Rising coastal groundwater as a result of sea-level rise will influence contaminated coastal sites and underground infrastructure

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Abstract

Sea-level rise (SLR) will cause coastal groundwater to rise in many coastal urban environments. Inundation of contaminated soils by groundwater rise (GWR) will alter the physical, biological, and geochemical conditions that influence the fate and transport of existing contaminants. These transformed products can be more toxic and/or more mobile under future conditions driven by SLR and GWR. We reviewed the vulnerability of contaminated sites to GWR in a US national database and in a case comparison with the San Francisco Bay region to estimate the risk of rising groundwater to human and ecosystem health. The results show that 326 sites in the US Superfund program may be vulnerable to changes in groundwater depth or flow direction as a result of SLR, representing 18.1 million hectares of contaminated land. In the San Francisco Bay Area, we found that GWR is predicted to impact twice as much land area as inundation from SLR, and 5,282 additional state-managed sites of contamination may be vulnerable to inundation from GWR in a 1.0 m SLR scenario. Increases of only a few centimeters of elevation can mobilize soil contaminants, alter flow directions in a heterogeneous urban environment with underground pipes and utility trenches, and result in new exposure pathways. Pumping for flood protection will elevate the saltwater interface, changing groundwater salinity and mobilizing metals in soil. Socially vulnerable communities are disproportionately exposed to this risk at both the national scale and in a regional comparison with the San Francisco Bay Area.

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Rising coastal groundwater as a result of sea-level rise will influence contaminated coastal sites and underground infrastructure

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Key Points:

- Rising sea levels will cause rising groundwater to inundate some coastal contaminated sites, mobilizing pollutants and causing corrosion.
- We found 326 Superfund sites that may be at risk nationally, and 5,282 state managed sites in a San Francisco Bay area comparison.
- Socially vulnerable communities are disproportionately exposed to this hazard, via impacts on indoor air, foundations and infrastructure.

Abstract

Sea-level rise (SLR) will cause coastal groundwater to rise in many coastal urban environments. Inundation of contaminated soils by groundwater rise (GWR) will alter the physical, biological, and geochemical conditions that influence the fate and transport of existing contaminants. These transformed products can be more toxic and/or more mobile under future conditions driven by SLR and GWR. We reviewed the vulnerability of contaminated sites to GWR in a US national database and in a case comparison with the San Francisco Bay region to estimate the risk of rising groundwater to human and ecosystem health. The results show that 326 sites in the US Superfund program may be vulnerable to changes in groundwater depth or flow direction as a result of SLR, representing 18.1 million hectares of contaminated land. In the San Francisco Bay Area, we found that GWR is predicted to impact twice as much land area as inundation from SLR, and 5,282 additional state-managed sites of contamination may be vulnerable to inundation from GWR in a 1.0 m SLR scenario. Increases of only a few centimeters of elevation can mobilize soil contaminants, alter flow directions in a heterogeneous urban environment with underground pipes and utility trenches, and result in new exposure pathways. Pumping for flood protection will elevate the saltwater interface, changing groundwater salinity and mobilizing metals in soil. Socially vulnerable communities are disproportionately exposed to this risk at both the national scale and in a regional comparison with the San Francisco Bay Area.

Plain Language Summary

We estimated the number of sites with known contamination in the US Superfund program at the national scale and found 326 Superfund sites that may be exposed to inundation from below as rising sea levels push groundwater higher along the coast. California, North Carolina, Virginia and New York have the largest area of federally-managed contaminated land that may be exposed. Thousands of additional sites are managed by state agencies. We conducted a comparison in the San Francisco Bay Area that included state-managed sites.

We found that 5,297 sites in the San Francisco region may be exposed to rising groundwater with SLR of 1.0 m, including 1,480 open sites, and an additional 3,817 closed sites that may contain residual contaminants. If the ratio of Superfund to state-managed sites in this region (1:352) holds, the number of at-risk contaminated sites nationally would be 115,000.

Low-income residents and people of color are disproportionately represented near these sites and therefore may face higher risks. Additional sub-regional research is urgently needed to understand these exposures. Interactions will occur between the salinity of rising coastal groundwater and shallow pumping, affecting infrastructure and building foundations. Adaptation plans must consider rising groundwater to avoid widespread failures.

1 Introduction

Higher sea levels and human adaptation actions can influence the elevation, discharge rates, and flow direction of unconfined coastal groundwater all around the world (Michael, Russoniello, and Byron 2013). Future sea levels are predicted to rise significantly in urban areas along the US coast (Sweet et al. 2022). Coastal cities have been designed for today's groundwater elevations, using the assumption that water supply pipes, sanitary sewers, storm sewers, electrical conduits, and even building foundations will either be dry or seasonally submerged in fresh groundwater. Future performance of critical infrastructure at the building and district scales is threatened by pressure and salinity changes associated with rising coastal groundwater (Tansel and Zhang 2022; Parkinson 2021; Habel et al. 2020; Hummel, Berry, and Stacey 2018; Noi and Nitivattananon 2015).

Coastal sediment, soil, and groundwater are frequently contaminated with chemicals that can threaten human and ecosystem health (Burman et al. 2022; Carter and Kalman 2020). Previous studies have identified substantial zones of mixing between fresh groundwater and ocean-derived or influenced groundwater that may strongly affect aqueous geochemical cycles and coastal water quality (Sawyer et al. 2015). A recent study estimated the number of hazardous sites that are exposed to SLR and GWR in California, and the social vulnerability of people nearby (Cushing et al 2023). However, the number of sites defined as exposed may be too low by an order of magnitude if groundwater processes are not considered using an appropriate conceptual model. No previous studies have estimated the number or area of contaminated sites that may be exposed to rising groundwater nationally in the US, or the number and characteristics of people who may be vulnerable to exposure along the US coast. In addition, no previous work has compared the national US number of sites to a detailed regional case to estimate the total number of sites managed by non-federal agencies.

Military bases, commercial sites such as fueling stations and cleaning facilities, industrial sites including oil refineries and chemical manufacturing, and transportation hubs such as air and shipping port facilities have left a legacy of contaminated land in coastal areas. The types of contaminants present on these sites are diverse: heavy metals, volatile organic compounds (VOC's), pesticides and herbicides, persistent organic pollutants, radioisotopes, and unexploded military ordnance. Contaminated earth materials including soil, sediment, and bedrock have typically been left in place and capped with low-permeability materials to exclude rainwater infiltration and isolate or immobilize contaminants (Palermo 1998). Site-scale biological, chemical, and other physical remedies have been developed and applied over the past 30 years (Warner et al. 2023). Although many *in situ* caps have not performed as intended due to the heterogeneity of site conditions and unanticipated interactions with contaminant chemistry (Pu et al. 2021), cost and environmental impact comparisons with removal actions have led to the widespread use of these *in situ* soil caps and treatment strategies instead of soil removal for treatment off-site or sequestration (Hou 2020). These site-by-site comparisons of costs and environmental impacts have not yet included the risk of rising coastal groundwater as a consequence of sea level rise.

