its LCP planning area. However, the Commission retains the authority to issue coastal development permits pursuant to the Coastal Act for tidelands, submerged lands and public trust lands. In the case of the City of Arcata, the Commission retains permit jurisdiction on approximately 969 acres (86%) of the 1,550 acres that are vulnerable to tidal inundation with 4.9 ft. (1.5 M) of sea level rise. The challenge for the City of Arcata and the Commission will be to integrate the application of their authorities to effectively and efficiently address the impacts of sea level rise on coastal resources and developments.

1 Introduction

The purpose of this report is to inform the public, property owners, agencies, and land use and resource decision-makers of the vulnerability and risk from sea level rise and tidal inundation that exists on Humboldt Bay.

This vulnerability assessment is needed to apply the tidal inundation modeling and mapping prepared for Humboldt Bay and inform people about areas and assets that are vulnerable to and at risk from sea level rise and tidal inundation. Relative sea level rise projections have also been developed for Humboldt Bay that can be utilized to assess risk to areas and assets. A region-wide vulnerability assessment of sea level rise exposure can provide opportunities for coordinating adaptation strategies, policies, and measures across jurisdictional boundaries.

The City of Arcata is updating its LCP and desires to identify areas that may be exposed to sea level rise. This inventory and assessment of the assets at risk to sea level rise builds on prior work by the Humboldt Bay Sea Level Rise Adaptation Planning Project. That planning effort began with inventorying and mapping (structure, cover, and elevation) the 102 miles of shoreline on Humboldt Bay and assigning a vulnerability rating to the shoreline reflecting its vulnerability to erosion or overtopping by extreme tides or projected sea level rise by 2050 (Laird and Powell 2013). The project also involved preparing relative sea level rise projections through 2100 (NHE 2014a) and a sea level rise hydrodynamic model and potential inundation maps of areas surrounding Humboldt Bay (NHE 2015). These potential inundation maps are available to the public as GIS shapefiles and Google Earth kmz files from the Humboldt Bay Harbor, Recreation and Conservation District (Harbor District) sea level rise adaptation planning project web site, http://humboldtbay.org/humboldt-bay-sea-level-rise-adaptation-planning-project .

The Humboldt Bay Sea Level Rise Adaptation Planning Project also involved the formation of a regional sea level rise adaptation planning group which included the City and twenty-one other regional stakeholders with land use, land management, or resources management responsibilities or advisory roles on lands adjacent to Humboldt Bay that are vulnerable to sea level rise impacts, and culminated in the production of a regional vulnerability assessment adaptation plan for Humboldt Bay (Laird 2015). These assessment and planning efforts led all three LCP authorities on Humboldt Bay (City of Arcata and Eureka, and Humboldt County) to request and secure grants to address sea level rise as part of the update of their LCPs.

The City would also like to assess what developments or land uses (assets) may be vulnerable (exposed, susceptible, and unable to cope) to sea level rise. This report would describe current sea level datums and shoreline conditions on Humboldt Bay (Laird 2013), potential sea level rise inundation areas for MAMW (1.1 ft.), and three sea level rise elevations—1.6 ft. (0.5 M), 3.3 ft. (1.0 M) and 4.9 ft. (1.5 M)] (NHE 2015). This report builds on previous vulnerability and risk assessments that were prepared by regional sea level rise adaptation planning efforts on Humboldt Bay, such as Laird and Powell (2014), NHE (2015), and Laird (2015 and 2016).

This report’s assessment of asset vulnerability and risk is presented under five major asset classes: shoreline, land uses, transportation, utilities, and coastal resources. While this report summarizes and presents information based on available GIS-based shoreline and inundation mapping of Humboldt Bay, it is not a substitute for using these mapping tools for site-specific information.

In summary, this vulnerability and risk assessment utilizes the best available science to identify areas and assets that might be exposed to sea level rise. This report would also describe existing asset vulnerabilities and risks not directly attributable to sea level rise but due to potential barrier-type (dike) shoreline failures. This information is critical to property owners, the public, and the City to inform land use decisions.

The City’s LCP, occupies approximately 1,550 acres above or landward of mean sea level (MSL) 3.4 ft. (Figure 2). The state has retained jurisdiction under the Coastal Act on approximately 969 acres (62.5%) of the 1,550 acres that are vulnerable to tidal inundation with 4.9 ft. (1.5 M) of sea level rise. There an additional 10 acres that are vulnerable to tidal inundation by 4.9 ft. (1.5 M) of sea level rise, which are inland of the City’s LCP planning area.

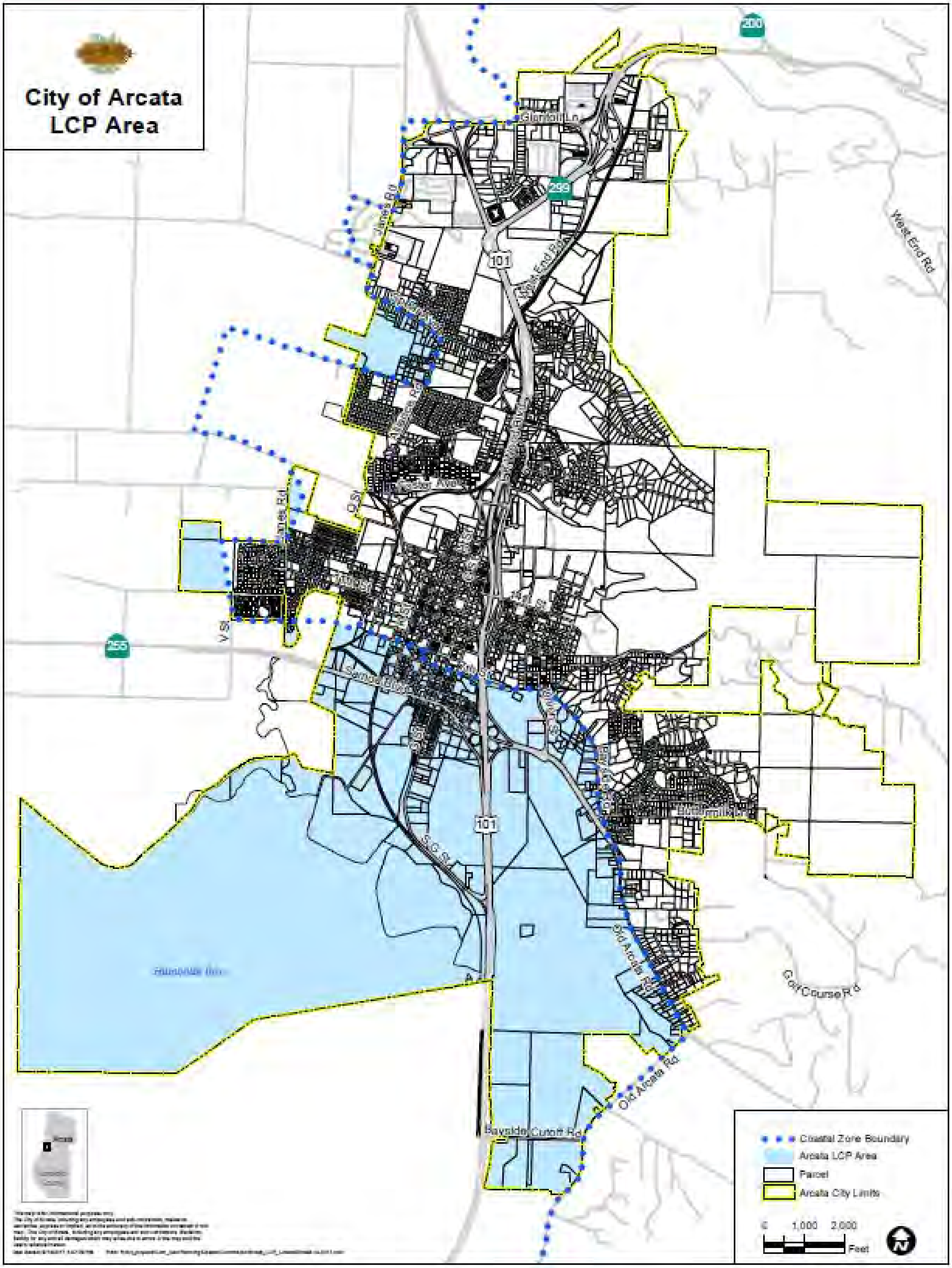

Figure 2. City of Arcata's LCP area.

The hydrodynamic model of Humboldt Bay produced in 2014 (NHE 2014b) is the source of potential tidal inundation (still-water) area predictions used to assess vulnerability and risk in this report. The inundation mapping assumes there are no shoreline structures and identifies potential conditions that could occur if barrier-like shoreline structures are breached or overtopped absent future implementation of sea level rise preparedness measures (NHE 2015). The limits of inundation that have been delineated are based on 2012 surface elevations (Figure 3). The Federal Emergency Management Agency (FEMA) has revised its Flood Insurance Rate Maps (FIRM) for Humboldt Bay. FEMA also did not consider existing shoreline structures on Humboldt Bay when it mapped flood hazard zones, unless they were federally certified structures. There are no federally certified structures on Humboldt Bay (FEMA 2016).

In this report, asset exposure is described using the following criteria:

- Assumes failure of barrier-like shoreline structures,
- Exposure to 1.1 ft. of sea level rise, equivalent to the MAMW elevation (8.8 ft.), and
- Sea level rise above the MMMW elevation in increments of 1.6 ft. (0.5 M) to 4.9 ft. (1.5 M).

Figure 3. Predicted tidal inundation areas (stillwater) on Mad River Slough, Mad River Bottom, and Arcata illustrate increasing inundation footprint for 1.1 ft. (MAMW), 1.6 ft. (0.5 M), 3.3 ft. (1.0 M), and 4.9 ft. (1.5 M) of sea level rise.

2 Sea Level Rise

2.1 Humboldt Bay Tidal Datums

There are a variety of different reference points, or tidal datums, used to measure tidal elevations, depending on the tidal phase of interest and the type of tides present along a shoreline (NOAA 2001). A typical tidal cycle involves two high tides and two low tides within a single daily cycle. On Humboldt Bay, the two high tides are not equivalent; one is higher than the other. The same is true for the low tides. These types of mixed tidal cycles result in tidal datums such as mean lower low water (MLLW) and mean higher high water (MHHW). Other recognized tidal datums include mean low water (MLW), mean sea level (MSL), mean high water (MHW, considered representative of the wetted shoreline), and mean annual maximum water (MAMW), often referred to as king tides (Table 1). The North Spit tide gauge record can be found at (http://tidesandcurrents.noaa.gov/stationhome.html?id=9418767).

Table 1. Tidal datums and elevations for Humboldt Bay as measured at the NOAA North Spit tide gage.

Tidal Datum	Description	Elevation (ft.)
MLLW	Mean Lower Low Water	-0.34
MLW	Mean Low Water	0.91
MSL	Mean Sea Level	3.36
MHW	Mean High Water	5.8
MHHW	Mean Higher High Water	6.51
MMMW	Mean Monthly Maximum Water	7.74
MAMW	Mean Annual Maximum Water	8.78

Because sea level is rising in response to climate change, the tidal datum against which sea levels are measured should be consistent. The Regional Humboldt Bay Sea Level Rise Adaptation Planning Project utilized MMMW of 7.7 ft., known as spring tides, as the tidal base elevation to assess shoreline vulnerability to map areas that could be vulnerable to tidal inundation should the existing barrier-like shoreline be breached. While not an official tidal datum that NOAA normally provides for its tide gauges, MMMW was selected. On Humboldt Bay MMMW is closely associated with the upper elevation of tidally influenced vegetation on natural shorelines and the tidal and upland boundary and is easy to delineate.

During a single year, sea levels on Humboldt Bay can vary by three ft. (±1.0 M). Daily MHW is 5.8 ft. and MMMW is 7.7 ft., and annual king tides (MAMW) are 8.8 ft. Sea levels on Humboldt Bay tend to be highest in the winter months. Mean annual maximum tides (MAMW) occur in winter and are typically one foot higher than MMMW. In addition, El Niño events, low pressure systems, stormwater runoff, and storm surges can also add up to one foot to winter tidal elevations. In 1983, a severe El Niño raised tides to 9.4 ft. Since 2001, there have been four years where annual maximum tides reached similar or greater elevations than the last significant El Niño events: 2001 (9.3 ft.), 2003 (9.5 ft.), 2005 (9.5 ft.), 2006 (9.5 ft.) (Figure 4).

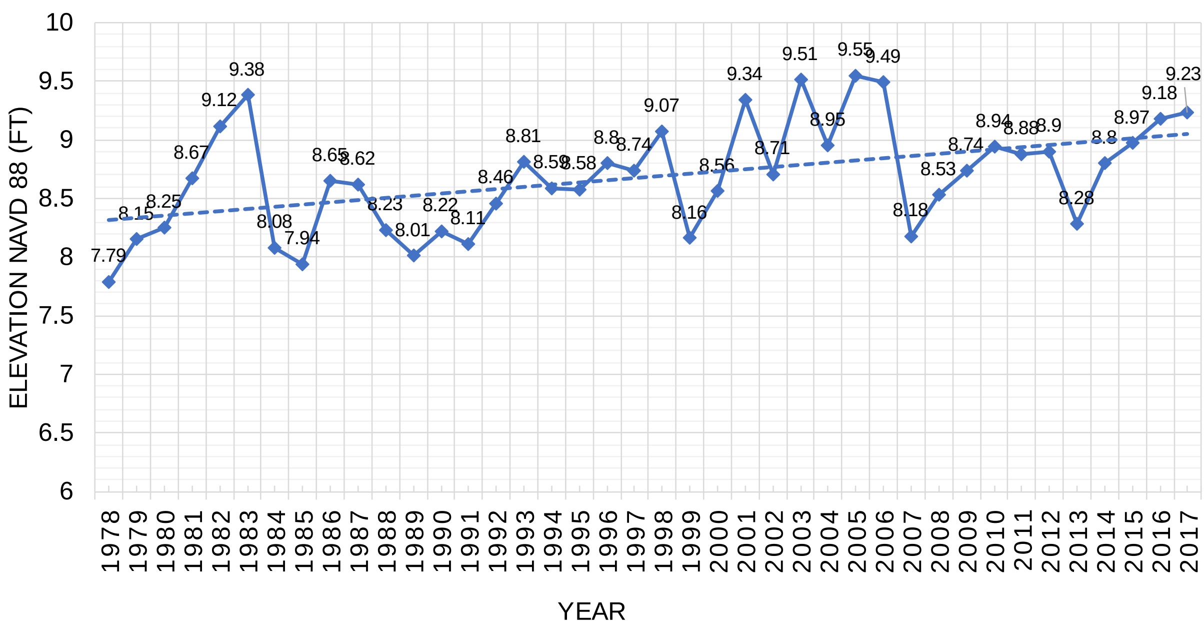

Figure 4. Annual maximum high tide elevations (king tides) at the North Spit tide gage.

Annual maximum or king tides elevations have varied by 1.8 ft. (ranging from 7.8 to 9.5 ft.) during the North Spit's 40-year record. The highest tide was 9.55 ft. and is illustrative of 1.9 ft. of sea level rise over the MMMW elevation of 7.7 ft., which is the high projection for 2050. The Governor declared a state of disaster on Humboldt Bay in 2006 in the aftermath of storm damage largely due to high rainfall and high winds, with storm surge combined with that extreme tide of 9.5 ft. as a contributing factor. This same tidal elevation could become the MMM—the monthly norm— tide elevation by 2050.

Unlike extreme storm events, also known as 100-year floods that have 1% probability of occurring in any year, sea levels are very predictable. The date, time, and expected height of king tides are known. Local and regional weather can affect water levels; therefore, there are often observable differences from the predicted tide elevations. This report, unlike hazard mitigation plans, does not utilize extreme storm events to conduct its vulnerability and risk assessment of assets on Humboldt Bay.

Tide frequency is also a predictable parameter. For example, the number of days that current MAMW elevation of 8.8 ft. is equaled or exceeded is four days per year, but with 1.6 ft. (0.5 M) of sea level rise, these high tides would equal or exceed 8.8 ft. 125 days per year. With 3.3 ft. (1.0 M) of sea level rise, these same high tides would equal or exceed MAMW 355 days per year (NHE 2017). Sea level rise would likely manifest as tidal inundation from king tides as nuisance flooding and increase in frequency with sea level rise to become chronic flooding and ultimately tidal conversion.

2.2 Sea Level Rise and Impacts

Currently, tidal elevations in Humboldt Bay are affected by regional sea levels and vertical land motion trends. Combining sea level rise and tectonic subsidence would result in a greater net change in water elevations than what would be experienced from sea level rise alone. Conversely, sea level rise combined with tectonic uplift could result in no net change in water elevation, which appears to be what is occurring at Crescent City. According to Cascadia GeoSciences, since 1977 Humboldt Bay has been subsiding -0.09 inches/year at an average rate of 0.18 inches/year (18 inches per century), which is greater than anywhere else in California (Patton 2014). While the Commission's Policy Guidance recommends assessing impacts from sea level rise based on high projections for 2030, 2050, and 2100, this report is focusing on specific water elevations for MAMW and 0.5-meter intervals of sea level rise (0.5, 1.0 and 1.5 M). Under present shoreline conditions, 51% of the diked shoreline on Humboldt Bay could be breached or be overtopped by approximately three feet (1.0 M) of sea level rise.

Sea level rise is an effect of climate change, specifically from the warming of the atmosphere and oceans up until now. Melting ice from areas like Greenland and Antarctica have the potential to greatly accelerate the rate and elevations of sea level rise, particularly after 2050. Sea levels can also increase or decrease because of vertical land movement, from tectonic forces. Rising sea levels would directly affect the shoreline and consequently adjacent lands and developments.

Sea level rise would likely exacerbate coastal hazards experienced in Humboldt Bay, including: tidal inundation (via shoreline breaching and/or overtopping), flooding (drainage impaired backwater and emerging groundwater), shoreline erosion and retreat, and salt water intrusion. Sea level rise would increase the hazard effects of extreme tides, wind waves, and low-pressure systems/storm surges on the shoreline of Humboldt Bay would reduce drainage capacity of water control structures, resulting in rising groundwater and salt water intrusion.

Rising sea level effects include:

- Increase in elevation of daily and monthly high tides as well as extreme high tides and 100-year storm flood elevations.
- Shoreline erosion and retreat.
- Overtop, slump, and/or breach of barrier-type shoreline structure such as earthen dikes.

- Increase in elevation of low tides and increased flooding of low-lying areas by delaying drainage through tide gates, impeding stormwater runoff.
- Increase in groundwater elevations and flooding of low-lying areas.
- Saltwater intrusion of low-lying agricultural lands, adjacent aquifers or underground structures such as sewer lines and potentially wastewater treatment facilities.
- Expansion of Humboldt Bay's tidal prism as diked former tidelands become inundated, which could increase wave heights in the entrance channel and affect sediment movement in and throughout Humboldt Bay.

Diked shorelines can and have breached under existing tidal and storm conditions. Sea level rise would increase the frequency of these breaches until dikes are overtopped, resulting in the tidal inundation of the lands behind the dikes. Flooding refers to dry land becoming temporarily covered in water, either episodically (*e.g.*, storm or tsunami flooding) or periodically (*e.g.*, tidal flooding). Floods do recede, and flooded lands generally do dry out again. Inundation as used in this report is a form of tidal flooding. Inter-tidal areas are those lands above the lowest tide and below the highest tide elevations. Areas that are below the lowest tide elevation are submerged lands, and thus are permanently inundated. Inundation maps used in this report depict areas that could be inundated by MMMW under various sea level rise scenarios, absent storm surge or wind wave conditions.

Sea level rise has the potential to adversely affect assets located in the coastal zone. Coastal developments are vulnerable and at risk from tidal inundation, and flooding caused by rising groundwater, stormwater runoff backwater, and increased 100-year flood elevations. Assets on diked former tidelands are vulnerable under contemporary condition if dikes are eroded or breached these assets could be tidally inundated now.

Low-lying areas are subject to saltwater intrusion and flooding as the capacity of drainage structures such as tide gates and culverts are reduced by rising low tides. Saltwater intrusion of shallow agricultural wells particularly in areas behind dikes may increase.

Coastal habitats such as dunes and seasonal freshwater wetlands may be eroded or converted, while other habitats like inter-tidal wetlands may drown if there are no physical pathways for their migration inland in response to sea level rise. Public access to the bay and sloughs may become impaired by shoreline erosion, tidal inundation, or flooding of boating facilities. There are also tribal cultural resource sites located on the lands around the bay that may become tidally inundated by 2100. Open, or un-treated, contaminated sites could become tidally inundated or flooded resulting in pollution of waterways and degradation of water quality.

While not a sea level rise impact, shoreline erosion under the current tidal regime could have significant consequences on Humboldt Bay. The Humboldt Bay Shoreline Inventory, Mapping, and Sea Level Rise Vulnerability Assessment provided the first comprehensive evaluation of shoreline conditions (Laird and Powell 2013). Seventy-five percent (77 miles) of Humboldt Bay's shoreline is artificial, predominately consisting of earthen dikes (53%, 41 miles) and railroad beds (14%, 11 miles). These two types of linear shoreline structures were constructed between 1890 and 1915, which today, more than a century later, are approximately 1.5 ft. lower relative to current sea levels due to tectonic subsidence and global sea level rise (Russell and Griggs 2012). The dikes were built to hold back extreme high tides around the turn of the 20th century; those extreme high tide elevations are currently reached by our annual maximum tides (king tides) due to sea level rise and subsidence of land in and around Humboldt Bay (NHE 2014a). At this time, the railroad has not been used commercially for more than two decades, and much of the railroad bed has not been maintained. As a result, much of the diked and railroad beds shoreline are currently vulnerable to overtopping by MAMW, storm surges and stormwater runoff, low pressure systems, wind waves, and El Niño conditions.

The vulnerability of these shoreline structures is compounded by the fact that no single entity is responsible for their improvement or maintenance. Approximately 21 miles of shoreline composed of dikes and railroad beds are rated highly vulnerable to breaching or being overtopped (Laird and Powell 2013). Shoreline vulnerability rating is a quantitative measure of vulnerability that uses combinations of shoreline attributes (cover type and relative elevation to modeled MMMW) to rank shoreline segment's vulnerability to erosion and/or overtopping due to extreme tides, storm surges, and sea level rise (Laird and Powell 2013).

These dikes are a historical legacy that could enable tidal inundation of the assets behind these dikes if they are breached. This is occurring with increasing frequency on Humboldt Bay. Sea level rise would only increase the risk posed by these dikes on protected assets, unless adaptation measures are employed to increase their resiliency.

3 Vulnerable and at-Risk Assets

Coastal hazard assessments can occur at many scales: regional, city-wide, or parcel specific. This sea level rise vulnerability and risk assessment report addresses assets within the City's LCP planning area, on Arcata Bay. This assessment includes assets that are in areas that could be tidally inundated by sea level rise of up to 4.9 ft. (1.5 M), which is an approximate elevation of 13 ft. at the North Spit tide gage. Assets have been treated equally regardless of ownership. Many assets critical to a region like Humboldt Bay are privately owned (PG&E's Humboldt Bay Power Plant (HBPP), Generating Station (HBGS), and Independent Spent Fuel (Nuclear) Storage Installation (ISFSI)) or under the control of another agency, such as state highways 101 and 255.

