

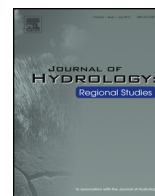


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Sea-level rise and coastal groundwater inundation and shoaling at select sites in California, USA

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ABSTRACT

Study region: The study region spans coastal California, USA, and focuses on three primary sites: Arcata, Stinson Beach, and Malibu Lagoon.

Study focus: 1 m and 2 m sea-level rise (SLR) projections were used to assess vulnerability to SLR-driven groundwater emergence and shoaling at select low-lying, coastal sites in California. Separate and combined inundation scenarios for SLR and groundwater emergence were developed using digital elevation models of study site topography and groundwater surfaces constructed from well data or published groundwater level contours.

New hydrological insights for the region: SLR impacts are a serious concern in coastal California which has a long (~1800 km) and populous coastline. Information on the possible importance of SLR-driven groundwater inundation in California is limited. In this study, the potential for SLR-driven groundwater inundation at three sites (Arcata, Stinson Beach, and Malibu Lagoon) was investigated under 1 m and 2 m SLR scenarios. These sites provide insight into the vulnerability of Northern California coastal plains, coastal developments built on beach sand or sand spits, and developed areas around coastal lagoons associated with seasonal streams and berms. Northern California coastal plains with abundant shallow groundwater likely will see significant and widespread groundwater emergence, while impacts along the much drier central and southern California coast may be less severe due to the absence of shallow groundwater in many areas. Vulnerability analysis is hampered by the lack of data on shallow coastal aquifers, which commonly are not studied because they are not suitable for domestic or agricultural use. Shallow saline aquifers may be present in many areas along coastal California, which would dramatically increase vulnerability to SLR-driven groundwater emergence and shoaling. Improved understanding of the extent and response of California coastal aquifers to SLR will help in preparing for mitigation and adaptation.

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1. Introduction

Sea level has varied globally over the past several millennia. Rates of sea-level rise (SLR) have ranged from 1 to 100 cm/century over the past 20,000 years, but have been accelerating over the last century (Scavia et al., 2002; Cayan

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et al., 2008). For example, global mean sea level rose at a rate of ~ 18 cm/century in the 20th century, but at a rate of more than 22 cm/century during the past few decades (Cayan et al., 2008). Recent increases have been attributed primarily to global climate change and associated melting of polar icecaps (Scavia et al., 2002; Rahmstorf, 2007; Cayan et al., 2008; Mastrandrea and Luers, 2012; IPCC, 2013).

Increases in sea level at California have generally followed the global trend, except for the past few decades when the rate of SLR has remained relatively constant at 17–20 cm/century (Cayan et al., 2008; Mastrandrea and Luers, 2012). In addition to global mean sea level, factors such as ocean and atmospheric circulation patterns, gravitational effects, heightened groundwater withdrawals (Konikow, 2011), and tectonics along the coast affect the rate of SLR along the California coast (National Research Council, 2012).

SLR impacts along the California coast are a substantial concern because the majority of the State's population (~ 34 million people or 87% of the 2014 population) lives in coastal counties (Crossett et al., 2004; Heberger et al., 2009; US Census, 2015b). California also has a long coastline (~ 1800 km, excluding bays, wetlands, and estuaries), with extensive development in the south, and coastal resources are a major asset in the State (Crossett et al., 2004; National Research Council, 2012; Arkema et al., 2013). Recent projections indicate that global sea level could rise by ~ 0.5 to 1.4 m by 2100 compared to 1990 levels, with similar increases projected for California (Rahmstorf, 2007; Cayan et al., 2008). These increases are unprecedented in modern human history (Cayan et al., 2008).

SLR-related impacts on coastal systems can occur in several ways (Wahl et al., 2015). Marine inundation will shift the coastline landward, erode beaches, accelerate cliff failure, degrade some coastal habitats, and potentially damage coastal infrastructure (Dawson et al., 2009; Arkema et al., 2013; Rotzoll and Fletcher, 2013). SLR can also contribute to the degradation of coastal aquifers, which have already been under pressure in much of California over the last century due to excessive water extraction and persistent and severe drought (Hanson et al., 2009; Nishikawa et al., 2009; Barlow and Reichard, 2010; Gibbs, 2012; Kostigen, 2014). Saltwater intrusion into freshwater aquifers in California coastal regions has been attributed predominantly to groundwater overdraft, especially in southern California (CA DWR, 2003; Zektser et al., 2005; Hanson et al., 2009; Nishikawa et al., 2009). However, recent studies have demonstrated that SLR also could contribute to saltwater intrusion in coastal regions by raising the interface between intruding saltwater and overlying freshwater (Werner and Simmons, 2009; Rotzoll and Fletcher, 2013). SLR is also expected to impact surface water via saltwater intrusion to deltas, which could have practical implications (CA DWR, 2015). For example, the amount of Delta water exported to southern California is expected to decrease by 21–25% by 2100 due to climate change impacts, including SLR (CA DWR, 2009). Average annual California snowmelt is predicted to decrease by ~ 15 to 60% for temperature increases of 1 to 4 °C, which would change the patterns and timing of surface runoff and impact recharge to coastal aquifers (CA DWR, 2009; CA DWR, 2015). In addition, extreme climate-associated events are projected to increase in frequency and intensity with climate change, which could exacerbate the risks of transient SLR-driven groundwater emergence and shoaling impacts on humans, coastal habitats, and infrastructure (Cayan et al., 2008; Miller et al., 2008; Heberger et al., 2009; Mastrandrea and Luers, 2012). Where shallow unconfined aquifers occur along the coast, more frequent and extensive wave runup and overwash will increase recharge from seawater, increasing groundwater levels over longer timescales.

Shallow coastal groundwater can occur in a variety of geologic settings, and may occur as shallow saline aquifers that either are in direct contact with the ocean or are recharged by intermittent overwash and infiltration during high tides and high wave events, or as brackish to fresh aquifers where there is significant freshwater recharge. Where unconfined fresh groundwater is in contact with underlying seawater, the fresh groundwater floats on the higher-density seawater, and the average elevation of the water table will be above mean sea level. The increased groundwater elevation due to floating freshwater is very small near the coast, but increases inland as the thickness of the freshwater lens increases. For the purposes of this study, the additional elevation due to freshwater is not considered because the very low topographic areas that are vulnerable to groundwater emergence all are very close to the coast. Near the coast, especially in relatively permeable substrates, both the seawater and saline or overlying fresh groundwater respond to tidal forcing, with the magnitude of the response diminishing inland from the coast (Cooper et al., 1964; Freeze and Cherry, 1979; Rotzoll and Fletcher, 2013). SLR and tidal forcing will cause the groundwater table to rise in these areas, and in low-lying areas the water table could approach and ultimately rise above the ground surface. In undeveloped areas this could expand existing, or create new wetlands, but in developed areas this could present serious problems (Rotzoll and Fletcher, 2013). Even where the water table does not rise above the land surface, groundwater at shallow and intermediate depths (e.g., <2 m depth), could present significant challenges to the maintenance of existing infrastructure and to new development. Consequently, groundwater shoaling and emergence in response to SLR is a potentially significant concern for low-lying coastal communities (Bjerklie et al., 2012; Rotzoll and Fletcher, 2013).

Several recent studies have investigated climate-change and SLR-associated marine inundation threats to coastal habitats and infrastructure (Dawson et al., 2009; Heberger et al., 2009; Arkema et al., 2013), but the potential impacts of SLR-driven groundwater inundation on coastal areas of California have not been systematically addressed. Existing studies in Hawaii and Connecticut have shown that SLR-driven groundwater inundation could be substantial and could even exceed SLR-driven marine inundation in low-lying coastal areas—for example, SLR-driven groundwater inundation is expected to account for 88% of the total flooded area in Nuuanu, Hawaii under a 0.66 m SLR scenario (Bjerklie et al., 2012; Rotzoll and Fletcher, 2013). However, these studies were performed in geologic and hydrologic settings that are very different from the complex geology and hydrology along California's coast, so results from these studies provide little insight into the potential vulnerability of