In US law, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as Superfund, authorizes government to respond to releases or threatened releases of hazardous substances into the environment (CERCLA 1980). Contaminated sites listed on the Superfund program's National Priorities List (NPL), maintained by the US Environmental Protection Agency (EPA), received special funding for remediation and community engagement (Summers, Lamper and Buck 2021). However, Superfund sites are not necessarily contaminated with more dangerous chemicals than other sites managed by US state agencies. Most US contaminated sites are managed by state or local agencies that receive their authority to require investigation, clean-up and monitoring of both public and private sites from CERCLA. Under this authority, the spatial and temporal patterns of groundwater and chemical concentrations in soil and groundwater at contaminated sites are typically studied only within the boundaries of the legal parcel where the contamination has been identified. The often slow and iterative cycles of investigation, monitoring, negotiations and court proceedings with private owners, and remediation can take several decades, leaving many sites effectively un-remediated (Summers, Lamper and Buck 2021).

A rising sea surface can alter the elevation, discharge rates or flow directions of groundwater in the saturated zone (Bjerklie 2012; Rotzoll and Fletcher 2012; Michael, Russoniello, and Byron 2013; Abarca et al. 2013; Gonneea, Mulligan, and Charette 2013; Plane and Hill 2017, Plane, Hill and May 2019; Befus et al. 2020). As groundwater rises and inundation of soil occurs, contaminants may be transformed and mobilized (Yuan et al 2023). As contaminants are mobilized, these new flows can create unexpected exposure pathways for humans and aquatic ecosystems. For example, underground utility trenches and pipes can become conduits for the volatile component of organic chemicals, potentially introducing these contaminants into indoor air via cracked plumbing seals or openings in building foundations (Roghani et al. 2021). Additionally, the changed hydrologic and biogeochemical conditions from rising groundwater may impair the intended performance of remedies and risk-management approaches for contaminated soil and groundwater (Warner et al. 2023).

Increased pumping to protect low-elevation land or buildings can raise the saltwater interface by tens of meters (Werner, Jakovovic and Simmons 2009; de Louw et al 2013; Jakovovic et al 2016; Kim, Yoon and Lee 2019). Increasing chloride and sulfate concentrations can mobilize metals in contaminated soils (Acosta et al 2011; Wen et al 2019; Yuan et al 2023).

Aquatic organisms are sensitive to metals such as arsenic, lead and chromium that are common at contaminated sites (Peakall and Burger 2003). In addition, tidally influenced groundwater cycles may remove fines in backfill under water supply pipes, destabilizing pipes at the joints. Higher groundwater also has significant impacts on sewer pipes, infiltrating and reducing their conveyance capacity and producing increased surface flooding (Habel et al. 2020). Finally, the inland and upwards movement of saline groundwater increases corrosion rates for underground utilities and structural foundations, presenting serious risks to human health and safety from structural failures (Parkinson 2021; Abdelhafez, Ellingwood and Mahmood 2022; Tansel and Zhang 2022).

Maps of shallow unconfined groundwater at the regional or urban district scale do not yet exist for most coastal urban areas. In response to the need for planned adaptation to sea level rise, new maps of current depth-to-water for unconfined, shallow coastal groundwater have been produced in some metropolitan areas, such as the San Francisco Bay region (Plane and Hill 2017; Plane, Hill, and May 2019) and for the entire California coast (Befus et al. 2020). Similar maps have been produced in Miami-Dade County, Florida, and Hampton Roads, Virginia, to support adaptation planning. In addition, process-based projections of rising groundwater in relation to sea level have been produced using numerical groundwater software such as MODFLOW (Befus et al 2020; Habel et al 2017; Bjerklie et al 2012) using various assumptions about hydraulic conductivity to represent the heterogeneity of hydrogeologic conditions. Unlike empirical maps of past and current groundwater depth, these process-based modeling studies offer opportunities to predict and identify critical thresholds for groundwater elevation in relation to rising sea level. Process-based models also support investigations of saline groundwater movement, allow evaluation of whether and how groundwater flow directions may change, and can estimate the magnitude of increase in discharge rates for surface streams.

To date, no study has estimated how many contaminated sites in the lower 23 US coastal states may be vulnerable to a rise in unconfined coastal groundwater. This represents a new and critical adaptation planning concern for all sites with legacy contamination. A previous study has evaluated risks of direct surface inundation by rising sea level at contaminated sites managed by federal agencies on the eastern and Gulf coasts of the US (Carter and Kalman 2020). Another recent study looked at the threats that federal NPL sites face from a wide range of natural hazards across the US (Summers, Lamper and Buck 2021), but did not include rising groundwater. While studies have begun to map and quantify the risk of surface flooding at contaminated sites and to map the potential for emergent groundwater as a component of compound flooding (Rahimi et al. 2020; Burman et al. 2022), the scale of the risk of inundation from below has not yet been systematically assessed outside of California. A recent California study by Cushing et al (2023) used topographic overlay methods that did not consider the depth of the actual contaminants or infrastructure conveyance pathways in the soil, in relation to the depth of the groundwater.

These gaps in the current literature prevent public agencies from effectively protecting people, ecosystems and public infrastructure assets from sea level rise hazards. One recent investigation found that coastal urban planning does not yet consider the risk of rising groundwater as a consequence of rising sea level (Hirschfeld, Hill, and Plane 2021), although this has been changing in the San Francisco Bay Area as a result of community-level advocacy, sustained media coverage and active public agency leadership. Globally, urban planners and engineers typically intend to use levees to protect vulnerable districts from surface flooding.

Planners and engineers are often unaware that groundwater can rise on the inland side of the levee, causing health and infrastructure problems before emerging at the surface as flooding (Hirschfeld et al 2023). In the US, the threat of contaminant mobilization by rising groundwater is of particular concern since people with greater social vulnerability than is typical of the US population are more likely to live near contaminated sites (Carter and Kalman 2020).

This study assessed the number of contaminated sites in the US Superfund program that may be exposed to rising coastal groundwater in the contiguous US and used a case comparison with the San Francisco Bay Area to estimate the total number. We used topographic data to estimate groundwater levels in coastal regions and identified the boundaries of highly contaminated soil areas using US EPA's Superfund site map database. In the San Francisco Bay Area comparison, two separate state databases provided the locations of contaminated sites using street addresses. These sites typically have been treated and/or capped from above but have little or no protection from changes in subsurface flows.