Generally, underground assets would be at risk earlier from sea level rise due to tidal inundation, rising ground water, and salt water intrusion. Impacts to most above ground assets, except for current shoreline structures such as dikes and those assets located behind dikes on former tide lands, would follow. It is important to note that most of the underground assets are utilities essential to sustaining above ground developments and land uses, independent of whether the above ground assets are presently vulnerable to or at risk from sea level rise or flooding.

Diked former tide lands have compacted as much as two to three feet over the last century and are very prone to flooding by rising ground water, stormwater runoff, and rising tides that reduce drainage capacity of water control structures such as dikes and culverts. Because of compaction, these lands would have increased water depths due to stormwater runoff and tidal inundation if the dikes are breached or overtopped. Maintenance of utilities traversing these lands would be much more difficult.

The assets that are vulnerable and at risk from sea level rise have been grouped into five broad classes: shoreline structures, land uses, transportation, utilities, and coastal resources. These asset classes are further stratified into discrete asset types composed of individual assets (Table 2).

Table 2. Summary of asset classes and individual assets affected by sea level rise.

Asset Class	Individual Assets
Shoreline Structures	Artificial Natural
Land Uses	Agricultural Residential Commercial Industrial Public
Transportation	Surface Rail
Utilities	Drinking (Municipal) water Wastewater Electrical Natural Gas
Coastal Resources	Public access sites Environmentally sensitive habitat areas Cultural sites

3.1 Existing Shoreline

The shoreline of any coastal waterbody is where the effects of changing sea levels are likely to manifest first. Shoreline structures are the first line of defense in protecting assets inland from the shoreline. Depending on surface topography, a breach or overtopping of a shoreline structure in one location can result in the tidal inundation of low-lying areas away from the shoreline. It is often the case that the owners of vulnerable assets inland of shoreline structures do not own or maintain the structures protecting their assets. On Humboldt Bay, many shorelines result from historical legacies of tideland developments and are among the most critical assets to the future of the Humboldt Bay region as it adapts to sea level rise.

The shoreline on Humboldt Bay consists of 670 individual assessor parcels and several layers of overlapping shoreline development authorities and jurisdictions. Pursuant to the California Coastal Act, there are three LCPs that cover the Humboldt Bay shoreline: City of Arcata's LCP (29 parcels or 4.3%), Humboldt County's Humboldt Bay Area Plan (450 parcels or 67.2%), and City of Eureka's LCP (191 parcels or 28.5%). LCP's contain land use and zoning regulations applicable within the coastal zone and provide the local jurisdiction with coastal development permitting authority in areas outside retained state permit jurisdiction. In areas within the state's retained jurisdiction, which is generally the entire shoreline on Humboldt Bay, coastal development permits are issued by the Commission.

This chapter describes Humboldt Bay's and the City of Arcata's existing shoreline conditions, and shoreline exposure and sensitivity to the current tidal regime (Figure 5) and future sea levels. This chapter relies on the comprehensive field work and findings of the *Humboldt Bay Sea Level Rise Adaptation Planning Project's Shoreline Inventory, Mapping, and Vulnerability Assessment* (Laird and Powell 2013).

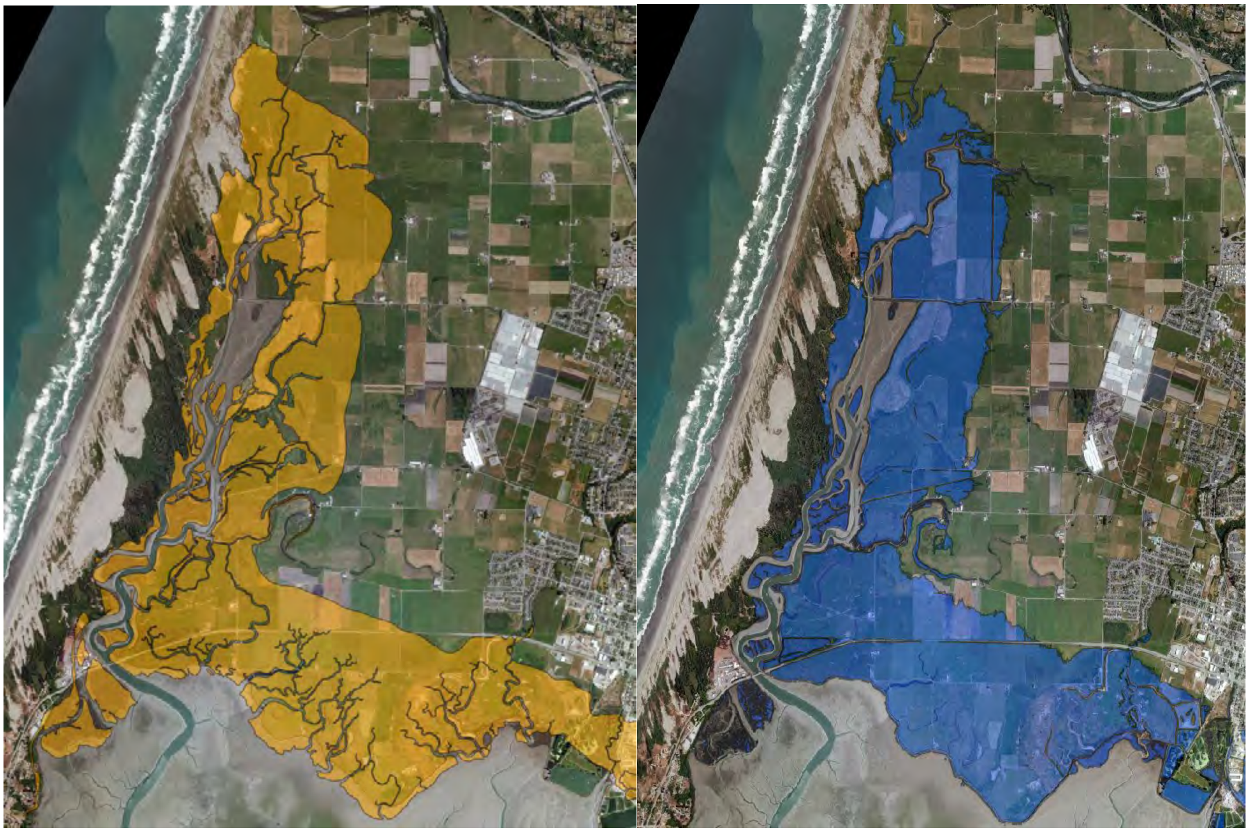

Figure 5. An example of the historic extent of tidal inundation on Mad River Slough and Arcata Bay, and the western portion of the City of Arcata (1870, yellow) and potential tidal inundation (stillwater), under current conditions by mean monthly maximum tides, if protective shoreline dikes are breached (blue).

3.1.1 Affected Shoreline Structures

Historically, as depicted in the original U.S. Surveyor General Township Plats of 1854, Humboldt Bay occupied approximately 25,800 acres: 15,300 acres (60%) was open water and inter-tidal mudflats, and 10,500 acres (40%) was inter-tidal wetlands (Laird 2007). Today Humboldt Bay still has roughly 15,300 acres of open water/mudflats. Only 1,545 acres of salt marsh remain today due to tideland reclamation for agricultural uses.

The shoreline of Humboldt Bay is defined as the boundary between the upper reach of the tidal zone and adjacent upland, often visible as the boundary between salt tolerant vegetation versus freshwater vegetation. Humboldt Bay naturally had approximately 60 miles of shoreline, which has increased to 102 miles under present conditions due to reclamation. On Humboldt Bay, the natural shoreline is closely associated with the MMMW surface elevation. Shorelines can be described, and their vulnerability assessed based on three attributes: structure, cover, and elevation.

There are two basic types of shoreline structure: natural and artificial (Figure 6). Beginning in 1892, the natural shoreline of Humboldt Bay underwent dramatic changes as the era of “tideland reclamation” began with the construction of a series of dikes to isolate salt marsh areas from tidal inundation. Tidegates were installed to allow the reclaimed fields to drain stormwater runoff during ebbing tides while preventing salt water inundation. By the 1930s, approximately 41 miles of earthen dikes had been constructed and nearly 8,100 acres (90%) of the salt marsh on Humboldt Bay was reclaimed for agricultural uses.

Figure 6. City of Arcata distribution of shoreline types: wastewater pond/marsh pond (red), fill (black), railroad grade (blue), dikes (yellow), and roads (turquoise).

Over the last century, with the loss of sediment accretion from daily tidal inundation, the surface elevation of these diked former tidelands has lowered due to compaction as organic material in the former salt marsh soils decomposed. Also, tectonic subsidence, as recorded at the North Spit tide gauge, has lowered the elevation of lands on Humboldt Bay by 15 inches in the past 100 years. Today, the combination of compaction and subsidence has caused former tidelands behind dikes to be much lower in elevation than adjacent salt marsh in Humboldt Bay. This circumstance, combined with the increased susceptibility of dikes overtopping by increasingly high tides, results in significant inundation risks to diked former tidelands because of sea level rise.

In 1895, a second wave of shoreline development ensued with construction of the first railroad tracks from the Eel River to Eureka, and then on to Arcata and Samoa. By 1904, railroad tracks would form 11 miles of shoreline on Humboldt Bay, isolating hundreds of acres of salt marsh. In 1912, the Redwood Highway (Highway 101) was constructed parallel to the railroad on the eastern shoreline of Humboldt Bay, thereby further reinforcing the tidal barrier and isolation of these former tidelands. Since the dramatic shoreline changes of the 1890s to 1910s, there have been only localized changes to the location of the shoreline. Today, there is no single entity responsible for the maintenance of the artificial shoreline on Humboldt Bay, which consists of 670 individual parcels and many different property owners.

In the City of Arcata's LCP planning area, there is approximately 7.0 miles of shoreline composed of the following types of structures (Figure 6):

1. wastewater pond/marsh dikes (1.9 miles or 27.1%),
2. fill (1.8 miles or 25.7%),
3. railroad grade (1.1 miles or 15.7%),
4. dike (1.0 miles or 14.3%), and
5. roads (0.8 miles or 11.4%).

In the City, there is only a limited 800-foot reach of natural shoreline located in the tidal zone of lower Jacoby Creek. Essentially the entire shoreline is composed of artificial structures located on 29 assessor parcels.

3.1.2 Exposure

Both natural and artificial shorelines are affected by extreme high tides and would be affected by sea level rise. On Humboldt Bay, artificial shoreline structures are primarily vulnerable to wave induced erosion and overtopping. Assets behind artificial shorelines are at risk from tidal inundation, flooding, and salt water intrusion. Sea level rise would reduce the drainage capacity of water control structures, while simultaneously causing rising groundwater and salt water intrusion.

One of the approaches to address sea level rise is to utilize the shoreline profile created for Humboldt Bay (Laird 2013). NOAA's 2012 LiDAR dataset, which reflects surface elevation in 2010, was used to generate a shoreline profile; an average relative elevation to MMMW elevation (7.7 ft.) was calculated in one-foot increments for each one-meter shoreline segment. With 75% of the shoreline on Humboldt Bay composed of man-made structures, it is important to establish the elevation of these structures. This information is necessary for an assessment of the shoreline's vulnerability to overtopping and inundation of the lands behind. Most (92%) of the artificial shoreline is less than or equal to an elevation that is six feet higher than MMMW elevation (13.7 ft.), 27% is less than or equal to an elevation that is just two feet higher than MMMW (9.7

ft.), and the majority (58%) of the artificial shoreline is less than or equal to an elevation that is only three feet higher than MMMW (10.7 ft.). As noted earlier, the extreme high tide of record on Humboldt Bay reached 9.5 ft., just 1.8 ft. higher than MMMW elevation. The resulting shoreline damage warranted the Governor declaring a state of emergency.

Barrier-like shoreline structures (dikes, railroad, and roads) can be breached by wave induced erosion, slumping, or overtopping. Independent of the size of the breach, this can tidally inundate significant areas of former tidelands.

Tidal inundation of other types of artificial shorelines (fortified and fill) can occur when tides overtop the shoreline structure. Under current conditions, overtopping would not tidally inundate significant areas of interior lands unless they are lower in elevation than the shoreline.

- Erosion

The shoreline segments in the City of Arcata that are actively eroding are limited in length and located at the foot of I Street at the Arcata Marsh parking lot, on Butcher Slough in the Arcata Marsh, and the earthen dikes on Gannon Slough. Should the earthen dikes on Gannon Slough be breached, approximately 360 acres could become tidally inundated by MMM tides reaching 7.7 ft. in elevation.

- Overtopping

Shoreline elevation is a critical attribute to the resiliency of shoreline structures to extreme high tides and sea level rise. While a well-fortified dike may not be vulnerable to coastal erosion on its waterward slope, if overtopped, a dike may be susceptible to breaching as the landward slope erodes.

Overtopping of shoreline structures is most likely to occur during MAMW or extreme high tides. Under the current tidal regime, MAMW elevation on Humboldt Bay is 8.8 ft., but it has varied by 1.8 ft. (7.8 ft. to 9.5 ft.) (Figure 4). In addition to the extreme high tides, FEMA has recently adopted a new 100-year flood elevation for Humboldt Bay of 10.2 ft., which is also capable of overtopping shoreline structures.

There are 4.3 miles of shoreline less or equal to 12.7 ft. in elevation that are vulnerable to five feet of sea level rise (Table 3).

Table 3.Shoreline structure length (miles) potentially overtopped by 1 feet (8.7 ft.), 2 feet (9.7 ft.), 3 feet (10.7 ft.), and 5 feet (12.7 ft.) of sea level rise and total length of shoreline type in City's LCP planning area.

Structure	8.7 ft.	9.7 ft.	10.7 ft.	12.7 ft.	Total Shoreline
Pond	0.0	0.1	1.1	1.8	1.9
Fill	0.3	0.5	1.0	1.1	1.8
Railroad	0.0	0.0	0.1	0.1	1.1
Dike	0.3	0.6	0.8	0.8	1.0
Road	0.1	0.1	0.3	0.3	0.8
None	0.1	0.1	0.1	0.1	0.2
Misc.	0.1	0.1	0.1	0.1	0.1
Total	**0.7**	**1.4**	**3.4**	**4.3**	**7.0**

Sea Level Rise of One foot

The current MAMW (8.8 ft.) approximates one foot of sea level rise, albeit for a limited number of days, and can result in nuisance flooding.

In the City, only 3,882 ft. (0.7 miles) of artificial shoreline are vulnerable to overtopping by one foot of sea level rise that would reach an elevation of 8.7 ft., potentially affecting:

- 1,374 ft. (0.26 miles) of dikes,
- 1,364 ft. (0.26 miles) of fill,
- 337 ft. (0.06 miles) of roads, and
- 183 ft. (0.03 miles) of pond dikes.

With one foot of sea level rise, the frequency of overtopping by MMMW of 8.6 ft. would be much greater than our current MAMW of 8.8 ft. The future MAMW would become approximately 9.7 ft., which is two feet higher than our current MMMW (7.7 ft.), and 1.4 miles of shoreline could be overtopped.

Sea Level Rise of Two feet

Based on the 2013 shoreline vulnerability assessment, there is a critical shoreline elevation threshold on Humboldt Bay between 9.7 feet and 10.7 ft. if the elevations of current artificial shoreline structures remain as they are today. With two feet of sea level rise, MMMW and MAMW elevations would reach 9.6 ft. and 10.7 ft.

With existing shoreline elevations, approximately 1.4 miles (20%) of the shoreline would be vulnerable to being overtopped in the City by two feet of sea level rise. Two feet of sea level rise would reach an elevation of 9.7 ft. potentially affecting:

- 2,727 ft. (0.5 miles) of shoreline on Butcher Slough, potentially tidally inundating the industrial and residential property west of H Street south of Samoa Blvd.,
- 2,893 ft. (0.6 miles) of earthen dikes primarily on Gannon Slough, which would place nearly 400 acres of agricultural lands,
- 8.7 acres of public facility lands at risk of being tidally inundated, daily, and
- overtopping of the Treatment Plant's pond dikes potentially could increase to 346 ft.

The rising MAMW by 2050 could increase to 10.7 ft.—higher than our current 100-year base flood elevation—which would significantly increase the number of miles of artificial shoreline vulnerable to overtopping by three feet to 3.4 miles. It is important to highlight that the Treatment Plant's pond dikes, in their current condition with two feet of sea level rise, would begin to experience overtopping by MAMW on 5,910 ft. (1.1 miles) or 58% of the pond dikes.

Sea Level Rise of Three feet

With three feet of sea level rise, MMMW could reach 10.9 ft. and MAMW 12.0 ft. elevation. Approximately 3.4 miles (48.6%) of shoreline would be vulnerable to being overtopped in the City by three feet of sea level rise. Three feet of sea level rise would reach an elevation of 10.7 ft. potentially affecting:

- 9,261 ft. (1.7 miles) of pond dikes,
- 5,179 ft. (1.0 miles) of fill mostly on Butcher Slough,
- 4,326 ft. (0.8 miles) of dikes, and
- 1,422 ft. (0.3 miles) of roads.

If current shoreline conditions are not enhanced, 48.6% of the shoreline in the City would experience overtopping, resulting in substantial tidal inundation of the Treatment Plant, residential, industrial, public facility properties, Arcata Marsh, and agricultural lands south of Samoa Boulevard. The future MAM tide would increase to 11.8 ft.

Sea Level Rise of Five feet

Five feet of sea level rise would raise MMM tide elevation from 7.7 to 13.1 ft. elevation. Based on existing artificial shoreline elevations, approximately 4.3 miles (61.7%) of the shoreline is vulnerable to being overtopped by five feet of sea level rise. Five feet of sea level rise would reach an elevation of 12.7 ft., potentially affecting:

- 9,261 ft. (1.7 miles) or 91% of Treatment Plant pond dikes,
- 5,971 ft. (1.1 miles) or 62% of the fill shoreline mostly along Butcher Slough,
- 4,415 ft. (0.8 miles) or 85% of the dikes,
- 1,708 ft. (0.3 miles) or 42% of the road, and
- 322 ft. or just 5% of the railroad.

The dikes on Arcata Bay outside of the City would also be overtopped with five feet of sea level rise. Highway 255, also outside of the City's limits, would become tidally inundated, which would expose residential properties on Villa Way in the Windsong subdivision in the City to tidal inundation. The future MAMW would increase to 13.8 ft.

- Flooding

Flooding or overtopping of artificial shoreline structures can occur, infrequently, from extreme storm events. Flooding of low-lying lands behind barrier type shorelines (dikes, railroad and road grades) can also occur during heavy rainfall when drainage to Humboldt Bay is impaired, resulting in backwater ponding. Flooding and ponding of water behind earthen dikes by stormwater runoff from interior watersheds can result in erosion and/or slumping of dike slopes, as fortification of dike slopes is generally limited to the bay side of the dikes.

Tsunamis are another form of flooding, and they are also not predictable. Tsunamis from a major Cascadia subduction event would overwhelm (overtop) any shoreline structures currently on Humboldt Bay, even if those shoreline structures were not affected by liquefaction. A tsunami would come into Humboldt Bay in waves. The height, velocity, and direction of these tsunami waves would likely be very different from normal tidal currents and or wind waves. The potential for erosion and overtopping of shoreline structures such as dikes or fill areas would depend on the height, velocity and direction of the tsunami waves.

3.1.3 Susceptibility

Susceptibility is the degree to which an asset may be adversely affected. By design, shoreline structures can be made to withstand coastal hazards such as erosion and tidal inundation. With appropriate design and maintenance, shoreline structures can continue to function even when exposed to sea level rise to some degree. There is no one entity responsible for maintaining the artificial shoreline, and there are 39 individual parcels that make up the artificial shoreline in the City's LCP planning area. Assets and land uses in a common hydrologic unit are very susceptible if a shoreline breach were to occur on just one of these 39 parcels.

The Humboldt Bay vulnerability index developed by Laird and Powell (2013) uses combinations of shoreline attributes (cover type and relative elevation to modeled MMMW) to rate a shoreline segment's vulnerability to erosion and/or overtopping due to extreme tides, storm surges, and future sea level rise. Shoreline segments that are vulnerable to overtopping and breaching in the City's LCP planning area have been identified (Figure 7). Results show there are 3.9 miles of shoreline rated highly vulnerable, 2.0 miles moderately vulnerable and 1.1 miles with a low vulnerability rating.

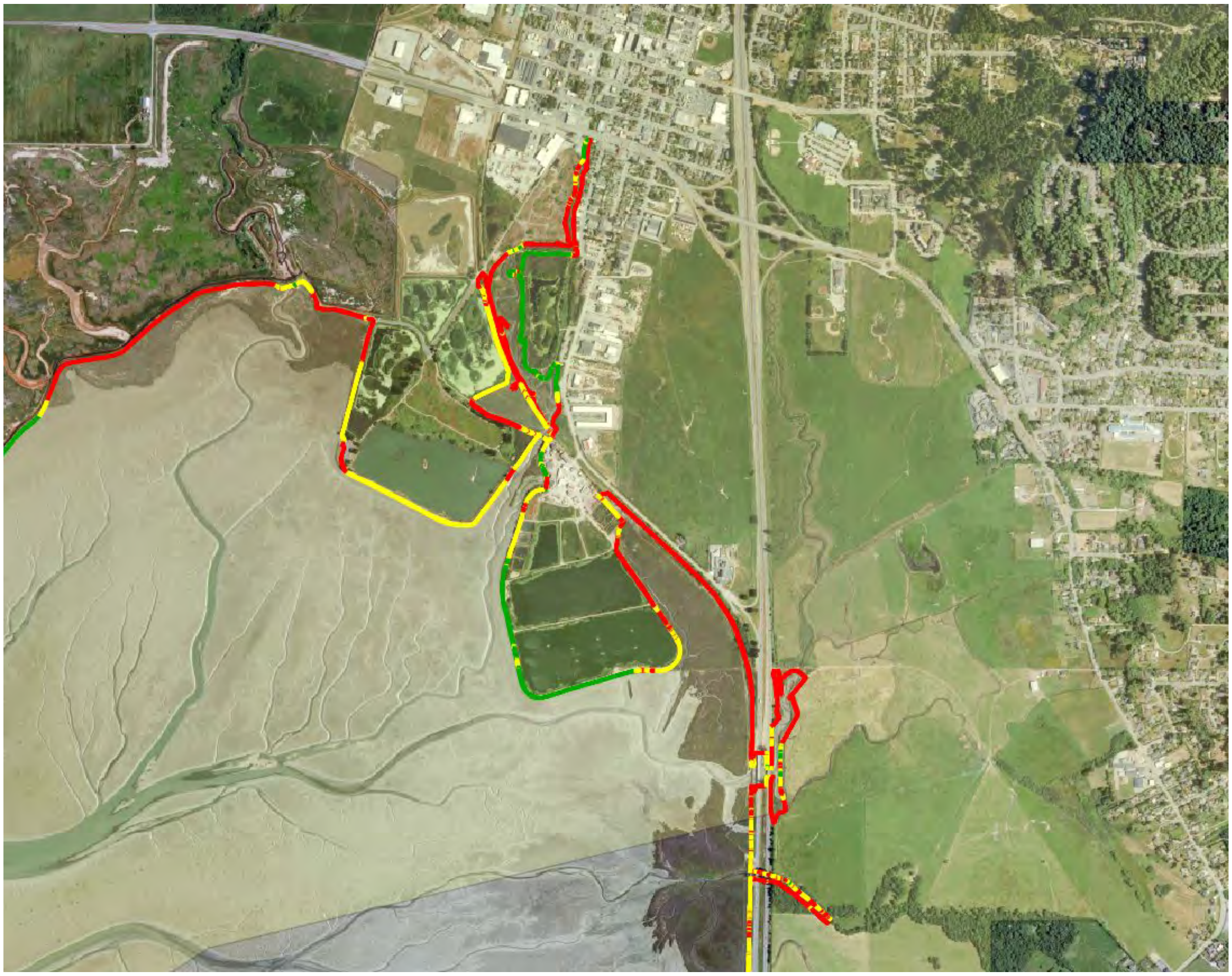

Figure 7. City of Arcata shoreline vulnerability rating: high (red), medium (yellow), and low (green).