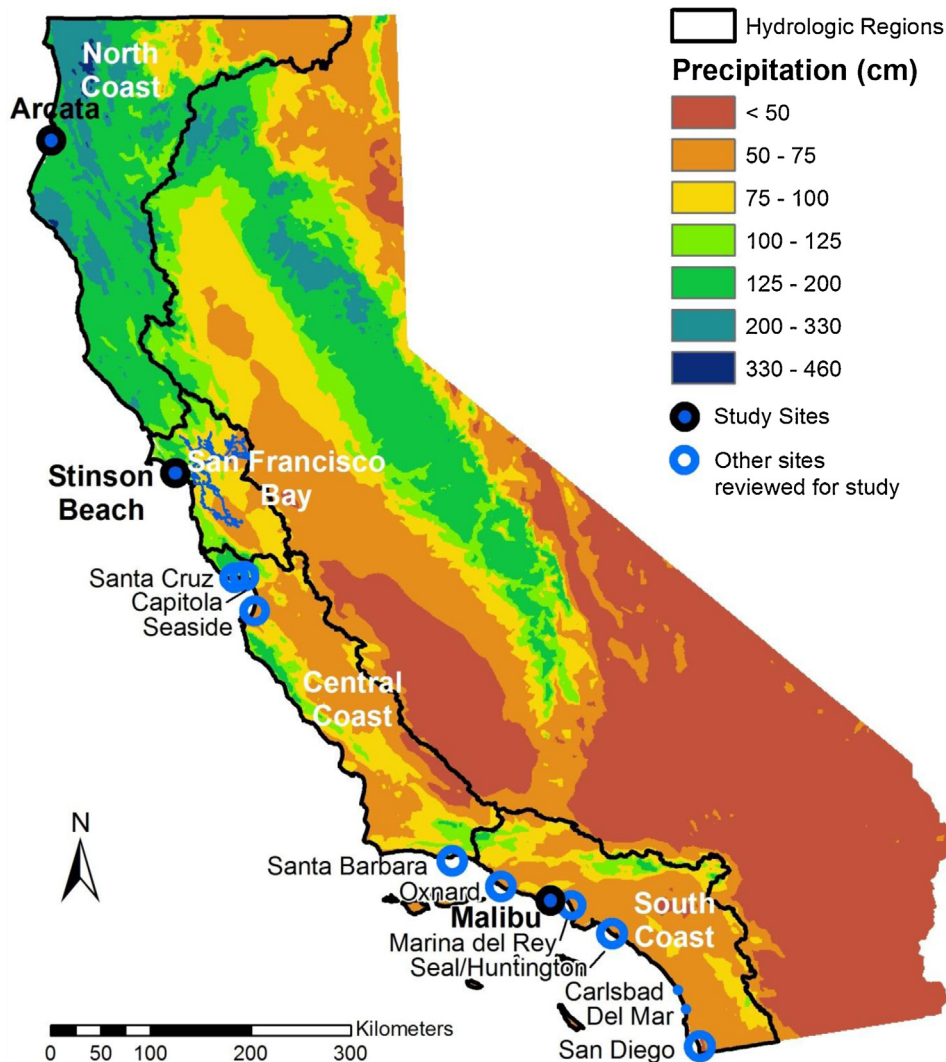


Fig. 1. Map of California showing the 4 coastal hydrologic regions (HRs), study sites and other locations referenced in the text, and average annual precipitation (1981–2010) for the State (<https://earthworks.stanford.edu/catalog/stanford-td754wr4701>). San Francisco Bay is outlined in blue within its HR.

California’s coastal communities and natural resources to SLR-driven groundwater shoaling and emergence. Such knowledge could help resource managers and coastal communities prepare for mitigation and adaptation.

This study provides a preliminary assessment of the potential for SLR-driven groundwater inundation and shoaling in select coastal regions of California. Because groundwater monitoring in the State is concentrated in inland aquifers and on aquifers with potable groundwater, systematic groundwater data are scarce for potable aquifers along the coast and largely absent for shallow saline aquifers. As a result, we focus on three case-study sites in Arcata, Stinson Beach, and Malibu Lagoon where data are sufficient to characterize the groundwater surface and to estimate depths to groundwater under varying SLR scenarios (Fig. 1). Because of the lack of data for shallow saline aquifers, we do not address the potential for SLR-driven groundwater inundation and shoaling in these systems, but anecdotal data indicates that they are widespread (J. Izbicki, pers. comm.) and thus may be a significant concern. We also recognize that global climate change may alter regional hydrology leading to changes in elevations in fresh groundwater aquifers and associated vulnerabilities, but assume for this simplified analysis that there is no change in regional hydrology.

Since our case-study sites occur in very different hydrologic and geologic settings, we briefly review the four coastal hydrologic regions in California and the selected study sites (Fig. 1).

2. California coastal hydrologic regions and study sites

California's coast is divided into four hydrologic regions (HRs): North Coast, San Francisco Bay, Central Coast, and South Coast (CA DWR, 2003; Crossett et al., 2004). These HRs differ in substantial ways, including climate, geology, hydrology, and population.

2.1. North Coast HR

The North Coast HR covers ~50,400 km² and has a coastline of ~550 km. It is the least populated of the coastal HRs, with only ~2% of the state's total population (CA DWR, 2003; NCRWQCB, 2011). It has 63 groundwater basins (and sub-basins) covering ~4140 km²; two of these basins are shared with Oregon (CA DWR, 2003). It is divided into two major natural drainage basins; the Klamath River Basin (~28,050 km²) and the North Coastal Basin (~22,170 km²) (NCRWQCB, 2011).

The North Coast HR receives the greatest precipitation and has the most abundant water resources of the 10 California HRs (Fig. 1) (CA DWR, 2003; CA DWR, 2013b). Annual rainfall within sub-basins ranges from 25.4 to over 250 cm (Fig. 1). The coast is generally foggy and sparsely populated due to its rugged terrain (CA DWR, 2003). Despite covering only ~12% of the total area of California, it accounts for ~41% of annual surface runoff in the state, contributing to replenishment of surface reservoirs and groundwater aquifers (NCRWQCB, 2011; CA DWR, 2013b). In the North Coast HR, we examined the potential SLR response of the unconfined groundwater aquifer in the coastal plain of Arcata (Fig. 2).

Arcata had an estimated 2014 population of 17,730 people (US Census, 2015a). The Arcata groundwater basin is primarily underlain with alluvium that is composed of clay, gravel, sand, and silt (Evenson, 1959; CA DWR, 2013b). A detailed discussion of the geology of the Arcata area can be found in Evenson (1959). Groundwater is used for agricultural and domestic needs (Evenson, 1959; CA DWR, 2003, 2013b); groundwater from the two northern wells in the study area is used for agriculture, while the southern well is for residential use. A conceptual numerical model of the potential impacts of SLR on groundwater was developed by Willis (2014), but is limited to predictions of general changes in maximum groundwater head and potential saltwater intrusion impacts along a single idealized cross-shore transect under a variety of aquifer and SLR conditions. Our study area in Arcata is limited by the areal extent of the available well data and covers only a small fraction of the Eureka Coastal Plain groundwater basin; as a result our analysis should be considered indicative of the type of behavior expected in this system but may not be applicable to the full aquifer.

2.2. San Francisco Bay HR

The San Francisco Bay HR is the smallest HR in California, covering ~11,655 km². Despite its small size, it has the second largest population among the HRs, with several major cities, including San Francisco, San Jose, and Oakland (CA DWR, 2003). The region imports ~70% of its water and gets the remaining 30% from local sources (CA DWR, 2013c). It has 28 recognized groundwater basins covering ~3,600 km² (~30% of the HR). Groundwater accounts for ~5% of water used in the HR, and less than 1% of the state's total groundwater use (CA DWR, 2003). Despite this, land subsidence attributed to groundwater extraction has been reported in the Santa Clara Groundwater Basin, which surrounds the southern lobe of San Francisco Bay (Fig. 1) (CA DWR, 2003; CA DWR, 2013c). In this study, we examine the potential impacts of SLR on groundwater in Stinson Beach.

Stinson Beach (Figs. 1 and 3) is a small coastal community located ~30 km north of San Francisco. The watershed has an area of ~29.3 km² and is 95% conservation land. Development is mostly within 100 m of the coastline and is mostly residential (de Sienes et al., 2008). It has a Mediterranean climate and receives annual rainfall of 60–120 cm, primarily between October and April (de Sienes et al., 2008; de Sienes, 2011). The unconfined aquifer in Stinson Beach is composed primarily of beach and dune sands; groundwater in the aquifer is a mixture of native groundwater and inputs from residential wastewater treatment systems. Potential contamination of groundwater from wastewater treatment systems is a concern in the area (de Sienes et al., 2008). The area contains numerous ephemeral streams that discharge into the ocean during the wet season, mainly through Bolinas Lagoon (de Sienes, 2011). As for our Arcata study site, our study area in Stinson Beach is limited by the areal extent of the available well data and covers only a fraction of the watershed and associated groundwater aquifer; as a result our analysis should be considered indicative only of the type of behavior expected in the coastal sand and spit portion of this or similar watersheds.

