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Key Points:
- Sea level rise-induced marine and groundwater flooding both threaten wastewater treatment plants
- Wastewater infrastructure exposure is spread across the coastal United States and may impact five times as many people as direct flooding of residences
- Variability in the temporal progression of flood exposure across the United States has implications for prioritizing adaptation investments

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Sea Level Rise Impacts on Wastewater Treatment Systems Along the U.S. Coasts

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Abstract As sea levels rise, coastal communities will experience more frequent and persistent nuisance flooding, and some low-lying areas may be permanently inundated. Critical components of lifeline infrastructure networks in these areas are also at risk of flooding, which could cause significant service disruptions that extend beyond the flooded zone. Thus, identifying critical infrastructure components that are exposed to sea level rise is an important first step in developing targeted investment in protective actions and enhancing the overall resilience of coastal communities. Wastewater treatment plants are typically located at low elevations near the coastline to minimize the cost of collecting consumed water and discharging treated effluent, which makes them particularly susceptible to coastal flooding. For this analysis, we used geographic information systems to assess the exposure of wastewater infrastructure to various sea level rise projections at the national level. We then estimated the number of people who would lose wastewater services, which could be more than five times as high as previous predictions of the number of people at risk of direct flooding due to sea level rise. We also performed a regional comparison of wastewater exposure to marine and groundwater flooding in the San Francisco Bay Area. Overall, this analysis highlights the widespread exposure of wastewater infrastructure in the United States and demonstrates that local disruptions to infrastructure networks may have far-ranging impacts on areas that do not experience direct flooding.

Plain Language Summary Wastewater treatment plants are susceptible to flooding resulting from sea level rise. Previous estimates of wastewater exposure have only considered the impacts of marine flooding at the local or regional scale. In this analysis, we quantify the exposure to marine flooding across the coastal United States and then consider the relative impacts of marine and groundwater flooding at the regional scale in the San Francisco Bay Area. We also estimate the number of people who may lose access to wastewater services if no actions are taken to prevent flooding at wastewater treatment plants. We find that the number of people impacted by sea level rise due to loss of wastewater services could be five times as high as previous predictions of the number of people who experience direct flooding of their homes or property. We also find that groundwater flooding poses a significant threat to wastewater plants in the San Francisco Bay region.

1. Introduction

Wastewater infrastructure plays a critical role in urban communities, providing for the safe and efficient conveyance and treatment of sewage to protect human health and the environment. In the United States, over 16,000 centralized wastewater treatment plants serve approximately 74% of the population (Environmental Protection Agency [EPA], 2004). The majority of these plants provide at least secondary treatment of wastewater before discharging to local water bodies. Some plants may also provide advanced treatment to remove additional constituents that could impair the quality of receiving waters (EPA, 2004).

Historically, in order to minimize the costs of treating wastewater, treatment plants in coastal communities have been constructed at low elevations near the coast. This facilitates the conveyance of wastewater flows to the plant by gravity and thus minimizes the number of pumping stations required. In addition, coastal locations allow for efficient discharge of treated effluent to neighboring water bodies (de Almeida & Mostafavi, 2016; Friedrich & Kretzinger, 2012). Despite the benefits of locating wastewater treatment plants in these areas, such siting can also leave plants exposed to flooding, especially due to large storm surges from hurricanes. After Hurricane Ivan made landfall in Pensacola, Florida, in September 2004, producing a 15-ft storm surge, the Emerald Coast Utilities Authority's Main Street Wastewater Treatment Plant, located within 300 yards of Pensacola Bay, experienced significant flooding and lost power. The plant resumed its treatment processes 4 days after Hurricane Ivan hit, but the utility ultimately chose to construct a new treatment plant located above the predicted Category 5 storm surge and to phase out the Main Street plant (Haag, 2009). More recently, Hurricane Harvey, which made landfall in Texas on 25 August 2017, as a Category 4 hurricane, caused as many as 40 wastewater treatment facilities to become inoperable for some length of time. Even a month later, seven plants remained inoperable (Texas Commission on Environmental Quality, 2017).

While hurricanes have historically posed a threat to wastewater infrastructure, sea level rise (SLR) is an emerging risk that also threatens to significantly disrupt the efficient treatment and discharge of wastewater. As seas rise, plants located at low elevations in coastal zones may experience permanent inundation, forcing operators to consider costly protective infrastructure or relocation. Even if protective structures are built to prevent marine flooding, rising groundwater levels could lead to constant inundation of infrastructure components (Friedrich & Kretzinger, 2012), requiring the installation of pumps to keep areas behind levees dry. Without these adaptive strategies, tanks and pipes could become overwhelmed, leading to discharges of untreated effluent. Electrical components that control operations at these plants could also be disrupted. In addition to flooding of treatment plants, higher sea levels can also prevent outfalls from functioning properly or interfere with underwater discharges of treated effluent, requiring larger pumps to overcome the increase in pressure above the outfall location (de Almeida & Mostafavi, 2016). Pumps and pipelines that convey wastewater to plants may also be threatened (de Almeida & Mostafavi, 2016; Friedrich & Kretzinger, 2012). Finally, the salinity of marine floodwaters could lead to corrosion of critical plant components (Flood & Cahoon, 2011). Thus, inundation due to SLR poses a serious threat to wastewater infrastructure in coastal communities.