The unfortified earthen dikes on Gannon Slough are the most susceptible shoreline segment to erosion and overtopping in the City's LCP planning area from two feet of sea level rise. While mostly agricultural lands and the City's wildlife reserve are at risk behind the dikes on Gannon Slough, it is the critical utility assets (City of Eureka's municipal water transmission lines, PG&E gas line and electrical transmission towers) that are currently very much at risk from tidal inundation. With 1.6 ft. (0.5 M) of sea level rise, the use of residential and industrial properties adjacent to the filled shoreline on Butcher Slough are at risk if the bank is allowed to be overtopped and inundate these properties. With three feet of sea level rise, the Treatment Plant oxidation ponds would be in jeopardy of tidal inundation resulting from 1.1 miles of overtopped dikes. The operation of the Treatment Plant ponds is very susceptible to salt water inundation and services provided by this facility are critical to the City of Arcata.

The shoreline in the Arcata Marsh is also vulnerable to overtopping by two to three feet of sea level rise. The freshwater wetlands are very susceptible to salt water inundation.

Most of the urban (residential, industrial and commercial) development south of Samoa Blvd, is not located on the shoreline of the Bay yet the continued use of these properties and developments and the mostly underground utilities that service these properties are very susceptible to tidal inundation beginning with 1.6 ft. (0.5 M) of sea level rise and resulting in full inundation with 3.3 ft. (1.0 M) of sea level rise.

3.2 Land Uses

The City's LCP and Zoning Ordinance, establish allowable land uses and development density. In the Coastal Zone, and on Humboldt Bay, the state has retained development jurisdiction on current and former tidelands pursuant to the Coastal Act. The state's retained jurisdiction on Humboldt Bay covers development on 86% (969 acres) of the area in the City of Arcata that is vulnerable to approximately 4.9 ft. (1.5 M) of sea level rise. There are also ten acres, inland of the City's LCP planning area and Coastal Zone, that are vulnerable to tidal inundation by 4.9 ft. (1.5 M) of sea level rise.

3.2.1 Affected Land Use Types

The City's LCP occupies approximately 1,542 acres, excluding areas below MHHW. Land use is predominately rural-open space (agricultural and natural resource) (76%) with a lesser amount of urban-developed areas (residential, industrial, commercial and public facility) (24%). The six land use types within the LCP are: agriculture, natural resources, residential, industrial, public facility, and commercial (Table 4).

Table 4.City of Arcata's LCP land use types, acreage, and percentage of total LCP area.

Zoning	Total Acres	Total %
Agriculture Exclusive	875	57%
Natural Resources	296	19%
Residential	141	9%
Industrial	136	9%
Public Facility	78	5%
Commercial	17	1%
Total	**1,542**	

There are no vulnerable coastal dependent industrial parcels or uses in the City of Arcata. The Arcata Marsh is zoned natural resource, which is a coastal-related use because it supports inter-tidal wetlands and public access and recreational opportunities associated with Humboldt Bay. The City's Treatment Plant is zoned public facility, also discharges to the Bay, and is therefore a coastal related land use.

3.2.2 Exposure

Artificial shorelines can be characterized as either barrier or fill structures. Agricultural and natural resource lands are strongly associated with barrier type shorelines (dike, railroad, and road). Urban lands are more closely associated with fill type shorelines. There are also urban lands inland of barrier type shorelines. The City's Treatment Plant and Arcata Marsh ponds are protected by a specially built system of dikes, roads, and pathways. The vulnerability of land uses in the City is strongly associated with the shoreline structures that are protecting these uses from coastal hazards.

In the City, the rural-open space lands that are vulnerable, specifically agricultural and natural resource lands, are concentrated on the north-eastern shore of Humboldt Bay on former tidelands behind barrier-type shorelines (dikes, railroad and highways). Nearly all the agricultural lands are former tidelands. Approximately 86% of the lands that are vulnerable to approximately 4.9 ft. (1.5 M) of sea level rise are rural open-space and 14% are urban-developed. The urban-developed areas in the City that are vulnerable are clustered mostly south of Samoa Boulevard on G and H Streets and south of Old Arcata Road (Figure 8).

A significant portion of the lands in the City vulnerable to sea level rise are also currently exposed to coastal hazards such as flooding and tidal inundation. There are approximately 618 acres of low-lying areas in the City that are vulnerable today from tidal inundation if protective shoreline structures are compromised or breached. These areas are also in FEMA's 100-year flood zone, as are most of the areas vulnerable to 3.3 ft. (1.0 M) of sea level rise. All the areas vulnerable to sea level rise of 4.9 ft. (1.5 meters) are also in California's tsunami evacuation area.

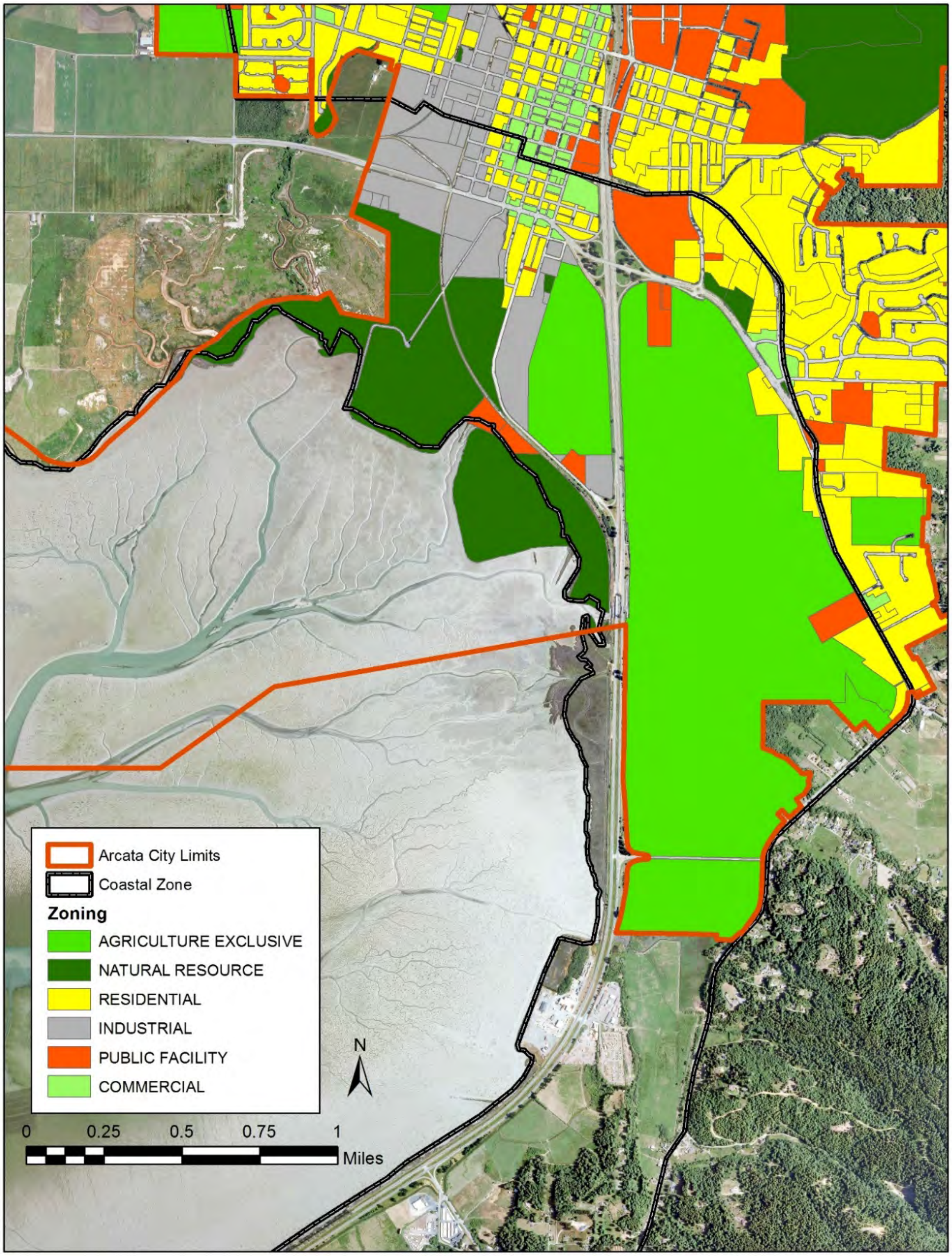

Figure 8. A portion of the City of Arcata's Local Coastal Program land use distribution that potentially could be tidally inundated by 4.9 ft. (1.5 M) of sea level rise.

Agriculture

Unlike much of the agricultural lands on Humboldt Bay, the 875 acres in the City of Arcata are not predominately protected by dikes. The agricultural lands to the west of Highway 101 are protected from tidal inundation by the railroad grade and South G Street, which drains through tide gates to Butcher Slough. The agricultural lands to the east of Highway 101 from Old Arcata Road south to Washington Gulch are also predominately protected from tidal inundation by the railroad grade and Highway 101. However, there are approximately 2,100 feet of dikes on Gannon Slough that also protect these agricultural lands to the east. Outside of the City's LCP planning area, approximately 2,000 feet of dikes on Washington Gulch prevent tidal inundation of the lands in the City to the north and to Bayside Cutoff.

Natural resources

There are approximately 260 acres of natural resources land in the City that are vulnerable to 4.9 ft. (1.5 M) of sea level rise, located predominately in the vicinity of the Arcata Marsh and Wildlife Sanctuary, on Janes Creek at Windsong Village, and east of Union Street north of Old Arcata Road. Approximately 188 acres are behind fortified dikes, roads, and pathways, and 72 acres are inter-tidal wetlands.

Residential

There are approximately 38 acres of residential properties that are vulnerable to 4.9 ft. (1.5 M) of sea level rise, predominately located south of Samoa between E and H Streets, south of 5th Street between the Highway off-ramp and E Street, in Windsong Village along Villa Way, and the apartment complexes at Union Street and Samoa Blvd., south of Old Arcata Road at Buttermilk Lane.

Industrial

Most of 75 acres of industrial zoned properties that are vulnerable to 4.9 ft. (1.5 M) of sea level rise are located south of Samoa Boulevard between E and H Streets, and the end of G Street at Highway 101.

Commercial

There is one acre of commercially zoned properties along Samoa Boulevard that is vulnerable to 4.9 ft. (1.5 M) of sea level rise.

Public Facility

Public facility zoned properties that are vulnerable to 4.9 ft. (1.5 M) of sea level rise are located at the Treatment Plant and communications property on south G Street, ball parks and California Highway Patrol offices south of Samoa Boulevard, Arcata Community Center, and the western portion of the Jacoby Creek School property.

Tidal Inundation

Shoreline structures and lands vulnerable to tidal inundation would be exposed first to extreme tides like the MAMW, (king tides), with the frequency of these exposures increasing to MMMW. Eventually the frequency of tidal inundation would increase to weekly and eventually daily high tides (MHHW) (Table 2).

Sea level rise vulnerability assessments on Humboldt Bay have utilized MMMW (7.7 ft.) elevation as the base from which to measure sea level changes. When assessing an asset's exposure to a specific level of sea level rise, evaluation of the corresponding MMMW elevation is necessary. The MAMW would also increase in elevation with sea level rise. MAMW are the event that would likely place vulnerable assets at risk of being tidally inundated. For example, areas exposed to two feet of sea level rise on a monthly frequency, as measured by MMMW elevations, would also be exposed to approximately three feet of sea level rise, although less frequently, by MAMW or (king tides). Both water levels would be assessed to understand the degree of exposure in the near-term that assets may experience in a given year from one to two feet of sea level rise. The frequency that MAMW (8.8 feet elevation) are equaled or exceeded is currently four times a year. With two feet of sea level rise, there could be 125 days a year that tides exceed 8.8 feet.

The acreage for each land use types vulnerable to tidal inundation by MMMW for 1.1 ft. to 4.9 ft. of sea level rise is described below (Table 5).

Table 5.City of Arcata's LCP planning area land use zones, acres of each land use zone, percentage of the total LCP area the zone occupies, and acreage that could be tidally inundated by 1.1 (MAMW), 1.6 ft. (0.5 M), 3.3 ft. (1.0 M), and 4.9 ft. (1.5 M) of sea level rise.

ZONING	LCP Acres	% of LCP	1.1 Ft.	1.6 Ft.	3.3 Ft.	4.9 Ft.
Agriculture Exclusive	875	63.2%	618	638	684	707
Natural Resources	296	23.2%	204	217	249	260
Residential	141	3.4%	2	5	21	38
Industrial	136	6.7%	29	40	63	75
Public Facility	78	3.4%	14	19	29	38
Commercial	24	0.1%	0	0	1	1
Total	**1,550**		**868**	**920**	**1,046**	**1,119**

- ### Sea Level Rise of 1.1 Ft.

Every year Humboldt Bay experiences on average 1.1 ft. of sea level rise above MMMW, reaching 8.8 ft. (MAMW, or king tide). Most of the shoreline (89%) in the City is higher than MAMW of 8.8 ft. and prevents tidal inundation of areas behind the shoreline from 1.1 ft. of sea level rise. The residential and industrial properties along the bank of Butcher Slough on H Street currently experience a minor amount of tidal inundation, particularly during king tides of 8.8 ft., when approximately 1,364 ft. of shoreline can be overtopped. The 72 acres of natural resources zoned inter-tidal wetlands outside of the Treatment Plant/Arcata Marsh are tidally inundated during king tides. The agricultural lands east of Highway 101 and south of Jacoby Creek down to Bayside Cutoff are also regularly tidally inundated during king tides and flooded during stormwater runoff from Jacoby Creek.

If the diked shorelines on Gannon Slough and Washington Gulch were to be breached, potentially 618 acres of agricultural lands could become tidally inundated, daily, impacting 71% of the agricultural lands in the City's LCP planning area.

Because the tidal inundation model does not consider shorelines that are currently protecting low-lying areas, it depicts that MMMW with 1.1 ft. of sea level rise (8.8 ft.) with the potential to inundate:

- 618 acres of agricultural lands,
- 204 acres of natural resource lands,
- 2 acres of residential lands,
- 29 acres of industrial property, and
- 14 acres of public facilities.

Unless the dikes are breached or the pathway at the outlet to Butcher Slough is overtopped, the areas to the east of G Street and Highway 101 would not be tidally inundated by 1.1 ft. of sea level rise.

However, with 1.1 ft. of sea level rise, future king tides would be two feet higher (9.8 ft.) than our current MMMW (7.7 ft.), at which point 1.4 miles of shoreline could be infrequently overtopped.

➢ Sea Level Rise of 1.6 Feet

With 1.6 ft. (0.5 M) of sea level rise, approximately 920 acres (63%) of the LCP planning area is vulnerable to tidal inundation (Figure 9):

- 638 acres (72.9%) of the agricultural lands,
- 217 acres (73.3%) of natural resource lands,
- 5 acres (3.6%) of residential property,
- 40 acres (29.4) of industrial property, and
- 19 acres (24.4) of public facilities.

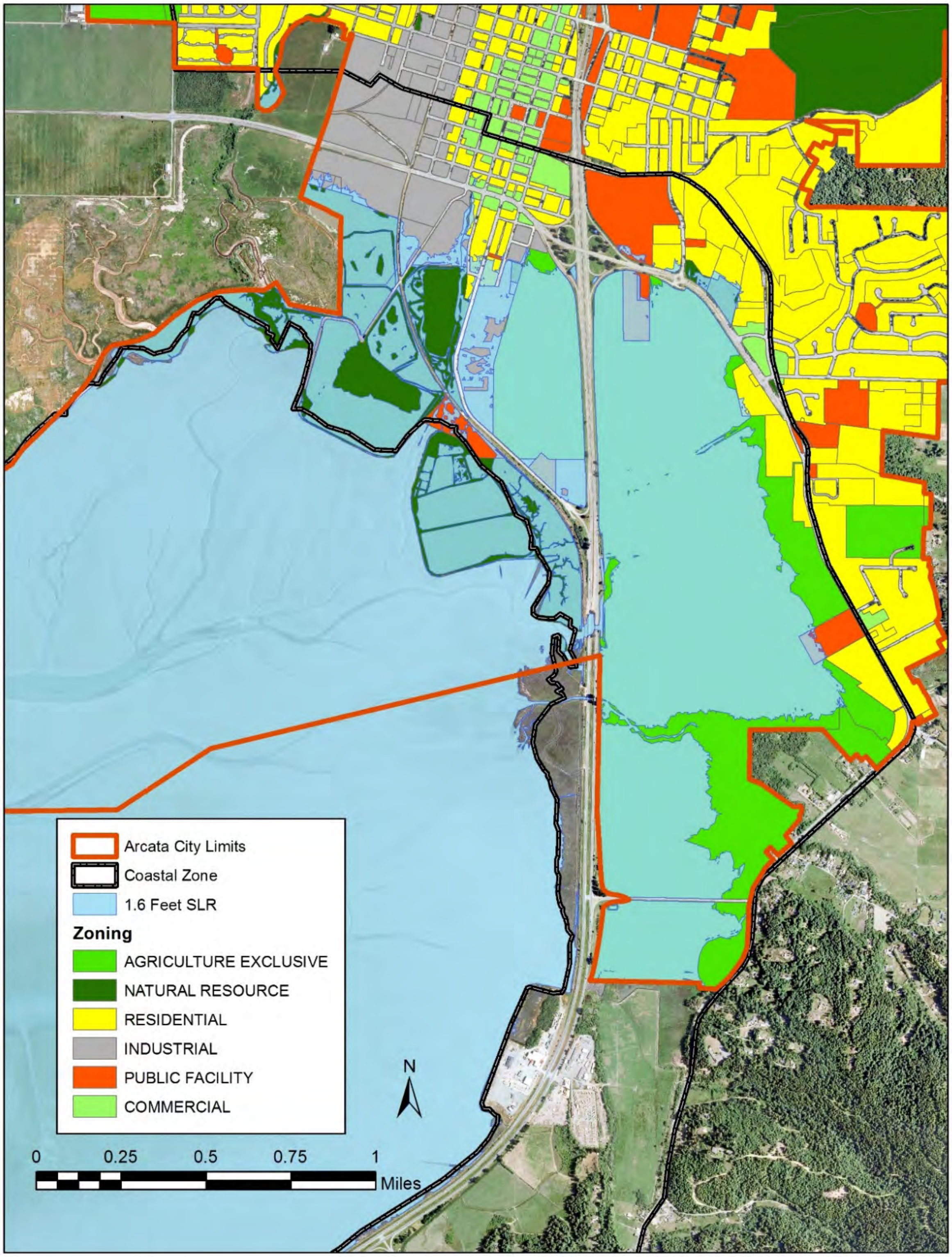

Figure 9. City of Arcata's Local Coastal Program land use distribution and potential areas of tidal inundation by 1.6 ft. (0.5 M) of sea level rise.

The eastern shoreline on Butcher Slough would likely be overtopped, tidally inundating of industrial and residential property west of H Street south of Samoa Boulevard In the Arcata Marsh and Wildlife Sanctuary, the tide gate next to the railroad and the WWTF provides a potential pathway for tidal inundation of industrial properties along South G Street and public facility and agricultural lands to the east. The eastern shoreline along the northern arm of the inter-tidal wetlands between the WWTF and the railroad south of the entrance to the facility may be overtopped and inundate south G Street and the agricultural and industrial lands to the east.

The dikes on Gannon Slough would likely be overtopped, as would the left bank of Jacoby Creek, Bayside Cutoff and the dikes on Washington Slough. This would inundate most of agricultural lands to the east of Highway 101 and south and west of Old Arcata Road, as well as 8.7 acres of public facility lands. The loss of the Gannon Slough dikes would result in the tidal inundation of the City of Eureka's two Mad River Pipelines. Sea level rise of 1.6 ft. (0.5 M) would overtop 346 feet of pond dikes, roads, and pathways protecting the Treatment Plant/Arcata Marsh complex. Overtopping of these dikes by MAMW (10.7 ft.), with 1.6 ft. of sea level rise, could significantly over top 5,910 ft. the pond dikes .

➢ Sea Level Rise of 3.3 Feet

With 3.3 ft. (1.0 M) of sea level rise, approximately 1,046 acres (67.5%) of the City's LCP planning area could be vulnerable to tidal inundation (Figure 10):

- 684 acres (78.2%) of the agricultural lands,
- 249 acres (84.1%) of natural resource lands,
- 21 acres (14.9%) of residential property,
- 63 acres (46.3%) of industrial property,
- 29 acres (37.2%) of public facility lands, and
- 1 acre (0.4%) of commercial property.

A substantial increase in tidal inundation by 3.3 ft. (1.0 M) of sea level rise and impact, residential lands (from 5 to 21 acres), industrial (from 40 to 63 acres), and public facility (from 19 to 29 acres). Tidal inundation, of the urban areas south of Samoa Boulevard and the Treatment Plant/Arcata Marsh complex would become significant.