2.3. Central Coast HR

The Central Coast HR covers an area of ~29,300 km² in central California (Fig. 1, CA DWR, 2003; CA DWR, 2013a). It has 50 identified groundwater basins, with an area of ~9,687 km² (~33% of the HR) (CA DWR, 2003). The Central Coast HR is home to ~4% of the State's population and uses groundwater to meet ~80% of its domestic, municipal, and agricultural water demands, making it the most groundwater-reliant HR in the state (CA DWR, 2013a). Though it receives only moderate rainfall (Fig. 1), its economy is heavily reliant on agriculture and viticulture (CA DWR, 2003; CA DWR, 2013a). Potential environmental issues in the region include groundwater overdraft, seawater intrusion, water quality degradation, and flood risk (CA DWR, 2013a).

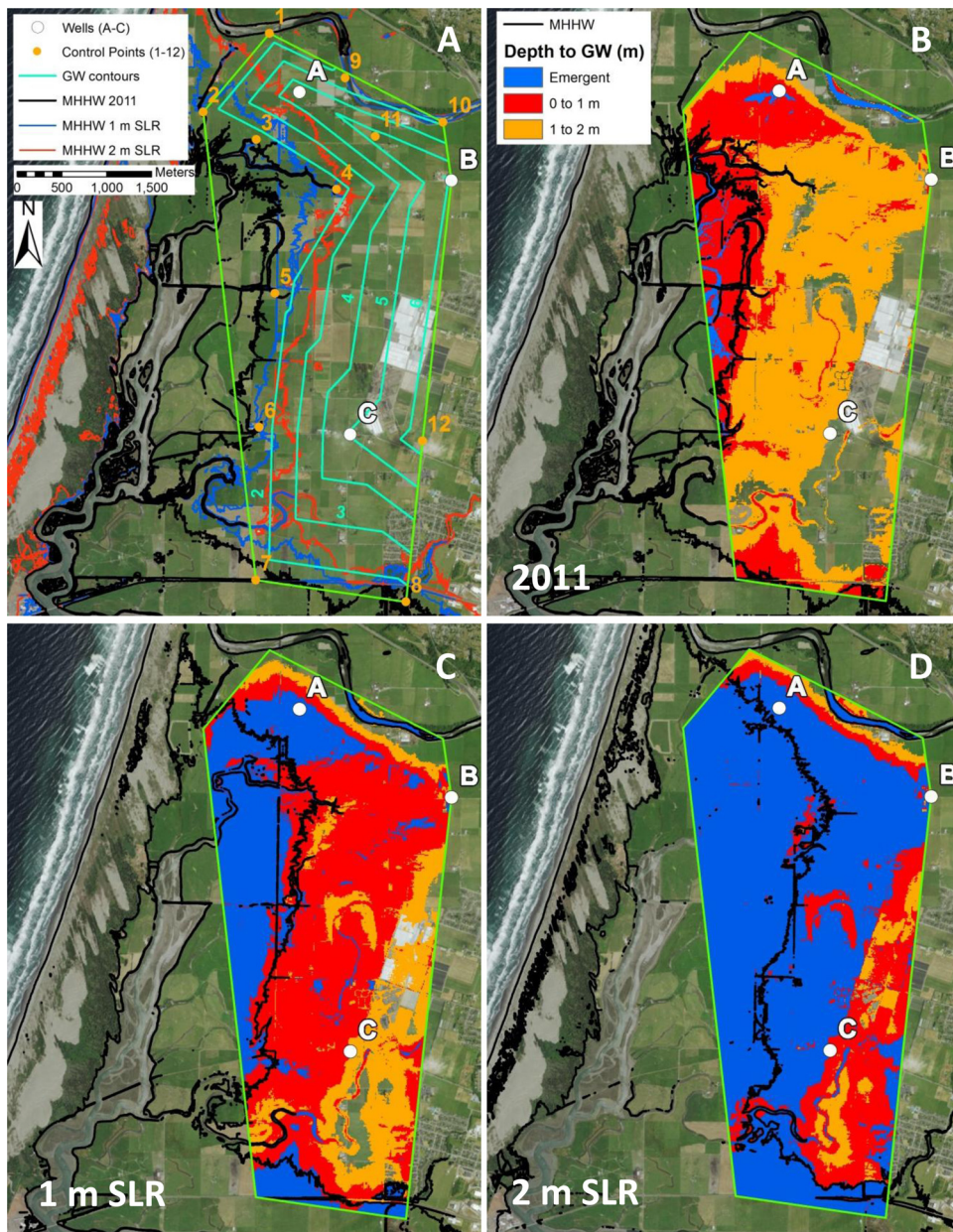


Fig. 2. Arcata study area, direct SLR inundation, and SLR-driven groundwater emergence and shoaling. (A) Overview map showing well and boundary control point locations, resulting groundwater contours, and extent of inundation by present day MHHW and 1 and 2 m increases to MHHW. Wells A–C are State well numbers 06N01E07M001H, 06N01E17D001H, and 06N01E19Q001H respectively. (B) Calculated depths to groundwater for present-day conditions. (C) Depth to groundwater for 1 m SLR. (D) Depth to groundwater for 2 m SLR. Note that direct inundation in the study area is via SLR impacts on Arcata Bay and the Mad River slough, south and west of the study area; high dunes along the beach prevent direct inundation from the ocean. GW = groundwater.

While no suitable groundwater data were identified for characterizing groundwater surfaces in low-lying areas of the Central Coast HR, evaluation of coastal topography and available groundwater data, particularly around streams and river mouths (e.g., the San Lorenzo River in Santa Cruz, Soquel Creek in Capitola, and in the Seaside region in southern Monterey Bay) suggests that the potential for adverse impacts due to SLR-driven shoaling of fresh groundwater is relatively low. For example, in the Seaside groundwater basin in southern Monterey Bay, groundwater contours in Yates et al. (2005) were digitized and compared to ground elevations, but groundwater was more than 5 m below the ground surface along the seaward edge of the groundwater contours (Table 1). Similar results were found in most of the coastal areas around the San Lorenzo River and Soquel Creek in northern Monterey Bay. These areas are generally representative of conditions along much of the Central Coast HR, which has extensive areas of bluffs interrupted occasionally by incised drainages. This analysis does not address the possibility of shallow saline aquifers in these areas that might be subject to SLR-driven groundwater shoaling