While previous studies have identified wastewater treatment plants that may be exposed to SLR-induced flooding at a regional scale (Heberger et al., 2011; Karamouz et al., 2016), no studies that we are aware of have performed a comprehensive exposure analysis at the national level. In addition, few studies have considered exposure to rising groundwater tables. Flood and Cahoon (2011) used multiple regression analysis on rain and tidal data to determine the relative impacts of inflow and infiltration on wastewater treatment plant flows but did not consider the impacts in terms of flooding. Finally, many studies have focused on determining the population or infrastructure components at risk due to SLR (Haer et al., 2013; Hauer et al., 2016; Nicholls, 2002) but usually only account for those people or components within the flood hazard zone, neglecting to incorporate those who lose access to critical services such as wastewater treatment. The work presented here builds on these previous studies of SLR impacts on coastal communities by analyzing the magnitude of exposure due to marine flooding for wastewater treatment plants and their associated service populations at a national level and then considering the additional exposure due to a higher groundwater table at a regional scale. The results of this analysis demonstrate the extent of disruption that would occur if investments are not made to protect, elevate, or relocate wastewater infrastructure.

2. Methods

This work aims to provide a better understanding of the potential impacts of SLR on wastewater infrastructure in coastal communities. We focus on identifying the wastewater assets that are located in the flood hazard zone for a range of SLR scenarios, which allows for a quantitative estimate of wastewater infrastructure exposure. We do not attempt to characterize each plant's vulnerability, which is determined by the combination of exposure, susceptibility (or proneness to damage), and response capacity (or ability to recover from flooding) (Adger, 2006; Merz et al., 2010). Susceptibility and response capacity are dependent on a variety of factors that can vary greatly from one plant to the next, including the age and material composition of infrastructure components and the flood response strategies that are in place. As a result, vulnerability assessments are often better suited to the scale of the individual plant.

Our analysis is divided into three parts, which are described in more detail below. These include a national-level assessment of wastewater treatment plant exposure to a range of SLR scenarios; an analysis of exposure to SLR-induced marine flooding in the San Francisco Bay Area; and an analysis of exposure to SLR-induced groundwater flooding in the San Francisco Bay Area.

2.1. National Assessment

To study the effects of flooding, geographic information systems was used to overlay National Oceanic and Atmospheric Administration (NOAA) inundation projections for SLR scenarios from 1 to 6 ft with wastewater treatment plant locations (NOAA, 2017a). The NOAA projections are based on linear superposition of SLR, which adds specific amounts of SLR onto current mean higher high water levels and then overlays the new water levels with digital elevation data to map flooding in hydrologically connected areas (NOAA, 2017b). The projections do not include dynamic effects that would result from higher sea levels, such as interactions with topography and shoreline infrastructure (Holleman & Stacey, 2014). They also do not incorporate tides, waves, and storm surge resulting from coastal storm events, which could further expand the flood hazard zone and increase the depth of inundation (Arns et al., 2017). As a result, this analysis estimates the infrastructure at risk of permanent inundation for each scenario but does not consider the additional infrastructure that could experience disruptions during large storm events. While regional models that incorporate dynamic effects and storms do exist (Barnard et al., 2014; Lee et al., 2017; Smith et al., 2010), the NOAA projections are the most comprehensive national data set and were thus used for the national assessment of exposure.

Locations for publicly owned wastewater treatment plants were obtained from the U.S. EPA's Facility Registry Service database (EPA, 2018). Because the Facility Registry Service data consist only of point data, results of the overlay were verified using imagery to ensure that location data were accurate and that plants experiencing any level of flooding, including flooding of access roads, were included. The residential population serviced by each treatment plant was obtained from 2017 self-reported facility information summarized in the EPA's Discharge Monitoring Report Pollutant Loading Tool (EPA, 2017). To further assess the magnitude of societal impacts from wastewater treatment disruptions, we then compared the estimated number of people who would lose wastewater services at 3 and 6 ft of SLR to past predictions of the population that would experience direct flooding as a result of living in the flood hazard zone, as reported by Hauer et al. (2016).

2.2. SLR-Induced Marine Flooding in San Francisco Bay

To gain a better understanding of the risks to wastewater infrastructure at a regional scale, a more detailed analysis was performed for wastewater treatment plants in the San Francisco Bay Area. For this analysis, 36 plants were identified along the bayshore or major tributaries to the bay. These plants, listed in Table 1, have a combined average discharge of approximately 600 million gallons per day and serve over 5.7 million residents.

U.S. Geological Survey inundation projections for SLR scenarios from 25 to 200 cm were overlaid with wastewater treatment plant footprints from the Pacific Institute (Pacific Institute, 2009). The U.S. Geological Survey SLR projections were developed through the Coastal Storm Modeling System (CoSMoS) project and are considered to be the state-of-the-art projections for California (Our Coast Our Future, 2017). The CoSMoS modeling effort uses nested models to downscale global wave and tide data to the regional scale and incorporates atmospheric forcing derived from Coupled Model Intercomparison Project Phase 5 global climate models to define wave and water level boundary conditions for future SLR and storm scenarios (Barnard et al., 2009, 2014). We chose to use the CoSMoS projections for the regional assessment to capture the dynamic interactions between higher sea levels and the coastline and to be consistent with ongoing modeling efforts in the region. Wastewater treatment plant footprints encompassed all operational areas, including tanks, ponds, pumps, and operations and maintenance facilities. Using these footprints, the percent area flooded was calculated for each plant to quantify the magnitude of flooding, and thus the level of disruption, that each facility may experience. This allows for a more nuanced understanding of the progression of exposure across SLR scenarios, in contrast to the binary flooded or not flooded metric used for the national analysis.