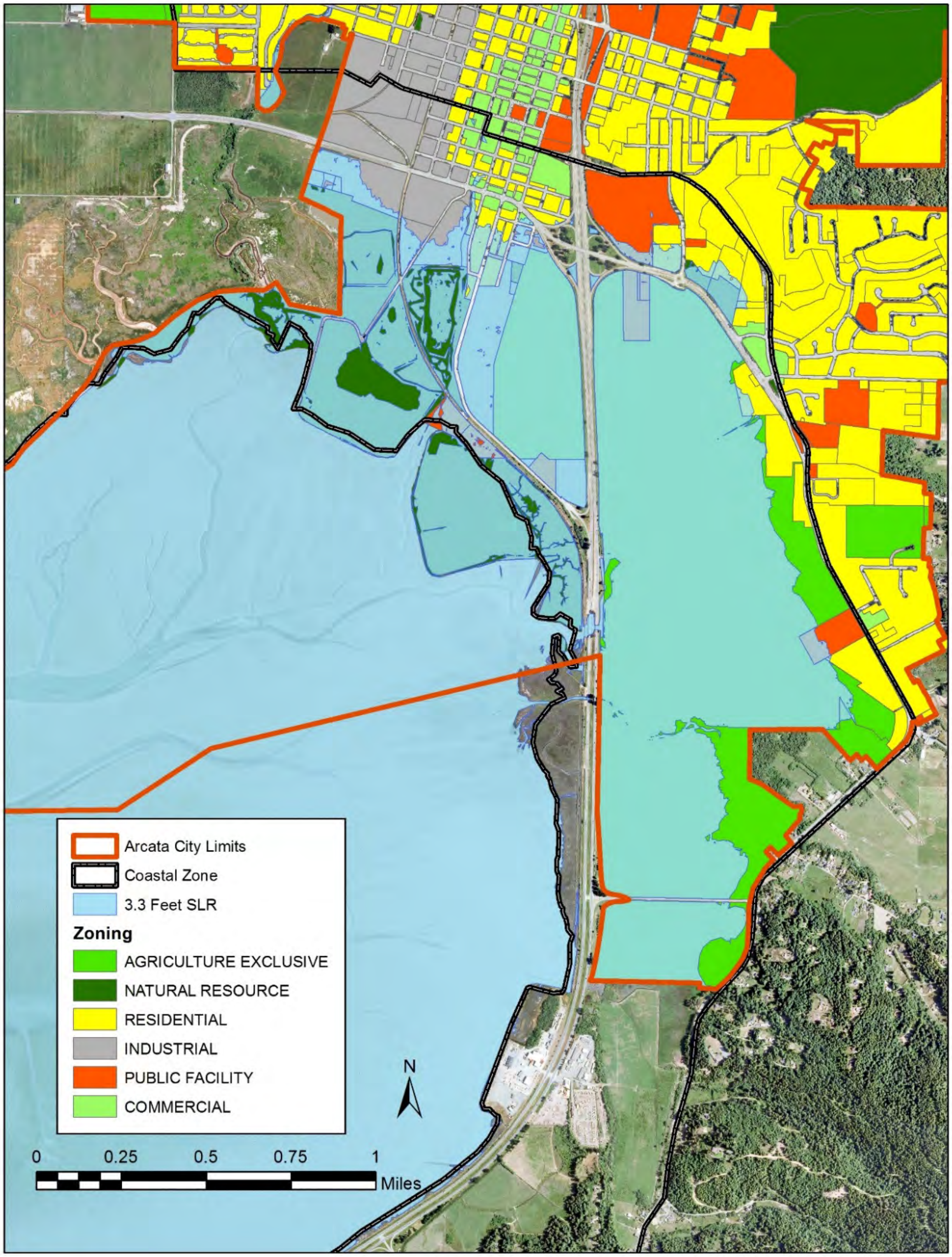

Figure 10. City of Arcata's Local Coastal Program land use distribution and potential areas of tidal inundation by 3.3 ft. (1.0 M) of sea level rise.

The dike along Arcata Bay to the west of the City limits could be overtopped and tidal inundation could overtop Highway 255, providing a pathway for tidal inundation of Janes Creek near Windsong. The dike, road, and pathway shoreline in the Arcata Marsh would be overtopped, leading to tidal inundation of most of the Arcata Marsh and providing a pathway for inundation of the urban area to the east, south of Samoa Blvd., and the Treatment Plant. Overtopping several reaches of perimeter dikes. The railroad and South G Street would be overtopped, allowing tidal inundation of the lands to the east. Segments of south bound lanes of Highway 101 could be tidally inundated. The area east of Highway 101 from Samoa Boulevard to Washington Gulch would become tidally inundated, including Bayside Cutoff.

While the inundation maps indicate that natural resources, public facility, and residential lands north of Samoa Blvd./Old Arcata Road would be inundated, there are no visible pathways for inundation, as the road would not be overtopped at this water level. However, pursuant to the author's disclaimer at the beginning of the report, this is a good example of the value of site specific knowledge, by City Staff, that contrary to what is depicted on the inundation map this low-lying does have drainage issues and would likely be inundated.

While only a short segment of Highway 101 in the City would become tidally inundated by 3.3 ft. (1.0 M) of sea level rise, most of the south bound lanes of the highway south of the City to Bracut would be tidally inundated, as would Highway 255 west of the City near Mad River Slough.

➢ Sea Level Rise of 4.9 Feet

With 4.9 ft. (1.5 M) of sea level rise, approximately 4.2 miles (61.7%) of the shoreline based on current conditions is vulnerable to being overtopped and approximately 1,119 acres (72.2%) of the City's LCP planning area are vulnerable to tidal inundation (Figure 11):

- 707 acres (80.8%) of the agricultural lands,
- 260 acres (87.8%) of natural resource lands,
- 38 acres (26.9%) of residential property,
- 75 acres (55.1%) of industrial property,
- 38 acres (48.7%) of public facility lands, and
- 1 acre (0.4%) of commercial property.

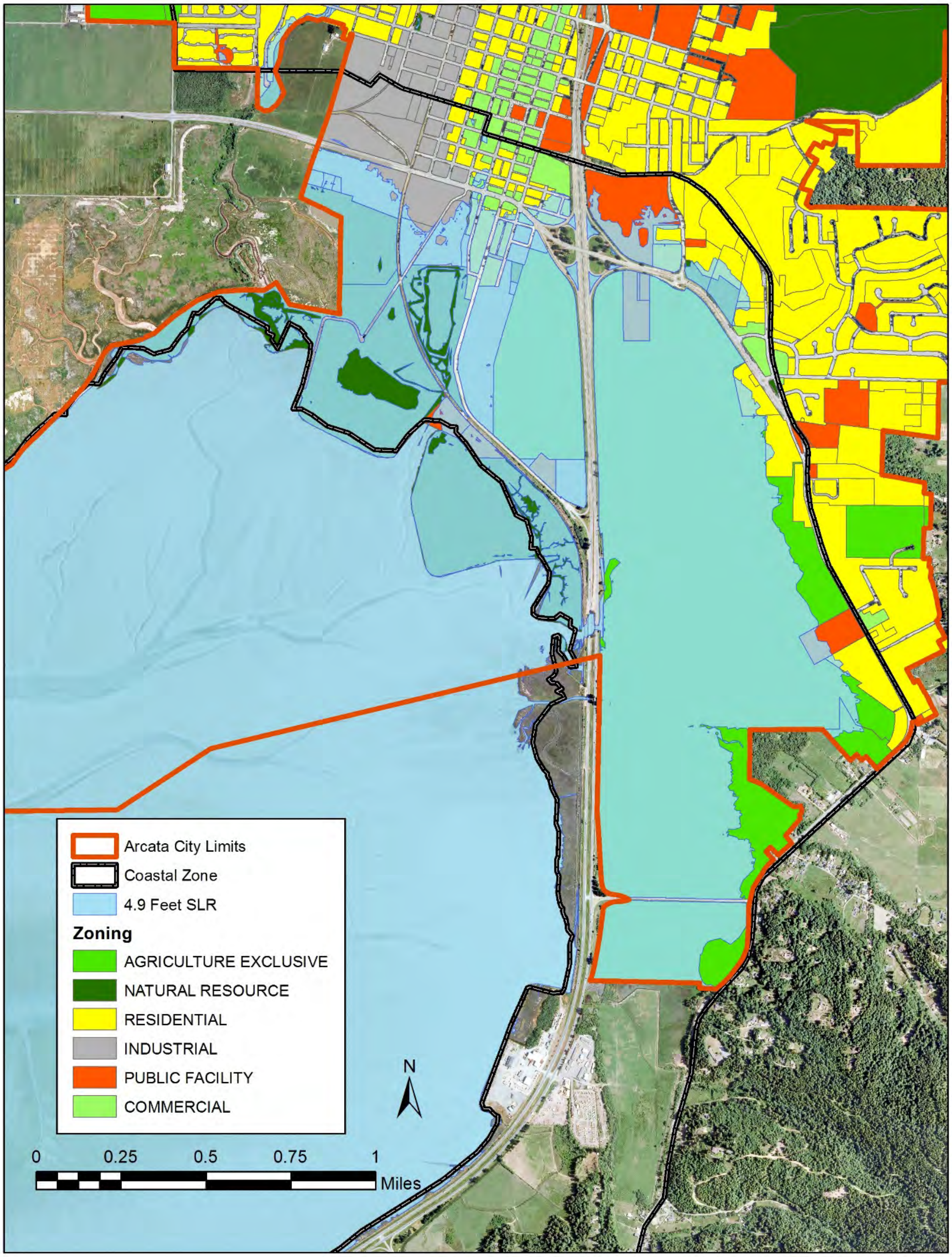

Figure 11. City of Arcata land uses vulnerable to 4.9 ft. (1.5 M) of sea level rise.

Flooding

Stormwater runoff from McDaniel Slough (Janes Creek), Butcher Slough (Jolly Giant Creek), Gannon Slough (Campbell and Beith Creeks), and Jacoby Creek drain large watersheds to the east directly to Humboldt Bay. Stormwater runoff during king tides can result in significant flooding of the agricultural lands east of Highway 101, both north and south of Bayside Cut-off, and Old Arcata Road at Jacoby Creek.

Flooding or overtopping of artificial shoreline structures can occur infrequently from extreme storm events (100-year flood). Flooding during a 100-year event (BFE 10.2 ft.) would likely affect the same 1,046 acres in the City that are vulnerable to 3.3 ft. (1.0 M) of sea level rise with a MMMW of 11.0 ft. Potentially 3.3 miles of shoreline would be vulnerable to overtopping. The extent of backwater flooding during a 100-year event would likely extend inland of the areas that are vulnerable to tidal inundation.

Flooding of low-lying lands behind barrier type shorelines (dikes, railroad and highway grades) can also occur during heavy rainfall as drainage to Humboldt Bay is impaired, resulting in backwater ponding. Flooding and ponding of water behind earthen dikes by stormwater runoff from interior watersheds can result in erosion and/or slumping of dike slopes, as fortification of dike slopes is generally limited to the bay side of the dikes.

Likewise, flooding can occur when rising groundwater emerges onto the surface in low-lying areas in response to winter storms or rising sea levels. Regardless of the type or condition of shoreline structures, fortifications, or elevation, low-lying areas such as diked former tidelands are vulnerable to flooding from rising groundwater in response to sea level rise. With sea level rise, this type of flooding would likely begin as nuisance flooding during the winter and slowly increase in duration over time until it becomes chronic flooding. The average elevation of groundwater on land adjacent to the shoreline is generally above MSL elevation of 3.4 ft. Diked former tidelands that were salt marsh were generally equal to or less than 6.5 ft. (MHHW) in elevation but have compacted as organic material in the original salt marsh soil has oxidized and are now much lower in elevation.

Groundwater elevations depend on surface elevations and the season. For example, groundwater near Mad River Slough can fluctuate from being at the surface down to three feet below the surface (Hoover 2015) (Figure 12 and Figure 13). As sea level rises, the denser saltwater would push fresh groundwater to higher elevations until the groundwater eventually emerges and floods the surface. Rising groundwater flooding would cause vegetative conversions, adversely affecting agricultural lands and natural resource areas. Rising groundwater can also affect foundations of structures such as building and roads, as well as permanently flood low-lying areas.

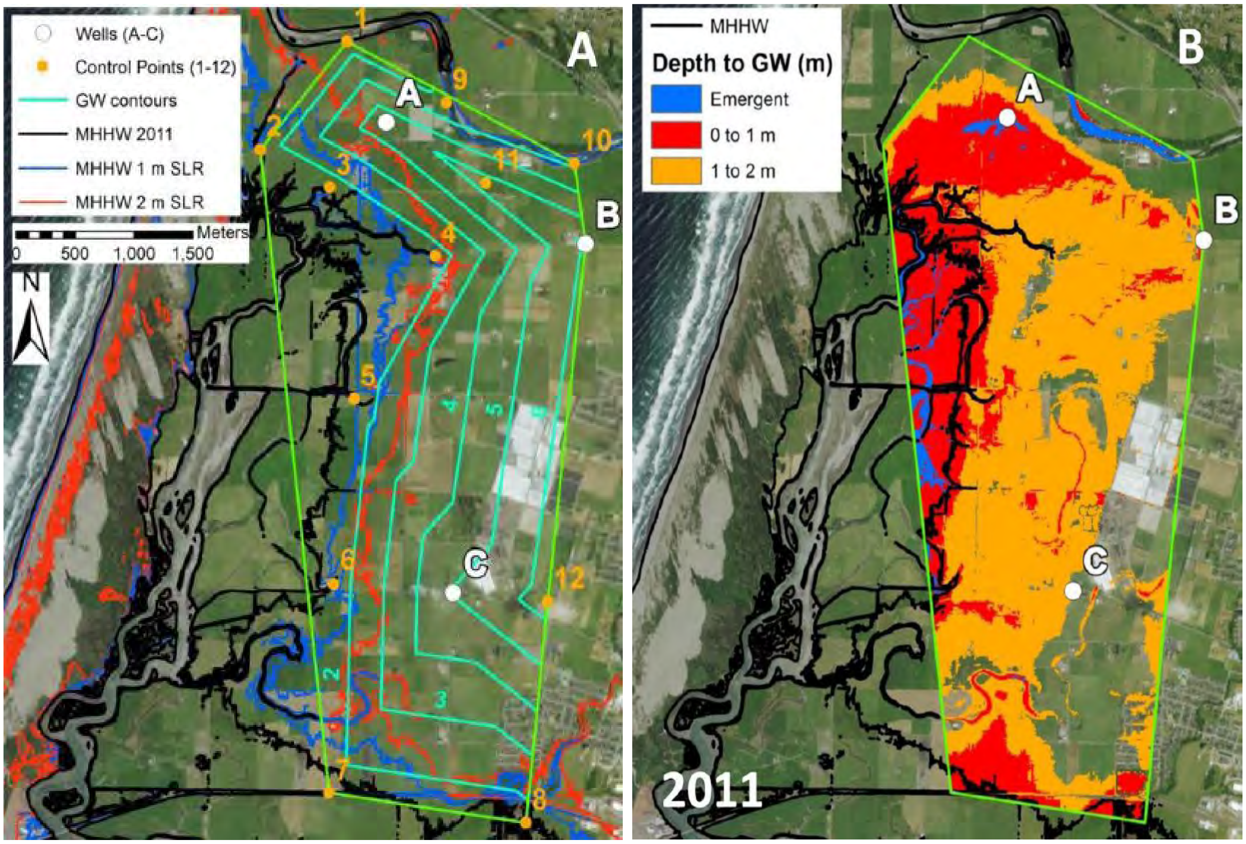

Figure 12. From Hoover 2015, as based on the work of Willis 2014. Fresh groundwater floats on higher-density seawater, and the average elevation of the water table would be above MSL 3.4 ft. MHHW is 6.5 ft.

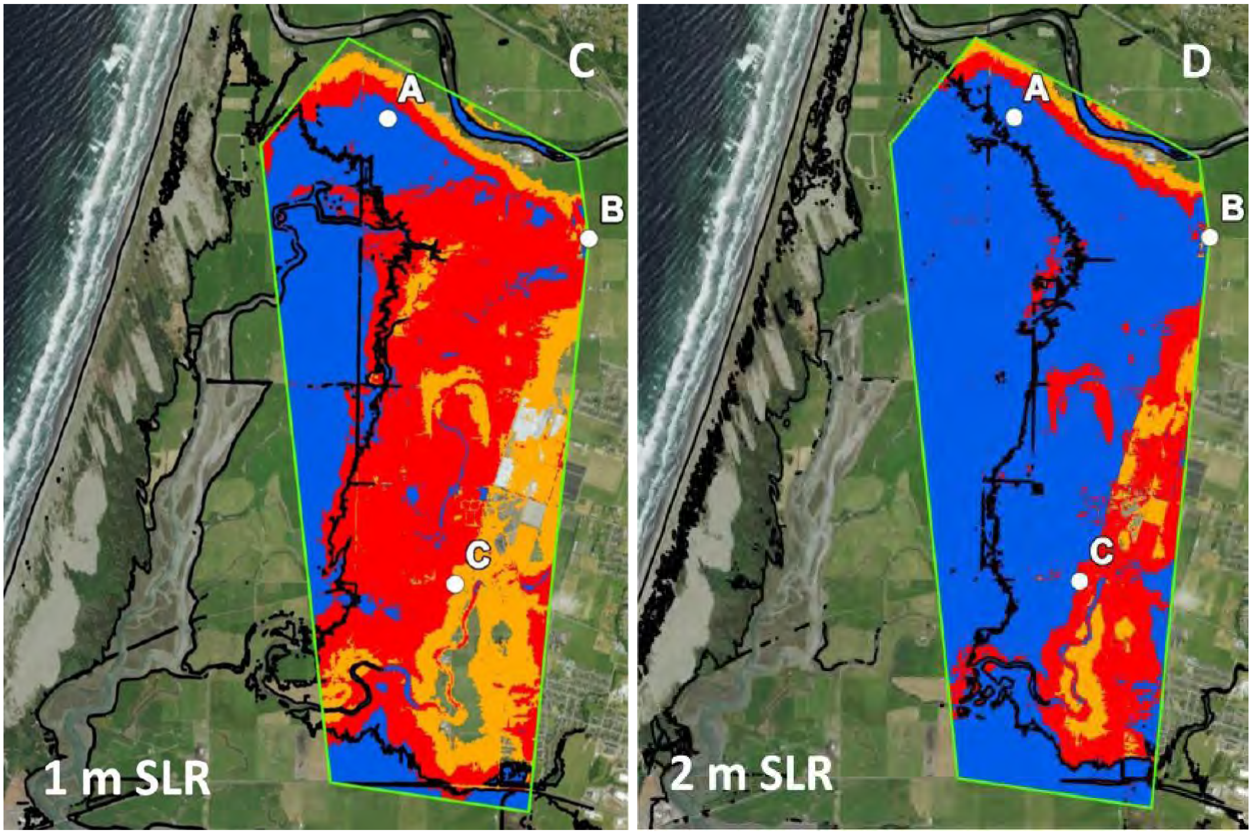

Figure 13. From Hoover 2015, based on Willis 2014, illustrating the difference of 1 M (3.3 ft.) of sea level rise. Blue = emergent, Red = 0 to 1 M, and Orange = 1 to 2 M (6.6 ft.).

Salt Water Intrusion

Salt water intrusion can contaminate shallow wells that support agricultural, residential, and other land uses. The largest extent of irrigated agricultural lands is on the Mad River bottom lands adjacent to the City of Arcata (Figure 14).

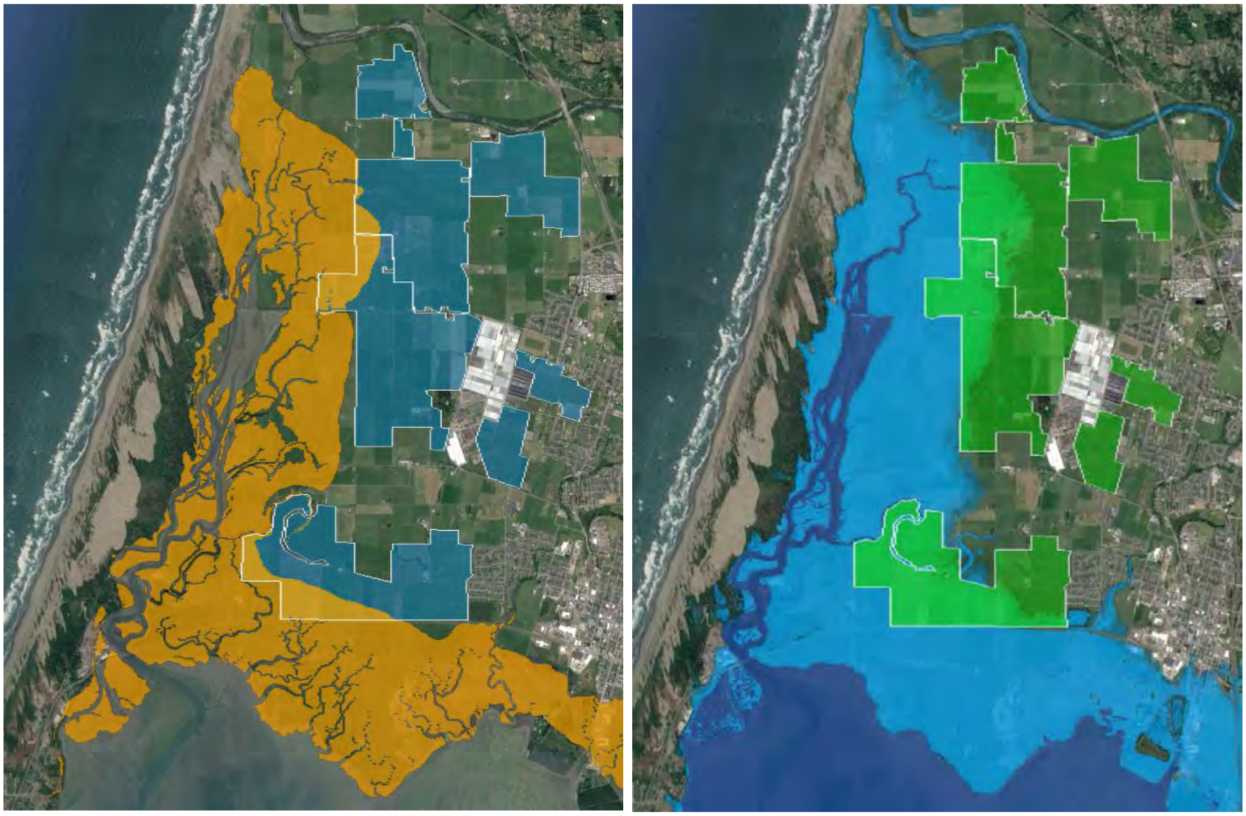

Figure 14. Irrigated agricultural lands adjacent to the City of Arcata, on Mad River bottom land, in relation to diked former tidelands (orange area) and potential 4.9 ft. (1.5 M) tidal inundation area (blue area).

Salt water intrusion can result in salt water entering the wastewater system in the form of infiltration to wastewater transmission lines and can lead to impairment or collapse of the biological processes required to treat wastewater. Salt water intrusion can also corrode underground structures (pipelines and culverts) or equipment (lift and pump stations).

Salt water intrusion and rising fresh groundwater flooding are linked as fresh groundwater floats on higher-density seawater. The elevation of groundwater can range across MSL 3.4 ft., MHW 5.8 ft., and MHHW 6.5 ft. Salt water intrusion of freshwater areas can lead to significant vegetative conversions from salt intolerant species to salt tolerant species, which would lead to changes in agricultural practices, wildlife and habitat (ESHA) distribution and abundance.