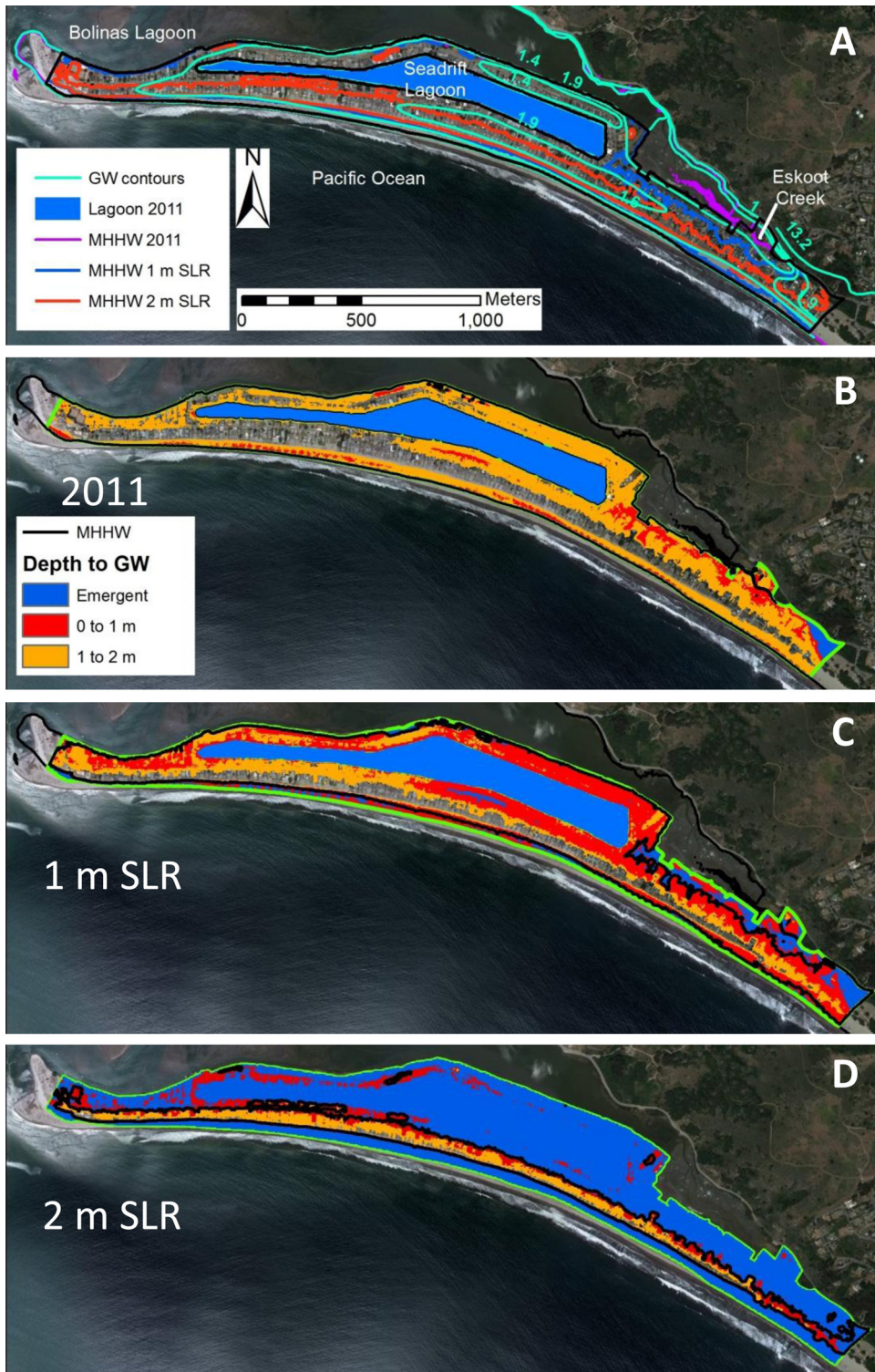


Fig. 3. Stinson Beach study area, direct SLR inundation, and SLR-driven groundwater emergence and shoaling. (A) Overview map showing groundwater contours in m, and inundation by present day MHHW and 1 and 2 m SLR increases. (B) Calculated depths to groundwater for present-day conditions. (C) Depth to groundwater for 1 m SLR. (D) Depth to groundwater for 2 m SLR GW = groundwater.

Table 1

Additional sites reviewed in this study. Except where noted, vulnerability assessment does not include possibility of undocumented shallow saline aquifers that could result in SLR-driven groundwater shoaling and emergence (cf., Oxnard).

Site	Area at risk	Development	Depth to GW	Vulnerability
Santa Cruz	Floodplain around San Lorenzo River mouth	Urban, suburban, wetlands	Unknown	TBD (moderate?). River is major water supply for city, little GW pumping. Wet years could elevate GW adjacent to river near coast
Capitola	Capitola village adjacent to Soquel Creek lagoon	Suburban	2 nearby coastal wells with shallow (0.8–3.6 m NAVD88) GW, but wells are on coastal bluffs (SqCWD and CWD, 2007)	TBD (moderate?). Groundwater major water supply for region. Heavy pumping just inland but seasonal fluctuations might allow coastal GW to reach shallow depths
Seaside	Beach face and coastal lagoons	Urban, suburban, wetlands	Probably >5 m (Yates et al., 2005)	Low. Land surface high relative to GW except in coastal lagoons
Santa Barbara	Relict stream drainages	Urban, suburban	Probably >5 m (Freckleton et al., 1998)	Low. Land surface high relative to GW
Oxnard	Santa Clara River coastal plain	Agricultural	Potentially shallow but very limited data near coast (e.g., VCWPD, 2015)	TBD (moderate?). Much of fresh coastal plain aquifer is confined, limiting SLR effects, but overlying saline aquifers may respond to SLR, including increased recharge via overwash and infiltration through estuaries
Marina del Rey	Wetlands to S, low-lying areas to N (flood plain?)	Suburban, wetlands	Unknown, probably deep	TBD (low?). No coastal GW data, but region generally dry with extensive GW pumping
Seal/Huntington Beach	Relict wetlands?	Urban, suburban, wetlands	Unknown, probably deep	TBD (low?). No coastal GW data, but region generally dry with extensive GW pumping
San Diego	Margins of San Diego Bay	Urban, wetlands	Unknown, probably deep	TBD (low?). Very little coastal GW data, region generally dry with extensive GW pumping

and emergence, and estuaries and developed coastal areas immediately adjacent to drainages could be subject to impacts similar to those discussed below for Malibu Lagoon, but additional data would be needed to assess actual vulnerabilities.

2.4. South Coast HR

The South Coast HR covers ~27,450 km² in southern California. It is the most populated of the HRs in California with >50% of the total population of the state, despite only covering ~7% of the state's surface area (CA DWR, 2003; CA DWR, 2013d). It is also the most urbanized and densely populated of the ten HRs (CA DWR, 2013d). It is home to some of the largest cities in the US, including Los Angeles and San Diego (CA DWR, 2013d; US Census, 2015b). It has 56 identified groundwater basins covering ~9,140 km² or ~33% of the HR (CA DWR, 2003). Groundwater extraction in the South Coast HR dates back over 100 years and seawater intrusion has been documented in the region. Consequently, the coastal aquifers are highly managed, with seawater intrusion barriers in several areas (CA DWR, 2003; CA DWR, 2013d). This study focused on the coastal community around Malibu Lagoon (Fig. 4).

Malibu is a small, predominantly residential community located northwest of Los Angeles, with a 2013 population of ~12,861 people (US Census, 2015b). The Malibu Creek Watershed (~270 km²) drains into Malibu Lagoon, an ephemeral brackish water body roughly 0.05 km² in area (Ambrose and Meffert, 1999; Ganguli et al., 2012). The Malibu Lagoon berm is often breached during the winter, resulting in a direct surface connection with the ocean (Ganguli et al., 2012). The Malibu Valley Groundwater Basin is relatively small (~2.48 km²) and predominantly alluvial—composed of silt, clay, sand, and gravel (McDonald Morrissey Associates Inc., 2014). Average annual precipitation, which normally occurs between November and March, is ~34 cm (Izbicki et al., 2012). Groundwater is not pumped for public supply; groundwater issues include contamination, mainly from wastewater treatment (septic systems), and seawater intrusion (Izbicki et al., 2012; Izbicki, 2014; McDonald Morrissey Associates Inc., 2014). Our study area covers 55% of the Malibu groundwater basin and most of the coastal portion—it thus should provide a fairly complete example of SLR-driven groundwater impacts in this type of system.

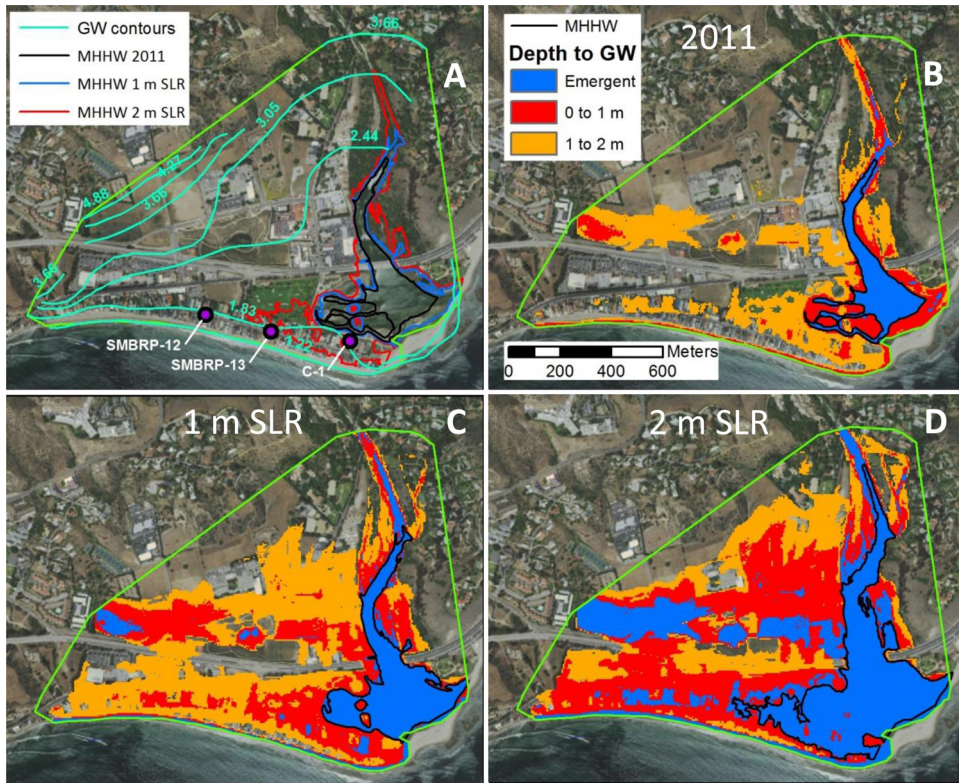


Fig. 4. Malibu Lagoon study area, direct SLR inundation (m), and SLR-driven groundwater emergence and shoaling. (A) Overview map showing locations of wells with tidal response data (Fig. 5), groundwater contours, and extent of lagoon expansion by present day MHHW and 1 and 2 m SLR increases. (B) Calculated depths to groundwater for present-day conditions. (C) Depth to groundwater for 1 m SLR. (D) Depth to groundwater for 2 m SLR. GW = groundwater.