2.3. SLR-Induced Groundwater Flooding in San Francisco Bay

In the San Francisco Bay region, groundwater basins are a mix of alluvial and fractured-rock aquifers. Alluvial aquifers comprise 31% of the entire San Francisco Bay hydrologic region and underlie most of the land adjacent to the bay, except in the northern part of the region (Department of Water Resources, 2015). In general, monitoring data on groundwater levels is lacking in the region, which has only 117 active wells monitored by public agencies and cooperating entities (Department of Water Resources, 2015).

Many previous studies of SLR impacts on infrastructure systems have focused on marine flooding, neglecting to consider the potential impacts of a rising groundwater table (Haer et al., 2013; Hauer et al., 2016; Heberger et al., 2011; Nicholls, 2002). However, past studies have shown that the area inundated due to SLR can more than double when a rising groundwater table is also accounted for (Rotzoll & Fletcher, 2013). To incorporate

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Table 1
Wastewater Treatment Plants in the San Francisco Bay Area, Organized in Geographical Order (Clockwise Around San Francisco Bay)

Facility name	Operator	NPDES permit	Service population	Average discharge (MGD)
Sausalito WWTP	Sausalito-Marin City Sanitary District	CA0038067	13,730	1.3
Tiburon WWTP	Marin County Sanitary District 5	CA0037753	6,849	0.8
Paradise Cove WWTP	Sausalito-Marin City Sanitary District	CA0037427	400	0.1
Sewerage Agency of Southern Marin WWTP	Sewerage Agency of Southern Marin	CA0037711	25,000	2.6
Central Marin Sanitation Agency WWTP	Central Marin Sanitation Ag	CA0038628	111,927	9.3
Las Gallinas WWTP	Las Gallinas Valley Sanitary District	CA0037851	30,000	2.0
Novato WWTP	Novato Sanitary District	CA0037958	56,251	4.4
Ellis Creek WRF	City of Petaluma	CA0037810	55,694	3.3
Sonoma Valley WWTP	Sonoma Valley County Sanitation District	CA0037800	29,750	3.0
Soscol WRF	Napa Sanitation District	CA0037575	110,000	6.3
American Canyon WWTP	City of American Canyon	CA0038768	12,000	2.0
Ryder Street WWTP	Vallejo Sanitation and Flood Control District	CA0037699	119,784	15.5
Benicia WWTP	City of Benicia	CA0038091	13,682	2.0
Fairfield-Suisun WWTP	Fairfield-Suisun Sewer District	CA0038024	152,000	13.4
Central Contra Costa Sanitary District WWTP	Central Contra Costa Sanitary District	CA0037648	438,920	34.8
Mt. View Sanitary District WWTP	Mt. View Sanitary District	CA0037770	22,000	1.3
Rodeo Sanitary District WWTP	Rodeo Sanitary District	CA0037826	8,515	0.6
Pinole/Hercules WWTP	City of Pinole	CA0037796	22,739	4.1
San Pablo WWTP	West County Wastewater District	CA0038539	90,000	7.8
Richmond WWTP	City of Richmond	CA0038539	101,373	25.7
East Bay Municipal Utility District WWTP	East Bay Municipal Utility District	CA0037702	781,359	55.8
San Leandro WWTP	City of San Leandro	CAL237869	55,000	5.0
Oro Loma-Castro Valley WWTP	Oro Loma-Castro Valley Sanitary District	CAL000484	182,000	12.0
Hayward WWTP	City of Hayward	CAL037869	153,000	11.3
Alvarado WWTP	Union Sanitary District	CAL337869	337,560	25.0
San Jose-Santa Clara WPCP	San Jose-Santa Clara	CA0037842	1,310,835	81.4
Sunnyvale WPCP	City of Sunnyvale	CA0037621	144,000	10.1
Palo Alto WQCP	City of Palo Alto	CA0037834	218,005	22.7
Silicon Valley Clean Water WWTP	Silicon Valley Clean Water	CA0038369	205,108	14.4
San Mateo WWTP	City of San Mateo	CA0037541	143,649	10.7
Burlingame WWTP	City of Burlingame	CA0037788	32,696	3.0
Millbrae WPCP	City of Millbrae	CA0037532	21,500	1.6
San Francisco International Airport WWTP	City and County of San Francisco	CA0038318	0	19.7
South San Francisco-San Bruno WQCP	South San Francisco	CA0038130	122,538	8.4
Southeast WWTP	San Francisco Public Utilities Commission	CA0037664	604,625	179.0
Treasure Island WWTP	San Francisco Public Utilities Commission	CA0110116	4,818	0.3
			5,737,307	600.7

Note. For each plant, the operating entity, Environmental Protection Agency National Pollutant Discharge Elimination System (NPDES) permit number, number of residents served, and average daily discharge are provided. MGD = million gallons per day.

potential groundwater impacts, an interpolated groundwater elevation surface was developed for locations within 2 km of the San Francisco Bay shoreline using groundwater level measurements taken over the past 20 years at local observation wells. The methods used to compile these measurements are described in more detail in Plane and Hill (2017). To improve the interpolation, additional groundwater elevation points were added at 100-m spacing along the San Francisco Bay shoreline, since the groundwater levels along the coastline should match mean water levels in the bay. A multiquadratic radial basis function was determined to be the optimal interpolation procedure based on leave-one-out cross-validation methods (Borga & Vizzaccaro, 1997; Davis, 1987). The interpolated groundwater elevation surface was then subtracted from the overlying topography to produce a depth-to-groundwater surface.