The agricultural lands in the City that are vulnerable to salt water intrusion average 6 to 7 ft. in elevation. During winter months, ground water often rises to the surface in these areas (Figure 15).

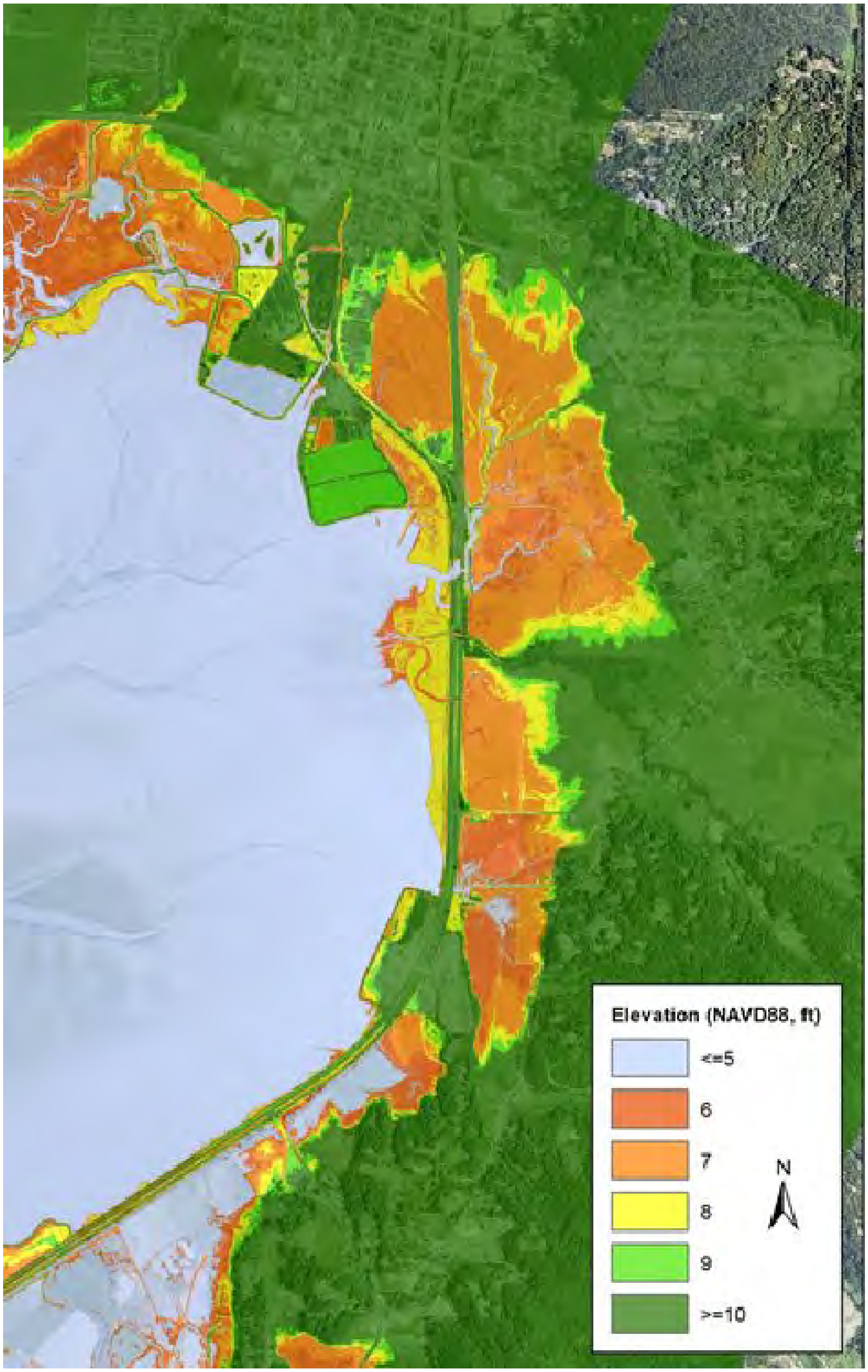

Figure 15. City of Arcata surface elevations in low elevation diked former tidelands, predominately used for agriculture and as a wildlife reserve.

3.2.3 Susceptibility by Land Use Type

Agriculture

The agricultural lands in the City's LCP planning area are vulnerable to tidal inundation are low-lying diked former tidelands. Approximately 81% of the agricultural zoned lands in the City are vulnerable to 4.9 ft. (1.5 M) of sea level rise. Grazing practices and pastures dominate the agricultural landscape. Current agricultural uses are based on raising forage for livestock grazing. They are very susceptible to tidal inundation, which would lead to a cessation of these agricultural uses. Saltwater inundation, even for short durations, can have a significant impact on saltwater intolerant plants. Frequent or chronic saltwater flooding would likely result in a vegetative conversion to salt tolerant plant species, and the collapse of agricultural endeavors.

Flooding from extreme storm events is infrequent, and current agricultural uses can recover from such flooding. Backwater flooding in the winter and spring months can seasonally restrict agricultural lands uses. Without improved drainage in response to rising sea levels, such flooding may lead to pastures converting to freshwater or brackish water wetlands. Emerging groundwater in response to sea level rise may ultimately cause the conversion of forage to wetland vegetation, which would be a significant impediment to continuing agricultural uses. Saltwater intrusion of shallow wells would impact irrigated agricultural lands significantly. Saltwater intrusion of groundwater as it emerges in response to sea level rise would lead to vegetative conversions to salt tolerant species and a reduction or elimination of livestock grazing.

Natural Resources

In the City, natural resource lands in the Arcata Marsh/Treatment Plant are composed of freshwater habitats that would be significantly impacted by salt water from tidal inundation, likely resulting in their conversion to salt water or brackish wetlands. The dikes protecting the natural resource lands are exposed to high energy waves. While they are fortified on the waterward side, over topping and erosion of the back side could lead to breaches.

Residential/Industrial/Commercial

Residential, industrial, and commercial structures and the utility and transportation infrastructure that supports these developments can recover from nuisance flooding. As the frequency of flooding increases and becomes chronic flooding, these structures, utilities and access/drainage infrastructure would become impaired, damaged, and economically infeasible to maintain. As mentioned earlier, a MAMW of 8.8 ft. is reached or exceeded on average four times a year, but with 1.6 ft. (0.5M) of sea level rise, the number of times tides would equal or exceed this 8.8 ft. elevation are likely increase to 125 times a year. This will result in chronic flooding, ultimately leading to weekly and then daily tidal inundation.

Existing residential, industrial, and commercial structures, their utility infrastructure, and access streets are not designed to accommodate frequent or chronic flooding or permanent tidal inundation. Electrical systems and metal structures are susceptible to salt water corrosion. Unsealed underground pipes may experience saltwater infiltration, which would cause a significant impairment of the affected wastewater system. Flooding from extreme storm events is infrequent, and residential areas can recover or rebuild from such nuisance flooding. Backwater flooding in the winter and spring months can impact streets and seasonally restrict access to residential areas, if not result in complete flooding of such areas. Residential, industrial, and commercial structures in low-lying areas are also susceptible to flooding from rising groundwater and salt water intrusion.

Public

Approximately 49% (38 acres) of the City's public facility properties in the LCP planning area are vulnerable to 4.9 ft. (1.5 M) of sea level rise, including the Treatment Plant, communications parcel on South G street, Arcata Community Center complex, California Highway Patrol office and ball park, and the Jacoby Creek School.

Existing structures, their utility infrastructure, and access streets are not designed to accommodate frequent flooding or permanent tidal inundation. Electrical systems and metal structures are susceptible to salt water corrosion.

Tidal inundation of Treatment Plant's ponds, buildings, pavement, infrastructure, particularly from chronic salt water inundation, would render this facility non-operational. Likewise, the California Highway Patrol office would not be able to function if tidally inundated. Buildings and parking areas at the Jacoby Creek School would not become tidally inundated and therefore are not susceptible. Public recreation properties and structures and access to these properties would be impaired and possibly eliminated by tidal inundation.

Flooding from extreme storm events are infrequent, and these structures can recover or rebuild from such flooding. Rising groundwater could compromise building foundations, asphalt covered areas, and possibly Highway 101, which is a non-city owned critical public facility.

3.3 Coastal Resources

3.3.1 Public Access and Recreation

The Arcata Marsh provides public access to approximately 300 acres of coastal habitats including freshwater marshes, salt marshes, tidal sloughs, grassy uplands, mudflats, brackish marsh, over five miles of walking and biking paths, an Interpretive Center, a boat launch, and multiple parking areas. The City has extended its Bay Trail, a significant new coastal access and recreational facility, south of the Arcata Marsh 1.9 miles toward Bracut. Of this trail expansion, approximately 1.0 miles is beyond the City LCP planning area.

Exposure

Tidal inundation of the Arcata Marsh was previously assessed under land use. The boat launch at the Arcata Marsh is nearly completely inundated during MAMW of 8.8 ft., and similarly with 1.6 ft. (0.5 M) of sea level rise. With 3.3 ft. (1.0 M) of sea level rise, the boat launch, parking area, and access streets are completely tidally inundated.

Based on the elevation of the adjacent railroad the new Bay Trail, which is not higher in elevation, 0.47 miles could become tidally inundated with 1.6 ft. (0.5M) of sea level rise, nearly all the new trail will inundate with 3.3 ft. (1.0 M).

Susceptibility

The public's use of the recreational boating facilities at Arcata Marsh could be adversely impacted by tidal inundation of access roads, parking lot, and boat ramp. With rising sea levels and repeated tidal inundation, the base of the Bay Trail would become saturated, causing the asphalt to buckle and require resurfacing. Rising tides can impair the capacity and function of water control structures, such as bridges, tide gates, and culverts, associated with the trail, which could increase flooding of adjacent areas.

3.3.2 Environmentally Sensitive Habitat Areas

The California Coastal Act defines ESHA as "any area in which plant or animal life or their habitats are either rare or especially valuable because of their special nature or role in an ecosystem and which could be easily disturbed or degraded by human activities and developments" (Section 30107.5).

On Humboldt Bay, there are five general types of ESHA that are being assessed for impacts from sea level rise: open water, eelgrass, mudflats, salt marsh, and seasonal freshwater wetlands on diked former tidelands. These ESHA types may undergo significant adjustments in response to changing shoreline conditions. Tidal habitats and seasonal freshwater wetlands are especially valuable habitats for a multitude of commercial and special status species.

One of the first surveys of Humboldt Bay depicts that it once occupied approximately 25,800 acres: 15,300 acres (59%) of open water, tidal channels, and mud flats, and 10,500 acres (41%) of inter-tidal wetlands (salt marsh and tidal channels) (USSG Township Plats 1854). Historically, seasonal freshwater wetlands (i.e. short-grass pasture that Aleutian geese currently use for grazing) did not exist. Today, Humboldt Bay occupies approximately 20,462 acres. Open water (5,776 acres) and mud flat (13,141 acres, including eelgrass habitat) cover approximately 18,917 acres (92.5%), and salt marsh covers approximately 1,545 acres (7.5%) (NOAA 2009 Imagery).

On Humboldt Bay, there are approximately 7,000 acres of diked former tidelands that presently support seasonal freshwater wetlands, known as "farmed wetlands", generally less than eight feet in elevation. This ESHA is predominately pasture that is used to graze livestock, and which significant numbers of Aleutian geese also use for grazing.

Humboldt Bay, as bound by the MHW shoreline, is 20,462 acres in extent and composed of open water (5,776 acres), eelgrass habitat (8,129 acres), mud flats (5,012 acres) and salt marsh (1,545 acres).

Exposure

Diked former tidelands, now pasture (waterfowl grazing habitat) and seasonal freshwater wetlands, (ESHA), are vulnerable to tidal inundation if barrier type shorelines are breached or overtopped. These lands and ESHA are also vulnerable to rising groundwater and salt water intrusion in response to sea level rise, even if the shorelines remain intact.

- Tidal Inundation

Eroding dike structures are at risk of breaching under our current tidal regime. The consequences of a dike breach could be significant, potentially tidally inundating ESHA throughout thousands of acres of former tidelands that are now pasture, seasonal freshwater wetlands, and Aleutian goose grazing habitat. The shoreline elevation profile for Humboldt Bay was in one-foot increments. Currently, there are 2.4 miles of diked shoreline that are vulnerable to being overtopped by MAMW of 8.8 ft. With 0.9 ft. of sea level rise, MAMW (9.7 ft.) could place 11.4 miles of dike at risk. With two feet of sea level rise, 23.4 miles would be at risk from MAMW (10.7 ft).

If the diked shoreline were compromised, today, Humboldt Bay could expand to 30,308 acres, which is 4,508 acres (17.5%) greater than what was mapped in 1850. The additional acreage is comprised predominately of potential inundation areas associated with Elk River, Swain Slough and Martin Slough, that were not mapped as salt marsh in 1854 (USSG) or 1870 (USCS) as well because of the 18 inches of relative sea level rise that has occurred over the last century, on Humboldt Bay. Sea level rise of 1.6 ft. to 4.9 ft. (0.5 M to 1.5 M) would incrementally increase the bay from 32,279 acres up to 34,987 acres as the area subject to tidal inundation expands (Figure 16). Conversely, the 15,459 acres of mostly agricultural pasture land in the HBAP planning area would decrease 13% to 13,490 acres if the diked shoreline is breached because of the 18 inches of relative sea level rise that has occurred over the last century, on Humboldt Bay. With 4.9 ft. (1.5 M) of sea level rise, the decrease would be approximately 30%, or 10,780 acres.

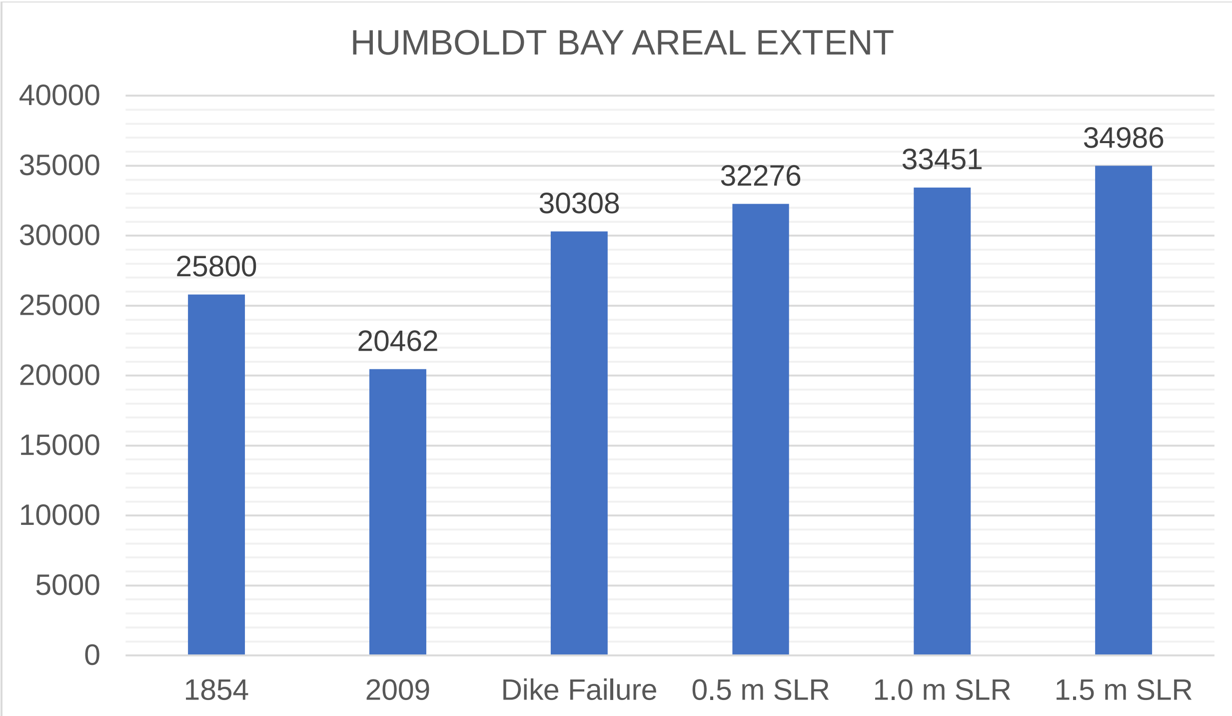

Figure 16. Areal extent (acres) of Humboldt Bay over time, if the diked shoreline is compromised, accounting for sea level rise projections ranging from 1.6 ft. to 4.9 ft. (0.5 M to 1.5 M).

Tidal habitat on Humboldt Bay can be segregated by maximum elevations for each type of habitat (Figure 17). With the addition of sea level rise, each habitat's maximum elevation increases, and its potential areal extent can be determined by surface elevations (Lidar). Due to a lack of data, estimates of areal extent of assume no sediment accretion.

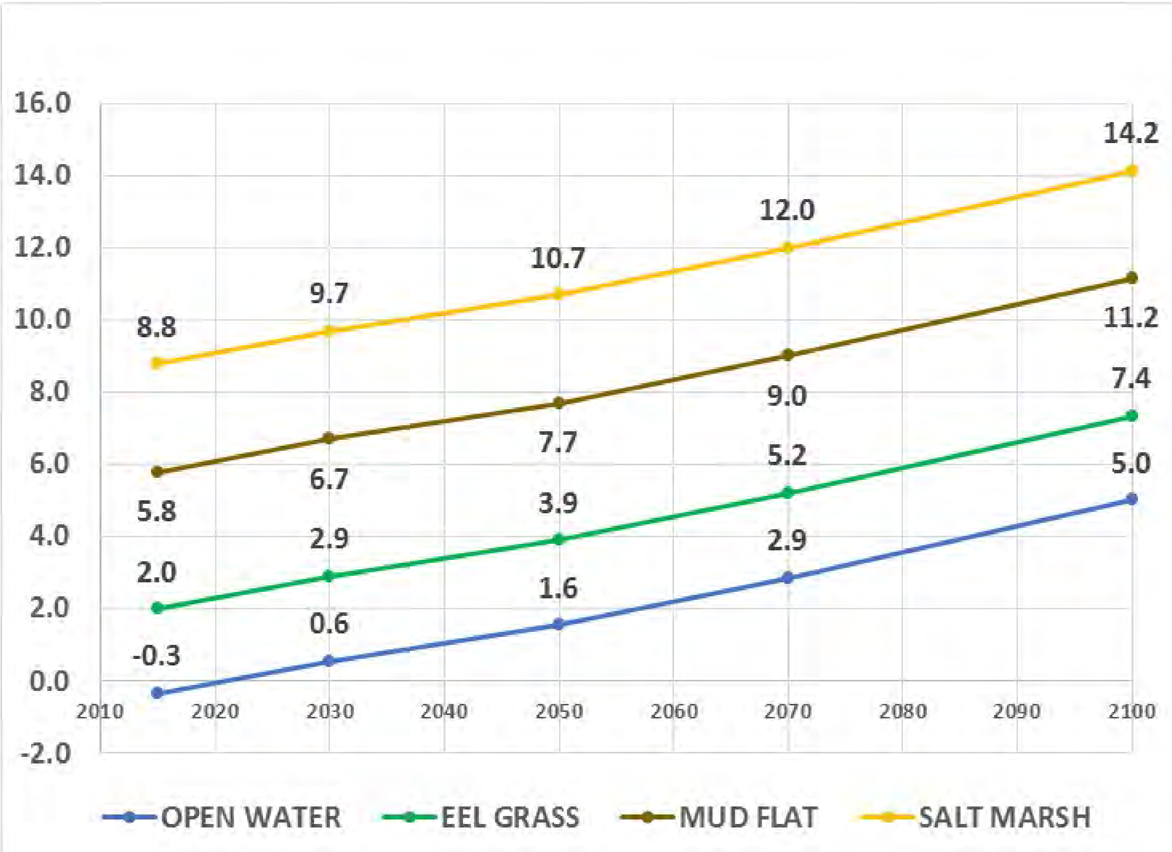

Figure 17. Maximum surface elevations in feet of Humboldt Bay habitat types with high projections for sea level rise of 0.9 ft. by 2030, 1.9 ft. by 2050, 3.2 ft. by 2070, and 5.4 ft. by 2100.

In the City's LCP planning area, there are 4.3 miles of shoreline vulnerable to being overtopped by 4.9 ft. (1.5 M) of sea level rise, which would cause Humboldt Bay and its tidal habitats to expand by 1,178 acres (Table 6). The responses of each of the five habitats (open water, eelgrass, mud flat, salt marsh, and pasture, which includes seasonal freshwater wetlands) to tidal inundation under existing tidal conditions and to sea level rise based on current (2010) surface elevations has been quantified.

Table 6.Change in habitat coverage (acres) if diked shoreline were to be compromised (2010), and with sea level rise of 1.6 ft., 3.3 ft., and 4.9 ft. (0.5 M, 1.0 M, and 1.5 M).

Habitats	Dike Failure	1.6 Ft.	3.3 Ft.	4.9 Ft.
Open Water	1	4	7	64
Eelgrass	3	32	62	552
Mud Flat	106	629	735	394
Salt Marsh	675	305	261	168
Pasture	854	669	574	461
Total	**1,639**	**1,639**	**1,639**	**1,639**

With sea level rise, each habitat's maximum surface elevation increases. Potential areal extent can be determined by surface elevations, utilizing 2009 Lidar surfaces. However, the most accurate depiction of the change in habitat distribution is the difference between the intact diked shoreline and the compromised diked shoreline because sediment accretion would not be a factor. Habitat distribution in response to sea level rise over time will need to account for sediment accretion, which for example would allow salt marsh habitat to rise in elevation in place; without sediment accretion, salt marsh would drown as sea levels rise.

Salt marsh habitat could expand by 675 acres if the diked shoreline is compromised. However, with 1.6 ft. (0.5 M) of sea level rise, salt marsh extent would actually decline to 305 acres unless sediment accretion is sufficient to maintain salt marsh with 1.6 ft. of sea level rise. Salt marsh habitat would continue to decline in areal extent with sea level rise, if sediment accretion cannot keep pace with sea level rise, to approximately 168 acres with an increase in water elevation of 4.9 ft. (1.5 M).

Similarly, mud flats would reach maximum coverage of 735 acres with 3.3 ft. (1.0 M) of sea level rise, absent sediment accretion of salt marsh areas before declining in areal extent with additional sea level rise. If sediment accretion cannot keep pace with sea level rise, mudflat ESHA will decline to 394 acres with 4.9 ft. (1.5 M) of sea level rise.

Eelgrass would expand significantly to 552 acres, and, to a lesser extent, open water habitat would increase in areal extent by 64 acres with 4.9 ft. (1.5 M) sea level rise. Existing surface topography of the lands around the bay would limit the areal extent of sea level rise. As Humboldt Bay gets deeper, salt marsh and mudflats would be submerged. Ultimately, the historical salt marsh extent of 10,000 acres in 1854 would not be restored with sea level rise; salt marsh would remain the rarest of tidal ESHAs on Humboldt Bay.