Table 2
Description of data sources used in this study.

Data	Site	Source
Groundwater level	Arcata	California Department of Water Resources (http://www.water.ca.gov/waterdatalibrary/)
Groundwater contour	Malibu	Izbicki (2014)
	Stinson Beach	Stinson Beach County Water District (http://stinson-beach-cwd.dst.ca.us/hydro/index.html)
Observed tide	Malibu	Stone Environmental, Inc. (2004)
	All	National Oceanic and Atmospheric Administration (NOAA)–Tides and Currents (http://tidesandcurrents.noaa.gov/stations.html?type=Water+Levels)
DEM	All	NOAA's Digital Coast Archive (http://coast.noaa.gov/dataregistry/search/collection)

3. Materials and methods

3.1. Data

Groundwater level data for study sites were obtained either from published contour maps (Stinson Beach and Malibu) or from well data (Arcata). Topographic data was obtained from high-resolution digital elevation models (DEMs) from the National Oceanic and Atmospheric Administration (NOAA) Digital Coast archive (<http://coast.noaa.gov/digitalcoast/>). Tide data were obtained from NOAA (2015). Data and sources are summarized in Table 2.

3.2. Analysis

We used sea-level rise scenarios of 0 m (present), 1 m, and 2 m, with Mean Higher-High Water (MHHW) from nearby NOAA tide gauges as the reference elevation for maximum inundation at each site. MHHW is the average of the higher of two tidal-day high tides over the most recent 19-year National Tidal Datum Epoch

Table 3
SLR-driven marine inundation at Arcata, California under current, 1 m and 2 m SLR scenarios.

SLR scenario	Area inundated		Dry land	
	km ²	% of study area	km ²	% of study area
2011 (present)	1.13	8.7%	11.9	91%
1 m SLR	3.21	25%	9.79	75%
2 m SLR	5.19	40%	7.80	60%

Table 4
SLR-driven groundwater inundation and shoaling at Arcata, California under current, 1 m and 2 m SLR scenarios.

SLR scenario	Area inundated (emergent groundwater) (km ²)	Dry land			
		Total area (km ²)	Areas (km ²) with different depths (m) to groundwater		
			0–1 m	1–2 m	>2 m
2011 (present)	0.35	12.6	3.19	5.97	3.48
1 m SLR	3.55	9.45	5.97	2.52	0.97
2 m SLR	9.51	3.48	2.52	0.81	0.15
Area as % of study area					
2011 (present)	2.7%	97%	25%	46%	27%
1 m SLR	27%	73%	46%	19%	7.4%
2 m SLR	73%	27%	19%	6.3%	1.2%

(https://tidesandcurrents.noaa.gov/datum_options.html)—as such it provides an estimate of high-water levels that are reached frequently and persistently in a particular region. SLR scenarios of 1 and 2 m represent relatively near-term and longer timeframes for considering SLR impacts based on current predictions of SLR (Rahmstorf, 2007; Cayan et al., 2008) and are widely used in the literature for evaluating potential SLR impacts. For all analyses topographic and groundwater elevations were referenced to the North American Vertical Datum of 1988 (NAVD88)—unless otherwise noted, all reported elevations in this paper are NAVD88. MHHW levels along the coast of California typically are on the order of 1.6 to 2.0 m, so initial assessments reviewed coastal sites with significant areas at elevations under 3 m as areas potentially vulnerable to SLR-driven groundwater emergence and shoaling. Of these sites only three (Arcata, Stinson Beach, and Malibu Lagoon) had both sufficient groundwater data for detailed analysis and had groundwater at depths shallow enough to result in groundwater emergence at 1–2 m of SLR. Site locations are shown in Fig. 1; sites reviewed but not analyzed for this study are summarized in Table 1.

We were interested in the contribution of SLR-driven groundwater emergence to total inundation by SLR. As a result we calculated both direct marine inundation and SLR-driven groundwater emergence. Direct marine inundation was estimated by extracting the appropriate “bathtub-ring” MHHW contour from the DEM and calculating the area of the study area seaward of the contour. SLR-driven groundwater shoaling and emergence was assessed by generating a raster groundwater surface from published contours (Stinson Beach and Malibu Lagoon) or from well data (Arcata), subtracting the land-surface DEM from the groundwater surface, and adding the desired amount of SLR using ArcGIS© (cf., Rotzoll and Fletcher, 2013). Since data were not available to accurately estimate spatially variable tidal responses in the study areas, we used a simple linear relationship between SLR and water table response. This produces a conservative result because any additional tidally-driven increases in groundwater levels would increase groundwater shoaling and emergence during high tides. This simplified model also does not account for other factors that can influence the water table, including aquifer geology, changes in rainfall patterns, groundwater withdrawal, and developments that impact percolation of rain water (CA DWR, 2003; Rotzoll and Fletcher, 2013). For all analyses, area changes are presented as percentages of the study area only; results should not be extrapolated to larger areas (e.g., associated aquifers) without appropriate supporting analyses or data.

4. Results and discussion

Potential SLR-driven marine and groundwater inundation under 1 and 2 m SLR scenarios at Arcata, Stinson Beach, and Malibu Lagoon are shown in Figs. 2–4. Inundation estimates for these SLR scenarios are summarized in Tables 3–7. Unless indicated otherwise, the baseline date for “present-day” scenarios is 2011.

4.1. Arcata

SLR-driven marine and groundwater inundation are presented for Arcata in Figs. 2A–D, with areas impacted by direct marine inundation and SLR-driven groundwater inundation in Tables 3 and 4, respectively. The groundwater surface for the site was constructed using data from wells A–C in Fig. 2A. Level data in these wells are available starting in 1973, 1952, and 1951 respectively, but continuous twice-yearly records are only available starting in 1990, so data from 1990 to 2015 were used for statistical analyses for all wells, with maximum groundwater levels used to estimate the worst-case (most elevated)

Table 5
SLR-driven marine inundation at Stinson Beach, California under current, 1 m and 2 m SLR scenarios.

SLR scenario	Area of Seadrift Lagoon		Area inundated with seawater		Area of dry land	
	km ²	% of study area	km ²	% of study area	km ²	% of study area
2011 (present)	0.17	18%	0	0%	0.75	82%
1 m SLR	0.19	21%	0.17	18%	0.58	64%
2 m SLR	–	–	0.71	78%	0.20	22%

Table 6
SLR-driven groundwater inundation and shoaling at Stinson Beach, California under current, 1 m and 2 m SLR scenarios.

SLR scenario	Area of Seadrift Lagoon (km ²)	Inundated area (emergent groundwater) (km ²)	Total land area (km ²)	Dry areas (km ²) with different depths (m) to groundwater		
				0–1 m	1–2 m	>2 m
2011 (present)	0.17	0.01	0.74	0.10	0.36	0.27
1 m SLR	0.19	0.10	0.63	0.36	0.16	0.11
2 m SLR	–	0.64	0.27	0.16	0.09	0.03
Areas as % of study area						
2011 (present)	18%	1%	81%	11%	39%	30%
1 m SLR	21%	11%	69%	39%	18%	12%
2 m SLR	–	70%	30%	18%	10%	3%

groundwater surface. The wells are used for agricultural and residential uses, so some local pumping-related depression in groundwater elevations is likely, making even the maximum observed levels slightly conservative. Since the study area only includes three wells, 12 boundary control points were created at surrounding locations where the DEM showed major drainage channels to the Mad River slough, in the Mad River channel, and at intermediate locations between study wells and boundary control points where additional elevations were needed to produce a reasonable groundwater surface.

For boundary control points, groundwater elevations were set at 1.5 m NAVD88 in Mad River Slough drainage channels west of the study area based on the expectation that the average groundwater elevation there would be somewhere between Mean Sea Level (MSL: 1.00 m) and Mean High Water (MHW: 1.81 m). Groundwater elevations in the Mad River channel were set at the channel depth near the bank and elevations for wells at intermediate locations were linearly interpolated. The resulting groundwater surface is consistent with the expected general shape based on local topography and drainage to adjacent waterbodies (Fig. 2A). Although no data were available on tidal response in the Arcata aquifer, any additional emergence and/or shoaling due to tidal forcing should be limited mostly to the seaward edge of the affected area based on the relatively large distances between the MHHW contours and actual wells (on the order of 1 km for present-day conditions—Fig. 2A). Since relatively efficient tidal response at the seaward margin is expected, the omission of tidal forcing from the analysis should make results along the seaward margin particularly conservative (cf., Willis 2014).