For each SLR scenario, we assumed that the groundwater table would increase linearly with sea levels, which is a reasonable assumption in flux-controlled groundwater systems where recharge to the ocean remains fairly constant over time (Ketabchi et al., 2016; Werner & Simmons, 2009). Thus, we added increments of 25 cm to the existing groundwater table and overlaid these new groundwater surfaces with the wastewater treatment plant footprints. This approach has been used previously to estimate SLR-induced groundwater flooding (Manda et al., 2015; Rotzoll & Fletcher, 2013). As was done for the analysis of marine flooding, the percent area flooded was calculated for each plant.

	wastewater treatment plants exposed to SLR-induced flooding						residents served by wastewater treatment plants exposed to SLR-induced flooding (thousands)					
	1ft	2ft	3ft	4ft	5ft	6ft	1ft	2ft	3ft	4ft	5ft	6ft
Maine	5	5	6	10	13	17	8	8	29	50	65	80
New Hampshire	2	2	3	3	3	4	28	28	41	41	41	51
Massachusetts			4	7	7	10			1,757	1,960	1,960	2,180
Rhode Island			1	1	2	4			8	8	14	33
Connecticut	4	7	9	11	14	17	137	236	288	384	585	824
New York	4	10	14	22	37	47	806	1,217	1,791	1,954	5,581	7,811
New Jersey	8	16	19	28	36	41	795	1,004	1,046	3,347	4,246	4,905
Delaware	1	1	3	3	5	6			2	2	13	536
Pennsylvania												
Maryland	2	8	9	16	20	22	3	23	174	197	1,833	1,892
Washington, D.C.												
Virginia	2	2	3	4	5	6	540	540	789	1,107	1,108	1,118
North Carolina	1	3	6	9	12	13	17	20	32	44	175	238
South Carolina	1	3	4	6	7	8	128	337	462	466	520	523
Georgia	1	3	4	8	8	9		145	145	195	195	195
Florida	2	6	14	28	36	41	1	304	421	1,460	2,903	3,059
Alabama						2						27
Mississippi	1	1	2	2	4	4	28	28	46	46	69	69
Louisiana	6	12	16	21	34	38	20	39	50	103	196	207
Texas	7	13	19	24	30	34	408	491	506	528	593	1,483
California	8	13	15	23	34	36	1,037	2,620	2,642	3,871	5,499	5,581
Oregon	2	2	4	7	11	13	4	4	14	41	63	71
Washington	4	4	7	12	18	22	174	174	198	523	592	692
Total	60	110	162	245	336	394	4,132	7,216	10,442	16,325	26,252	31,573

Figure 1. Wastewater exposure summarized by state. The number of wastewater treatment plants exposed to various sea level rise (SLR) scenarios and the number of residents served by those wastewater treatment plants are both included. Colors indicate the relative level of exposure for each state and SLR scenario, with green signifying low exposure and red signifying high exposure.

3. Results

3.1. National Assessment

Figure 1 summarizes the number of wastewater treatment plants and the associated service populations that are exposed to SLR scenarios from 1 to 6 ft. Colors indicate the relative level of exposure for each state and SLR scenario, with green signifying low exposure and red signifying high exposure. Across the United States, 60 wastewater treatment plants, serving over 4 million people, are exposed to flooding with 1 ft of SLR. The largest increases in exposure occur from 3 to 4 ft of SLR, when an additional 83 plants serving 5.9 million people become exposed, and 4 to 5 ft of SLR, when an additional 91 plants serving 9.9 million people become exposed. By 6 ft of SLR, a total of 394 plants is exposed, and over 31 million people could be impacted by loss of wastewater services.

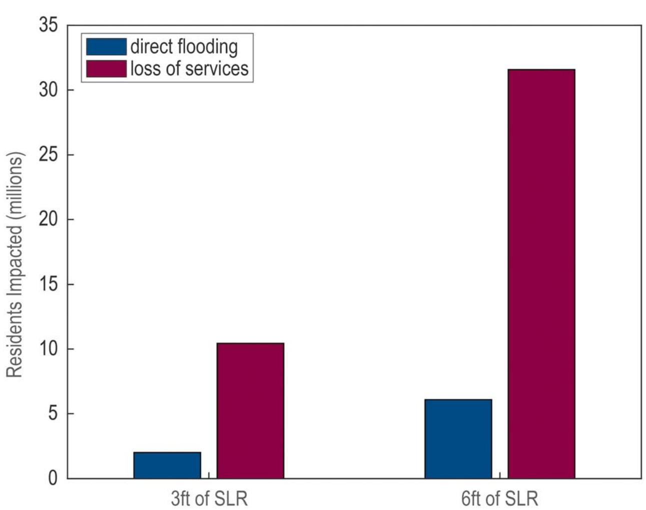

Figure 2. Comparison of population impacts from sea level rise. The blue bars show the number of residents living within the flood hazard zone, who would experience direct flooding of homes and property, from Hauer et al. (2016). The red bars show the number of people who would lose access to wastewater services due to flooding of wastewater plants.

At low levels of SLR, California, New York, New Jersey, and Virginia have the greatest exposure, each with more than 500,000 residents impacted after just 1 ft of SLR. A combined 5.4 million people in these states would be at risk of losing services at 2 ft of SLR. Other states, including Massachusetts, Florida, Maryland, and Texas, experience large increases in their exposure at 3, 4, 5, and 6 ft of SLR, respectively.