We compared these site locations to maps by Befus et al (2020) that used a process-based model to estimate groundwater rise along the California coast in two sea level rise scenarios, 0.5 m and 1.0 m. The 2020 Befus et al. study concluded that the San Francisco Bay region has extensive areas where shallow unconfined groundwater will rise with sea level. Although levees and seawalls are currently in use and more are planned, emergent groundwater will continue to present significant risks on the inland side of such coastal structures. Pumping frequently occurs as a response to high groundwater, elevating the salt water interface and creating new inundation and salinity conditions in some contaminated soils, along with risks of substantial land subsidence (Jakovovich et al 2016; Kim, Yoon and Lee 2019).

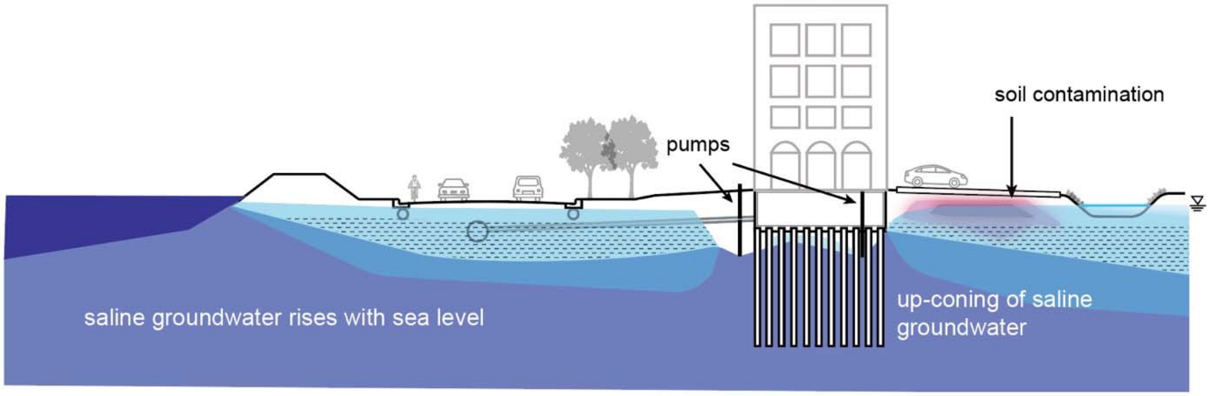
2 Methods

2.1 Conceptual Models for Contaminated Sites

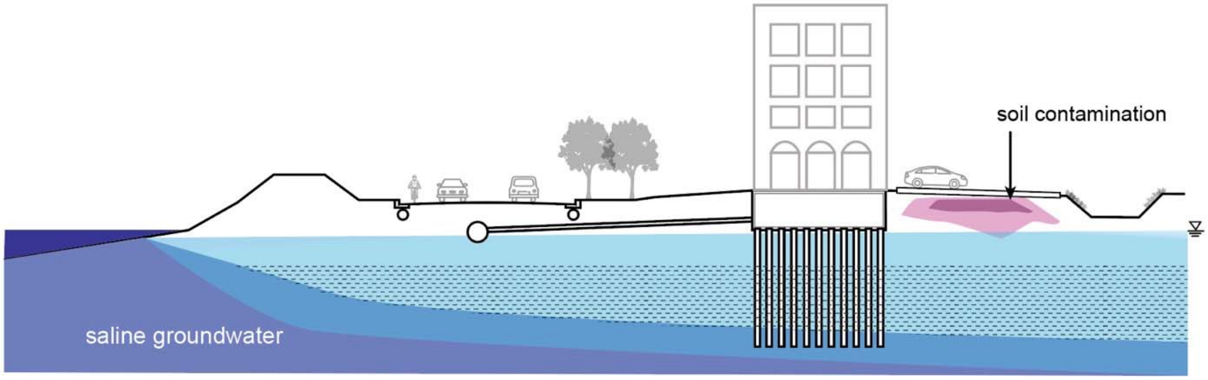
Models of coastal groundwater and contaminant movement are rarely constructed as a synthesis that includes tidal effects on a range of geochemical conditions, interactions with urban infrastructure or heterogeneous fill materials, and contaminant movement (Warner et al 2023). Yet these conditions can be highly altered by rising sea levels and infiltrating sea water, depending on the hydrogeologic environment (Pratt et al 2022). The dominant conceptual model of advection-dispersion for contaminant transport in groundwater has failed to predict the field behavior of tracers at highly monitored sites, leading to arguments for advection-diffusion as the dominant processes (Hadley and Newell 2014). In advection-diffusion, sediment grains are conceptualized as tiny baffles that induce vertical diffusion as well as lateral dispersion. The relative dominance of vertical or horizontal contaminant movement may also be influenced by the hydraulic pressure response during tidal dynamics, potentially arguing for greater consideration of diffusion as a significant process in coastal contaminant flows.

A synthetic conceptual model is needed of groundwater dynamics at coastal urban sites with increasing rates of sea level rise. It must represent heterogeneous conditions with significant anthropomorphic influences, including urban development activities such as parcel-scale pumping to protect individual structures, water and sewer pipes placed in tidally-influenced groundwater, deferred maintenance of pipe systems and building foundations, and the use of treatment or containment strategies at coastal landfills and other contaminated sites that include permeable and impermeable barriers, pumping, and injection of materials. In addition to current activities, urban fill was historically placed in large quantities in urban coastal areas. Adding fill produced large areas with highly variable hydraulic conductivities as a result of the diverse and disorganized material constituents, and heavy traffic corridors with compacted soils can elevate groundwater levels on their upgradient side (Plane, Hill, May 2019).

To account for an increased sea level, this conceptual model must also represent hydrological changes that will impact urban conditions, including geochemical interaction with contaminated soils that could lead to mobilization of contaminants (Pratt et al 2023), increased salinization that accelerates corrosion of conduits and building materials, increased liquefaction risks, changes in hydrostatic pressure, and increased groundwater discharge to streams and underground pipes (Biswas et al 2018). Successful design and management decisions for infrastructure systems and individual building sites must consider these physical and chemical drivers. Ignoring these drivers could lead to loss of life in extreme precipitation or seismic events and increase both human and ecosystem health risks from exposure to contaminants. Maintenance and replacement costs for infrastructure systems are also likely to increase.



Future conditions with rising sea level and rising groundwater.



Current conditions in coastal cities with protective levees.