The present-day MHHW contour on the DEM results in direct inundation of 9% of the study area (Fig. 2B, Table 3). Comparing this contour to the depth to groundwater calculations shows that the contour does not match the predicted groundwater inundation area, lining up more closely with the transition between shallow (0–1 m depth) and intermediate (1–2 m depth) groundwater regions (Fig. 2B). This is unrealistic and suggests that while the average (during a tidal cycle) elevation of the seaward edge of the groundwater surface may be close to 1.5 m, groundwater elevation along the seaward edge probably increases significantly at higher tides to produce emergent groundwater more closely matching the MHHW contour. Thus, this model appears to be conservative with respect to groundwater emergence and shoaling, particularly along the seaward margin. Calculated depths to groundwater show that under current conditions emergent and shallow (<1 m) groundwater mostly occurs along the seaward and southern margin, but with a small patch of emergent groundwater and a substantial area of shallow groundwater around well A (Fig. 2B). Intermediate (1–2 m) depth groundwater covers 46% of the study area, with 27% of the study area having groundwater at depths greater than 2 m. While this analysis likely underestimates the areal extent of emergent and shallow groundwater as noted above, all of these areas appear to be in agricultural fields that already would be managed for the existing conditions and likely have little infrastructure.

Increasing sea level by 1 m shifts groundwater up by the same amount and results in the present-day shallow (0–1 m depth) groundwater regions becoming emergent groundwater areas, while the present-day intermediate (1–2 m depth) areas become shallow 0–1 m regions. In this scenario, the extent of emergent groundwater is a much better match with the MHHW inundation contour, although it is still slightly seaward (Fig. 2C). Groundwater inundation and shoaling calculations thus probably still are slightly conservative, indicating that emergent groundwater covers somewhat more than 27% of the study area, with shallow and intermediate groundwater covering on the order of 46 and 19% respectively. In the 1 m SLR scenario, only 7% of the study area has groundwater at depths greater than 2 m.

For the 2 m SLR case, emergent groundwater covers 73% of the study area and extends well inland of the MHHW inundation contour (Fig. 2D). The emergent groundwater boundary is almost linear between wells B and C, with a patchwork of shallow and intermediate depths inland of there. While the groundwater surface in this area is dependent on the elevations chosen

Table 7
SLR-driven groundwater inundation and shoaling at Malibu Lagoon, California under current, 1 m and 2 m SLR scenarios.

SLR scenario	Area of Malibu Lagoon (km ²)	Inundated area (emergent groundwater) (km ²)	Total land area (km ²)	Dry areas (km ²) with different depths (m) of groundwater		
				0–1 m	1–2 m	>2 m
2011 (present)	0.08	0.001	1.27	0.09	0.23	0.95
1 m SLR	0.12	0.05	1.18	0.23	0.38	0.57
2 m SLR	0.22	0.19	0.95	0.38	0.23	0.34
Areas as % of study area						
2011 (present)	5.9%	0.1%	94%	6.9%	17%	70%
1 m SLR	9.2%	3.7%	87%	17%	28%	42%
2 m SLR	16%	14%	70%	28%	17%	25%

for surface boundary control at points 8 and 12 (Fig. 2A), DEM topography is consistent with the general distribution of groundwater depths shown. In this case only 1% of the study area has depths to groundwater greater than 2 m.

4.2. Stinson Beach

Marine and SLR-driven groundwater inundation and shoaling for Stinson Beach are presented in Fig. 3A–D, with direct inundation estimates in Table 5 and areas affected by SLR-driven groundwater inundation and shoaling in Table 6. Groundwater in most of the study area is heavily impacted by inputs from onsite residential wastewater treatment systems—natural recharge is completely absent from about May to September and is sporadic in the winter months, with maximum recharge rates typically less than 15 cm/month, while onsite wastewater systems contribute on the order of 7 cm/month year-round (de Sieyes et al., 2008; de Sieyes, 2011). The groundwater surface for this site was constructed using contours from an online report prepared for the Stinson Beach County Water District (<http://stinson-beach-cwd.dst.ca.us/hydro/index.html>), which shows areas of high groundwater (1.89 m NAVD88) under residential areas on the ocean side of Seadrift Lagoon, and to a lesser degree on the Bolinas Bay side of the lagoon. Water level data for the report were collected from 9/3/1997 to 10/28/1997. The published contours are said to reflect “average” conditions—maximum elevations would be more appropriate for assessing potential groundwater emergence, but maximum elevations in the limited data collected in the study generally do not exceed nearby contours by more than ~0.15 m, and most are within 0.06 m, so no adjustment was made for this analysis. The existing contours were insufficient to produce a realistic groundwater surface along the edges of the peninsula and of the interior lagoon, so additional contours were constructed along these boundaries at a level of 1.43 m NAVD88 (between MSL (0.97 m) and MHW (1.61)), and consistent with the general slope of the groundwater surface suggested by the placement of the 1.59 and 1.89 m contours), and an intermediate contour was constructed at 1.74 m to provide a more realistic groundwater surface transition between the 1.89 and 1.59 contours shown in the report. Well elevations were collected only intermittently, but the relatively large range in values in wells close to the ocean and Bay, and smaller ranges in wells located more inland from the margins of the peninsula indicate that there is significant tidal response in the aquifer that attenuates noticeably with distance inland. Data from de Sieyes et al. (2008) show a similar pattern in tidal response in 4 wells distributed along a transect near the west end of the study area. Thus, while we did not attempt to adjust for tidal response in this analysis, it clearly is important, particularly along the edges of the peninsula, so calculations of SLR-driven groundwater emergence and shoaling will be particularly conservative in these areas. The relatively short and intermittent nature of the data collected in the field study also suggest that the groundwater surface used in this study may be even more conservative than already suggested, as the field measurements are unlikely to have captured the full range of variability in aquifer elevations.

The present day shoreline around the peninsula is roughly equivalent to the MHHW contour on the DEM, so there is no direct inundation of the study area. The lagoon covers 18% of the study area, and there is a small region (1% of the study area) at the western end of the study area with groundwater emergence, but this is an interpolation artifact due to the relatively coarse groundwater contours in this area. The area is small compared to subsequent inundation areas due to SLR, so it was not corrected for this analysis (Fig. 3B, Table 6). Most of the non-lagoon area has groundwater at depths greater than 1 m, with intermediate (1–2 m depth) groundwater covering 39% of the study area, and 30% having deeper groundwater. Shallow (0–1 m) groundwater covers only 11% of the study area and occurs primarily in undeveloped areas along the inland margin at the eastern end where Eskoot Creek enters the Bay.

Increasing sea level by 1 m shifts groundwater up by the same amount and results in the present-day shallow (0–1 m depth) groundwater regions becoming emergent groundwater areas, while the present-day intermediate (1–2 m depth) areas become shallow 0–1 m regions (Fig. 3C). In this scenario, emergent groundwater still is relatively limited in extent, although some small areas of emergent groundwater affect residential properties. While most of the homes along the seaward side of the peninsula are located in the area of the greatest depth to groundwater (typically at intermediate or greater depths), much of the developed area along the inland side of the peninsula now has shallow groundwater, with some inundation incursions along the Bolinas Bay side. Overall, in the 1 m SLR case, the lagoon has expanded slightly from

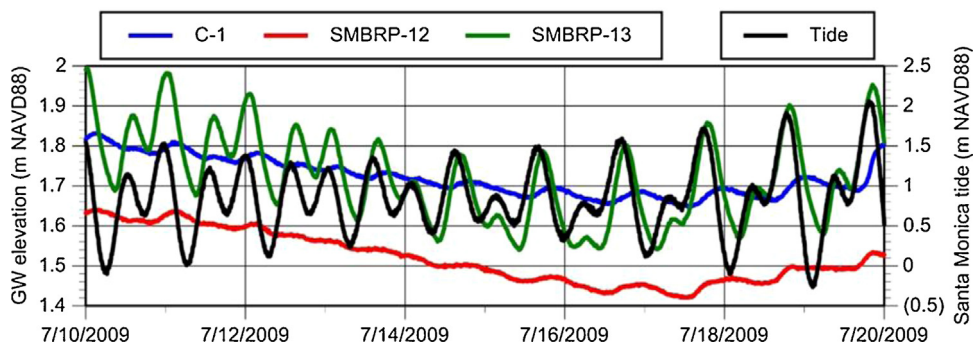


Fig. 5. Groundwater levels in select Malibu wells (SMBRP-13 [USGS 340156118411401], SMBRP-12 [USGS 340158118412401], and C-1 [USGS 340155118410201]) (J. Izbicki, pers. comm.) and observed tide (Santa Monica—NOAA, 2015). Note that well and tide data are plotted on different scales to facilitate visualization of tidal response in wells (well scale is $5 \times$ tide scale). Wells SMBRP-12, SMBRP-13 and C-1 are 65, 60 and 115 m from the ocean, respectively, but well C-1 also is in close proximity to Malibu Lagoon (Fig. 4) which likely attenuates tidal response at well C-1.