➢ Existing Tidal Conditions with Shorelines Compromised

If the barrier type shorelines are compromised or breached within the City's LCP planning area, salt marsh habitat could expand by 675 acres. This is a substantial increase considering there are presently only 1,545 acres of salt marsh on Humboldt Bay (Figure 18 and Figure 19). Mudflats would expand by 106 acres in areas where existing surface elevations are less than 5.8 ft. There would be approximately 854 acres of upland and pasture habitat in the City's LCP planning area.

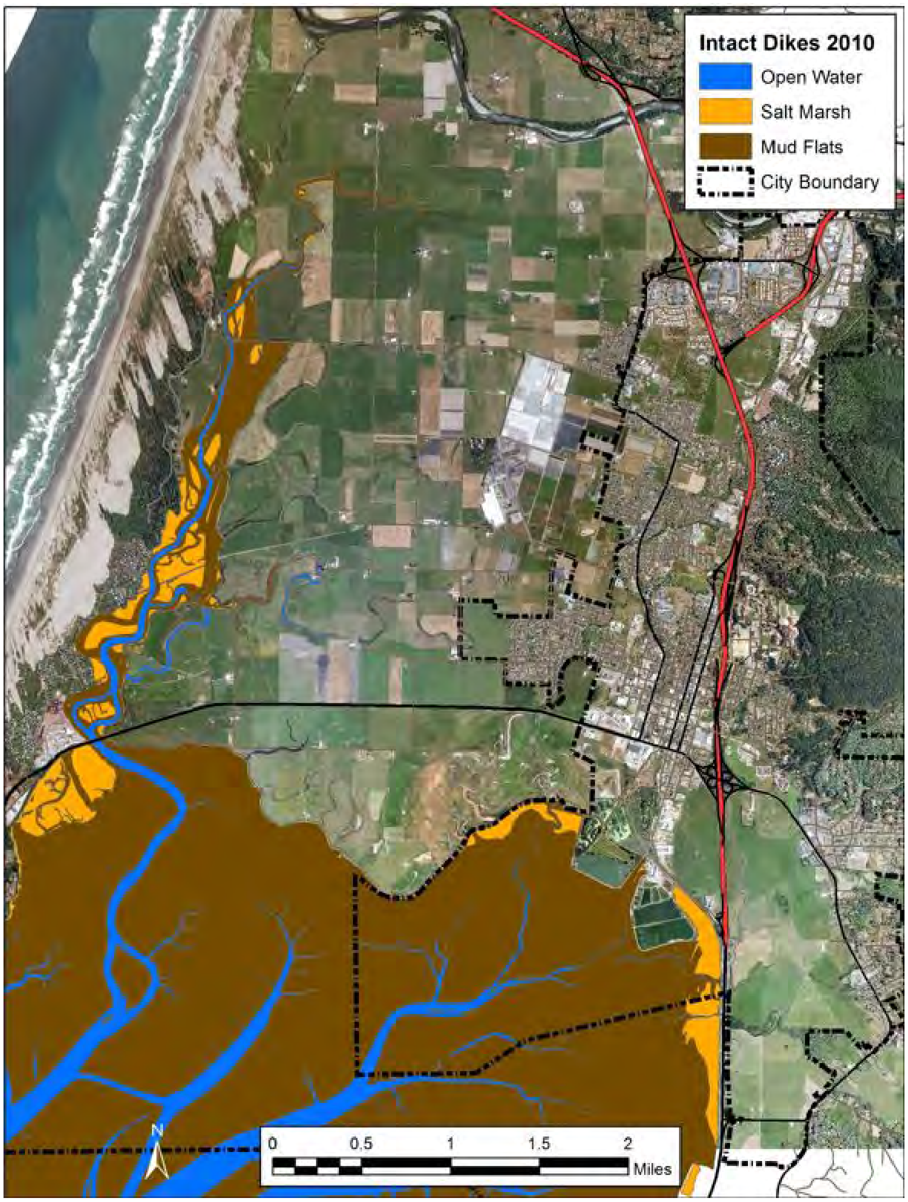

Figure 18. Mad River Slough-Mad River Bottom-City of Arcata habitat type distribution with diked shoreline intact (2009 Lidar).

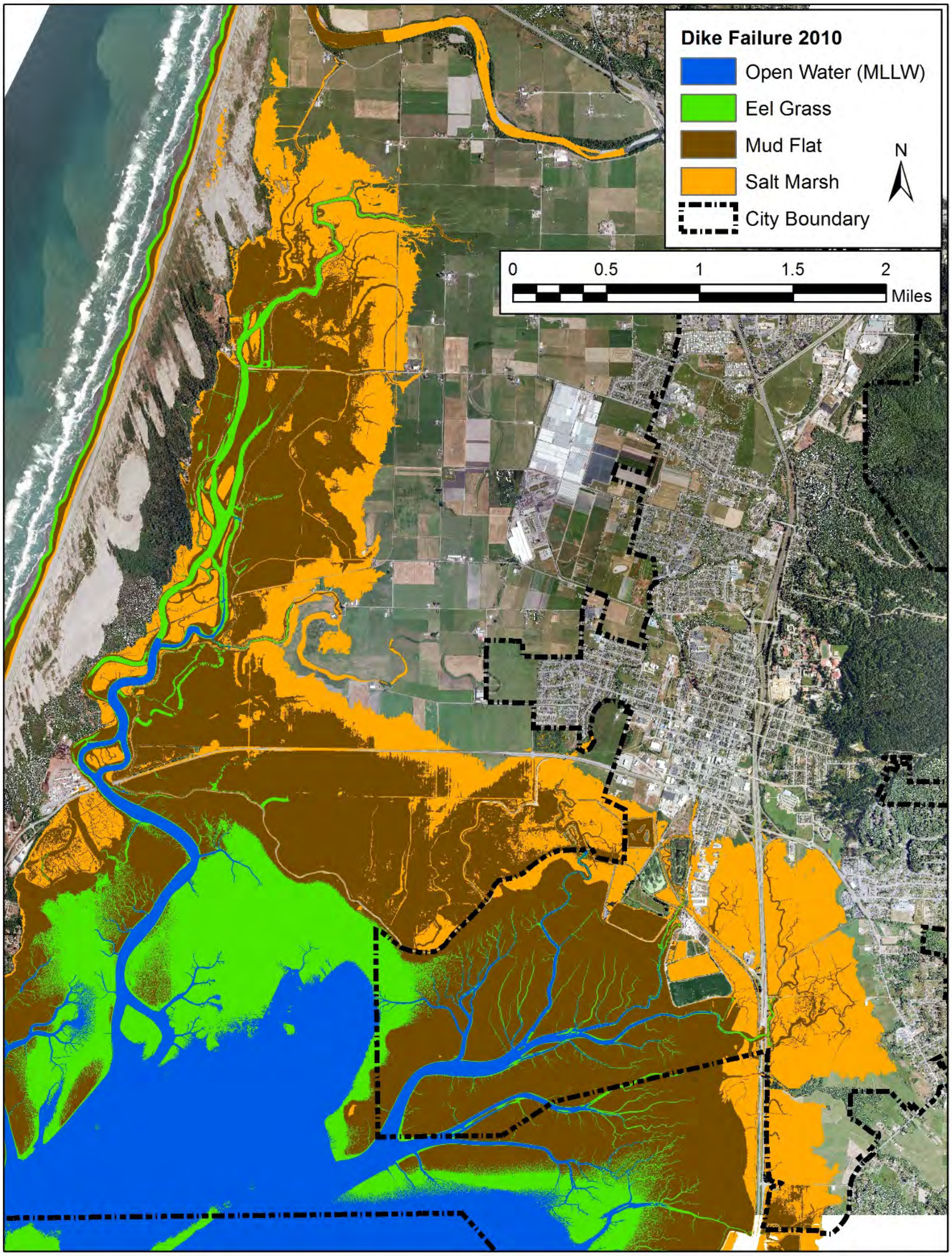

Figure 19. Mad River Slough-Mad River Bottom-City of Arcata habitat type distribution with diked shoreline compromised (2009 Lidar).

Sea Level Rise of 1.6 Feet

If the barrier type shorelines are compromised with 1.6 ft. (0.5 M) of sea level rise, eelgrass habitat could increase by 32 acres. Mudflats would increase substantially by 629 acres. Salt marsh habitat could decline substantially by 370 acres without sufficient sediment accretion to maintain its distribution with sea level rise. The initial expansion of salt marsh to 675 acres without sea level rise in response to shoreline failure, would decline to 305 acres (Figure 20). Upland and pasture habitat would decline to 670 acres.

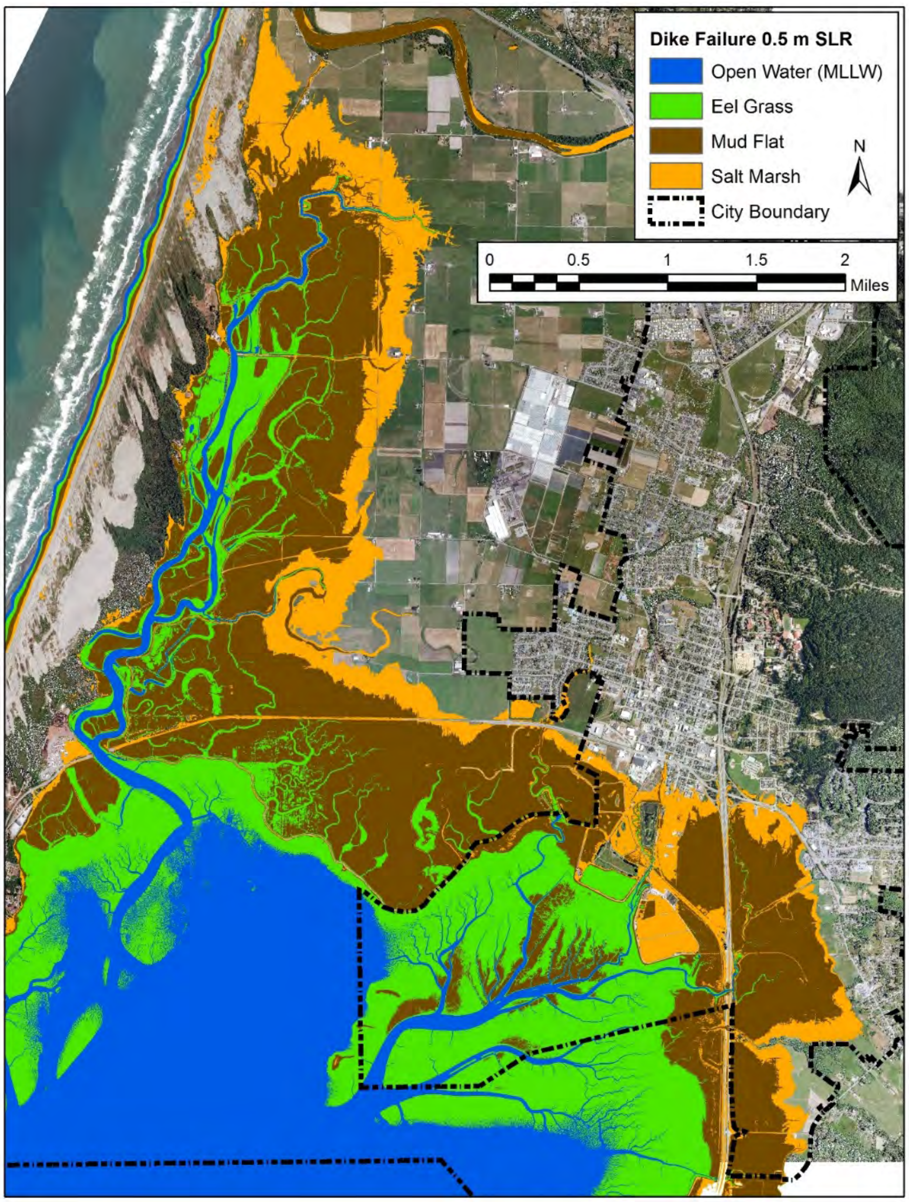

Figure 20. Mad River Slough-Mad River Bottom-Bayside habitat type distribution with diked shoreline compromised and 1.6 ft. (0.5 M) of sea level rise (2009 Lidar).

Sea Level Rise of 3.3 Feet

With 3.3 ft. (1.0 M) of sea level rise, eelgrass habitat could increase to 62 acres, mudflats could increase to 735 acres, and salt marsh habitat could decline to 261 acres without sufficient sediment accretion to maintain its habitat (Figure 21). Upland and pasture habitat would decline to 573 acres.

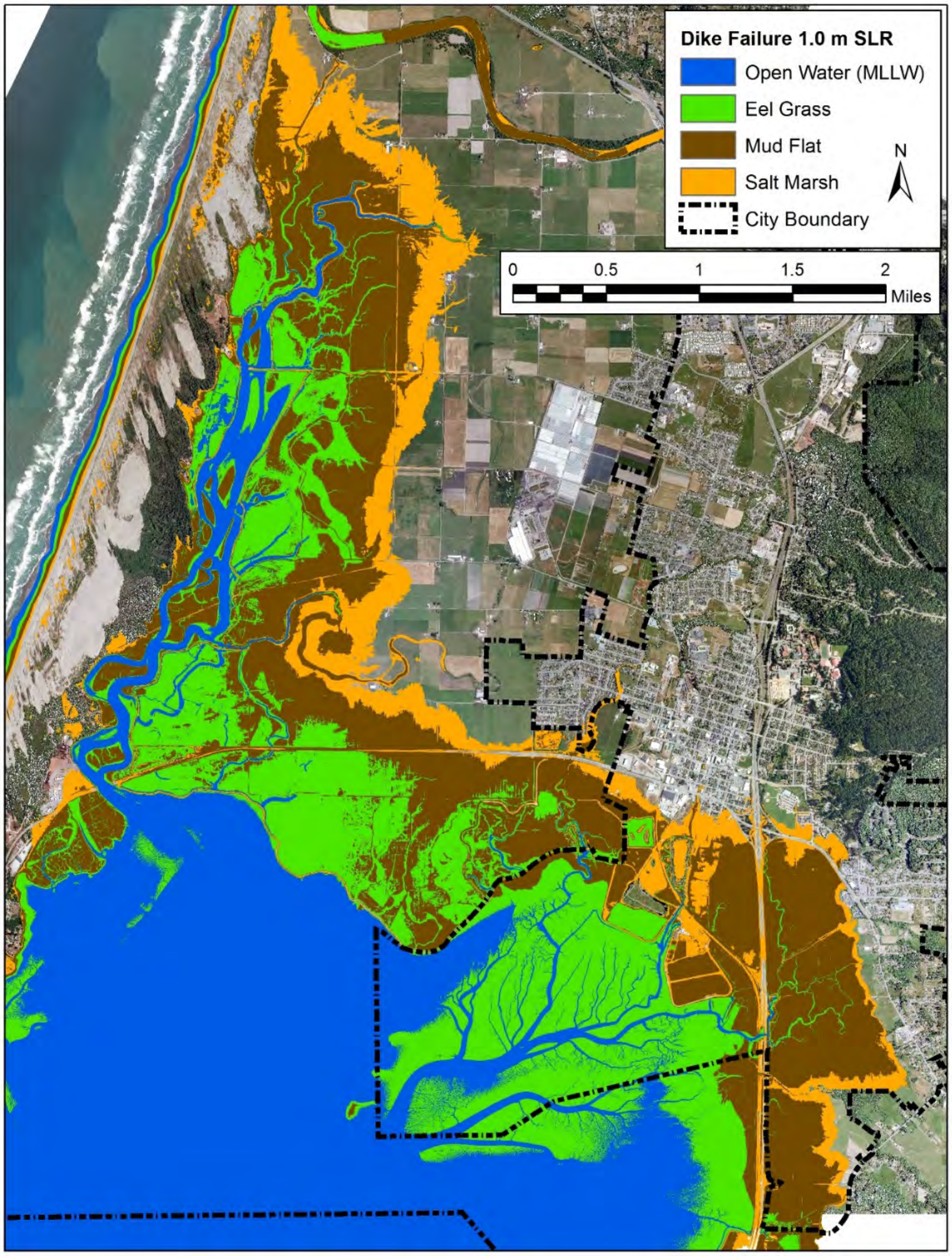

Figure 21. Mad River Slough-Mad River Bottom-Bayside habitat type distribution with diked shoreline compromised and 3.3 ft. (1.0 M) of sea level rise (2009 Lidar).

Sea Level Rise of 4.9 Feet

In the City, with 4.9 ft. (1.5 M) of sea level rise, eelgrass habitat could increase substantially to 552 acres on former tidelands. Mudflats could actually decrease substantially without sufficient sediment accretion to 394 acres. Salt marsh habitat could continue its decline to 168 acres without sufficient sediment accretion to maintain its habitat (Figure 22). Upland and pasture habitat would decline to 461 acres.

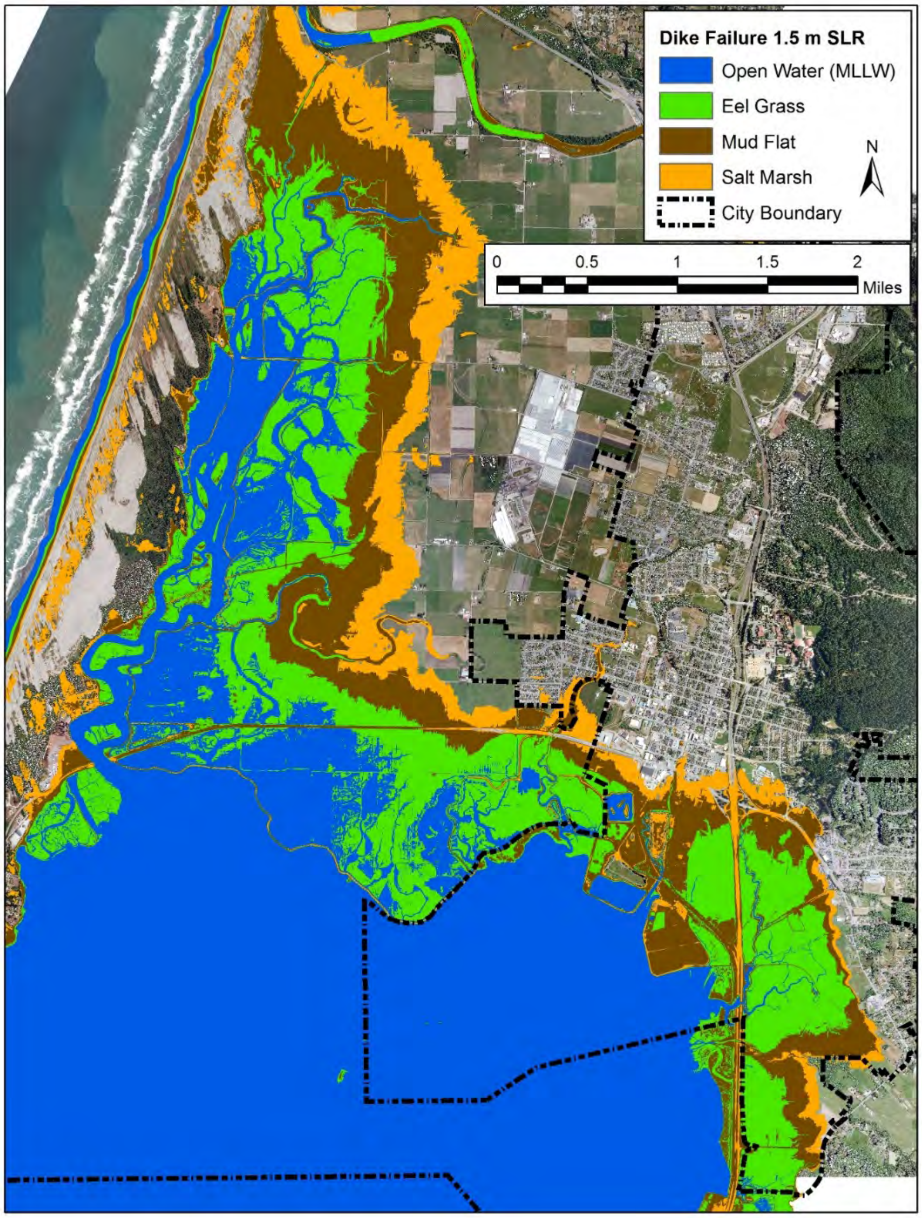

Figure 22. Mad River Slough-Mad River Bottom-Bayside habitat type distribution with diked shoreline compromised and 4.9 ft. (1.5 M) of sea level rise (2009 Lidar).

- Flooding

Flooding during a 100-year event could rise to 10.2 ft., and overtop more than 20.9 miles of artificial shoreline structures that are less than or equal to 9.7 ft. elevation, or two feet above MMMW elevation.

The 100-year flood would likely affect the same diked former tidelands that are vulnerable to 3.3 ft. (1.0 M) of sea level rise (MMMW of 11.0 ft.), potentially putting 6,600 acres of seasonal freshwater wetlands and Aleutian goose grazing habitat at risk of tidal inundation in those areas where protective dikes are breached or overtopped.

Flooding of low-lying lands behind barrier type shorelines can also occur during heavy rainfall as drainage to the bay is impaired, resulting in backwater ponding. Flooding and ponding of water behind dikes by stormwater runoff from interior watersheds can also result in erosion and/or slumping of earthen dike slopes, as fortification of dike slopes is generally limited to the bay side of the dikes.

Likewise, flooding can occur in the short-term when rising groundwater emerges onto the ground surface in low-lying areas in response to winter storms, king tides or rising sea levels. Regardless of protective shoreline structure, fortification, or elevation, low-lying areas behind these structures such as diked former tidelands and seasonal freshwater wetlands, including Aleutian grazing habitats, are vulnerable to flooding from rising groundwater. Ultimately, if the land surface elevation is not increased, emerging groundwater would inundate these low-lying areas and they would transition to emergent and then submergent wetlands.

The average elevation of groundwater on land adjacent to the shoreline is generally above MSL elevation of 3.4 ft. On Humboldt Bay, diked former tidelands are generally equal to or less than 6.5 ft. MHHW in elevation. Groundwater, depending on surface elevations and the season, can fluctuate from the ground surface down to three feet (Hoover 2015). As sea level rises, the denser saltwater would push groundwater to higher elevations, eventually emerging and flooding the ground surface. With sea level rise, this type of flooding would likely begin as nuisance flooding during the winter and increase in duration over time until it becomes chronic flooding and eventually permanent inundation. King tides that equal or exceed MAMW elevation of 8.8 ft. presently occur now approximately four times a year. With 1.6 ft. (0.5 M) of sea level rise, similar tides would reach 8.8 ft. 125 days each year, constituting chronic flooding (NHE 2017).

On Humboldt Bay, rising groundwater during winter and spring months creates seasonal freshwater wetlands on diked former tidelands. If not tidally inundated, rising groundwater in response to sea level rise would likely form emergent and submergent freshwater wetlands and eventually open water habitat. Once barrier type shorelines are breached or overtopped, daily tidal inundation would convert freshwater wetlands to inter-tidal wetlands. With sea level rise, inter-tidal wetlands would become submerged or open water.