Figure 1. A synthetic conceptual model of rising coastal groundwater interacting with soil constituents, soil chemistry, urban infrastructure, and pumping. Current conditions are shown in the lower diagram and future conditions in the upper diagram. Dark blue represents ocean water, medium blue is saline groundwater with a diffusion zone, light blue represents fresh

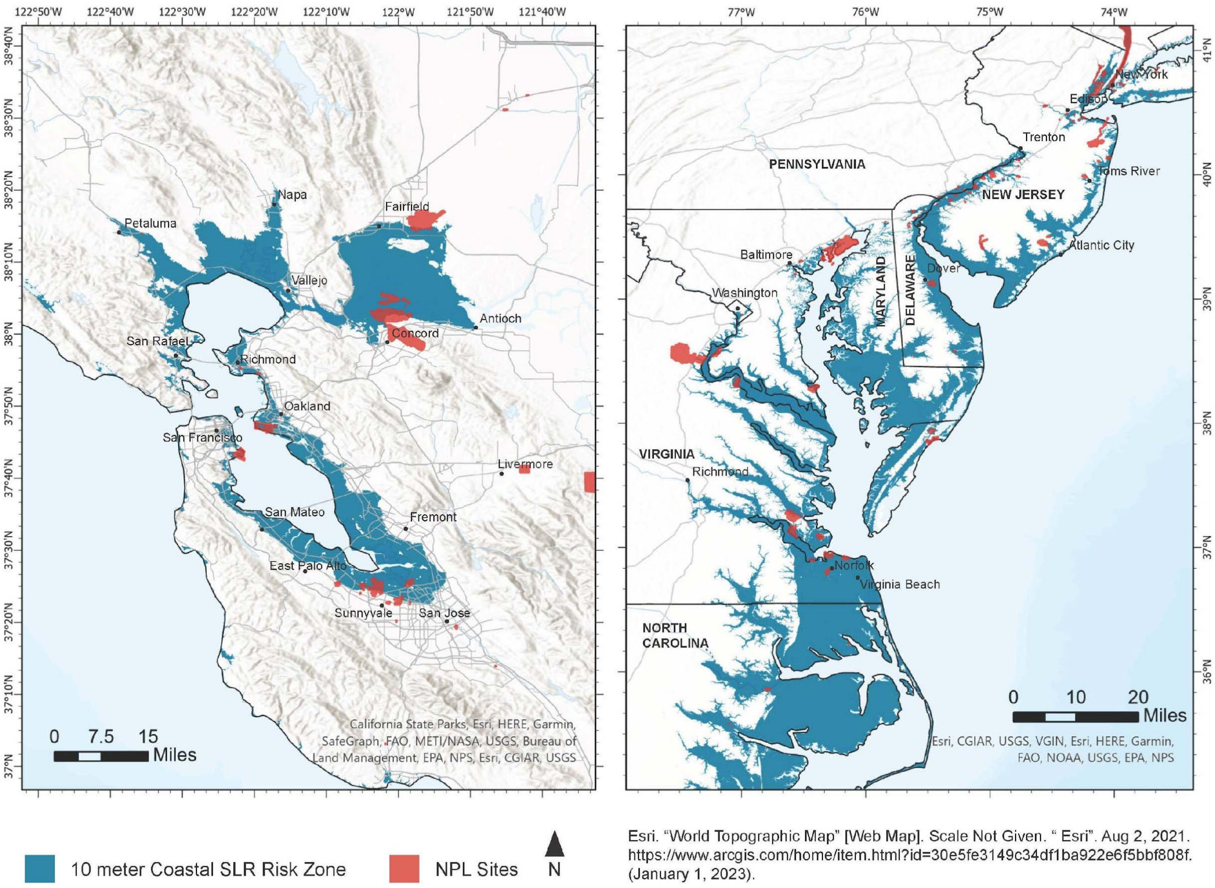
groundwater. Small horizontal dashes in the light blue zone represent anoxic groundwater conditions, and pink represents contaminated soil. Under future conditions, building foundations are exposed to more corrosive saline groundwater, particularly if pumping occurs and causes up-coning in the saltwater interface. Soil contaminants may be inundated by oxic, anoxic and saline groundwater. The sanitary sewer under the road and connected to the building, as well as the storm drains, may be infiltrated and have reduced capacity. Creek water levels will increase as groundwater discharge increases.

We propose the use of a synthetic conceptual model (Figure 1) that includes critical chemical and structural relationships affected by rising and increasingly saline groundwater. It represents the depth of fresh groundwater, which can increase liquefaction risk in seismic events; inundation of pipes and catch basins that impact infrastructure performance; the saltwater interface, which will rise in relation to sea level and will exhibit up-coning as a response to pumping, accelerating corrosion rates of foundations and pipes; and inundation of previously dry contaminated soils by groundwater. These interactions may occur even if shoreline levees are constructed. This synthetic conceptual model allows regulatory agencies, property owners, urban planners and infrastructure managers to anticipate future conditions at contaminated sites and make choices that consider the interactions of changes in these physical systems with adaptation strategies such as pumping.

2.2 National Assessment of Exposed and Contaminated Sites

To identify all Superfund sites that may be exposed to potential coastal groundwater inundation or influence from changed groundwater flow directions, we delineated coastal areas where groundwater conditions may be affected by a rising sea surface. Such coastal areas include the 23 mainland US states that are influenced by tidal flows (see Table 2). Rather than estimate exposure using distance from the tidal shoreline, we used elevation derived from digital elevation model (DEM) data provided by NOAA (Office of Coastal Management, 2023). This data was subsequently used to create two continuous coastal datasets (one for the US East and Gulf coasts, and one for the West coast). We then identified all areas of land below 10 meters of elevation as potentially exposed to rising groundwater. Elevation was selected as a key parameter rather than distance from the shoreline to recognize the important role topography plays in the relationship between rising sea levels and groundwater (Befus et al 2020). This approach is intended as a rapid assessment method designed to capture all sites with potential exposure since it can be applied to extensive and complex coastal areas where process-based groundwater maps are not yet available. The area within 10 meters of mean sea level is shown in Figure 2 for the San Francisco Bay Area (A) and Chesapeake Bay (B) to draw attention to the extensive areas at risk from rising groundwater in low-lying estuary environments.

Next, we overlaid a national dataset of US EPA Superfund contamination boundaries onto our map of coastal land located within approximately10 meters of mean sea level. For this analysis we relied on a map dataset created by Shared Enterprise Geodata and Services (SEGS) for the EPA. This dataset contains polygons that define the Operable Unit and represent the current understanding of the full extent of contamination (US EPA, 2021), and includes 1,852 Superfund sites throughout the United States. For the purposes of our analysis, we included sites that are considered either open (ie, actively being investigated or remediated) or closed (where investigation and remediation activities are considered complete). Sites that are administratively closed often contain residual contamination (dela Cruz et al 2014). We identified all Superfund sites that are fully or partially located within the topographic coastal risk area, and identified the specific contaminants located at each site based on the Contaminant of Concern Data for Decision Documents by Media, FYs 1982-2020 (US EPA, 2022). We categorized the sites as having (a) only volatile organic compounds (VOC's), (b) only metals, or (c) a mixture of pollutants that included both these types of materials as well as unusual components such as unexploded ordinances. (See Supplementary materials.)