Figure 2 shows a comparison between our projections of the population that would lose access to wastewater services and previous estimates of the population living in the flood hazard zone at 3 and 6 ft of SLR (Hauer et al., 2016). Across the continental United States, approximately 10.4 million people are estimated to lose wastewater services at 3 ft of SLR, as compared to the 2.0 million people who would experience direct flooding of their homes. Similarly, 31.6 million people could be without wastewater services at 6 ft of SLR, while only 6.1 million people would be living in the flood hazard zone. Thus, when incorporating service areas, the number of people who would be negatively impacted by flooding increases more than fivefold. This illustrates the

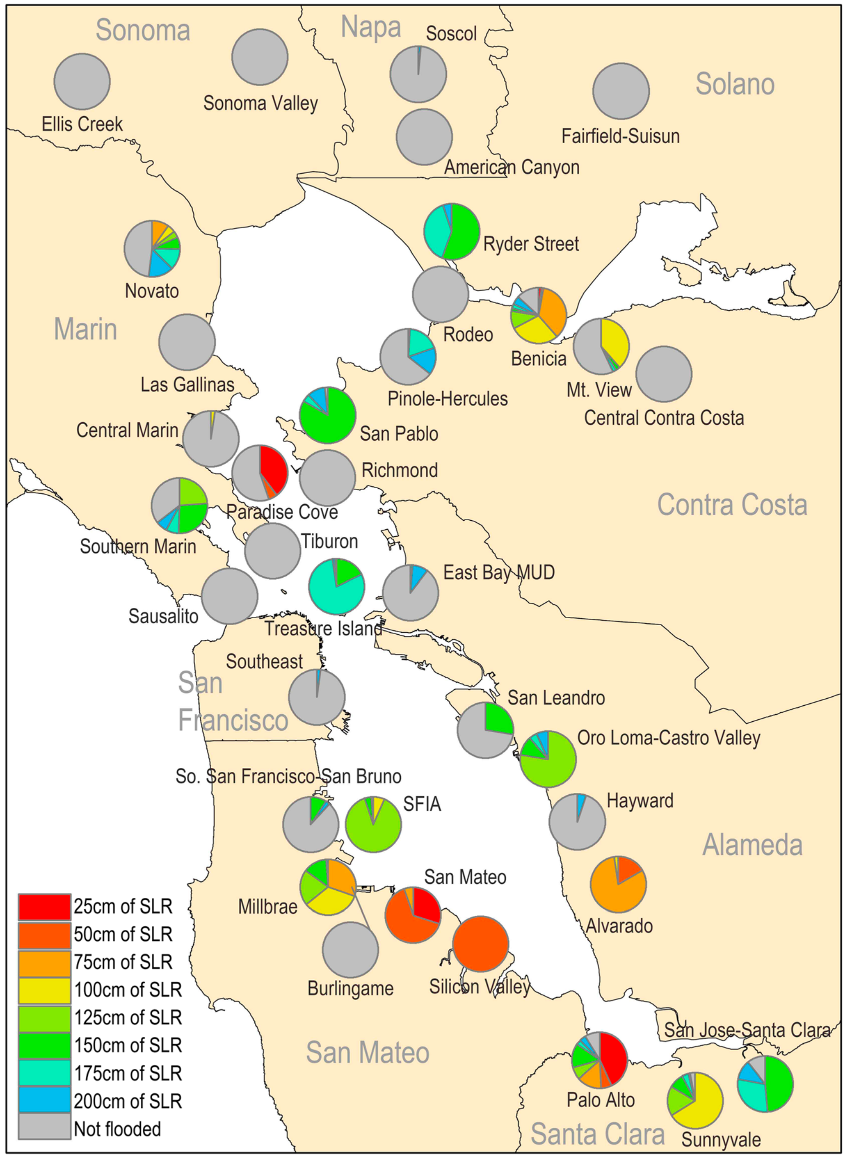

Figure 3. Map of marine flooding impacts to wastewater treatment plants in the San Francisco Bay Area. Each pie chart represents flooding at a single wastewater treatment plant and shows the incremental percent increase in area flooded at the plant for the given sea level rise scenarios.

importance of considering service areas when assessing exposure, since looking only at the people and infrastructure in the flood hazard zone can underestimate the true impacts of SLR on coastal communities.

3.2. SLR-Induced Marine Flooding in San Francisco Bay

Wastewater infrastructure in the San Francisco Bay region is particularly susceptible to impacts due to SLR. Of the 36 treatment plants in California that are exposed to flooding from some amount of SLR based on the NOAA and CoSMoS projections, 30 (or 83%) are located around San Francisco Bay.

Figure 3 shows the incremental percent increase in area flooded due to marine flooding for each wastewater treatment plant over the range of SLR scenarios. In general, plants in the southern part of San Francisco Bay are considerably more exposed to flooding at low levels of SLR than plants in the northern part of the region. By 75 cm of SLR, more than half of the Silicon Valley, Palo Alto, San Mateo, and Alvarado plants would be flooded. Other plants in the southern part of the Bay experience significant flooding at slightly higher levels of SLR, including the Sunnyvale and Millbrae plants at 100 cm of SLR, the Oro Loma-Castro Valley and San