- Salt Water Intrusion

Salt water intrusion and rising groundwater flooding are linked, as fresh groundwater floats on higher-density seawater. Salt water intrusion, like tidal inundation, can lead to significant vegetative conversions from salt intolerant species to salt tolerant species, or even mudflats, if the area is inundated for extended periods of time. In the City's LCP planning area, the conversion of current freshwater ESHA, such as seasonal freshwater wetlands and Aleutian goose grazing habitat (pasture) would lead to significant changes in wildlife composition, distribution, and abundance. Diked former tidelands, now agricultural lands, that are vulnerable to salt water intrusion average six to seven feet in elevation. During winter months, ground water often rises to the surface in these areas.

Once barrier type shorelines are breached or overtopped, tidal inundation would convert freshwater wetlands. As a result, there would be no effect on inter-tidal wetlands from salt water intrusion under this scenario.

Susceptibility

The freshwater ESHA habitats in the City of Arcata that are vulnerable to tidal inundation, flooding, and salt water intrusion are mostly located on low-lying diked former tidelands, now agricultural lands. Approximately 81% of the agricultural lands in the City's LCP planning area are vulnerable to 4.9 ft. (1.5 M) of sea level rise.

Current agricultural uses are based on raising forage for livestock grazing. Saltwater inundation, even for short durations, can have a significant impact on non-saltwater tolerant plants such as forage. Agricultural practices are very susceptible to tidal inundation. Frequent or chronic flooding with salt water would likely result in a vegetative conversion to salt tolerant plant species, and the collapse of agricultural endeavors. Flooding from extreme storm events is infrequent, and current agricultural uses can recover from such flooding. Backwater flooding in the winter and spring months can seasonally restrict agricultural lands uses. Without improved drainage in response to rising sea levels, such flooding may lead to pastures converting to freshwater or brackish water wetlands. Emerging groundwater may also result in the conversion of forage to wetland vegetation, which would be a significant impediment to continuing agricultural uses. Saltwater intrusion of shallow wells would impact irrigated agricultural lands significantly. Saltwater intrusion of groundwater would lead to vegetative conversions to salt tolerant species and a reduction or elimination of livestock grazing.

3.3.3 Wiyot Cultural Resources

Humboldt Bay, or Wigi, is home to the Wiyot people. In 1918, L.L. Loud published his ethnographic report on the Wiyot, which included a map of 103 cultural sites on Humboldt Bay. A copy of his 1913 field map was used to delineate the location of cultural sites. Loud's field map did not cover all the area and sites contained in his published ethnographic report. Consultation with a Wiyot Tribal Historic Preservation Officer (THPO) enabled additional sites to be added in areas beyond Loud's field map, and enabled revisions to the location of several of Loud's field map site locations.

Consultation with the THPO confirmed the status (whether the presence of the site has been field verified) of all sites, locations and their uses. Of the 103 sites on Humboldt Bay identified by Loud, 6 are in the City of Arcata's LCP jurisdiction, 75 are within Humboldt County's HBAP planning area, 15 are in the City of Eureka's LCP jurisdiction, and 4 are in the unincorporated area of the County but inland of the HBAP planning area.

The number and distribution of the 103 Loud cultural sites near Humboldt Bay include:

- 11 sites on Mad River Slough
- 24 sites on Arcata Bay
- 12 sites on Eureka Slough
- 21 sites on Eureka Bay
- 1 site on Elk River Slough
- 34 sites on South Bay

Of the 103 sites located by Loud, there are three sites in the City's LCP planning area but only two appear to be vulnerable to 4.9 ft. (1.5 M) of sea level rise. These two sites may be located on publicly owned properties.

Exposure

Sea levels rise and increased wave action could erode unfortified shorelines, exposing cultural sites to erosion and inundation, including in low-lying areas generally consisting of diked former tidelands. The vulnerability of diked former tidelands to tidal inundation is dependent on the integrity of the entire shoreline of the hydrologic unit within which they are located. Therefore, those sites below 12.6 ft. elevation that are located behind diked shorelines could experience erosion and become tidally inundated if any segment along the shoreline (not just the segment in front of the site) of the hydrologic unit is breached or overtopped. Shoreline erosion could expose and destroy Wiyot artifacts, burials, and the structure of shell middens at these sites.

In 2006, the Wiyot Tribe installed composite fiberglass sheet piling protection at Tuluwat on Indian Island to prevent further shoreline erosion of the site. Rising groundwater and salt water intrusion, could also lead to acidification and calcification of buried artifacts from sea level rise. This may also affect the archaeological integrity of Wiyot sites characterized as shell middens.

With 1.1 ft. of sea level rise (8.8 ft.), one site in the City's LCP planning area could become tidally inundated and exposed to shoreline erosion. With 1.6 ft. (0.5 M) of sea level rise (9.6 ft.), another site could become vulnerable. It is not known if rising groundwater and salt water intrusion from sea level rise would further degrade these Wiyot sites.

Susceptibility

On Humboldt Bay, there are potentially 52 Wiyot sites that are likely to be physically damaged due to tidal inundation from sea level rise. Four sites could be damaged by shoreline erosion and bluff retreat. Permanent tidal inundation would prevent access and use of these sites. Shoreline erosion due to rising sea levels or extreme storm events could physically damage or even eliminate sites. The cultural and archaeological significance of sites actively eroded or destroyed would be diminished or lost. Impacts from sea level rise on these sites to the Wiyot people would be significant.

3.4 Transportation

There are currently three modes of transportation and supporting infrastructure in the City's LCP planning area include surface and rail transport. Rail transport was closed in 1998 by the Federal Railroad Administration. A third mode transportation, the Humboldt Bay Trail has just been completed and is located east of the railroad grade along the shoreline of Humboldt Bay. Infrastructure for all modes of transportation in the City's LCP planning area are vulnerable to the 4.9 ft. (1.5 M) of sea level rise projected for 2100. The City is responsible for the maintenance of local streets and the portion of the Humboldt Bay Trail in the City's LCP planning area. Caltrans is responsible for the state and inter-state infrastructure City's LCP planning area: Highways 101 and 255.

3.4.1 Affected Modes of Transportation

In the City's LCP planning area, the vulnerable local transportation system of streets is concentrated south of Samoa Boulevard (Highway 255). Other City streets that are in the potential tidal inundation footprint for 4.9 ft. (1.5 M) of sea level rise include the southern end of Villa Way, the area south of 5th Street, and streets east of E Street. City collector roads that could become tidally inundated are Old Arcata Road just west and east of Union Street and the Bayside Cutoff. Highway segments in the City that are vulnerable to tidal inundation are Highway 255at the intersection with H Street and on/off ramps connecting Highway 101. Both north and south bound lanes of Highway 101 are vulnerable from Highway 255 overpass south to Bracut (Figure 23).

There are approximately two miles of the NCRA railroad in the City's LCP planning area. Slightly more than one mile comprises the shoreline of Arcata Bay. The City has constructed a 1.8-mile trail along the Bay from the Arcata Marsh to Bracut.

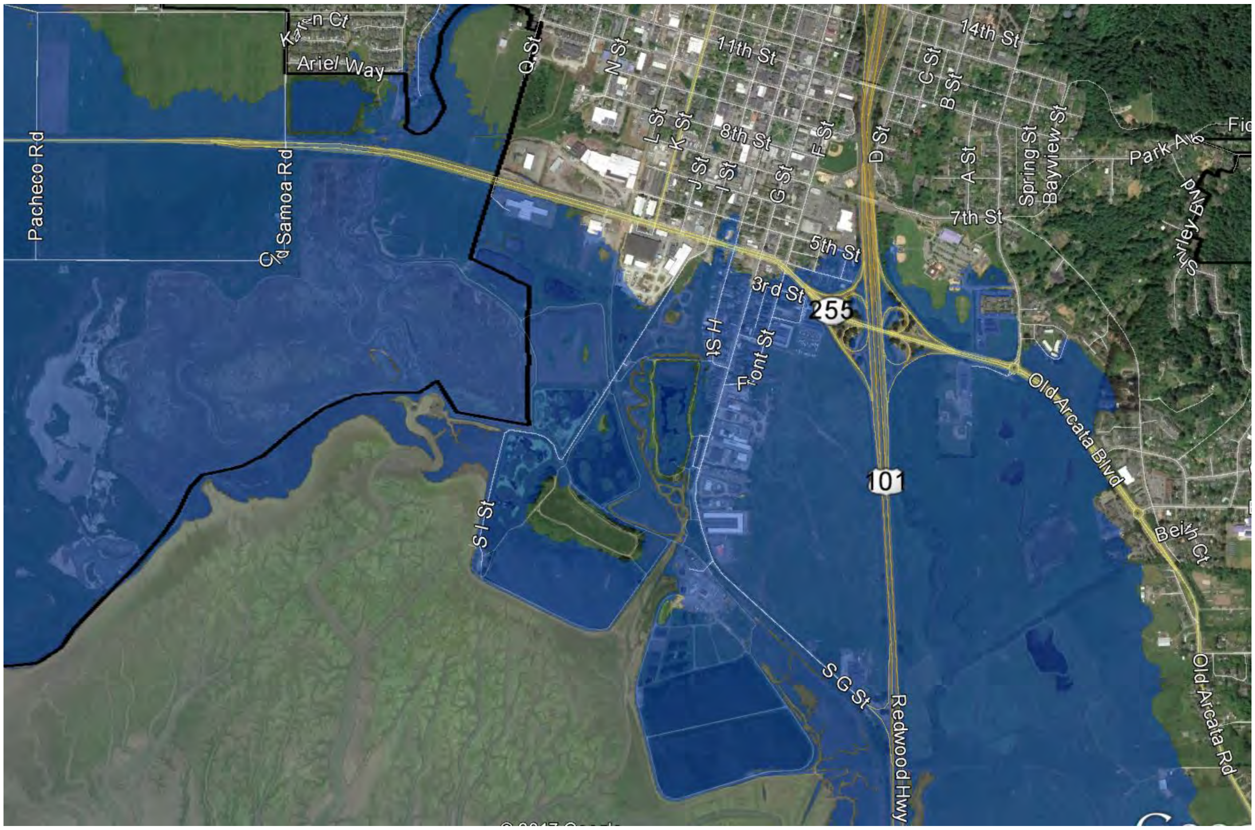

Figure 23. City streets, collectors, and highways that would be tidally inundated by 4.9 ft. (1.5 M) of sea level rise.

3.4.2 Exposure

Sea level rise would impact transportation assets that are in low-lying coastal areas. These impacts can manifest directly through erosion of street and highway fill/embankments or bridge abutments, and/or inundation of road and highway surfaces and drainage structures. Impacts can also manifest indirectly through impacts to road and highway fill/embankments or surfaces from rising groundwater and saltwater intrusion, which could corrode underground structures such as culverts.

Tidal Inundation

- **Sea Level Rise of 1.1 Ft.**

With 1.1 ft. of sea level rise, the inundation modeling and mapping depicts 1.3 miles of streets and 0.2 miles of collectors become inundated, which would not occur unless the protective shoreline structures on Butcher Slough and Washington Gulch are breached (Table 7). As is evident during king tides, there are just a few areas in the Arcata Marsh that become tidally inundated.

Table 7. Surface transportation infrastructure tidally inundated (miles) by 1.1 to 4.9 ft. of sea level rise.

Roadway Type	1.1 Ft.	1.6 Ft.	3.3 Ft.	4.9 Ft.
Streets	1.3	1.7	2.5	3.4
Collectors	0.2	0.3	1.0	2.2
Arterials/Highways	0.0	0.1	0.5	1.2
Total	**1.5**	**2.2**	**4.0**	**6.9**

➢ Sea Level Rise of 1.6 Ft.

Based on existing shoreline elevations approximately 1.4 miles would be vulnerable to being overtopped by 1.6 feet (0.5 M) of sea level rise. Primarily, the 0.5 miles of shoreline on Butcher Slough, 0.6 miles of earthen dikes on Gannon Slough, and 0.4 miles on Washington Gulch could be overtopped by 1.6 ft. of sea level rise.

Approximately, 1.7 miles of streets south of Samoa Boulevard (I Street, H Street, G Street, and Front Street) and 0.3 miles of collectors (Bayside Cutoff) could become inundated. The only access routes to the City's Arcata Marsh and Treatment Facility: South G, H, and I Streets would be inundated. Approximately, 0.5 miles of railroad between the Treatment Facility and Gannon Slough would become tidally inundated.

➢ Sea Level Rise of 3.3 Feet

With 3.3 ft. (1.0 M) (11.0 ft.) of sea level rise, 3.4 miles of shoreline may become tidally inundated, including:

- 5,179 feet (1.0 miles) of fill mostly on Butcher Slough,
- 4,326 feet (0.8 miles) of dikes, and
- 1,422 feet (0.3 miles) of roads.

Approximately 2.5 miles of streets south of Samoa Boulevard and south of 3rd Street down G Street to Highway 101 would become tidally inundated. Most of Bayside Cutoff would be inundated too. Approximately 0.5 miles of the north and south bound lanes of Highway 101 just south of the Samoa Blvd interchange would become inundated, and the south bound lanes south of Jacoby Creek to Bracut would be inundated.

Highway 255 outside of the City's LCP planning area could become tidally inundated as protective dike shorelines on Arcata Bay are overtopped, leading in turn to inundation of V Street and potentially Villa Way near Janes Creek and McDaniel Slough.

Nearly the entire length of railroad and Bay Trail from Samoa Boulevard south to the City's limit near Gannon Slough would become tidally inundated, approximately 1.4 miles.

- Sea Level Rise of 4.9 Feet

Approximately 4.2 miles (61.7%) of the shoreline based on current conditions is vulnerable to being overtopped by 4.9 ft. (1.5 M) of sea level rise.

The 3.4 miles of City streets that are in the potential tidal inundation area include the south and east sides of Villa Way, south of Samoa Boulevard, south of 5th Street, and east of E Street. City collector roads that could become tidally inundated are Old Arcata Road just west and east of Union Street and the Bayside Cutoff. Highway segments in the City that are vulnerable to tidal inundation are Highway 255 at the intersection with H Street and on/off ramps with Highway 101. Both north and south bound lanes of Highway 101 would be tidally inundated between the Highway 255 overpass in the City south to Bracut.

Nearly the entire length of railroad and Bay Trail from Samoa Boulevard south to the City's limit near Gannon Slough would become tidally inundated, approximately 1.5 miles.

Flooding

Under current MMMW conditions, if the protective shorelines to the west and east are compromised by breaching or overtopping, Highway 101 would become a causeway, similar in function to a dike, traversing the low-lying segments on Humboldt Bay. The highway would continue as a causeway until it became inundated by rising tides. If the water control and drainage structures located in the protective shoreline to the east or beneath Highway 101 fail or are impaired, flooding of lands behind the protective shorelines may occur, flooding the road prism and surface of Highway 101.

On Arcata Bay, shorelines to the west and east of Highway 101 protect the highway from tidal inundation. The dikes at Gannon Slough have tide gates draining the low-lying areas east of the highway. There are three primary tributaries (Gannon-Beith Creeks, Jacoby Creek, and Washington-Rocky Gulch) draining watersheds to the east. Stormwater runoff from these streams, particularly during high tides, can overwhelm water control and drainage structures, resulting in overbank flows that can flood local roads and Highway 101 (Figure 24).

Figure 24. Highway 101 traverses several tributaries and streams to Arcata Bay that convey stormwater runoff and can flood land to the east of Highway 101.

3.4.3 Susceptibility

Streets, roads, and highways that traverse low-lying regions on Humboldt Bay are vulnerable to sea level rise and at risk of being tidally inundated. If protective dikes or railroad shoreline structures are breached and tidal waters allowed to reach U.S. Highway 101, State Highway 255 and local road prisms could become exposed. Over time and under chronic flooding or repeated tidal inundation (MMMW), road bases would become saturated, causing the asphalt to buckle and requiring resurfacing. Rising tides can also impair the capacity and function of water controls structures that are part of the surface transportation infrastructure such as tide gates and culverts. Roadway embankments, if not fortified in reaches that are exposed to wave action, are susceptible to erosion as well as overtopping.

Temporary or nuisance flooding may result in temporary closures of roadways and re-routing of traffic. Frequent or chronic inundation of street or highway segments would likely not be tolerable. The adaptive capacity to address sea level rise impacts on City or state roadways is complicated by that fact that most of the streets and highways do not form the shoreline on Humboldt Bay. On Humboldt Bay, diked shorelines that protect low-lying segments of streets and highways from tidal inundation or flooding consist of 170 parcels owned by a mix of public and private entities.

The railroad is susceptible to adverse impacts from tidal inundation during MAMW and wave action during storms and 100-year extreme events. The railroad has not been used since 1998 and has only been maintained or repaired at the sea wall. Without regular maintenance, bridges, culverts and tide gates in a marine environment would degrade. Tidal inundation could result in slumping, erosion and washing away of ballast. Like roadways, the capacity and function of drainage structures such as bridges, culvert and tide gates would be impaired with rising sea levels.

3.5 Utilities

The City's land uses are enabled by utilities that provide essential services. The utility infrastructure and services in the City are municipal water, waste water, energy (electrical and natural gas), and communications. Impairment of utility infrastructure can affect all land uses and properties served by the affected utility. Many of the utilities have underground infrastructure (water, sewer, gas lines, and optical fibers), exacerbating their vulnerability to sea level rise. The infrastructure and operations for energy and communications utility services in the City are the responsibility of private companies.

PG&E operates the Humboldt Bay Generating Station in King Salmon, which provides electricity in the City's LCP planning area. PG&E maintains a system of electrical transmission towers, sub-stations, and distribution poles to deliver electricity in the City. PG&E also provides natural gas via underground gas lines and associated infrastructure throughout the City's LCP planning area.

Communications systems (telephone, cable, optical fiber) in the City's LCP planning area are privately owned and maintained. Infrastructure can consist of cell towers, utility poles and overhead lines, underground lines, and various types of above and below ground infrastructure.

The exact location of underground natural gas and optical fiber infrastructure are not known due to utility company policies limiting access to location information for security purposes, making it difficult to assess the vulnerability of this infrastructure to sea level rise.

As urban areas become tidally inundated, the underground utilities (municipal water, waste water, gas lines, and optical fibers) serving these areas would also become tidally inundated. Overhead utilities structures can also be impacted, as flooding or tidal inundation can hamper access for their repair and maintenance, and can reduce the stability of above-ground structures supporting these utilities.

An inventory of utility infrastructure located in the City's LCP planning area that are vulnerable to sea level rise of 4.9 ft. (1.5 M) includes water lines and pump stations, sewer lines, lift stations, the Treatment Plant, natural gas lines, electrical transmission towers, and distribution poles (Table 8).

Table 8. Utility infrastructure located in the City's LCP planning area that are vulnerable to 1.1 ft. (MAMW), 1.6 ft. (0.5 M), 3.3 ft. (1.0 M), and 4.9 ft. (1.5 M) of sea level rise.

Utilities	1.1 Ft.	1.6 Ft.	3.3 Ft.	4.9 Ft.
Water Lines (miles)	2.0	2.1	2.6	3.3
Sewer Lines (miles)	1.4	2.0	3.7	4.4
Gas Lines (miles)	2.4	2.5	2.8	3.1
Electrical Transmission Towers	8	8	9	10
Electrical Distribution Poles	62	64	70	85

3.5.1 Municipal Water

The Humboldt Bay Municipal Water District (HBMWD) supplies the City with most of its municipal and potable water. The City also owns and operates wells to augment is municipal water supply that are not in the City's LCP planning area. The City then disinfects and distribute potable water to customers within its service area.

The City of Eureka has 2.3 miles of its Mad River Pipelines (MRP) (two 48-inch pipelines) convey water from the "Eureka Turnout," located at 7th and A Streets. The pipelines then traverse the City of Arcata's LCP planning area and are vulnerable now if the dikes on Gannon slough are breached, or when sea level rises 1.6 feet (0.5 M) and the dikes are overtopped.

Exposure

The City has one booster-pump station at an elevation 9.5 ft. that would be vulnerable when sea level rises 1.9 ft. The City also has water lines that are in areas which are vulnerable to tidal inundation, including 2.0 miles, 2.1 miles, 2.6 miles and 3.3 miles with 1.1 ft. (MAMW), 1.6 ft. (0.5 M), 3.3. ft. (1.0 M), and 4.9 ft. (1.5 M) of sea level rise, respectively (Figure 25).

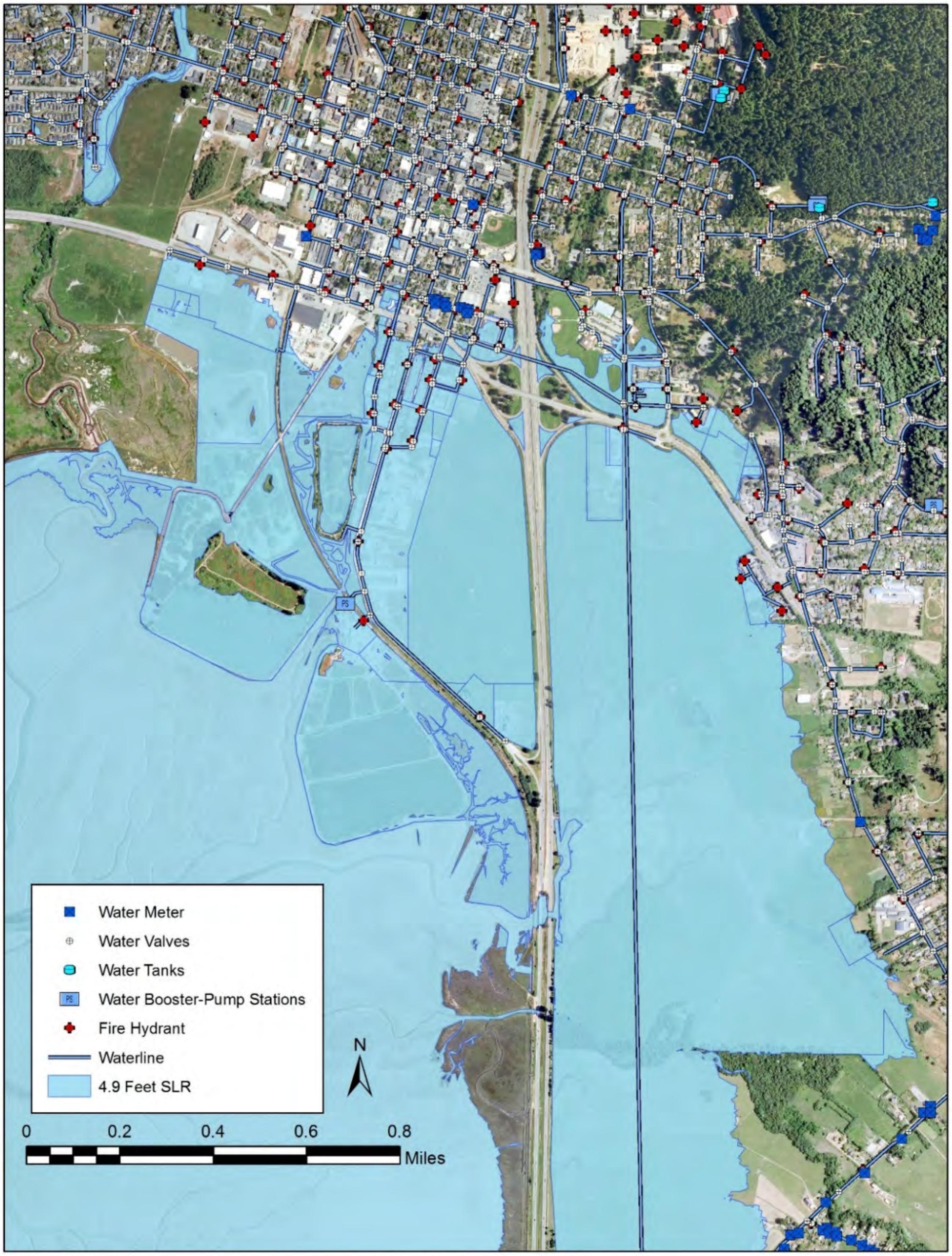

Figure 25. City's municipal water distribution infrastructure and with tidal inundation area of 4.9 ft. (1.5 M) of sea level rise. 3.3 miles of water line and one pump station are vulnerable.