Esri. "World Topographic Map" [Web Map]. Scale Not Given. " Esri". Aug 2, 2021. https://www.arcgis.com/home/item.html?id=30e5fe3149c34df1ba922e6f5bbf808f. (January 1, 2023).

Figure 2. Coastal areas potentially exposed to rising groundwater and National Priorities List (Superfund) sites for the San Francisco Bay (left) and the Chesapeake Bay (right), showing land with an elevation of 10m or lower in blue.

In addition, we estimated the number of socially vulnerable households in proximity to these sites that may be at risk of exposure from potential changes in groundwater level. Following the method of a previous study of contaminated sites vulnerable to surface inundation (Carter and Kalman 2020), we defined households within three different radii (one, three, and five kilometers) of Superfund sites as potentially at risk. We described these households using the American Community Survey from the US Census Bureau (US Census Bureau, 2022), which defined households living in extreme poverty as those that earn less than $30,000 per year. To identify communities of color in the risk area, we subtracted the number of "white alone" individuals from the total number of people living in each census block group. For both groups (people of color or people living in poverty) we identified the total number of people and the percentage relative to the population living in the buffer zone by replicating methods used by Carter and Kalman (2020).

2.3 San Francisco Bay Comparison with Superfund and State-Managed Sites

We used a similar study of the San Francisco Bay Area to estimate the number of state-managed contaminated sites that may be exposed to rising coastal groundwater, in addition to Superfund sites. State-managed sites are not necessarily less hazardous than federal Superfund sites and are far more numerous. A database of Superfund sites alone does not include thousands of contaminated sites in the San Francisco Bay Area, and a similar situation exists in other regions. It may be possible to establish a more realistic initial estimate of the number of exposed contaminated sites in US coastal areas using a ratio of Superfund sites to state-managed sites.

DTSC (Envirostor)		**WRCB (GeoTracker)**	
Included	*Excluded*	*Included*	*Excluded*
Border Zone/Haz Waste Evaluation	Calmortgage	NPDES	Sampling Point
Corrective Action		Cleanup Program Site	Non-Case
Evaluation		Land Disposal Site	UIC
Federal Superfund		LUST Cleanup Site	Project
Historical		Military Cleanup Site	Well Stimulation Project
Military Evaluation		Military Privatized Site	
School Clean Up		Military UST Site	
School Investigation		Other Oil and Gas	
State Response			
Tiered Permit			
Voluntary Cleanup			

Table 1. The types of contaminated sites included in this study are listed here. We included all sites that currently have or have had contamination, or are being investigated for contamination, using categories from the two California databases maintained by DTSC (Department of Toxic Substance Control) and WRCB (Water Resources Control Board).

A comprehensive set of contaminated sites was prepared by combining the sites from the two separate publicly available statewide databases of contaminated sites: Envirostor, which is managed by California Environmental Protection Agency (CalEPA), Department of Toxic Substance Control (DTSC), and GeoTracker, which is developed and maintained by the CalEPA

State Water Resources Control Board (SWRCB) (CA WRCB 2023). Most sites listed in these two databases are unique, but for historical reasons related to the timing of when a given site was regulated by a prior agency, a small number are contained in both databases. We removed duplicate site listings or location errors from the data sets, then combined the data sets to create the first comprehensive map of contaminated sites in the region. Because some sites may be closed administratively but still contain residual contamination, we included both active and closed sites in this combined dataset. Former military, landfill, industrial and commercial sites are included on this list that contain radioisotopes, volatile organic compounds (VOC's), heavy metals, and municipal household wastes, among other contaminants. The sites range in size from multiple hectares to a single parcel with a leaky underground fuel tank.

We used current and projected groundwater head from Befus et al (2020) to represent both current and future groundwater levels in the San Francisco Bay Area, with SLR scenarios of 0.5 m and 1.0 m. Befus et al (2020) produced groundwater elevation maps for a range of hydraulic conductivities (0.1 Kh, 1.0 Kh and 10.0 Kh). We selected the value of 1.0 Kh to represent what may be an average condition in a heterogeneous geomorphic region that includes artificial fill and compacted road and railroad beds, as well as Holocene alluvial fans, sand dunes and paleochannels. The modeled groundwater surfaces in Befus et al (2020) indicate that approximately twice as much land area in the Bay Area will be affected by rising groundwater in comparison to direct inundation with 1.0 m of SLR. In eight of the nine counties of the region, more land area will be affected by rising groundwater than by direct inundation in both SLR scenarios. Santa Clara County is the only part of the San Francisco Bay Area where more land will be affected by direct inundation than by rising groundwater in both SLR scenarios (see Supplemental materials).

Next, we identified the contaminated sites in this combined dataset that are currently located over shallow groundwater. We defined shallow groundwater as groundwater within approximately 3 m of the surface for two reasons: first, additional sediment has been placed on many of the larger contaminated sites, without raising the remaining soil contamination which remains close to the saturated zone; and second, because sanitary sewer pipes and other utilities are typically located within 3 m of the ground surface. Pipes and trenches create exposure pathways that can make building occupants vulnerable to VOC mobilization and health impacts (Roghani et al 2021).

We limited our analysis to areas where at least 0.10 m of groundwater rise is predicted in either the 0.5m or 1.0m SLR scenarios (Befus et al 2020). Given the relatively low resolution of the groundwater surface produced by their statewide study, we questioned the significance of very small changes in elevation and omitted those areas from our defined zones of rising groundwater.

Our final question for comparison with the national results was whether socially vulnerable communities are more exposed to risks from this emerging hazard than the general population of the San Francisco Bay Area. In a recent study, the San Francisco Bay Conservation and Development Commission (BCDC) assigned ordinal social vulnerability scores to census blocks across the entire region using variables such as income, education, and race (BCDC 2020). We used Kendall's tau to test the strength of the association between the number of exposed contaminated sites per hectare and BCDC's four ranked categories of social vulnerability using IBM SPSS Statistics (version 27).

3 Results

3.1 National Assessment of Exposed Contaminated Sites

Table 2 summarizes the data for all 23 coastal states in the contiguous United States. The table shows the total coastal area for each state we identified as at risk, the number of NPL sites that intersect with the at-risk coastal area, the area of those NPL sites, and the ratio of the area of Superfund sites to the area of coastal lowlands we defined as at risk (i.e., less than 10 meters above mean sea level in elevation). Across the 23 coastal states in the contiguous United States, we found that approximately 18 million hectares of land are at elevations low enough to potentially be impacted by groundwater rise along coastal corridors.