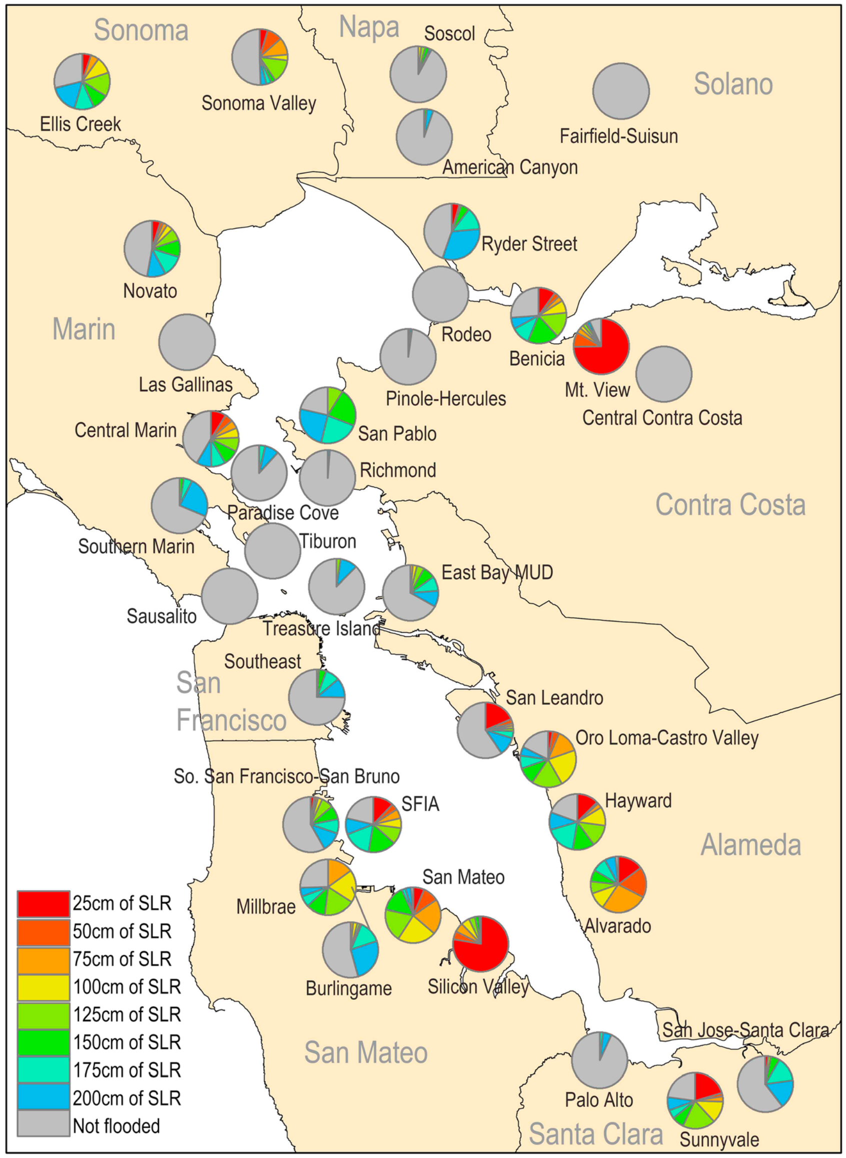

Figure 4. Map of groundwater flooding impacts to wastewater treatment plants in the San Francisco Bay Area. Each pie chart represents flooding at a single wastewater treatment plant and shows the incremental percent increase in area flooded at the plant for the given sea level rise scenarios.

Francisco International Airport plants at 125 cm of SLR, and the San Jose-Santa Clara plant at 150 cm of SLR. In the northern part of the bay, plants typically do not experience flooding of more than half of their areas until 150 cm of SLR, with the exception of the Benicia plant, which experiences 50% inundation by 100 cm of SLR. Across the region, 25% of the wastewater treatment plants experience flooding of at least a quarter of their surface areas by 100 cm of SLR.

3.3. SLR-Induced Groundwater Flooding in San Francisco Bay

Groundwater also poses a threat for wastewater treatment plants around San Francisco Bay. Figure 4 shows the incremental percent increase in area flooded due to groundwater flooding for each wastewater treatment plant over the range of SLR scenarios. Groundwater flooding primarily impacts plants in Alameda and San Mateo counties, in the southern part of the region. In contrast to marine flooding, which leads to large increases in flooded area at specific thresholds of SLR, the progression of groundwater flooding at the plants proceeds more gradually and incrementally. Three plants that are not exposed to marine flooding from SLR experience potentially significant groundwater flooding, including the Ellis Creek, Sonoma Valley, and Burlingame plants.

At low levels of SLR, groundwater flooding could have substantial impacts on the Mt. View and Silicon Valley plants, which experience over 75% inundation with only 25 cm of SLR. The Central Marin and Novato plants in Marin County, the Ellis Creek and Sonoma Valley plants in Sonoma County, the Ryder Street plant in Solano County, and the Benicia and San Pablo plants in Contra Costa County also experience significant inundation by 200 cm of SLR. Overall, by 100 cm of SLR, 28% of the plants in the region experience flooding of at least a quarter of their surface areas**.**

4. Discussion

4.1. Implications for Wastewater Treatment Plants

In this analysis, we focus on estimating the exposure of wastewater treatment plants to nuisance flooding and permanent inundation for various SLR scenarios. Previous work by Moftakhari et al. (2017) suggests that the cumulative costs of nuisance flooding may exceed costs associated with extreme flood events. In the case of wastewater infrastructure, these cumulative costs would include frequent pumping to keep critical infrastructure components dry, as well as a reduction in the life span of these components if they are frequently exposed to brackish water. Although we do not consider the compounding effects of storm events, it may be possible to quantify the effects of extreme events on wastewater exposure without creating new flood projections. For example, the Bay Conservation and Development Commission, which regulates the San Francisco Bay shoreline, has developed an approach to SLR planning called One Map, Many Futures, which proposes using total water level scenarios that can represent either permanent inundation due to SLR or infrequent inundation from temporary high tides due to extreme events (Bay Conservation and Development Commission, 2017). This approach could allow for an assessment of combined SLR and storm impacts, even in areas where regional models that incorporate tides, waves, and storm surge do not exist.