18% of the study area to 21%, inundated area has increased from 1% to 11%, and shallow and intermediate groundwater now cover 39% and 18% of the study area respectively with only 12% of the study area having deeper groundwater (Table 6).

For the 2 m SLR case, the lagoon is completely inundated, and most (70%) of the study area is covered by emergent groundwater (Fig. 3D, Table 6). Dry land exists only in a narrow strip along the seaward ridge of the peninsula and in scattered small islands, mostly along the western end of the inland portion of the peninsula. Shallow groundwater occurs over 18% of the study area, with intermediate covering 10%, and only 3% having groundwater at greater than 2 m depth.

Comparison of inundation areas for direct inundation by SLR and SLR-driven groundwater emergence in Tables 6 and 7 show that direct inundation produces more inundation than SLR-driven groundwater emergence for both 1 and 2 m SLR scenarios. This result is counterintuitive, as the addition of groundwater floating on underlying seawater would be expected to exacerbate direct inundation results. The mismatch in this case is due to the assumptions used to construct the groundwater surface, with lagoon and peninsula perimeter levels set at 1.43 m NAVD88, which is 36 cm below MHHW. While these contours are consistent with the general shape of the groundwater surface suggested by the published contours, they clearly would be incorrect under MHHW conditions, when the margins of the groundwater surface should rise with the tide. While tidal effects will be less in the interior of the peninsula, this highlights the conservative nature of the groundwater surface calculations used here and the need for more accurate groundwater surface models in areas subject to significant tidal variability. The need is particularly great for narrow peninsular geometries like Stinson Beach, where tidal forcing occurs along both sides of the land mass, and where the aquifer is made up of highly transmissive material like beach sand. However, while a refined groundwater surface model would result in some additional inundation over direct SLR inundation, direct inundation in this case already is quite severe, so the additional effects of emergent groundwater may not be as significant here as they might be in other settings.

4.3. Malibu Lagoon

Marine and SLR-driven groundwater inundation for the developed area around Malibu Lagoon are presented in Fig. 4A–D, with areas affected tabulated in Table 7. The study area around Malibu Lagoon is delineated by the areal extent of the groundwater contours used for the analysis (see below). In this analysis direct inundation effects occur almost exclusively as expansion of the lagoon area (albeit with a narrow strip of inundation along the exposed beach), so direct inundation results are combined with SLR-driven groundwater emergence and shoaling results in a single table. The modeled groundwater surface for this site was obtained by digitizing published contours from groundwater level measurements made on 9/25/2003 under flooded lagoon conditions (Stone Environmental Inc., 2004). The same study included contours for 3/9/2004 and 12/8/2009 (both under breached conditions), both of which look similar to the flooded condition contours, with none of the datasets showing distinctively higher groundwater levels near the coast than the others. While the datasets are similar, suggesting that groundwater levels in this area are relatively stable, the data almost certainly do not reflect worst-case conditions (i.e., unusually high groundwater), so they should represent a lower limit for potential groundwater shoaling and emergence. Additional emergence/shoaling due to tidal forcing seems unlikely to be a major factor here, as the report includes some data on well tidal responses that suggest only modest (decimeter scale) response. More recent data show significant damping of tidal response with distance from shore, with about 15% of the tidal signal visible in a well 60 m from shore (SMBRP-13), but only about 1% in one 115 m from shore (C-1) (Figs. 4A and 5). While the tidal response in well C-1 may be reduced by its proximity to Malibu Lagoon, which shows little to no tidal response under impounded conditions, well SMBRP-12 also has less than 1% tidal response, despite being located only 65 m from shore and being in a very similar setting to SMBRP-13 (Figs. 4A and 5). The difference in tidal response in these wells suggests significant heterogeneity in the transmissivity of the surface aquifer, as suggested by Stone Environmental Inc. (2004).

The present day MHHW contour on the DEM matches the lagoon perimeter quite closely, confirming that it is a reasonable proxy for the extent of marine inundation. Mapping depth to groundwater shows that under current conditions the lagoon is surrounded by an area of shallow (<1 m) groundwater near the ocean, with a small patch of shallow groundwater in the inland/western portion of the study area (a natural wetland), and with a few small patches in the residential area between the lagoon and the beach (Fig. 4B). Intermediate depth groundwater (1–2 m depth) is more extensive, covering 17% of the study area. Most of the shallow and intermediate groundwater areas are in undeveloped land, so impacts likely are minor, although shallow groundwater in residential areas by the beach potentially could affect infrastructure or development there. Overall, under present-day conditions the lagoon occupies only 6% of the study area and 94% is dry, with 70% of the study area having groundwater at greater than 2 m depth.

Increasing sea level by 1 m shifts groundwater up by the same amount and results in the present-day shallow (0–1 m depth) groundwater regions becoming emergent groundwater areas, while the present-day intermediate (1–2 m depth) areas become shallow 0–1 m regions (Fig. 4C, Table 7). In this scenario, 3.7% of the study area is inundated by emergent groundwater, while direct marine inundation in the lagoon has increased its size by about 50% over present-day conditions. While most of the inundated (direct marine and emergent groundwater) areas are undeveloped, a few homes near the lagoon that currently have shallow (0–1 m groundwater) would see emergent groundwater. In addition, the amount of the study area subject to shallow (0–1 m) groundwater increases from 6.9% in the present-day scenario to 17% with 1 m of SLR. This area includes most of the residential development adjacent to the lagoon and about half of the homes along the inland edge of the development to the west (Fig. 4C), as well as substantial areas in the mall development west of the lagoon, and a large zone around the wetland. In the 1 m SLR scenario, the area with intermediate (1–2 m depth) groundwater also increases significantly, from 17% to 28% of the study area. Overall the lagoon now covers 9% of the study area and 87% of the study area is dry, with 42% of the study area having groundwater at greater than 2 m depth.

For the 2 m SLR case, groundwater emerges over a large area outside of the lagoon, and most of the dry parts of the study area now have shallow groundwater (<1 m depth) (Fig. 4D). In this case 30% of the study area is under water, with over half of this the lagoon proper (now covering 16% of the study area), which is associated with expansion similar to what would be expected from direct marine inundation. Emergent areas outside of the lagoon now cover 14% of the study area, particularly along a band contiguous with the wetland, and in the residential area along the beach (Fig. 4D, Table 7). Shallow groundwater also expands dramatically, increasing to 28% of the study area. Together, emergent and shallow-groundwater conditions now cover 42% of the study area, including virtually all of the developed areas. The remainder of the study area consists of an extensive region (17% of study area) of intermediate (1–2 m) depth groundwater and a slightly larger area (25% of study area) with deeper groundwater along the eastern and inland margins of the study area, where there is more topographic relief. The lagoon now covers 16% of the study area, and while 70% of the study area technically is dry, almost all of the low-elevation areas have groundwater at shallow or intermediate depths, with only 25% of the study area having groundwater at greater than 2 m depth.

4.4. Implications

Most of the drier areas along California's coast are unlikely to be affected by SLR-driven emergence or shoaling of fresh groundwater, primarily due to low precipitation and heavy groundwater use that has resulted in lowered groundwater levels, often leading to persistent saltwater intrusion. Shallow saline aquifers may represent a more widespread pathway for SLR-driven groundwater impacts, but data are not yet available to address their areal extent and associated vulnerability. However, for fresh groundwater the case studies evaluated here show that SLR-driven groundwater shoaling and emergence may have significant impacts in certain settings. The potentially vulnerable settings identified here are Northern California coastal plains, coastal residential communities built on beach sand or sand spits, and developed areas around coastal lagoons associated with seasonal streams and berms.