Louisiana, Florida, and Texas have the greatest amount of land area at risk with 4.5, 3.8, and 2.3 million hectares, respectively. A total of 326 Superfund sites are completely or partially contained within this at-risk area, covering nearly 300,000 hectares in all 23 coastal states studied. When the land area of at-risk contaminated soils on Superfund sites is compared to the total area of at-risk coastal land, California, New York, and New Hampshire have the highest proportional risks (24%, 21%, and 13% respectively). Southern and Gulf coast states have the lowest risk, since South Carolina, Mississippi, Texas, Georgia and Louisiana all have less than 0.5% of their at-risk coastal land included in Superfund contamination area. With the exception of Mississippi, this is partly due to these states' large areas of low-elevation coastal land.

State	EPA Region	Coastal SLR Risk Area (Hectares)	Number of Superfund Sites at risk of SLR	Superfund Site Area (Hectares)	Percentage Superfund Area / Coastal SLR Risk Area
Maine	1	123,584	3	1,421	1.15%
New Hampshire	1	13,488	1	1,699	12.60%
Massachusetts	1	160,854	8	10,299	6.40%
Rhode Island	1	30,563	3	1,156	3.78%
Connecticut	1	61,785	2	374	0.61%
New York	2	178,156	19	37,121	20.84%
New Jersey	2	382,655	54	12,961	3.39%
Delaware	3	198,157	16	1,773	0.89%
Pennsylvania	3	25,184	9	177	0.70%
Maryland	3	716,998	11	20,971	2.92%
District of Columbia	3	4,415	1	31	0.71%
Virginia	3	823,338	17	41,659	5.06%
North Carolina	4	1,806,062	13	46,485	2.57%
South Carolina	4	1,188,518	8	3,230	0.27%
Georgia	4	703,006	4	387	0.06%
Florida	4	3,813,313	51	18,854	0.49%
Alabama	4	265,172	5	1,907	0.72%

Mississippi	4	213,801	2	450	0.21%
Louisiana	6	4,465,579	19	819	0.02%
Texas	6	2,257,767	23	3,500	0.16%
California	9	293,723	27	70,520	24.01%
Oregon	10	162,387	6	3,587	2.21%
Washington	10	208,551	24	16,186	7.76%
TOTAL:		**18,097,055**	**326**	**295,568**	

Table 2. This table lists the number of exposed Superfund sites by US EPA region, along with the hectares of each coastal risk area, number of superfund sites in each coastal risk area, the area of contaminated land at each Superfund site, and the proportion of Superfund land area to coastal risk area for each of the 23 coastal states in the United States (excluding Alaska and Hawai'i). Total summary numbers are provided at the bottom of the table. The states are listed starting in the northeast and moving south, then west, then north, around the coastline of the contiguous United States. States are clustered by US EPA region.

Superfund site exposure for socially vulnerable populations is shown in Table 3. For each US state and three buffer distances from Superfund boundaries (1km, 3km, and 5km), Table 3 contains the percent of the total exposed population that is non-white (left) and living in extreme poverty (right). Colors highlight low percentages (blue) and high percentages (red) relative to the range within the study area. A smaller percentage of people who may be exposed are non-white in the US Northeast (Maine, New Hampshire, Massachusetts, Rhode Island & Connecticut). Our results show that in the District of Columbia, Virginia, Georgia, Mississippi, Louisiana, and California, higher percentages of residents who may be exposed to these risks are non-white, at more than 50%.

People in extreme poverty represent a lower percentage of those who may be exposed to risks from rising groundwater near Superfund sites, relative to the percentages of non-white residents. The highest percentage of people in extreme poverty who may be exposed is 22% (Georgia), while for non-white residents it is 73% (District of Columbia). Except for Texas, southern US states have higher percentages of people in extreme poverty who may be exposed to risks of rising groundwater at Superfund sites. West coast states have a relatively low percentage of people in extreme poverty who may be exposed to the risk of rising groundwater at Superfund sites.

	% of people of color			**% of people in poverty**		
State	**1km**	**3km**	**5km**	**1km**	**3km**	**5km**
Maine	12%	9%	7%	12%	11%	10%
New Hampshire	9%	9%	9%	11%	8%	8%
Massachusetts	29%	25%	24%	14%	11%	9%
Rhode Island	26%	15%	13%	10%	8%	7%
Connecticut	19%	27%	31%	5%	7%	8%
New York	37%	42%	44%	9%	10%	10%
New Jersey	40%	46%	46%	10%	9%	9%
Delaware	36%	40%	42%	11%	9%	9%

Pennsylvania	64%	47%	47%	15%	11%	11%
Maryland	40%	45%	50%	8%	9%	10%
District of Columbia	54%	64%	73%	9%	10%	11%
Virginia	67%	62%	59%	13%	12%	11%
North Carolina	32%	34%	34%	7%	10%	10%
South Carolina	41%	44%	44%	11%	13%	12%
Georgia	51%	64%	62%	22%	17%	17%
Florida	49%	48%	46%	16%	14%	13%
Alabama	29%	35%	40%	13%	14%	14%
Mississippi	59%	64%	57%	17%	17%	16%
Louisiana	60%	55%	55%	21%	18%	17%
Texas	34%	35%	35%	9%	9%	9%
California	55%	55%	55%	4%	4%	5%
Oregon	23%	23%	22%	6%	7%	7%
Washington	34%	39%	37%	7%	8%	8%

Table 3. Exposure of socially vulnerable residents summarized by state and by distance from Superfund sites. The percent of the exposed population that is non-white (left) or living in extreme poverty (right) is represented within 1km, 3km, and 5km buffer distances from at-risk Superfund sites. States are listed starting in the northeast and moving south, then west, then north around the contiguous United States. States are clustered by EPA region. Colors indicate upper and lower ends of the percentage ranges, with blue signifying relatively low percentages and red representing relatively high percentages.

3.2 San Francisco Bay Area Comparison: Superfund and State-Managed Sites

We found 15 contaminated Superfund sites within the San Francisco Bay Area that may be exposed to GWR in the 1.0m SLR scenario. We identified an additional 5,282 state-managed sites in that same scenario where soil and/or groundwater currently or formerly contained VOC's, heavy metals, radioisotopes, and other contaminant substances, establishing a ratio of 1:352 (Superfund sites to state-managed sites) in the San Francisco Bay region. Figure 3 provides examples of the density and location of contaminated sites in this urbanized area.