As demonstrated by the national analysis, exposure of wastewater treatment infrastructure to SLR-induced marine flooding is widespread along the U.S. coasts. When combined with estimates of the rates of relative SLR in each region or state, such as those presented by Sweet et al. (2017) suggesting that relative SLR along the East and Gulf coasts is higher than along the West Coast under certain emissions scenarios, a timeline of national wastewater exposure can be developed. Comparing the extent and timing of this exposure nationally provides important information about the progression of exposure over time, highlighting when regions first become exposed or experience large increases in exposure. These results can help decision makers at the federal and state levels identify which regions have the most imminent exposure and prioritize investments in those areas, which will promote more effective use of funding opportunities. Currently, to finance new wastewater infrastructure and upgrades to existing infrastructure, the federal government appropriates money to Clean Water State Revolving Funds. States must match 20% of the federal contribution and can then prioritize projects and provide low-interest loans to wastewater utilities (Government Accountability Office, 2015). Because of the widespread need for infrastructure upgrades and the limited funding available for adaptation actions (Government Accountability Office, 2015; Natural Resources Defense Council, 2014), understanding this time trajectory of exposure can facilitate more targeted and effective investments that can be phased to coincide with rising sea levels.

Similar insights can be obtained from the regional analysis in San Francisco Bay, providing state agencies and public work directors with information about the spatial and temporal distribution of wastewater exposure. While San Mateo and Santa Clara counties face the most imminent threat, Alameda, Marin, Contra Costa, and Solano counties will also need to invest in adaptation to protect their wastewater systems in the future (Figures 3 and 4). Some adaptation efforts are already underway in the Bay Area. For example, a pilot project at the Oro Loma plant consists of a treatment wetland, which will use native vegetation to filter effluent from the plant before discharging it to the bay and can also provide storage during wet-weather events. On the bayward side of this wetland is a horizontal levee, which has a more gradual slope than typical levees and is planted with vegetation. The vegetated slope is intended to create new habitat for local species and provide additional wave attenuation to protect the plant from SLR (Oro Loma Sanitary District, 2015). A similar solution is planned for the San Jose-Santa Clara plant (San Jose-Santa Clara Water Pollution Control Plant, 2013).

However, even if shoreline protection is implemented effectively to prevent marine flooding, groundwater still poses a threat to wastewater treatment plants. Many existing or planned shoreline adaptation projects have not considered the impact of SLR on the groundwater table and thus do not protect against rising groundwater levels (San Jose-Santa Clara Water Pollution Control Plant, 2013). Traditional levees and sea walls may even exacerbate flooding in areas with high groundwater tables by trapping water on the landward side of the shoreline, requiring pumping to keep these areas dry. Groundwater flooding not only threatens above-ground infrastructure when it emerges from the land surface but can also damage subsurface infrastructure. Groundwater may leak into pipes and other structures that are not properly sealed, causing a reduction in conveyance or storage volume. In addition, intrusion of saltwater from the coastal zone could lead to corrosion of buried infrastructure (Flood & Cahoon, 2011). Thus, in order to protect wastewater infrastructure, adaptation strategies must combat the dual threat of marine and groundwater flooding, especially at plants that are prone to both. If proper adaptation actions are not implemented, the number of residents affected by wastewater disruptions will likely be even higher than our national estimates, which are based purely on marine flooding and do not consider groundwater flooding.

4.2. Adaptation Planning at the Individual Plant Scale

Adaptation strategies are typically divided into three categories: protection, accommodation, or relocation. Protection approaches consist of building sea walls or levees to prevent marine flooding. However, these structures may not protect against groundwater flooding and could actually exacerbate flooding by trapping water that emerges from the subsurface on the landward side of the shoreline. As a result, pumping infrastructure would be required to keep the plant dry. Accommodation, which could consist of elevating structures at the plant to allow high water levels to temporarily flood the site until water levels retreat, is not a viable option at wastewater treatment plants since extensive networks of pipes and electrical components may be buried below ground. Relocation would likely provide the greatest reduction in flood exposure in the long term. However, the difficulty of finding and permitting a new location may be prohibitive, especially in highly developed areas where land is scarce and property values are high. Considering the long-term progression of SLR, protection may be feasible up to a point, after which relocation is the best alternative.

To identify the transition point between continuing to protect an existing plant and relocating, decision makers need to weigh the costs and benefits of each strategy, as well as the temporal progression of the threat of flooding and the required upgrades to aging infrastructure components. For the protection option, the cost of constructing and maintaining protective infrastructure to prevent marine and groundwater flooding must be considered, as well as the capital investments needed to maintain the current level of treatment or make necessary improvements to the treatment process. For the relocation option, the cost of acquiring land, constructing a new plant, and restructuring the sewer network must be considered. For example, the Sunnyvale plant in Santa Clara County has reported that it will need to spend $427 million over the next 20 years to improve advanced treatment processes at the plant (EPA, 2016). This plant is projected to experience moderate groundwater flooding after only 25 cm of SLR and substantial marine flooding after 100 cm of SLR. The high costs of the required capital improvements and the short timeline before SLR begins to impact the plant may suggest an earlier transition from protection to relocation. In contrast, the Palo Alto plant will only require an estimated $4.5 million in capital improvements over the next 20 years (EPA, 2016). Although the plant experiences significant marine flooding at 25 cm of SLR, it is not projected to experience substantial groundwater flooding, so protective shoreline infrastructure may be sufficient to prevent flooding at the plant for the foreseeable future.