Susceptibility

The vulnerability of the City's municipal water system to tidal inundation does not vary significantly from 1.1 ft. to 4.9 ft. (1.5 M) of sea level rise (2.0 to 3.3 miles of water lines). Most of the City's underground municipal water transmission pipelines are not susceptible to the adverse effects of sea level rise. However, older water transmission lines are chronically susceptible to corrosion if the cathodic protection systems are not maintained and from differential settlement, should the ground supporting the pipes become saturated and mobile. Ground saturation and mobility is likely to happen with rising ground water and tidal inundation.

Indirectly, the City's municipal water system may be susceptible to tidal inundation if the City's ability to perform maintenance and emergency repairs of the water transmission lines is impaired. Without regularly scheduled maintenance and repair, the pipeline would develop holes and cracks. Newer transmission lines would be resilient depending on the type of materials with which they are made (high-density polyethylene).

The City only has one booster-pump station that is vulnerable to sea level rise of 1.9 ft. Booster pump stations include mechanical and electrical systems that are very susceptible, should they be tidally inundated. The mechanical systems (valves and pumps) need regular maintenance.

If the dikes on Gannon Slough that are preventing tidal inundation of the areas that the City of Eureka's pipe lines traverse fail, getting trucks and heavy equipment access for emergency repairs may eventually become impossible. Deferred maintenance could cause long-term, chronic problems with that conveyance system, resulting in significant interruption of service and eventually complete failure of the system. The water transmission lines are the primary conveyance of potable water to the City of Eureka. Impairment of the conveyance capacity of these transmission lines would be catastrophic. The City of Eureka has approximately five days of water storage. Repairs that take longer than this would be consequential to the City of Eureka and likely necessitate drastic conservation efforts.

3.5.2 Wastewater

The City's wastewater infrastructure consists of a collection system of lift stations, sewer lines and the Treatment Plant. The City's Treatment Plant occupies approximately 71 acres. Primary treatment facilities include a series of treatment marshes and oxidation ponds to provide secondary treatment. Polishing marshes (equivalent to secondary treatment) are located at the Arcata Marsh. The Arcata Marsh is an innovative wastewater treatment technology, consisting of three treatment wetlands in series. The Treatment Plant discharges secondary treated wastewater to the Arcata Marsh and effluent from the Arcata Marsh is pumped back to the Treatment Plant for disinfection before final disposal to Humboldt Bay via an outfall on Butcher Slough (COA UWMP 2015). The Treatment Plant also has several sludge compost beds, pump stations and pipelines.

Exposure

Inflow and infiltration is an existing problem that could be exacerbated by tidal inundation and rising groundwater, which could adversely impact affected portions of the wastewater collection system and the operation of the Treatment Plant.

The City has four sewer lift stations (elevations: 10.5, 11.5, 12.1, and 13. ft.) and 4.4 miles of sewer lines within the tidal inundation area for 4.9 feet (1.5 M) of sea level rise (13.1 feet) (Figure 26).

The Treatment Plant has a 1.3-mile perimeter, of which 0.9 miles is composed of earthen pond dikes that enclose approximately 8.4 acres. While most of these dikes are fortified, approximately 0.5 miles would be overtopped by 3.3 ft. (1.0 M) of sea level rise, and 0.9 miles by 4.9 ft. (1.5 M) of sea level rise (Figure 27).

The Arcata Marsh has 3.9-mile perimeter that is composed of dikes, pathways/roads, and railroad that enclose 225 acres, of which 61 acres consist of treatment marshes and oxidation ponds adjacent to the Treatment Plant. Most of the perimeter of the Arcata Marsh, except for 0.5 miles of dikes on the oxidation ponds, would be overtopped by 3.3 ft. (1.0 M) of sea level rise. Essentially all the Arcata Marsh habitat areas would become tidally inundated.

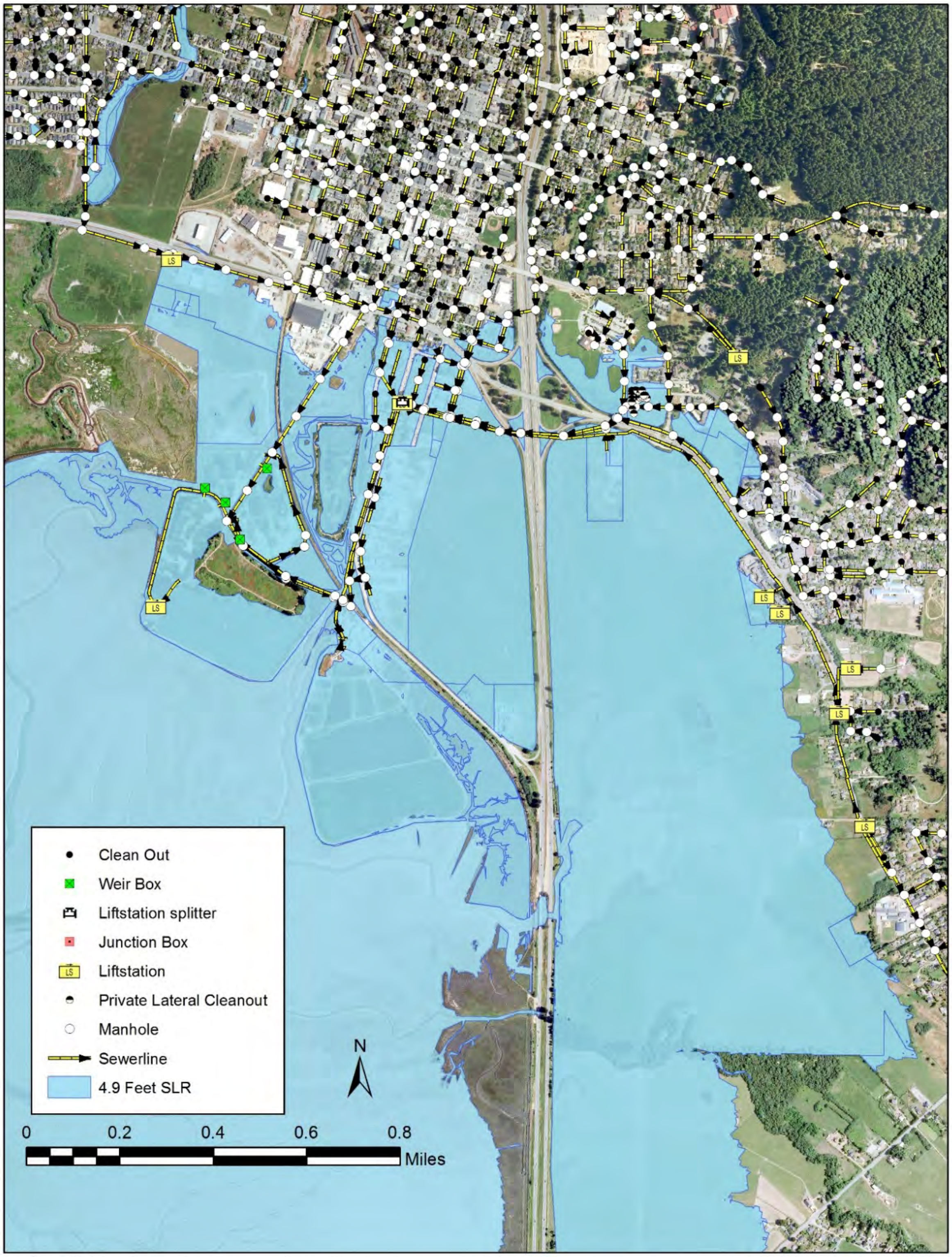

Figure 26. City's waste water distribution infrastructure within the tidal inundation area for 4.9 ft. (1.5 M) of sea level rise.

Figure 27. The City's wastewater treatment plant (yellow) and the Arcata Marsh and Wildlife Sanctuary (white) with respect to the tidal inundation area for 3.3 ft. (1.0 M) of sea level rise.

Susceptibility

With sea level rise, it is possible that increasingly long periods of ground saturation could result in settlement or movement and possibly floating of wastewater pipes. In general, the wastewater collection system (including the lift stations) is fairly insensitive to flooding and tidal inundation. However, the lift stations and collection pipe network's exposure to tidal inundation could allow salt water into the collection and treatment system. This would hydraulically overload the collection and treatment system and cause a breakdown in the treatment process. If too much salt water is introduced into the treatment process, the biological system within the treatment plant would cease to function, resulting in a failure of the treatment process. The biological system would not able to cope with this sea level rise impact.

Electrical components of the lift stations are very susceptible to being tidally inundated or flooded. If the electric supply and control systems are exposed to salt water, they are likely to malfunction.

The biological treatment process of a wastewater treatment facility is very sensitive to saltwater, that could be introduced by inflow/infiltration (I/I) to a collection system that traverses areas subject to tidal inundation.

The loss of functionality of the Treatment Plant would be devastating to the entire City. If the I/I become too big of an issue, the City may opt to restrict the use of the collection system in the affected areas. This would seriously impact the residential, commercial and industrial uses of those areas and areas upstream that are tributary to those sections of the collection system. Future growth could also be impacted by loss of treatment capacity if the system has excessive I/I. If the Treatment Plant ceases to function, the impacts would be felt by all the users in the City's service areas.

3.5.3 Energy

PG&E's Humboldt Bay Generating Station (HBGS) is a local natural gas-fired power plant in King Salmon, that provides electricity to the City. In the City, PG&E has electrical transmission and distribution infrastructure. There are no electrical substations in areas that are vulnerable to 4.9 ft. (1.5 M) of sea level rise. There are high voltage electrical transmission towers (69 kV (yellow) and 138 kV (white) are in low-lying areas protected from tidal inundation by earthen dikes, which are vulnerable to 4.9 ft. (1.5 M) of sea level rise (Figure 28).

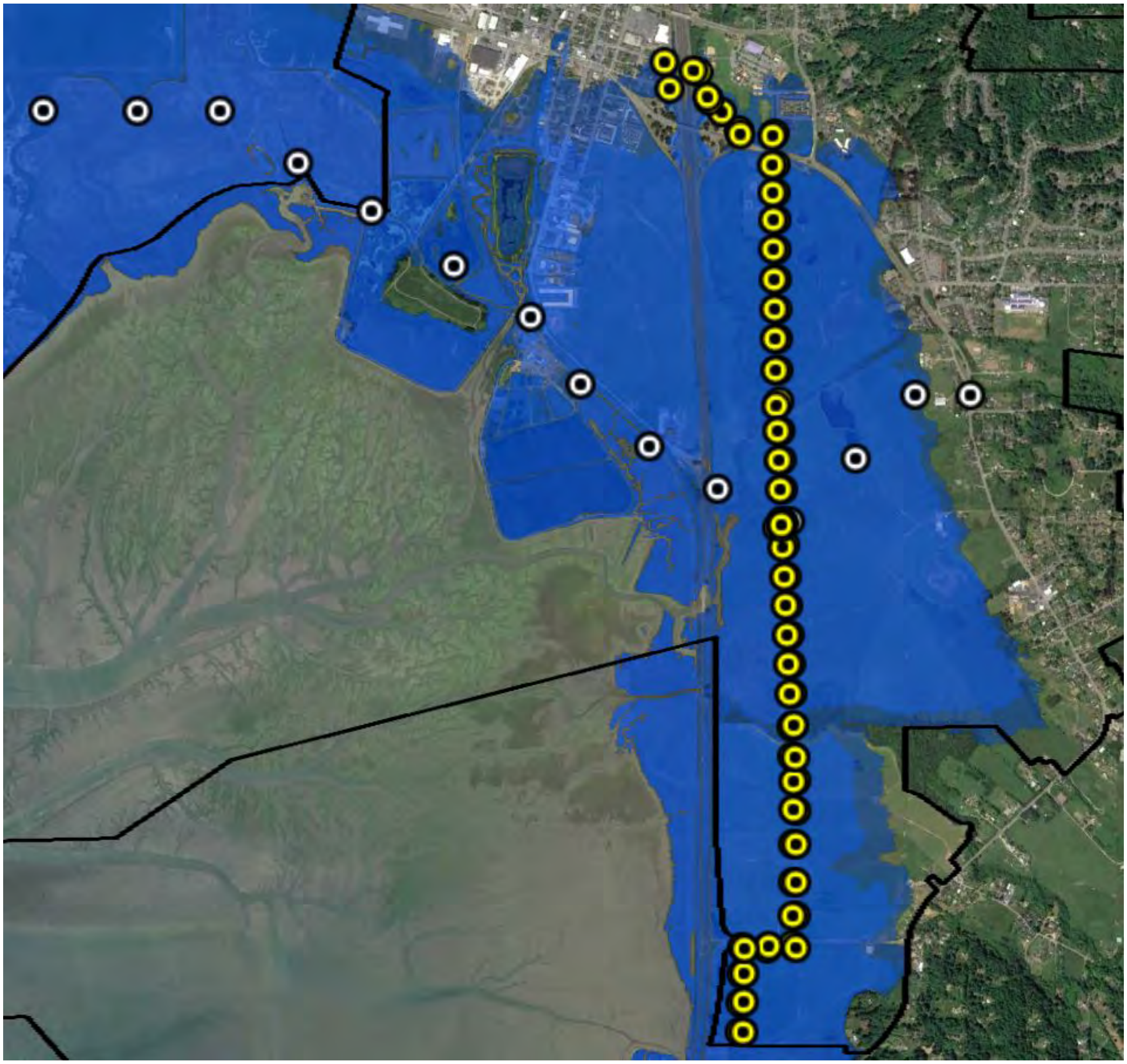

Figure 28. PG&E'S electrical transmission towers (white) and distribution poles (yellow) that could be affected by the tidal inundation from 4.9 ft. (1.5 M) of sea level rise.

Exposure

PG&E has electric transmission towers and distribution poles located in diked former tidelands that are low-lying areas behind dikes on Gannon Slough and Arcata Marsh.

Electric transmission towers and distribution poles in low-lying areas could be destabilized by tidal inundation and rising groundwater. Pole-mounted electrical distribution lines, transformers, and service panels run throughout low-lying areas along the bay and sloughs. Diked former tide lands and other low-lying areas would be tidally inundated if the shoreline structures fail, resulting in loss of adequate support of poles and guy wires due to increased and continuous soil saturation, exposure of ground mounted transformers and electrical equipment to salt water and flooding, causing burnout, and increased rates of equipment corrosion. Tidal inundation caused by dike failure or rising tide elevations may limit repair and maintenance access to electrical infrastructure during high tide and extreme weather events, leading to prolonged power outages. In some locations, access may be eliminated altogether.

With 1.1 ft. of sea level rise, eight electrical transmission towers could be tidally inundated along with 62 distribution poles. With 3.3 ft. of sea level rise, nine electrical transmission towers could be tidally inundated along with 70 distribution poles. With 4.9 ft. of sea level rise (1.5 M), ten electrical transmission towers could be tidally inundated along with 85 distribution poles.

Susceptibility

Electrical facilities are very susceptible to tidal inundation and flooding. In the City's LCP planning area, electric transmission towers and distribution poles in diked low-lying areas could become destabilized by tidal inundation and rising groundwater. Pole-mounted electrical distribution lines, transformers, and service panels run throughout low-lying areas along the bay. Diked former tide lands and other low-lying areas could potentially be tidally inundated if the shoreline structures fail, resulting in loss of adequate support of poles and guy wires due to increased and continuous soil saturation, exposure of ground mounted transformers and electrical equipment to salt water and flooding, causing burnout, and increased rates of equipment corrosion. Tidal inundation caused by dike failure or rising tide elevations may limit repair and maintenance access to electrical infrastructure during high tide and extreme weather events, leading to prolonged power outages. Access may be eliminated altogether. Areas protected by earthen dikes are vulnerable and at risk from tidal inundation now and increasingly vulnerable with high projections for sea level rise. Tidal inundation of these diked lands could significantly impact transmission and distribution support structures.

The sustainability of development in the City's LCP planning area is predicated on having secure and reliable electricity. The stability of the transmission towers and distribution poles are essential to delivering electricity to the City. These electrical distribution structures can be made resilient to tidal inundation.

3.5.4 Natural Gas

In the City, PG&E has underground natural gas pipelines that traverse former tidelands protected by earthen dikes, railroad grade, City streets, and Highway 101 (Figure 29). The exact location of natural gas pipelines and stations are not known and unavailable due to PG&E's security concerns, making it difficult to assess the vulnerability of this infrastructure to sea level rise.

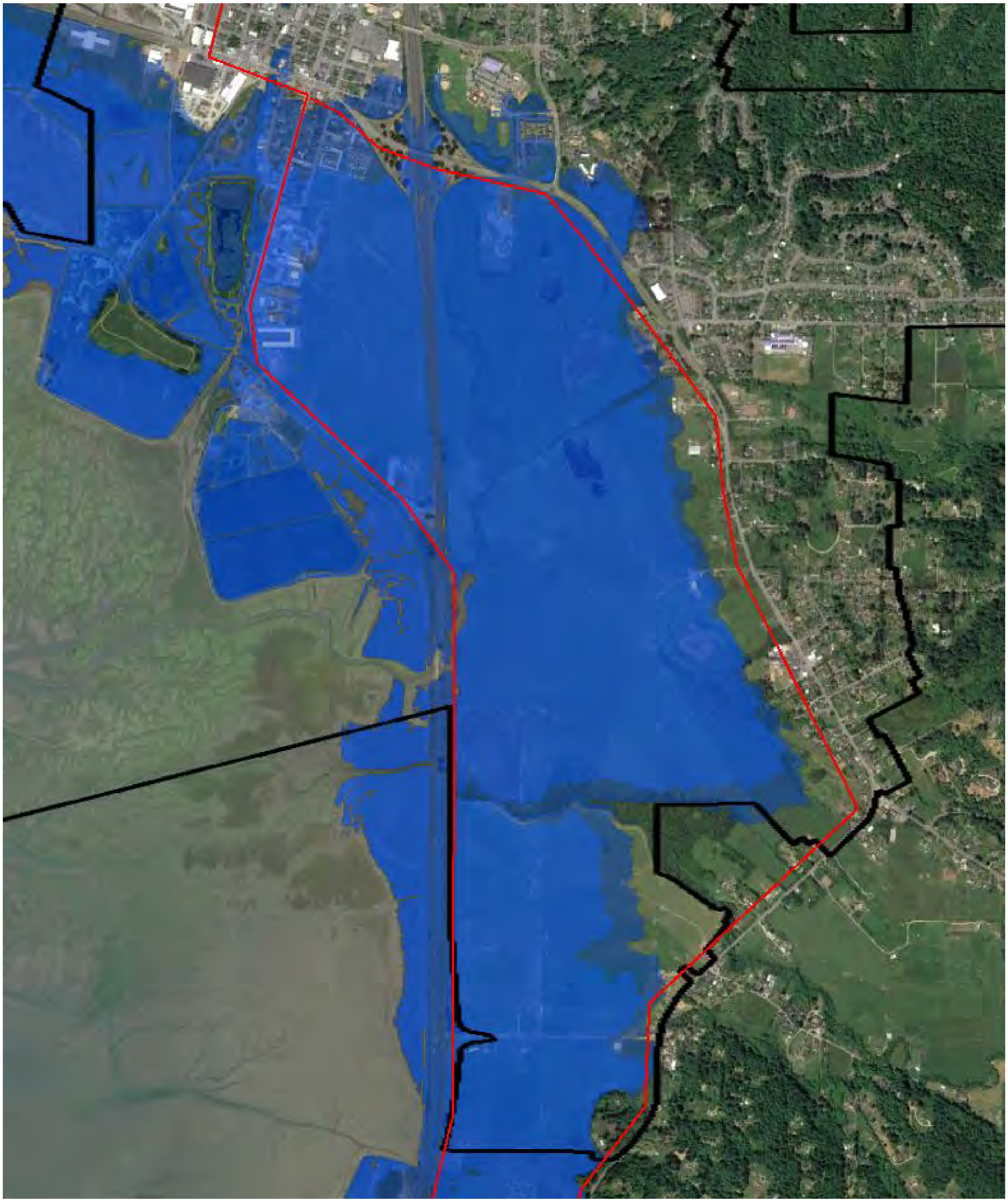

Figure 29. Approximate, location of PG&E natural gas transmission lines (red) in the City of Arcata (black lines) with respect to the 4.9 ft. (1.5 M) sea level rise tidal inundation area.

Exposure

Natural gas transmission and distribution systems within the City are vulnerable and at risk from tidal inundation, as they are in low-lying areas and can experience loss of access by maintenance personnel during tidal inundation and stormwater-created flood events. Additional coordination with PG&E is necessary to be able to more fully evaluate the vulnerability of this infrastructure.

Based on available information in the City's LCP planning area, there are approximately, 2.4 miles of gas lines located in areas that would be tidally inundated if protective shoreline structures such as dikes on Gannon Slough or Washington Gulch are breached. Additionally, 2.5 miles, 2.8 miles and 3.1 miles would become inundated with 1.6 ft. (0.5 M), 3.3 ft. (1.0 M), and 4.9 ft. (1.5 M) of sea level rise, respectively.

Susceptibility

Very little is known about the underground gas lines other than their approximate location. Tidal inundation is likely to infiltrate into the gravel bedding and potentially into the pipes through cracks and/or leaking joints. It is possible that increasingly long periods of ground saturation could result in settlement or movement of the pipes.

While saltwater may not affect underground gas lines significantly, tidal inundation and flooding could adversely affect access to these gas lines for emergency repairs and maintenance. A loss or interruption of access to natural gas would be a significant impairment to the City.

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