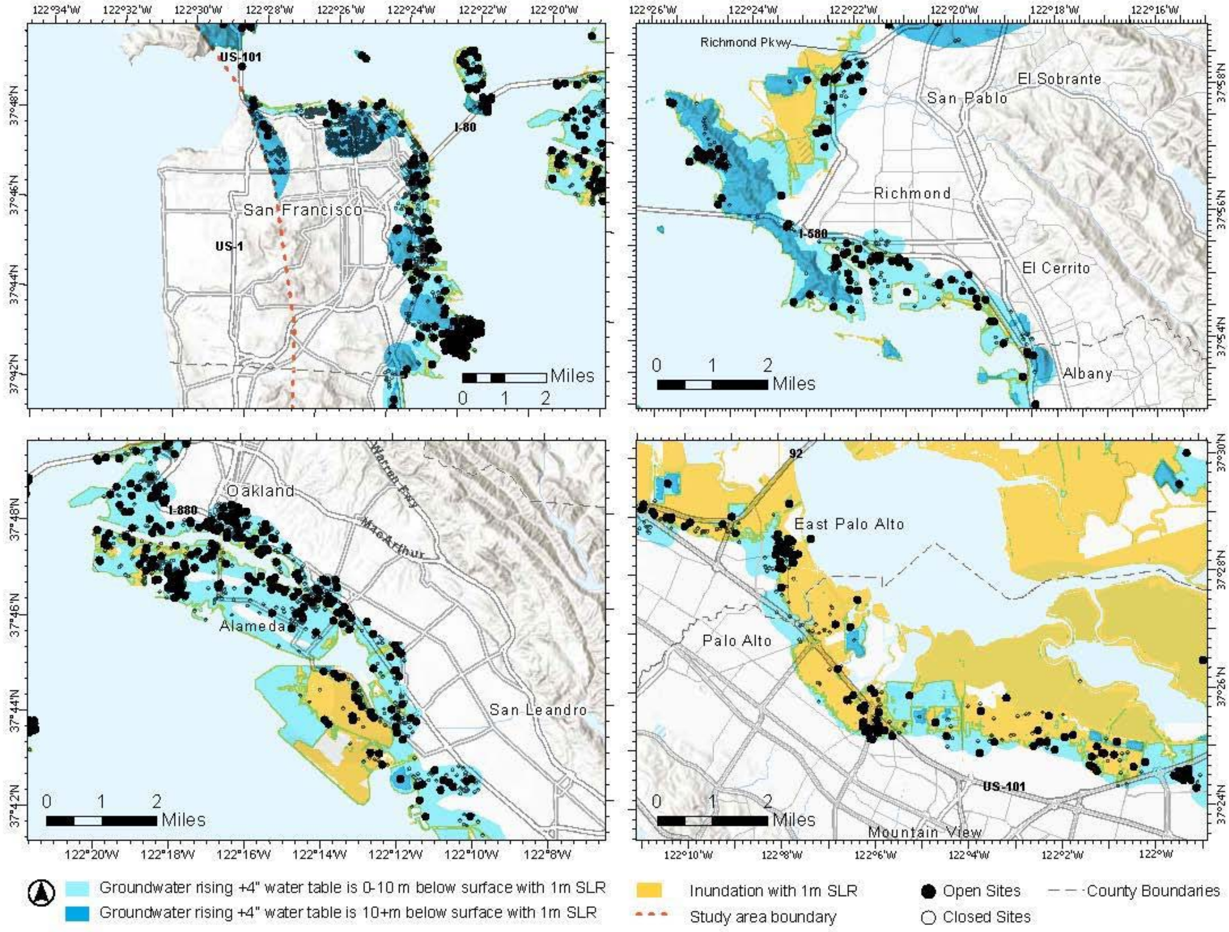


Figure 3. Maps of selected cities in the San Francisco Bay Area with Richmond at upper right, Palo Alto at lower right, Oakland at lower left, and San Francisco at upper left. Known contaminated sites (empty circles are open sites, filled black circles are closed sites) are shown where groundwater is predicted to rise (blue) or inundation is predicted to occur (yellow) in the 1.0 m SLR scenario.

SF Bay Area County	**0.5 m SLR**	**1.0 m SLR**
Alameda	339 (745)	425 (954)
Contra Costa	191 (233)	245 (344)
Marin	79 (183)	88 (225)
Napa	24 (133)	27 (168)
San Francisco	225 (535)	237 (839)

San Mateo	156 (343)	211 (552)
Santa Clara	100 (121)	127 (172)
Solano	81 (364)	91 (448)
Sonoma	20 (92)	29 (115)
Total by status	1,215 (2,749)	1,480 (3,817)
Total	3,964	5,297

Table 4. Summary by county of the number and status of contaminated sites, including Superfund sites, that are located over rising groundwater or inundated under the 0.5m and 1.0m SLR scenarios. The number of closed sites is shown in parentheses, following the number of open sites. The final total includes both open and closed sites.

Next, we estimated the number and density of potentially exposed sites in census blocks by overlaying the map of contaminated sites exposed to rising groundwater onto a map of census blocks, characterized by relative social vulnerability (BCDC 2020) (Table 5).

	Low SOVI	**Moderate SOVI**	**High SOVI**	**Highest SOVI**	**Unrated Census Blocks**
Open sites	549	368	280	142	165
Closed sites	1,627	805	724	406	181
Total area (ha)	177,790	55,860	8,363	5,010	7,586
Total sites	2,176	1,173	1,004	548	346
Site density (#/ha)	0.012	0.021	0.120	0.110	N/A

Table 5. Number and density of contaminated sites that may be exposed to rising groundwater with 1.0 m SLR within census blocks characterized by low, medium, high and highest social vulnerability (BCDC 2020). Site density includes both open and closed sites. A total of 165 open sites are in census blocks with no documented residents (115) or in open water (50) with this SLR scenario.

To test the relationship between the density of contaminated sites and social vulnerability, we first combined the two top social vulnerability categories ("high" and "highest") to obtain a land area for the upper rank with the same order of magnitude as the area for "moderate" SOVI. Using Kendall's tau (IBM SPSS Statistics, v. 27), we found that the correlation between the density of contaminated sites and increasing social vulnerability was positive and significant at the 0.01 level. Using only the density of open sites compared to these same three categories of social vulnerability, we found that the correlation was still positive and significant at the 0.01 level, suggesting that the process of remediating contaminated sites has not proceeded more quickly in areas with higher social vulnerability.

5 Conclusions

5.1 Implications of our results

A synthetic conceptual model is needed for contaminated sites that represents the full range of hazards in a changing climate including rising groundwater, changes in groundwater salinity and other chemical characteristics, and potential changes in groundwater flow direction. In the heterogeneous conditions of actual urban areas, groundwater flow directions, elevation and salinity will be altered by artificial soils, utility trenches, and pumping that occurs to protect subsurface structures from rising groundwater. Since contaminated soils will be impacted by physical and chemical changes at scales beyond the original parcel where contamination occurred, district-scale modeling will be needed to identify potential interactions and protect human and ecosystem health.