4.3. Implications for the Wastewater Network

In addition to considering the implications of flooding at the scale of the individual plant, it is also useful to consider the wastewater treatment network as a whole. Typical wastewater systems are characterized by a tree-like network structure, with a distributed network of customers (i.e., homes and businesses) connected to sewer lines that discharge to a single wastewater treatment plant. As a result, there is little to no redundancy in these systems, and if one plant goes offline due to flooding, sewage cannot be routed elsewhere. This is in contrast to other infrastructure networks, such as the transportation system, which typically consists of multiple links connecting many distributed nodes and thus offers redundant routes between a variety of destinations. The power grid is a hybrid of these two structures, with distributed power generation and redundant transmission at the regional scale and a tree-like structure in which one substation serves a subset of customers at the local level. Thus, the transportation network and regional electric grid are characterized by both a distributed and redundant structure, which may provide greater resilience against disruptions by allowing for the maintenance of appropriate flows (Wang & Ip, 2009).

Most municipal wastewater treatment systems lack one or both of these characteristics, which makes them particularly susceptible to disruptions due to flooding. For example, Stamford, Connecticut, has only one wastewater treatment plant, which serves approximately 60% of its 123,000 residents. This plant is susceptible to flooding at 5 ft of SLR, which could threaten the entire system due to its centralized exposure and lack of interconnections with other systems. On the other hand, the greater Charleston, South Carolina, area has a more distributed wastewater network, with six wastewater treatment plants serving a total of 520,000 customers, but interconnections between these systems are still lacking. One plant serving 25% of the total customers is exposed to flooding after only 1 ft of SLR. By 3 ft of SLR, four plants serving 81% of the customers are exposed, and at 5 ft of SLR, all six plants could experience flooding. Because Charleston's system is distributed, the threat is spread out over time and does not impact the entire population at once. However, the lack of redundancy in the current system prevents sewage from flooded plants from being routed to other plants outside of the flood hazard zone. Thus, while a distributed system may provide some benefits in terms of reducing the impact felt when a single plant is flooded, this can lead to additional costs in the long run if several plants are susceptible to SLR and would all require investment in protective infrastructure. In contrast, because of the centralized structure of Stamford's wastewater system, the exposure to flooding is localized, and decision makers can focus on implementing protective actions at only one site.

The ownership structure of the wastewater treatment system may also have implications for adaptation planning. Wastewater infrastructure is typically owned and operated by local municipalities, which may limit the capacity to consider regional approaches to adaptation and resilience if individual owners have disparate visions. In the San Francisco Bay region, only two sets of plants are operated by the same entity (the Southeast and Treasure Island plants, operated by the San Francisco Public Utilities Commission, and the Sausalito and Paradise Cove plants, operated by the Sausalito-Marin City Sanitary District). In contrast, Pacific Gas and Electric provides electricity to the entire Bay Area, and the Metropolitan Transportation Commission oversees the planning and financing of the transportation network, which may make these networks more accommodating to regional approaches to SLR adaptation.

4.4. Areas for Additional Research

The results of this analysis provide an initial estimate of the exposure of wastewater infrastructure to flooding and assume that any level of flooding would lead to potential disruptions at the plants. We do not take into account microtopography (under 2 m horizontal resolution) or the elevation of infrastructure components at each plant. As a result, plants that are identified in this analysis may wish to undertake more extensive vulnerability assessments to determine which components are most at risk.

Our analysis assumes a steady state, uniform rise in the groundwater table due to SLR. However, groundwater dynamics are inherently more complex. Future work will explore the coupling of high-resolution groundwater and surface water models to simulate the impacts of various time scales of sea level changes on the groundwater table and to more accurately assess the combined threat of flooding from marine and groundwater sources.

A limitation of this approach is that it focuses mainly on wastewater treatment plants, which are the critical endpoints of the wastewater network, but does not incorporate other wastewater infrastructure components, such as sewer lines and pump stations. Even if wastewater treatment plants are protected from flooding, disruptions to pump stations could lead to backups in sewer pipes and prevent sewage from reaching the plant. Infiltration into leaky pipes could cause a reduction in capacity, which may lead to overflows of untreated sewage. Incorporating these data would allow for a more thorough characterization of the vulnerability of specific critical components and the wastewater system as a whole. Unfortunately, the quality and availability of data on pipes and pump stations vary from system to system, making a regional exposure analysis of these components difficult.

5. Conclusions

This study assessed the exposure of wastewater infrastructure to future SLR, considering marine and groundwater sources of inundation. Our findings suggest that while national exposure is spread throughout the coastal states, some areas will feel the impacts of marine inundation earlier than others. Understanding the progression of the threat is useful for decision makers who need to prioritize adaptation planning efforts. The national assessment also demonstrates the need to consider the potential cascading impacts of flooding of critical infrastructure components, which could lead to service disruptions even for those residents who live a safe distance from the coast and thus do not experience direct flooding of their properties. Our estimates do not attempt to incorporate future population changes but focus instead on the disruptions that would occur if no action is taken to adapt to rising sea levels, thus providing insight into the magnitude of investment that would be required to prevent such disruptions.

At the regional level, our findings highlight the magnitude of potential disruptions due to flooding in the San Francisco Bay Area and suggest that groundwater flooding, which is often not considered in SLR adaptation planning, could have substantial impacts on wastewater infrastructure. As a result, efforts to adapt to future flooding should consider both marine and groundwater sources and seek out innovative approaches that can address both simultaneously. In addition to plant-level adaptation, approaches that address the current deficiencies in the structure of the wastewater network as a whole should be considered in order to improve overall system resilience to flood disruptions.

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