1 Northern California coastal plains. Relatively high precipitation and runoff and abundant groundwater in the major drainages along the northern California coast result in extensive coastal plains with groundwater at shallow depths. The Arcata case study shows that in these systems there is potential for significant interaction between SLR and coastal groundwater, with emergent and shoaling groundwater exacerbating direct SLR inundation. Increasing inundation would result in a net loss of usable land, and changes in groundwater depth might require changes in land use, but while extensive, impacts to infrastructure in these areas may be relatively minor compared to more urban and suburban areas. A mitigation scheme here might involve direct management of groundwater by pumping and redirecting or disposing of "excess" groundwater. Such a scheme could be expensive and would require consideration of potential negative effects (e.g., exacerbated seawater intrusion), but some of the costs potentially could be offset by exporting "excess" water to areas of high water demand. It is noteworthy that vulnerability may vary even in coastal plain settings; for instance a preliminary assessment of the Oxnard coastal plain in southern California showed that fresh groundwater is present at shallow depths in monitoring wells, but the shallow pumped aquifer in this area is overlain by an even shallower, highly saline aquifer that crops out immediately offshore and is recharged by wave overwash and infiltration through coastal wetlands during high wave and flood events (Table 1) (Izbicki, 1996). In this type of system, SLR will not result in shoaling or emergence of the confined fresh groundwater, but will drive shoaling and emergence in hydraulically connected portions of the saline surface aquifer, and increased overwash and wetland infiltration due to SLR will increase recharge

to the saline surface aquifers, increasing the potential for saline groundwater shoaling and emergence in those aquifers even where they are not hydraulically connected to the adjacent ocean.

- 2 Coastal beach developments. Beach homes are a part of California's coastal landscape, and in some areas they are built directly on beach sand. In isolated areas they typically use onsite wastewater disposal systems, resulting in elevated water levels in the groundwater aquifer beneath the homes, which discharges to the ocean through the sand. While these systems have been subject to significant scrutiny due to their potential to contaminate receiving waters, the Stinson Beach case study also shows that they have the potential to exacerbate SLR inundation through emergence and shoaling of the artificial groundwater. In this case, groundwater emergence may also have health implications due to the potential for high nitrate and bacterial concentrations associated with septic discharge. Options for mitigation in this situation appear to be few—as the primary source of the groundwater is domestic wastewater, the only option would appear to be diversion of the wastewater to another disposal site. Because this likely would be very expensive, and because the degree to which SLR-driven groundwater shoaling will exacerbate direct SLR effects will depend heavily on the actual groundwater table and on tidal response, detailed groundwater studies would be needed to provide an accurate assessment of vulnerability compared to the simplified approach used here.
- 3 Coastal lagoon developments. In Central and Southern California, the relatively dry coastline is interrupted periodically by small lagoon/estuarine systems associated with small drainages. In California many of these are protected as wetlands—in these areas SLR-driven groundwater emergence will simply increase the inundated area of the lagoon/estuary and the adjacent areas with shallow and deep groundwater. However, in areas with adjacent urban or suburban development like Malibu, developed areas may be at significant risk of inundation, there may be impacts to existing infrastructure, and future development may be increasingly limited by expansion of areas of shallow and intermediate groundwater. [Table 1](#) includes two sites in central California that may fall into this category (Santa Cruz and Capitola), and there are a number of sites in southern California that were not reviewed for this study but have similar settings, including several estuarine lagoon systems between Carlsbad and Del Mar ([Fig. 1](#)). Response and remediation in these areas might be a combination of those noted above for managing “excess” groundwater in northern California coastal plains and onsite wastewater in beach communities—groundwater could be pumped and disposed of or used elsewhere (with appropriate consideration for potential negative effects and beneficial uses), and onsite wastewater could be diverted to another disposal site. As for the beach areas, detailed study of groundwater conditions and tidal response likely would be needed to determine actual vulnerability and potential responses.

5. Conclusions

The extent and degree of SLR-driven groundwater inundation and shoaling are expected to vary from one location to another in California. Differences will be driven by proximity of the water table to the ground surface, local geology, hydrology, and anthropogenic factors, e.g., the extent of groundwater extraction or additions ([Bjerklie et al., 2012](#); [Rotzoll and Fletcher, 2013](#)). Areas with shallow saline aquifers will be vulnerable to SLR-driven groundwater shoaling and emergence, but data are not yet available to assess the areal extent and importance of these aquifers. Coastal communities in central and southern California that do not have shallow saline aquifers are not expected to have major SLR-driven groundwater emergence issues, even in low-lying areas, primarily because heavy groundwater use will keep groundwater levels low. Saltwater intrusion has been and likely will continue to be the major coastal groundwater problem in these communities. However, SLR-driven groundwater emergence and shoaling may impact certain areas of the California coast, as suggested by the three case studies examined in this paper.

The study sites addressed here represent a diverse group of settings. Arcata is located in the North Coast HR coastal plains, which are associated with major drainage basins, have abundant groundwater and relatively flat terrain, and are primarily used for agriculture ([CA DWR, 2013b](#)). Impacts of SLR on urban communities and infrastructure in this HR are expected to be small, but emergence and shoaling of groundwater could substantially affect the total area available for agricultural use. Mitigation efforts could include groundwater pumping to reduce emergence and shoaling, with “excess” groundwater exported to areas of high water demand, such as central and southern California, or diverted through waterways to the ocean.

Stinson Beach is a small, predominantly residential community that exemplifies densely developed coastal communities built along sand beaches where onsite treatment systems are used for wastewater disposal, resulting in a local, concentrated input to groundwater ([de Sienes et al., 2008](#); [de Sienes, 2011](#)). Given the already severe impacts of direct SLR inundation on this site, SLR-driven groundwater inundation impacts might appear to be only a minor addition to the existing problem. However, groundwater emergence at this site may have health risks associated with it, and any groundwater emergence will accelerate flooding of the study area. Given the severity of overall inundation in the 2 m SLR case, where most of the present-day dry land in the study area is submerged, and the potential for present-day worst-case groundwater levels to be significantly higher than the “average” levels used here, additional groundwater level data would be desirable to better constrain the contribution of groundwater to SLR-driven inundation at Stinson Beach.

The area around Malibu Lagoon is representative of coastal lagoon developments in California where groundwater is a combination of native groundwater and septage from onsite treatment systems ([Izbicki, 2014](#)). In this area, groundwater emergence is expected to occur both along the coast and in low-lying inland areas, with higher elevation land separating the inundated inland area from the coastal strip. SLR-driven groundwater emergence and shoaling impacts on neighborhoods

and infrastructure could be substantial, with potential health risks due to septic contributions, but existing infrastructure also may provide options for direct management of “excess” groundwater, as suggested above for Arcata.

SLR is widely recognized as a concern in California because it could degrade coastal habitats and damage coastal infrastructure in a region that already is stressed by increasing population and expects an increasing frequency of extreme storm and wave events (Crossett et al., 2004; Heberger et al., 2009; National Research Council, 2012; Arkema et al., 2013; Hallegatte et al., 2013). Direct marine inundation likely will be the dominant mechanism of inundation in low-lying areas of the California Coast, but areas with coastal aquifers less than 4 m from the ground surface should be considered for their potential to contribute to SLR impacts via groundwater emergence and shoaling, and existing underground infrastructure such as basements, pipes, and tunnels will be increasingly vulnerable to flooding as sea level rises (Bjerklie et al., 2012). This problem will require continuing attention because coastal communities have been growing rapidly over the past century, with ~153 million Americans (~53% of the nation’s estimated population) living in coastal counties in 2003 (Crossett et al., 2004). Both maintenance of existing infrastructure and new development will become increasingly challenging and costly in vulnerable low-lying coastal regions (Hallegatte et al., 2013). It also is noteworthy that the above analyses address only the effects of overall increases in sea level and associated tides, and that transient events will produce more severe conditions. For instance, heavy precipitation can cause short-lived increases in groundwater elevations due both to increased groundwater flow from upslope areas and direct infiltration (Swarzenski et al., 2016; this issue), and low atmospheric pressures and large waves (both associated with storms) can result in unusually high tides, increasing direct inundation by direct sea-level rise and wave runup (Barnard et al., 2014). These types of events could increase groundwater levels in shallow, perched saline aquifers, and could cause transient increases in fresh groundwater elevations. While some of these elevation increases might be temporary, the impacts of associated groundwater emergence and shoaling could persist after groundwater levels decline (Cayan et al., 2008). Where the occurrence of these types of events is correlated in time, synergistic impacts could be especially damaging to low lying coastal communities (cf., Wahl et al., 2015). Current research efforts are improving our understanding of the vulnerability of California’s coastline to direct inundation due to SLR and to storm-related inundation (Barnard et al., 2014), but more detailed study of groundwater conditions in vulnerable areas will be needed to accurately predict the contribution of groundwater emergence and shoaling to SLR-related impacts in these sites.

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