In our national assessment we found that potential exposure of Superfund sites to increases in groundwater elevations is widespread on the coast of the contiguous US. California, New York, and New Hampshire appear to have the highest proportional risks when we considered the area of exposed contaminated land vs. the total area of exposed low-elevation land in those states. California's elevated statewide risk of sea level rise impacts was also identified in a previous national study of coastal flooding that did not consider rising groundwater (Summers, Lamper and Buck 2021).

Our results for the contiguous US suggest that more low-income and non-white Americans may be exposed to the hazards associated with rising groundwater at Superfund sites. This is likely to be a result of historical and contemporary policies and market dynamics that influence housing choices and job opportunities in those communities, along with policy decisions that led to the geographic concentration of polluting land uses (Bullard 1994).

We found a ratio of at-risk Superfund sites (15) to potentially exposed state-managed sites in the San Francisco Bay Area (5,282) of 1:352. If this ratio is representative of other coastal regions, the total number of contaminated sites potentially exposed to rising groundwater in the contiguous US may be 114,752 or more. Given California's elevated exposure relative to other states, this estimate may be high. However, it is critical that all sites with potential exposure are identified so that trust can be built with local communities, as sites would be removed from the list as local investigations proceed instead of added.

As our San Francisco Bay case also demonstrated, analytical overlay methods that combine a topographic surface and a groundwater surface to identify exposed sites are inadequate where fill materials have been mounded on top of the original contaminated soils unless shallow groundwater is defined as 3m below the ground surface. This omission of potentially exposed sites would overlook most landfill sites, for example, as well as heavily contaminated military or industrial sites where the ground has been raised to create a higher elevation surface for new urban development. This type of raised surface is currently planned as a base for dense new housing at highly contaminated shoreline sites in Richmond and San Francisco, California.

In the San Francisco Bay area, SLR and GWR modeling by Befus et al (2020) predicts that twice as much land will be affected by rising groundwater as the area that will be inundated directly by SLR. Other low-lying regions around the US and the world may experience similar proportional impacts, although this is mediated by geology and vertical land motion. In addition to soil contamination, underground infrastructure and building foundations in these regions are likely to be impacted by both fresh and saline groundwater. In contexts where inspections are rare and maintenance is often deferred, this could lead to harmful health impacts and risks of system failures.

The number of contaminated sites that may be exposed to rising groundwater in the San Francisco Bay case was higher than we expected. The potential for contaminants to be mobilized at these sites represents an important new public health hazard, in addition to the potential for negative impacts on nearshore water quality and ecosystems with federally threatened and endangered species, and on important fish and shellfish resources.

Our work indicates that policy changes will be needed at the state and federal levels in the US. In 2022, the San Francisco Regional Water Quality Control Board (RWQCB), a district of the State WRCB, changed its policy to require landfill operators to consider rising coastal groundwater. California's DTSC changed its statewide policy to require managers of contaminated sites to consider rising coastal groundwater as an impact on site conditions in early 2023, without specifying how. The US Environmental Protection Agency (EPA) has committed to considering the most recent climate science as it reviews site remedies every five years but has not specifically described how these reviews will identify risks or prepare for rising coastal groundwater (US EPA 2021). These changes must become more specific by requiring the necessary scientific investigations at the sub-regional and district scales and accelerating the review of existing site remedies.

5.2 Additional Research Needs

The results of our analyses provide an initial estimate of the number and area of Superfund sites threatened by changes in groundwater elevation in US coastal regions and indicate that the percentage of socially vulnerable residents near these sites is often high. Our rapid assessment method for the national scale and our use of statewide groundwater modeling projections in the San Francisco Bay area both point to the need for many localized studies to assess exposure risks more accurately using higher-resolution process-based models of groundwater elevation and dynamics. Our method does not account for specific ways in which groundwater elevations may change in heterogeneous settings, including different soil contexts and recharge conditions (Werner and Simmons 2009, Michael et al 2013). Much future work is needed to couple high-resolution groundwater and surface water models to simulate and identify thresholds of impact in sea-level rise scenarios using the regional projections of Sweet et al. (2022) or even more accurate local projections and offer higher-resolution representations of the dynamic threat of rising groundwater.

Studies that take advantage of continuous projections of SLR over time instead of single-year scenarios will provide further insight into the timing and progression of exposure to GWR at contaminated sites, highlighting temporal thresholds in exposure risks. These results could help decision makers at the federal, regional, state and local levels identify sites that should be prioritized for protective investment or full clean-up actions. Hydraulic contaminant control measures, including a range of physical and chemical, active and passive approaches, will be necessary to control both groundwater and contaminant occurrence and migration. These control strategies will need to be coordinated at a sub-regional scale to avoid unexpected interactions and will require a change from current practice, in which both modeling and protective actions are considered on a parcel-by-parcel basis.

Future actions may also require cap and barrier materials that are durable and resilient under conditions of sea water inundation for periods that may be temporary or permanent. In cases where *in situ* management costs or technical challenges cannot be met, removal of contaminated soil and treatment or off-site sequestration may be required. These actions can create new environmental justice impacts that result from transport or landfilling. In any of these situations, new costs will impact owners and new funding mechanisms for remediation and management are likely to be required, particularly in locations with a high density of sites or extensive areas of contamination.

The most important methodological insight we gained is that regional or national-scale overlay analyses must use a greater groundwater depth as the threshold for inundation of contamination in soil because additional fill has often been mounded on contaminated sites, altering the topographic surface. The depth of the contaminants in the soil and the relationship of that depth to the saturated zone are the essential variables for process-based studies that consider the potential for rising groundwater to mobilize soil contaminants. Obtaining depth-to-contaminant information is much more difficult and may require investigators to automate acquisition of data from the extensive reports that exist for thousands of sites in each US region. Future studies will also benefit from automated methods for extrapolating contaminant movement, and spatial data for the locations of sewer pipes and other utility trenches that could allow VOC's to enter indoor air. These data acquisition challenges must be overcome to undertake more accurate process-based modeling at sub-regional scales, which is essential for identifying serious local health risks from contaminant inundation, mobilization, and flow direction in complex urbanized coastal systems.

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Open Research

US Census data used in this paper are available online (US Census Bureau, 2021). Digital Elevation Models used to identify exposed sites at the US national scale were obtained from NOAA (Office of Coastal Management, 2016). Superfund program site boundaries were produced by (U.S. Environmental Protection Agency, 2023). The data layers are stored in the DataDryad repository (doi:10.6078/D15X4N, no registration is required) along with all Geographic Information System (ArcGIS) files used in the analyses. Model output from Befus et al (2020) predicting current and future groundwater elevations in the San Francisco Bay Area is available through the US Geological Survey link in the references below (USGS 2020). Data processing for Superfund data occurred in the RStudio programming environment using (RStudio 2020). Maps and figures were made with ArcGIS, produced by ESRI, Inc. (ESRI 2022), or Adobe Illustrator (Adobe 2019).

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